Measurement of Optical Properties in the Delaware Estuary

Mingzhu Wang*, David R. Lyzenga† and Victor V. Klemas‡

*70 Olcott Street
Watertown, MA 02172, U.S.A.
†HRIM, P.O. Box 134001
Ann Arbor, MI 48103-4001, U.S.A.
‡Robinson Hall
University of Delaware
Newark, DE 19716, U.S.A.

ABSTRACT


In situ measured optical, biological and other data of Delaware estuarine water were analyzed to improve our understanding of the spectral effects of the major dissolved and particulate substances on the optical properties of case II waters. The attenuation coefficient and irradiance reflectance were calculated from the measured optical parameters. The data show that Delaware estuarine water is optically unstratified in the upper three meters or within one Secchi depth. The variation in the concentrations of the measured constituents and the correlations among pairs of concentrations were studied. The concentration of seston is highly correlated with the attenuation coefficient from 400 to 800 nm, and even more strongly correlated from 600 to 720 nm. It has good correlation with reflectance from 700 to 800 nm. Secchi depth and the attenuation coefficient from 400 to 700 nm are inversely related.

Major light attenuating constituents were selected with statistical methods. Specific attenuation coefficients of seston and dissolved organic materials are determined with multiple regression analysis. The results show that seston makes important contributions to the light attenuation from 400 to 800 nm. The importance of chlorophyll a to the light attenuation is only shown between 670 nm and 680 nm. DOC (Dissolved Organic Carbon), DON (Dissolved Organic Nitrogen), and HC (Humic Acid Carbon) can all be used as indicators for gelbstoff (dissolved organic material). The attenuation coefficient of water, calculated from the attenuation model developed by statistical analysis is remarkably similar to the measured spectrum from Secchi depth. The specific attenuation coefficient of gelbstoff follows the exponential form from 400 to 630 nm, and has a null region from 720 to 770 nm when HC is used as an indicator. Using DOC or DON as an indicator, a similar relationship is obtained but without the null region. The relative contributions of these constituents to the total light attenuation in Delaware estuarine water were demonstrated.

ADDITIONAL INDEX WORDS: Attenuation, reflectance, Secchi depth, case II water, seston, gelbstoff.

INTRODUCTION

In contrast to waters of the open ocean, estuarine waters are usually turbid with high concentrations of suspended organic and inorganic particles and dissolved organic materials. These materials affect geochemical processes such as trace metal and pollutant transport and biological production by reducing the light available to phytoplankton. Many of these materials are optically active and have an influence on the spectral distribution of light in the water column and above the water surface. This suggests the possibility of studying the distribution and estimating the concentrations of these materials through optical remote sensing techniques.

In 1987 and 1988, a set of optical and bio-chemical measurements was made along the Delaware estuary as part of the Delaware Sea Grant program. An optical, biological and chemical data bank has been established based on these measurements. The relationships among bio-chemical data, and between bio-chemical data and optical data are explored in this paper.

Based on the optical and biological measurements on Delaware estuary in 1987 and 1988, a series of statistical analyses have been performed to improve our understanding of the light effects of major constituents and the water quality of Delaware estuary. The objectives of this work were experimentally determining the specific optical properties of the major constituents and the relative contributions of these constituents to the total attenuation in Delaware Bay.

Figure 1 shows the location of 26 sampling stations in the Delaware estuary situated between Trenton, New Jersey, and near the mouth of the Delaware Bay. Ship surveys were performed along these stations once a month during 1987 and 1988 on 24 cruises. Biological and chemical data were sampled on almost all the 24 cruises. Optical data were obtained on five cruises. In addition, there was one cruise across the mouth of the bay, designated as SHWTR-1 (Shear Water cruise).
Optical Parameters

