CHAPTER IV

Factors Contributing to Water-Column Light Attenuation

The penetration of sunlight into coastal waters places severe constraints on the survival and spatial distribution of submerged aquatic vegetation. Currently the best estimate for the minimum amount of light required for survival of SAV is as high as 22 percent of incident sunlight for mesohaline and polyhaline estuarine species (Chapter III).

Light penetration through the water column is controlled by the amount and kinds of materials that are dissolved and suspended in the water. Quantitative understanding of the mechanisms by which the various materials affect the transmission of light through water forms the basis for setting water quality requirements for the restoration and protection of SAV. Light reaching the surface of an SAV leaf is further attenuated by attached epiphytic algae and other mineral and organic detritus adhering to the leaf. Therefore, target concentrations of optically active water quality constituents must be regarded as minimum requirements for SAV survival and growth, which may be modified as needed by conditions that promote growth of epiphytic algae on leaf surfaces (Chapter V).

This chapter documents the development and management application of diagnostic tools for defining the necessary water quality conditions to develop goals and management actions for restoring and protecting SAV. The diagnostic tool pertains only to water quality conditions that influence light attenuation within the water column. The additional light attenuation occurring at the leaf surface due to the accumulation of epiphytes and associated material is addressed in Chapter V. The process of light attenuation underwater is briefly summarized. It will be shown that, in spite of known nonlinearities, a linear expression relating the attenuation coefficient to water quality concentrations is all that is justifiable, because of the variability in the optical properties of the water quality constituents and in the measurements. The diverse origins of suspended particulate matter is one factor that increases the difficulty of modeling light attenuation over such a large geographic extent as Chesapeake Bay. The contribution of phytoplankton to total suspended solids is estimated to better define the relative roles of nutrient reduction and sediment controls increasing light penetration for different locations. The use of a linear model of light attenuation to plot a range of water quality conditions that will result in depth specific attainment of minimum light requirements is then demonstrated.

WATER-COLUMN LIGHT ATTENUATION

Light underwater is diminished by two processes: absorption and scattering (Kirk 1994). Absorption removes light altogether, whereas scattering changes the direction of propagation. Scattering does not directly remove light from the water, but rather increases the probability that it will be absorbed, by increasing the path length or distance that the light must travel.

Absorption and scattering interact in a complex and nonlinear manner to govern the attenuation of light underwater. The equations governing the propagation of light underwater, called the radiative transport equations, have no exact solution; but several computer programs have been written to solve the equations by various numerical methods (Mobley *et al.* 1993). Despite the complexities of the radiative transport equations, field measurements of underwater irradiance nearly always show a negative exponential decay of light with depth. In the absence of strong discontinuities in water quality, such as nepheloid layers, subsurface chlorophyll *a* maxima or humic-stained surface layers, measurements of photosynthetically active radiation (PAR, 400-700 nm) are well described by a single exponential equation of the form

$$I_{Z2} = I_{Z1}\exp[-K_d(Z_2 - Z_1)] \qquad \text{(IV-1)}$$

where I_{Z1} and I_{Z2} are irradiances at depth Z_1 and Z_2 ($Z_2>Z_1$), and K_d is the diffuse attenuation coefficient for PAR. Several expressions useful for describing the light available to SAV are easily derived from Equation IV-1. For example, if Z_1 represents the surface (depth=0) and Z_2 is the maximum depth of SAV colonization, Z_{max}, then the percentage of surface light penetrating through the water (PLW) to the plants at depth Z_{max} is given by

$$PLW = \exp(-K_d Z_{max})*100 \qquad \text{(IV-2).}$$

We denote the minimum PLW required for growth as the water-column light requirement (WCLR). In Equation IV-2 and the equations that follow, it should be understood that decimal fractions are being used for quantities such as PLW and WCLR, expressed as percentages (i.e. 22 percent=0.22). If WCLR is known, then the largest diffuse attenuation that would permit growth to depth=Z_{max} is given by

$$K_d = \ln(WCLR)/Z_{max} \qquad \text{(IV-3).}$$

Expressing K_d in Equation IV-3 as a function of the optically active water quality parameters forms the basis for the diagnostic tool for identifying a range of water quality conditions necessary for achieving the water-column light target.

PARTITIONING SOURCES OF WATER-COLUMN LIGHT ATTENUATION

Underwater light is attenuated by water itself and by certain dissolved and particulate substances. The optically important water quality parameters are colored dissolved organic matter or yellow substance (Kirk 1994), and suspended particulate matter. Suspended particulate matter can be further characterized by its contributions from fixed (i.e., noncombustible) suspended solids composed of clay, silt and sand mineral particles, and volatile (i.e., combustible) suspended solids composed of phytoplankton chlorophyll *a* and nonpigmented organic detritus. Each of the materials has characteristically shaped light absorption spectra. Because PAR is measured over a wide range of wavelengths, the spectral dependence of absorption means that the effect of one material, for example, phytoplankton, on light attenuation will depend on the concentrations of other materials present at the same time. For this and other reasons related to the nonlinearity of the radiative transport equations, the concept of a partial attenuation coefficient for the various optical water quality parameters is only an approximation, and one that has been criticized (Kirk 1994). In spite of these known limitations in partitioning the diffuse attenuation coefficient into contributions due to individual components, that approach is adopted here because of the need to derive a tool that is simple to use with large amounts of data and can be interpreted by managers unacquainted with the details of radiative transport theory.

First, the attenuation coefficient for downwelling (moving down through the water) light is expressed as the sum of that due to water (W) plus dissolved organic matter (DOC), phytoplankton chlorophyll *a* (Chl) and total suspended solids (TSS). Based on the analyses presented below, it is assumed that attenuation due to dissolved matter is relatively constant and may be included with water itself. We further assume that the contributions to light attenuation due to chlorophyll *a* and total suspended solids are proportional to their concentrations, so that the diffuse attenuation coefficient may be written as

$$K_d = K_{(W+DOC)} + k_c[Chl] + k_s[TSS] \qquad \text{(IV-4)}$$

where $K_{(W+DOC)}$ is the partial attenuation coefficient due to water plus colored dissolved matter, and k_c and k_s are the specific-attenuation coefficients due, respectively, to chlorophyll *a* and to total suspended solids. By combining equations IV-3 and IV-4, combinations of chlorophyll *a* and total suspended solids that just meet the WCLR may be calculated using:

$$\ln(WCLR)/Z_{max} = K_{(W+DOC)} + k_c[Chl] + k_s[TSS] \qquad \text{(IV-5).}$$

By assuming that $K_{(W+DOC)}$ is constant, Equation IV-6 can be used to calculate linear combinations of concentrations of total suspended solids and chlorophyll *a* that just meet the WCLR,

$$[TSS] = \{[\ln(WCLR)/Z_{max}] - K_{(W+DOC)}k_c[Chl]\}/k_s \qquad \text{(IV-6).}$$

For a 1-meter colonization depth and PLW equaling 22 percent, $\ln(WCLR)/Z_{max}=1.51$. Parallel lines for other colonization depths are found by dividing ln(PLW) in Equation IV-5 by the appropriate value of Z_{max}. Adjustment of the colonization depth for tidal range is a simple but important modification presented in Chapter VI.

DIAGNOSTIC TOOL COEFFICIENTS

Application of the diagnostic tool requires values for three coefficients: the attenuation due to water plus dissolved matter, $K_{(W+DOC)}$, the specific-attenuation coefficients for phytoplankton chlorophyll, k_c, and total suspended solids, k_s. Initially, coefficients (including a separate specific-attenuation coefficient for dissolved organic carbon) were estimated by multiple linear regression of K_d (dependent variable, calculated from vertical profiles of underwater quantum sensor readings measured by the Chesapeake Bay Phytoplankton Monitoring Program) against dissolved organic carbon, chlorophyll *a* and total suspended solids (independent variables) measured through the Chesapeake Bay Water Quality Monitoring Program. Statistical summaries of the measured water quality parameters at stations for which light profiles were measured are reported in Table IV-1, and results of the linear regressions are given in Table IV-2.

Due to variability in the data, coefficients of determination were generally low, and occasionally (at five stations for k_c) negative specific-attenuation coefficients were calculated. Therefore, coefficients were selected using a combination of approaches in which coefficients estimated by linear regression with the Chesapeake Bay Monitoring Program data were first examined. The resulting linear regression estimates were compared with literature values where available, and refined using the optical model of Gallegos (1994), in which individual water quality parameters can be varied independently. Predictions made with the refined linear regression were again compared with measurements made through the Chesapeake Bay Water Quality Monitoring Program to correct for overall bias.

Water Alone

The attenuation due to water alone is taken to be the intercept of a regression of K_d against the three optical water quality parameters, dissolved organic carbon, chlorophyll *a* and total suspended solids. Intercepts in the regressions of K_d against dissolved organic carbon, chlorophyll *a* and total suspended solids ranged from 0.4 to 1.1 m^{-1} at mainstem Chesapeake Bay Water Quality Monitoring Program stations, and from 0.6 to 3.2 m^{-1} at tidal tributary Chesapeake Bay Water Quality Monitoring Program stations. In general, these are very high values and cannot represent the actual attenuation due to water itself that would occur if all other optically active constituents were removed.

