

Article

Spectral Response of Remote Sensing Reflectance to Variation in CDOM, Phytoplankton, and Mineral Particles in Baltic Waters

Henryk Toczek , Kamila Haule  and Włodzimierz Freda 

Department of Physics, Gdynia Maritime University, 81-225 Gdynia, Poland; k.haule@wm.umg.edu.pl (K.H.); w.freda@wm.umg.edu.pl (W.F.)

* Correspondence: h.toczek@wm.umg.edu.pl

Highlights

What are the main findings?

- A spectral response function (SRF) was introduced to quantify the response of R_{rs} to relative changes in CDOM, chlorophyll-*a*, and mineral particles.
- The applied spectral response function reveals that mineral particles have a secondary but condition-dependent influence on R_{rs} , primarily through scattering processes.

What are the implications of the main findings?

- The results highlight limitations of single-band and band-ratio algorithms in optically complex Baltic waters, where multiple constituents simultaneously affect the signal.
- The proposed spectral response framework provides a quantitative basis for improving bio-optical models and remote sensing algorithms for Case 2 waters.

Abstract

Remote sensing reflectance (R_{rs}) in optically complex waters is controlled by the combined effects of phytoplankton, colored dissolved organic matter (CDOM), and suspended mineral particles. In the Baltic Sea, strong CDOM absorption and variable particle loads complicate the interpretation of ocean color signals and the retrieval of biogeochemical properties. In this study, we investigate the individual and combined influence of these optically significant constituents on R_{rs} using a set of HydroLight radiative transfer simulations representing typical Baltic Sea conditions. A wide range of chlorophyll-*a* ($0.25\text{--}10\text{ mg}\cdot\text{m}^{-3}$), CDOM absorption ($0.5\text{--}15\text{ m}^{-1}$), and particulate inorganic matter ($0.04\text{--}4\text{ g}\cdot\text{m}^{-3}$) was considered. To quantify the influence of each component, a spectral response function was applied, defined as the change in R_{rs} relative to a normalized perturbation of each input parameter. This approach preserves information about the magnitude of the reflectance signal and allows direct comparison of the impact of different constituents across the visible spectrum. The spectral response analysis reveals that the relative influence of each constituent varies with wavelength and environmental conditions, highlighting the limitations of single-band or ratio-based algorithms in optically complex waters. These findings provide a quantitative framework for interpreting spectral variability of R_{rs} in the Baltic Sea and other optically complex water basins, support the development of more robust bio-optical algorithms for Case 2 waters. Similar spectral response analysis can be conducted in other water basins in order to quantify combined constituent-specific effects on R_{rs} .



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Keywords: remote sensing reflectance; optically complex waters; coastal waters; phytoplankton; chlorophyll-*a*; mineral particles; particulate inorganic matter; color dissolved organic matter; Baltic Sea

1. Introduction

The Baltic Sea is one of the world's largest semi-enclosed brackish water bodies and provides numerous ecosystem services that support the economies of the surrounding countries. Its coastal and marine ecosystems sustain fisheries, maritime transport, tourism, recreation, and other economic activities while contributing to nutrient cycling, carbon sequestration, and biodiversity conservation [1,2]. At the same time, the Baltic Sea is subject to substantial anthropogenic pressure, including eutrophication, pollution, and climate-driven environmental changes, making continuous environmental monitoring a key requirement for sustainable management of the region [3].

Monitoring the distribution and variability of seawater constituents, such as phytoplankton pigments, colored dissolved organic matter (CDOM), and suspended particulate matter, is essential for assessing ecosystem status and understanding biogeochemical processes in the Baltic Sea [4]. These constituents directly influence water quality, primary productivity, and light penetration and serve as indicators of eutrophication and other environmental changes [5,6]. However, the Baltic Sea is optically complex due to strong spatial gradients in salinity, high terrestrial inputs of organic matter, and independently varying concentrations of phytoplankton, CDOM, and suspended particles, which complicate both in situ and satellite-based observations [7].

Satellite ocean-color remote sensing offers an effective means of monitoring seawater constituents across large spatial scales and with high temporal frequency. Recent advances in sensors such as Sentinel-3 OLCI have improved the capability to retrieve chlorophyll-*a* (Chl-*a*), CDOM, and suspended matter concentrations in Baltic waters, enabling long-term assessments of ecosystem dynamics and supporting environmental management initiatives [8,9]. Consequently, the development and validation of robust remote sensing approaches for the Baltic Sea remain important research priorities for both scientific understanding and operational monitoring of this environmentally and socio-economically significant marine ecosystem.

The absorption coefficient, together with the volume scattering function, defines the inherent optical properties (IOPs) of a water body. IOPs can be measured in situ or in the laboratory, providing local and temporal information on seawater composition and quality. Total absorption and scattering coefficients in seawater are the sums of the corresponding coefficients for each optically significant component [10]:

$$a(\lambda) = a_w(\lambda) + a_{chl}(\lambda) + a_{CDOM}(\lambda) + a_{PIM}(\lambda), \quad (1)$$

$$b(\lambda) = b_w(\lambda) + b_{chl}(\lambda) + b_{PIM}(\lambda), \quad (2)$$

where $a_w(\lambda)$ is the absorption of pure water, $a_{chl}(\lambda)$ is the absorption of Chl-*a* (the organic fraction of total suspended particulate matter), $a_{CDOM}(\lambda)$ is the absorption of CDOM, and $a_{PIM}(\lambda)$ is the absorption of particulate inorganic matter (PIM). Correspondingly, $b_w(\lambda)$, $b_{chl}(\lambda)$, and $b_{PIM}(\lambda)$ are the scattering coefficients of pure water, Chl-*a*, and mineral particles.

In contrast, apparent optical properties (AOPs) are derived from measurements of downwelling and upwelling light intensity obtained using remote techniques—from space, offshore platforms, optical buoys, or sensors deployed directly in the water [11].

In ocean optics, remote sensing reflectance (R_{rs}) is a key quantity used to interpret the color of the ocean and to retrieve the concentrations of individual seawater components from satellite or airborne sensors. It provides a normalized measure of water-leaving radiance and is defined as [10]

$$R_{rs}(\lambda) = \frac{L_w(\lambda)}{E_d(\lambda)} \quad (3)$$

where $L_w(\lambda)$ is the water-leaving radiance ($\text{W} \cdot \text{m}^{-2} \cdot \text{sr}^{-1}$) and $E_d(\lambda)$ is the downwelling irradiance ($\text{W} \cdot \text{m}^{-2}$). In open-ocean waters, the spectrum of R_{rs} is primarily shaped by Chl-*a* concentration and co-varying CDOM [12]. In coastal waters, estuaries, and inland seas, the relationship between R_{rs} and the concentrations of individual components becomes more complex, driven by local interrelationships. Nevertheless, R_{rs} plays a critical role in coastal water observation for environmental, ecological, and human-activity-related purposes. The spectral variability of R_{rs} carries information about seawater component concentrations, but the effects of multiple components often overlap. Understanding the potential influence of each component on water-leaving light is therefore essential for correctly interpreting R_{rs} data. Therefore, there is a need to establish multi-band and multi-band ratio relationships between R_{rs} and component concentrations. This is particularly important in coastal and optically complex waters, where global algorithms and models have limited applicability, and the use of inappropriate models can lead to misinterpretation of results. Most previous studies have focused on empirical relationships between selected R_{rs} band ratios and individual water constituents, such as chlorophyll-*a*, colored dissolved organic matter (CDOM), or suspended mineral particles [4,13–15]. While these approaches have proven useful for the development of constituent-specific retrieval algorithms, there remains a lack of methods capable of quantifying the relative spectral response of R_{rs} to simultaneous changes in multiple optically significant constituents. This limitation is particularly important in optically complex waters, where phytoplankton, CDOM, and mineral particles coexist and interact to shape the observed reflectance spectrum [10,16].

To address this gap, we analyzed a set of unbiased R_{rs} spectra generated through radiative transfer modeling using representative ranges of IOPs measured in the Baltic Sea. The aim of this study is to identify and discuss the spectral features of R_{rs} associated with variations in CDOM, phytoplankton, and mineral particle concentrations, with particular emphasis on the optically complex environment of the Baltic Sea. Although the influence of optically significant constituents on remote sensing reflectance has been extensively investigated, relatively few studies have quantitatively characterized these relationships specifically for Baltic Sea waters, which are distinguished by high CDOM concentrations, strong seasonal variability, and large spatial gradients in constituent composition [7,13,14,17]. One important knowledge gap is the absence of a comprehensive framework for identifying spectral regions that remain sensitive to a given constituent under varying concentrations of other coexisting constituents.

To overcome this limitation, we propose the use of the spectral response function (SRF) as a measure of the sensitivity of R_{rs} to relative changes in CDOM, Chl-*a*, and mineral particles. Previous studies have investigated sensor-specific spectral response functions (also referred to as relative spectral response functions) and their influence on ocean-color products, sensor intercomparisons, and R_{rs} retrievals [18–21]. However, these investigations have primarily focused on sensor characteristics and global ocean-color applications rather than on the spectral response of R_{rs} to variations in water constituents, particularly in the Baltic Sea. Analogous to the use of sensor response functions for cross-sensor harmonization, the SRF proposed here can be applied to radiative transfer modeling datasets to identify wavelength regions that are most sensitive to phytoplankton, CDOM, and mineral particles while explicitly accounting for their simultaneous occurrence in varying propor-

tions. Such information may support the development, optimization, and interpretation of bio-optical algorithms by linking spectral sensitivity directly to constituent concentrations.

The objectives of this study are:

- To assess the individual and combined influence of phytoplankton, CDOM, and mineral particles on remote sensing reflectance within concentration ranges representative of optically complex Baltic Sea waters, using radiative transfer modeling.
- To provide a quantitative and convenient measure of the spectral sensitivity of R_{rs} to optically significant constituents under Baltic Sea conditions and in similar coastal and inland waters.

2. Materials and Methods

2.1. Study Site

The Baltic Sea is a very atypical water basin, with limited water exchange with the North Sea and a high riverine freshwater input, resulting in very low surface salinity of about 7 PSU. It is a semi-enclosed sea with one of the highest transport intensities in the world, making it particularly susceptible to long-term pollution and the cumulative effects of excessive nutrient inputs [22]. The Baltic Sea is relatively shallow, with an average depth of about 55 m, and 86% of its area is shallower than 100 m [23]. The euphotic zone in the Baltic Sea ranges from 1 to 5 m in estuaries and small gulfs to about 13 m in the Baltic Proper, reaching up to 22 m in the largest Bothnian Bay and Bothnian Sea [24].

From an optical perspective, the Baltic Sea is a complex water basin classified as Case 2 waters [25]. Its inherent optical properties are primarily shaped by three types of components: phytoplankton, colored dissolved organic matter (CDOM), and suspended mineral particles. Phytoplankton, typically characterized by the concentration of its main pigment, chlorophyll-*a* (Chl-*a*), exhibits strong seasonal variability, with maxima during spring and summer blooms. Chl-*a* concentrations typically range from 0.1 mg·m⁻³ in the winter season in deeper areas to 15 mg·m⁻³ in gulfs and estuaries (see Table 1) [26]. Average Chl-*a* concentrations tend to increase over the years due to persistent eutrophication [27], and spring and summer blooms are becoming more frequent and prolonged [28].

Table 1. Typical ranges * of optical parameters in different regions of the Baltic Sea [24,26,29].

Baltic Sea Area Type	Chl- <i>a</i> Winter mg·m ⁻³	Chl- <i>a</i> Summer mg·m ⁻³	$a_{CDOM}(440)$ m ⁻¹	PIM g·m ⁻³
Deep waters (northern part)	0.1–0.2	0.5	1–3	0.4–9
Baltic Proper	0.25	3	0.2–0.5	0.04–0.35
Small gulfs (shallow coastal waters)	0.3–0.7	5–10	3–5	0.2–2.5
Estuaries	1–5	10–15	10–15	1–20

* Temporal higher values are not included in this summary.

Baltic Sea waters are characterized by a relatively high content of CDOM, which dominates the process of light absorption. The absorption coefficient spectrum of CDOM decreases exponentially across the ultraviolet-visible range. It is characterized by the absorption at a reference wavelength, $a_{CDOM}(\lambda_0)$, where λ_0 is usually 440 nm, and by the slope of the exponential curve, γ . Values of $a_{CDOM}(\lambda_0)$ typically range from 0.25 m⁻¹ in open Baltic waters to 5 m⁻¹ in coastal waters and up to 15 m⁻¹ in turbid estuaries. The slope γ has been reported to vary between 0.007 and 0.036 with a median of 0.018–0.020 [29,30].

At the same time, large riverine inflows make coastal Baltic waters rich in suspended particulate matter (SPM) of inorganic origin. The inorganic part of the total SPM is often

referred to as PIM—particulate inorganic matter. Mineral particles primarily affect light scattering, contributing to the total scattering coefficient and altering the directional distribution of scattering, as described by the volume scattering function. Particle scattering and backscattering coefficients are spectrally described by power-law functions. Typical concentrations of mineral particles in the Baltic Sea range from $0.04 \text{ mg} \cdot \text{m}^{-3}$ in open waters to several $\text{g} \cdot \text{m}^{-3}$ in coastal areas [26,29].

