# PRIMARY FACTORS AFFECTING WATER CLARITY AT SHALLOW WATER SITES THROUGHOUT THE CHESAPEAKE AND MARYLAND COASTAL BAYS

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## INTRODUCTION

The Chesapeake Bay and its tributaries, which constitute the largest estuary in the United States, stretch approximately 290 km along the Nation's mid-Atlantic Coast. The total estuarine system (open bay and tidal tributaries) traverses six States (New York, Pennsylvania, Maryland, West Virginia, Virginia, and Delaware) and the District of Columbia. Historically, the shallow water portions of this estuary (< 2 m) supported a diverse and abundant community of submerged aquatic vegetation (SAV), which provided critical habitat for juvenile fish and shellfish, contained one of the world's most important spawning grounds for striped bass (*Morone saxatilis*), provided food for migratory birds, and stabilized bottom sediments (Phillips 2002). Since the 1960's, SAV acreage has decreased dramatically in the Chesapeake and Coastal Bays. This decline has been attributed to reductions in light availability caused by increased levels of sediment and nutrients entering the bays. To address this issue, scientists and resource managers established threshold levels for the primary water quality parameters that affect water clarity. Thus, SAV habitat requirements were established for active chlorophyll-a (Chla) (an indicator of phytoplankton biomass), total suspended solids (TSS), dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP), and light attenuation ($K_d$) for both the tidal fresh/oligohaline and mesohaline/polyhaline portions of the bay (Dennison et al. 1993; Kemp et al. 2000). Of these factors, light attenuation is considered the primary requirement for SAV growth and survival (Dennison 1987). In addition, minimum light requirements (MLR) are greater for SAV species that inhabit meso- (5 to 18 psu) to polyhaline (18 to 30 psu) portions of the bay. The MLR for SAV survival at a 1.0 m depth is a $K_d \leq 2.0$ (13% of surface irradiance) in tidal fresh (0 to 0.5 psu) and oligohaline (0.5 to 5 psu) areas and a $K_d \leq 1.5$ (22% of surface irradiance) in mesohaline (5 to 18 psu) and polyhaline (18 to 30 psu) areas.

The amount of surface irradiance available at a given depth is a function of the absorption and scattering of light photons by water itself, colored dissolved organic matter (CDOM), Chla, and TSS (Gallegos 1994, Gallegos and Moore 2000). The amount of light available to SAV is further diminished by aquatic plants' requirement for photosynthetically active radiation (PAR), a small bandwidth of light from 400 to 700 nanometers. Underwater quantum sensors often are used to measure PAR and calculate the diffuse attenuation coefficient of downward propagated irradiance ($K_d$). Once $K_d$ is established, radiative transport equations can be used to calculate the percent of surface light (% light) available to SAV at a given depth (Kirk 1994; Gallegos and Moore 2000). Percent light calculations are used to evaluate the suitability of a site to meet the water clarity requirements for SAV growth. However, the need to better assess the duration and spatial extent over which criteria are met (US EPA 2003) has spurred the use of new sampling technologies to measure the light levels available to SAV.

Turbidity, an optical property that measures the scattering by light at 90° from an incident beam, increasingly is being used to assess water clarity. In recent years, the Chesapeake Bay Program's water quality monitoring efforts have expanded from mid-channel sites to include the near-shore, shallow water areas that support SAV. In an effort to better understand the light environment in these areas, *in situ* water quality meters measure turbidity continuously throughout the SAV growing season (April-October). Turbidity data eventually may be used to determine if Chesapeake Bay River segments are in compliance with the water clarity standards set forth in the Clean Water Act (US EPA 2003). However, it is unclear if turbidity is a good predictor of $K_d$ in the Chesapeake and Coastal Bays.

In 2002, the Maryland Department of Natural Resources (MDDNR), in conjunction with the U.S. Geological Survey (USGS), expanded the scope of their *in situ* program to include weekly PAR measurements. We analyzed weekly water quality data to determine if water quality during the growing season met the five SAV habitat criteria at each site and to determine if compliance with these criteria related to the presence/absence of SAV. Furthermore, we analyzed the ability of turbidity to predict $K_d$ values and determined primary factors other than turbidity that explained variability in $K_d$ at individual sites. Finally, we evaluated the utility of an optical model, which partitions light attenuation due to TSS and Chla, to predict $K_d$ and to provide further insight into the need for nutrient or sediment reduction strategies at individual study sites.

