SPECTRAL SIMULATION ON REMOTE SENSING REFLECTANCE OF MIXED WATER WITH PETROLEUM AND SANDS USING HYDROLIGHT

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ABSTRACT: In the water with petroleum pollution, some oil substances will adsorb on the surface of suspended matter, which will change the scattering coefficient of suspended particles, and then affect the remote sensing reflectance (R_{rs}). R_{rs} is one of the critical parameters of remote sensing inversion model for water component concentration. Understanding the contribution of suspended sediment and petroleum substance to R_{rs} can improve the accuracy of remote sensing inversion model for petroleum pollution concentration. Petroleum concentration, the specific absorption coefficient and the specific scattering coefficient measured at sites near Dalian Port, Liaoning Province, China, August 25-27th, 2018 were used as the inputs of the USER-DEFINEDED IOP MODEL integrated in the radiation transmission model Hydrolight to simulate R_{rs} of mixed water with petroleum and sands in the visible wavelength range (400-700 nm). With the results, a theoretical discuss was made on the influence of petroleum substance and sands on the remote sensing reflectance respectively. The results show that: (1) the presence of suspended sediment makes the spectral curve of petroleum substances move towards the long wave direction, and the shape and size of the spectrum are related to the concentration of suspended sediment; (2) With the increase of petroleum concentration, the remote sensing reflectance of mixed water decreases, but when the suspended sediment concentration is more than 5.0 mg/L, the remote sensing reflectance curve of mixed water of petroleum and sands is similar to that of suspended sediment; (3) The presence of petroleum substances has uncertainty on the remote sensing reflectance of suspended sediment in the blue-green band (400-500 nm), which may increase or decrease, and increase the remote sensing reflectance in the 500-700 nm band.

1. INTRODUCTION

Remote sensing reflectance (R_{rs}) is an important physical parameter to characterize the apparent optical properties of water. It is defined as the ratio of the water-leaving radiance (L_w) to the downward irradiance (E_d), which contains the optical properties of the inner water layer at a certain depth. R_{rs} is one of the basic physical parameters and apparent optical properties of ocean color remote sensing bio-optical model. The core idea of bio-optical model in ocean color remote sensing is based on the relationship between R_{rs} and intrinsic optical parameter absorption coefficient (a) and backscattering coefficient (b_b) (Mobley, 1994).

R_{rs} is closely related to the backscattering radiation of the incoming radiation from various components of the water body, such as inorganic particulates and organic debris. The scattering characteristics of water are closely related to water environmental parameters such as suspended particulate matter and concentration (Sun et al., 2007). Previous studies have shown that the main components affecting the backscattering characteristics of water bodies are suspended sediment, chlorophyll and CDOM (Colored dissolved organic matter), also known as the three elements of ocean color. Throughout the research reports on the influence of three factors of ocean color on backscattering coefficient, scholars have always believed that suspended sediment is an important factor affecting backscattering coefficient (Gallie and Murtha, 1992; Le et al., 2009; Song and Tang, 2006; Stramski et al., 2004). For petroleum contaminated water bodies, some petroleum substances will adsorb on the surface of water suspended particulate matter, and the inorganic suspended matter will change the scattering characteristics of the water body (Huang et al., 2009), which will have a certain impact on R_{rs}.

For petroleum contaminated water, the current research mainly focuses on the influence of oil film on the optical properties of water surface and the decomposed oil, and has made considerable progress (Haule et al., 2015; Stelmaszewski et al., 2009). However, little research has been done on petroleum-bearing water without obvious oil film. Huang et al. (2009) took the data collected in the rivers in Panjin City, Liaoning Province, China as examples to study the characteristics of backscattering coefficient of petroleum-contaminated water bodies. The results show that backscattering coefficient is linearly related to the concentration of petroleum substances. Song et al. (2010) established a parameterized backscattering coefficient model for retrieving the concentration of petroleum substances in water based on field measurement and proportioning experiments. However, the backscattering coefficient of measured water contains the contribution of petroleum and particulate matter, and further separation of the contribution of petroleum substances and particulate matter to backscattering is needed. Some studies have shown that the influence of petroleum substances on absorption coefficient is mainly reflected by CDOM, and the influence of scattering coefficient is mainly reflected by inorganic suspended matter. Therefore, it is considered that petroleum in water without obvious oil film is one of the ocean color factors (Huang et al., 2009; Huang et al., 2010; Krol et al., 2006; Song et al., 2010). That is to say, the existence of petroleum substances changes the radiation transfer characteristics of petroleum-contaminated water bodies. Nowadays, a series of studies have been carried out on the apparent and intrinsic optical properties of petroleum-contaminated water bodies. The results obtained lay a solid foundation for the study of radiation transfer in petroleum contaminated water bodies. Monte Carlo model and Hydrolight model based on radiation transfer theory are important tools for studying underwater light field of petroleum-contaminated water bodies (Haule and Freda, 2016; Rudz et al., 2013). Huang et al. (2017) selected quartz sand with known refractive index, used oil-bearing water as petroleum substance, and then used Mie scattering theory to carry out petroleum-sand mixing experiments. The results show that the petroleum adsorbed on the surface of suspended matters increases the particle size of suspended matters and the backscattering of water. Finally, a petroleum-sand mixed separation algorithm is proposed to provide technical support for the separation of backscattering coefficients of petroleum and particulate matter. However, the effects of inorganic suspended particulates and petroleum substances on R_{rs} of water bodies are still unknown, and further research is needed.

