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Quantifying contributions to light attenuation in estuaries and coastal embayments: Application to Narragansett Bay, Rhode Island

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Abstract

In Narragansett Bay, light attenuation by total suspended sediments (TSS), colored dissolved organic matter (CDOM), and phytoplankton chlorophyll-a (chl-a) pigment is 129%, 97%, and 70%, respectively, of that by pure seawater. Spatial distribution of light attenuation indicates higher values in the upper Bay, where rivers with sediment and nutrient-rich waters enter and elevate TSS, CDOM, and chl-a concentrations. The temporal trends of light attenuation during the summer months (July-August) differed at various locations in the Bay, having the highest values in July. For the same period, spectral methods overestimated attenuation throughout the Bay. These findings quantify the behavior of light attenuation in space and time, providing information that can guide decisions related to improving water clarity and help understanding the effects of various environmental and management scenarios on it.

Keywords

Mathematical model; light attenuation; irradiance; normalization; embayment; Narragansett Bay

Introduction

Adequate irradiance is a major factor in the health of algae and seagrass beds in estuarine and coastal systems. The concentrations of phytoplankton, total suspended solids, and colored dissolved organic matter in the water column are the primary factors in determining water clarity. They control the amount of light that penetrates to any depth as well as the irradiance near the bed, which affects submerged aquatic vegetation (SAV). The importance of water clarity to the ecological health of estuaries and coastal systems has driven many researchers to develop quantitative methods to calculate irradiance in the water column (Prieur and Sathyendranath 1981; Dennison 1987; Gallegos 1994; Gallegos and Kenworthy 1996; Gallegos 2001; Keith et al. 2002; Gallegos and Neal 2002; IOCCG 2003; Kenworthy et al. 2014; Thursby et al. 2015). The complexity of this task arises from the variability not only in the spectral distribution of irradiance but also in the water column and its turbidity. The concentration of CDOM, suspended solids, and phytoplankton in the water column controls the amount of light that penetrates to any given depth.

There are two approaches to estimate the irradiance in the water column: (1) direct measurements of irradiance from the water surface or remotely sensed with airborne systems (e.g., aircraft, satellites), or (2) mathematically modeled irradiance within the water column. For both approaches, optical models are developed to calculate the spectral diffuse attenuation coefficient of the spectral irradiance through the water depth. These models have to be calibrated based on field measurements of both water properties (i.e., color and turbidity from both phytoplankton and TSS), and associated spectral irradiance. This work focuses on developing and testing a mathematical model to calculate irradiance through the water column. The ultimate future goal is to incorporate the developed mathematical model with mechanistic models to predict future scenarios for water clarity in Narragansett Bay and similar estuarine systems. While other mathematical methods exist (see Mobley et al. 1993, Alver et al. 2014, Murray et al. 2015, Conmy et al. 2016, Watanabe et al. 2015), none has been applied to Narragansett Bay and they are not ready for use with high resolution predictive mechanistic models for large spatial and temporal coverages. The presented methodology is applicable to any system via properly calibrated bio-optical models for that system (e.g., Thursby et al. 2015, Murray et al. 2015).

The main objective of this work is to apply mathematical modeling techniques to calculate the irradiance at any depth at specified locations and times in Narragansett Bay (Fig. 1). The specific objective is to quantify contributions to light attenuation from the various attenuators to properly guide future management decisions for improving water clarity, which influences phytoplankton, SAV habitat, primary production, hypoxia, and fish predation behavior. The mathematical methodology to estimate light attenuation in Narragansett Bay accounts for absorption by pure water, total suspended solids (TSS), colored dissolved organic matter (CDOM), and phytoplankton pigment, as well as backscattering by pure seawater and TSS. Existing field measurements of total suspended solids and chlorophyll-a (chl-a) are used to calculate light attenuation due to absorption and backscattering. An innovative normalization for light attenuation is presented to validate comparisons between water clarity measures in the same or different systems in space and time.

This paper is organized as follows: theoretical, mathematical, and empirical relationships for light attenuation are presented in the Methods section together with an innovative normalization to quantify attenuation, and an error analysis. The Data section follows with site specific information from Narragansett Bay. Next, the Calibration and Validation section confirms the reliability of the developed methods. The Results section follows with quantitative analysis of contributions to light attenuation. Finally, the Discussion section concludes with further implications of the presented methodology.

Methods

The concentrations of TSS, CDOM, and phytoplankton chlorophyll (chl-a) are obtained from field measurements (see Data). These concentrations are used to develop the mathematical methodology and to estimate the reduction in irradiance throughout the water column at specified locations (x, y, and z) within the Bay at specific times (t). Figure 2 presents a sketch of the relation between water column concentrations of chl-a (C), total

suspended solids (S), and CDOM (g) as well as the incident and reduced light intensities (E). The subscripts x, y, z, and t denoting space and time are sometimes dropped for simplicity.

Attenuation of the incident irradiance through the water column is a function of absorption and scattering by pure seawater and dissolved and particulate materials. The irradiance at any depth can be represented by the Beer-Lambert law given by

$$E_{\ell} = E_0 e^{-(a+b)\ell} \quad (1)$$

Where E_0 is the total incident irradiance at the incidence surface (e.g., the water surface, $\mu\text{mol quanta m}^{-2} \text{s}^{-1}$), E_{ℓ} ($\mu\text{mol quanta m}^{-2} \text{s}^{-1}$) is the irradiance at distance ℓ (m) from the incidence surface (Fig. 2), a is the absorption coefficient (m^{-1}), and b is the scattering coefficient (m^{-1}) (Table 1 presents definitions of all abbreviations and symbols). The E_0 values were redistributed within the photosynthetic available radiation (PAR) (i.e., the visible light range with wavelengths 400 nm - 700 nm) as described below.

The major contributors to the attenuation of light through the water column include: (1) absorption by pure water, (2) absorption by phytoplankton pigment, (3) absorption by TSS, (4) absorption by dissolved organic matter (also called yellow substances-Gelbstoff, or colored dissolved organic matter, CDOM), (5) backscattering by TSS, and (6) backscattering by pure seawater (Kenworthy et al. 2014; IOCCG 2003; Sathyendranath 1984; Prieur and Sathyendranath 1981). The following equations define the mathematical values for the absorption and backscattering coefficients for Narragansett Bay. Figure 3 and Table 2 present the spectral distributions for the PAR including absorption values for pure water (Kirk 1994), for TSS, CDOM, and chl-a (Thursby et al. 2015), and backscattering values for TSS (Thursby et al. 2015) and for pure water (Buitemveld et al. 1994), in addition to the derived spectral distribution function for the incident light (Appendix A).

Overall light attenuation

The mathematical model uses n layers in the vertical direction to calculate light attenuation (Fig. 2). The top of the surface layer is the incident surface for the short wave solar radiation from the sun, E_0 . The attenuated irradiance, E_1 , is calculated at the bottom of the same layer with thickness ℓ_1 (m). The same procedure is applied at the next layer below the top layer using the attenuated irradiance at the bottom of previous layer, E_1 , as the incident irradiance at the top of the next layer, ℓ_2 . The procedure continues until the last layer n (on top of the bottom sediment) is reached. As the mathematical calculations proceed, the measured chl-a and TSS concentrations for each layer are used to calculate the absorption and backscattering coefficients through that layer at a specific location for the specified time in the year as presented below. The last value represents the irradiance that reaches the bottom at that location and time.

To calculate the penetration of the PAR to a depth ℓ (m), the following equation is used for each wavelength, λ (Weast 1980).

$$E_1(\lambda) = E_0(\lambda)e^{[-K_1(\lambda)\ell_1]} \quad (2)$$

Where $E_0(\lambda)$ is the irradiance of the incident wavelength λ as quantum flux density ($\mu\text{mol quanta m}^{-2} \text{ s}^{-1} \text{ nm}^{-1}$) at the water surface, $E_1(\lambda)$ is the irradiance of wavelength λ ($\mu\text{mol quanta m}^{-2} \text{ s}^{-1} \text{ nm}^{-1}$) at a downward distance $\ell_1 = z_1 - z_0$ (meter, m), and K_1 is the extinction coefficient of the downward propagating irradiance (m^{-1}) (Lee and Rast 1997; Barausse 2008; Civera et al. 2011; Oviatt et al. (submitted)). The irradiance of the incident wavelength λ can be represented by

$$E_0(\lambda) = E_0 f(\lambda) \quad (3)$$

Where E_0 is the total direct and diffuse irradiance of the incident light just below the incidence surface (e.g., the water surface, see Data) and $f(\lambda)$ is the distribution function of the incident light between the various wavelengths within the PAR. Appendix A presents the approximation for $f(\lambda)$ (Table 2) which was used to redistribute the solar radiation within the PAR. Although the incident solar radiation values may vary with time during the day, the spectrum distribution function, $f(\lambda)$, is assumed to be invariant with time. Values of the distribution function are obtained at 5 nm increments within the PAR where $\sum_j^{61} f(\lambda_j) = 1$ (Appendix A). Introducing $f(\lambda)$ allows the incident irradiance to change not only with the wave length, λ , but also with time throughout the year according to the incident irradiance at the water surface, E_0 .