Measurements of upwelling and downwelling irradiance profiles were performed with a Licor model LI-1800 scanning spectroradiometer in the upper 10 m of the water column (Lyzenga et al., 1988). The signal from Licor is proportional to the light irradiance. Both downwelling irradiance $E_d(Z, \lambda)$ and upwelling irradiance $E_u(Z, \lambda)$ are functions of depth $Z$ and wavelength $\lambda$. Figure 2 shows the scenario for the measurement of light profiles of downward light and upward light. The irradiance was recorded at wavelengths from 400 nm to 800 nm in intervals of 10 nm. It takes approximately 30 seconds for the spectroradiometer to scan a range from 400 to 800 nm at the intervals of 10 nm. The irradiance measured at the first depth near the water surface is the average value of three scans in order to eliminate cloud and wave effects. The irradiance collector used in the Licor is a cosine collector. After each scan, spectral data were automatically corrected for the immersion effect, which was wavelength dependent (Licor, 1982). To minimize shading effects, the sensor was always lowered on the sunny side of the boat.

Concentrations and Other Ship Measurements

Bio-chemical data from 26 cruises were measured by Dr. Jonathan Sharp's group, University of Delaware, from 1987 to 1988. Water samples were collected at each station at a depth of 1 meter below the water surface and analyzed for total seston (SES); chlorophyll-a (CHLA); dissolved organic carbon (DOC), dissolved organic nitrogen (DON), and dissolved organic phosphate (DOP); particulate organic carbon (PC), particulate organic nitrogen (PN), and particulate organic phosphate (PP); humic acid carbon (HC), and humic acid nitrogen (HN) (Sharp and Culberson, 1982).

The particulate matter was defined as the suspended material which was retained by a filter with pore diameter 0.45 μm. The dissolved material was defined as that passing through the 0.45
μm pore. Other measured parameters are salinity (ppt), Secchi depth (cm), broad band attenuation (1/m) (an attenuation of filtered light averaged from 400 nm to 700 nm), and other chemical and biological constituents (Sharp and Culberson, 1982).

DATA ANALYSIS

Bio-chemical Data Analysis

Descriptive statistical analyses were performed on biological and other measurements. Correlations among the measurements were calculated. The variation of the measurements along the designed stations was explored.

Optical Data Analysis

Calculation of K

Linear regression analysis was applied for study of the measured downwelling irradiance versus depth. The light attenuation coefficient K of estuarine water was calculated from the equation

\[ E_d(Z, \lambda) = E_d(0, \lambda) \exp(-K(\lambda)Z) \]  

(1)

using the measured downwelling irradiance \( E_d(Z, \lambda) \) and \( E_d(0, \lambda) \) values, where \( Z \) is the depth and \( \lambda \) is the wavelength. Equation 1 can be transformed into Equation 2

\[ \ln(E_d(Z, \lambda)) = \ln(E_d(0, \lambda)) - K(\lambda)Z \]  

(2)

At each station, the measured \( E_d(Z, \lambda) \) is a function of wavelength and depth. Equation 2 was applied to each wavelength from 400 to 800 nm at intervals of 10 nm. At each wavelength, the K value is calculated by using regression analysis (Zar, 1984) on depth. After applying the regression analysis on depth at all the wavelengths, the spectrum of the attenuation coefficient K at one station was calculated.

Calculation of R

The subsurface irradiance reflectance R is calculated from Equation 3

\[ R(\lambda) = \frac{E_u(\lambda, 0)}{E_d(\lambda, 0)} \]  

(3)

where \( E_u(\lambda, 0) \) and \( E_d(\lambda, 0) \) are the upwelling irradiance and downwelling irradiance just below water surface \((Z = 0.25 \text{ m or } 0.50 \text{ m})\), respectively.

Attenuation Coefficient Model

We assume that the additive assumption can be applied to the attenuation model, that is, the total light attenuation coefficient is equal to the sum of attenuation coefficient of water and the attenuation effect by different constituents.

\[ K(\lambda, \text{st}) = K_w(\lambda) + \sum K^*(\lambda)C_i(\text{st}) \]  

(4)

where \( \lambda \) is the wavelength, \( \text{st} \) is the station number, \( i \) is the number of constituents, \( K \) is the total light attenuation coefficient, \( K_w \) is the attenuation coefficient of water, \( K^* \) is the specific attenuation coefficient of the \( i \)th constituent, \( C \) is the concentration of the \( i \)th constituent.

