Light propagation, coefficient attenuation, and the depth of one optical depth in different water types

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Abstract. The ocean color satellite can only sense a water column up to one optical depth. However, literature regarding the depth of one optical depth is very limited to none. This study aimed to determine light propagation, attenuation coefficient ($K_d$), and the depth of one optical depth in different water types. We used in situ data of downwelling irradiance ($E_d$) with depth taken using the instrument of submersible marine environmental radiometer (MER) in the northeastern gulf of mexico (NEGOM) in April 2000. We also used SeaWiFS data such as water leaving radiance ($L_w$), remote sensing reflectance ($R_s$), and chlorophyll-a concentration (Chla). The results showed that the light propagation pattern generally decreased with increasing depth. The reduction in light intensity with depth was very strong in the red wavelengths, lower in the green wavelengths, and the lowest in the blue wavelengths. In contrast, $K_d$ values were generally found the lowest at the blue wavelengths, slightly increase at the purple and green wavelengths, and the highest at the red wavelengths. The depth of one optical depth in the case-1 waters was found as deep as $39.79$ m ($\lambda=475$ nm), followed by intermediate water of $31.79$ m ($\lambda=475$ nm), and in the case-2 waters of $16.08$ m ($\lambda=490$ nm). Both $K_d$ (490) in situ and modelled results showed a good correlation ($r=0.83-0.84$) and $R^2$ values of 0.68-0.71.

Keywords: case-1 and case-2 waters, coefficient attenuation, one optical depth, propagation

1. Introduction

In general, light entering in to the water column will undergo a process of absorption and scattering by the water itself and the materials contained in the water column [1-3]. The process of light loss due to absorption and scattering in the water column is called the attenuation process. In general, the attenuation coefficient is influenced by factors such as the material contained in the water column, the sun's zenith angle, water surface conditions, and variations in depth [4, 5]. The attenuation coefficient, also known as the diffuse attenuation coefficient, is a decrease in light intensity in the water column exponentially with depth [1, 2, 6, 7, 8]. Furthermore, the diffuse attenuation coefficient can be divided into the diffuse downwelling attenuation coefficient ($K_d$) and the diffuse upwelling attenuation coefficient ($K_u$). The coefficient of diffuse downwelling attenuation ($K_d$) is defined as the reduction in the amount of downwelling irradiance ($E_d$) with depth, which consists of the irradiance (photons) received by the sensor pointing upwards or photons pointing downwards [1, 2]. On the other hand, the diffuse upwelling attenuation coefficient ($K_u$) is defined as the decrease in the amount of light upwelling irradiance ($E_u$) with depth which consists of irradiance (photons) received by the sensor facing downwards or photons pointing upwards [1, 2].

The diffuse downwelling attenuation coefficient ($K_d$) is often analogous to the attenuation coefficient ($K_d$) and is a commonly used parameter to determine the amount of light loss due to absorption and scattering with depth [1, 2, 9]. This also happens because the light (irradiance) from the sun that enters the water column is a downwelling irradiance and the $K_d$ value is much greater than the $K_u$ value [1, 2].

One optical depth is the depth where the total irradiance at that depth is found 37% of the total surface irradiance. This one optical depth parameter is very important in marine remote sensing, especially in
ocean color remote sensing because ocean color satellites can only detect a maximum water column up to one optical depth [10, 11]. Therefore, ocean color satellites cannot always detect the depth of the maximum chlorophyll concentration [12, 13]. Many phytoplankton blooms occurring deep in the water column or with extremely low Chl-a (<0.1 mg m$^{-3}$) remain unreported because they are not always observed in satellite images but yet are known to occur [14, 15]. Algal blooms detected by satellite sensors often cover large areas, but their typically “patchy” distributions make them difficult to model [16].

Research related to one optical depth is still very rare and there has not even been a publication regarding the value of one optical depth. Therefore, this research is very important to find out the depth of one optical depth for different water types (type-1, intermediate, and type-2 waters). By knowing the depth of one optical depth, then, we can find out the water column depth that can be detected by ocean color satellites.