In order to analyze the influence of suspended sediment and petroleum substances on R_{rs} in mixed water with petroleum and sands, the R_{rs} of petroleum substances, suspended sediment and mixed water with both was simulated by using the radiative transfer Hydrolight model developed by ocean color factor. The influence of petroleum substances and suspended sediment on R_{rs} was studied theoretically. Except for the concentration, absorption and scattering coefficients of the petroleum substances, which are based on the measured data of Dalian Port, the inherent optical characteristics of the remaining water components and the external conditions for providing the calculation of the radiation transfer equation (RTE) are all using the initial data and built-in modules of Hydrolight. Research on the influence of petroleum substances and suspended sediment on R_{rs} is helpful to further establish parameterized model of R_{rs} of petroleum-sands mixed water and inversion model of petroleum substances and suspended sediment concentration in water body. The foundation of underwater light field research of mixed water with both in water body is laid, and the application of remote sensing technology in water environment monitoring is expanded.

2. MATERIAL AND METHODS

2.1 Research area and site distribution

Dalian Port is rich in crude oil reserves and a major trading port. There have been several oil spills, so its water quality and environment are largely polluted by oil. From August 25 to 27, 2018, three sites in Dalian Port were observed for 10 consecutive hours (7:00-17:00), as shown in Fig. 1. The water depth of site A was 21.5m (the record time of water depth was 7:00, and the record time of water depth was the same at all sites). There was an explosion of petroleum pipeline in the port area. The water depth of site B is 24.8m. The site is located on the east side of the crude oil berth and is polluted by petroleum substances to a certain extent. The water depth of site C is 33.0m, and compared with the two sites above, the frequency of ships passing through the site is smaller. Samples are numbered according to site number and time. Sample number is in the form of site number plus time number. The time number is from 7:00 to 17:00, respectively, and is 1 to 10. For example, the sample of site A at 7:00 is A1.

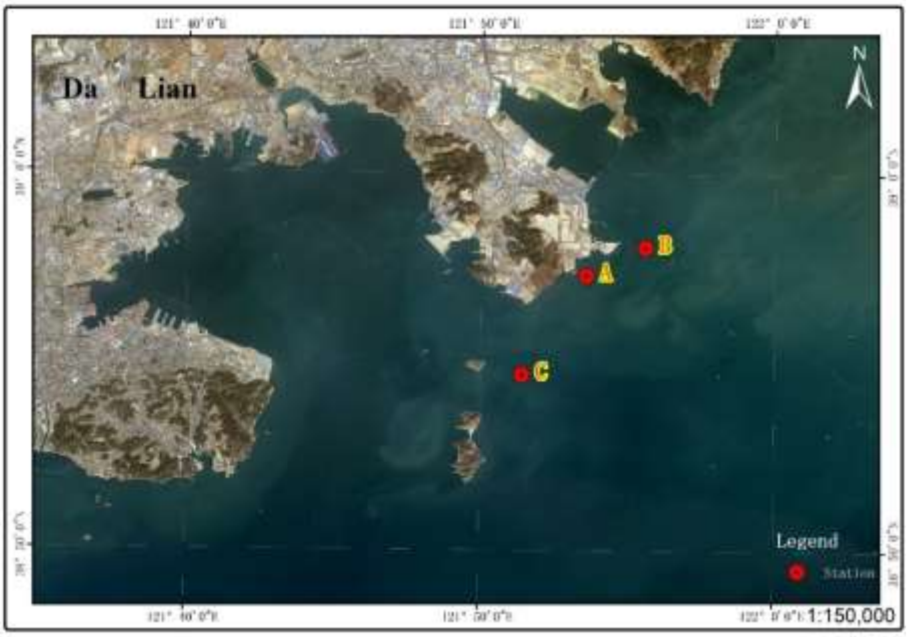

Figure 1 Distribution of observation sites

2.2 Parameter setting of radiation transfer model Hydrolight 5.3

Hydrolight has been widely used in various fields of ocean optics and water color remote sensing (Martin et al., 2017; Schott et al., 2016). Through continuous improvement and verification, it can obtain more accurate apparent optical characteristics. It is also an effective model for studying radiative transmission characteristics of oil-bearing water bodies (Huang et al., 2019).