## MATERIALS AND METHODS

**Study Area:** In 2002, MDDNR's *in situ* program assessed water quality at 10 sites within the following Chesapeake and Maryland Coastal Bay River Segments: Pocomoke River (Rehobeth, Cedar Hall Wharf, and Shelltown), Fishing Bay (Drawbridge Road), Severn River (Ben Oaks and Sherwood Forest), Magothy River (Whitehurst and Stonington Station), and Isle of Wight Bay (Bishopville Prong and Turville Creek) (Figure 1). Three of the sites (Sherwood Forest, Stonington Station, and Whitehurst) were vegetated in 2002.

***In Situ* Sampling:** MDDNR installed YSI Environmental's 6600 multi-parameter instruments at each of the 10 sites to measure temporal variability in water quality during the SAV growing season. At the eight Chesapeake Bay sites, a single YSI sonde floated within a perforated PVC housing unit that was attached to a dock, pier, or piling. At the two Coastal Bay sites, which were shallower than the Chesapeake Bay sites, housing units were anchored 0.3 m above the bottom sediments. The placement of the housing units in both bays allowed the field probes attached to the sondes to float approximately 1 m below the surface of the water. Data loggers recorded the following environmental parameters at 15 minute intervals: dissolved oxygen concentration (DO, mg $l^{-1}$), dissolved oxygen saturation (DO%), salinity, water temperature (°C), pH, turbidity (ntu), and total chlorophyll (µg $l^{-1}$). Throughout the growing season, the multi-parameter instruments were downloaded and replaced weekly with freshly calibrated units.

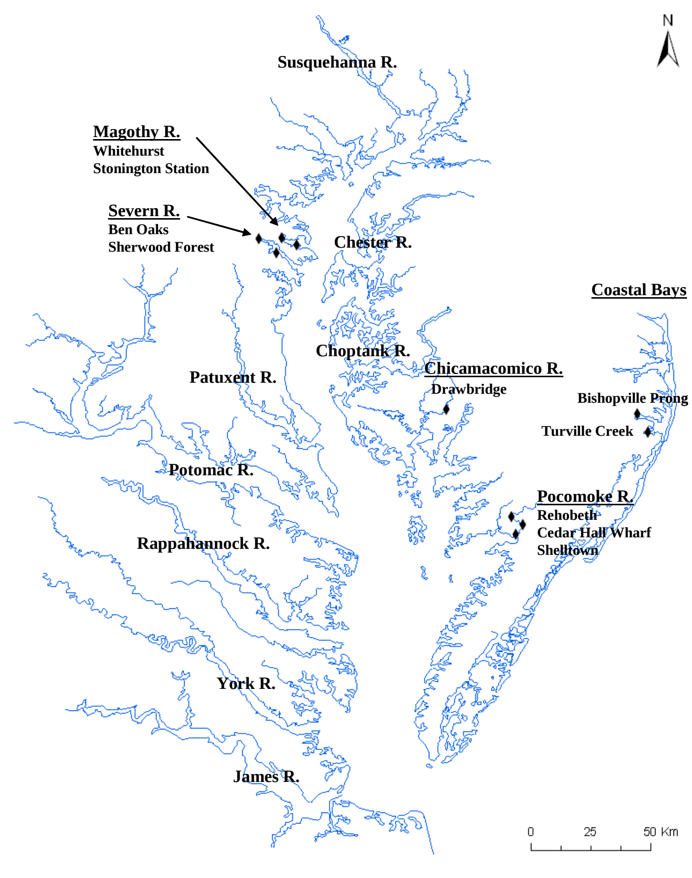


Figure 1. The 2002 Maryland Department of Natural Resources shallow water Continuous Monitoring sites in the Chesapeake and Maryland Coastal Bays.

In 2002, PAR was measured weekly at each site, although initiation of measurements at individual sites varied from April to July. Downwelling PAR was measured simultaneously at two depths (0.05 m and 0.55 m or 0.05 m and 1.0 m) with two LI-COR LI-193 Underwater Spherical Quantum Sensors. From these data, $K_d$ was calculated as

$$K_d = (-(\ln(PAR\_max\_z)-\ln(PAR\_min\_z)))/(max\_z-min\_z) \quad (1)$$

where PAR_min_z is irradiance at 0.05 m and PAR_ max_z is irradiance at either 0.55 m or 1.0 m.

**Laboratory Analysis:** During the weekly site visit to service the YSIs, discrete water samples were collected from the same depth as that of field probes. The Nutrient Analytical Services Laboratory (NASL) at the Chesapeake Biological Laboratory (CBL) analyzed the dissolved and particulate constituents of these samples. Turbidity and Chla were analyzed by the Maryland Department of Health and Mental Hygiene (DHMH). The MDDNR collection methods, and the CBL and DHMH analytical procedures, can be found in Michael et al. (2004).