The relationship between apparent optical properties (AOP) and inherent optical properties (IOP) was used to understand how to relate $K_d$ variation to remote sensing reflectance ($R_a$) [17]. Apparent optical properties (AOP) are the water optical properties that are influenced by the medium and the content of the medium as well as the intensity and geometric structure of the incident light field such as remote sensing reflectance ($R_a$) and the coefficient of diffuse downwelling attenuation ($K_d$). Meanwhile, inherent optical properties (IOP) are optical properties that are only affected by the medium and the content of the medium such as absorption, scattering, and attenuation of the water column. $R_{rs}$ is defined as the ratio between the radiance coming out of the water column (upwelling radiance) and the total irradiance received at the water surface (downwelling irradiance). $K_d$ can be used to study the optical properties of fine waters in both spatial and temporal scales [18, 19].

The calculation of $K_d$ from the ocean color algorithm is basically carried out at a wavelength of 490 nm, especially in open water [20, 21]. This is because $K_d$ at 490 nm is a widely accepted parameter, used for various ocean color applications and has wide application in the field of water optics and remote sensing [9]. The empirical method for estimating $K_d$ (490) directly uses blue-green wavelengths [9, 21, 22, 23]. In addition, $K_d$ (490) can also be calculated using an empirical model based on the spectral relationship of $K_d$ ($\lambda$) and chlorophyll-a concentration [20, 24].

Efforts in developing empirical model for $K_d$ (490) data collection in coastal and oceanic waters are increasing. The empirical algorithm was first developed by [22] by using the ratio of the wavelength of the blue-green water leaving radiance ($L_w (443)/L_w (550)$) to the coefficient of pure seawater ($K_{se}=0.022$ m$^{-1}$) to calculate $K_d$ (490). Then to get the attenuation coefficient value $K_d$ (490) from the SeaWiFs sensor, [21] proposed an equation using the ratio of the water leaving radiance ($L_w (490)/L_w (555)$) with a value of $K_{se}=0.0166$.

A modified version of the Mueller model by [23] used the ratio of remote sensing reflectance ($R_a$) blue-green wavelengths ($R_a (490)/R_a (555)$) instead of the water leaving radiance. The algorithm was later updated in 2009 using in situ data from the NASA bio-optical Marine Algorithm (NOMAD) data set. The model described the most suitable polynomial that related the variable $K_d$ (490) which was transformed by logarithm to the ratio of the transformation logarithm of $R_a$. The polynomial form replaced the power law form used in the previous $K_d$ algorithm (equations 1, 2, and 3).

The blue-green ratio-based algorithm has been well validated in clear waters dominated by chlorophyll-a and CDOM (case-1), but is not optimal for turbid waters, so [19] developed an algorithm with a red-green wavelength approach. [9] also developed an algorithm using the blue-green wavelength approach ($R_a (443)/R_a (555)$) for the red sea with low chlorophyll-a water conditions. In addition, algorithm development was also carried out using the chlorophyll-a approach for open water [20].

The NEGOM is a very dynamic ecosystem that is influenced by fresh water input from several large rivers (such as the Mississippi, Mobile, Escambia, Chokawhatchee, Apalachicola, and Suwannee rivers), upwelling, seasonal seawater circulation, local wind, and Loop Current circulation [25, 26]. River discharges deliver large amounts of nutrients that promote primary and secondary productivity [27]. NEGOM receives water input from the Mississippi River, Mobile River, Escambia River, Chokawhatchee River, Apalachicola River, Suwannee River, and several other small rivers. River
water discharge varies seasonally, with the maximum discharge occurring in the spring which occurs in March-June. According to [25] the concentration of chlorophyll in the NEGOM increased fourfold during the winter to spring transition in 1998. This was related to the occurrence of the ENSO phenomenon and very strong upwelling along the coast in the spring of 1998 [25, 26]. The purposes of this study were to determine light propagation, attenuation coefficient, the value of one optical depth in different water types, and compared the $K_d$ value of in situ data with the $K_d$ value of empirical modeling results.

2. Materials and methods

2.1. Location and data
Downwelling irradiance ($E_d$) data were collected on April 15 - 26, 2000 in the NEGOM with coordinates of $27^\circ18' - 30^\circ42' N$ and $82^\circ36' - 89^\circ36' W$. The data collection was carried out in coordination with the Institute of Marine Remote Sensing, College of Marine Science, University of South Florida using the Texas A&M University Gyre research vessel. Data collection locations were limited to a depth of 10 m near the coast to 1000 m offshore (Figure 1). $E_d$ data collections using the instrument submersible marine environmental radiometer (MER) were carried out when the sea conditions were relatively calm i.e., with wave height < 0.5 m, clear sky (cloud cover < 30%), between 10-11:30 or 13:00 - 14:30 local time. $E_d$ data were taken at stations 1, 2, 5, 6, 9, 10, 14, and 15 (group A) for case-1 waters (offshore), stations 8, 11, and 12 (group B) for intermediate waters (waters) between inshore and offshore), and stations 3, 4, 7, 12, and 13 (group C) for case-2 waters (inshore) (Figure 1).

