chapter iv

Water Clarity Criteria

BACKGROUND

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

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

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

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

APPROACH

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

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

THE RELATIONSHIPS BETWEEN WATER QUALITY, LIGHT AND UNDERWATER BAY GRASSES

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

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

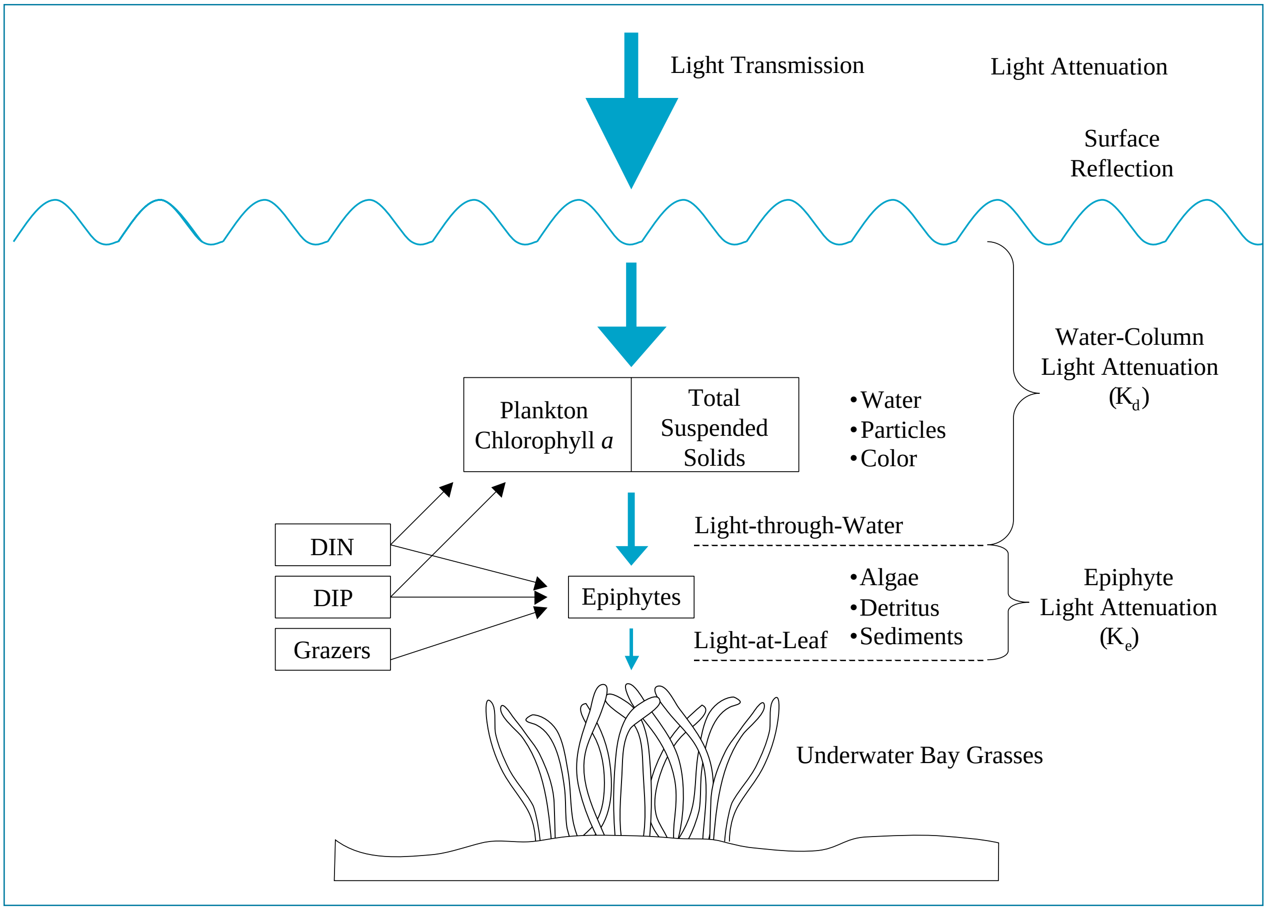

Figure IV-1: Availability of light for underwater bay grasses is influenced by water-column and at-the-leaf surface light attenuation processes. DIN = dissolved inorganic nitrogen and DIP = dissolved inorganic phosphorus.