From Equation 1, the total attenuation coefficient \( K \) was calculated on 41 wavelengths from 400 nm to 800 nm in the interval of 10 nm. So there are 41 attenuation models on 41 wavelengths in the form of Equation 4. With the calculated \( K \) at each station and measured concentrations of different constituents at these stations, the spectrum of specific attenuation coefficients of different constituents can be calculated with Equation 4 using multiple regression analysis.

Measured concentrations are concentrations of seston (SES), chlorophyll-a (CHLA), dissolved organic carbon (DOC), dissolved organic nitrogen (DON), dissolved organic phosphate (DOP), particulate organic carbon (PC), particulate organic nitrogen (PN), particulate organic phosphate (PP), humic acid carbon (HC) and humic acid nitrogen (HN). We believe these constituents either have direct effect on light attenuation or are indicators for constituents which affect light attenuation. If we include all of these concentrations into the attenuation model, there will be two problems: the first, from the physical aspect, the attenuation effects by these constituents may be duplicated since several of them may be just the indicators for one light-attenuating constituent; the second,
from the statistical aspect, some of them may have much less contribution to the total light attenuation compared to the others and their specific attenuation coefficients may not be statistically significant. This will influence the accuracy of the calculated specific attenuation coefficient for the other constituents. Since PC, PN and PP are included in the total seston, we will not include them in the model. For gelbstoff (dissolved organic material), it is needed to find out which is the best indicator for it among DOC, DON, DOP, HC and HN.

To decide which measured concentration should be included in the model at each wavelength, statistical subset selection methods were used to select the models with best fitness on each wavelength. Among many statistical subset selecting methods, Mallow's $C_p$ criterion was found to be the best for this study. By applying Mallow's $C_p$ criterion (Daniel and Wood, 1971; SAS, 1985; Whitlock, 1977) to the 41 models in the form of Equation 4 on 41 wavelengths, the important constituents for light attenuation were selected on each wavelength.

Multiple regression analysis was then applied on each of the selected models to calculate the specific attenuation coefficient of the major light attenuating constituents. From the result of multiple regression, the P-value (Zar, 1984) was used to check whether the calculated coefficient was statistically significant or not. The attenuation model, Equation 4, can be expressed in Equation 5.

$$K(\lambda_i, \text{ST}) = K_0(\lambda_i) + K_{\text{ses}}(\lambda_i)C_{\text{ses}}(\text{ST})$$

$$+ K_{\text{dom}}(\lambda_i)C_{\text{dom}}(\text{ST})$$

$$i = 1, \ldots, 41,$$

where SES stands for seston and DOM stands for dissolved organic material.

We first choose the model suggested by $C_p$ criterion at each wavelength with the $K$ as dependent variable and the concentrations of selected constituents as independent variables. The multiple regression analysis was applied to the model at each wavelength to calculate the intercept and the coefficient of each independent variable. We then use the concentration of each measured dissolved organic material (DOC, DON, HC, and HN) as indicator for dissolved organic material individually to improve our understanding on their optical properties.

## RESULTS

### Bio-chemical and Other Properties

The statistical descriptions of the measured data are listed in Table 1, where (a) gives the description of the data from all the cruises and (b) gives the description of the data from optical cruises, which were used for developing the attenuation model. The variation of the concentrations of the constituents and other features of the water properties in the Delaware estuarine water are revealed by the following biological characteristics.

1. Figure 3 shows the mean value of the measurement along the designed stations. The vertical bars show the variations of the measurements from different cruises. From the plot of salinity versus station, it shows that from station 1 to station 12 the water mass is fresh water and from station 14 to 26 the salinity increases steadily. The variation range of salinity at each station is almost the same. This variation is caused by

### Table 1. General statistical description of the measured data:
(a) from all the stations (b) from stations with other optical measurements.