2.2. Radiative Transfer Simulations

In the present study, we selected a typical range of inherent optical properties for the Baltic Sea and then used the HydroLight numerical model (Numerical Optics Ltd., Devon, UK) to compute remote sensing reflectance. The HydroLight software 6.0 version solves the radiative transfer equation (RTE) using a direct solution based on the invariant embedding method developed by Mobley [10]. The RTE is a differential–integral equation that describes changes in the directional distribution of radiance with depth in water. In the case of horizontally homogeneous water, the time-independent RTE is given as follows [10]:

$$\cos \theta \frac{dL(z, \theta, \phi, \lambda)}{dz} = -[a(z, \lambda) + b(z, \lambda)]L(z, \theta, \phi, \lambda) + b(z, \lambda) \int_0^{2\pi} \int_0^\pi L(z, \theta', \phi', \lambda) \tilde{\beta}(z, \theta', \phi' \rightarrow \theta, \phi, \lambda) \sin \theta' d\theta' d\phi' + S(z, \theta, \phi, \lambda), \quad (4)$$

where $L(z, \theta, \phi, \lambda)$ is the directional and spectral radiance at depth z ; $a(z, \lambda)$ and $b(z, \lambda)$ are the total absorption and scattering coefficients at depth z ; $\tilde{\beta}$ is the phase function of the volume scattering function, and the scattering angle in $\tilde{\beta}$ is defined as the angle between the incident light direction (θ, ϕ) and the scattered direction (θ', ϕ') . The source function $S(z, \theta, \phi, \lambda)$ is usually considered to represent inelastically scattered light at other wavelengths (by chlorophyll-bearing particles and CDOM) or an internal light source such as bioluminescence.

Figure 1 shows a schematic block diagram of the HydroLight radiative transfer model applied in this study. All simulations were conducted using the same air–water and seabed boundary conditions in order to compare specific features of R_{rs} shaped solely by seawater components.

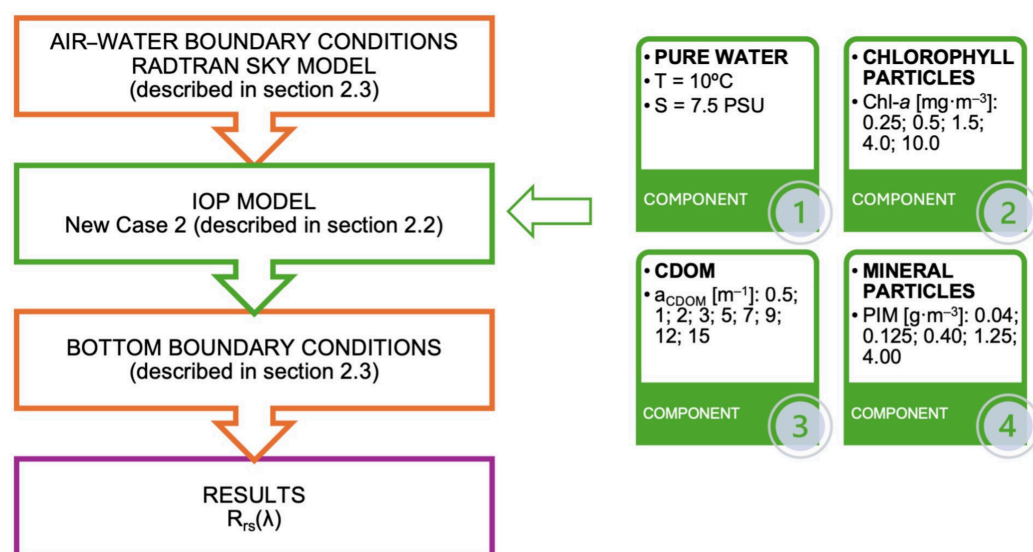


Figure 1. Block diagram of the applied radiative transfer model from HydroLight software. Elements framed in orange are constant in all simulations; elements framed in green are variable.

2.3. Bio-Optical Model of the Baltic Sea

In this study, we customized the New Case 2 IOPs model suitable for optically complex waters. The model consists of four components: pure water, chlorophyll-bearing particles, CDOM, and mineral particles.

Pure water. Optical properties of pure seawater were computed as functions of the water temperature (T) and salinity (s) after Röttgers et al. [31] and Zhang et al. [32], using T = 10 °C (most typical of the spring–summer season, when measurements are conducted) and s = 7.5 PSU (average for the Baltic Proper) [33].

Chlorophyll-dependent components. Chlorophyll-*a* concentration was assumed to be constant with depth and varied from 0.25 mg·m^{−3} to 10 mg·m^{−3}, based on typical values measured in the Baltic Sea and included in datasets from Woźniak et al. [29] and Kratzer and Moore [26]. All IOPs were determined as functions of Chl-*a* concentration, using combined data from Morrison and Nelson [34] and Bricaud et al. [35] for absorption coefficients, and from Morel et al. [36] for scattering coefficients and phase functions:

$$a_{chl}(\lambda) = A(\lambda) \cdot C_{chl-a}^{E(\lambda)} \quad (5)$$

$$b_{chl-a}(\lambda) = b_0(C_{chl-a})^n \cdot \left(\frac{\lambda}{550}\right)^v, \quad (6)$$

where $A(\lambda)$ and $E(\lambda)$ are experimentally derived coefficients over a large dataset from Bricaud et al. [33]; while $b_0(C_{chl-a})$, n , and v are experimentally derived parameters by Morel et al. [36] applied in the HydroLight model. Technically, the model separates small- and large-particle phase functions, and the fraction of their contribution is determined by chlorophyll concentration. Medium UV absorption was assumed.

CDOM. The absorption of CDOM decreases exponentially with wavelength according to Mobley and Sundman [37]:

$$a_{CDOM}(\lambda) = a_{CDOM}(\lambda_0)e^{-\gamma(\lambda-\lambda_0)}, \quad (7)$$

where $a_{CDOM}(\lambda_0)$ is the CDOM absorption at the reference wavelength $\lambda_0 = 440$ nm, expressed in m^{−1}, and γ is the slope of the exponential decay. The range of $a_{CDOM}(440)$ values varied from 0.5 m^{−1} (typical for open Baltic Sea waters) to 15 m^{−1} (characteristic of turbid estuarine waters). For all simulations, we assumed the same representative Baltic Sea value of the slope, $\gamma = 0.018$, following Kratzer and Moore [26].

Regarding mineral particles, the concentration of mineral particles was assumed to be constant with depth and ranged from 0.04 g·m^{−3} (minimum values for open Baltic waters) to 4 g·m^{−3}, representing typical maximum concentrations of particulate inorganic matter observed in bays during the spring season [26]. The absorption coefficient of PIM was described by an exponential decay function [37]:

$$a_{PIM}(\lambda) = C \cdot a_{PIM}^*(\lambda_0)e^{-S(\lambda-\lambda_0)}, \quad (8)$$

where C is the PIM concentration in g·m^{−3}; $a_{PIM}^*(\lambda_0)$ is the mass-specific absorption coefficient at the reference wavelength $\lambda_0 = 400$ nm, expressed in m²·g^{−1}; and S is the slope of the exponential decay. The value of $a_{PIM}^*(400)$ was set to 0.09189 m²·g^{−1} following Woźniak et al. [38], and the slope $S = 0.011$ after Bowers et al. [39] and Babin et al. [40].

The scattering coefficient of PIM was described by a power-law function of the wavelength [37]:

$$b_{PIM}(\lambda) = C \cdot b_{PIM}^*(\lambda_0) \cdot \left(\frac{\lambda_0}{\lambda}\right)^m, \quad (9)$$

where $b_{PIM}^*(\lambda_0)$ is the mass-specific scattering coefficient of PIM at the reference wavelength $\lambda_0 = 550$ nm, expressed in $\text{m}^2 \cdot \text{g}^{-1}$, and m is the spectral exponent. Typical values of m in the Baltic Sea range between -1 and 1 . In this study, the values $b_{PIM}^*(550) = 0.016 \text{ m}^2 \cdot \text{g}^{-1}$ and $m = 1$ were selected as most representative, following Woźniak et al. [38].

The scattering phase function for PIM was described using a Fournier–Forand function, parameterized by the ratio of the backscattering coefficient $b_{b,PIM}$ to the total scattering coefficient b_{PIM} [40]. For pure inorganic particles, the ratio $b_{b,PIM}/b_{PIM}$ has been shown to be nearly wavelength-independent in the visible range (0.022–0.024) based on long-term Baltic Sea observations [38]; therefore, a constant value of 0.023 was assumed.

Figure 2 presents the scheme of the modeling series conducted for 25 combinations of five mineral particle concentrations (M1–M5) and five Chl-*a* concentrations (C1–C5). Corresponding values of $a_{CDOM}(440)$ were selected to represent realistic Baltic Sea conditions: lower CDOM absorption values, associated with low CDOM concentrations, are typical of open Baltic waters characterized by low Chl-*a* and low PIM concentrations, whereas higher concentrations of Chl-*a* and PIM correspond to higher CDOM levels. This controlled selection of parameters allowed us to analyze specific spectral features of remote sensing reflectance attributable to individual seawater components.

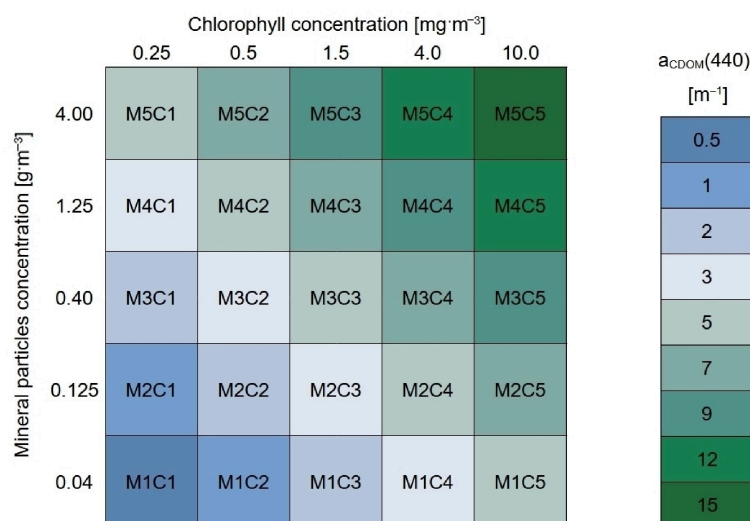


Figure 2. Scheme of the HydroLight modeling series conducted for 25 combinations of five mineral particle concentrations, marked as M1–M5 in the rows, and five Chl-*a* concentrations, marked as C1–C5 in the columns. Corresponding values of $a_{CDOM}(440)$ are displayed using color shades and explained by the color bar.

2.4. Boundary Conditions

Simulations were performed using a set of representative boundary conditions for the Baltic Sea. All boundary conditions were kept constant in order to isolate the effects of individual seawater components on remote sensing reflectance.

The air–water interface was modeled using an azimuthally isotropic Cox–Munk wave slope distribution, parameterized by a wind speed of $5 \text{ m} \cdot \text{s}^{-1}$. The wavelength-dependent refractive index of seawater was computed for a temperature of $T = 10$ °C and salinity $s = 7.5$ PSU, following the empirical formulation of Quan and Fry [41]. The direct and diffuse components of downwelling irradiance were calculated using the RADTRAN-X sky model included in HydroLight. The sky model parameters were set to a solar zenith angle of 30° and 30% cloud cover in open waters above Gdansk Bay (55.0N; 19.0E). Default values were applied for most RADTRAN-X parameters, with the exception of sea-level pressure (101,325 kPa) and airmass type (type five was assumed in this study).

All simulations included the effects of inelastic scattering, namely Chl-*a* fluorescence, CDOM fluorescence, and Raman scattering by water. The depth of the water column was assumed to be infinite, which is a common approximation for optically complex and turbid waters such as the Baltic Sea. Due to relatively high concentrations of CDOM, phytoplankton, and mineral particles, light penetration in the Baltic Sea is strongly limited and typically does not reach the seabed. The depth of the euphotic zone in the Baltic Sea generally ranges from 1 to 5 m in estuaries and coastal gulfs to approximately 10–15 m in the Baltic Proper, reaching up to about 20–25 m in the Bothnian Sea and Bothnian Bay [22,24,25]. In contrast, the average bottom depth of the Baltic Sea is substantially greater. As a result, the euphotic zone occupies only the upper 10–30% of the water column in most regions (and up to ~50% in the Bothnian Bay), leaving the seabed permanently aphotic.

2.5. Spectral Response Function of R_{rs}

Simulations of R_{rs} enable a quantitative assessment of the impact of individual seawater constituents on the reflected signal. To compare the influence of Chl-*a*, colored dissolved organic matter (CDOM), and particulate inorganic matter (PIM), a spectral response function (SRF) was defined and evaluated across the visible spectrum.