Light absorption by pure water varies strongly over the visible spectrum, being minimal in the blue and increasing sharply at red wavelengths. Because of the spectral narrowing caused by the selective absorption of red wavelengths, the attenuation attributable to water itself varies strongly with the depth range considered (Morel 1988). Lorenzen (1972) estimated the attenuation due to water alone to be 0.038 m^{-1}, though his measurements were for deep ocean conditions, in which measurements generally commence at depths > 5 meters.

The optical model of Gallegos (1994) with water as the only factor contributing to attenuation predicts a range of K_W from about 0.16 to 0.13 m^{-1} as the depth is varied from 1 to 3 meters. Though the variation may seem small, the same model calculates Lorenzen's (1972) value of 0.038 m^{-1} for seawater over a 51-meter depth interval. Thus, in shallow water, the attenuation due to water itself is not negligible, though much smaller than the intercepts estimated by linear regression in Table IV-2. Evidently, the regressions lump much unexplained variance into the intercept.

Dissolved Organic Carbon

Statistically significant coefficients for specific attenuation of dissolved organic carbon were obtained at only two stations, giving specific-attenuation coefficients of 0.09 and 0.2 $m^2\ g^{-1}$ (Table IV-2). The overall coefficient of determination and accompanying

TABLE IV-1. Statistical summaries of concentrations of optical water quality parameters—chlorophyll, dissolved organic carbon and total suspended solids for Chesapeake Bay Water Quality Monitoring Program stations at which underwater light measurements were made.

Station	Number of Observations	Mean	Median Derivation	Standard	Minimum	Maximum
CHESAPEAKE BAY MAINSTEM STATIONS						
Chlorophyll (μg/L)						
CB1.1	164	8.28	7.60	6.38	1.00	52.0
CB2.2	174	5.03	3.62	4.51	1.00	27.9
CB3.3C	177	15.5	11.6	15.7	1.00	105
CB4.3C	176	8.10	7.20	4.36	1.70	24.4
CB5.2	176	9.44	7.05	8.01	1.10	44.0
Dissolved Organic Carbon (mg/L)						
CB1.1	165	2.68	2.61	0.656	1.26	5.88
CB2.2	170	2.76	2.71	0.558	1.60	5.87
CB3.3C	174	2.79	2.71	0.427	0.820	4.07
CB4.3C	173	2.85	2.74	0.667	2.09	8.97
CB5.2	175	2.95	2.78	0.744	2.13	8.86
Total Suspended Solids (mg/L)						
CB1.1	174	10.8	7.18	12.8	1.50	108
CB2.2	175	16.9	14.7	11.0	1.85	87.3
CB3.3C	180	7.61	6.85	3.79	2.50	29.9
CB4.3C	179	4.59	4.40	1.33	1.60	10.3
CB5.2	181	4.91	4.50	1.80	1.50	11.5
TIDAL TRIBUTARY STATIONS						
Chlorophyll (μg/L)						
MEE3.1	5	4.72	4.69	2.15	1.82	7.79
MET4.2	7	9.26	9.12	1.92	6.94	12.71
MET5.1	141	49.6	31.80	56.29	4.58	391.2
MET5.2	137	12.05	9.64	10.30	0.83	66.18
MLE2.2	147	14.7	11.4	11.9	2.18	

continued

TABLE IV-1. Statistical summaries of concentrations of optical water quality parameters—chlorophyll, dissolved organic carbon and total suspended solids for Chesapeake Bay Water Quality Monitoring Program stations at which underwater light measurements were made (*continued*).

Station	Number of Observations	Mean	Median Derivation	Standard	Minimum	Maximum
MWT5.1	141	49.6	31.8	56.3	4.58	391
PXT0402	150	40.3	35.7	30.3	0.260	126
XDA1177	129	6.89	4.38	7.70	0.880	43.8
XDE5339	158	19.3	15.3	18.7	2.57	189
XEA6596	90	16.0	9.72	16.4	0.430	71.4
XED4892	89	14.0	11.7	13.9	0	122
Dissolved Organic Carbon (mg/L)						
MEE3.1	5	3.52	3.58	0.155	3.25	3.63
MET4.2	7	2.76	2.78	0.200	2.41	3.01
MET5.1	138	6.13	5.83	2.25	0.820	19.7
MET5.2	105	3.85	3.62	1.27	1.70	8.73
MLE2.2	110	3.33	3.27	1.22	0.820	7.84
MWT5.1	110	3.46	3.26	1.35	0.780	6.97
PXT0402	147	4.67	4.69	1.07	1.11	8.10
XDA1177	54	3.99	3.69	1.21	1.42	7.54
XDE5339	136	3.16	3.13	0.725	1.22	5.90
XEA6596	60	3.86	3.73	1.09	1.67	7.25
XED4892	86	4.52	4.50	0.854	2.27	7.09
Total Suspended Solids (mg/L)						
MEE3.1	5	13.2	16	10.6	2	27
MET4.2	7	6.57	7	3.87	1	12
MET5.1	143	33.1	30.5	17.1	5	96
MET5.2	138	13.8	12.2	9.00	1	52
MLE2.2	147	11.8	11	6.81	1	40
MWT5.1	142	17.3	15	11.3	1	58
PXT0402	152	36.1	33	19.1	1	156
XDA1177	130	20.1	18	11.5	3.5	71
XDE5339	158	11.3	9.62	6.03	1	39
XEA6596	93	19.1	17	9.37	2	51
XED4892	89	34.2	29.3	20.6	9.5	136

TABLE IV-2. Coefficients (an estimate of specific-attenuation coefficient) and intercepts (an estimate of attenuation due to water alone) estimated by linear regression of diffuse attenuation coefficient, K_d (dependent variable), against concentrations of dissolved organic carbon, phytoplankton chlorophyll and total suspended solids. Data from Chesapeake Bay Water Quality Monitoring Program, but limited to stations at which underwater light measurements were made. ns = not statistically significant, P>0.05.

Station	Coefficient of Determination	Degrees of Freedom	Intercept	Dissolved Organic Carbon (m^2g^{-1})	Phytoplankton Chlorophyll (m^2mg^{-1})	Total Suspended Solids (m^2g^{-1})
Mainstem Chesapeake Bay						
CB1.1	0.569	104	0.581	0.1015 ns	0.0022 ns	0.101
CB2.2	0.528	117	1.143	-0.0100 ns	-0.0082 ns	0.074
CB3.3C	0.453	129	0.610	0.0142 ns	-0.0012 ns	0.076
CB4.3C	0.148	121	0.533	-0.0091 ns	0.0192	0.041
CB5.2	0.271	121	0.393	0.0209 ns	0.0105	0.042
Tidal Tributaries						
MET5.1	0.208	96	3.227	0.1960	-0.0236	0.033
MET5.2	0.378	80	0.605	0.0931	0.0170	0.013
MWT5.1	0.530	78	1.581	-0.0493 ns	0.0108	-0.001 ns
PXT0402	0.109	104	2.833	0.3065 ns	-0.0113 ns	0.043
XDA1177	0.338	42	1.327	0.0695 ns	-0.0153 ns	0.047
XDE5339	0.219	100	0.807	0.0409 ns	0.0048 ns	0.042
XEA6596	0.321	47	1.271	0.0074 ns	0.0020 ns	0.064
XED4892	0.463	71	2.096	0.1225 ns	-0.0461	0.058

coefficients for specific-attenuation of total suspended solids were anomalously low at these two tidal tributary stations, casting doubt on the reliability of these values.

Only a variable fraction of dissolved organic carbon, referred to as colored dissolved organic matter, contributes to light attenuation (Cuthbert and del Giorgio 1992). Therefore, the lack of statistically significant coefficients at most stations is not surprising. Colored dissolved organic matter absorbs light but does not contribute appreciably to scattering (Kirk 1994). In the PAR waveband, absorption by colored dissolved organic matter is maximal in the blue region of the spectrum and decreases exponentially with wavelength. Optically, the effect of colored dissolved organic matter on attenuation is best quantified by the absorption coefficient of filtered estuary water (0.2 or 0.4 mm membrane filter) at a characteristic wavelength, which, by convention, is most often 440 nm (Kirk 1994).

In an effort to quantify the contribution of colored dissolved organic matter to attenuation, the regression of Gallegos *et al.* (1990) between absorption coefficient (corrected to 440 nm) and dissolved organic carbon was incorporated into the model of Gallegos (1994). Water quality conditions for other parameters, chlorophyll *a* and total suspended solids, were chosen to represent average conditions for a range of water quality monitoring stations along the upper length of the mainstem Chesapeake Bay (Table IV-1).

The specific attenuation coefficient of dissolved organic carbon calculated by the model varied from 0.026 m^2 g^{-1} for upper Bay tidal fresh conditions to 0.031 m^2 g^{-1} for lower Bay mesohaline conditions. Concentrations of dissolved organic carbon were surprisingly uniform along the axis of the mainstem Chesapeake Bay, ranging from about one to six mg $liter^{-1}$ in the upper Chesapeake Bay to two to nine mg $liter^{-1}$ at station CB5.2, located in the mainstem Chesapeake Bay off the mouth of the Potomac River (Table IV-1). The contribution of dissolved organic carbon to light attenuation can, therefore, be expected to average about 0.07 m^{-1} and range from about 0.03 to 0.23 m^{-1}. The average contribution of dissolved organic carbon to light attenuation is less than that of water itself (i.e., >0.13 m^{-1}, see above) in shallow systems and therefore can be expected to be difficult to detect in monitoring data, which are subject to expected levels of sampling and analytical error.