**Statistical Analysis:** Median seasonal values for $K_d$, Chla, TSS, DIN, and DIP were calculated to determine whether the 10 sites met the previously established SAV water clarity requirements for growth during 2002 (Dennison et al. 1993; Kemp et al. 2000; Figure 2). In addition, total volatile solid (TVS) medians were calculated for each site to compare TSS and its organic component (TVS) (Figure 2).

Data were log-transformed prior to their use in regression analyses. Using S-Plus 6.1, simple linear regression models were developed to determine if turbidity was a good predictor of $K_d$ at each of the 10 sites, and collectively when all 10 sites were combined. Both simple and all possible regression analyses were used to determine the primary factors, other than turbidity, that affected $K_d$ in 2002. The following explanatory variables were tested: TSS, TVS, total fixed solids (TFS), Chla, YSI chlorophyll (Fluor), DIN, DIP, total nitrogen (TN), total phosphorus (TP), dissolved organic carbon (DOC), and salinity. The all possible regression procedure tested for multicolinearity among the variables through a comparison of the variance inflation factors (VIF). Any multiple variable models whose coefficients possessed VIF scores greater than five, or were not significant at $p<0.05$, were excluded from consideration for the overall best-fit multiple variable model.

We also evaluated the relative importance of Chla and TSS in attenuating light using the Optical Model for Determining Water Quality Goals for SAV Habitat Restoration (Gallegos 1994, download the model @ www.chesapeakebay.net/cims/). This model uses raw Chla and TSS values to estimate a seasonal median $K_d$ value for a site and then predicts the suitability of water clarity for SAV growth at 0.5 m, 1.0 m, and 2.0 m depths. Additionally, the optical model produces multiple management options that indicate how reductions in Chla and TSS together, TSS alone, or Chla alone, might meet the SAV water clarity requirements at a given depth.

## RESULTS

**SAV Habitat Criteria:** The three vegetated sites (Sherwood Forest, Stonington Station, and Whitehurst) met the SAV habitat criteria for TSS and $K_d$ in oligohaline SAV communities (Figure 2). Sherwood Forest, additionally, met the SAV water clarity goals for Chla and $K_d$ in meso- to polyhaline SAV communities (Figure 2). The seven unvegetated sites did not meet the habitat criteria for $K_d$, TSS, or Chla; although, some sites met one or both of the requirements for DIN and DIP (Figure 2). The TVS concentrations were low with minimal ranges at the three vegetated sites and at the two un-vegetated lower Pocomoke River sites (Figure 2).

**Turbidity as a Surrogate for $K_d$:** Turbidity was a significant predictor of $K_d$ at 6 of 10 sites: Cedar Hall Wharf ($r^2$=0.34, p=0.019), Ben Oaks ($r^2$=0.40, p<0.001), Sherwood Forest ($r^2$=0.32, p=0.003), Whitehurst ($r^2$=0.23, p=0.011), Stonington Station ($r^2$=0.62, p<0.001), and Bishopville Prong ($r^2$=0.36, p=0.008) (Table 1). Both simple and all possible regression analyses revealed that turbidity was the best single variable predictor of $K_d$ at Ben Oaks, Sherwood Forest, Whitehurst, Stonington Station, and Bishopville Prong (Table 1). Turbidity was also the best single variable predictor of $K_d$ ($r^2$=0.63, p<0.001) bay-wide (Figure 3).

**Primary Factors Influencing $K_d$:** An all possible regression analysis, excluding turbidity, was used to identify the best-fit single and multiple parameter models that explained the most variance in $K_d$ during 2002 (Table 2). Total phosphorus was the best single predictor for $K_d$ at: Whitehurst ($r^2$=0.17, p=0.031), Stonington Station ($r^2$=0.32, p=0.003), and Turville Creek ($r^2$=0.47, p=0.003); DOC at Sherwood Forest ($r^2$=0.18, p=0.033) and Bishopville Prong ($r^2$=0.33, p=0.012); salinity at Shelltown ($r^2$=0.25, p=0.034) and Drawbridge Road ($r^2$=0.50, p<0.001); TN at Rehobeth ($r^2$=0.30, p=0.019); DIN at Cedar Hall