The SRF is expressed as

$$SRF(\lambda) = \frac{\Delta R_{rs}(\lambda)}{\Delta X/X}, \quad (10)$$

where $R_{rs}(\lambda)$ is the remote sensing reflectance at wavelength λ , and X is the input parameter (Chl-*a* concentration, a_{CDOM} or PIM concentration), the fraction $\Delta X/X$ is the relative change in the input parameter, while $\Delta R_{rs}(\lambda)$ represents the corresponding absolute change in reflectance.

In practice, the relative perturbation of the input parameter was defined using a symmetric (centered) formulation:

$$\frac{\Delta X}{X} = \frac{x_i - x_j}{(x_i + x_j)/2} \quad (11)$$

where x_i and x_j denote two arbitrary values of the parameter within the considered range. The SRF was evaluated for all pairwise combinations of parameter values, allowing the response of $R_{rs}(\lambda)$ to be assessed across the full range of variability rather than only for local perturbations. Accordingly, the SRF was computed as

$$SRF(\lambda) = \left| \frac{R_{rs}(\lambda, x_i) - R_{rs}(\lambda, x_j)}{\frac{x_i - x_j}{(x_i + x_j)/2}} \right| \quad (12)$$

This formulation corresponds to a centered finite-difference approximation and provides a numerically stable estimate of the response across the full range of parameter variability. The SRF represents the absolute change in R_{rs} in response to a relative perturbation of the input parameter and therefore retains the same units as R_{rs} (sr^{-1}).

Unlike dimensionless sensitivity metrics, the SRF preserves information about the magnitude of the reflectance signal, which is essential for remote sensing applications. In the limit of small perturbations, this formulation converges to $X \cdot \frac{dR_{rs}}{dX}$, providing a physically consistent measure of the response of R_{rs} to changes in optically significant constituents.

3. Results

The modeling results of global variation in all three parameters are presented in Figure 3. It shows 25 remote sensing reflectance spectra generated using the HydroLight

modeling software for 25 different parameter sets. The modeled scenarios varied in the concentration of PIM (five levels, shown in the rows of Figure 2), phytoplankton (represented by five levels of Chl-*a* concentration, shown in the columns of Figure 2), and CDOM, represented by nine different values of absorption at 440 nm, $a_{CDOM}(440)$ (see color scale in Figure 2).

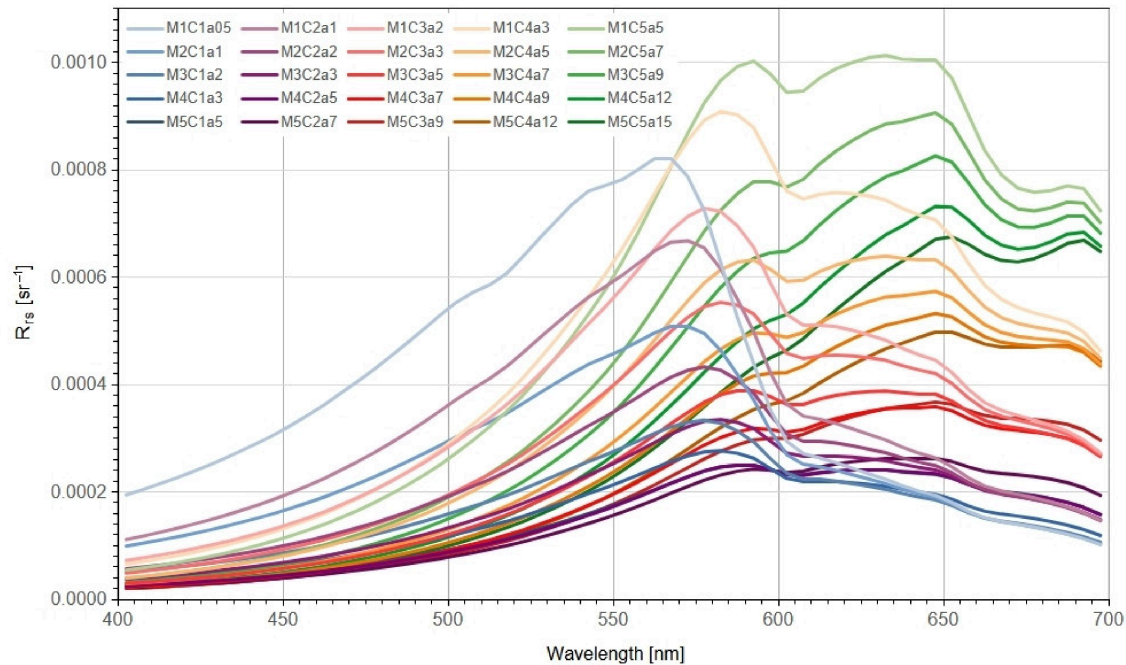


Figure 3. Summary of 25 remote sensing reflectance (R_{rs}) spectra obtained for different parameter sets of PIM concentration, Chl-*a* concentration, and CDOM absorption. The variation in these parameters is summarized in Figure 1.

Despite the inclusion of 25 spectra in a single figure (Figure 3), the use of distinct line colors and brightness levels allows several clear patterns to be identified. In the central part of the spectrum, the maximum R_{rs} values correspond to scenarios characterized by the lowest concentrations of mineral suspended particles, which are also associated with low CDOM levels. At shorter wavelengths (400–565 nm), the highest R_{rs} is observed for the M1C1a05 scenario, representing the lowest concentrations of CDOM, PIM, and Chl-*a*. At wavelengths above 570 nm, R_{rs} is dominated by the M1C5a5 scenario, which is characterized by minimal PIM concentration but the highest Chl-*a* concentration.

Spectra associated with high concentrations of mineral particles and Chl-*a* generally exhibit the lowest R_{rs} values in the short- and mid-wavelength ranges. In the red spectral region, above 620 nm, a clear stratification and ordering of the spectra emerge, primarily driven by differences in Chl-*a* concentration.

The highest R_{rs} values in the red spectral bands are associated with waters characterized by the highest Chl-*a* concentration (symbol C5), whereas the lowest R_{rs} values correspond to waters with the lowest Chl-*a* concentration (symbol C1). At wavelengths above 655 nm, the spectra become completely separated and grouped according to chlorophyll concentration. With increasing wavelength, the influence of the other parameters—namely, the PIM concentration and CDOM—progressively decreases, and their effect on the shape of the R_{rs} spectra becomes negligible.

The compilation of 25 spectra shown in Figure 3 motivated a more detailed analysis of the influence of individual (one-at-a-time) seawater components on the shape of R_{rs} spectra. Three additional local modeling series were conducted in order to isolate and highlight specific spectral features of R_{rs} associated with individual seawater components, as summarized in Table 2:

- Effect of PIM. The influence of particulate inorganic matter was analyzed under two representative conditions: a typical Baltic Proper scenario (fixed $\text{Chl-}a = 0.25 \text{ mg}\cdot\text{m}^{-3}$ and $a_{\text{CDOM}} = 1 \text{ m}^{-1}$) and a typical gulf scenario (fixed $\text{Chl-}a = 4 \text{ mg}\cdot\text{m}^{-3}$ and $a_{\text{CDOM}} = 7 \text{ m}^{-1}$).
- Effect of $\text{Chl-}a$. The influence of $\text{Chl-}a$ was examined for a typical Baltic Proper scenario (fixed $\text{PIM} = 0.04 \text{ g}\cdot\text{m}^{-3}$ and $a_{\text{CDOM}} = 1 \text{ m}^{-1}$) and for a typical gulf scenario (fixed $\text{PIM} = 4 \text{ g}\cdot\text{m}^{-3}$ and $a_{\text{CDOM}} = 7 \text{ m}^{-1}$).
- Effect of CDOM. The influence of CDOM was also analyzed under four scenarios: (i) low $\text{PIM} = 0.04 \text{ g}\cdot\text{m}^{-3}$ and low $\text{Chl-}a = 0.25 \text{ mg}\cdot\text{m}^{-3}$, representing typical Baltic Proper values; (ii) high $\text{PIM} = 4 \text{ g}\cdot\text{m}^{-3}$ and low $\text{Chl-}a = 0.25 \text{ mg}\cdot\text{m}^{-3}$, representing gulf waters without an active phytoplankton bloom; (iii) low $\text{PIM} = 0.04 \text{ g}\cdot\text{m}^{-3}$ and high $\text{Chl-}a = 4 \text{ mg}\cdot\text{m}^{-3}$, representing open Baltic waters during a phytoplankton bloom; and (iv) high $\text{PIM} = 4 \text{ g}\cdot\text{m}^{-3}$ and high $\text{Chl-}a = 4 \text{ mg}\cdot\text{m}^{-3}$, representing typical gulf values during a bloom.

Table 2. Parameters of the additional modeling series representing the most typical Baltic Sea scenarios, conducted to analyze the influence of individual seawater components on the shape of R_{rs} spectra.

Scenario	PIM, $\text{g}\cdot\text{m}^{-3}$	Chl- a , $\text{mg}\cdot\text{m}^{-3}$	a_{CDOM} , m^{-1}	Figure
Baltic Proper scenario	variable	0.25	1	Figure 4a
	0.04	variable	1	Figure 5a
	0.04	0.25	variable	Figure 6a
	0.04	4	variable	Figure 6c
Typical gulfs and bays scenario	variable	4	7	Figure 4b
	4	variable	7	Figure 5b
	4	0.25	variable	Figure 6b
	4	4	variable	Figure 6d

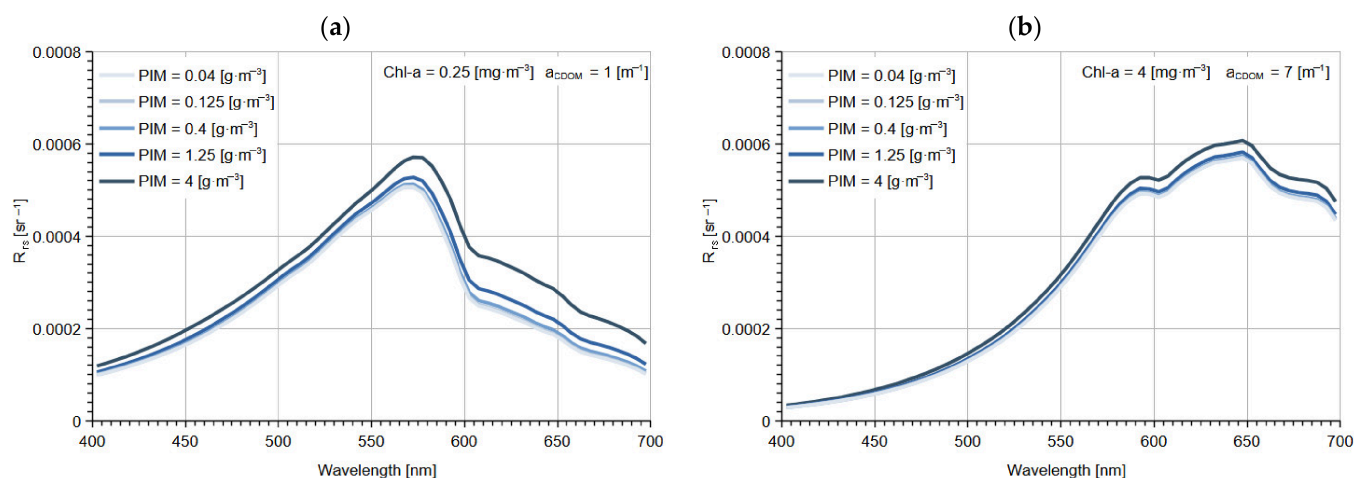


Figure 4. Effect of suspended mineral particles concentration on R_{rs} for (a) low $\text{Chl-}a$ and low CDOM concentrations representing a typical Baltic Proper scenario, and (b) for high $\text{Chl-}a$ and CDOM concentrations, representing a typical gulf scenario.

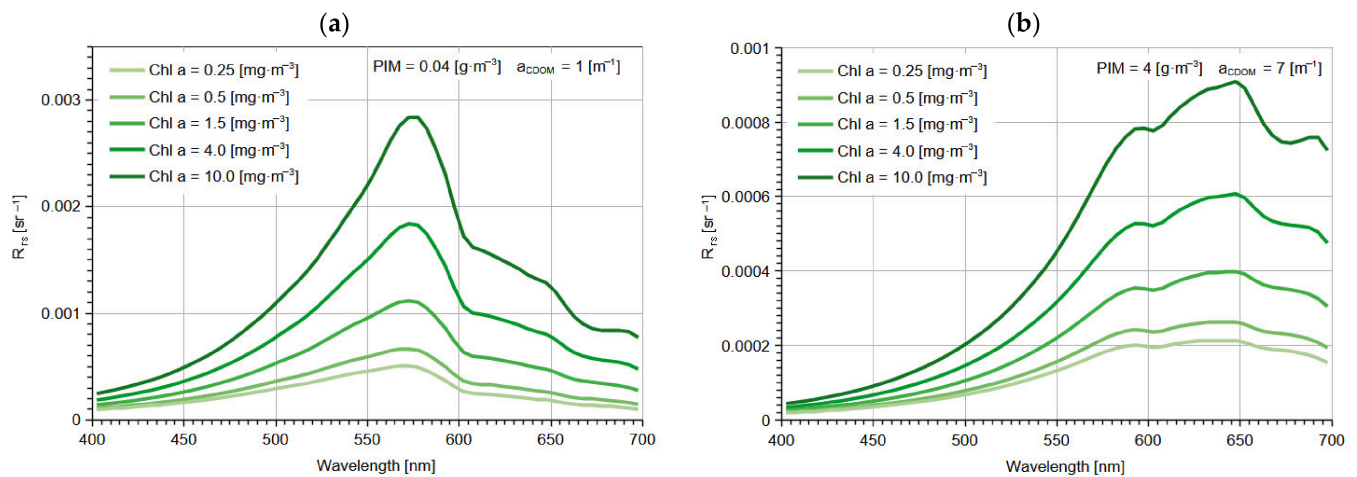


Figure 5. Effect of Chl-*a* concentration on R_{rs} for (a) low PIM and CDOM concentrations, representing typical Baltic Proper conditions, and for (b) high PIM and CDOM concentrations, representing typical Gulf water conditions.