Therefore, as discussed above, the effect of dissolved organic carbon was incorporated into the regression for K_d as a constant term lumped in with the attenuation due to water itself. It must be recognized that this approximation will not be applicable to tidal tributaries with high concentrations of humic-stained water, such as the Pocomoke River. Site-specific approaches will be needed to tailor the diagnostic tool for such systems, including collection of optically relevant water quality data, namely absorption by dissolved matter at 440 nm (ideally) or color in Pt. units.

A trial value for the combined attenuation due to water and dissolved organic carbon, $K_{(W+DOC)}$, was determined by setting total suspended solids and chlorophyll *a* concentrations in the model of Gallegos (1994) to zero, and allowing concentrations of dissolved organic carbon to vary according to a normal distribution with mean of 2.71 mg $liter^{-1}$ and standard deviation of 0.44 mg $liter^{-1}$, similar to observations at Chesapeake Bay Water Quality Monitoring Program station CB3.3C (Table IV-1). Attenuation due to water and dissolved organic carbon calculated in this manner varied from 0.21 to 0.31 m^{-1} and averaged 0.26 m^{-1}, which was used as a trial value.

Phytoplankton Chlorophyll

Phytoplankton, being pigmented cells (i.e., particles), contribute both to absorption and the scattering of light. Light absorption by phytoplankton varies strongly with wavelength. The shape of the *in vivo* absorption spectrum of phytoplankton varies with species, but generally, peaks occur at about 430 nm and at 675 nm, with a broad minimum in the green region of the spectrum (Jeffrey 1981). Because of this spectral dependence, the contribution of phytoplankton to attenuation varies with the depth and composition of the water (Atlas and Bannister 1980), and to a lesser extent in natural populations, with species composition.

By linear regression on data from the Chesapeake Bay Water Quality Monitoring Program, statistically significant estimates for the specific-attenuation coefficient for chlorophyll *a* were obtained at 6 of 13 stations (Table IV-2). Two of those were negative values and must be considered spurious. Significant positive values ranged from 0.011 to 0.019 m^2 (mg Chl)$^{-1}$. This range compares favorably with values reported in the literature. For example, Atlas and Bannister (1980) used a fixed specific absorption spectra and calculated a range of the chlorophyll-specific attenuation coefficients near the surface ranging between 0.013 and 0.016 m^2 (mg Chl)$^{-1}$. The overall magnitude of the chlorophyll-specific absorption spectrum, however, varies considerably with physiological state, photoadaptation, and recent history of light exposure of the phytoplankton population. A wider survey of the literature, reviewed by Dubinsky (1980) suggested values between 0.005 and 0.040 m^2 (mg Chl)$^{-1}$, but most estimates range more narrowly between 0.01 to 0.02 m^2 (mg Chl)$^{-1}$ (Lorenzen 1972; Smith and Baker 1978; Smith 1982; Priscu 1983).

Model-generated estimates of k_c can be similarly variable. The effect of chlorophyll *a* on K_d is incorporated in the optical model through the chlorophyll-specific absorption spectrum. The coefficient of variation in measured chlorophyll-specific absorption spectra in the Rhode River was about 50 percent (Gallegos 1994) and overall range varied by about a factor of four (Gallegos *et al.* 1990). When this degree of variability in the chlorophyll-specific absorption spectrum is incorporated into the optical model of Gallegos (1994), calculated k_c range from <0.01 to 0.035 m^2 (mg chl)$^{-1}$, with an average of about 0.016 m^2 (mg Chl)$^{-1}$. Therefore, an initial estimate for k_c of 0.016 m^2 (mg Chl)$^{-1}$ was chosen. This value is near the center of the observed range and is commensurate with the optical water quality model and literature estimates (Bannister 1974; Smith and Baker 1978; Priscu 1983).

Total Suspended Solids

Statistically significant estimates for the specific-attenuation coefficient for total suspended solids were obtained by the linear regression analysis at all but one station (Table IV-2). Values for k_s ranged from 0.013 to 0.101 m^2 g^{-1}. Because of the wide range of coefficients and because the lower values (< 0.05 m^2 g^{-1}) were generally associated with lower coefficients of determination (Table IV-2), literature and model-generated values for k_s were also examined.

Literature estimates of k_s in estuaries tend to cluster around the middle of the range estimated from the Chesapeake Bay Water Quality Monitoring Program data. For example, Cloern (1987) estimated k_s of 0.06 m^2 g^{-1} for San Francisco Bay, similar to Malone's (1976) value for the New York Bight. Pennock (1985) estimated a specific-attenuation coefficient of 0.075 m^2 g^{-1} in the Delaware Estuary, similar to two of the mainstem Chesapeake Bay water quality stations (Table IV-2). Verduin (1964; 1982 cited in Priscu 1983) found k_s averaged 0.12 m^2 g^{-1} for a number of river-dominated freshwater systems, similar to the regression estimate for upper Chesapeake Bay station CB1.1 (Table IV-2).

The optical model of Gallegos (1994) accounts for the combined effects of scattering and absorption by suspended particulate matter using the equations of Kirk (1984). As discussed above, scattering contributes to light attenuation by increasing the path length that light travels, thereby increasing the probability of absorption. Direct measurement of scattering is difficult; but by fortunate coincidence, the turbidity of a water sample measured in nephelometric turbidity units (NTU) using commercially available turbidimeters has been shown to be a good estimate of scattering coefficient in relatively turbid waters, including estuaries, by a number of authors (Kirk 1981; Oliver 1990; Di Toro 1978; Vant 1990). Operationally, this is understandable from the manner in which a turbidimeter works, i.e., by measuring the intensity of light scattered at 90 degrees from a beam shone upward through the bottom of the sample. That the units of the measurement should scale with scattering coefficient is, however, serendipitous (Kirk 1981).

Turbidity has not been routinely monitored in the Chesapeake Bay Water Quality Monitoring Program. Measurements in two systems, the Rhode River, Maryland, a Chesapeake Bay tidal tributary, and Chincoteague Bay, a coastal lagoon on the Maryland-Virginia border, indicate that scattering in both systems is strongly dominated by the mass concentration of suspended solids (Figure IV-1A). The relationship between turbidity and total suspended solids in the two systems was nearly identical, despite a much greater contribution of chlorophyll *a* to the suspended material in the Rhode River (Figure IV-1B) (Gallegos 1994). Evidently, phytoplankton contribute to scattering on a dry-weight basis approximately as much as inorganic suspended solids and organic detritus. The generality of these observations is uncertain. It is likely that relationships as precise as these would be difficult to obtain if the geographic extent or length of time

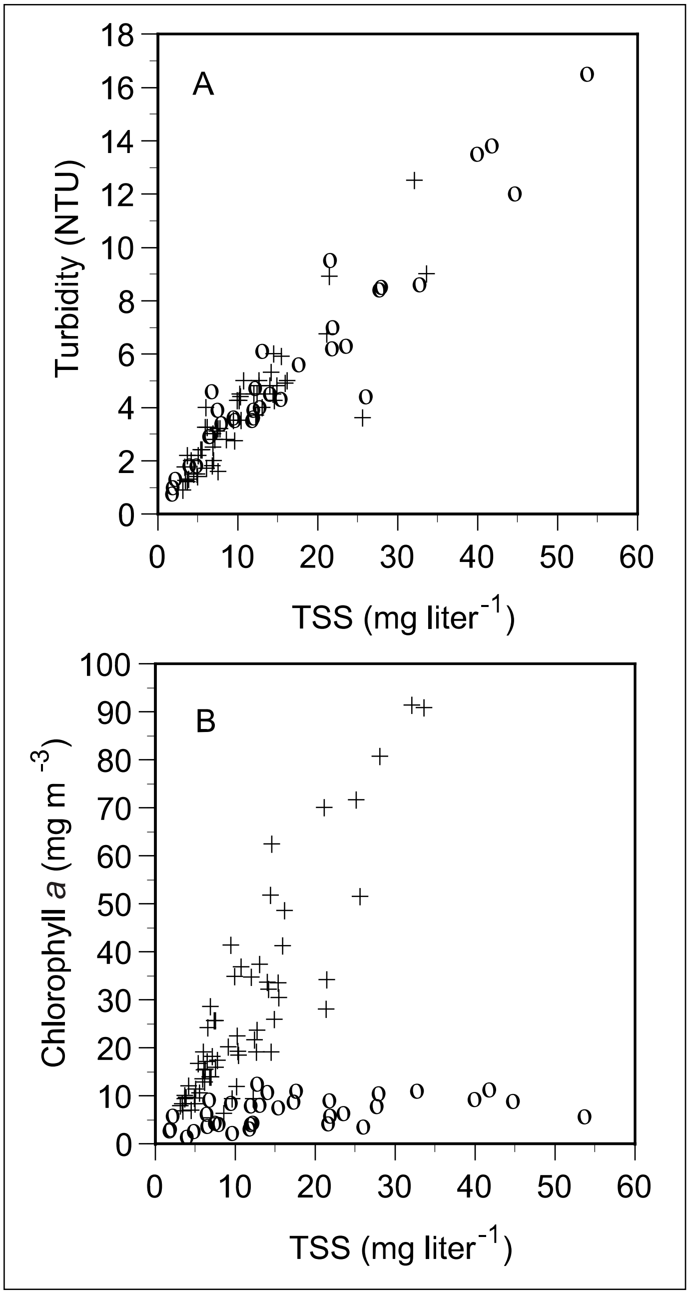

FIGURE IV-1. Relationship of Turbidity and Chlorophyll to Total Suspended Solids: Rhode River and Chincoteague Bay. This figure illustrates the relationship between turbidity (an estimate of scattering coefficient, see text) and total suspended solids (TSS) in (+) the Rhode River, Maryland, a tributary sub-estuary of Chesapeake Bay, and in (o) Chincoteague Bay, a coastal lagoon (A). Despite similar relationships between turbidity and TSS, the Rhode River and Chincoteague Bay contrast in their composition of TSS; chlorophyll contributes a much greater proportion to TSS in the Rhode River than in Chincoteague Bay (B).

covered were increased, and different instruments and standards were employed.