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

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

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

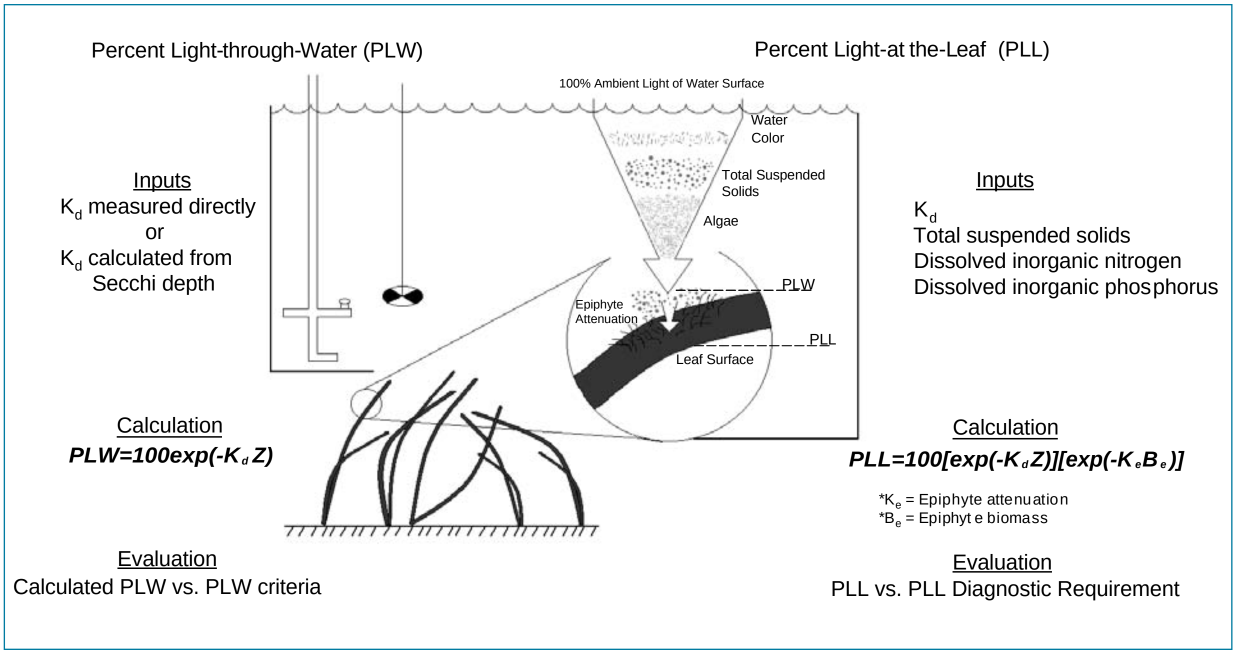

Figure IV-2: Illustration of the inputs, calculation and evaluation of the two percent-light parameters: percent light-through-water (PLW) and percent light-at-the-leaf (PLL).

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

DETERMINING LIGHT REQUIREMENTS

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

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

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

STRENGTHS AND LIMITATIONS OF THE CRITERIA DERIVATION PROCEDURES

Scientific Syntheses

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

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

Light Availability Studies

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

Light Requirements for Sparse versus Dense UnderwaterBay Grass Beds

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

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

Effective Depth of Photosynthesis/Application Depth Relationship

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

Plant Morphology's Influence on Determining Light Requirements

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

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

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

Validation of Predicted versus Actual Bay Grass Distribution

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

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

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

Natural Water Color

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

Other Environmental Factors

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

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

Particle sinking and other sedimentological processes alter the texture, grain-size distribution and organic content of bottom sediments. These alterations can affect underwater bay grass growth by modifying the availability of nutrients in the sediments (Barko and Smart 1986) and by producing reduced sulfur compounds that are toxic to underwater plants (Carlson et al. 1994). In addition, pesticides and other anthropogenic chemical contaminants tend to inhibit underwater bay grass growth. An extensive review of the literature has revealed that certain underwater bay grass species appear to have limited tolerance of certain physical, sedimentological and chemical variables (Koch 2001).

