



Article

Sentinel-2 MSI Observations of Water Clarity in Inland Waters across Hainan Island and Implications for SDG 6.3.2 Evaluation

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Abstract: Freshwater on islands represents a precious resource and highly vulnerable ecosystem. For monitoring freshwater, satellite remote sensing is efficient and has large-scale application. This study proposed a modified model of the quasi-analytical algorithm ($Z_{SD-QAAv6m}$) to retrieve the water clarity of inland waters ($>1 \text{ km}^2$) across Hainan Island, China using Sentinel-2 multispectral instrument data. By adjusting the threshold of $R_{rs}(665)$, the proposed model could accurately estimate water clarity with diverse optical properties on the island and avoid underestimation in moderately clear waters. Based upon this, the first spatiotemporal analysis of recent water clarity in Hainan Island was conducted. The results show that lake water clarity in the central region was generally higher (with average value of 1.4 m) than that of coastal regions (with average value of 1.2 m). Seasonally, the water clarity during the wet season was usually lower than that in the dry season, with average values of 1.1 m and 1.3 m across the island respectively. From 2017 to 2021, the proportion of water bodies with water clarity $> 0.5 \text{ m}$ increased from 60% to 100%. The overall spatial pattern of water clarity was correlated to the regional vegetation cover in Hainan Island, with higher clarity associated with higher vegetation cover in the central regions. The seasonal variation of water clarity may be attributed to heavy rainfall and runoff during the wet season; while the distinct annual variation may be benefited from the strengthened surface water protections in Hainan Province in recent years. This study provides a practical approach for evaluating the SDG 6.3.2 indicator in Hainan Island using remote sensed water clarity as a comprehensive water quality indicator and the findings could facilitate the island's water resource management and conservation.

Keywords: water clarity; QAA; Hainan Island; inland water; SDG6



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1. Introduction

Hainan Island is the main island of Hainan Province which is the southernmost province of China. Often promoted as “China’s Hawaii”, the climate of Hainan Island is tropical—characterized by hot and humid summers, with mild, pleasant winters. Rainfall in Hainan Island is abundant; the average annual precipitation is 1800 mm but with an uneven spatiotemporal distribution [1–3]. Considering islands in general, their relatively small size compared to that of mainland regions renders them particularly vulnerable to economic and environmental stresses imposed by rapidly growing populations, increasing economic development, and global climate change [2,4,5]. Freshwater represents one of the most precious resources and vulnerable ecosystems on islands. For Hainan Island, although the overall inland water is relatively rich, most of the water bodies consist of smaller artificial reservoirs with an area of less than 10 km^2 [2,5]. With the acceleration of urbanization on Hainan Island, its lakes and reservoirs are facing increasingly serious water quality

issues, such as industrial pollution, domestic sewage, and other water pollution. Recently, Hainan Province was identified as a target for multiple conservation measures including water quality consolidation and improvement and ecological protection of its critical lakes, reservoirs, and watersheds. Moreover, the 2018 construction of the “Hainan Free Trade Port” and the 2021 designation of Hainan Province as a distinctive provincial demonstration area in China for the implementation of Sustainable Development Goals (SDGs) has further promoted protection of the island’s hydro-ecological environment. The hydro-ecological environment of Hainan Island is vital to the overall development of Hainan Province and its water has been specifically recognized as a target of the United Nations (UN) SDGs, of which, SDG 6 is set to “provide and sustainably manage water and sanitation for all”. In the specific target indicators, SDG 6.3.2 is defined as the proportion of water bodies in the country with good ambient water quality [6]. Therefore, the monitoring of inland water quality on Hainan Island is important for evaluating SDG 6.3.2 and understanding the water quality status of its inland water bodies.

With the development of satellite remote sensing technology, satellite remote sensing data have become an important and low-cost data source for monitoring surface water quality on a large scale. Water clarity is an important water quality indicator for assessing water cleanliness and the degree of eutrophication [7]. Water clarity is generally measured using a traditional Secchi-disk, where the disk is lowered into the water and the depth at which the Secchi-disk disappears from the observer’s sight is recorded as the water clarity; this measurement is therefore also called the Secchi-disk depth (Z_{SD}) [8–10]. As a synoptic water quality indicator, water clarity is closely related to the five core water quality parameters proposed by the UN-Water, in the evaluation of SDG 6.3.2, and is considered an important reporting parameter [11].

In the recent decades, a series of remote sensing algorithms for water clarity have been developed, and they can generally be classified into two types: empirical and semi-analytical. While empirical algorithms mainly use single-band or band-combination methods to establish a simple or multiple regression relationship between remotely sensed reflectance and measured water clarity [12–15], semi-analytical algorithms are supported by clear mechanistic models, which can overcome certain regional and temporal limitations of the modeling data [16]. In the updated semi-analytical Z_{SD} model proposed by Lee et al. [16], Z_{SD} was expressed as a function of the remote sensing reflectance (R_{rs}) and the diffuse attenuation coefficient K_d . This algorithm has been widely applied in marine, coastal, and inland waters. However, inland waters are known to possess complex bio-optical characteristics, the model’s application in inland waters often necessitates further calibration [10,17–22]. In particular, the retrieval of water clarity in turbid water bodies using the semi-analytical Z_{SD} model, can be problematic because the choice of reference wavelengths or their thresholds may not be applicable to diverse water types, leading to underestimation of water clarity. [19,23–25]. Although various studies have attempted to improve the semi-analytical Z_{SD} model, most of them have only involved simple calibration of the model without in-depth study on the mechanism of the model. The applicability of the semi-analytical Z_{SD} model in regional water bodies remains to be explored.