The spectral specific-absorption curves of suspended solids, including both inorganic silts and clays and organic detritus, typically have a negative exponential shape similar to that of dissolved organic matter (Kirk 1994). A single curve was sufficient to model absorption by non-algal turbidity in the Rhode River and Chincoteague Bay, Maryland (Gallegos 1994), but different site-specific curves were needed in the Indian River Lagoon, Florida (Gallegos and Kenworthy 1996). Overall, the spatial variability of absorption by non-algal suspended particulate matter has not been well studied.

With absorption and scattering accounted for in the optical model (Gallegos 1994), the specific-attenuation coefficient for total suspended solids was calculated by making small increments in total suspended solids concentrations, as was done above for dissolved organic carbon. The resulting value for k_s was 0.072 m^2 g^{-1}, with only minor dependence on other water quality parameters. This value is very similar to literature estimates, although the calculation is based on a single specific-absorption curve and does not take into account possible changes in the specific-absorption curve caused by potential variations in the mineralogical or humic content of soils around the Bay region. Based on the similarity of literature and model estimates, an initial estimate for k_s of 0.074 m^2 g^{-1} was selected.

EVALUATION OF THE K_d REGRESSION

Based on the initial selections of specific-attenuation coefficients, the predicted diffuse-attenuation coefficients from Chesapeake Bay Water Quality Monitoring Program data are given by the linear regression

$$K_d = 0.26 + 0.016[\mathrm{Chl}] + 0.074[\mathrm{TSS}] \qquad \text{(IV-7)}.$$

An examination of the predicted values against measured values (Figure IV-2) showed a tendency for the regression to underestimate measured K_d at both mainstem Bay (Figure IV-2A) and tidal tributary (Figure IV-2B) water quality monitoring stations. At mainstem Chesapeake Bay water quality monitoring stations there appeared to be bias in the slope of predicted against observed, whereas at tidal tributary stations there appeared to be an offset as well. By trial

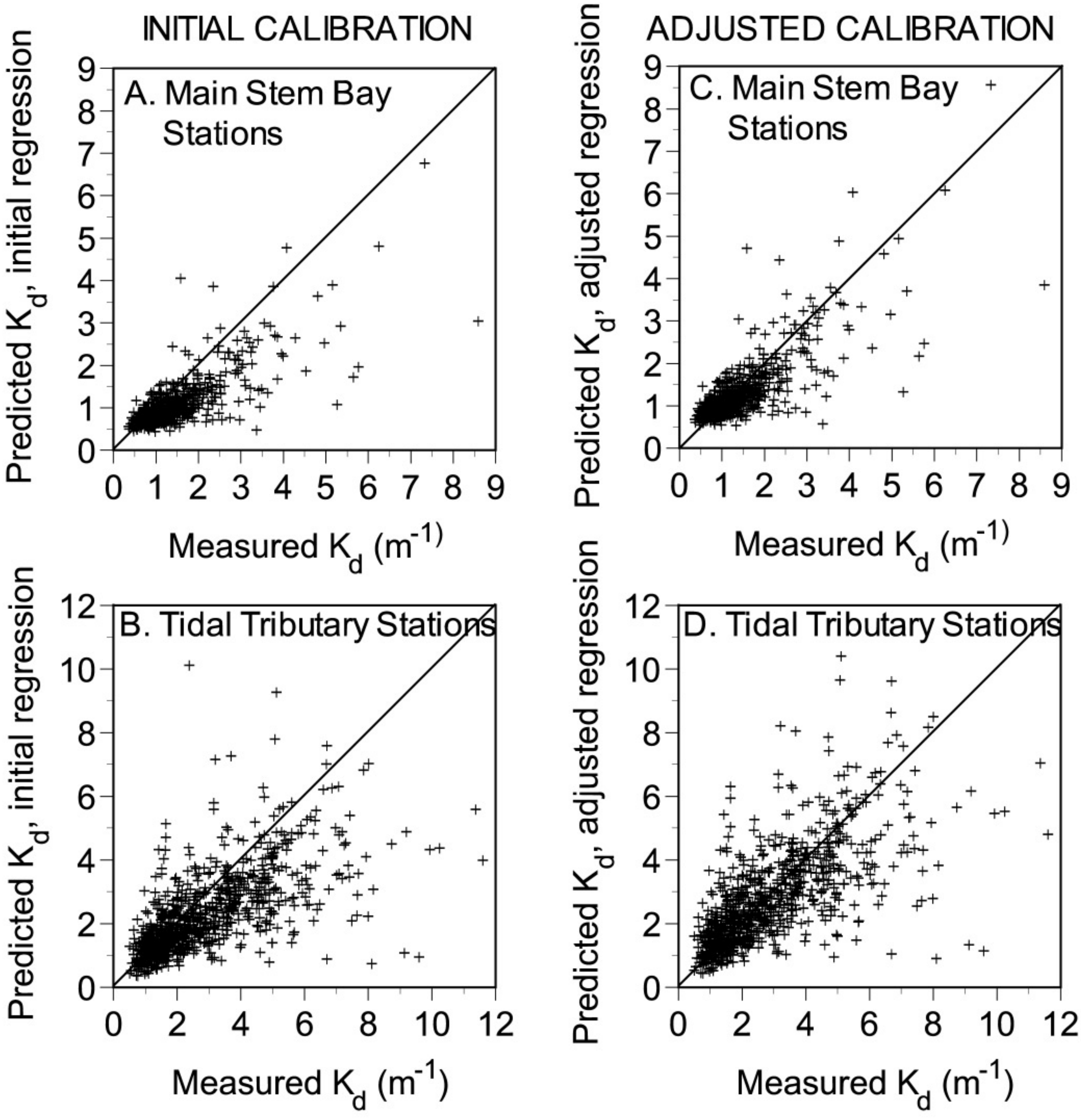

FIGURE IV-2. Comparison of Measured K_d with Predictions by Linear Regression Model. Comparison of measurements of diffuse attenuation coefficient (K_d) made in the Chesapeake Bay Water Quality Monitoring Program (1986-1996) with predictions made by linear regression against optical water quality parameters. (A) and (B) are predictions based on initial estimates of coefficients (Equation IV-7); (C) and (D) are predictions based on Equation IV-8, in which attenuation due to water plus dissolved organic carbon and partial attenuation coefficient of total suspended solids were adjusted upward. (A) and (C) are data from mainstem Chesapeake Bay stations; (B) and (D) are data from Maryland tidal tributary stations.

and error, predictions were improved by adjusting the estimated $K_{(W+DOC)}$ to 0.32 m^{-1} and the specific-attenuation coefficient of total suspended solids to 0.094 $m^2\ g^{-1}$ (Figure IV-2C, -2D), possibly indicating that the highest attenuation coefficients are dominated by times and locations of highest river flows. These modifications result in a final regression model of

$$K_d = 0.32 + 0.016[\mathrm{Chl}] + 0.094[\mathrm{TSS}] \qquad \text{(IV-8).}$$

Overall, the scatter in these plots indicates that more sophisticated models cannot be considered, given the limited amount of optical information in the data that are available. The r^2 for the final fits are 0.61 for mainstem Chesapeake Bay stations, and only 0.37 for tidal tributary stations. It is also likely that site-specific coefficients for k_s and possibly $K_{(W+DOC)}$ will be needed as a future refinement. Present experience with regressions on the monitoring data (Table IV-2) indicate that site-specific refinements to coefficients will need to be computed from optical modeling, based on direct determination of specific-absorption and specific-scattering spectra of total suspended solids from a wide range of sites around the Bay.

With these coefficients, Equation IV-6 can be used to write equations for combinations of chlorophyll *a* and total suspended solids that meet the WCLR for depths of 0.5, 1.0 and 2.0 meters. For mesohaline and polyhaline habitats where WCLR = 0.22 (22 percent, from Chapter III), the equations are

0.5 m $[\mathrm{TSS}] = 28.8\ 0.17[\mathrm{Chl}], [\mathrm{Chl}] < 169.4$ (IV-9a)

1.0 m $[\mathrm{TSS}] = 12.7\ 0.17[\mathrm{Chl}], [\mathrm{Chl}] < 74.7$ (IV-9b)

2.0 m $[\mathrm{TSS}] = 4.65\ 0.17[\mathrm{Chl}], [\mathrm{Chl}] < 27.4$ (IV-9c)

where the upper bound on [Chl] is the chlorophyll *a* concentration at which the predicted [TSS] = 0 for that depth; that is, higher chlorophyll *a* concentrations would result in a prediction of a 'negative concentration' for [TSS].