<table>
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<th>Variable</th>
<th>Unit</th>
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1. ATTT...
Table 2. Correlation among the measured data: (a) from all measured data (b) from stations with optical measurements.

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<th>DON</th>
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<td>0.1</td>
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the tidal status. From the plots of broad band attenuation (ATT) versus station, seston versus station and Secchi depth versus station, it shows that at station 16 the broad band attenuation and the concentration of seston have the largest value and Secchi depth has the lowest value. Apparently the water mass around station 16 is the turbidity maximum. From the plots of DOC, DON, HC and HN versus station, it shows that from station 11 to the mouth of the bay the concentrations of dissolved organic materials (DOC, DON, HC and HN) decrease. The variations of the concentrations of PC, PN and PP along the station have almost the same pattern as that of seston.

2. The correlations among these concentrations are listed in Table 2, where (a) shows the result from all the cruises and (b) from the optical cruises. Broad band attenuation has significant negative correlation with salinity and Secchi depth, and positive correlation with seston.

3. The measurement data shows that Secchi depth and broad band attenuation are inversely related. From the measured data of all cruises the relation between Secchi depth and broad band attenuation coefficient is found as $SEC \cdot ATT = 1.82$, where the unit of Secchi depth is meter and the unit of broad band attenuation is m$^{-1}$. The regression coefficient between $1/SEC$ and ATT is 0.94. This result is close to the one given by Gordon and Wouters, (1978): $Z_c \cdot K = n$, with $1.4 < n < 1.7$, where $Z_c$ is Secchi depth and $K$ denotes the broad band attenuation.

Optical Properties

Attenuation

Figure 4 illustrates the log value of downwelling irradiance ($ln E_d$) versus depth with the regression line and 95% confidence interval at 440 nm at stations 3, 18, 20 and 22 on cruise 24. These are the examples from many measurements. The regression results show that the linear relationship between ($ln E_d$) and station is statistically significant, that is, all of the calculated $K$ values are...
Figure 3. Measurements versus station from all cruises.
uniform at the measured depths and statistically significant. This result suggests that in the upper 3 m of the water column the Delaware estuarine water is optically homogeneous.

Figure 5 gives the calculated spectra of $K(\lambda)$ at the designed stations from wavelength 400 nm to 800 nm on cruises 15, 17, 20, 22, 24 and the Shear Water cruise. The measurements from other cruises are with the same pattern as cruise 15. The general shape of the attenuation coefficients is high between 40 and 500 nm and between 700 and 800 nm, and relatively flat between 500 and 700 nm. Generally from station 16 to station 20, $K$ from 400 to 500 nm is much higher than $K$ at the rest of the wavelengths. At the other stations, $K$ from 700 to 800 nm is higher than $K$ at the other wavelengths or comparable to the $K$ between 400 and 500 nm. The highest $K$ happens around station 16. The highest value of $K$ is as high as 16 m$^{-1}$. This implies that the turbidity maximum is near station 16.

The attenuation coefficient spectrum $K(\lambda)$ was calculated from measurements with a cosine collector. In conjunction with this measurement, the averaged attenuation coefficient (broad band attenuation, ATT) value from 400 nm to 700 nm was also measured as mentioned above. ATT is the vertical attenuation coefficient for scalar irradiance. Monte Carlo calculations show that for media with $b/a$ ranging from 0.3 to 30, where $b$ is the backscattering coefficient and $a$ is absorption coefficient, average $K(\lambda)/\text{ATT}$ varies only between about 1.01 and 1.06 (Kirk, 1983). With all of the measured data on Delaware estuarine water, the comparison of $K(\lambda)$ (average of $K$ from 400 to 700 nm), and ATT is illustrated in Figure 6 at each experiment station. They are very close to each other. Though the ratio of $R/\text{ATT}$ varies between 0.65 and 1.84, at most of the stations it ranges from 0.9 to 1.4. This is also a good validation of the measurement.