![Figure 1](image-url)
The MER device was first calibrated at the Marine Remote Sensing Laboratory, Institute of Marine Remote Sensing, College of Marine Science, University of South Florida using a standard lamp as a light source. Then, dark current measurements were also carried out at night at sea to calibrate the instrument from disturbances in voltage differences that may occur on the MER device during data collection. The MER device was lowered from the ship’s deck to a depth of about 50-60 m in offshore, 40-55 m in the intermediate waters, and 10-30 m in the coastal region slowly while recording data. The data recorded by the MER instrument were upwelling radiance \( (L_u) \), downwelling radiance \( (L_d) \), upwelling irradiance \( (E_u) \), downwelling irradiance \( (E_d) \), depth, and other parameters. The measurements of \( E_d, L_u, E_u, L_d \), and depth values were carried out at the wavelengths of 380 nm, 412 nm, 443 nm, 455 nm, 475 nm, 490 nm, 510 nm, 532 nm, 555 nm, 589 nm, 665 nm, 683 nm, and Photosynthetically Active Radiation (PAR) wavelengths. In this study, we used downwelling irradiance \( (E_d) \) and depth data.

Remote sensing reflectance \( (R_r) \), water leaving radiance \( (L_w) \), and chlorophyll-a concentration of level 2 data from the SeaWiFS ocean color satellite were uploaded from the NASA website (https://oceancolor.gsfc.nasa.gov/), with an image resolution of 1.1 km\(^2\). The uploaded data were daily data on April 15-26, 2000.

2.2. Data analyses

We develop house made programs in Python and Matlab to process in situ data and to filter \( E_d \) data from biases. The \( E_d \) data was then filtered using the exponential Curve Fitting Tool in Matlab software. To get a picture of light propagation with depth, the fitted \( E_d \) values and depth were visualized into a graph according to the color grouping of the wavelengths. We grouped the light spectrum into 4 groups, i.e., purple (400-430 nm), blue (430-480 nm), green (480-560 nm), and red (570-690 nm) [28].

The \( E_d \) values were then used to calculate \( K_d \) based on the formula in equation 7. The downwelling attenuation diffusion coefficient was defined as the downwelling irradiance differential between two different depths [1, 2].

\[
K_d(z, \lambda) = -\frac{1}{E_d(\lambda)} \frac{dE_d}{dz} \tag{1}
\]

where: \( K_d(z, \lambda) \) = attenuation coefficient \( (m^{-1}) \); \( E_d(\lambda) \) = downwelling irradiance \( (Wm^{-2}) \); \( dE_d \) = differential in downwelling irradiance \( (Wm^{-2}) \) between two different depths; and \( dz \) = differential of depths \( (m) \).

The \( K_d \) values were calculated based on the difference in the \( E_d \) values at each 0.2 m depth difference, then the \( K_d \) values from the surface to the maximum depth were averaged to get the final \( K_d \) value at each station.

The value of one optical depth was calculated in this study to get an idea of how deep the ocean color satellite can detect water column in case-1, intermediate, and case-2 waters. In general, one optical depth is the depth at which the amount of incident light \( (E_d) \) remains 37% of the total \( E_d \) on the surface water. The depth of one optical depth can generally be calculated using the following equation [1, 2].

\[
z@1\zeta = \frac{1}{K_d(z, \lambda)} \tag{2}
\]

where: \( z@1\zeta \) = the depth at one optical depth \( (m) \), \( K_d(z, \lambda) \) = attenuation coefficient \( (m^{-1}) \).