In this paper, we use the built-in module 7 of Hydrolight 5.3 - "A User Defined Model" - to simulate the radiation transfer in mixed water with petroleum and sands. The purpose of this module is to provide the concentration, absorption, scattering and phase functions of water components for solving the RTE (Hedley et al., 2017). It defines three water components: pure water, oil and suspended sediment. The parameters of pure water and suspended matter are set using the data from Hydrolight, and the absorption and scattering of pure water are using Pope and Fry (1997) and Smith and Bake (1981). The parameters of suspended sediment are set as follows: minzdataEx04(ex04), 0.2, 0.5, 0.8, 1.0, 2.0, 3.0, 5.0 and 10 mg/L, and astarmin_redclay and bstarmin_redclay files are selected for absorption and scattering. The input files of the parameters of oil substances are based on the concentration, specific absorption and specific scattering data calculated from the measured data of Dalian Port. As for the phase function, Kirk (1981) considers that the backscattering probability bb/b (the ratio of backscattering to total scattering) of 0.019 is more suitable for coastal and turbid waters. Asa et al. (2005) and other studies have shown that bb/b is related to particle size. The smaller the particle size, the larger the bb/b. Generally, it varies between 0.017 and 0.029, and the upper limit is 0.5. Therefore, the phase functions of oil and suspended sediment are FFbb018 and 0.028. External conditions are assumed as follows: 1. No inelastic scattering and internal light sources are included; 2. Wind speed is 0m/s and refractive index n = 1.34; 3. Sky mode is selected based on RADTRAN-X, with the zenith angle of 30 degrees; 4. Mode depth is infinite; 5. Output wavelength is 400-700 nm with an interval of 2 nm; Output depth is 0-16 m with an interval of 2 m.

3. RESULTS AND DISCUSSION

3.1 Remote sensing reflectivity of petroleum substances

Using Hydrolight to simulate R_{rs} of pure petroleum at each site. Figure 2 shows the results of the output R_{rs} of Hydrolight varying with the wavelength. Figure 2 shows that there are differences in the R_{rs} of different sites, which may be related to the properties of petroleum substances. The particle sizes of petroleum with different components are different. Haule et al (2015, 2016) considers that the concentration and particle size of oil droplets and euphotic zone are important factors affecting the apparent optical properties of water bodies. The different refractive coefficients and distributions of different components of petroleum substances lead to the change of water scattering coefficients. These factors make the R_{rs} measured at each site different, so the simulation analysis does not consider the influence of oil droplet size.

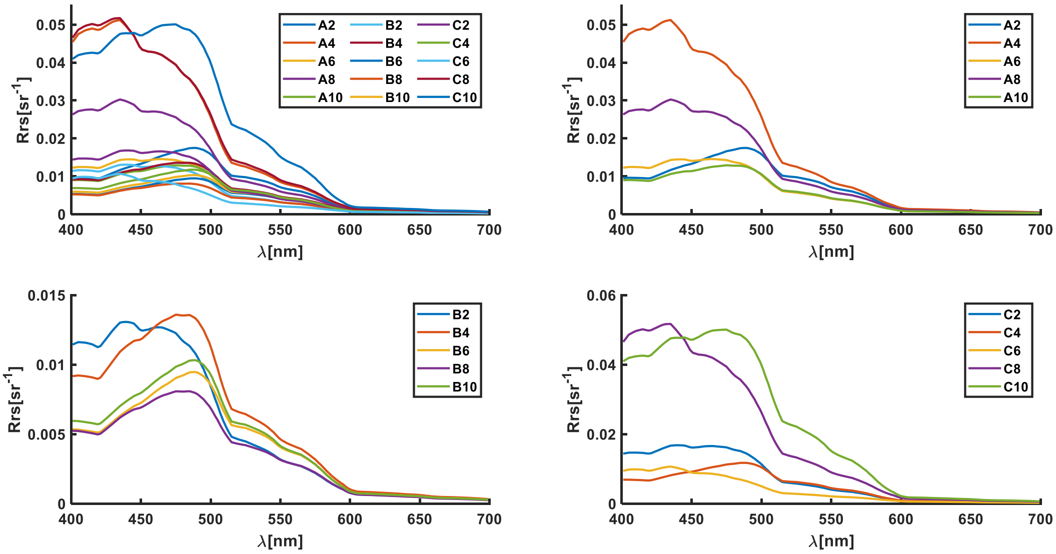

Figure 2 The remote sensing reflectance of each site calculated by Hydrolight. A) remote sensing reflectance of three site. B) remote sensing reflectance of site A. C) remote sensing reflectance of site B. D) remote sensing reflectivity of site C

According to data of Dalian Port, the average range of petroleum concentration at sites A, B and C is 1.731-2.869 mg/L, 2.794-6.478 mg/L and 0.327-4.473 mg/L, respectively. The 15 measurements are classified into three categories according to the average values: the average concentration of petroleum is 0-2 mg/L in water with low petroleum content; the average concentration of petroleum is 2-4 mg/L in water with medium petroleum content. The water with high petroleum content is > 4 mg/L. The specific classification is shown in Table 1.