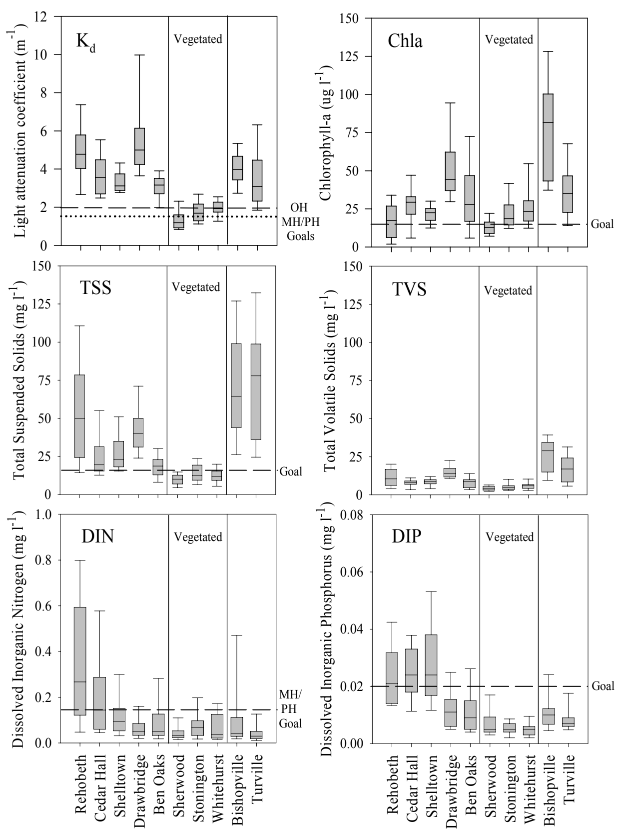


Figure 2. Box plots of median seasonal values for $K_d$, Chla, TSS, TVS, DIN, and DIP are shown for the 2002 sites. Each box represents 50% of the data; whiskers indicate the 10th and 90th percentiles. There are no established criteria for TVS. SAV habitat criteria are shown for the oligohaline (OH), mesohaline (MH), and polyhaline (PH) salinity zones in the Chesapeake and Maryland Coastal Bays, 2002.

Wharf ($r^2$=0.61, p<0.001); and TVS at Ben Oaks ($r^2$=0.20, p=0.020) (Table 2).

The best regression models for Rehobeth, Whitehurst, and Turville Creek contained a single predictor variable. For the other seven sites (Cedar Hall Wharf, Shelltown, Drawbridge, Ben Oaks, Sherwood Forest, Stonington Station, and Bishopville Prong) the best models were multiple regressions (Table 2).

Table 1 Results of the simple linear regression analyses describing the relation between $K_d$ and turbidity in the Chesapeake and Maryland Coastal Bays, 2002. The sites where turbidity was a significant predictor of $K_d$ are in bold. An * indicates that turbidity was the best single variable predictor of $K_d$ when included in an all possible regression analysis.

| River | Site | Salinity regime | F-statistic | $r^2$ | p-value |
|---|---|---|---|---|---|
| Pocomoke | Rehobeth | oligohaline | 1.48 | 0.08 | 0.242 |
| | **Cedar Hall Wharf** | oligohaline | **7.07** | **0.34** | **0.019** |
| | Shelltown | oligohaline | 0.05 | 0.00 | 0.834 |
| Chicamacomico | Drawbridge | mesohaline | 2.65 | 0.11 | 0.118 |
| Severn | **Ben Oaks** * | mesohaline | **16.68** | **0.40** | **<0.001** |
| | **Sherwood Forest** * | mesohaline | **11.43** | **0.32** | **0.003** |
| Magothy | **Whitehurst** * | mesohaline | **7.61** | **0.23** | **0.011** |
| | **Stonington Station** * | mesohaline | **38.71** | **0.62** | **<0.001** |
| St. Martin | **Bishopville Prong** * | polyhaline | **9.10** | **0.36** | **0.008** |
| Turville Creek | Turville | polyhaline | 3.49 | 0.20 | 0.083 |

**<u>The Impact of TSS on $K_d$:</u>** In 2002, TSS and its organic (TVS) and inorganic (TFS) fractions explained a small portion of the variability in $K_d$. However, TVS was the primary factor affecting light attenuation at Ben Oaks ($r^2$=0.20, p=0.020) (Table 2). TSS and TFS were not the best single variable descriptors of $K_d$ at any of the sites. However, TSS was significantly related to $K_d$ at Stonington Station ($r^2$=0.23, p=0.013) and Turville Creek ($r^2$=0.27, p=0.041); TVS at Cedar Hall Wharf ($r^2$=0.37, p=0.023), Ben Oaks ($r^2$=0.20, p=0.020), Stonington Station ($r^2$=0.17, p=0.035), and Turville Creek ($r^2$=0.39, p=0.013); and TFS at Cedar Hall Wharf ($r^2$=0.46, p=0.010).