Reflectance

Figure 7 gives the calculated spectra of reflectance $R$ at cruises 15, 17, 20, 22, 24, and Shear Water cruise. The $R$ data in the samples are from 0.005 to 0.15. On most cruises the highest peak is between 550 nm and 600 nm. In the turbidity maximum near station 16 there seems to be a broad band peak from 500 to 700 nm. In addition to the first peak, the second peak is around 680 to 700 nm, which may be due to the chlorophyll fluorescence emission.
Figure 4. Downward irradiance versus depth on cruise 24 with the regression line and 95% confidence interval at 440 nm.

Figure 5. Spectra of attenuation coefficient K.
Figure 6. Comparison of K and ATT.

Figure 7. Spectra of irradiance reflectance R.
Figure 8. Correlations between the attenuation coefficient $K$ and the concentration of seston versus the wavelength.

Figure 9. Correlations between the irradiance reflectance $R$ and the concentration of seston versus wavelength.
The Relation Between Optical and Bio-chemical Measurement

As shown in Figure 8 the correlation between K and the concentration of seston is higher than 0.82 from 400 nm to 800 nm. It is even higher than 0.92 between 460 nm and 720 nm.

As shown in Figure 9 the correlation between R and the concentration of seston gradually increases from 0 and 0.1 between 400 and 450 nm, to 0.7 and 0.8 between 700 and 800 nm. The highest correlation between R and the concentration of seston is between 700 and 800 nm. This suggests that at shorter wavelengths R is influenced not only by seston but also by dissolved organic material and chlorophyll, while at longer wavelengths R is dominated by seston only. This result is the same as that found by Ritchie et al. (1976) that the reflectance above the water surface has the highest correlation with suspended sediment concentration of surface water between 700 and 800 nm.

Major Light-Attenuating Constituents

For each model on each wavelength, Mallow’s Cₚ model-selection method was used to select the best fitted model among the measured concentrations of the constituents. The result from Mallow’s Cₚ selection is shown in Figure 10. From the available data sample from Delaware estuarine water, the concentrations of SES and DON are highly correlated with the total light attenuation coefficient K or they are statistically important for light attenuation at almost all the wavelengths from 400 to 800 nm; CHLA is important between 670 and 690 nm; HC is important at shorter wavelengths and some longer wavelengths.

The Mallow’s Cₚ criteria suggested that Equation 6 is the best fitted model at each wavelength. We also studied Equation 7, Equation 8 and Equations 9. It should be noticed that each of the equations represents 41 models at wavelengths 400 to 800 nm in the interval of 10 nm.

$$K(\lambda, \text{ST}) = K_s(\lambda) + K^*_{\text{SES}}(\lambda)C_{\text{SES}}(\text{ST}) + K^*_{\text{DON}}(\lambda)C_{\text{DON}}(\text{ST}) + K^*_{\text{CHLA}}(\lambda)C_{\text{CHLA}}(\text{ST})$$  \hspace{1cm} (6)

$$K(\lambda, \text{ST}) = K_s(\lambda) + K^*_{\text{SES}}(\lambda)C_{\text{SES}}(\text{ST}) + K^*_{\text{DOP}}(\lambda)C_{\text{DOP}}(\text{ST}) + K^*_{\text{CHLA}}(\lambda)C_{\text{CHLA}}(\text{ST})$$  \hspace{1cm} (7)

$$K(\lambda, \text{ST}) = K_s(\lambda) + K^*_{\text{SES}}(\lambda)C_{\text{SES}}(\text{ST}) + K^*_{\text{HC}}(\lambda)C_{\text{HC}}(\text{ST})$$  \hspace{1cm} (8)

$$K(\lambda, \text{ST}) = K_s(\lambda) + K^*_{\text{SES}}(\lambda)C_{\text{SES}}(\text{ST}) + K^*_{\text{DOC}}(\lambda)C_{\text{DOC}}(\text{ST}) + K^*_{\text{CHLA}}(\lambda)C_{\text{CHLA}}(\text{ST})$$  \hspace{1cm} (9)