Table 1 Classification of petroleum substances with different concentrations in three

Water with low petroleum	Water with meddle petroleum	Water with high petroleum
A4、A6、C8、C10	A2、A8、A10、B2、B4、C6	B6、B8、B10、C2、C4

Figure 3 is the R_{rs} image of pure petroleum after classification. Analysis of Fig. 3 shows that with the increase of the average concentration of petroleum, or with the increase of petroleum concentration, the R_{rs} of pure petroleum water decreases. In addition, it can be found that the R_{rs} image of pure petroleum water is "single peak", and the peak region is between 430 and 440 nm, or the wavelength is between 480 and 490 nm. This may be due to the different composition of petroleum-dominated substances in water body at different times. According to the range of peak value, the classification status is shown in Table 2. Figure 4 is the R_{rs} diagram corresponding to Table 2. Analysis of Fig. 4 shows that the peak R_{rs} of petroleum does not shift with the change of concentration, and concentration only changes the magnitude of R_{rs}.

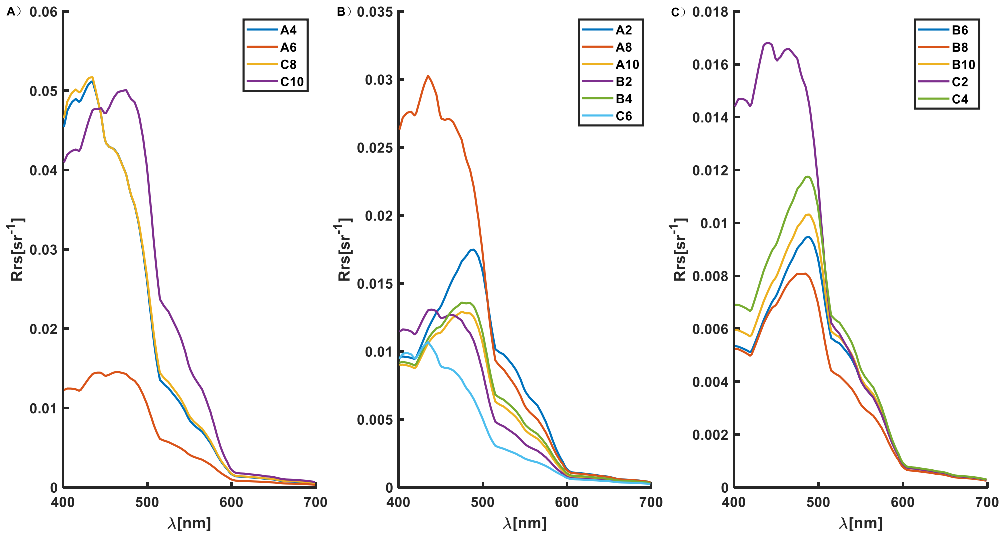

Figure 3 Remote sensing reflectance of petroleum in different average concentration ranges. A) the remote sensing reflectance curve of water with low petroleum; B) the remote sensing reflectance curve of water with meddle petroleum; C) the remote sensing reflectance curve of water with high petroleum

Table 2 Classification table of two kinds of petroleum substances. The first peak is between 430 and 450 nm. The second peak is between 480 and 490nm

Category I petroleum Substances	Category II petroleum Substances
A4、A6、A8、B2、C2、C6、C8	A2、A10、B4、B6、B8、B10、C4、C10

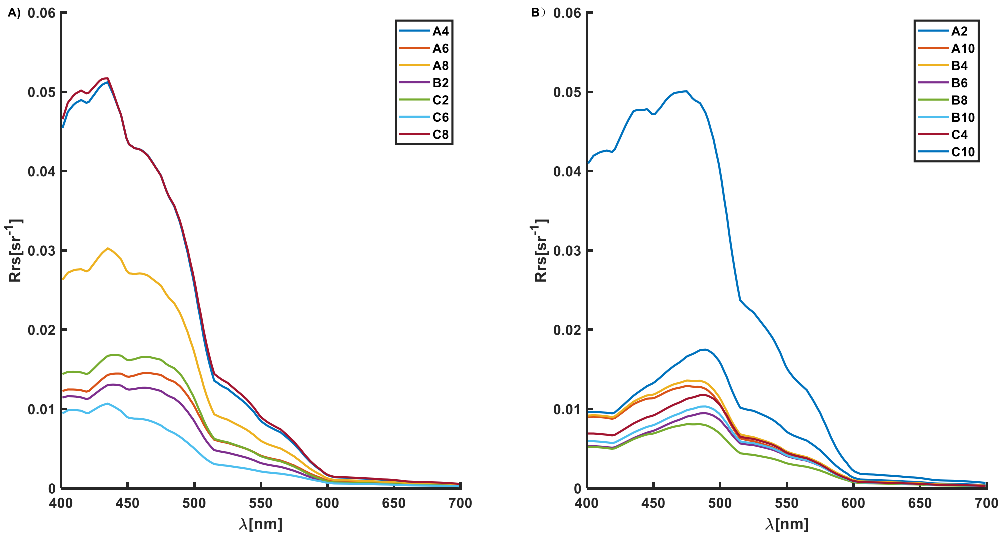

Figure 4 Remote sensing reflectance of two kinds of petroleum substances. A) the peak value of remote sensing reflectance for petroleum substances is between 430 and 440 nm; B) the peak value of remote sensing reflectance for petroleum substances is between 480 and 490 nm.