In this paper, the semi-analytical Z_{SD} model was improved by adjusting the threshold of $R_{rs}(665)$ in classifying the clear and turbid water types to avoid the underestimation issues in moderately clear waters. With this modification, the performance of the Z_{SD} model was enhanced in regional inland waters across Hainan Island, and it also provides a valuable reference for improving the applicability of the semi-analytical model to derive water clarity in diverse types of inland waters. Based on the modified semi-analytical Z_{SD} model, the water clarity of lakes and reservoirs larger than 1 km² across Hainan Island was estimated using Sentinel-2 multispectral instrument (MSI) data, and analysis the spatiotemporal variations of Inland water in Hainan Island from 2017 to 2021. In addition, the implications for SDG 6.3.2 evaluation and the influencing factors of their spatiotemporal variations are preliminarily discussed.

2. Datasets and Methods

2.1. Study Area

Hainan Island is the largest tropical island in China ($18^{\circ}10'–20^{\circ}10'N$, $108^{\circ}37'–111^{\circ}03'E$, $\sim 33,200\text{ km}^2$), located in the southernmost part of China. The island falls under a marine tropical monsoon climate, characterized by warm temperatures throughout the year. The average daily sunshine is 5.5 h and the average daily temperature is $>10^{\circ}\text{C}$. The terrain of Hainan Island presents a unique pattern of high elevation in the middle and low elevation in the coastal areas. The island also boasts a bountiful precipitation regime, predominantly concentrated between May and October, yielding an average annual rainfall of over 1600 mm. However, the spatial and temporal distribution of rainfall is uneven, exhibiting distinct wet and dry seasons, and the central and eastern parts of the island are relatively more humid. At the same time, the island hosts abundant surface water resources, with most of its lakes and reservoirs being artificial and relatively small, and with river runoff being abundant. Due to the influence of dry and wet monsoons and the island's topography, the surface water of Hainan Island has uneven temporal and spatial distribution characteristics [26]. Moreover, due to the acceleration of urbanization on the island and the advancement of its social economy, the lakes and reservoirs are facing increasingly serious water pollution problems. Thus, the surface water quality of Hainan Island in particular has received increasing attention by the whole Hainan Province.

2.2. In Situ Datasets

In this paper, lakes and reservoirs with a water area larger than 1 km^2 on Hainan Island were selected as the study area (Figure 1). Two in situ measured datasets were obtained for this study: the optical experimental dataset collected from five inland water areas around Sanya City (Dataset I), and a water quality monitoring dataset from 20 inland water areas across Hainan Island, collected by the Center of Ecology Environment Monitoring of Hainan Province (Dataset II). Dataset I was obtained by field surveys around Sanya City from 6–12 January 2022, for which 53 sampling points were obtained from five inland water bodies with the Z_{SD} ranging from 0.7–3.5 m. In addition to Z_{SD} , water sample and remote sensing reflectance were also collected at each sampling point. For these measurements, a typical black and white Secchi-disk was used in the field campaigns to determine Z_{SD} . The disk was lowered into the water, and the Z_{SD} was determined as the depth at which the disk was no longer visible by an observer from the water surface. A portable field spectrometer (ASD FieldSpec[®]3) was used to measure the R_{rs} in the wavelength range of 350–2500 nm according to the “above-water” method [27,28]. Using collected water samples in Dataset I, the concentrations of Chla-a and TSM and the absorption coefficient of CDOM at 440 nm were determined in the laboratory according to the method described in the relevant protocols [27]. In Dataset II, the water clarity data were collected from 20 inland waters across Hainan Island during 2019 and 2021 with the aforementioned method.

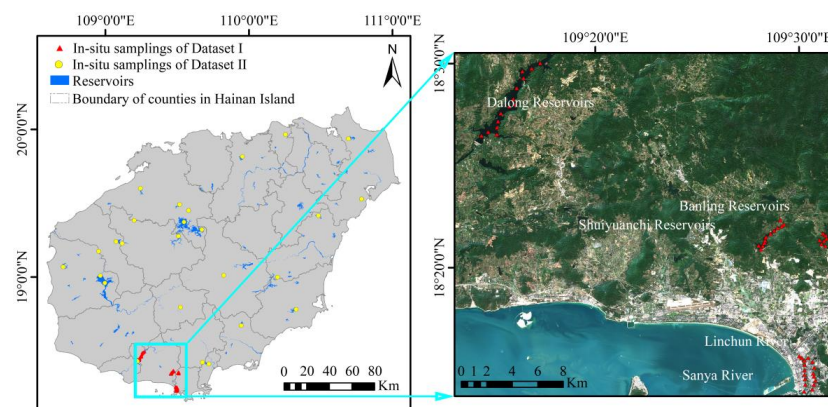


Figure 1. Distribution of the study area and sampling points.