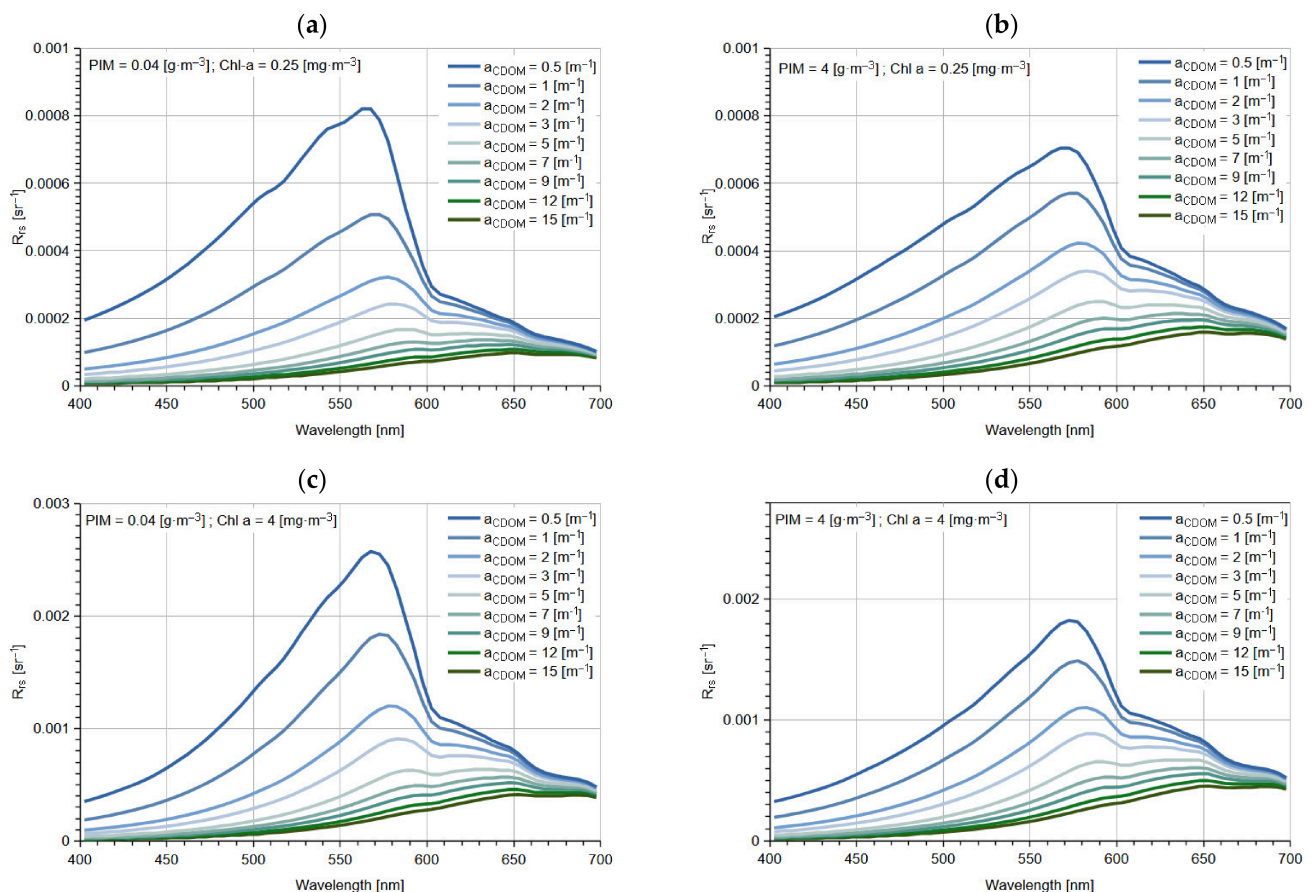


Figure 6. Influence of CDOM concentration, indicated by increasing a_{CDOM} , on R_{rs} for four representative scenarios: (a) low PIM and low Chl-*a*, typical open Baltic waters; (b) high PIM and low Chl-*a*, gulf waters without an active phytoplankton bloom; (c) low PIM and high Chl-*a*, open Baltic waters during a phytoplankton bloom; and (d) high PIM and high Chl-*a*, gulf waters with an active phytoplankton bloom.

The analyses presented in the following sections focus on the effect of variations in the concentration of only one of the three optically significant seawater components at a time.

3.1. Influence of Mineral Particles on R_{rs} Spectra

Results presented in Figure 4 illustrate the influence of mineral particles on R_{rs} . Simulations were performed for five PIM concentrations—0.04, 0.125, 0.4, 1.25, and $4 \text{ g}\cdot\text{m}^{-3}$ —while all other parameters were held constant. The highest PIM concentration is two orders of magnitude greater than the lowest.

Figure 4a shows R_{rs} spectra for low Chl-*a* concentration and low CDOM absorption ($a_{\text{CDOM}}(440) = 1 \text{ m}^{-1}$), while Figure 4b presents results for elevated Chl-*a* concentration ($4 \text{ mg}\cdot\text{m}^{-3}$) and higher CDOM absorption ($a_{\text{CDOM}}(440) = 7 \text{ m}^{-1}$). Under low Chl-*a* and CDOM conditions, representing a typical Baltic Proper scenario, the R_{rs} spectra exhibit a characteristic shape, with low values at short and long wavelengths and a pronounced maximum in the green spectral region around 570–575 nm. Across all PIM concentrations, peak R_{rs} values are only about five times higher than the minimum values at the spectral edges. The highest reflectance corresponds to the largest PIM concentration, and the lowest to the smallest. The relative difference in R_{rs} between these two cases varies spectrally, reaching approximately 20% in the blue region, about 9% in the 525–550 nm range, and up to 66% in the red region.

In contrast, Figure 4b, representing a typical gulf scenario in the Baltic Sea, demonstrates R_{rs} variability under elevated phytoplankton and CDOM concentrations, where spectral differences are much more pronounced. Maximum R_{rs} values, observed near 645–650 nm, exceed the minimum values by nearly a factor of 20. Despite a 100-fold difference in PIM concentration, its influence on the spectral shape is minor. Although the highest R_{rs} values still correspond to the largest PIM concentration, the overall spectral form remains nearly unchanged. A comparison between PIM concentrations of 0.04 and $4 \text{ g}\cdot\text{m}^{-3}$ shows that R_{rs} increases by only ~17% at short wavelengths (400–450 nm), ~7% in the 580–660 nm range, and ~9% at longer wavelengths (680–700 nm).

Comparing R_{rs} spectra for waters with low Chl-*a* and CDOM (Figure 4a) and those with high concentrations of both components (Figure 4b) reveals a characteristic spectral shift. Elevated Chl-*a* and CDOM result in increased R_{rs} in the red spectral region ($>600 \text{ nm}$), similar values in the central part of the spectrum, and reduced R_{rs} at shorter wavelengths. While variations in PIM concentration have a relatively moderate effect on R_{rs} magnitude and shape, phytoplankton—represented by Chl-*a*—is expected to introduce substantially greater spectral variability. This influence is examined in the following subsection under fixed CDOM and PIM conditions.

3.2. Influence of Chlorophyll on R_{rs} Spectra

Figure 5 presents simulations conducted for five Chl-*a* concentrations representing, for example, the development of a phytoplankton bloom. The concentrations selected for modeling (corresponding to the columns in Figure 2) were 0.25, 0.5, 1.5, 4, and $10 \text{ mg}\cdot\text{m}^{-3}$, spanning a 40-fold range between the lowest and highest values.

The simulations were first performed for low and fixed concentrations of particulate inorganic matter ($\text{PIM} = 0.04 \text{ g}\cdot\text{m}^{-3}$) and CDOM ($a_{\text{CDOM}}(440) = 1 \text{ m}^{-1}$) (Figure 5a). The modeling was then repeated for high and fixed values of both parameters, namely $\text{PIM} = 4 \text{ g}\cdot\text{m}^{-3}$ and $a_{\text{CDOM}}(440) = 7 \text{ m}^{-1}$ (Figure 5b). In both scenarios, the highest R_{rs} values correspond to the highest Chl-*a* concentration.

For low PIM and low CDOM conditions, representing typical bloom development conditions in the Baltic Proper, the spectral shape of R_{rs} remains similar across all chlorophyll concentrations, with maxima consistently occurring in the 570–580 nm range. Under high PIM and high CDOM conditions, representing typical bloom development conditions in gulfs, the position of the R_{rs} maximum shifts toward longer wavelengths, occurring near 640–650 nm.

A comparison between spectra obtained for the lowest and highest Chl-*a* concentrations indicates that a 40-fold increase in Chl-*a* results in a 1.5-fold increase in R_{rs} at the shortest wavelengths (~400 nm), a 4.5-fold increase in the vicinity of the spectral maximum (570–580 nm), and approximately a 6.5-fold increase at the longest wavelengths near 700 nm.

3.3. Influence of CDOM on R_{rs} Spectra

In the last step, the influence of CDOM was analyzed under four representative scenarios:

- Low PIM and low Chl-*a* concentrations (Figure 6a), representing typical open Baltic waters without an active phytoplankton bloom;
- High PIM and low Chl-*a* concentrations (Figure 6b), representing gulf waters in the Baltic Sea without an active phytoplankton bloom;
- Low PIM and high Chl-*a* concentrations (Figure 6c), representing open Baltic waters during a phytoplankton bloom;
- High PIM and high Chl-*a* concentrations (Figure 6d) representing gulf waters with an active phytoplankton bloom.

In all scenarios, the highest R_{rs} values occurred at the lowest CDOM content, corresponding to an absorption coefficient $a_{CDOM}(440) = 0.5 \text{ m}^{-1}$, whereas the lowest R_{rs} values were observed at the highest CDOM absorption ($a_{CDOM}(440) = 15 \text{ m}^{-1}$). A comparison across the four scenarios indicates that the largest absolute R_{rs} values are associated with low PIM concentrations combined with high Chl-*a* levels, as illustrated in Figure 6c. For low CDOM concentrations, the R_{rs} spectrum exhibits a single dominant maximum at approximately 570–580 nm. As CDOM concentration increases, this maximum progressively decreases in magnitude and shifts toward longer wavelengths. Simultaneously, additional maxima emerge in the red spectral region (650–680 nm) and become dominant across the spectrum at the highest CDOM levels.

The presence of mineral particles can either increase or decrease R_{rs} values, depending on the Chl-*a* and CDOM concentrations. Under conditions of low Chl-*a* and low CDOM, high PIM concentrations reduce the absolute R_{rs} values; however, this effect reverses at $a_{CDOM} \geq 1 \text{ m}^{-1}$, where higher PIM concentrations lead to increased R_{rs} compared to low-PIM conditions. In contrast, under high Chl-*a* conditions, the R_{rs} -damping effect of PIM persists up to $a_{CDOM} \leq 3 \text{ m}^{-1}$, indicating that the backscattering contribution of mineral particles becomes apparent only at higher CDOM levels. In the following subsection, we discuss the obtained modeling results in the context of recent Baltic Sea research.

4. Discussion

4.1. Variability of Blue-to-Green R_{rs} Ratios in Relation to Chl-*a*, CDOM, and PIM Concentrations in the Baltic Sea: Overview Based on Global Variability 25 Simulated Spectra

Many bio-optical models are based on correlations between blue-to-green remote sensing reflectance ratios and Chl-*a* concentration. The most commonly applied ratios are $R_{rs}(443)/R_{rs}(560)$ and $R_{rs}(490)/R_{rs}(560)$ [16,42,43]. In this study, we analyzed the same band ratios calculated from HydroLight modeling results (with input parameters shown in Figure 2 and summarized results presented in Figure 3) to demonstrate the potential range of influence of three optically significant components in the Baltic Sea: chlorophyll-bearing particles (phytoplankton), colored dissolved organic matter (CDOM), and mineral particles. In Case 1 waters, these ratios are primarily used to retrieve Chl-*a* concentration [44], whereas in optically complex Case 2 waters, they act as indicators of the combined concentrations of light-absorbing and light-scattering constituents [45,46]. In general, lower ratio values correspond to higher concentrations of optically significant seawater components.