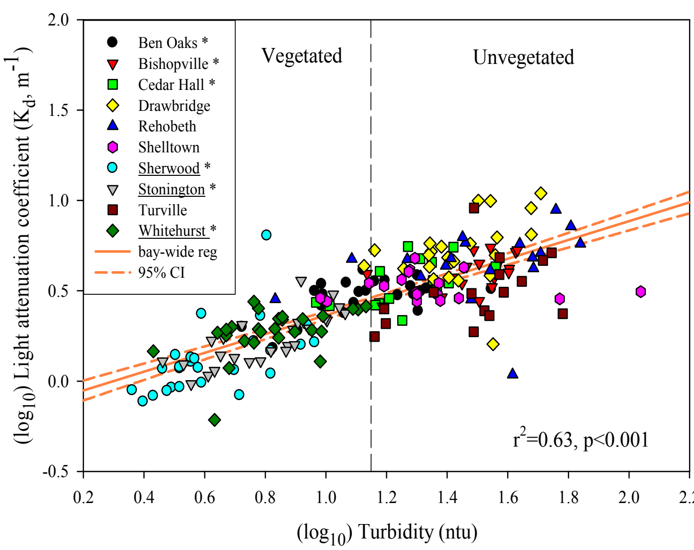


Figure 3. The regression line, 95% Confidence Interval (CI), and test statistic ($r^2$) for the bay-wide regression of $K_d$ and turbidity. Each site is identified by an individual color. An * indicates those sites at which turbidity was significantly (p<0.05) related to $K_d$; sites with SAV present in 2002 are underlined. The turbidity at the vegetated sites was <11.1 ntu ($log_{10}$ 1.15).

## <u>Optical Model for Determining $K_d$</u>

An Exact Wilcoxon Signed-Rank Test was used to compare the $K_d$ values estimated by the Gallegos optical model (1994) to those calculated from PAR measurements (Figure 4). This analysis revealed that the estimated $K_d$ values were not significantly different from the calculated $K_d$ values (signed-rank statistic V =22, p=0.625) (Figure 4).

Table 2 Results of the best simple (SLR) and multiple (MLR) linear regression analyses describing the relation between $K_d$ and total suspended solids (TSS), total volatile solids (TVS), total fixed solids (TFS), active chlorophyll-a (Chla), YSI chlorophyll (Fluor), dissolved inorganic nitrogen (DIN), dissolved inorganic phosphorus (DIP), total nitrogen (TN), total phosphorus (TP), dissolved organic color (DOC), and salinity (Sal) in the Chesapeake and Maryland Coastal Bays, 2002. At Rehobeth, Whitehurst, and Turville Creek, none of the multiple regression models were significant at $p \leq 0.05$. As a result, the best regression models were single variable models (shown in bold).

| Site | Type of Regression Model | Parameters | F-statistic | $r^2$ | p-value |
|---|---|---|---|---|---|
| **Rehobeth** | **SLR** | **TN** | **6.84** | **0.30** | **0.019** |
| Cedar Hall Wharf | SLR | DIN | 21.78 | 0.61 | <0.001 |
| | MLR | TFS+Fluor | 31.63 | 0.86 | <0.001 |
| Shelltown | SLR | Sal | 5.39 | 0.25 | 0.034 |
| | MLR | TFS+TN+TP+Sal | 5.70 | 0.66 | 0.008 |
| Drawbridge | SLR | Sal | 22.39 | 0.50 | <0.001 |
| | MLR | Sal+TVS | 12.45 | 0.55 | <0.001 |
| Ben Oaks | SLR | TVS | 6.23 | 0.20 | 0.020 |
| | MLR | TVS+TFS+DIP+TN | 8.79 | 0.62 | <0.001 |
| Sherwood Forest | SLR | DOC | 5.13 | 0.18 | 0.033 |
| | MLR | DIP+Sal+DOC | 5.01 | 0.43 | 0.009 |
| **Whitehurst** | **SLR** | **TP** | **5.25** | **0.17** | **0.031** |
| Stonington Station | SLR | TP | 11.06 | 0.32 | 0.003 |
| | MLR | TP+TN+Fluor | 6.26 | 0.46 | 0.003 |
| Bishopville Prong | SLR | DOC | 8.03 | 0.33 | 0.012 |
| | MLR | Fluor+TFS | 7.72 | 0.51 | 0.005 |
| **Turville Creek** | **SLR** | **TP** | **12.60** | **0.47** | **0.003** |

According to the model, six sites met requirements for SAV growth at 0.5 m: Cedar Hall Wharf, Shelltown, Ben Oaks, Sherwood Forest, Whitehurst, and Stonington Station; three sites (Sherwood Forest, Whitehurst, and Stonington Station) met requirements for SAV growth at 1.0 m (Table 3). No sites met the water clarity requirements for growth at 2.0 m. Four sites (Rehobeth, Drawbridge, Bishopville, and Turville) were not predicted to support SAV growth at any depth in 2002.