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

Areas for Refinement

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

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

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

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

WATER CLARITY CRITERIA DERIVATION

MINIMUM LIGHT REQUIREMENTS

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

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

Photosynthesis-Irradiance Measurements

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

Field Observations of Maximum Depth and Available Light

Numerous studies around the world link observations of the maximum depth to which an underwater grass species grows (Z_{max}) to the available light (I_m) at that depth (see Appendix A in Batiuk et al. 2000). Individual maximum-depth-of-colonization studies were not particularly useful for setting up minimum light requirements for Chesapeake Bay environments. Most studies were of freshwater and oligohaline species in freshwater lakes, where the water was clear and the percent of surface light in midsummer on a clear day was not indicative of the plant's seasonal light environment. Determinations were based on the maximum depth at which the plants were rooted, disregarding chance fragments or propagules that might have established outlier populations and not survive an entire growing season (e.g., Moore 1996). Measurement frequency is a significant problem that should be considered in these studies. However, taken in the aggregate, these field observations serve as a basis for models that predict maximum depths of colonization or minimum light requirements (see section titled "Light Availability Models" below).

Light Manipulation Experiments

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

Light Availability Models

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

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

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

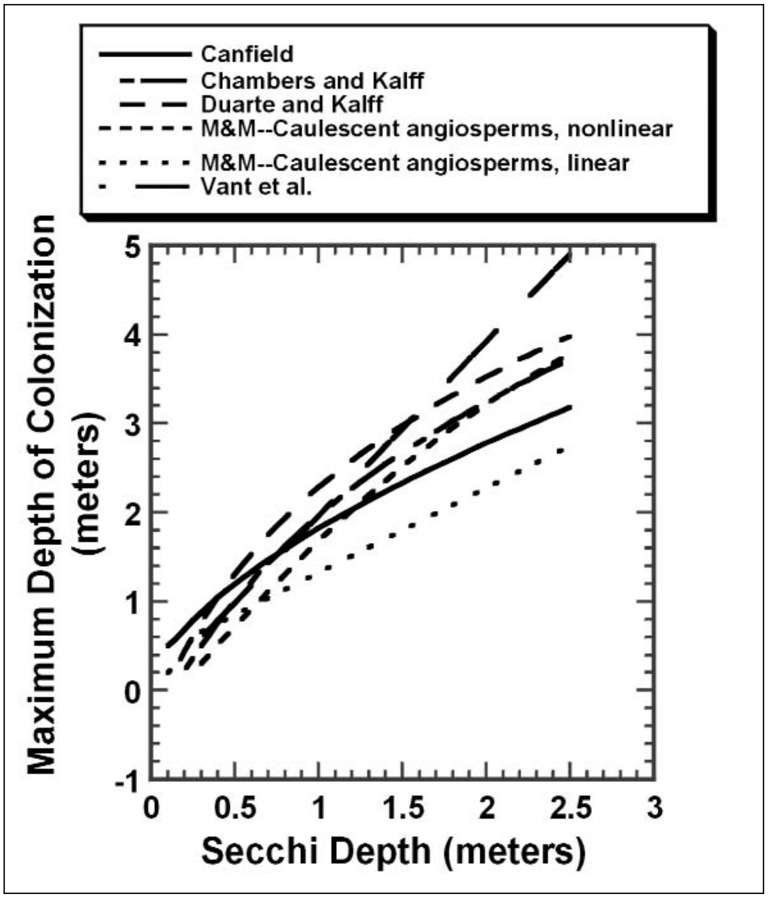

Figure IV-3. Relationship of maximum depth of colonization (Z_{max}) to Secchi depth for freshwater SAV species as modeled by Canfield et al. (1985), Chambers and Kaff (1985), Duarte and Kalff (1987), Middleboe and Markager (1997) and Vant et al. (1986).