The wavelength-dependent extinction coefficient, $K_1(\lambda)$, includes attenuation effects from the above-mentioned six contributors on the irradiance of wavelength λ , i.e.,

$$K_1(\lambda) = a_w(\lambda) + a_c^1(\lambda) + a_s^1(\lambda) + a_g^1(\lambda) + b_s^1(\lambda) + b_w(\lambda) \quad (4)$$

Where the letters a and b refer to absorption and backscattering, respectively; the subscripts w, c, s, and g refer to water, chl-a, TSS, and Gelbstoff (CDOM/yellow substance), respectively; and the superscript indicates the layer number (Fig. 2). It is implicitly understood that the extinction coefficient varies in the water column as chl-a, TSS, and CDOM change in space and time. The above equations can be put in the following form for numerical integration using absorption and backscattering values every 5 nm over the PAR.

$$E_i(\lambda_j) = E_{i-1}(\lambda_j) \left[e^{-a_w(\lambda_j)\ell_i} \times e^{-a_c^i(\lambda_j)\ell_i} \times e^{-a_s^i(\lambda_j)\ell_i} \times e^{-a_g^i(\lambda_j)\ell_i} \times e^{-b_s^i(\lambda_j)\ell_i} \times e^{-b_w(\lambda_j)\ell_i} \right] \quad (5)$$

$$E_i = 5 \sum_{j=1}^{61} E_i(\lambda_j) = 5D \sum_{j=1}^{61} (E_{i-1}(\lambda_j) \times RR_i(\lambda_j)) \quad (6)$$

Where

$$RR_i(\lambda_j) = e^{-a_w(\lambda_j)\ell_i} \times e^{-a_c(\lambda_j)\ell_i} \times e^{-a_s(\lambda_j)\ell_i} \times e^{-a_g(\lambda_j)\ell_i} \times e^{-b_s(\lambda_j)\ell_i} \times e^{-b_w(\lambda_j)\ell_i} \quad (7)$$

Where $RR_i(\lambda_j)$ is the reduction ratio (dimensionless) of the incident light within λ_j through layer ℓ_i , and D is an overall calibration coefficient which accounts for unconsidered optical effects (e.g., directional scattering, water column stratification, etc.). The subscript j refers to the discrete values of the normalized absorption coefficients at λ_j values representing the PAR at 5nm increments ($j = 1, 61$; Table 2). According to Simpson's Rule, only half of the first and last values can be used in each summation (i.e., at $j=1$ and $j=61$). Introducing the 5-nm increment in Eq. (6) preserves the total irradiance within the PAR (E_i , $\mu\text{mol quanta m}^{-2} \text{ s}^{-1}$). The numerical integration procedure is executed for each layer within the water column. The superscripts are dropped for convenience.

1) Light absorption by pure water, a_w —Kirk (1994) presented the absorption coefficient values, $a_w(\lambda_j)$, for pure water at discrete wavelengths, λ_j (Table 2, Fig. 3). The same notation is used in the following descriptions of the various absorption coefficients at the same discrete wave lengths considering λ and λ_j to be synonymous.

2) Light absorption by algal pigment, a_c —Light absorption by phytoplankton pigments is given by the following relationship for Narragansett Bay (Thursby et al. 2015)

$$a_c(\lambda) = A(\lambda) [C_{x,y,z,t}]^{B(\lambda)} \quad (8)$$

Where $a_c(\lambda)$ is the absorption coefficient by the phytoplankton's chl-a pigment (m^{-1}) at any wavelength λ , and the two coefficients $A(\lambda)$ and $B(\lambda)$ depend on the wave length (Table 2). $C_{x,y,z,t}$ is the concentration of chl-a ($\mu\text{g L}^{-1} = \text{mg m}^{-3}$) at the spatial location, (x -eastward, y -northward), and at the layer's vertical location z -below the water surface (m), and at the time, t , as measured in the field (see Data).

3) Light absorption by TSS, a_s

$$a_s(\lambda) = a_s(440) \exp(-0.0136(\lambda - 440)), \text{ Thursby et al. (2015)} \quad (9)$$

$$a_s(440) = 0.31(S_{x,y,z,t}), \text{ Thursby et al. (2015)} \quad (10)$$

Where $a_s(\lambda)$ is the absorption coefficient by TSS (m^{-1}) at any wavelength λ , $a_s(440)$ is the absorption coefficient by TSS (m^{-1}) at wavelength 440 nm, and $S_{x,y,z,t}$ is the concentration of TSS (mg L^{-1}) at the same location and time as chl-a measurements. Recent studies indicate that the TSS vs λ absorption curve has an exponential decay shape (Bricaud and Stramski 1990; Bricaud et al. 1995; Matsuoka et al. 2011) similar to CDOM. However, understanding of the TSS behavior is still very limited and more detailed studies are recommended (Matsuoka et al. 2011). The vertical trend of $S_{x,y,z,t}$ is obtained from recent measurements in Narragansett Bay (see Data). For simplicity, this trend is assumed to exist in the Bay at all locations and times. More complex spatial and temporal structures of TSS are discussed elsewhere (Abdelrhman 2016b).

Narragansett Bay values of the spectral distribution $a_s^+(\lambda) = \exp(-0.0136 (\lambda - 440))$ are presented in Table 2 and Fig. 3.

4) Light absorption by CDOM, a_g

$$a_g(\lambda) = a_g(440)\exp(-SS_g(\lambda - 440)), \text{Thursbyetal. (2015)} \quad (11)$$

Where $a_g(\lambda)$ is the absorption coefficient by CDOM (m^{-1}) at any wavelength λ , $a_g(440)$ is the absorption coefficient by CDOM (m^{-1}) at wavelength 440 nm with an average value of 0.603 for Narragansett Bay, SS_g is the spectral slope for CDOM with an average value of 0.0159 (see Data). The value of $a_g(440)$ has to be directly measured or modeled. Earlier data from 51 samples collected during May 1999 to June 2000 indicated a comparable average SS_g of 0.0166 (Keith et al. 2002). These spectral slopes for CDOM in Narragansett Bay are also consistent with the average of 0.0176 for coastal waters around Europe (Babin et al. 2003). In contrast, IOCCG 2003 offered a statistical approach to estimate $a_g(\lambda)$ for ocean waters which is parameterized with respect to chl-a concentration. For the Baltic Sea, Kowalczyk et al. (2006) discussed three approaches to identify $a_g(\lambda)$: annual/monthly average from direct measurement of water samples, prediction from remote sensing measurements, and prediction from dynamic modeling of salinity and chl-a. Until parameterization of CDOM attenuation (or CDOM concentration, $g_{x,y,z,t}$, Fig. 2) becomes available for Narragansett Bay (see Discussion), the above-mentioned Bay-average values of SS_g are assumed to be applicable at all locations and times. Narragansett Bay values of the spectral distribution of $a_g^+(\lambda) = \exp(-0.0159 (\lambda - 440))$ are presented in Table 2 and Fig. 3.

5) Light backscattering by TSS (detritus, phytoplankton, minerals, and others), b_s —Similarly, the calculations of backscattering for TSS particles include the wavelength dependent parameters for backscattering for the whole 400–700 nm spectrum, which are based on normalized values referenced to the wavelength $\lambda = 470$ nm.

$$b_s(\lambda) = b_s(470)(1.678 - 0.00144\lambda)\text{Thursbyetal. (2015)} \quad (12)$$

$$b_s(470) = 0.0095[S_{x,y,z,t}]^{0.379} \text{Thursby et al. (2015)} \quad (13)$$

Where $b_s(\lambda)$ is the backscattering of TSS at wavelength λ , $b_s(470)$ is the backscattering of TSS at wavelength 470 nm, and $S_{x,y,z,t}$ is the TSS concentration (mg L^{-1}). Narragansett Bay values of the spectral distribution of $b_s^+(\lambda) = (1.678 - 0.00144 \lambda)$ are presented in Table 2 and Fig. 3.