Reductions in both Chla and TSS levels at all 10 sites are expected to have resulted in water clarity improvements that favored SAV growth at 0.5 m, 1.0 m, and 2.0 m (Table 3). However, the magnitude of the recommended reductions varied greatly among sites and among depths at the same site. All sites, except for Drawbridge Road and Bishopville Prong at 2.0 m, could meet the habitat requirements for SAV by reducing TSS levels and maintaining current Chla levels (Table 3). Based on the model, no sites were expected to meet SAV water clarity requirements for growth through reductions in Chla alone.

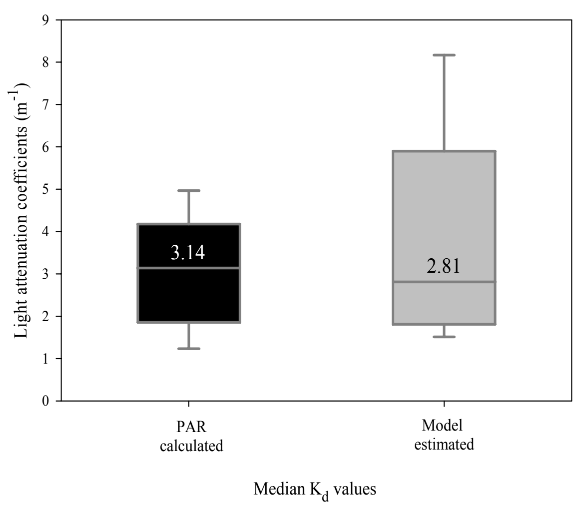


Figure 4. Box plots of the PAR calculated and model estimated (Gallegos 1994) combined median $K_d$ values (n=10) for the 2002 Chesapeake and Maryland Coastal Bay sites. Each box represents 50% of the data; whiskers indicate the $10^{th}$ and $90^{th}$ percentiles. An Exact Wilcoxon Signed-Rank Test revealed that the estimated $K_d$ median was not significantly different from the calculated $K_d$ median (p<0.05).

Table 3 The PAR calculated and model estimated $K_d$ values for the 10 Chesapeake and Maryland Coastal Bay sites, 2002. Based on the estimated $K_d$ value, the optical model predicted whether or not a site met the water clarity habitat requirements for SAV growth at 0.5 m, 1.0 m, and 2.0 m depths. No sites met the water clarity requirements at 2.0 m. The sites and depths that met the SAV water clarity goals are shown in bold. The management options that would allow each site to meet the water clarity goals for each depth are shown (X). In 2002, no sites would have been expected to meet the water clarity habitat requirements through reductions in Chla alone.

| Site | SAV (YES/NO) | PAR calculated medain $K_d$ ($m^{-1}$) | Model estimated median $K_d$ ($m^{-1}$) | Depth (m) | SAV habitat requirements (met/not met) | Reduce Chla & TSS | Reduce TSS only |
|---|---|---|---|---|---|---|---|
| Rehobeth | NO | 4.77 | 5.3 | 0.5 | not met | X | X |
| | | | | 1.0 | not met | X | X |
| **Cedar Hall Wharf** | **NO** | **3.56** | **2.52** | **0.5** | **met** | | |
| | | | | 1.0 | not met | X | X |
| **Shelltown** | **NO** | **3.12** | **3.10** | **0.5** | **met** | | |
| | | | | 1.0 | not met | X | X |
| Drawbridge Road | NO | 4.99 | 4.79 | 0.5 | not met | X | X |
| | | | | 1.0 | not met | X | X |
| **Ben Oaks** | **NO** | **3.16** | **2.46** | **0.5** | **met** | | |
| | | | | 1.0 | not met | X | X |
| **Sherwood Forest** | **YES** | **1.19** | **1.48** | **0.5** | **met** | | |
| | | | | **1.0** | **met** | | |
| **Whitehurst** | **YES** | **1.93** | **1.82** | **0.5** | **met** | | |
| | | | | **1.0** | **met** | | |
| **Stonington Station** | **YES** | **1.63** | **1.79** | **0.5** | **met** | | |
| | | | | **1.0** | **met** | | |
| Bishopville Prong | NO | 3.98 | 7.69 | 0.5 | not met | X | X |
| | | | | 1.0 | not met | X | X |
| Turville Creek | NO | 3.09 | 8.22 | 0.5 | not met | X | X |
| | | | | 1.0 | not met | X | X |