3.2 Remote sensing reflectivity of suspended sediment

The change of suspended sediment in water results in the change of turbidity of water body, which affects the light transmission in water and the reflectance spectrum characteristics of water body. The R_{rs} and characteristic band of water body will change and migrate with different suspended sediment content. The curve of R_{rs} under different suspended sediment concentration is simulated in Fig. 5. Analysis of Fig. 5 shows that, with the increase of suspended sediment concentration, except for the R_{rs} of 0.5 mg/L suspended sediment, the overall R_{rs} shows an increasing trend and its peak value gradually moves to long wave with the increase of suspended sediment concentration due to the scattering characteristics of suspended sediment without considering the influence of particle size. In the green-yellow band (510-590 nm), R_{rs} not only corresponds well with suspended sediment concentration, but also rises with the increase of suspended sediment concentration, even surpasses the merger front peak, and the trough at 510 to 520 nm gradually disappears. Some studies have shown that in the visible and near infrared bands, with the increase of suspended sediment content, the reflectivity of water body increases, and with the increase of suspended sediment concentration, the reflection peak position moves to the long wave direction (Han and Rundquist, 1994). This study is similar to the simulation results in this paper.

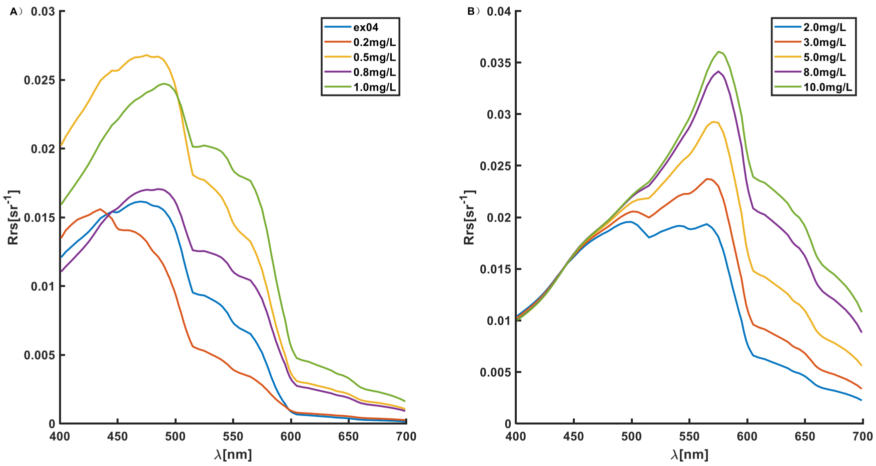

Figure 5 Remote sensing reflectance of suspended sediment at different concentrations. A) remote sensing reflectance image of suspended sediment concentration at 1 mg/L; B) remote sensing reflectance image of suspended sediment concentration at 2-10 mg/L.

3.3 Remote sensing reflectivity of mixed water with petroleum and sands

In order to analyze the cross-effects of suspended sediment and petroleum substances on remote sensing reflectance, the remote sensing reflectance of mixed water with petroleum and sands at different suspended sediment concentrations was simulated. The concentrations of suspended sediment were Ex04, 0.2, 0.5, 0.8, 1.0, 2.0, 3.0, 5.0, 8.0 and 10.0 mg/L, respectively.

3.3.1Effect of suspended sediment on remote sensing reflectivity of petroleum substances: The concentrations of low, medium and high oil substances are represented by A4, A2 and B10, respectively. The R_{rs} of each site with suspended sediment concentration were simulated, as shown in Figs. 6-8. It can be found that when the suspended sediment concentration is less than 1.0 mg/L, the variation of R_{rs} with the suspended sediment concentration in the blue-green band (400-500 nm) is irregular. It is possible to increase the R_{rs} or decrease the R_{rs}. The peak value of R_{rs} is in the range of 430 to 440 nm or 480 to 490 nm, which may be related to the composition and characteristics of petroleum substances. With the increase of suspended sediment concentration (>1.0 mg/L), R_{rs} increased in the wavelength range of 500 to 700 nm, even exceeding and merging the pre-peak. In general, the existence of suspended sediment makes the peak R_{rs} of petroleum substances move towards the long wave direction. When the suspended sediment concentration is less than 1 mg/L, the R_{rs} of petroleum substances varies irregularly in the blue-green band (400-500 nm) with the increase of suspended sediment concentration, while when the suspended sediment concentration is more than 1 mg/L, the R_{rs} curve of mixed water with petroleum and sands is similar to that of suspended sediment gradually with the increase of suspended sediment concentration. When the suspended sediment concentration reaches a certain level, the R_{rs} of mixed water with petroleum and sands is similar to that of suspended sediment. This shows that under the condition of high suspended sediment concentration, the remote sensing reflectance signal of petroleum substances is concealed by the signal of suspended sediment.