Specific Attenuation Coefficients

By applying the multiple regression analysis on the K model of Equation 6 at each wavelength, the calculated attenuation coefficient of water, specific attenuation coefficient of seston, specific attenuation coefficient of DON, and their standard deviations are calculated at each wavelength. These actually give us the values of the spectra of the specific attenuation coefficients which are plotted in Figure 11, where the continuous line represents the coefficient value and the vertical
bar represents the coefficient value plus and minus one standard deviation.

Figure 11 (a) is the spectrum of the attenuation coefficient of water (1/m) calculated from the model. The values in the range from 400 to 570 nm should be equal to zero as the P-value is very large. The water has very little attenuation to the light in the shorter wavelength and very significant attenuation between 700 and 800 nm. Near infrared light does not penetrate far into the water column. Figure 11 (b) gives the spectrum of specific attenuation coefficient of seston (1/m·mg). As Jerlov (1976) states, the attenuation caused by a mixture of particles of different compositions would increase towards shorter wavelengths. The shape of the spectrum of the specific attenuation coefficient of seston is very similar to that of gelbstoff. This is largely due to particulate humic material existing either bound to mineral particles or as free particles of humus.

Figure 11 (c) gives the spectrum of the specific attenuation coefficient of DON (as an indicator for gelbstoff). It shows a very good exponential form between 400 nm and 630 nm.

From Equation 6 to Equation 9, we calculated the specific attenuation coefficients of DON, DOC, HC and HN. Figure 12 gives the log value of 10 times the specific attenuation coefficient of DOM (DON, DOC, HC and HN) versus wavelength. It should be noticed that the slope of the regression line through these data is the same as that of the log value of the specific attenuation coefficient of DOM. It also should be mentioned that the figure illustrates the log values of the coefficients, but the slopes are calculated from the ln values of the coefficients. The absolute values of the slopes of the regression line of ln(K*DON), ln(K*DOC), ln(K*HC) and ln(K*HN) vs wavelength are calculated and listed in Table 4.

Water Types

From the above study, we found the following model simulates the total light attenuation in the Delaware estuarine water based on the measurements,

\[ K(\lambda) = K_w(\lambda) + K_{*\text{SES}}(\lambda) C_{\text{SES}} + K_{*\text{DOM}}(\lambda) C_{\text{DOM}}. \]  

(10)
The light in the water column is attenuated by water itself, total seston (including minerals, phytoplankton and other particulate materials) and gelbstoff (DON or DOC is used as an indicator). The ratios \( K^{*}_{\text{DOM}}(\lambda)C_{\text{DOM}} \) to \( K \) and \( K^{*}_{\text{SES}}(\lambda)C_{\text{SES}} \) to \( K \) at 440 nm were calculated in each station and illustrated in Figure 13. This gives a visual idea of the water type at each station at the moment the experiment was conducted. It shows that at 440 nm the total light attenuation of this water mass is dominated by seston or gelbstoff. The attenuation by water itself at 440 nm is near to zero. In the turbidity maximum, station 16, or 18, the attenuation is always dominated by seston. The ratio of \( K^{*}_{\text{SES}}(\lambda)C_{\text{SES}} \) to \( K \) is always larger than 50\%. In the upper or lower estuary, the water mass is mostly dominated by gelbstoff.