## DISCUSSION

We found that the minimum light requirements were a good indicator of SAV presence at the near shore sites (Figure 2). The three vegetated sites (Sherwood Forest, Stonington Station, and Whitehurst), located in the mesohaline portion of the bay, met the oligohaline SAV water clarity criteria (13% of surface irradiance). Additionally, Sherwood Forest met the mesohaline light requirement (22% of surface irradiance). These results indicate that water clarity at Stonington Station and Whitehurst may have been adequate to support freshwater and oligohaline species but not meso- or polyhaline species. The species consistently present at the vegetated sites were widgeon grass (*Ruppia maritima*), redhead grass (*Potamogeton perfoliatus*), sago pondweed (*Potamogeton pectinatus*), and horned pondweed (*Zannichellia palustris*) (Orth et al. 2003). These species typically survive fluctuating salinity conditions in oligo- to mesohaline environments (Davis and Reel 2001). We also found that weekly turbidities at vegetated sites were less than 11.1 NTUs, and that unvegetated sites showed turbidity values exceeding 11.1 NTUs (Figure 3). As additional sites and years of data accumulate, the near shore, *in situ* data could be used to develop turbidity criteria for SAV growth, as was done for other SAV habitat criteria (Kemp et al. 2000).

During the 2002 growing season, turbidity was significantly related to $K_d$ at six of the *in situ* sites (Table 1); however, it explained ≤ 40% of the temporal variability in $K_d$ at five of those sites and ~63% of the spatial and temporal variability when all 10 sites were combined (Table 1, Figure 3). The low explanatory ability and large degree of variability in the regression models for $K_d$ and turbidity indicate that the relation between the two variables needs to be better defined before turbidity can be used to predict water clarity or determine the interval during the growing season that a site meets established water clarity criteria (US EPA 2003).

We developed simple regression models to determine the primary factors, other than turbidity, that influenced $K_d$. Total phosphorus was the best predictor of Kd at three sites, nitrogen at two sites, DOC at two sites, salinity at two sites, and TVS at one site (Table 2). These results indicate that nutrient reduction and subsequent Chla reduction would have a greater effect on water clarity than TFS (mineral sediment) reductions.

Due to the low predictive abilities ($r^2$) of the single variable models, we developed multiple regression models of $K_d$ and 11 independent variables. For Rehobeth, Whitehurst, and Turville Creek, the inclusion of additional variables in the regression model did not improve upon the results of the best single variable model (Table 2). For the remaining sites, the overall best-fit models included a combination of total nutrients (TP and TN), components of TSS (TVS, TFS, and Fluor), and dissolved constituents (DIP and salinity). These regression results are consistent with previous studies that have shown that TSS and/or Chla were good predictors of $K_d$ in the Potomac River and Estuary (Carter and Rybicki 1990), the Chesapeake Bay (Gallegos 1994), and the Indian River Lagoon in Florida (Gallegos and Kenworthy 1996).

Total nitrogen (TN) and total phosphorus (TP) affected water clarity at various sites. Previous work in the Potomac River has shown that TP positively and TN negatively correlate to Chla and TSS, which in turn negatively correlate with secchi depth (Carter et al. 2000). These results indicate that TP and TN are indirectly involved in light attenuation, possibly through their relationships to Chla and TSS. An analysis of additional parameters, such as particle size, particle density, and chemical composition, may enhance our understanding of the relation among nutrients, suspended particulate material, and light attenuation.

The positive relationship between $K_d$ and salinity may be an indirect effect of flow and its impact on the delivery of particulates to the sites. When river discharge is low, as it was in 2002 (Langland et al. 2004), the estuarine turbidity maximum (ETM) carries more saline waters upstream. As the ETM moves across a site that otherwise is located near, but upstream, of the turbidity maximum, turbidity and $K_d$ may increase. The ETM is typically located downstream of both Shelltown and Drawbridge (US EPA 2003); perhaps low-flow conditions and the migration of the ETM upstream explain the positive relation between $K_d$ and salinity at those two sites.

Finally, we compared our simple and multiple regression models with the output of the Gallegos (1994) optical water clarity model. The model predictions of the sites that met the SAV water clarity habitat requirements at 1.0 m matched the three sites (Sherwood Forest, Stonington Station, and Whitehurst) that supported SAV in 2002. In addition, the Gallegos model (1994), which computes an estimated $K_d$ value for a site based on TSS and Chla values, was a good overall predictor of $K_d$ at the shallow water sites during 2002. These results indicate that the optical model is a useful tool for estimating seasonal median $K_d$ values when only Chla and TSS values are available. Additionally, the model reliably predicted the water clarity requirements for SAV growth.