The $R_{rs}(443)/R_{rs}(560)$ ratio is sensitive to both Chl-*a* and CDOM concentrations; however, in CDOM-rich waters, the influence of CDOM absorption, together with enhanced mineral backscattering, can dominate the signal. Consequently, in Baltic Sea bio-optical algorithms, this ratio is most often used to characterize CDOM concentration [9] or to separate CDOM and phytoplankton contributions [47]. By contrast, the $R_{rs}(490)/R_{rs}(560)$ ratio is less sensitive to CDOM absorption while remaining highly responsive to Chl-*a* concentration, which makes it more suitable for application in turbid waters [26,48].

Because the relationship between blue-to-green R_{rs} ratios and Chl-*a* concentration exhibits a hyperbolic-like shape, the correlations are presented in Figure 7 as functions of the inverse chlorophyll concentration. The ratio $R_{rs}(443)/R_{rs}(560)$ illustrated in Figure 7a starts from a common value of approximately 0.14 at the highest Chl-*a* concentration of $10 \text{ mg} \cdot \text{m}^{-3}$ under conditions of relatively high CDOM and variable PIM concentrations, which is consistent with typical eutrophic optical conditions (e.g., [49–51]). Regardless of the variability in PIM and a_{CDOM} , the $R_{rs}(443)/R_{rs}(560)$ ratio in this case remains within a narrow range of 0.140–0.143. With decreasing Chl-*a* concentration, the blue-to-green R_{rs} ratio increases, reaching a maximum value of 0.360 for waters characterized by the lowest concentrations of Chl-*a*, CDOM, and PIM. High Chl-*a* combined with high CDOM concentrations dominates the value of this ratio, while the influence of mineral particles is negligible, which is typical for optically complex waters [52].

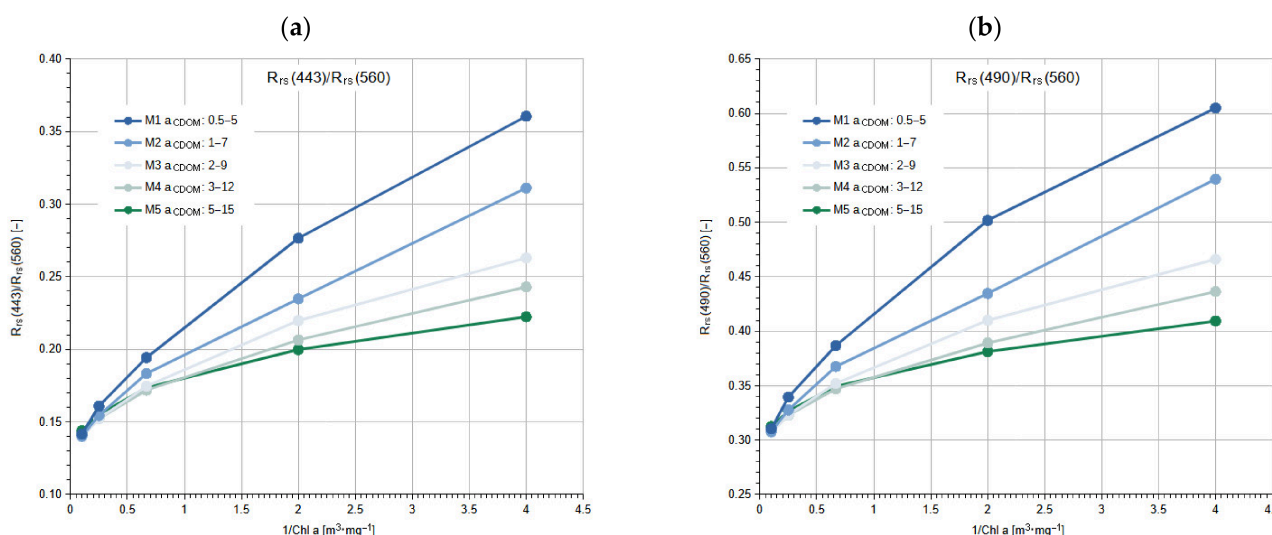


Figure 7. Blue-to-green R_{rs} ratios plotted against the inverse of Chl-*a* concentration: (a) $R_{rs}(443)/R_{rs}(560)$ and (b) $R_{rs}(490)/R_{rs}(560)$.

The $R_{rs}(490)/R_{rs}(560)$ ratio exhibits a similar relationship (Figure 7b). At the highest Chl-*a* concentration, the ratio is approximately 0.310, varying only slightly between 0.307 and 0.312. As Chl-*a* concentration decreases, the ratio increases, reaching a maximum value of 0.605 for waters with the lowest CDOM and PIM concentrations; again, PIM has a negligible effect on this ratio. The values of $R_{rs}(490)/R_{rs}(560)$ are approximately 50% higher than those of $R_{rs}(443)/R_{rs}(560)$, which makes the former more suitable for ocean color retrievals, as previously concluded by Darecki and Stramski [53] and Kowalczyk et al. [30]. Moreover, Woźniak and Meller [54] also emphasize the need for “locally calibrated” bio-optical algorithms in the Baltic Sea, based on a set of HydroLight simulations. They demonstrate the applicability of the ratio of $R_{rs}(490)/R_{rs}(625)$ to retrieve the total SPM concentration.

Due to the overlapping effects of phytoplankton and CDOM absorption in the blue spectral bands, a single R_{rs} ratio is rarely used alone in bio-optical algorithms for tur-

bid waters. Instead, it is commonly combined with absolute R_{rs} values in the red or near-infrared (NIR) spectral regions, their ratios, or normalized differences [54–56]. Accordingly, Figure 8 illustrates the range of $R_{rs}(665)$ values obtained for all 25 combinations of Chl-*a*, CDOM, and PIM concentrations representative of typical Baltic Sea scenarios. The highest $R_{rs}(665)$ values are associated with high Chl-*a* and low PIM concentrations. The contribution of CDOM to $R_{rs}(665)$ is explicitly visualized along the *x*-axis. Identical Chl-*a* concentrations are connected by green dashed lines, while extreme values of the same mineral particle concentrations are connected by blue dashed lines. An increase in CDOM concentration leads to an increase in $R_{rs}(665)$ only at low Chl-*a* levels (C1–C2, corresponding to 0.25–0.5 mg·m^{−3}). A similar pattern is observed for mineral particles, which increase absolute $R_{rs}(665)$ values only at comparably low Chl-*a* concentrations. At higher Chl-*a* concentrations, $R_{rs}(665)$ decreases with increasing CDOM and PIM. Overall, Chl-*a* exerts a much stronger effect on $R_{rs}(665)$ than either CDOM or mineral particles. $R_{rs}(665)$ increases significantly with Chl-*a* concentration, from approximately 0.00015–0.00020 sr^{−1} at 0.25 mg·m^{−3} to 0.00064–0.00081 sr^{−1} at 10 mg·m^{−3}, representing more than a five-fold increase in reflectance associated with a forty-fold increase in Chl-*a* concentration.

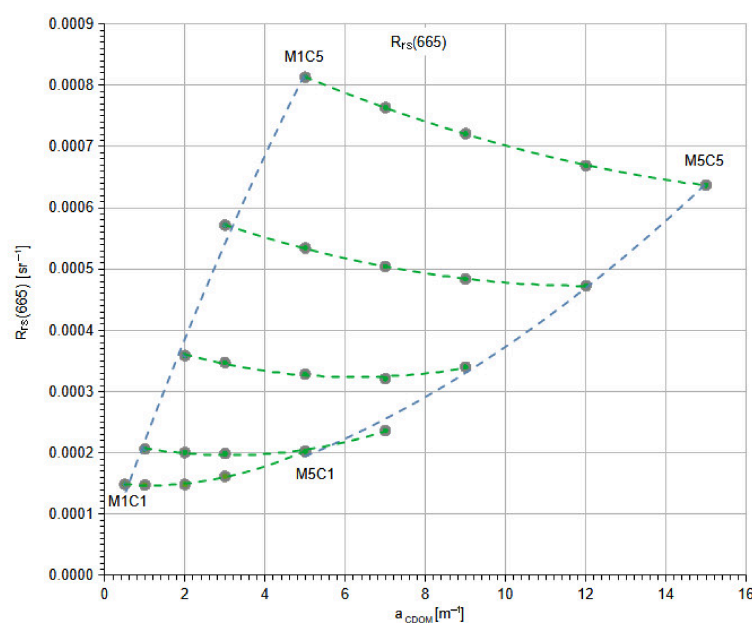


Figure 8. Remote sensing reflectance at 665 nm plotted against the CDOM absorption coefficient at 440 nm for 25 combinations of Chl-*a*, CDOM, and PIM concentrations representing typical Baltic Sea conditions. Green dashed lines connect points with fixed Chl-*a* concentrations (C1, . . . , C5) and varying PIM concentrations (M1–M5), while blue dashed lines connect the two extreme scenarios of fixed PIM concentrations (M1 and M5) and varying Chl-*a* concentrations (C1–C5).

Moreover, R_{rs} in the red and NIR spectral bands are closely related to turbidity. Dogliotti et al. [57] applied $R_{rs}(645)$ and $R_{rs}(859)$ in a semi-empirical, single-band algorithm and demonstrated that this approach is largely insensitive to variations in particle type, size, and composition. The use of the red band around 665 nm is particularly recommended for waters with low to moderate turbidity (approximately 1–10 NTU). Typical turbidity values in the Baltic Sea range from approximately 0.2–1 NTU in offshore waters to 1–5 NTU in most coastal areas and 5–20 NTU in estuaries [55,58,59]. Despite generally lower turbidity compared to sediment-dominated estuaries, Baltic Sea waters are optically complex due to strong CDOM absorption. Consequently, turbidity retrievals in this region rely primarily on red and NIR reflectance, including bands centered near 665 nm [57,60,61]. In this context, our results demonstrate that $R_{rs}(665)$, and by extension turbidity, in the Baltic Sea is strongly

influenced by scattering from both chlorophyll-bearing particles and mineral particles. At Chl-*a* concentrations below $1.5 \text{ mg} \cdot \text{m}^{-3}$, $R_{rs}(665)$ increases exponentially with increasing PIM concentration by approximately 10–33%, whereas above this chlorophyll threshold, $R_{rs}(665)$ decreases with increasing PIM by approximately 21–26%.

To isolate the contribution of mineral particles to individual R_{rs} spectral bands, Figure 9 presents the results for three wavelengths: (a) 443 nm, (b) 560 nm, and (c) 665 nm. The R_{rs} values are derived from the set of 25 HydroLight simulations shown in Figure 3 and are plotted as a function of PIM concentration. In all graphs, the results are displayed as five series distinguished by brightness, with the lightest color representing the lowest Chl-*a* concentration of 0.25 mg m^{-3} (the first column in Figure 2) and the darkest color corresponding to the highest Chl-*a* concentration of 10 mg m^{-3} (the last column in Figure 2). All three plots share the same vertical-axis scale to facilitate direct comparison.

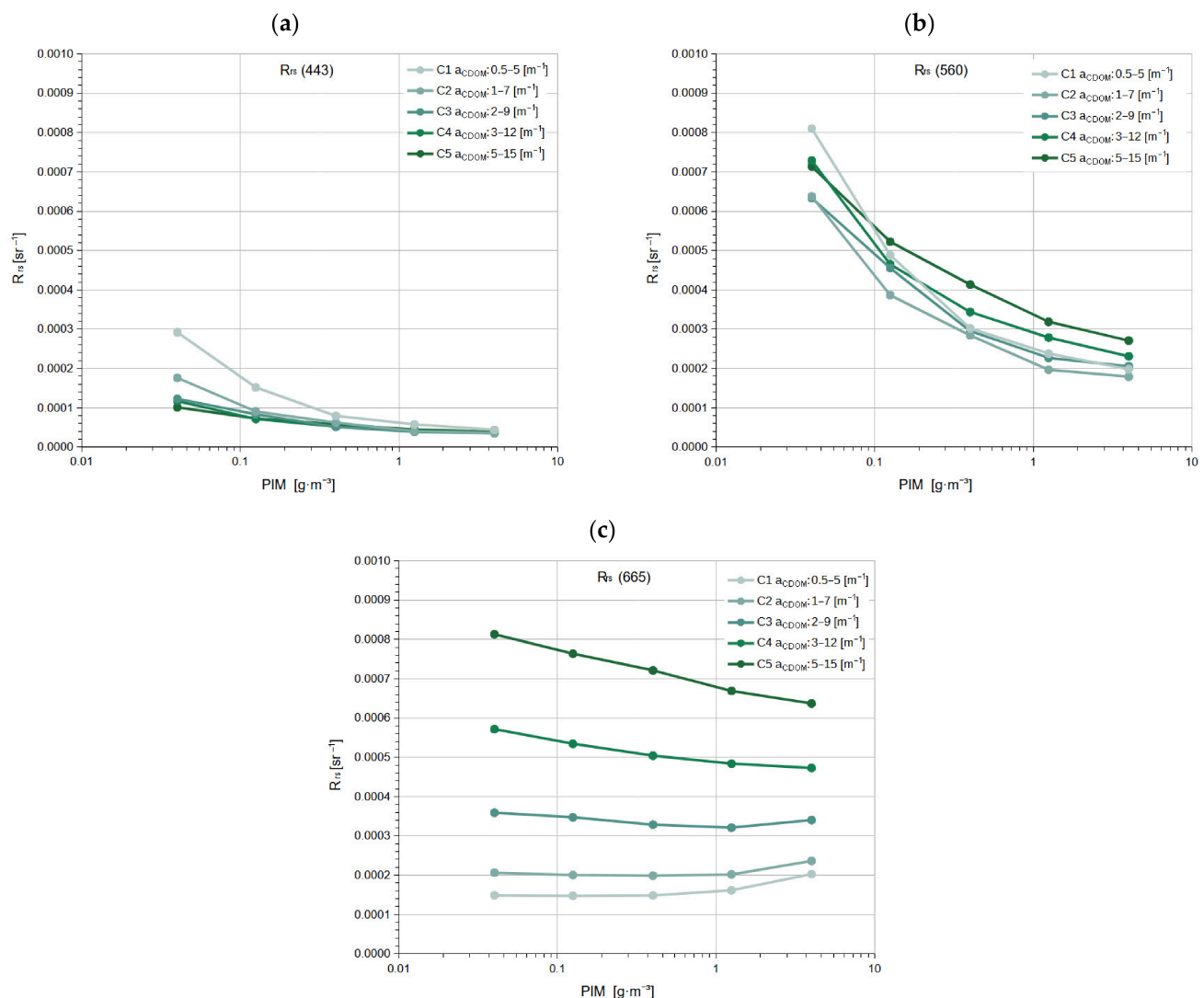


Figure 9. Remote sensing reflectance for spectral bands: (a) 443 nm, (b) 560 nm, and (c) 665 nm, plotted with PIM concentration.