6) Light backscattering by pure seawater, b_w —Buiteveld et al. (1994) presented the backscattering coefficient values, $b_w(\lambda)$, for pure seawater at 10 nm increments within the visible range. These values were linearly interpolated at 5 nm increments to fit within the same range of the numerical integration for the other coefficients (Table 2, Fig. 3).

7) Normalization of contributions to light attenuation—Since attenuation due to water is inevitable and cannot be controlled in any system and since water absorption and backscattering do not change in space or in time (Table 2), water attenuation is used to normalize contributions to light attenuation from the other three contributors: chl-a, TSS, and CDOM, at all locations and times. This normalization facilitates quantitative comparisons between the various contributors, locations, and times. Equation (6) is applied for each contributor separately. The following example of normalization is presented for any contributor, r , when it exists in the water

$$[N_i]_r = \frac{E_o - [E_i]_r}{E_o - [E_i]_w} = \frac{1 - ([E_i]_r/E_o)}{1 - ([E_i]_w/E_o)} \quad (14)$$

Where

$$[E_i]_r = \sum_{j=1}^{61} E_{i-1}(\lambda_j) e^{-[a_w(\lambda_j) + b_w(\lambda_j) + a_r(\lambda_j) + b_r(\lambda_j)]\ell_i} \quad (15)$$

$$[E_i]_w = \sum_{j=1}^{61} E_{i-1}(\lambda_j) e^{-[a_w(\lambda_j) + b_w(\lambda_j)]\ell_i} \quad (16)$$

Where N represents the normalized light attenuation by the specific contributor (subscript r) with respect to light attenuation by water (subscript w) at the specific layer (ℓ_i), spatial location (x,y), and time (t).

In order to validate comparison of light attenuation between various locations (x,y) and/or times (t) at any place in the world, the normalized overall vertical profile within the water column, Eq. (14), is vertically averaged, i.e.,

$$[NUA_Z]_r = \frac{1}{Z} \sum_{i=1}^{i=Z} \left(\frac{1 - ([E_i]_r/E_o)}{1 - ([E_i]_w/E_o)} \right) \quad (17)$$

Where NUA_Z is the average of the normalized universal attenuation to a reference depth Z (m). The reason for the universality of the normalization in Eqs. (14 and 17) is due to the universality of water absorption and backscattering in the denominator of the equations (see Table 2, Kirk 1994, Buiteveld et al. 1994). It suffices to calculate water absorption and backscattering once for a known surface incident irradiance, E_0 , and then use it for the same reference Z at all other sites and times. The effect of different incident light intensities, E_0 , for diverse sites and/or times is eliminated from the measured and/or calculated attenuation by using $[E_0-E_i]/E_0$ for both the numerator and denominator in Eqs. (14 and 17). The dimensionless magnitude of $[NUA_Z]_r$ is assigned an innovative unit similar to its name (NUA_Z), which reflects its meaning and reference depth.

8) Error Analysis—The error is the deviation between observed and calculated light intensities, (E_{observed} and $E_{\text{calculated}}$, respectively) at each depth, with $E_{\text{calculated}}$ as given by Eq. (6). Two types of errors are used to evaluate the methodology: the overall difference, E ; and the relative Euclidean Distance, ED (Abdelrhman and Bedford 1990), where

$$\Delta E = \sum_{i=1}^{i=n} (E_{\text{observed}} - E_{\text{calculated}})_i = \sum_{i=1}^{i=n} \Delta E_i \quad (18)$$

$$ED = 100 \left[\sum_{i=1}^{i=n} (E_{\text{observed}} - E_{\text{calculated}})_i^2 \right]^{1/2} / \left[\sum_{i=1}^{i=n} (E_{\text{observed}})_i^2 \right]^{1/2} \quad (19)$$

and n is the number of layers in the vertical profile of irradiance in the water column. Both types of errors are used for calibration and validation (see Calibration and Validation).

Data

Existing historical irradiance data were used to calibrate and validate the presented methodology. Two different sources of data existed as described below.

1. URI data—Observed data profiles of irradiance, incident light, and chl-*a* concentrations are available for Narragansett Bay in 2009 (Oviatt et al. (submitted), personal communication: Candace Oviatt and Heather Stoffel URI-GSO, Narragansett, RI). Profiling of PAR irradiance was performed at six stations along the salinity gradient: BR, CP, NPI, MV, QP1, and GD (Fig. 1). Data were collected 3–4 times during the summer months (June, July, and August). A movable light sensor (Li-Cor, model LI-190R) collected PAR irradiance every 0.5 m as it was lowered through the water column and also as it was

brought up back to the surface. A second stationary light sensor remained at the water surface to measure the incident irradiance, E_0 , each time the movable sensor recorded a reading. A total of 39 data sets were collected in 2009. It took about 10–20 minutes to collect the light profile at each station. Changes and patchiness in cloud cover were caught by the stationary sensor. Only 21 irradiance profiles when the surface sensor indicated no cloud interference were selected for calibration and validation (see Calibration and Validation). Station NPI is used to illustrate the methodology because it is centrally located within the Bay and the data expands its relatively deep water column.

The instantaneous surface irradiance measurements, E_0^- , at the beginning and end of irradiance profiling were compared with the corresponding values just above the surface values, E_0^+ . The correlation between 78 points (representing the 39 sets of data) is presented in Figure 4a. The data shown spans the full range from low irradiance ($50 \mu\text{mole m}^{-2} \text{s}^{-1}$, during cloudy conditions) to very high irradiance ($2076 \mu\text{mole m}^{-2} \text{s}^{-1}$, under clear skies). After enforcing a zero intercept, the slope of the trend line was 0.99 ($R^2 = 0.93$), which is very close to 1.0 for maximum positive correlation. This high correlation between E_0^+ and E_0^- indicates insignificant impact of the water surface on incident irradiance (e.g., Fresnel reflectance, see Discussion). Accordingly, in the remainder of this work, the irradiance just below the water surface is considered to represent the incident irradiance, E_0 . The spectral values for the surface irradiance, $E_0(\lambda)$, are calculated using the spectral shape function, $f(\lambda)$ (Table 2, Appendix A). Also, the incident average surface irradiance from URI data during the 10–20 minute deployment was compared with hourly total solar radiation (direct and diffuse) received at the earth's surface from the National Solar Radiation Data Base (NSRDB-Wilcox 2012). The PAR was calculated as 42.3% of the total incident irradiance (Gibson 2000). Figure 4b indicates a good correlation (slope = 0.91, $R^2 = 0.8$) between PAR from URI and NSRDB data. Thus, the hourly NSRDB data for incident irradiance can be used to study irradiance through the water column in Narragansett Bay during other times.

Along with the irradiance profiles, chl-a concentration profiles were also collected. These profiles represented the phytoplankton pigment concentration, $C_{x,y,z,t}$, in the presented methods. The contribution of phytoplankton particles to TSS can be estimated from the carbon to chl-a ratio (varies with species and light availability, but assumed for convenience to be 43 (mg carbon) (mg chl-a) $^{-1}$, Abdelrhman 2016a). Phytoplankton effects on absorption and backscattering are implicitly included in the TSS. Figure 5 shows the vertical profiles and ranges of concentrations of chl-a concentration profile (Fig. 5a) together with contribution of phytoplankton particles to TSS (Fig. 5b). It is worth mentioning that for the same chl-a concentration, a higher carbon to chl-a ratio will increase contribution of phytoplankton carbon to the total TSS. Consequently, TSS impact on absorption and backscattering will increase (i.e., $S_{x,y,z,t}$ in Eq. (10) and Eq. (13), respectively) (See Discussion about *carbon to chl-a ratio*).