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

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

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

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

Chesapeake Bay Research and Monitoring Findings

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

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

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

Tidal-Fresh/Oligohaline Potomac River Findings. From 1983 through 1996, underwater bay grass coverage in the tidal Potomac River varied greatly in both the tidal-fresh and oligohaline reaches. The change in underwater bay grass coverage from the previous year and the median PLW calculated from growing season Secchi depth varied greatly, but both exhibited a general downward trend during this period. When the change in underwater bay grass coverage from the previous year is plotted against the median PLW at 1 meter during the underwater bay grass growing season (April 1 through October 31), underwater bay grasses increased with increases in the PLW. When median PLW was greater than 13 percent, underwater bay grass coverage showed only positive increases over three years. However, positive increases occurred even in years when median percent light at 1 meter was considerably less than 13 percent, indicating that other factors besides light also influence changes in coverage, or that underwater bay grasses were growing at depths < 1 meter.

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

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

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

Mesohaline Potomac River Findings. In the mesohaline segment of the Potomac River, underwater bay grasses have continued to increase steadily since 1983, although the coverage remains relatively small compared to pre-1960 conditions. Colonization by underwater bay grasses has taken place primarily in areas less than 1 meter deep. Midchannel light conditions are better in the mesohaline segment of the river compared to either the tidal-fresh or oligohaline segments, with the median seasonal Secchi depth generally never dropping below 1 meter for the period of 1983 through 1996. Secchi depth is only reported to 0.1 meters, so the error in the median measurements is at least ±0.05 meters. If median Secchi depth is 1 meter, then using a conversion factor of 1.45 to calculate K_d median light conditions of 23.5 percent at 1-meter depth, with a range of 21.7 percent to 25.1 percent (Batiuk et al. 2000). Thus, the Chesapeake Bay water-column light requirements published previously by Batiuk et al. (1992) for mesohaline and polyhaline segments are consistent with those observed in the mesohaline region of the Potomac River where underwater bay grasses are recovering.

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

Light-through-Water Requirements

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

Based on published model findings reviewed in detail by Carter, Rybicki and Landwehr in Batiuk et al. (2000) and confirmed by a review of the results of recent tidal Potomac and Patuxent River research and monitoring studies (see above), a PLW requirement of 13 percent was determined to apply to Chesapeake Bay tidal-fresh and oligohaline species. This light requirement was calculated using Equation IV-1 and the appropriate 1992 SAV habitat requirement for K_d of 2 meter^{-1} (Batiuk et al. 1992). The PLW requirement also is consistent with the 13.5 percent value published by Dennison et al. (1993).

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

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

Salinity Regime	Water Clarity Criteria as Percent Light-through-Water	Water Clarity Criteria as Secchi Depth								Temporal Application
		Water Clarity Criteria Application Depths								
		0.25	0.5	0.75	1.0	1.25	1.5	1.75	2.0	
		Secchi Depth (meters) for above Criteria Application Depth								
Tidal-fresh	13 %	0.2	0.4	0.5	0.7	0.9	1.1	1.2	1.4	April 1 - October 31
Oligohaline	13 %	0.2	0.4	0.5	0.7	0.9	1.1	1.2	1.4	April 1 - October 31
Mesohaline	22 %	0.2	0.5	0.7	1.0	1.2	1.4	1.7	1.9	April 1 - October 31
Polyhaline	22 %	0.2	0.5	0.7	1.0	1.2	1.4	1.7	19	March 1 - May 31, September 1 - November 30

[2] Base on application of Equation IV-1, PLW = 100exp($-K_dZ$), the appropriate PLW criterion value and the selected application depth are inserted and the equation is solved for K_d. The generated K_d value is then converted to Secchi depth (in meters) using the conversion factor K_d = 1.45/Secchi depth.

CHESAPEAKE BAY WATER CLARITY CRITERIA

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

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

When these water clarity criteria were derived, there was an insufficient scientific basis for deriving a set of water clarity or related (e.g., total suspended solids) criteria for protection of open-water designated use habitats. The EPA will derive and publish criteria addressing water clarity-related impairments for open-water habitat when the necessary scientific data becomes available.

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