The values of \( K_d(490) \) from this study were also compared with \( K_d(490) \) values based on empirical model using water leaving radiance [21], remote sensing reflectance [9, 29, 30], and chlorophyll-a concentration [20] (Table 1). The values of water leaving radiance, remote sensing reflectance, chlorophyll-a concentration were obtained from the SeaWiFS satellite data at the research location and the same time period as the field data collection. The coefficient of determination between \( K_d(490) \) in situ and \( K_d(490) \) empirical modeling result based on satellite data was determined by linear regression method.
Table 1. Several empirical model to estimate $K_d (490)$ using water leaving radiance, remote sensing reflectance, dan konsetransi klorifl-a from SeaWiFS data.

| Algorithm model                                      | Algorithm equation                                                                 | Reference |
|------------------------------------------------------|------------------------------------------------------------------------------------|-----------|
| Empirical algorithm using Remote sensing reflectance | $K_d (490) = K_w + 0.1565 \left( \frac{L_w(490)}{L_w(555)} \right)^{-1.540}$       | [21]      |
|                                                      | where, $K_w = 0.016$                                                               |           |
|                                                      | $K_d (490) = 0.1853 \times \left( \frac{R_{rs} (490)}{R_{rs} (555)} \right)^{-1.349}$ | [29]      |
|                                                      | $K_d (490) = 10^{-0.8515 \times 1.8263X + 1.8714X^2 - 2.4414X^3 - 1.0690X^4} + 0.0166$ | [30]      |
|                                                      | where, $X = \log 10 \left( \frac{R_{rs} (490)}{R_{rs} (555)} \right)$             |           |
|                                                      | $K_d (490) = 0.1189X^4 - 0.3703X^3 + 0.4549X^2 - 0.3448X - 0.14$                     | [9]       |
|                                                      | where, $X = \log 10 \left( \frac{R_{rs} (443)}{R_{rs} (555)} \right)$             |           |
| Empirical algorithm using Chla conc.                 | $K_d (490) = 0.0166 + 0.0773 \times (\text{Chl-a})^{0.6715}$                       | [20]      |

3. Results and discussion

3.1. Downwelling irradiance ($E_d$) propagation in different type of water column

The NEGOM waters have dynamic water characteristics due to the input of fresh water from several rivers, Loop Current, local winds, and upwelling which greatly affect the variability of chlorophyll, dissolved colored organic matter (CDOM), other organic matter, and particulates [25, 26]. In this study, the locations of data collection were divided into three regions i.e., region A, B, and C (see Figure 1). Region A represented case-1 (offshore) waters, which its inherent optical variability is dominantly influenced by the variability of phytoplankton concentrations and is not influenced by shallow water zones and rivers [2]. Region C represented case-2 (inshore) waters, which its inherent optical properties are influenced by the variability of the concentration of phytoplankton, suspended solids, inorganic particles, organic matter, and CDOM [2]. Region B represented the intermediate or transitional waters from case-2 and case-1 waters.

In general, the light propagation pattern at region A (case-1/offshore) decreased exponentially with depth (Figure 2). At region A, the light propagation pattern in the purple wavelength spectrum group ($\lambda = 380$ and 412 nm) began with the $E_d$ value at a depth of 0 m ranging from 71.92-86.43 Wm$^{-2}$ ($\lambda = 380$ nm) and 120.26-142.80 Wm$^{-2}$ ($\lambda = 412$ nm). The light intensity on the surface at the blue wavelengths ($\lambda = 443, 455,$ and 475 nm) was in the range of 137.15-176.80 Wm$^{-2}$, at the green wavelengths ($\lambda = 490, 510, 532,$ and 555 nm) of 143.69-179.50 Wm$^{-2}$, and at the red wavelengths ($\lambda = 589, 665,$ and 683 nm) of 142.05-189.99 Wm$^{-2}$. This indicated that the light intensity reaching the seawater surface at shorter wavelengths was less than that of the light intensity at higher wavelengths (Figure 2a, b). However, in light propagation, blue spectrum wavelength propagated deeper than that green and purple spectrum wavelengths. Meanwhile, red spectrum wavelengths propagated the least (Figure 2a, b).
Figure 2a. The pattern of light propagation in case-1 waters (region A) at stations 1, 2, 5, and 6.
Figure 2b. The pattern of light propagation in case-1 waters (region A) at stations 9, 10, 14, and 16.
Region B was categorized into an intermediate water because this water had transitional characteristics between case-1 and case-2 waters. It was also assumed that within this region some impacts from coastal region were still observed. In general, light propagation in this intermediate water also decreased exponentially with increasing depth, and experienced a significant decrease of light to almost zero within 6-8 m deep in red wavelength spectrums (665 and 683 nm) (Figure 3).