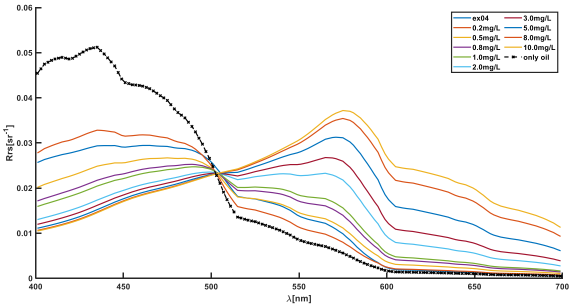

Figure 6 Remote sensing reflectivity of A4 site (low petroleum concentration) with suspended sediment concentration

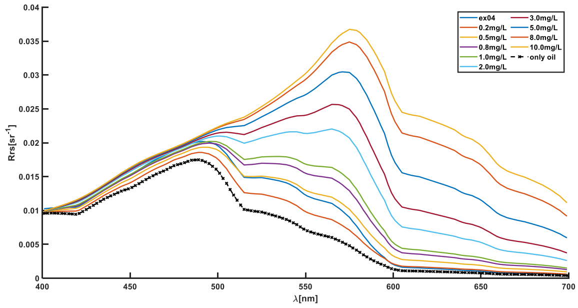

Figure 7 Remote sensing reflectivity of A2 site (meddle petroleum concentration) with suspended sediment concentration

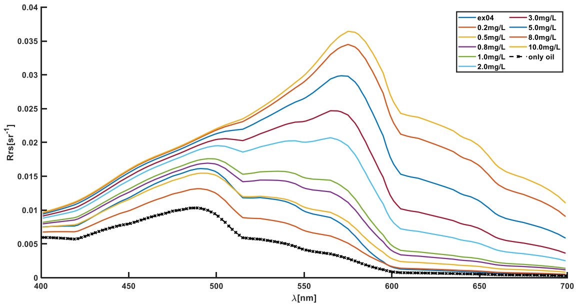

Figure 8 Remote sensing reflectivity of B10 site (high petroleum concentration) with suspended sediment concentration

3.3.2Effect of petroleum substances on remote sensing reflectivity of suspended sediment: In order to explore the effect of petroleum on R_{rs} of suspended sediment, different concentrations of petroleum were added at suspended sediment concentrations of 0.8, 2.0 and 8.0 mg/L, respectively, as shown in Figs 9-11. Analysis of Figs. 9-11 shows that R_{rs} of mixed water with petroleum and sands gradually decreases with the increase of petroleum concentration. In the visible light range, the petroleum substances have uncertainty on the R_{rs} of suspended sediment in blue-green band (400-500 nm), and increase the R_{rs} of wavelength from 500 to 700 nm. When the concentration of suspended sediment reaches 8.0 mg/L, the variation range will not be obvious, even the R_{rs} curve of mixed water with petroleum and sands is equivalent to that of suspended sediment, that is, the spectral shape is similar.

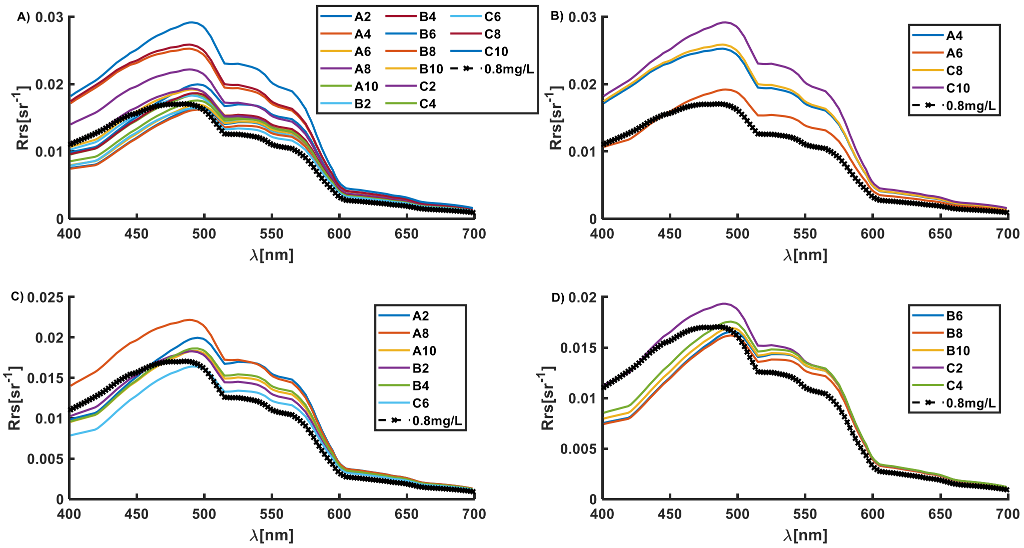

Figure 9 Remote sensing reflectance of suspended sediment concentration at 0.8mg/L varying with petroleum concentration. The black dotted line is the remote sensing reflectance only containing suspended sediment. A) remote sensing reflectance of each site. B) remote sensing reflectance of low petroleum concentration. C) remote sensing reflectance of petroleum concentration. D) remote sensing reflectivity of high petroleum concentration