Comparable equations for tidal fresh and oligohaline habitats are determined by substituting 0.13 (13 percent from Chapter III) for WCLR in Equation IV-6,

0.5 m $[\mathrm{TSS}] = 40.0 - 0.17[\mathrm{Chl}], [\mathrm{Chl}] < 235$ (IV-10a)

1.0 m $[\mathrm{TSS}] = 18.3 - 0.17[\mathrm{Chl}], [\mathrm{Chl}] < 107$ (IV-10b)

2.0 m $[\mathrm{TSS}] = 7.45 - 0.17[\mathrm{Chl}], [\mathrm{Chl}] < 43.8$ (IV-10c).

COMPONENTS OF TOTAL SUSPENDED SOLIDS

Total suspended solids consist of the dry weight of all particulate matter in a sample, including clay, silt and sand mineral particles, living phytoplankton and heterotrophic plankton, including bacteria and particulate organic detritus. Therefore, phytoplankton and the heterotrophic community it supports contribute to what is measured by total suspended solids. As shown above, optically it is difficult to distinguish the effect of particulate organic matter, including that contributed by phytoplankton, from that of mineral particulates. Nevertheless, it is useful to examine their relative contributions to the measurement of total suspended solids, since organic particulates (due, in part, to nutrient over-enrichment) must be controlled differently than mineral particulates (due, in part, to erosion or sediment resuspension). In particular, a reduction in chlorophyll *a* will be accompanied by a proportional reduction in total suspended solids due to the dry weight component of phytoplankton. This additional reduction in total suspended solids needs to be incorporated into the predicted response of K_d when using equations (IV-9a-c) for determining the water quality conditions necessary for achieving the minimum light requirements.

Upon combustion, the particulate organic matter in a sample is oxidized, leaving behind the mineral component and ash of the organic fraction. The fraction remaining after combustion is referred to as fixed suspended solids (FSS), and the difference between the total and the fixed fraction of suspended solids is called total volatile suspended solids (TVSS). The percentage of total suspended solids that is of organic origin can then be estimated as TVSS/TSS*100.

Fixed suspended solids and total volatile suspended solids have been measured at the Virginia tidal tributary and mainstem stations of the Chesapeake Bay Water Quality Monitoring Program. At very high concentrations of total suspended solids, total volatile suspended solids appears to approach a relatively constant fraction, about 18 percent, of total suspended solids (Figure IV-3). The extremely high concentrations probably represent flood conditions, and the fraction of total volatile suspended solids in those samples are probably characteristic of the terrestrial soils. At more realistic total suspended solids concentrations, i.e., those < 50 mg liter^{-1}, a much wider range in the percentage of total volatile suspended solids is observed (Figure IV-3, inset), exceeding 90 percent in some samples.

The relationship between total volatile suspended solids and particulate organic carbon shows a great deal of scatter (Figure IV-4A) but on average, particulate organic carbon is about 30 percent of total volatile suspended solids. This estimate is larger than that of living phytoplankton (26 percent) (Sverdrup *et al.* 1942) and lower than that of carbohydrate (37 percent). The particulate organic carbon in a sample consists of living phytoplankton, bacteria, heterotrophic plankton, their decomposition products, organic detritus from marshes or terrestrial communities and resuspended SAV detritus. As expected, a plot of particulate organic carbon against phytoplankton chlorophyll *a* displays considerable scatter (Figure IV-4B), but during sudden phytoplankton blooms, phytoplankton might comprise the major component of carbon in a sample. The ratio of carbon to chlorophyll *a* in

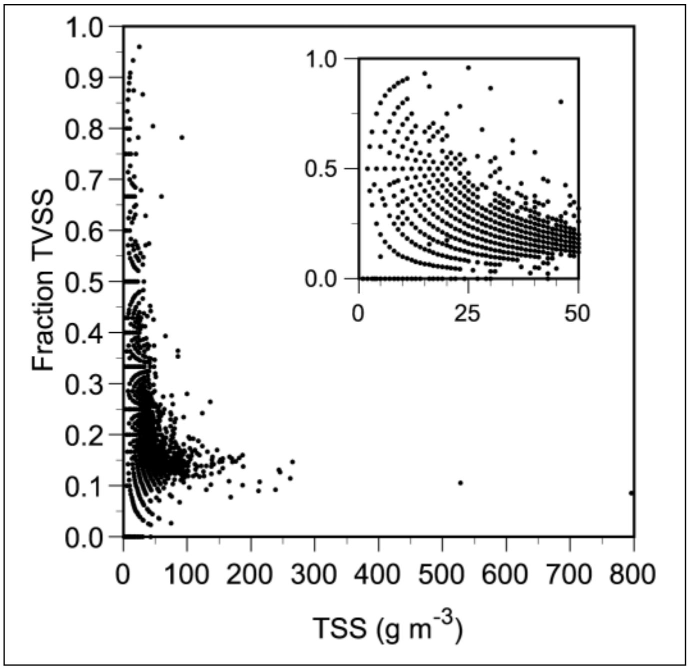

FIGURE IV-3. Fraction of Total Suspended Solids Lost on Ignition. Fraction of total suspended solids (TSS) that is lost on ignition as a function of TSS. At concentrations of TSS < 50 mg liter^{-1} (inset), the fraction of TSS that is volatile varies from 0 to >90 percent. Total volatile suspended solids (TVSS) calculated as total suspended solids minus fixed suspended solids, that is, the mass remaining after combustion. Fraction total volatile suspended solids calculated as total volatile suspended solids divided by total suspended solids. Data from Chesapeake Bay Water Quality Monitoring Program, Virginia tidal tributary stations, 1994-1996.

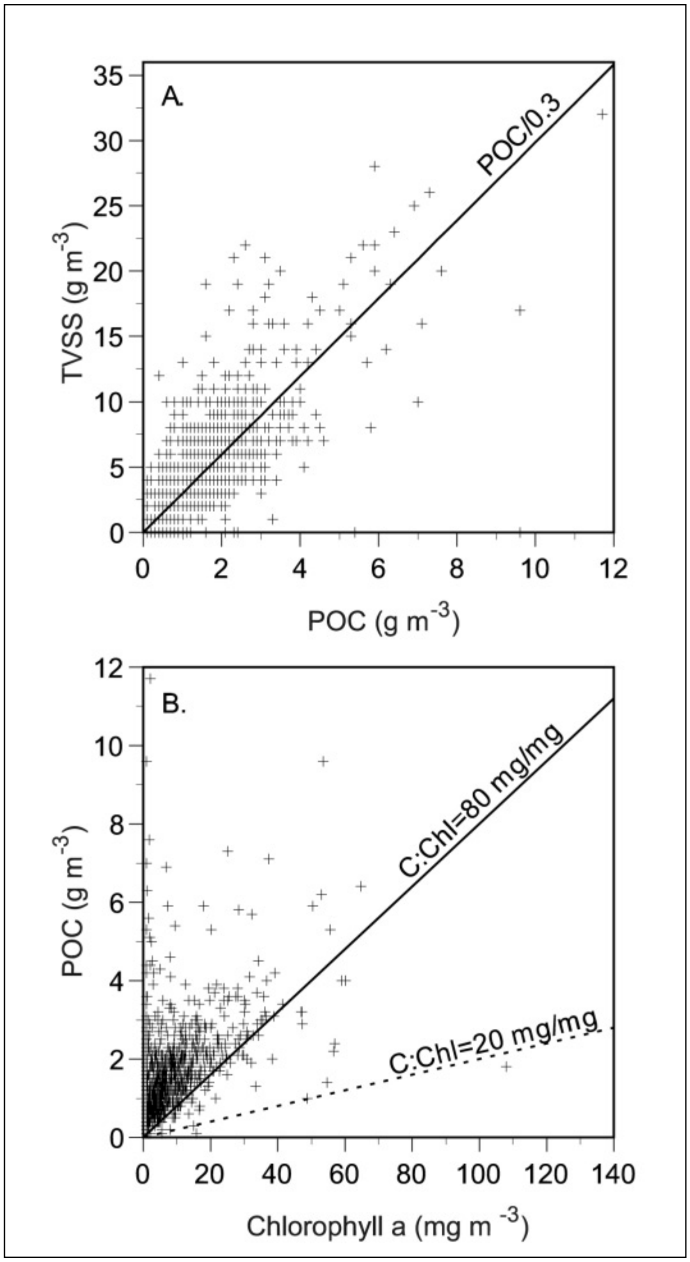

FIGURE IV-4. Relationships of Total Volatile Suspended Solids, Particulate Organic Carbon and Chlorophyll. Concentration of total volatile suspended solids (TVSS) as a function of particulate organic carbon (POC) for Virginia tidal tributary stations, 1994-1996. Line shows estimate of TVSS as POC/0.3 (A). Relationship of particulate organic carbon to chlorophyll concentration for Virginia tidal tributary stations (B). Lines bracket approximate contribution of phytoplankton to POC based on a range of phytoplankton carbon:chlorophyll ratios from 20 (dashed line) to 80 mg C (mg chlorophyll)$^{-1}$(solid line).

phytoplankton varies widely (Geider 1987). A range of about 20 to 80 mg C (mg chl)$^{-1}$ provides a lower bound of most of the points in Figure IV-4B, and this range is well within the physiological limits of phytoplankton (Geider 1987). Choosing 40 mg C (mg chl)$^{-1}$—the geometric mean of 20 and 80–as a representative carbon:chlorophyll *a* ratio, and using the 30 percent particulate organic carbon:total volatile suspended solids ratio from Figure IV-4A, the minimum contribution of phytoplankton chlorophyll *a* to total volatile suspended solids, designated ChlVS, is estimated as

$$\mathrm{ChlVS} = 0.04[\mathrm{Chl}]/0.3 \qquad \text{(IV-11)}$$

where the 0.04 results from the conversion of μg to mg chlorophyll liter^{-1}. Thus, although the optical effects of particulate organic detritus cannot be distinguished from that of mineral particles, the minimum contribution of phytoplankton to the measurement of total suspended solids is approximately given by ChlVS. This also implies that management action to reduce the concentration of chlorophyll *a* at a site will also result in a reduction of total suspended solids by an amount approximated by ChlVS. The actual reduction may be larger if a substantial heterotrophic community and the organic detritus generated by it are simultaneously reduced. This observation has significant implications for the implementation of site specific management approaches.