2. AED-data

2.1. TSS data: Monthly water samples were collected by the staff of United States Environmental Protection Agency (USEPA) Atlantic Ecology Division (AED) at the surface, mid-depth, and bottom at 8 stations in the Bay during the years 2014 and 2015 (Fig. 1). The

concentration of TSS (mg L^{-1}) and % organics and minerals were calculated (Abdelrhman 2016b). The average TSS concentration for the whole Bay was 5.12 mg L^{-1} . The organic matter (34.65 %) is considered to include detritus from the watershed, human organics from wastewater treatment plants, phytoplankton (alive and dead) in the water column, and detached particles from organism carcasses. The minerals (65.35%) are assumed to originate from the watershed (i.e., silt and clay) as well as from the resuspended bed sediment. The AED data are used for calibration and validation of the calculated irradiance. The TSS concentrations were calculated at the same depth locations of the URI chl-a and light measurements (Fig. 5a) from the general vertical trend for the whole Bay as described below.

Statistical analysis was performed on the surface, mid-depth, and bottom measurements for the summer months of the two years 2014 and 2015. A total of 16 measurements were analyzed at each monitored depth location (Table 3). A trend analysis was performed on the observations ($R^2 = 0.1312$) and their mean values ($R^2 = 1.0$) to identify the general shape of the vertical profile of TSS during the summer months of any year. The trend equation was

$$S_z = 3.3841Z^2 - 1.8218Z + 3.4957 \quad (19)$$

Where S_z (mg L^{-1}) is the calculated TSS concentration at the normalized depth, Z , below the water surface. Figure 5b presents an example of the vertical concentration profile of TSS at station NPI (see Discussion about TSS modeling).

2.2. CDOM data: Fifty-one water samples were collected at 20 stations in Narragansett Bay during the summer of 2013 (on 6/20, 7/17, 8/7, and 8/28) and the spring of 2014 on 4/25 and the spectral CDOM absorption coefficient, $a_g(\lambda)$, was calculated as described in Keith et al. (2002) (Thursby et al. 2015). Some stations were sampled more frequently than others. Only CDOM data from stations close to measured irradiance and chl-a (i.e., URI stations, Fig. 1) were used here. In general, there was a gradient in $a_g(\lambda)$ from higher values in the north (where nutrient rich riverine inflows enter the Bay) to lower values in the south (where the seaward open boundary exists) (Fig. 1). The shape of this spatial distribution of $a_g(\lambda)$ along the Bay was consistent in time (Fig. 6a) and its magnitude changed slightly with time (see Discussion about spatial and temporal variability). The average values at each station were used to calculate $a_g(\lambda)$ at that station. Except for station GD (near the seaward boundary), all other locations had very close $a_g(\lambda)$ values. The displayed overall average of the 51 samples for the whole Bay was normalized to its value at $\lambda=440 \text{ nm}$ and compared with Eq. (11), which showed a high correlation (slope 1.031, $R^2 = 0.9984$, Fig. 6b). Table 4 presents the $a_g(440)$ for the six stations along the Bay, which can be used in Eq. (11) to reproduce the spectral values of $a_g(\lambda)$ at these stations. (see Discussion about CDOM modeling.)

Calibration and Validation

Calibration and validation of the presented methodology went through two important steps: 1) calibration with observed data in 2009, and 2) statistical validation with all observed data in 2009.

1) Calibration with observed data in 2009—The main purpose of the calibration is to define the value of the tuning coefficient, D , in Eq. (6). A value of $D = 1.0$ confirms that the presented relationships and their coefficients are adequate (see Discussion). The measured incident irradiance at the water surface represented E_0 , the modeled irradiance at each depth represented E_i , and the depth increment between measurements (~ 0.5 m) represented the layer thickness, l . The average chl-a and TSS concentrations within the layer represented $C_{x,y,z,t}$ and $S_{x,y,z,t}$ in the above equations (see Methods, Fig. 2). It is worth noting that sometimes observations of the incident light at the water surface changed during the profiling process, indicating interference by clouds or other environmental or human factors. Such profiles were not included in the calibration and validation.

The calibration started with the values of $D = 1.0$ and proceeded to improve the fit to observations by minimizing the Euclidean distance (ED, Eq. (19)) and define the coefficient of determination (R^2) between calculated and observed irradiance profiles. Figure 7 presents an example of the calibrated irradiance profile at station NPI on June 1, 2009 with $D = 1.2544$ (Fig. 7a). The scatter plot (Fig. 7b) indicates that the calculated irradiance agreed with observed values ($R^2 = 0.9883$). Enforcing a zero intercept, the slope of the trend line was 0.9923, which is very close to 1.0 representing the 45° line for optimum correlation between calculations and observations. The ED between observed and calculated values was 9.0855% for station NPI on June 1, 2009. Table 5 presents analysis from 21 calibrations at all other stations during various dates in 2009.

2) Statistical validation—Descriptive statistics of the tuning coefficient, D , were used to validate the calibration results with observed data. Table 6 presents values of the statistical parameters from the calibrated 21 irradiance profiles. The mean value of the calibration coefficient was $D = 1.01$ (with a standard error of 0.06 and standard deviation 0.25), which is very close to 1.0 indicating that the presented methodology, equations, and coefficients are adequate for Narragansett Bay. Interesting observations about the spatial and temporal behavior of D are presented in the Discussion. Table 5 presents the slopes of all the scatter plots between calculated and observed irradiance values (e.g., Fig. 7b). The mean value of all scatter slopes is 0.97 with standard deviation of ± 0.01 (Table 6), which is very close to 1.0, indicating adequate calculations ($R^2 = 0.9$ –1.0). It is worth mentioning that the validated calculations covered a wide range of incident light intensities, E_0 , from 138.13 to 2065.80 $\mu\text{mole m}^{-2} \text{s}^{-1}$, which supports the robustness of the presented methods.

The relative Euclidean distances for irradiance profiles (ED in Eq. (19)) are presented in Table 5 for calculations with calibrated D values, ED_1 , and without calibration ($D = 1$), ED_2 . The ED_1 for calibrated profiles had a mean value of 15.54% (range 4.77% - 40.63%) and without calibration the mean ED_2 was 27.18% (range 7.18% - 70.62%) (Table 6). It is worth stating the following two important outcomes from the mean Euclidean distances. First, ED_1

indicates that calibration does not eliminate the difference between observed and calculated irradiance and that this difference is inevitable. Second, such difference may almost double without calibration (i.e., $ED_2 \sim 1.7ED_1$).

Results

The main objective of this work has been fulfilled by presenting, calibrating, and validating the mathematical methodology to calculate the irradiance at any depth at specified locations and times in Narragansett Bay. The specific objective of quantifying contributions to light attenuation from the various attenuators is presented here.

Equation (5) calculates the attenuated irradiance at the bottom of each layer after accounting for all the associated absorption and backscattering in the layer starting from the surface and going down to the bottom (Fig. 2). An example of the attenuation caused by each constituent in Eq. (5) is presented for station NPI on June 1, 2009 (Fig. 8). The contributors to light attenuation have to exist in the water and their inseparable contributions to absorption and backscattering have to be combined. Thus, the following four contributions to light attenuation are studied: $a_w + b_w$, $a_w + b_w + a_s + b_s$, $a_w + b_w + a_c$, and $a_w + b_w + a_g$. The order of attenuation by these contributors from highest to lowest is attenuation by TSS, chl-a, CDOM, and then water.

An example to quantitatively evaluate the effect from each contributor is presented at station NPI on June 1, 2009 (Fig. 9). Equation (14) was applied to normalize attenuation by each contributor, N_r , throughout the 12m water column. The depth-averaged normalized values for each contributor are calculated as $N_w = 1.0$, $N_s = 2.29$, $N_c = 1.7$, and $N_g = 1.97$ in NUA_{12} . In other words, contributions to light attenuation by TSS, chl-a, and CDOM are 1.29, 0.70, and 0.97 more than attenuation by clear water, respectively. The total impact on light attenuation N_{all} was 2.51 NUA_{12} , which is almost one and a half times more than the attenuation by clear water.

The normalized universal attenuation values, NUA_4 (Eq. (17)), from all field measurements are presented in Table 5 using the minimum monitored depth at station GD (i.e., 4 m) as the reference for all stations. The highest water clarity (i.e., minimum NUA_4) was 2.48 at station QP1 on July 20, 2009 and the lowest clarity (i.e., maximum NUA_4) was 3.54 at station NPI on August 20, 2009. Figure 10 presents spatial and temporal variations in NUA_4 in the Bay during the summer of 2009. Higher N values (3.0–3.5 NUA_4) exist in the upper Bay and lower values (~ 2.5 – 2.9 NUA_4) exist in the lower Bay (Fig. 10a). The temporal variations of NUA_4 during the three summer months (June–August) show a slight increase from early- to mid-summer before slowly dropping later in August (Fig. 10b). Nonetheless, longer periods of observations (e.g., full-year) are needed to resolve seasonal variability.