Figure 9a demonstrates that at 443 nm, all R_{rs} values decrease with increasing PIM concentration. The highest $R_{rs}(443)$ values occur in waters characterized by the lowest PIM and the lowest Chl-*a* concentration, represented by the lightest-colored series. As PIM concentration increases, the influence of Chl-*a* concentration diminishes, and $R_{rs}(443)$ values converge toward similar levels across all series.

In Figure 9b, showing $R_{rs}(560)$, all reflectance values are higher than those observed at 443 nm. $R_{rs}(560)$ decreases markedly with increasing PIM concentration, by up to a factor of four for the C1 series representing the lowest Chl-*a* concentration. At the same time, a consistent ordering of $R_{rs}(560)$ values by Chl-*a* concentration cannot be identified across the full PIM range. At low PIM concentrations, the highest $R_{rs}(560)$ values are associated with the C1 series, whereas at high PIM concentrations, the highest $R_{rs}(560)$ values occur for the C5 series, corresponding to the highest Chl-*a* concentration.

Figure 9c, which presents $R_{rs}(665)$, reveals a distinctly different ordering of the series compared to the blue and green bands. For the highest Chl-*a* concentration (darkest lines and symbols), $R_{rs}(665)$ reaches the largest values and decreases monotonically with increasing PIM concentration. In contrast, for the lowest Chl-*a* concentration, $R_{rs}(665)$ values are substantially lower, by a factor of approximately three to five, and remain nearly constant over the PIM range from 0.04 to 0.4 g·m^{−3}. At higher PIM concentrations, $R_{rs}(665)$ increases for these low-Chl-*a* conditions. Similarly, Nechad et al. [62] concluded that the concentration of total suspended matter can be retrieved from R_{rs} at 665–750 nm with similar accuracy up to 30%, depending on the satellite sensor; this accuracy can be improved by using multi-band algorithms.

4.2. Scaled Spectral Sensitivity of R_{rs} to Optically Significant Constituents Under Baltic Sea Conditions

Finally, based on the extended local modeling series presented in Table 2, our results are synthesized in Figure 10. This figure summarizes the ranges of absolute R_{rs} values obtained for different combinations of three optically significant components in Baltic Sea waters. The ranges correspond to representative, typical (rather than extreme) low (L) and high (H) levels of the following constituents: chlorophyll-*a* (Chl-*a*; L = 0.25 mg·m^{−3}, H = 4 mg·m^{−3}), colored dissolved organic matter (CDOM; L corresponding to $a_{CDOM} = 1$ m^{−1} and H to $a_{CDOM} = 7$ m^{−1}), and particulate inorganic matter (PIM; L = 0.04 mg·m^{−3}, H = 4 mg·m^{−3}).

We compared R_{rs} at three spectral bands that are most characteristic of remote sensing of optically complex waters: 490 nm (blue band), 560 nm (green band), and 650 nm (red band). With increasing Chl-*a* concentration (Figure 10a), R_{rs} also increases, but at different rates. The most rapid increase occurs in the green band under low CDOM and PIM levels, whereas the slowest increase is observed in the blue band under high CDOM and PIM conditions. Notably, the lowest $R_{rs}(490)$ values obtained under low remaining parameters are comparable to the highest $R_{rs}(650)$ values obtained under high levels of those parameters. Figure 10b illustrates the range of the PIM effect on R_{rs} in different spectral bands under low and high levels of the remaining parameters. The most pronounced increase in R_{rs} is observed in the red band under low Chl-*a* and low CDOM conditions. In contrast, $R_{rs}(490)$ remains nearly constant under high Chl-*a* and high CDOM conditions. These results are consistent with Kratzer and Moore [26], who compared the typical Baltic optical properties to other seas and oceans, suggesting that the red/green R_{rs} ratio could be a better alternative to improve the quantitative retrieval of Chl-*a* from CDOM-dominated waters.

Whereas increasing concentrations of Chl-*a* and PIM lead to higher R_{rs} values across the visible spectrum, the effect of CDOM, illustrated in Figure 10c, is opposite: increasing CDOM concentrations reduce remote sensing reflectance. R_{rs} in the blue and green bands decrease at similar, approximately exponential rates with increasing CDOM under both low and high levels of the remaining parameters. The absolute values of $R_{rs}(490)$ under high PIM and high Chl-*a* conditions are comparable to those of $R_{rs}(560)$ under low PIM and low Chl-*a* conditions. In the red band, the effect of CDOM becomes nearly linear.

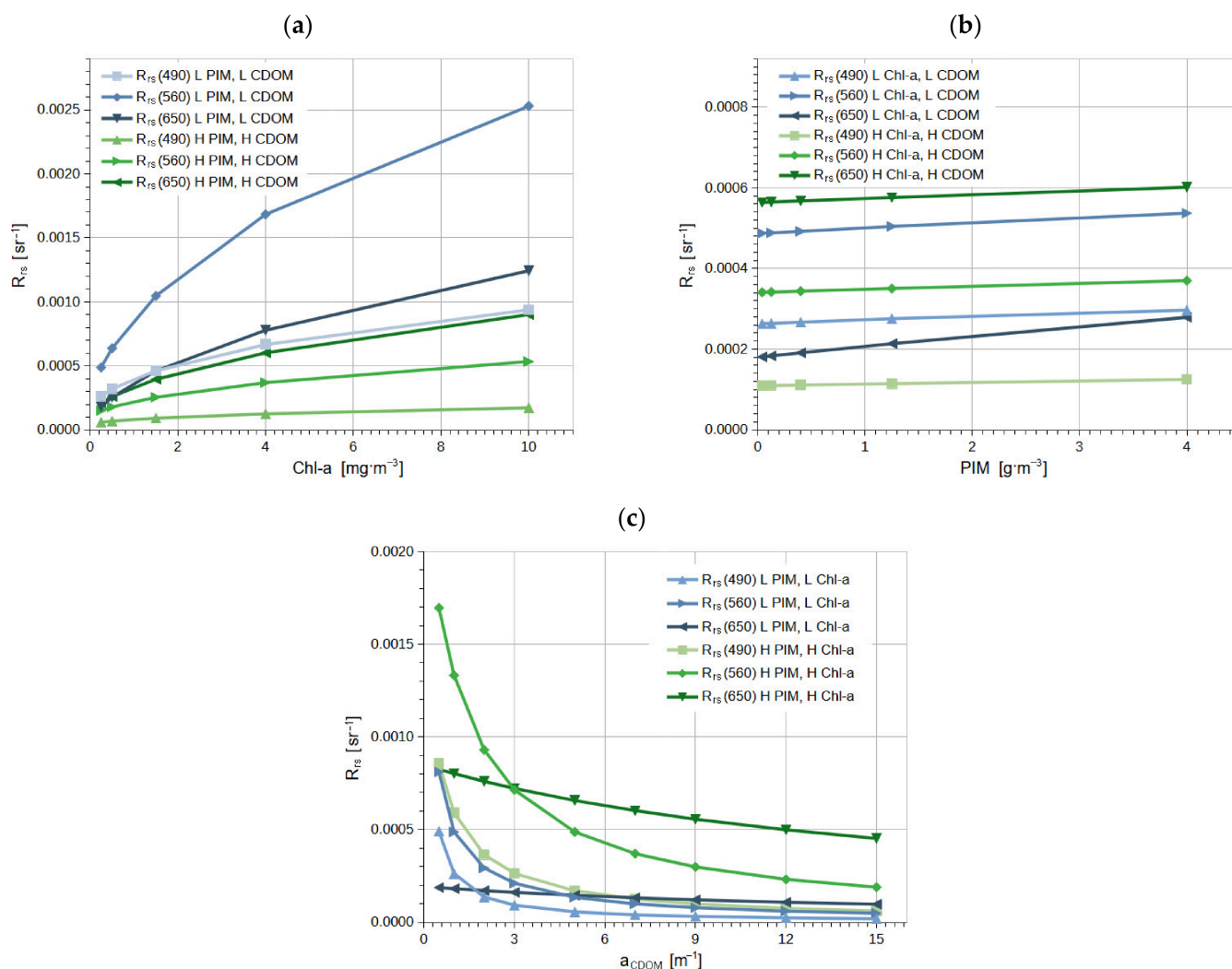


Figure 10. Summarized typical ranges of absolute R_{rs} values in three spectral bands (490 nm, 560 nm, and 650 nm) obtained for different combinations of Chl-*a*, PIM, and CDOM concentrations. Graphs show R_{rs} variability with increasing (a) Chl-*a*, (b) PIM, and (c) CDOM under low remaining parameters (blue lines) or high remaining parameters (green lines), with the following low (L) and high (H) levels: Chl-*a*: L = 0.25 mg·m⁻³, H = 4 mg·m⁻³; CDOM: L corresponding to a_{CDOM} = 1 m⁻¹ and H to a_{CDOM} = 7 m⁻¹, and PIM: L = 0.04 mg·m⁻³, H = 4 mg·m⁻³.

To complement the analysis presented above, the results were further interpreted in terms of the spectral response $SRF(\lambda)$, defined in Section 2.3 (Equation (8)). This formulation enables direct comparison of the influence of CDOM, phytoplankton, and mineral particles across the visible spectrum for all scenarios shown in Figures 4–6.

Analysis of the spectral distribution of $SRF(\lambda)$, together with its maxima $SRF_{max}(\lambda)$ and corresponding wavelengths λ_{max} , allows identification of spectral regions where R_{rs} is most responsive to each constituent under representative Baltic Sea conditions. Distinct patterns emerge for each component, reflecting the different roles of absorption and scattering processes (Figure 11). The figure presents only the maximum values of $SRF(\lambda)$ and their associated wavelengths, although full spectra were evaluated for all considered variations in the input parameter X .

The horizontal axis of the figure represents the central wavelengths of the spectral bands. It can be observed that the highest values of $SRF_{max}(\lambda)$, occur when CDOM absorption is the varying parameter, particularly under conditions of low PIM concentration (0.04 g m⁻³) and high Chl-*a* concentration (4 mg m⁻³). Under these conditions, $SRF_{max}(\lambda)$,

reaches its maximum in the central part of the spectrum, corresponding to the spectral bands at approximately 560–570 nm, and is associated with variations at the lowest CDOM absorption level ($a_{CDOM} = 0.5 \text{ m}^{-1}$).