SUMMARY OF THE DIAGNOSTIC TOOL

The exponential decline of light intensity under water (Equation IV-1) allows for the percentage of surface light penetrating to a given depth to be written as a simple function of the diffuse attenuation coefficient (Equation IV-2). Equation IV-4 expresses in a general (albeit approximate) way the relationship between the diffuse-attenuation coefficient and the concentrations of optical water quality parameters. Once the SAV minimum light requirement and the SAV restoration depth are specified, Equation IV-4 may be rearranged to predict the concentrations of total suspended solids and chlorophyll *a* that exactly meet the water-column light requirement (Equation IV-6). Equations IV-9a-c express these water quality relationships for mesohaline and polyhaline regions for three depth ranges, and in terms of the specific-attenuation coefficients estimated for Chesapeake Bay from the literature, by optical modeling and by analysis of data from the Chesapeake Bay Water Quality Monitoring Program. Equations IV-10a-c express the same relationships for tidal fresh and oligohaline regions. Equation IV-11 estimates an approximate minimum concentration of total suspended solids attributable to phytoplankton. Equation IV-11 is used to better predict the reduction in total suspended solids, and, therefore, the diffuse attenuation expected to occur when the chlorophyll *a* concentration is reduced.

APPLICATION OF THE DIAGNOSTIC TOOL

A plot of measured total suspended solids against chlorophyll *a* concentrations from a given station in relation to lines defined by equations IV-9a-c demonstrates the extent to which the water-column light requirement is met at that location. In addition, a line representing Equation IV-11 shows the minimum contribution of chlorophyll *a* to total suspended solids at the location. Three examples from the Chesapeake Bay Water Quality Monitoring Program demonstrate information that may be determined by examining plots of total suspended solids against chlorophyll *a* in relation to the restoration depth-based water-column light requirements (Figure IV-5).

Suspended Solids Dominant Example

At station CB2.2, located in the upper Chesapeake Bay mainstem near the turbidity maximum, total suspended solids dominates the variability in light attenuation (Figure IV-5A). The median water quality concentrations fail to meet the 1-meter water-column light requirement, and the predominant direction of variability in the scatter of individual data points is vertical, i.e., parallel to the total suspended solids axis. Stations characterized by elevated total suspended solids and low chlorophyll *a* indicate cases in which suspended solids dominate the variation in light attenuation. Depending upon site-specific factors, the source of suspended solids may be due to land-based erosion, channel scour and/or the resuspension of bottom sediments due to winds or currents. When measurements are principally parallel to the total suspended solids axis, reductions in total suspended solids will be needed to achieve light conditions for SAV survival and growth.

Phytoplankton Bloom Example

Variations in chlorophyll *a* dominate the variability in attenuation at tidal tributary Chesapeake Bay Water

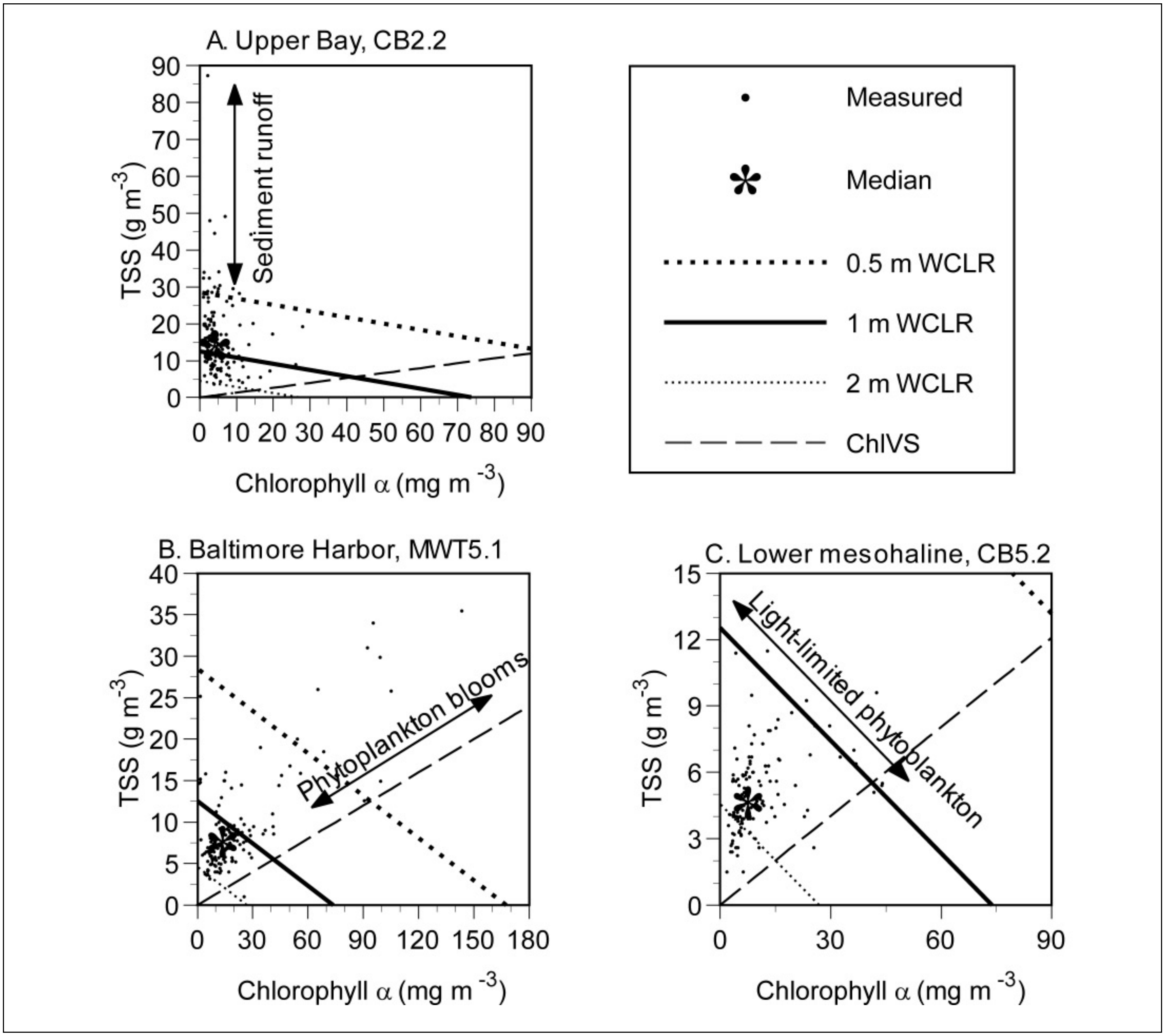

FIGURE IV-5. Application of the Diagnostic Tool Illustrating Three Primary Modes of Variation in the Data. Application of diagnostic tool to two mainstem Chesapeake Bay stations and one tributary station, which demonstrate three primary modes of variation in the data: (A) variation in diffuse attenuation coefficients is dominated by (flow related) changes in concentrations of total suspended solids (TSS) (upper Bay station CB2.2); (B) variation in attenuation coefficients is dominated by changes in chlorophyll concentration (Baltimore Harbor, MWT5.1); and (C) maximal chlorophyll concentration varies inversely with TSS indicative of light-limited phytoplankton. Plots show (points) individual measurements and (asterisk) growing season median in relation to the water-column light requirements (WCLR) for restoration to depths of 0.5 m (short dashes), 1.0 m (solid line), and 2.0 m (dotted line); water-column light requirements calculated by equations IV-9a-c (see text). Note the change in scale. Approximate minimum contribution of chlorophyll to TSS (ChlVS) is calculated by Equation IV-11 (long dashes). Data from Chesapeake Bay Water Quality Monitoring Program, April through October, 1986-1996.