The light propagation pattern in the purple wavelength spectrum ($\lambda$=380 and 412 nm) begins with the $E_d$ value at a depth of 0 m in the range of 71.66-79.95 Wm$^{-2}$ ($\lambda$=380 nm) and 116.77-135.23 Wm$^{-2}$ ($\lambda$=412 nm). In blue wavelength spectrum, light intensity on the surface was in the range of 133.24-171.51Wm$^{-2}$ ($\lambda$=443, 455, and 475 nm) and in green wavelength spectrum light intensity on the surface was in the range of 142.75-166.01 Wm$^{-2}$ ($\lambda$=589, 665, 683 nm) (Figure 3). Similar to region A, the light propagation with depth in region B, blue wavelengths propagated deeper than green and purple wavelengths, while the red wavelengths propagated the least. Within the red wavelengths, it seemed that more light loss in region B (intermediate) than in region A (case-1 waters).

Water column at region C (case-2/inshore waters) are influenced by the number of river inputs such as the Mississippi River, Mobile River, Escambia River, Chogtawhatce River, Apalachicola River, Suwannee River, and several other small rivers. River water discharge sends a large amount of nutrients enhancing primary productivity and secondary productivity which affect light absorption [27, 28]. This water conditions can be categorized as a case-2 waters that causes a sharper decrease in the $E_d$ value compared to the decrease in the $E_d$ value at locations that contain little nutrients such as Location A (case-1/offshore waters).

At region C (case-2/inshore waters), light propagation propagation for all wavelength spectrums were similar to the light propagation at region A (case-1/offshore and intermediate waters). However, the loss of light with depth in region C (case-2/inshore waters) was higher than in region A (case-1/offshore waters) and region B (intermediate waters) at all wavelength spectrums (Figure 4). The water characteristics in region C (case-2/inshore waters) which contains relatively high organic matters, phytoplankton, particulates, and microscopic organisms that are able to absorb and scatter large amounts of light at various wavelengths can limit light transmission to only a few meters [6, 30, 31].

### 3.2. The depth at one optical depth

One optical depth is the depth of the water column where the amount of incident light ($E_d$) is only found 37% of the amount of light on the surface water. Up to this depth (from surface to one optical depth), the ocean color satellite sensor can detect signals coming out of the water column. Thus, the deeper the one optical depth, the more information obtained by the satellite and indicates the clearer the water column [32].

The study showed that in general the shallowest one optical depths was found at the red wavelength, increasing at the green wavelength, and the maximum (deepest) at the blue wavelength then decreasing again at the purple wavelength (Figure 5). The result was consistent with the nature of water which absorbs light the most at the red wavelength and the least at the blue wavelength.

The values of one optical depth at the red wavelengths (665 and 685 nm) in all three water types (case-1/offshore, intermediate, case-2/inshore) were within similar range i.e., 1.72-2.35 m (Figure 5). These results indicated that the absorption and scattering at the red wavelengths up to one optical depth did not give significantly different values.

The value of one optical depth at green wavelengths (490, 510, 532, and 555 nm) was higher in case-1/offshore waters (11.54-24.65 m), decreased in intermediate waters (11.76-19.89 m), and the lowest in case-2/inshore waters (9.31-14.32 m) (Figure 5). The lowest value of one optical depth in case-2/inshore waters was caused by the relatively high concentration of particulate elements (phytoplankton and detritus) and organic matter (color dissolved organic matter and other organic matters) in case-2/inshore waters compared to intermediate and case-1/offshore waters.

The higher values of one optical depth were found in blue wavelengths (443, 455, and 475 nm) compared to other red, gree, and purple wavelength spectrum. For case-1/offshore waters, the range values of one optical depth was 25.37-39.79 m, for intermediate waters with a range of 17.55-31.28 m,
and for case-2/inshore waters with the range of 6.65-16.08 m (Figure 5). The results showed the nature of water that absorbs little light at blue wavelengths so that it can penetrate deeper. Particulates and other organic matters which cause more absorption and scattering and are relatively more commonly found in case-2/inshore waters compared to case-1/offshore waters and intermediate waters produce the value of one optical depth become smaller in case-2/inshore waters.

According to [33] a low optical depth value in a water indicated that these waters were coastal waters classified as case-2, while a deeper optical depth value indicated that the waters were clearer and classified into case-1 waters.