The optical model indicated that TSS reduction alone, but not Chla reduction alone, would lower $K_d$ to meet the minimum light requirements. This finding does not necessarily indicate sediment reduction is a better strategy than nutrient reduction at these sites. It is problematic to use the Gallegos model (1994) to distinguish between the relative importances of sediment or nutrients in attenuating light using only TSS and Chla values. TSS is composed of the dry weight of all particulate matter including both TVS (phytoplankton, heterotrophic plankton, bacteria, and particulate organic detritus) and TFS (clay, silt, and sand). Although TVS was a substantial portion of the TSS at some sites (especially sites with low TSS and TFS) (Figure 2), the optical model would determine that Chla had a greater effect on water clarity than TSS only if a site was affected by prolonged algal blooms (Gallegos and Moore 2000). The habitat criteria for Chla (15 $\mu g\ l^{-1}$ seasonal median), however, suggests that algal bloom conditions are not necessary to inhibit SAV growth. Increased understanding of the type and size of material (TFS), and species of plankton composing TVS will enhance understanding of the appropriate strategies needed to improve water clarity. Future research to determine factors causing light attenuation, based on ecological models (Cloern 2001), sediment nutrient flux, process oriented studies, and regression analyses, will improve our understanding and serve as a guide in determining the effectiveness of management strategies to establish nutrient and sediment loading rates that allow for restoration of SAV.

## REFERENCES

Carter, V. and N.B. Rybicki. (1990). "Light attenuation and submersed macrophytes distribution in the tidal Potomac River and Estuary," Estuaries 13:441-452.

Carter, V., N.B. Rybicki, J.M. Landwehr, and M. Naylor. (2000). Light requirements for SAV survival and growth, in Chesapeake Bay submerged aquatic vegetation water quality and habitat-based restoration targets: A second technical synthesis: U.S. Environmental Protection Agency, Chesapeake Bay Program, p. 11-33.

Cloern, J.E. (2001). "Our evolving conceptual model of the coastal eutrophication problem," Marine Ecology Progress Series 201:223-253.

Davis, R.C. and J.T. Reel. (2001). Chesapeake Bay submerged aquatic vegetation identification guide. J.W. Boarman Co.

Dennison, W.C. (1987). "Effects of light on seagrass photosynthesis, growth, and depth distribution," Aquatic Botany 27:15-26.

Dennison, W.C., R.J. Orth, K.A. Moore, J.C. Stevenson, V. Carter, S. Kollar, P.W. Bergstrom, and R.A. Baituk. (1993). "Assessing water quality with submersed aquatic vegetation. Habitat requirements as barometers of Chesapeake Bay health," Bioscience 43:86-94.

Gallegos, C.L. (1994). "Refining habitat requirements of submersed aquatic vegetation: role of optical models," Estuaries 17:198-219.

Gallegos, C.L. and W.J. Kenworthy. (1996). "Seagrass depth limits in the Indian River Lagoon (Florida, U.S.A.): application of an optical water quality model," Estuarine, Coastal, and Shelf Science 42:267-288.

Gallegos, C.L. and K.A. Moore. (2000). Factors contributing to water column light attenuation, in Chesapeake Bay submerged aquatic vegetation water quality and habitat-based restoration targets: A second technical synthesis: U.S. Environmental Protection Agency, Chesapeake Bay Program, p. 35-54.

Kemp, M., R.A. Batiuk and P.W. Bergstrom. (2000). SAV, water quality, and physical habitat relationships in Chesapeake Bay submerged aquatic vegetation water quality and habitat-based restoration targets: A second technical synthesis: U.S. Environmental Protection Agency, Chesapeake Bay Program, p. 3-9.

Kirk, J.T.O. (1994). Light and photosynthesis in aquatic ecosystems. Cambridge University Press, Cambridge.

Langland, M.J., United States Environmental Protection Agency, Chesapeake Bay Program, Maryland Dept. of Natural Resources, Virginia Dept of Environmental Quality, U.S. Geological Survey. (2004). Changes in streamflow and water quality in selected nontidal sites in the Chesapeake Bay basin, 1985-2003. U.S. Geological Survey Scientific Investigations Report number 2004-5259.

Michael, B., E.L. Ebersole, M. Trice and C.J. Heyer. (2004). Quality assurance project plan for the Maryland Department of Natural Resources Chesapeake Bay shallow water quality monitoring program. Maryland Department of Natural Resources.

Orth, R.J., D.J. Wilcox, L.S. Nagey, A.L. Owens, J.R. Whiting and A. Serio. (2003). 2002 distribution of submerged aquatic vegetation in the Chesapeake and Coastal Bays. VIMS Special Scientific Report Number 139. Final report to U.S. EPA, Chesapeake Bay Program.

Phillips, S.W. (2002). The U.S. Geological Survey and the Chesapeake Bay-the role of science in environmental restoration. U.S. Geological Survey Circular 1220.

United States Environmental Protection Agency. (2003). Ambient water quality criteria for dissolved oxygen, water clarity, and chlorophyll a for the Chesapeake Bay and its tidal tributaries. U.S. Environmental Protection Agency, Chesapeake Bay Program and Region 3 Water Protection Division.