Quality Monitoring Program station MWT5.1 in Baltimore Harbor, Maryland (Figure IV-5B). Median concentrations indicate that conditions for growth of SAV to the 1-meter depth are met, but many individual points violate both the 1-meter and 0.5-meter water-column light requirements (Figure IV-5B). The main orientation of points that violate 1-meter and 0.5-meter water-column light requirements is parallel to the ChlVS line (Figure IV- 5B, long dashes). Stations with elevated chlorophyll *a* concentrations that exhibit variability parallel to the ChlVS line can be classified as nutrient-sensitive, because attenuation is often dominated by phytoplankton blooms, indicating a susceptibility to eutrophication. Reduction of chlorophyll *a* concentrations would simultaneously reduce total suspended solids, moving the system parallel to the ChlVS line.

Light-Limited Phytoplankton Example

Another recognizable pattern exhibited in the data is an apparent upper bound of total suspended solids and chlorophyll *a* concentrations, aligned parallel to the water-column light requirements seen at mainstem Chesapeake Bay Water Quality Monitoring Program station CB5.2 (Figure IV-5C). Such behavior indicates that the maximal phytoplankton chlorophyll *a* concentrations are dependent on total suspended solids concentrations, and that the phytoplankton are light-limited (i.e., nutrient-saturated). Under those conditions, reducing suspended solids concentrations alone would not improve conditions for SAV, since phytoplankton chlorophyll *a* would increase proportionately to maintain the same light availability in the water column. This process is well-described by Wofsy's model (1983), in which water-column or mixing-layer depth is an important parameter. Application of Wofsy's (1983) Equation 17 with the specific-attenuation coefficients in Equation IV-7 (above) suggests that the community exhibits nutrient-saturated behavior with a mixing depth of 6 to 7 meters. The data indicate that conditions for growth of SAV to 1 meter are nearly always met at CB5.2, but if water with these properties were advected to shallower areas and maintained sufficient residence time there, it would support higher chlorophyll *a* concentrations.

It is, of course, possible for a system to display all three modes of behavior at a given location, particularly where there is strong seasonal riverine influence. For example, high total suspended solids and low chlorophyll *a* might be observed at spring flooding; nutrient-saturated behavior might occur as total suspended solids concentrations decline after spring floods subside; and blooms aligned parallel to the ChlVS line could occur in response to episodic inputs of nutrients at other times. Alignment along any of the trajectories described need not occur as a sequence in time. That is, floods, phytoplankton blooms, or nutrient-saturated combinations of total suspended solids and chlorophyll *a* in separate years will generally tend to align in the directions indicated in Figure IV-5. However, because of the high degree of seasonal and interannual variability in such data, these patterns might not be discernible at many stations, especially shallow locations where nutrient-saturated combinations of total suspended solids and chlorophyll *a* might be indistinguishable from phytoplankton blooms.

Generation of Management Options

A computer spreadsheet program for displaying data and calculating several options for achieving the water-column light requirements has been developed and has been made available in conjunction with this report through the Chesapeake Bay Program web site at www.chesapeakebay.net/tools. The spreadsheet program calculates median water quality concentrations, and evaluates them in relation to the minimum light requirements for growth to 0.5-, 1- and 2-meter restoration depths. Provisions are included for specifying a value for the water-column light requirement (WCLR) appropriate for mesohaline and polyhaline and regions (WCLR=0.22) or for tidal fresh and oligohaline areas (WCLR=0.13). When the observed median chlorophyll *a* and total suspended solids concentrations do not meet the water-column light requirement, up to four target chlorophyll *a* and total suspended solids concentrations that do meet the criteria are calculated based on four different management options (Figure IV-6). Under some conditions, some of the management options are not available because a ‘negative’ concentration would be calculated.

Option 1 is based on projection from existing median conditions to the origin (Figure IV-6A). This option calculates target chlorophyll *a* and total suspended solids concentrations as the intersection of the water-column light requirement line with a line connecting the existing median concentration with the origin, i.e., chlorophyll=0, TSS=0. Option 1 always results in positive concentrations of both chlorophyll *a* and total suspended solids.

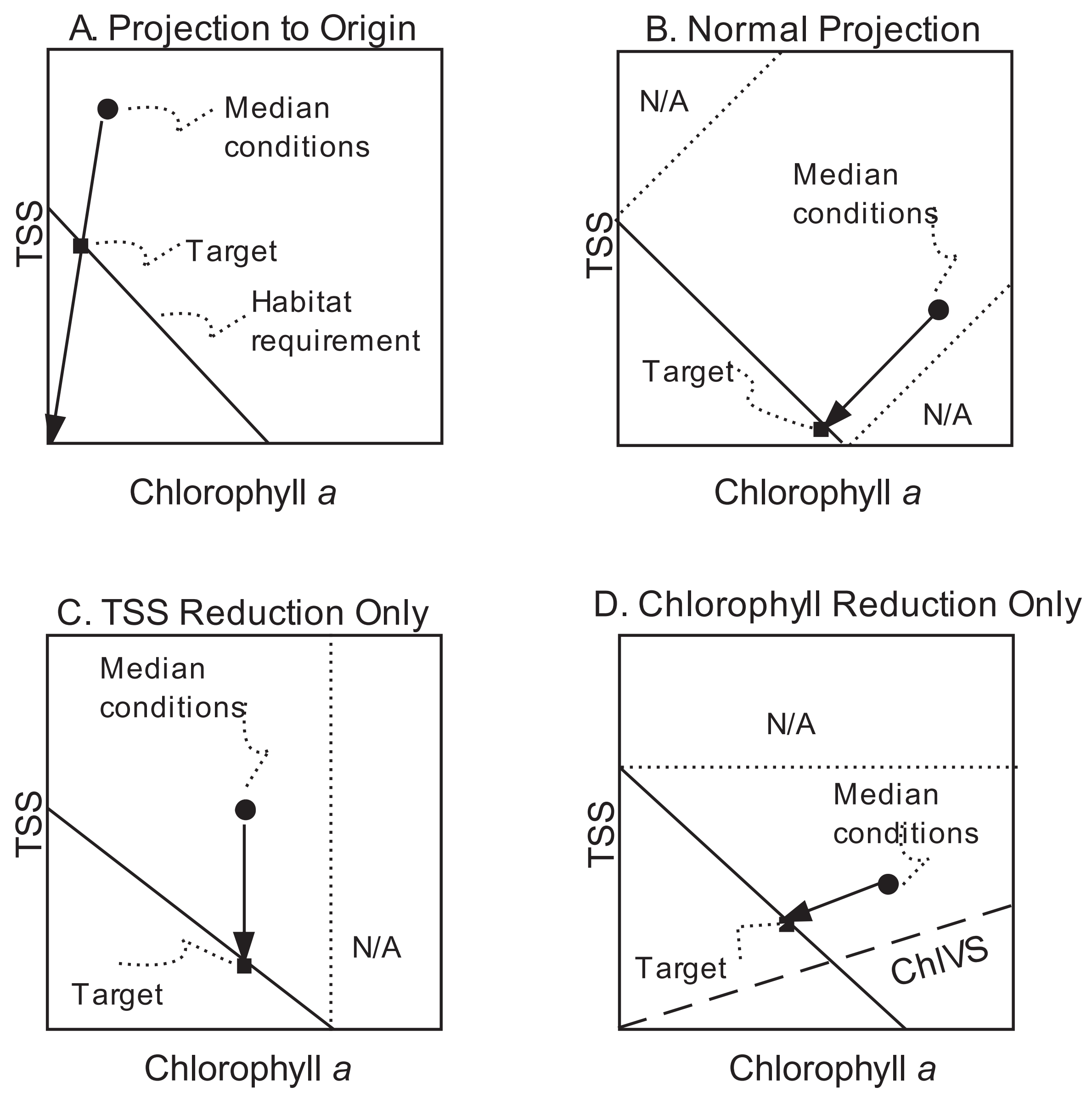

FIGURE IV-6. Illustration of Management Options for Determining Target Concentrations of Chlorophyll *a* and Total Suspended Solids. Illustration of the use of the diagnostic tool to calculate target growing-season median concentrations of total suspended solids (TSS) and chlorophyll *a* for restoration of SAV to a given depth. Target concentrations are calculated as the intersection of the water-column light requirement, 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 water-column light 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.

Option 2 is based on normal projection (Figure IV-6B). It calculates target chlorophyll *a* and total suspended solids concentrations as the projection from existing median conditions perpendicular to the water-column light requirement. Geometrically, option 2 is the one that 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 IV-6C). This option calculates target chlorophyll *a* and total suspended solids concentrations assuming the target can be met by only reducing the concentration of total suspended solids. Option 3 is not available anytime the median chlorophyll *a* exceeds the TSS=0 intercept. Whenever a system is nutrient-saturated and light-limited, 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 water-column light requirements lines as illustrated previously in Figure IV-5C (Wofsy 1983).

Option 4 is based on a chlorophyll *a* reduction only (Figure IV-6D). This option calculates target chlorophyll *a* and total suspended solids concentrations, assuming that the target can be met by only reducing the concentration of chlorophyll *a* (Figure IV-6D). Option 4 is not available whenever the median total suspended solids concentration exceeds the chlorophyll = 0 intercept of the water-column light requirement. The target total suspended solids concentration reported for option 4 is actually lower than the existing median, due to the suspended solids removed by reduction of phytoplankton and associated carbon, i.e., ChlVS.