Discussion

A mathematical approach is presented to calculate irradiance in embayments and coastal waters. The methodology was applied to Narragansett Bay, RI. The methodology is site-specific and it can be applied to any system. Proper calibration of the bio-optical model remains an essential factor for any site specific application. This work concentrates on the

behavior of downwelling irradiance within the water column. Impacts from local conditions at the water surface (i.e., solar zenith, cloud cover, Fresnel surface reflectance, and atmospheric parameters: wind speed, surface waves, etc.) can be treated as described elsewhere (e.g., Alver et al. 2014).

In any system, light attenuation by water cannot be separated from other attenuators. Normalizing by water attenuation indicates that the order of attenuators in Narragansett Bay from highest to lowest is TSS, CDOM, chl-a, and water. Contrasting behavior existed in Greenland's fjords (Murray et al., 2015) where attenuation by water dominated such systems, followed by chl-a in the inner parts or TSS in the outer parts and attenuation by CDOM was last in most cases. Another contrasting behavior existed in a drinking water reservoir (Watanabe et al. 2015) where attenuation by CDOM dominated in the upper layer and by water in the lower layer; TSS was next followed by chl-a. Similarly, four Florida estuaries (Conmy et al. 2016) showed dominance of CDOM followed by TSS then chl-a.

The major results from this work include: (1) quantifying the contributions from water, chl-a, TSS, and CDOM to light attenuation throughout the water column in Narragansett Bay; (2) identifying spatial variability in light attenuation; (3) identifying temporal variability in light attenuation; and (4) comparing light attenuation between various systems. Except for water, the other three contributors (TSS, CDOM, and chl-a) can have contrasting effects on light attenuation within the same system or in other systems. For example, while the effects of chl-a on light attenuation are expected to be more pronounced during the warmer summer season in a temperate embayment (e.g., Narragansett Bay), these effects will be minimal during the colder seasons or in arctic systems. Likewise, while TSS showed the highest impact on light attenuation in Narragansett Bay (Figs. 8,9) due to particulate and nutrient loads from its watershed, other systems with lower loads (e.g., coastal embayments) may be less impacted by TSS. Ocean waters are the least impacted by such loads due to their remoteness from land. The spatial trend of water clarity along Narragansett Bay (Fig. 10) is expected to manifest in similar systems with major riverine inflows at the head and the seaward open boundary at the mouth. Quantitative comparisons between water clarity in various systems (e.g., Fig. 10a) can provide useful information on both local and regional scales.

The major drivers of light attenuation are seawater, water color, phytoplankton, and total suspended solids. There is no management process that can eliminate absorption and backscattering by pure seawater. Next in the level of difficulty to manage is absorption by colored water, which results from the dissolution of any colored substance into seawater. Only a portion of these colors comes from dissolved organic matter originating from biological sources including phytoplankton exudation. This portion may be susceptible to some management. Absorption and backscattering due to the last two drivers, phytoplankton and TSS particulates, may yield to some management decisions. The TSS includes both organic and mineral particles (Abdelrhman 2016b). The organic particles include phytoplankton and detritus, which may be managed. Phytoplankton cells flourish when temperature, light, and nutrients are not limiting. Management decision to limit any of these factors can reduce phytoplankton cells and their impact on water clarity through their contributions to water color, chl-a pigment, TSS particles, and their self-shading. Of course

water temperature is the hardest to limit. Similarly, light is hard to control. However, management decisions can reduce nutrient loading from waste water treatment facilities, regulate the type and amount of fertilizers used in farm land, and manage animal waste from farms. Limiting nutrients can cause the phytoplankton population to decline and the water clarity to improve. In addition, the contribution of dead phytoplankton cells to detritus and TSS will be reduced and further improvement to water clarity can take place. On the other hand, the major sources of mineral particulates include erosion from the watershed and resuspension from the bed. The latter is hard to manage without altering the flow patterns to reduce bed shear stress. Management decision to limit erosion from watersheds can include controlling deforestation, reducing impervious surfaces, providing natural and artificial sedimentation transitions.

In addition to quantifying the behavior of total irradiance in space and time, the methodology can identify the spectral distribution of irradiance, which dictates the quality of light. Figure 11 illustrates the spectral distribution of irradiance at Station NPI on June 1, 2009. Such distribution is quantified for each wavelength at each layer (Eq. (5)). Based on water clarity, irradiances from various wavelengths may extinct at different water depths (Fig. 12), which affects the overall quality of light at that depth. For example, irradiances of wavelengths 400–450 nm were almost extinct at 3m deep (Fig. 11). Although, the range of the spectrum with wavelengths 550–600 nm reached 6m deep, its irradiance was only $3 \mu\text{mole m}^{-2} \text{s}^{-1}$. The importance of such information about light quality on the wellbeing of pelagic and benthic organisms, plankton, and SAV is evident, but it is beyond the scope of this work.

Normalized absorption and backscattering values were utilized to partition the loss of irradiance between the major contributors: pure water, chl-a, TSS, and CDOM. The benchmark for the ideal ecological condition is when water clarity is at its maximum possible value, i.e., when only pure water exists in the system. Other situations, when phytoplankton, TSS, and CDOM are present, would cause less water clarity and reduced irradiance.

The novelty in the presented approach lies in: (1) normalizing the overall attenuation as well as attenuations by the various contributors by water attenuation and introducing the Normalized Universal Attenuation (NUA_Z) unit, which establishes the base for intercomparisons between different locations and times within the same system and also between different systems (Fig.10a); (2) the use of the calibration coefficient, D , and the Euclidean Distance, EC , to minimize the deviation between calculated and observed irradiance profiles enabled further analysis of such deviations in space and time (Fig.13); (3) introducing the spectral shape function, f , allowed the reconstruction of the incident PAR from the total incident irradiance; (4) inclusion of absorption and backscattering from all contributors rather than a subset of them; (5) the use of the full PAR rather than a representative wave length (e.g., 490 nm, Xiu and Chai 2014) quantified the light quality from the downwelling propagation of all wave lengths throughout the water depth (Figs. 11 and 12).

The Normalized Universal Attenuation to a referenced depth Z (NUA_z) was introduced to relate attenuation by various contributors to attenuation by pure water. For example, assuming that a hypothetical mitigation measure can completely eliminate attenuation by chl- a ; the maximum improvement can reach 70 % from the base attenuation by clear water at station NPI. This quantitative description can provide the context for management decisions related to improving water clarity. In addition, the normalization facilitated comparisons between water clarity (light attenuation) of the same or different systems in space and time. To illustrate the universality of this normalization and its NUA_z units, NUA_4 values from three lakes (Arbutis, WI; Oneida, NY; and Onondaga, NY) are plotted on Fig. 10a with values from Narragansett Bay. It is clear that Lake Arbutis has the least water clarity (3.67 NUA_4) not only between the three lakes, but also when compared to Narragansett Bay. On the other hand, Lake Onondaga has the clearest water in the three lakes (2.94 NUA_4); nonetheless, water in the lower Narragansett Bay at QP1 is clearer (~2.5 NUA_4) than this lake. (Irradiance profiles for the three lakes are presented by the State University of New York, College of Environmental Science and Forestry: www.esf.edu/efb/schulz/Limnology/Laboratory/Light2006Thurs.ppt)

As implicitly indicated in the presented methodology, there are at least two levels of calibration to reduce the level of uncertainty in the final irradiance calculations. First, the accuracy of calibration of the bio-optical models for the system of interest (e.g., Thursby et al. 2015 for Narragansett Bay). Second, the overall calibration coefficient, D , to fine-tune the calculated overall attenuation (see below). The final judge of the quality of the calculated irradiance would be determined by comparison with field observations. For Narragansett Bay, various evaluations between calculated and observed irradiance were presented in the calibration and validation section, which indicated that the presented methodology is capable of reproducing observed irradiance values (Fig. 7). To use this methodology in other geographical areas, bio-optical models have to provide the site-specific relations and parameters for light attenuation by phytoplankton, TSS, and CDOM (see Methods).