**DISCUSSION**

**Attenuation of Chlorophyll**

In this model, there is no individual item of the attenuation effect of chlorophyll. We include the total seston which includes the phytoplankton. The phytoplankton includes the chlorophyll. Although phytoplankton is involved in seston, it is a very small part. The major part of seston is minerals and detritus (dead organic particulate matter). The difference between the weight of mineral and chlorophyll in the total seston might be very large. In the regression analysis, we use the weight or concentration of the different constituents to get their specific attenuation coefficients. If we do not include the CHLA in the model separately, and only include the total seston, the calculated specific attenuation coefficient of seston presumed to include the attenuation effect by chlorophyll. But since the weight (concentration) difference between mineral and chlorophyll is very large, the specific attenuation coefficient of seston may be dominated by minerals. Furthermore, we do include the CHLA as an individual agent in the attenuation model in addition to the seston. But the F-value of the coefficient of CHLA calculated from the model is so large that the coefficient is not significant and has a large standard deviation. CHLA is thus dropped from the model. This is caused by both the influence of the attenuation by gelbstoff, especially from 400 to 600 nm, and the sample itself. In the Delaware estuary with large amounts of gelbstoff, it is difficult to apply simple color ratio
algorithms for mapping phytoplankton distribution. A separation of phytoplankton absorption from the gelbstoff absorption may be possible only by measuring chlorophyll-a via its fluorescence at 685 nm. At 670, 680 and 690 nm we have calculated the specific attenuation coefficients as 23.2, 21.9, 14.1 (1/m·mg·CHLA), which are of the same order as the average value of the specific attenuation coefficient given by MOREL (1988) and KIEFER and SOOHOO (1982). But the standard deviation at these three wavelengths is still large. More samples taken from the phytoplankton bloom period and stations are needed.

Comparison of the Optical Properties of Dissolved Organic Material

The reason for the bump around 740 to 750 nm on the curve of the specific attenuation coefficient of DOM (Figure 11c) is unknown. This phenomenon was also found by WITTE et al. (1982) from the study of water mass in major rivers of Georgia. A laboratory experiment for studying the light attenuation by gelbstoff was also carried out by WITTE et al. (1982). Commercially available humic acid (Aldrich H1, 675-2) was used as a "gelbstoff-type" dissolved organic concentration. They found that the humic material had little effect in a null region between 730 and 760 nm from the lab study, while their field data do not show this null-region characteristic. They explained this as the effect of differences in chlorophyll concentrations and the different components of sediment. However, two other reasons should also be considered. The first one is the definition and measurement of the dissolved organic material. Those passing through the 0.45 μm pore are defined as the dissolved materials, while part of them may be colloid material and scatter light. The second one is related to the composition of gelbstoff. Figure 14 shows the P-values of the coefficient of the concentration of DON, DOC, HC and HN from the multiple regression analysis. When P-value is greater than 0.05, the coefficient calculated from the model on that wavelength is not statistically significant and should be set to zero. This result shows with humic acid carbon as an indicator for gelbstoff there is a null region between 730 and 760 nm, while both DON or DOC as an indicator, this null region does not show. At most of the shorter wavelengths (400 nm to 560 nm), the calculated specific attenuation coefficients of DON,
DOC, and HC are statistically significant since their p-values are less than 0.05. The calculated specific attenuation coefficients of DON and DOC between 720 nm and 770 nm are also statistically significant.

BRICAUD et al. (1981) studied the absorption characteristics of yellow substances (gelbstoff) and found that the exponential model was a satisfactory representation of the absorption spectra of yellow substances in a wide variety of seawater samples. It is shown that throughout the near-UV-visible domain (350 to 700 nm) absorption by yellow substances can reasonably be considered to obey a law of the form

\[ a(\lambda) = a(\lambda_0) \exp(-S(\lambda - \lambda_0)) \quad (\lambda \text{ in nm}) \quad (11) \]

where S is independent of the choice of \( \lambda_0 \). The coefficient S (mean slope) was published by several authors with data from different types of water. It is summarized by BRICAUD et al. (1981) in Table 3.

Concerning the attenuation coefficients, where scattering is included, Kalle claimed that the ratios of attenuation coefficients at 420 and 665 nm are related to the nature of the organic material. This ratio and the mean slope for pheno-humics from KALLE (1966) are shown in Table 4.