SENSITIVITY OF TARGET CONCENTRATIONS TO PARAMETER VARIATIONS

The sensitivity of target concentrations calculated by each of the four management options was examined by calculating the change in target concentrations of chlorophyll *a* and total suspended solids in response to a 20 percent increase in each of the parameters (except Z_{max}) in Equation IV-5 that define the behavior of the diagnostic tool (Table IV-3). The diagnostic tool is formulated so that, in general, increases in parameter values result in decreases in target concentrations. An increase in the water-column light requirement increases the light required by SAV, resulting in lower target concentrations of total suspended solids and chlorophyll *a*. Increases in the specific-attenuation coefficients increase the light-attenuation coefficient, which reduces light availability at Z_{max}, and, therefore, also reduces the target water quality concentrations. Parameters in Equation IV-11 were an exception. Reduction in the ratios of particulate organic carbon:chlorophyll *a* and total volatile suspended solids:particulate organic carbon resulted in a negligibly higher target chlorophyll *a* concentration under option 1 (Table IV-3).

Reductions in target water quality concentrations were by far the most sensitive to increases in WCLR (Table IV-3). For management options 1 and 2, target chlorophyll *a* concentrations were reduced by about 27 percent from about 22 μg liter^{-1} to 16 μg liter^{-1}, and target total suspended solids by about 29 percent from nine mg liter^{-1} to 6.3 mg liter^{-1} with a 20 percent increase in WCLR (Table IV-3). Management options 3 and 4 were eliminated by a 20 percent increase in WCLR (Table IV-3). The large sensitivity to WCLR occurs because an increase in WCLR moves the entire line described by Equation IV-5 closer to the origin without changing the slope, i.e., in a manner similar to increases in Z_{max} (see Figure IV-5B).

The sensitivity of calculated target concentrations of chlorophyll *a* and total suspended solids to 20 percent increases in the remaining parameters in Equation IV-5 differed according to management option and parameter. Lowest target concentrations and greatest percentage reductions for chlorophyll *a* occurred in management option 4, i.e., chlorophyll *a* reduction only. The target concentration of chlorophyll *a* was, of course, insensitive to parameter variations under management option 3, total suspended solids reduction only. For management options 1 and 2, the calculated target chlorophyll *a* concentration was most sensitive to the parameter k_s, the specific-attenuation coefficient of total suspended solids, and relatively insensitive to increases in k_c, the specific-attenuation coefficient of chlorophyll *a*. Insensitivity to k_c may seem counterintuitive, because k_c governs the relative contribution of chlorophyll *a* to overall attenuation, and we might expect higher values to attribute more attenuation to chlorophyll *a*; but higher values of k_c also imply that a given reduction in chlorophyll *a* is more effective in reducing overall K_d, and hence less of a reduction is needed to achieve the target.

For total suspended solids, the lowest target concentrations and largest percentage reductions were calculated for option 3, total suspended solids reduction only (Table IV-3). Target total suspended solids concentrations were slightly sensitive to parameter variations under management option 4, due to the contribution of chlorophyll *a* to total suspended solids as expressed in Equation IV-11. For management options 1 and 2, the calculated target total suspended solids concentration was most sensitive to k_S. The higher sensitivity to k_S occurs because of the additional contribution of chlorophyll *a* to total suspended solids, so that increasing k_S has an effect similar to that of increasing the water-column light requirement.

SUMMARY AND CONCLUSIONS

The empirically observed exponential decay of light underwater, which can be characterized by a single attenuation coefficient, provides the means of deriving a simple expression for the percentage of surface light available to SAV at the bottom of a water column of any specified depth. The magnitude of the attenuation

TABLE IV-3. Percent change of the target chlorophyll *a* and total suspended solids concentrations calculated by the diagnostic tool in response to 20 percent increases in each of the parameters describing the dependence of diffuse attenuation coefficient on water quality (Equation IV-8). Baseline parameter values and the value after the 20 percent increase are given under the parameter name and units. Data used in the analysis were from the Maryland Chesapeake Bay Water Quality Monitoring Program for MWT5.1 station in Baltimore Harbor, restricted to the SAV growing season (April through October) 1986-1995. Baseline target concentrations are those calculated for the 1 m restoration depth minimum light requirement (Equation IV-9b) for each of the management options: 1-projection to origin; 2-normal projection; 3-total suspended solids reduction only; and 4-chlorophyll *a* reduction only (see text). N/A=not available.

Sensitivity of Management Option

	Chorophyll *a*				Total Suspended Solids			
Parameter varied:	1	2	3	4	1	2	3	4
Baseline target	22.18	22.85	34.1	11.6	8.93	8.81	6.9	10.73
WCLR 0.22 to 0.264	-28.2	-25.8	N/A	N/A	-28.2	-29.2	N/A	N/A
k_C, ($m^2\ mg^{-1}$) 0.016 to 0.0192	-5.6	-2.5	0.0	-10.1	-5.6	-7.4	-16.8	-1.5
k_S, ($m^2\ g^{-1}$) 0.094 to 0.113	–12.4	–14.2	0.0	–56.0	–12.3	–11.4	–16.7	–7.2
K_{W+DOC}, (μ^{-1}) 0.32 to 0.384	-5.4	-4.9	0.0	12.9	-5.4	-5.6	-9.9	-2.8
POC:Chl (mg μg^{-1}) 0.04 to .048	0.0	–3.8	0.0	–14.9	–0.1	–1.9	0.0	–3.2
TVSS:POC 0.3 to 0.36	0.0	-3.8	0.0	-10.1	0.0	1.7	0.0	-8.0

coefficient is governed mainly by the concentrations of three water quality parameters: dissolved organic carbon, chlorophyll *a* and total suspended solids. Of these, only chlorophyll *a* and total suspended solids show substantial contribution to light attenuation at most locations around Chesapeake Bay. Sites where colored dissolved organic matter contributes substantially to attenuation, such as the Pocomoke River on the Maryland/Virginia border, are not considered in this analysis.

Linear partitioning of the diffuse-attenuation coefficient into contributions due to water plus dissolved organic carbon, phytoplankton chlorophyll *a* and total suspended solids involves known compromises in realism but is an approximation that has proved useful in the past and leads to a tractable solution for purposes of water quality management. Due to unexplained variability in the data from the Chesapeake Bay Water Quality Monitoring Program, specific-attenuation coefficients for water plus dissolved organic carbon, chlorophyll *a* and total suspended solids were estimated by a combined approach using statistical regression, optical modeling and comparison with literature values.

It will be shown elsewhere (Gallegos, unpublished) that the use of a single linear regression (Equation IV- 4), when applied across the full range of observed water quality conditions, produces biased diffuse-attenuation coefficients with respect to a more mechanistic model of light attenuation. Nevertheless, unbiased diffuse-attenuation coefficients can be obtained from a suitably calibrated optical water quality model. The present version of the diagnostic tool incorporates unbiased diffuse-attenuation coefficients determined by an optical model calibrated for a site near the mesohaline region of the mainstem Bay (Gallegos 1994). There is an urgent need for a regionally customized application of this approach (see “Directions for Future Research”).

The diagnostic tool is based on a plot of measured concentrations of total suspended solids versus chlorophyll *a*, in relation to the linear combination of total suspended solids and chlorophyll *a* that meet the minimum light habitat requirement. Characteristic behaviors can be identified by the orientation of points: points scattered along the vertical (TSS) axis indicate attenuation dominated by episodic inputs of total suspended solids; points oriented parallel to the line defining the contribution of chlorophyll *a* to total suspended solids indicate variation of light attenuation governed by phytoplankton blooms; and points oriented parallel to the line describing the water-column light habitat requirement indicate that maximal chlorophyll concentrations are dependent on the concentration of total suspended solids, signifying a nutrient-saturated system.

An analysis of total suspended solids indicated that total volatile suspended solids were a variable fraction of total suspended solids, and that on average, particulate organic carbon is about 30 percent of total volatile suspended solids. Using a reasonable estimate of the phytoplankton carbon:chlorophyll *a* ratio, along with the contribution of particulate organic carbon to total volatile suspended solids, indicated that phytoplankton carbon contributes to the overall total suspended solids. Any reduction in chlorophyll *a* would be accompanied by a proportionate decrease in total suspended solids.

Up to four management options for moving the system to conditions that meet specified water-column light requirements are calculated by the diagnostic tool. The precision of the calculations obviously 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 tradeoffs that are available. Furthermore, the spreadsheet reports the frequency with which the water-column light requirements for each restoration depth are violated by the individual measurements. This information may be useful in the future if water-column light requirements for SAV growth and survival become better understood in terms of tolerance of short-term light reductions.

Directions for Future Research

Continued collection of monitoring data is necessary to track recovery (or further degradation) of the system with respect to the optical water quality targets defined for the various regions using the diagnostic tool. However, it is doubtful that additional monitoring data will improve the ability to derive statistical estimates of specific-attenuation coefficients by regression analysis. Inherent variability in the spectral absorption and scattering properties of the optical water quality parameters, combined with normal uncertainty associated with sampling and laboratory analyses, probably account for the low coefficients of determination and statistically insignificant estimates of some specific-attenuation coefficients.

Nevertheless, some attempt to determine regionally based estimates of optical properties should be made, because of the pronounced changes in the nature of particulate material that occur from the headwaters to the mouth of major tributaries as well as the mainstem Chesapeake Bay itself. An approach based on direct measurement of particulate absorption spectra and optical modeling will be needed to obtain regionally customized diagnostic tools.