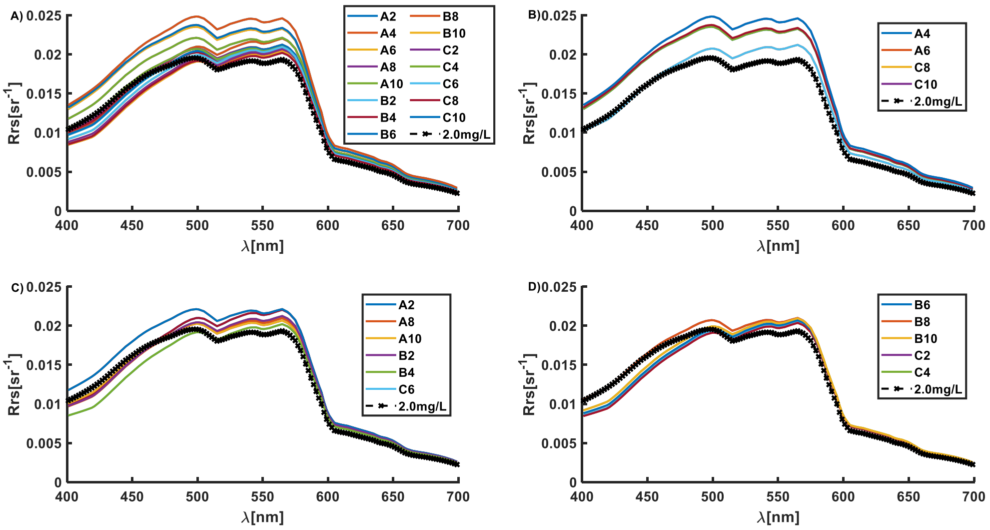

Figure 10 Remote sensing reflectance of suspended sediment concentration at 2.0mg/L varying with petroleum concentration. A) remote sensing reflectance of each site. B) remote sensing reflectance of low petroleum concentration. C) remote sensing reflectance of petroleum concentration. D) remote sensing reflectivity of high petroleum concentration

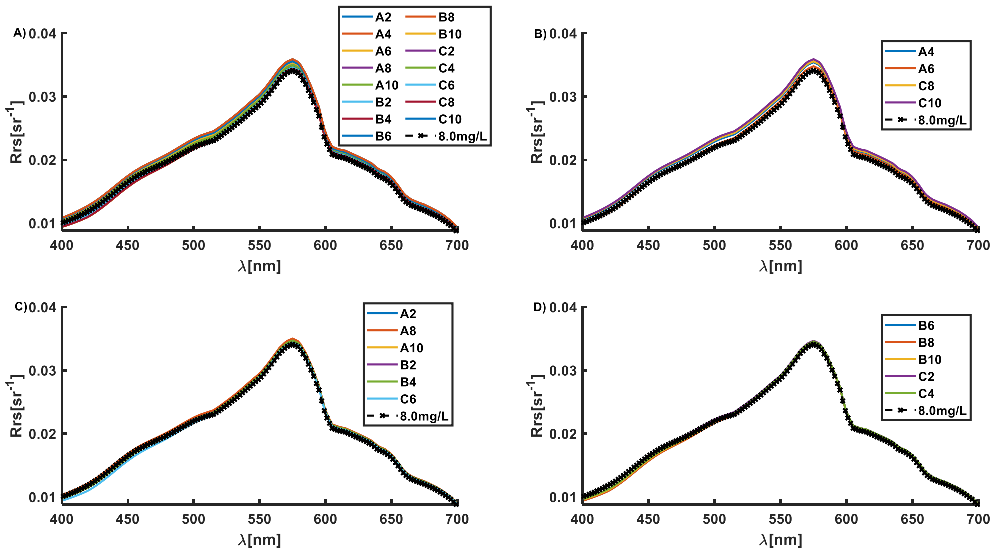

Figure 11 Remote sensing reflectance of suspended sediment concentration at 8.0mg/L varying with petroleum concentration. A) remote sensing reflectance of each site. B) remote sensing reflectance of low petroleum concentration. C) remote sensing reflectance of petroleum concentration. D) remote sensing reflectivity of high petroleum concentration