The overall calibration coefficient, D , was introduced to fine-tune the method. A value of $D > 1.0$ indicates that the methods underestimate observations and vice versa $D < 1.0$ indicates overestimation. The general statistics indicate that D has an overall mean value of ~1.0 (range 0.60–1.54) (Table 6) confirming the adequacy of the method for Narragansett Bay. However, values of D fluctuated in space and time (Fig. 13). For example, on August 3, 2009, the calibration coefficient D was consistently < 1.0 at locations BR, CP, and NPI, which indicated that the methodology overestimated light attenuation and had to be reduced using a value of $D < 1.0$. Observations of chl- a concentrations at the three stations indicate higher concentrations in the top ~3–4 m. Abdelrhman (2015) indicated the existence of strong stratification at these locations during August, 2009. Thus, it should be emphasized that other factors, not covered by the presented method, may exist in the field during specific situations, locations, and times; however, the adequacy of the methodology is confirmed statistically for Narragansett Bay as a whole (Table 6).

Addressing spatial and temporal variability of the various attenuators (TSS, CDOM, and chl- a) in Narragansett Bay is planned for future extensions of this work using predictive multidimensional numerical models. For convenience, the average profile of TSS (Fig. 5b,

Eq. (19)) was assumed to represent the vertical distribution of TSS concentration at all times. This assumption will be revisited in the future by using TSS predictions from numerical models. Recently, Abdelrhman (2016b) presented the methodology to predicted TSS concentrations in space and time within Narragansett Bay. Such information is analogous to modeling phytoplankton concentrations in space and time using water quality models for the Bay (Abdelrhman 2016a). Also, the average longitudinal distribution of CDOM absorption was considered to represent the Bay conditions at all times (Fig. 6a). Modeling CDOM absorption with respect to dissolved organic carbon (i.e., Zhang et al. 2007) can be implemented in the future using water quality models (Abdelrhman 2016a) to resolve the spatial and temporal variability of CDOM concentration in the Bay. The spatial and temporal resolution of such predictions will eliminate the need for coarse representations using averaged values.

Similarly, for convenience, the carbon to chl-a ratio was assumed to be 43 (Abdelrhman 2016a). This ratio has a large range of variation within a single phytoplankton group and between the various groups (Geider 1987). Gallegos and Moor (2000) mentioned a range of 20 to 80 for their data and they used an intermediate value of 40, which is close to the value assumed here. More robust estimates of this ratio can be obtained through coupling phytoplankton with optical models (Fujii et al. 2007). The modeled range of this ratio was 10 to 40 in the PAR range of $400\text{--}0\text{ W m}^{-2}$ ($1,828\text{--}0\text{ }\mu\text{mole m}^{-2}\text{ s}^{-1}$) for picoplankton and diatoms (Fujii et al. 2007). This approach is under consideration for future modeling in Narragansett Bay. Recent numerical models that provide phytoplankton, TSS, and CDOM concentrations implement similar methodology to predict light attenuation in estuaries and coastal embayments (Xiu and Chai 2014, Mobley et al. 2015). Employing numerical modeling with bio-optical modeling will validate the use of the approach presented to examine water clarity due to future scenarios related to changes in natural and anthropogenic forcing.

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Appendix A.: Spectrum Distribution Function (Table 2)

The spectrum distribution function is calculated from the extraterrestrial solar irradiance at the top of the atmosphere. Gregg and Cader (1990) present mean extraterrestrial irradiance values at all wave lengths λ within the range 350 nm to 700 nm. Values of the spectrum distribution function are identified from this information. First, irradiance values at 5 nm increments are extracted, $F(\lambda_j)$ ($\text{W m}^{-2}\text{ nm}^{-1}$), λ_j is the wave length (nm), and j is a counter for values within the PAR (400 nm - 700 nm) ($j = 1$ to 61). Second, the normalized values,

which represent the distribution function $f(\lambda_j)$, are obtained by dividing each $F(\lambda_j)$ by the total sum of all the extracted values, i.e.,

$$f(\lambda_j) = \frac{F(\lambda_j)}{\sum_{j=1}^{61} F(\lambda_j)} (A - 1)$$

Where $f(\lambda_j)$ (dimensionless) is the distribution function which has a unit area, i.e.,

$$\sum_{j=1}^{61} f(\lambda_j) = 1.0(A - 2)$$

It is assumed that the spectrum distribution function, $f(\lambda_j)$, maintains its shape and unit area throughout the atmosphere down to the water surface (Table 2). The 5-nm increment cancels out from the numerator and denominator in Equation (A-1).

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Fig. 1. Map of Narragansett Bay showing URI observation stations for chl-a and Light measurements, and AED observation stations for TSS measurements

Fig. 2.

Definition sketch of the vertical structure for the mathematical model and its utilization to study irradiance throughout the water column. Concentrations of chl-a ($C_{x,y,z,t}$), TSS ($S_{x,y,z,t}$), and CDOM ($g_{x,y,z,t}$) should be identified at each monitoring location (x,y) (e.g., Fig. 1), at every layer depth below the water surface (z), and at every monitoring time (t), as described in the text

Fig. 3.

Spectral distributions of the normalized absorption coefficients for pure water, a_w , (Kirk 1994), total suspended solids, a_s^+ (Thursby et al. 2015), and colored dissolved organic matter, a_g^+ (Thursby et al. 2015); and backscattering coefficients of total suspended solids, b_s^+ (Thursby et al. 2015), and pure water b_w (Buiteveld et al. 1994), in addition to the spectral distribution function of the incident light for the photosynthetic available radiation, $f(\lambda)$ (Appendix A) and the spectral distributions of the coefficients A and B (Eq. 8, Thursby et al. 2015) with broken lines read on the right axis

Fig. 4. Incident surface irradiance from 39 measurements in Narragansett Bay: (a) comparison between irradiance just above and just below the water surface from URI data, and (b) comparison between measured irradiance from URI data and modeled direct and diffuse irradiance on a horizontal disk at the water surface from NSRDB data

Fig. 5.

Vertical profiles and ranges of concentrations: (a) observed average vertical concentration profile of chl-a, and (b) calculated phytoplankton carbon and the estimated total TSS. Chl-a concentrations are reported at ~ 0.5 m depth increments and TSS concentrations are interpolated at the same depth locations for chl-a measurements. Phytoplankton concentration is calculated from chl-a concentration using a carbon to chl-a ratio of 43 and TSS concentration is calculated from Eq. (19)

Fig. 6. Values of CDOM absorption coefficient $a_g(\lambda)$ in Narragansett Bay: (a) longitudinal distribution of $a_g(440)$, (b) correlation between the observed bay-average normalized CDOM absorption ($a_g(\lambda)/a_g(440)$) with calculated values from Equation (11)

Fig. 7. Example of calibration showing calculated and observed irradiance at Station NPI on June 1, 2009: (a) calculated irradiance, observed irradiance, and their difference, E ; and (b) scatter plot between observed and calculated irradiances; the dashed line shows the trend of the scatter points with respect to the 45° solid line for the best (one to one) correlation

Fig. 8. Individual light attenuation by each contributor at station NPI on June 1, 2009. The incident light is included as the benchmark for comparison

Fig. 9. Profiles of normalized light attenuation by each contributor with respect to attenuation by pure water at station NPI on June 1, 2009.

Fig. 10.

Spatial and temporal variations of the normalized universal attenuation, NUA_4 , in Narragansett Bay during the summer of 2009. (a) spatial variation along the Bay at stations BR, CP, and NPI on July 10, 2009; and stations MV, QP1, and GD on July 13, 2009 with values from three arbitrarily chosen lakes (Arbutis, WI; Oneida, NY; and Onondaga, NY) to illustrate the universality of the normalization, (b) temporal variations of NUA_4 at all stations (Table 5)

Fig. 11.
Change of irradiance spectral distribution from the water surface to -6 m deep at station NPI on June 1, 2009. Notice the extinction of some wave lengths at various water depths

Fig. 12.
Light attenuation profiles for various colors at station NPI on June 1, 2009. Such profiles dictate the quality of light at various depths

Fig. 13.

The temporal variations of the calibration coefficient, D , at stations BR, CP, and NPI during the summer season of 2009 showing values consistently <1.0 on August 3, 2009 at the three stations

Table 1.