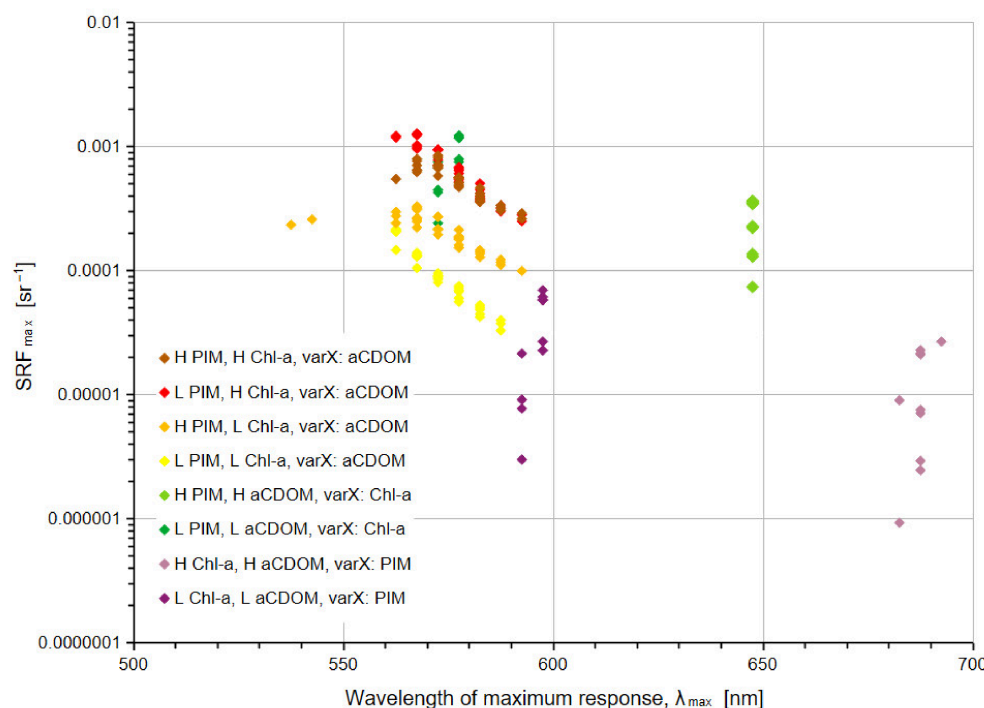


Figure 11. Maximum of the spectral response function, $SRF_{max}(\lambda)$ for variables X (CDOM absorption, Chl-*a* concentration, and particulate inorganic matter—PIM), plotted against the wavelengths (λ_{max}) at which these maxima occur. Each point represents the maximum SRF value identified from the full spectral response.

Similarly high spectral responses are observed for variability in Chl-*a* concentration under conditions of low a_{CDOM} and low PIM concentrations (green points in Figure 11). In this case, the maximum occurs at slightly longer wavelengths, around the 575–580 nm spectral band. The highest $SRF_{max}(\lambda)$ values are observed for the largest Chl-*a* concentrations ($4\text{--}10 \text{ mg m}^{-3}$).

The majority of $SRF_{max}(\lambda)$ values occur within the spectral range of approximately 560–600 nm. Variations in CDOM absorption lead to maxima distributed over a relatively broad spectral range. In contrast, variability in Chl-*a* and PIM exhibits a more constrained behavior: depending on the values of the remaining parameters, the maxima occupy one, two, or three adjacent spectral bands.

For example, variability in Chl-*a* under conditions of high CDOM absorption and high PIM concentration results in maximum spectral responses confined to a single spectral band at 645–650 nm. The lowest values of $SRF_{max}(\lambda)$ are observed for variability in PIM concentration. Under conditions of low Chl-*a* and low CDOM absorption, $SRF_{max}(\lambda)$ ranges from 3×10^{-6} to 7×10^{-5} , with maxima spanning two spectral bands between 590 and 600 nm. Even lower values of $SRF_{max}(\lambda)$ are obtained for PIM variability under conditions of high CDOM absorption and high Chl-*a* concentration. In this case, $SRF_{max}(\lambda)$ ranges from 9×10^{-7} to 3×10^{-5} , and the maxima extend across three spectral bands between 680 and 695 nm.

The spectral patterns obtained in this study are generally consistent with previous observations showing that CDOM is the dominant absorber in Baltic Sea waters and strongly affects the blue part of the R_{rs} spectrum, whereas chlorophyll-*a* exerts the strongest control over reflectance in the red and red-edge regions (e.g., Darecki and Stramski [53],

Kowalczyk et al. [30], Kratzer and Moore [26]). However, most previous studies were focused on empirical relationships between selected band ratios and individual water constituents, while the present work quantifies the relative spectral response of R_{rs} to simultaneous changes in CDOM, phytoplankton, and mineral particles across a broad range of realistic Baltic Sea conditions.

A key difference from earlier studies is that the proposed spectral response function (SRF) allows the magnitude of constituent-specific effects to be compared directly on a common scale. The results demonstrate that CDOM dominates spectral variability below approximately 550 nm, whereas chlorophyll-*a* becomes the principal driver of variability in the red spectral region. In contrast, mineral particles have a secondary but non-negligible influence that depends strongly on the optical background conditions. This finding extends previous Baltic Sea studies, which often treated suspended particles mainly as a source of additional scattering, by showing that their contribution becomes significant only under specific combinations of CDOM and phytoplankton concentrations.

The comparison with previous research, therefore, provides a new understanding of the spectral partitioning of constituent effects in optically complex Case 2 waters. Rather than identifying only spectral bands correlated with a given parameter, the SRF framework reveals where and under which environmental conditions each constituent dominates the reflectance signal. This information may support the development of more robust regional bio-optical algorithms and improve constituent retrieval in waters where strong CDOM absorption and variable particle loads limit the performance of conventional band-ratio approaches.

5. Conclusions

The spectral shape and magnitude of R_{rs} in the Baltic Sea are controlled by the combined and interdependent effects of the three optically dominant constituents: CDOM, phytoplankton, and mineral particles. Among these components, Chl-*a* plays the dominant role in scaling the overall magnitude of the R_{rs} spectrum. In contrast, CDOM is primarily responsible for reducing R_{rs} , particularly in the blue and green spectral regions, and for shifting the reflectance maximum toward longer wavelengths. Mineral particles generally increase absolute R_{rs} values through enhanced backscattering; however, their contribution remains secondary and becomes significant mainly under low-absorption conditions.

The present study quantifies the expected range and direction of R_{rs} variability across a broad spectrum of constituent concentrations representative of typical Baltic Sea conditions. The results demonstrate that the influence of individual components cannot be considered independently, as their optical effects are strongly modulated by the concentrations of the remaining constituents. A forty-fold increase in Chl-*a* corresponds to more than a five-fold increase in R_{rs} , whereas a thirty-fold increase in CDOM absorption induces a seven- to sixteen-fold reduction in reflectance, depending on background conditions. In contrast, even a hundred-fold increase in PIM produces only a limited response, with R_{rs} increasing by up to 1.5 times in the red band. The backscattering contribution of particulate inorganic matter becomes apparent only when CDOM absorption is sufficiently low, whereas high CDOM concentrations suppress the influence of scattering particles and dominate the spectral response.

The analysis of the spectral response function can improve the understanding of how optically significant constituents shape the R_{rs} spectrum in the conditions of low and high concentrations of other components in coastal waters. The identified wavelengths of maximum spectral response may provide guidance for the selection of spectral bands used in future satellite retrieval algorithms for chlorophyll-*a*, CDOM, and suspended particles in Baltic Sea waters, and they may support the development of regionally optimized bio-

optical models for optically complex environments. In particular, the results highlight the importance of accounting for strong CDOM absorption and constituent interactions when retrieving Chl-*a* and suspended particle properties in the Baltic Sea and similar optically complex environments. We recommend conducting R_{rs} spectral response analyses over large locally measured and modeled data sets in order to advance the algorithm-based retrieval of individual seawater component concentrations.

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Abbreviations

The following abbreviations are used in this manuscript:

IOPs	Inherent Optical Properties
AOPs	Apparent Optical Properties
Chl- <i>a</i>	Chlorophyll- <i>a</i>
CDOM	Colored Dissolved Organic Matter
PIM	Particulate Inorganic Matter
RTE	Radiative Transfer Equation
SPM	Suspended Particulate Matter
SRF	Spectral Response Function

References

1. Heckwolf, M.J.; Peterson, A.; Jänes, H.; Horne, P.; Künn, J.; Liversage, K.; Sajeva, M.; Reusch, T.B.H.; Kotta, J. From ecosystems to socio-economic benefits: A systematic review of coastal ecosystem services in the Baltic Sea. *Sci. Total Environ.* **2021**, *755*, 142565. [\[CrossRef\]](#) [\[PubMed\]](#)
2. Jernberg, S.; Kuosa, H.; Boström, C.; Burdon, D.; Haavisto, F.; Heiskanen, A.-S.; Kiviluoto, S.; Kuningas, S.; Kunnasranta, M.; Uusitalo, L.; et al. Linking natural capital stocks with ecosystem services in the Northern Baltic Sea. *Ecosyst. Serv.* **2024**, *65*, 101585. [\[CrossRef\]](#)
3. HELCOM. *HELCOM Annual Report 2025. Baltic Sea Environment Proceedings 2026*; No. 209; HELCOM: Helsinki, Finland, 2026.
4. Stramska, M.; Jakacki, J. Variability of chlorophyll *a* concentration in surface waters of the open Baltic Sea. *Oceanologia* **2024**, *66*, 365–380. [\[CrossRef\]](#)
5. Ahtiainen, H.; Artell, J.; Czajkowski, M.; Hasler, B.; Hasselström, L.; Huhtala, A.; Meyerhoff, J.; Smart, J.C.R.; Söderqvist, T.; Alemu, M.H.; et al. Benefits of meeting nutrient reduction targets for the Baltic Sea—A contingent valuation study in the nine coastal states. *J. Environ. Econ. Policy* **2014**, *3*, 278–305. [\[CrossRef\]](#)
6. Andersen, J.H.; Axe, P.; Backer, H.; Carstensen, J.; Claussen, U.; Fleming-Lehtinen, V.; Järvinen, M.; Kaartokallio, H.; Knuuttila, S.; Korpinen, S.; et al. Getting the measure of eutrophication in the Baltic Sea: Towards improved assessment principles and methods. *Biogeochemistry* **2011**, *106*, 137–156. [\[CrossRef\]](#)
7. Hieronymi, M.; Behr, D.; Bi, S.; Röttgers, R. Optical complexity of North Sea, Baltic Sea, and adjacent coastal and inland waters derived from Sentinel-3 OLCI satellite data. *Earth Syst. Sci. Data* **2026**, *18*, 1307–1329. [\[CrossRef\]](#)
8. O’Kane, S.; McCarthy, T.; Fealy, R.; Kratzer, S.A. Validation of OLCI Sentinel-3 Water Products in the Baltic Sea and an Evaluation of the Effect of System Vicarious Calibration (SVC) on the Level-2 Water Products. *Remote Sens.* **2024**, *16*, 3932. [\[CrossRef\]](#)