The result from the Delaware estuarine data is summarized in Table 4 and shows that the attenuation coefficient of gelbstoff also obeys an exponential law. With DON, DOC, HC or HN as an indicator for gelbstoff, respectively, the mean slope S and the ratio of the coefficient at 420 nm to that at 665 nm falls in or near to the range given by KALLE (1966) as compared in Table 4. However, the absolute value of the slope is smaller with HC or HN as an indicator than that with DOC or DON as an indicator.

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<th>S Value</th>
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<td>wide variety of sea water</td>
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<tr>
<td>0.015</td>
<td>Jerlov</td>
<td>Baltic waters</td>
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<tr>
<td>0.011-0.017</td>
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<td>lake waters</td>
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<tr>
<td>0.013-0.016</td>
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Table 4. Ratios and mean slope of attenuation coefficient of DOM from Kalle (1966) and from this research.

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<th>Item</th>
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<th>From the Model</th>
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<tr>
<td>Indicator phyno-humics</td>
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<tr>
<td>Ratio $K_{DOM}/K_{H}$</td>
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<tr>
<td>Slope (400 nm - 630 nm)</td>
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<td>0.00845</td>
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The Comparison of the Attenuation Coefficient of Water

Figure 15 gives the plots of the spectrum of attenuation coefficient of clearest ocean water measured by Smith and Baker (1981) and that calculated from the attenuation model using multiple regression analysis. These two lines fit very well. From the result of the regression stated in the previous section, we know that the p-values of the attenuation coefficient of water from 400 to 570 nm are very large and the attenuation coefficient of water in this range should be set to zero. The result from statistical analysis shows the very low attenuation effect by water itself from 400 to 570 nm. The discrepancy around 680 nm is probably caused by the attenuation by chlorophyll because in the model we did not include the attenuation contribution by chlorophyll individually. In addition, the $K_e$ from the model is calculated by statistical analysis from the water with different salinity, including fresh water.

Factors Influencing the Specific Attenuation Coefficient

Since these specific attenuation coefficients are calculated by statistical analysis, they may change to some extent from place to place, from time to time. The specific attenuation coefficient of seston may be influenced by particle composition, size and shape. The specific attenuation coefficient of DOM may change in different season and different location (upper estuary or lower estuary) be-

![Figure 15. Comparison of attenuation coefficient of water from the model with that for the clearest ocean water measured by Smith and Baker (1981).]
cause of the composition and the source of the dissolved organic material. In the upstream, the gelbstoff may be caused by the river run-off, while in the downstream it may be caused by the organic detritus. The specific attenuation coefficient of chlorophyll also changes from species to species. For developing the inverse model, the precision of predicting the concentrations from measured irradiance reflectance through remote sensing will be influenced by the precision of these statistical coefficients. Nevertheless these calculated specific attenuation coefficients, as we explained in the previous sections, indicate the basic and important optical characters of each constituent we have concerned in the model. They will play a significant role in inverse model development and further study.

CONCLUSIONS

From the statistical analysis of the in situ measured optical, biological and other estuarine data, we found that at the upper 3 m of the water column in Delaware estuary water that the light attenuation coefficient K is uniform. The concentration of seston was highly correlated with the measured attenuation coefficient K from 400 nm to 800 nm and correlated with the measured reflectance R from 700 nm to 800 nm. Secchi depth and the measured broad band average attenuation coefficient are inversely related.

In the linear attenuation model, seston plays an important role. The concentration of DOC, DON, and HC can all be used as indicators for dissolved organic material. The specific attenuation coefficient of dissolved organic material has a null region from 730 nm to 770 nm when HC is used as an indicator. Using DOC or DON as an indicator, this null region does not show. The attenuation coefficient of water calculated from the attenuation model was remarkably similar to the one measured by Smith and Baker (1981). The influence of chlorophyll-a to the total light attenuation was only detected at 670 nm to 690 nm. The comparison of the results from this paper with the results from other research confirms the validity of the measurements and the statistical method applied.

ACKNOWLEDGEMENTS

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LITERATURE CITED