Definitions of all abbreviations and symbols.

Symbol	Definition	Dimension
<u>Abbreviations</u>		
AED	Atlantic Ecology Division of the USEPA	
CDOM	Colored dissolved organic material	
chl-a	Chlorophyll a	
NAPs	Non-algae particles	
PAR	Photosynthetic available radiation	
SAV	Submerged aquatic vegetation	
TSS	Total suspended solids	
URI	University of Rhode Island	
WWTP	Waste water treatment plant	
<u>Parameters</u>		
A	Coefficient	dimensionless
a_w	Absorption coefficient of water	m^{-1}
a_c	Absorption coefficient of chl-a ^a	m^{-1}
a_s	Absorption coefficient of TSS	m^{-1}
a_g	Absorption coefficient of CDOM	m^{-1}
B	Coefficient	dimensionless
b_w	Backscattering coefficient of water ^a	m^{-1}
b_s	Backscattering coefficient of TSS/NAPs ^a	m^{-1}
C	chl-a concentration	$\mu g L^{-1}$
D	Calibration coefficient	dimensionless
E_0	Irradiance at the water surface	$\mu mol \text{ quanta } m^{-2} s^{-1}$
E_i	Irradiance at the bottom of the i th layer, ℓ	$\mu mol \text{ quanta } m^{-2} s^{-1}$
e	Exponentiation base (e=2.718281828459)	dimensionless
ED	Euclidean distance %	dimensionless
f	Spectrum distribution function	dimensionless
g	CDOM concentration (not implemented)	$\mu g L^{-1}$
K	Extinction coefficient ^a	m^{-1}
ℓ	Layer thickness ($z_i - z_{i-1}$)	M
NUA_z	Normalized Universal Attenuation to a reference depth Z	dimensionless
$RR_i(\lambda_j)$	Reduction ratio of wave length λ_j at the i th layer	dimensionless
S	TSS concentration	$mg L^{-1}$
SS_g	CDOM spectral slope	dimensionless
λ	Wave length	nm
<u>Subscripts</u>		
i	Counter for the water layer,	
j	counter for the wave length λ	

Symbol	Definition	Dimension
t	time	
x	eastward spatial location (see Fig. 2)	
y	northward spatial location (see Fig. 2)	
z	vertical spatial location below water surface (see Fig. 2)	

^aTo avoid confusion in the subscripts presented in the various equations: b is used instead of b_b for backscattering, K is used instead of K_d for the downwelling extinction coefficient, and a_c is used instead of a_{ph} for absorption by phytoplankton pigment.

Table 2.

Spectral values of pure water absorption and backscattering coefficients, absorption factors for TSS and CDOM, backscattering factors for TSS, the spectrum distribution function for the PAR, and the two coefficients A and B (Eq. 8). Letters a and b refer to absorption and backscattering, respectively. The + sign indicates a spectrally distributed factor (see Methods).

1	2	3	4	5	6	7	8	9	10
j	λ	a_w	a_s+	a_g+	b_s+	b_w	$f(\lambda)$	A	B
1	400	0.0180	1.7229	1.8889	1.1020	0.0053	0.0155	0.0576	0.6360
2	405	0.0180	1.6096	1.7446	1.0948	0.0051	0.0153	0.0617	0.6420
3	410	0.0170	1.5038	1.6112	1.0876	0.0048	0.0150	0.0663	0.6440
4	415	0.0170	1.4049	1.4881	1.0804	0.0046	0.0165	0.0703	0.6430
5	420	0.0160	1.3126	1.3744	1.0732	0.0043	0.0160	0.0634	0.6690
6	425	0.0160	1.2263	1.2693	1.0660	0.0042	0.0162	0.0641	0.6620
7	430	0.0150	1.1457	1.1723	1.0588	0.0039	0.0131	0.0675	0.6690
8	435	0.0150	1.0704	1.0827	1.0516	0.0038	0.0164	0.0702	0.6720
9	440	0.0150	1.0000	1.0000	1.0444	0.0036	0.0159	0.0695	0.6730
10	445	0.0150	0.9343	0.9236	1.0372	0.0034	0.0182	0.0675	0.6670
11	450	0.0150	0.8728	0.8530	1.0300	0.0033	0.0198	0.0642	0.6700
12	455	0.0160	0.8155	0.7878	1.0228	0.0031	0.0188	0.0632	0.6690
13	460	0.0160	0.7619	0.7276	1.0156	0.0030	0.0188	0.0627	0.6660
14	465	0.0160	0.7118	0.6720	1.0084	0.0029	0.0184	0.0611	0.6640
15	470	0.0160	0.6650	0.6206	1.0012	0.0027	0.0181	0.0588	0.6590
16	475	0.0170	0.6213	0.5732	0.9940	0.0026	0.0188	0.0557	0.6580
17	480	0.0180	0.5804	0.5294	0.9868	0.0025	0.0192	0.0533	0.6610
18	485	0.0190	0.5423	0.4889	0.9796	0.0024	0.0181	0.0506	0.6730
19	490	0.0200	0.5066	0.4516	0.9724	0.0023	0.0180	0.0476	0.6860
20	495	0.0230	0.4733	0.4171	0.9652	0.0022	0.0186	0.0436	0.7010
21	500	0.0260	0.4422	0.3852	0.9580	0.0021	0.0174	0.0389	0.7170
22	505	0.0310	0.4131	0.3558	0.9508	0.0020	0.0179	0.0344	0.7310
23	510	0.0360	0.3860	0.3286	0.9436	0.0019	0.0180	0.0302	0.7480
24	515	0.0420	0.3606	0.3035	0.9364	0.0019	0.0172	0.0266	0.7630
25	520	0.0480	0.3369	0.2803	0.9292	0.0018	0.0170	0.0238	0.7740
26	525	0.0500	0.3147	0.2589	0.9220	0.0017	0.0174	0.0213	0.7870
27	530	0.0510	0.2941	0.2391	0.9148	0.0017	0.0182	0.0190	0.8020
28	535	0.0540	0.2747	0.2208	0.9076	0.0016	0.0181	0.0172	0.8100
29	540	0.0560	0.2567	0.2039	0.9004	0.0015	0.0171	0.0156	0.8160
30	545	0.0600	0.2398	0.1883	0.8932	0.0015	0.0177	0.0140	0.8190
31	550	0.0640	0.2240	0.1739	0.8860	0.0014	0.0174	0.0126	0.8180
32	555	0.0680	0.2093	0.1607	0.8788	0.0014	0.0176	0.0111	0.8190
33	560	0.0710	0.1955	0.1484	0.8716	0.0013	0.0169	0.0097	0.8310
34	565	0.0760	0.1827	0.1370	0.8644	0.0013	0.0171	0.0094	0.8140
35	570	0.0800	0.1707	0.1266	0.8572	0.0012	0.0168	0.0089	0.8150