9. González Vilas, L.; Brando, V.E.; Di Cicco, A.; Colella, S.; D'Alimonte, D.; Kajiyama, T.; Attila, J.; Schroeder, T. Assessment of ocean color atmospheric correction methods and development of a regional ocean color operational dataset for the Baltic Sea based on Sentinel-3 OLCI. *Front. Mar. Sci.* **2024**, *10*, 1256990. [\[CrossRef\]](#)
10. Mobley, C.D. (Ed.) *The Oceanic Optics Book*; International Ocean Colour Coordinating Group (IOCCG): Dartmouth, NS, Canada, 2022; 924p. [\[CrossRef\]](#)
11. Dutkiewicz, S. (Ed.) *Synergy Between Ocean Colour and Biogeochemical/Ecosystem Models*; Report Series 19; International Ocean Colour Coordinating Group (IOCCG): Dartmouth, NS, Canada, 2020.
12. Groom, S.; Sathyendranath, S.; Ban, Y.; Bernard, S.; Brewin, R.; Brotas, V.; Brockmann, C.; Chauhan, P.; Choi, J.K.; Chuprin, A.; et al. Satellite Ocean Colour: Current Status and Future Perspective. *Front. Mar. Sci.* **2019**, *29*, 485. [\[CrossRef\]](#) [\[PubMed\]](#)
13. Lednicka, B.; Kubacka, M.; Freda, W.; Haule, K.; Ficek, D.; Sokólski, M. Multi-Parameter Algorithms of Remote Sensing Reflectance, Absorption and Backscattering for Coastal Waters of the Southern Baltic Sea Applied to Pomeranian Lakes. *Water* **2023**, *15*, 2843. [\[CrossRef\]](#)
14. Soomets, T.; Toming, K.; Paavel, B.; Kutser, T. Evaluation of remote sensing and modeled chlorophyll-a products of the Baltic Sea. *J. Appl. Remote Sens.* **2022**, *16*, 046516. [\[CrossRef\]](#)
15. Ostrowska, M.; Ficek, D.; Stoltmann, D.; Stoń-Egiert, J.; Zdun, A.; Kowalewski, M.; Zapadka, T.; Majchrowski, R.; Pawlik, M.; Dera, J. Ten years of remote sensing and analyses of the Baltic Sea primary production (2010–2019). *Remote Sens. Appl. Soc. Environ.* **2022**, *26*, 100715. [\[CrossRef\]](#)
16. Lee, Z.-P. (Ed.) *Remote Sensing of Inherent Optical Properties: Fundamentals, Tests of Algorithms, and Applications*; Report Number 5; International Ocean Colour Coordinating Group (IOCCG): Dartmouth, NS, Canada, 2006; 126p.
17. Ligi, M.; Kutser, T.; Kallio, K.; Attila, J.; Koponen, S.; Paavel, B.; Soomets, T.; Reinart, A. Testing the performance of empirical remote sensing algorithms in the Baltic Sea waters with modelled and in situ reflectance data. *Oceanologia* **2017**, *59*, 57–68. [\[CrossRef\]](#)
18. Gordon, H.R. Remote sensing of ocean color: A methodology for dealing with broad spectral bands and significant out-of-band response. *Appl. Opt.* **1995**, *34*, 8363–8374. [\[CrossRef\]](#) [\[PubMed\]](#)
19. Melin, F.; Sclep, G. Band shifting for ocean color multi-spectral reflectance data. *Opt. Express* **2015**, *23*, 2262–2279. [\[CrossRef\]](#) [\[PubMed\]](#)
20. Salem, S.; Higa, H.; Ishizaka, J.; Pahlevan, N.; Oki, K. Spectral band-shifting of multispectral remote-sensing reflectance products: Insights for matchup and cross-mission consistency assessments. *Remote Sens. Environ.* **2023**, *299*, 113846. [\[CrossRef\]](#)
21. Pahlevan, N.; Smith, B.; Binding, C.; O'Donnell, D.M. Spectral band adjustments for remote sensing reflectance spectra in coastal/inland waters. *Opt. Express* **2017**, *25*, 28650–28667. [\[CrossRef\]](#)
22. HELCOM. *Effectiveness of Measures to Reduce Nutrient Inputs—Importance of Point Sources*; Baltic Sea Environment Proceedings 203; HELCOM: Helsinki, Finland, 2025. Available online: https://helcom.fi/wp-content/uploads/2025/05/Effectiveness_of_measures_to_reduce_nutrient_inputs-1.pdf (accessed on 20 January 2026).
23. Jakobsson, M.; Stranne, C.; O'Regan, M.; Greenwood, S.L.; Gustafsson, B.; Humborg, C.; Weidner, E. Bathymetric properties of the Baltic Sea. *Ocean Sci.* **2019**, *15*, 905–924. [\[CrossRef\]](#)
24. System Satbałytk. Available online: <https://www.satbaltyk.pl/> (accessed on 20 January 2026).
25. Kaczmarek, S.; Woźniak, B. The application of the optical classification of waters in the Baltic Sea [Case 2 Waters]. *Oceanologia* **1995**, *37*, 285–297.
26. Kratzer, S.; Moore, G. Inherent Optical Properties of the Baltic Sea in Comparison to Other Seas and Oceans. *Remote Sens.* **2018**, *10*, 418. [\[CrossRef\]](#)
27. Andersen, J.H.; Carstensen, J.; Conley, D.J.; Dromph, K.; Fleming-Lehtinen, V.; Gustafsson, B.G.; Josefson, A.B.; Norkko, A.; Villnäs, A.; Murray, C. Long-term temporal and spatial trends in eutrophication status of the Baltic Sea. *Biol. Rev.* **2017**, *92*, 135–149. [\[CrossRef\]](#) [\[PubMed\]](#)
28. HELCOM. Chlorophyll-a, HELCOM Core Indicator Report. 2023. Available online: <https://indicators.helcom.fi/indicator/chlorophyll/> (accessed on 20 January 2026).
29. Woźniak, S.B.; Meler, J.; Lednicka, B.; Zdun, A.; Stoń-Egiert, J. Inherent optical properties of suspended particulate matter in the southern Baltic Sea. *Oceanologia* **2011**, *53*, 691–729. [\[CrossRef\]](#)
30. Kowalczyk, P.; Olszewski, J.; Darecki, M.; Kaczmarek, S. Empirical relationships between Coloured Dissolved Organic Matter (CDOM) absorption and apparent optical properties in Baltic Sea waters. *Int. J. Remote Sens.* **2005**, *26*, 345–370. [\[CrossRef\]](#)
31. Röttgers, R.; McKee, D.; Utschig, C. Temperature and salinity correction coefficients for light absorption by water in the visible to infrared spectral region. *Opt. Express* **2014**, *22*, 25093–25108. [\[CrossRef\]](#) [\[PubMed\]](#)
32. Zhang, X.; Hu, L.; He, M.-X. Scattering by pure seawater: Effect of salinity. *Opt. Express* **2009**, *17*, 5698–5710. [\[CrossRef\]](#) [\[PubMed\]](#)
33. Lehmann, A.; Myrberg, K.; Post, P.; Chubarenko, I.; Dailidienė, I.; Hinrichsen, H.-H.; Hüseyin, K.; Liblik, T.; Meier, H.E.M.; Lips, U.; et al. Salinity dynamics of the Baltic Sea. *Earth Syst. Dynam.* **2022**, *13*, 373–392. [\[CrossRef\]](#)

34. Morrison, J.R.; Nelson, N.B. Seasonal cycle of phytoplankton UV absorption at the Bermuda Atlantic Time-series Study (BATS) site. *Limnol. Oceanogr.* **2004**, *49*, 215–224. [\[CrossRef\]](#)
35. Bricaud, A.; Morel, A.; Babin, M.; Allali, K.; Claustre, H. Variations of light absorption by suspended particles with chlorophyll a concentration in oceanic (case 1) waters: Analysis and implications for bio-optical models. *J. Geophys. Res. Ocean.* **1998**, *103*, 31033–31044. [\[CrossRef\]](#)
36. Morel, A.; David, A.; Gentili, B. Bidirectional reflectance of oceanic waters: Accounting for Raman emission and varying particle scattering phase function. *Appl. Opt.* **2022**, *41*, 6289–6306. [\[CrossRef\]](#) [\[PubMed\]](#)
37. Mobley, C.D.; Sundman, L.K. *HydroLight-EcoLight*, Version 6.0; Technical Documentation; Numerical Optics Ltd.: Witheridge, UK, 2024.
38. Woźniak, S.; Meler, J.; Stoń-Egiert, J. Inherent optical properties of suspended particulate matter in the southern Baltic Sea in relation to the concentration, composition and characteristics of the particle size distribution; new forms of multicomponent parameterizations of optical properties. *J. Mar. Syst.* **2022**, *229*, 103720. [\[CrossRef\]](#)
39. Bowers, D.G.; Harker, G.E.L.; Stephan, B. Absorption spectra of inorganic particles in the Irish Sea and their relevance to remote sensing of chlorophyll. *Int. J. Remote Sens.* **1996**, *17*, 2449–2460. [\[CrossRef\]](#)
40. Babin, M.; Morel, A.; Fournier-Sicre, V.; Fell, F.; Stramski, D. Light scattering properties of marine particles in coastal and open oceanwaters as related to the particle mass concentration. *Limnol. Oceanogr.* **2003**, *48*, 843–859. [\[CrossRef\]](#)
41. Quan, X.; Fry, E.S. Empirical equation for the index of refraction of seawater. *Appl. Opt.* **1995**, *34*, 3477–3480. [\[CrossRef\]](#) [\[PubMed\]](#)
42. Konik, M.; Kowalczyk, P.; Zabłocka, M.; Makarewicz, A.; Meler, J.; Zdun, A.; Darecki, M. Empirical Relationships between Remote-Sensing Reflectance and Selected Inherent Optical Properties in Nordic Sea Surface Waters for the MODIS and OLCI Ocean Colour Sensors. *Remote Sens.* **2020**, *12*, 2774. [\[CrossRef\]](#)
43. O'Reilly, J.E.; Werdell, J.P. Chlorophyll algorithms for ocean color sensors-OC4, OC5 & OC6. *Remote Sens. Environ.* **2019**, *229*, 32–47. [\[PubMed\]](#)
44. Bailey, S.W.; Werdell, P.J. A multi-sensor approach for the global measurement of ocean chlorophyll: The “Matchup” data set. *Remote Sens. Environ.* **2006**, *102*, 12–23. [\[CrossRef\]](#)
45. Werdell, P.J.; McKinnis, L.I.W.; Boss, E.; Tzortziou, M.; Zhang, X. An overview of approaches and challenges for retrieving marine inherent optical properties from ocean color remote sensing. *Prog. Oceanogr.* **2018**, *160*, 186–212. [\[CrossRef\]](#) [\[PubMed\]](#)
46. Haule, K.; Freda, W.; Darecki, M.; Toczek, H. Possibilities of optical remote sensing of dispersed oil in coastal waters. *Estuar. Coast. Shelf Sci.* **2016**, *195*, 76–87. [\[CrossRef\]](#)
47. Tilstone, G.H.; Pardo, S.; Simis, S.G.H.; Qin, P.; Selmes, N.; Dessailly, D.; Kwiatkowska, E. Consistency between Satellite Ocean Colour Products under High Coloured Dissolved Organic Matter Absorption in the Baltic Sea. *Remote Sens.* **2022**, *14*, 89. [\[CrossRef\]](#)
48. Ficek, D.; Zapadka, T.; Dera, J. Remote sensing reflectance of Pomeranian lakes and the Baltic. *Oceanologia* **2011**, *53*, 959–970. [\[CrossRef\]](#)
49. Doxaran, D.; Cherukuru, N.; Lavender, S.J. Apparent and inherent optical properties of turbid estuarine waters: Measurements, empirical quantification relationships, and modeling. *Appl. Opt.* **2006**, *45*, 2310–2324. [\[CrossRef\]](#) [\[PubMed\]](#)
50. Le, C.; Hu, C. A hybrid approach to estimate chromophoric dissolved organic matter in turbid estuaries from satellite measurements: A case study for Tampa Bay. *Opt. Express* **2013**, *21*, 18849–18871. [\[CrossRef\]](#) [\[PubMed\]](#)
51. Wei, J.; Yu, X.; Lee, Z.; Wang, M.; Jiang, L. Improving low-quality satellite remote sensing reflectance at blue bands over coastal and inland waters. *Remote Sens. Environ.* **2020**, *250*, 112029. [\[CrossRef\]](#)
52. Kowalczyk, P.; Darecki, M.; Zabłocka, M.; Górecka, I. Validation of empirical and semi-analytical remote sensing algorithms for estimating absorption by Coloured Dissolved Organic Matter in the Baltic Sea from SeaWiFS and MODIS imagery. *Oceanologia* **2010**, *52*, 171–196. [\[CrossRef\]](#)
53. Darecki, M.; Stramski, D. An evaluation of MODIS and SeaWiFS bio-optical algorithms in the Baltic Sea. *Remote Sens.* **2004**, *89*, 326–350. [\[CrossRef\]](#)
54. Woźniak, S.B.; Meler, J. Modelling Water Colour Characteristics in an Optically Complex Nearshore Environment in the Baltic Sea; Quantitative Interpretation of the Forel-Ule Scale and Algorithms for the Remote Estimation of Seawater Composition. *Remote Sens.* **2020**, *12*, 2852. [\[CrossRef\]](#)
55. Lednicka, B.; Kubacka, M. Semi-Empirical Model of Remote-Sensing Reflectance for Chosen Areas of the Southern Baltic. *Sensors* **2022**, *22*, 1105. [\[CrossRef\]](#) [\[PubMed\]](#)
56. Uudeberg, K.; Aavaste, A.; Kõks, K.-L.; Ansper, A.; Uusõue, M.; Kangro, K.; Ansko, I.; Ligi, M.; Toming, K.; Reinart, A. Optical Water Type Guided Approach to Estimate Optical Water Quality Parameters. *Remote Sens.* **2020**, *12*, 931. [\[CrossRef\]](#)
57. Dogliotti, A.I.; Ruddick, K.; Nechad, B.; Doxaran, D.; Knaeps, E. A Single Algorithm to Retrieve Turbidity from Remotely-Sensed Data in All Coastal and Estuarine Waters. *Remote Sens. Environ.* **2015**, *156*, 157–168. [\[CrossRef\]](#)
58. Haule, K.; Kubacka, M.; Toczek, H.; Lednicka, B.; Pranszke, B.; Freda, W. Correlation between Turbidity and Inherent Optical Properties as an Initial Recognition for Backscattering Coefficient Estimation. *Water* **2024**, *16*, 594. [\[CrossRef\]](#)

59. Kari, E.; Kratzer, S.; Beltrán-Abaunza, J.M.; Harvey, E.T.; Vaičiūtė, D. Retrieval of suspended particulate matter from turbidity—Model development, validation, and application to MERIS data over the Baltic Sea. *Int. J. Remote Sens.* **2017**, *38*, 1983–2003. [[CrossRef](#)]
60. Chowdhury, M.; Vilas, C.; van Bergeijk, S.; Navarro, G.; Laiz, I.; Caballero, I. Monitoring turbidity in a highly variable estuary using Sentinel-2A/B for ecosystem management applications. *Front. Mar. Sci.* **2023**, *10*, 1186441. [[CrossRef](#)]
61. Wu, Z.; Pang, J.; Li, J.; Wang, Y.; Ruan, J.; Zhang, X.; Yang, L.; Pang, Y.; Gao, Y. A review of remote sensing-based water quality monitoring in turbid coastal waters. *Intell. Mar. Technol. Syst.* **2025**, *3*, 24. [[CrossRef](#)]
62. Nechad, B.; Ruddick, K.G.; Park, Y. Calibration and validation of a generic multisensor algorithm for mapping of total suspended matter in turbid waters. *Remote Sens. Environ.* **2010**, *114*, 854–866. [[CrossRef](#)]

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