In conclusion, with the increase of petroleum concentration, R_{rs} of mixed water with petroleum and sands decreased gradually. When suspended sediment is more than 5.0 mg/L, the presence of petroleum will change the R_{rs} of suspended sediment, but the range is not large. The reason may be that petroleum adsorbs on the surface of suspended sediment and enlarges the particle size, which leads to the increase of backscattering coefficient (Huang, et al. 2017), and also affects the absorption coefficient, because the influence of petroleum on the absorption coefficient of water is mainly reflected by CDOM (Huang, et al. 2010). As a result, R_{rs} has changed. Song et al. (2010) considered that the presence of petroleum substances had some influence on the spectral shape of backscattering coefficient, but had little effect. The backscattering coefficient is related to suspended sediment, so to some extent, the presence of petroleum does not change the shape of R_{rs} in high suspended sediment.

3.3.3 Factor of introducing error: The above results are carried out under ideal conditions. The factors that may lead to errors include the following: (1) wind speed and tidal current have some influence on the measurement of inherent optics of petroleum substances; (2) Empirical algorithms are used to calculate specific absorption coefficient and specific scattering coefficient of petroleum substances, and more data are needed to verify their applicability and accuracy; (3) When measuring the concentration of petroleum substances, it is necessary to extract petroleum substances with hexane or carbon tetrachloride. According to the CDOM absorption coefficient measurement standard, hexane or carbon tetrachloride can be used as reference sample instead of pure water. However, carbon tetrachloride is toxic and volatile, and hexane is more suitable. Which of the two methods is more suitable for further standardization and standardization studies? (4) The phase function is defined as the volume scattering function divided by the scattering coefficient. For the phase function of the petroleum substance, the volume scattering function can be calculated according to the Mie theory, and the phase function of the petroleum substance can be obtained. However, the volume scattering function is mainly affected by the ratio of backscattering coefficient to scattering coefficient (called backscattering probability), particle size distribution and refractive index. These three parameters have empirical methods. However, because the adsorption of petroleum substances will change the volume scattering function, how to determine these three parameters in water is the key to accurate simulation (Huang et al., 2019). In addition, the scattering phase function has strong regionality, and its expression needs to be modified according to the water body characteristics of the study area (Raúl, et al., 2016); (5) The influence of droplet size on simulation results is neglected. Haule and Freda (2016) studies show that the effect of droplet size distribution on R_{rs} can be as high as 20% at the same crude petroleum concentration.

4. CONCLUSION

R_{rs} is the basic input of bio-optical model in ocean color remote sensing. It is a bridge connecting the apparent optical quantities and the inherent optical quantities. In the water body affected by petroleum substances, inorganic suspended particles in water will adsorb petroleum substances, which will change the scattering characteristics of water, and then change the R_{rs}. The non-linear effect of petroleum on R_{rs} is the result of multi-factor superposition. It can be used to study petroleum contaminated water through radiation transfer mode, such as Hydrolight. It can accurately depict the distribution of underwater light field in petroleum contaminated water, and it is one of the effective tools to study the effects of various components of petroleum contaminated water on remote sensing reflectance.

Based on the measured data of petroleum substances in Dalian Port, the R_{rs} of mixed water with petroleum and sands is simulated and analyzed by Hydrolight. The influence of petroleum substances and suspended sediment on the R_{rs} of water is discussed, which lays a foundation for studying the influence of petroleum substances and suspended sediment on the R_{rs}, The results show that: (1) the R_{rs} of petroleum-only water decreases with the increase of petroleum concentration; (2) the R_{rs} of mixed water decreases with the increase of petroleum concentration; (3) the spectral curve of petroleum-only water will change under the influence of suspended sediment. The peak value of R_{rs} of petroleum substances moves to the long wave direction, and its spectral shape and size are related to the concentration of suspended sediment; (4) Influenced by petroleum substances, the R_{rs} of suspended sediment in blue-green band (400-500 nm) is uncertain, which may increase or decrease, and is increased in the wavelength range of 500 to 700 nm; (5) When the concentration of suspended matter is more than 5.0 mg/L, the spectral curve of petroleum-sand hydrate is similar to that of suspended sediment, which makes the spectral signal of petroleum-sand substance concealed by the spectral signal of suspended sediment.

Because Hydrolight is used to simulate the R_{rs} of mixed water with petroleum and sands to analyze the influence of petroleum substances and suspended sediment on the R_{rs}, there are some errors in the input parameter setting, such as the choice of phase function of petroleum substances. The phase function is FFbb018, which may differ from the actual phase function of the petroleum substance. The model study on the absorption and scattering characteristics of petroleum substances with depth has not been carried out, which makes the simulation results may have some errors. The difference of composition and characteristics of petroleum substances and the influence of droplet size on the theoretical analysis are neglected. Further analysis and testing are needed. Therefore, the above results are only a preliminary result, which needs to be verified by the spectra of petroleum-sand mixed water in the follow-up simulation calculation.

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