1	2	3	4	5	6	7	8	9	10
j	λ	a_w	a_s^+	a_g^+	b_s^+	b_w	$f(\lambda)$	A	B
36	575	0.0940	0.1595	0.1169	0.8500	0.0012	0.0172	0.0081	0.8400
37	580	0.1080	0.1490	0.1080	0.8428	0.0011	0.0172	0.0075	0.8620
38	585	0.1330	0.1392	0.0997	0.8356	0.0011	0.0173	0.0074	0.8670
39	590	0.1570	0.1300	0.0921	0.8284	0.0011	0.0163	0.0071	0.8700
40	595	0.2010	0.1215	0.0851	0.8212	0.0010	0.0167	0.0068	0.8670
41	600	0.2450	0.1135	0.0786	0.8140	0.0010	0.0163	0.0067	0.8690
42	605	0.2680	0.1060	0.0725	0.8068	0.0010	0.0164	0.0071	0.8720
43	610	0.2900	0.0991	0.0670	0.7996	0.0009	0.0160	0.0077	0.8810
44	615	0.3000	0.0926	0.0619	0.7924	0.0009	0.0157	0.0085	0.8860
45	620	0.3100	0.0865	0.0572	0.7852	0.0009	0.0161	0.0089	0.8850
46	625	0.3150	0.0808	0.0528	0.7780	0.0008	0.0155	0.0093	0.8810
47	630	0.3200	0.0755	0.0488	0.7708	0.0008	0.0154	0.0098	0.8770
48	635	0.3250	0.0705	0.0450	0.7636	0.0008	0.0154	0.0102	0.8610
49	640	0.3300	0.0659	0.0416	0.7564	0.0008	0.0151	0.0104	0.8440
50	645	0.3400	0.0615	0.0384	0.7492	0.0007	0.0150	0.0104	0.8350
51	650	0.3500	0.0575	0.0355	0.7420	0.0007	0.0145	0.0103	0.8580
52	655	0.3800	0.0537	0.0328	0.7348	0.0007	0.0136	0.0116	0.8910
53	660	0.4100	0.0502	0.0303	0.7276	0.0007	0.0140	0.0158	0.8950
54	665	0.4200	0.0469	0.0279	0.7204	0.0006	0.0145	0.0220	0.8820
55	670	0.4300	0.0438	0.0258	0.7132	0.0006	0.0142	0.0272	0.8670
56	675	0.4400	0.0409	0.0238	0.7060	0.0006	0.0139	0.0282	0.8550
57	680	0.4500	0.0382	0.0220	0.6988	0.0006	0.0137	0.0237	0.8640
58	685	0.4750	0.0357	0.0203	0.6916	0.0006	0.0135	0.0162	0.8880
59	690	0.5000	0.0334	0.0188	0.6844	0.0006	0.0134	0.0089	0.9130
60	695	0.5750	0.0312	0.0173	0.6772	0.0005	0.0132	0.0050	0.9040
61	700	0.6500	0.0291	0.0160	0.6700	0.0005	0.0131	0.0032	0.8790

Column 1: counter, j, for the 5 μ m wave length within the PAR

Column 2: the wave length, λ μ m

Column 3: from Kirk (1994), page 56

Column 4: $a_s^+ = \exp(-0.0136 (\lambda - 440))$, from Thursby et al. (2015)

Column 5: $a_g^+ = \exp(-0.0159 (\lambda - 440))$, from Thursby et al. (2015)

Column 6: $b_s^+ = (1.678 - 0.00144 \lambda)$, From Thursby et al. (2015)

Column 7: modified from Buiteveld et al. (1994) at 5 nm increments

Column 8: as presented in Appendix (A)

Columns 9 & 10: from Thursby et al. (2015)

Table 3.

Statistical values from field observations of TSS at the surface, mid-depth, and bottom waters in Narragansett Bay during 2014 and 2015.

Statistical parameter	Surface	Mid-depth	Bottom
Mean	3.50	3.43	5.06
Standard Error	0.33	0.44	0.67
Median	3.32	3.12	4.24
Standard Deviation	1.31	1.77	2.67
Sample Variance	1.72	3.13	7.13
Kurtosis	-0.72	3.75	0.18
Skewness	0.45	1.58	0.99
Range	4.19	7.22	8.38
Minimum	1.60	1.29	2.14
Maximum	5.79	8.51	10.53
Count	16	16	16
Confidence Level (95.0%)	0.70	0.94	1.42

Table 4.

Reference CDOM absorption coefficients at $\lambda=440$ nm, $a_g(440)$, at six stations along Narragansett Bay

Station name	$a_g(440)$
Bullocks Reach, BR	0.556
Conimicut Point, CP	0.574
North Prudence Island, NPI	0.579
Mount View, MV	0.518
Quonset Point, QP1	0.608
Graduate School of Oceanography, GD	0.347
Overall average	0.531

Table 5.

Calibration results from observations at six stations in Narragansett Bay during the summer of 2009.

1	2	3	4	5	6	7		8		9
Station		Monitored		E_0	Calibration	Trend Slope		Euclidean Distance (%)		N
Name	Date	Depth	n		Coefficient					
		(m)		($\mu\text{mole m}^{-2} \text{s}^{-1}$)	D	D	D=1	ED1	ED2	(NUA_4)
BR	6/1/2009	6.50	13	1691.23	1.1460	0.9813	0.8563	13.75	18.65	3.18
BR	7/10/2009	7.50	15	1540.23	0.8890	0.9655	1.0860	18.64	22.32	3.38
BR	8/3/2009	7.25	14	1273.07	0.7520	0.8357	1.1113	40.63	50.66	3.41
BR	8/20/2009	7.50	15	1362.33	0.9090	0.9502	1.0454	22.33	24.37	3.37
CP	6/1/2009	7.50	15	1887.87	1.0002	0.9943	0.9942	7.18	7.18	3.12
CP	7/10/2009	9.00	18	1819.50	0.8550	0.9796	1.1458	14.33	22.06	3.28
CP	7/22/2009	8.30	18	2010.00	0.8960	0.9705	1.0831	17.21	20.67	3.19
CP	8/3/2009	7.50	15	1565.60	0.6010	0.8951	1.4893	32.34	70.62	3.37
CP	8/20/2009	8.00	16	1672.75	1.0090	0.9660	0.9574	18.89	18.90	3.16
NPI	6/1/2009	11.80	24	1917.75	1.2544	0.9923	0.7910	9.09	22.11	3.13
NPI	6/25/2009	12.00	24	1004.63	1.1210	0.9802	0.8744	14.07	17.62	3.12
NPI	7/10/2009	15.00	30	2065.80	1.0860	0.9977	0.9187	4.77	9.23	3.21
NPI	7/22/2009	11.00	22	744.77	0.8308	0.9770	1.1760	15.18	25.18	3.10
NPI	8/3/2009	13.00	26	1795.23	0.6824	0.9738	1.4270	16.29	48.72	3.33
NPI	8/20/2009	11.00	22	1902.50	0.9480	0.9865	1.0405	11.65	12.86	3.54
MV	7/13/2009	7.50	15	1076.87	1.3900	0.9970	0.7173	5.06	28.51	3.10
MV	8/5/2009	6.75	14	1478.36	1.0100	0.9407	0.9314	17.86	18.04	3.26
QPI	7/13/2009	7.00	14	1174.50	1.5421	0.9860	0.6394	12.31	36.92	2.50
QPI	7/20/2009	7.90	16	1017.05	1.4490	0.9849	0.6797	12.23	33.11	2.48
GD	6/9/2009	3.80	9	138.13	0.7080	0.9872	1.3944	11.49	42.60	2.89
GD	7/13/2009	4.00	8	1761.25	1.2090	0.9879	0.8171	10.95	20.38	2.91

Column 1: Station name

Column 2: Date of monitored irradiance and chl-a profiles

Column 3: Monitored depth which may be less than the actual depth

Column 4: Number of horizontal layers in the monitored profile

Column 5: Incident irradiance, E_0 , during monitoring (see statistics in Table 6)

Column 6: Calibration coefficient, D (Eq. 6) (see statistics in Table 6)

Column 7: Slope of the trend of the scatter plot (e.g., Fig. 7b) (see statistics in Table 6)

Column 8: Euclidean distance (Eq. 19), ED1 with D (from column 6), and ED2 with D=1

Column 9: Normalized observed irradiance in units of Normalized Universal Attenuation, $Z=4\text{m}$

Table 6.

Statistical analysis of the calibration results for Narragansett Bay presented in Table 4.

Statistical Parameter	Incident light	Calibration Coefficient	Scatter Slope		Euclidean Distance		NUA ₄
	E ₀	D			ED ₁	ED ₂	
	($\mu\text{mole m}^{-2} \text{s}^{-1}$)		with D	with D=1	with D	with D=1	
Mean	1471.40	1.01	0.97	1.01	15.54	27.18	3.14
Standard Error	105.10	0.06	0.01	0.05	1.83	3.34	0.06
Median	1565.60	1.00	0.98	0.99	14.07	22.11	3.18
Standard Deviation	481.64	0.25	0.04	0.23	8.38	15.32	0.27
Sample Variance	231972.31	0.06	0.00	0.05	70.28	234.61	0.07
Kurtosis	1.40	-0.31	7.24	-0.15	3.49	2.00	1.88
Skewness	-1.15	0.48	-2.59	0.50	1.63	1.37	-1.32
Range	1927.67	0.94	0.16	0.85	35.86	63.45	1.06
Minimum	138.13	0.60	0.84	0.64	4.77	7.18	2.48
Maximum	2065.80	1.54	1.00	1.49	40.63	70.62	3.54
Count	21	21	21	21	21	21	21
Confidence Level (95.0%)	219.24	0.12	0.02	0.11	3.82	6.97	0.12