Figure 3. The pattern of light propagation at region B (transition between case-1 and case-2 waters) at stations 8, 11, and 15.
Figure 4. The pattern of light propagation at region C (case-2 waters) at stations 3, 4, 7, and 12.

For purple wavelengths (380 and 412 nm), the values of one optical depth were generally higher in case-1 waters, then decreases in intermediate waters, and the lowest found in case-2 waters (Figure 5).
3.3. Attenuation coefficient ($K_d$) and its correlation with model results

The attenuation coefficient values ($K_d$) based on region and wavelength was presented in Figure 6. At region A (case-1/offshore waters), the $K_d$ values in the purple wavelength spectrum ($\lambda=380$ and 412 nm) had a range of 0.03-0.06 m$^{-1}$. For the blue wavelength spectrum ($\lambda=443$, 455, and 475 nm), in general, the $K_d$ values were almost similar but slightly lower than the range of $K_d$ values in the purple wavelength spectrum i.e., 0.02-0.04 m$^{-1}$. Then, the $K_d$ value increased in the green wavelength spectrum ($\lambda=490$, 510, 532, and 555 nm) with the range of 0.02-0.08 m$^{-1}$. The value of $K_d$ in this green wavelength spectrum seemed to increase with increasing the wavelength. In general, the value of $K_d$ in the purple, blue, and green wavelength spectrums showed no significantly different from one station to another. Furthermore, the $K_d$ values increased significantly in the yellow-red wavelength spectrum ($\lambda=589$, 665, and 683) with the range of 0.14-0.68 m$^{-1}$ (Figure 6, top right). The maximum $K_d$ value was obtained in the red wavelength spectrum ($K_d(683)=0.68$ m$^{-1}$) at station 1 and there was a significant difference in $K_d$ values between stations in this region (Figure 6, upper right). Station 1 (near to the Mississippi river plume) had the highest $K_d$ value compared to other stations due to the large number of suspended particles and organic matter originating from the Mississippi river inflow compared to other stations in this region (Figure 6, top right).

In the intermediate waters (middle part of Figure 6), the $K_d$ values for the purple wavelength spectrum ($\lambda=380$ and 412 nm) were in the range of 0.04-0.08 m$^{-1}$. Then the $K_d$ value decreased for the blue
Figure 6. The distribution pattern of the attenuation coefficient ($K_d$) values in the purple, blue, green, and red wavelength spectrums in region A (case-1/offshore waters), region B (intermediate waters), and region C (case-2/inshore waters).
wavelength spectrums ($\lambda = 443, 455, \text{ and } 475 \text{ nm})$ with a range of 0.03-0.05 m$^{-1}$, while in the green wavelength spectrums ($\lambda = 490, 510, 532, \text{ and } 555 \text{ nm}$) the $K_d$ value increased slightly with a range of 0.03-0.08 m$^{-1}$. The distribution pattern of $K_d$ in the purple-blue-green wavelength spectrums in intermediate waters was generally the same as the distribution pattern of $K_d$ values in case-1 waters. Furthermore, the value of $K_d$ in the red wavelength spectrums ($\lambda = 589, 665, 683 \text{ nm}$) increased sharply in the range of 0.14-0.59 m$^{-1}$. The range of $K_d$ values in intermediate waters was slightly lower than the range of $K_d$ values in case-1 waters.

For case-2 waters (bottom Figure 6), the $K_d$ values in the purple wavelength spectrums ($\lambda = 380 \text{ and } 412 \text{ nm}$) were in the range of 0.10-0.35 m$^{-1}$. Then the values of $K_d$ decreased in the blue wavelength spectrums ($\lambda = 443, 455, \text{ and } 475 \text{ nm}$) and green wavelength spectrums ($\lambda = 490, 510, 532, \text{ and } 555 \text{ nm}$) with a range of 0.06-0.12 m$^{-1}$. Then there was a significant increased in the red wavelength spectrums ($\lambda = 589, 665, \text{ and } 683 \text{ nm}$) with a range of 0.10-0.58 m$^{-1}$ (Figure 6).

Overall, the $K_d$ values in the purple wavelength spectrums were slightly higher than the $K_d$ values in the blue and green wavelength spectrums. This occurred because the purple wavelength spectrums were more easily absorbed by the content of color dissolved organic matter (CDOM) and other organic matters compared to the blue wavelength spectrums [34] The maximum value of $K_d$ found in the red wavelength spectrums was due to the nature of seawater absorbing maximum at red wavelengths [1, 2, 35].

The study results indicated that the $K_d$ values in case-2/inshore waters were generally higher than the $K_d$ value in intermediate and case-1/offshore waters, except for the red wavelength spectrums at station 1 (close to the Mississippi River fresh water inflow). The higher $K_d$ value in case-2/inshore waters compared to intermediate and case-1/offshore waters was due to the content of suspended particles, organic matter, phytoplankton, and detritus in case-2/inshore waters was higher than in intermediate and case-1/offshore waters [3, 5, 11, 25].

The $K_d$ values calculated from field data were then compared with the $K_d$ values from empirical modeling with the value of water leaving radiance [21], remote sensing reflectance [9, 28, 29], and chlorophyll-a concentration [20] showed a good correlation values ($r = 0.83-0.84$) with a coefficient determination values ($R^2 = 0.68-0.71$) (Figure 7). The smallest correlation value ($r = 0.83$) was obtained from the results of [21] while the best correlation values were generated from modeling of [9, 20, 36] each with a value of $R^2=0.71$ (Figure 7).

The lowest coefficient determination ($R^2$) was found using [21] model. This happened because the algorithm developed by [21] worked better on case-1 waters or clear waters. According to [5] in the Chesapeake Bay, empirical algorithm generated by NASA using $R_s (490)/R_s (555)$ worked better in clear sea waters and decreased in coastal areas and cloudy waters. According to [21] in China’s coastal waters using the empirical algorithm produced an $R^2$ value of 0.52. Then the value of $R^2$ increased in the algorithm developed by [30]. This algorithm was an algorithm produced by NASA which carried out further development by [21, 29] algorithms.

According to [37] in the East Sea of England, $K_d (490)$ based on [30] and [20] models resulted an inaccurate $K_d (490)$ value in turbid waters. This also happened in the study of [33] stated that the [29] and [20] algorithms produced a more accurate $K_d (490)$ value in clear waters (offshore), but in general these algorithms failed to provide an accurate estimate for $K_d (490)$ in turbid waters as happened in the waters of the NEGOM, Arabian Sea, and Baltic Sea.

In Figure 7, it can be seen that the highest $R^2$ value was obtained from the estimated $K_d (490)$ generated by the [9] algorithm. [9] conducted research in the Red Sea, and made an algorithm that was suitable for the Red Sea, which was slightly different from other water conditions. The Red Sea contained higher Colored Dissolved Organic Matter (CDOM), high aerosol dust counts, and low chlorophyll content [38, 39, 40]. The characteristics of the Red Sea indicated that the resulting algorithm was suitable for coastal waters, where coastal waters also contain a lot of CDOM from river water discharge, so it was not surprising that this algorithm produced an estimated value of $K_d (490)$ which was more accurate than the other four algorithms.
Figure 7. Comparison of the in situ $K_d(490)$ (m$^{-1}$) values with the estimated $K_d(490)$ calculated using five empirical algorithms.
4. Conclusions
The light propagation patterns generally decreased with increasing depth and the patterns were almost similar for case-1, intermediate, and case-2 waters. The most reduction in light intensity with depth was found in the red wavelength, less in the green and purple wavelengths, and the lowest in the blue wavelength. The reduction in light intensity based on depth was greater in the case-2 water column compared to the intermediate and case-1 waters.

In general, the lowest $K_d$ values were found at the blue wavelength, slightly increased at the purple and green wavelengths, and the highest at the red wavelengths in both case-1, intermediate, and case-2 waters. Based on the water type, the values of $K_d (490)$ were generally higher in case-2 waters compared to intermediate and case-1 waters. The increase in $K_d (490)$ values in case-2 waters was influenced by the amount of organic matter, particulate, phytoplankton, detritus, and color dissolved organic matter content that absorbs and scatters light.

The depth at one optical depth in case-1 waters was found at the deepest of 39.79 m ($\lambda=475$ nm), in intermediate water at the deepest of 31.28 m ($\lambda=475$ nm), and case-2 water at the deepest of 14.32 m ($\lambda=475$ nm). In general, the observed $K_d (490)$ had a very good correlation with the modeled $K_d (490)$ values with correlation and determination coefficients of $r=0.83$-$0.84$ and $R^2=0.68$-$0.71$, respectively.

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