The in situ measured data were spatiotemporally matched with the Sentinel-2 MSI data for model development and validation using the following criteria: (1) The time window was set to ≤ 5 days between the satellite and field-measurement data; (2) the median of the 3×3 window centered at the sampling point was taken for the matches [29]. The criteria yielded 52 pairs of matched data from Dataset I and 43 pairs of matched data from Dataset II (Figure 1, Table 1).

Table 1. Experimental data for Hainan Island.

No.	Water Body	Lat (°)	Lon (°)	Sampling Date (2022)	No. of Samples	Z_{SD} Range (m)
1	Dalong Reservoir	18.4445	109.2456	6 January	15	2.35–3.50
2	Sanya River	18.2349	109.4965	8 January	9	0.87–1.17
3	Linchun River	18.2349	109.5116	8 January	8	0.78–0.96
4	Shuiyuanchi Reservoir	18.3633	109.4762	11 January	11	2.02–2.68
5	Banling Reservoir	18.3556	109.5247	12 January	9	1.28–1.52

2.3. Sentinel-2 MSI Data

Sentinel-2 is a wide-swath, high-resolution, multispectral Earth Observation satellite mission launched by the European Space Agency through the “Copernicus project”, which is composed of the Sentinel-2A and Sentinel-2B satellites. The double satellites enable the MSI data to cover the same area of the equator every 5 days. The Sentinel-2 MSI covers 12 spectral bands, including 4 visible bands (centered at 443, 490, 560, and 665 nm), 6 near-infrared bands (centered at 705, 740, 783, 842, 865, and 945 nm), and 2 shortwave infrared bands (centered at 1610 nm and 2190 nm), with spatial resolutions of 10, 20, and 60 m, respectively.

The Sentinel-2 MSI Level-2A (L2A) data used in this study were surface reflectance data atmospherically corrected by the Sen2Cor processor based on Sentinel-2 Level-1C (L1C) data. Sentinel-2 MSI L1C data covering Hainan Island from 2017–2018 were acquired from the official website of the European Space Agency (ESA) (<https://scihub.copernicus.eu/dhus/#/home>, accessed on 1 April 2022) and then atmospherically corrected for surface reflectance data using the Sen2Cor processor plugged into the Sentinel Application Platform software. The Sentinel-2 MSI L2A data from 2019–2021 were obtained from the Google Earth Engine (GEE) cloud platform. The surface reflectance data were cloud masked using the QA60 band included in the Sentinel-2 products. Based on the cloud mask, images with >30% cloud cover were excluded. Finally, 968 images were obtained. The specific number of images in the wet and dry seasons each year is shown in Figure 2.

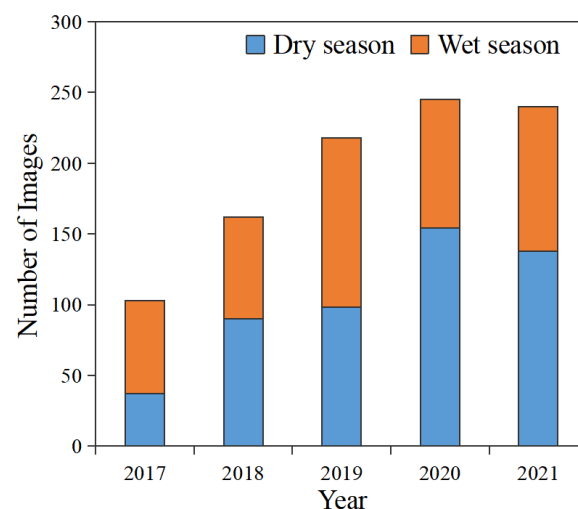


Figure 2. Sentinel-2 data distribution covering Hainan Island for 2017–2021.

2.4. Remote Sensing Reflectance Correction

A pixel-based correction method was used to correct Sentinel-2 MSI L2A data for removing the effects of sun glints and skylight reflections from the surface reflectance data, where it subtracts the minimum value of the near-infrared and shortwave infrared bands from the reflectance of each band [30,31]. Previous studies have shown that this method can be applied to derive remote sensing reflectance from surface reflectance data over large-scale inland waters with acceptable and stable accuracy. The correction formula is as follows:

$$R_{rs}(\lambda) = \frac{R(\lambda) - \min(R_{NIR} : R_{SWIR})}{\pi}, \quad (1)$$

where $\min(R_{NIR}:R_{SWIR})$ represents the minimum reflectance value of the Sentinel-2 MSI L2A data in the near-infrared and shortwave infrared bands.

2.5. Water Area Extraction

In order to determine the best thresholding value for every water body, the algorithm combining the normalized difference water index (NDWI) and Otsu's automatic threshold segmentation was adopted for automatic threshold segmentation of water bodies [32]. Moreover, to ensure the representativeness of small water bodies in the segmentation, the thresholding value for each connected water body was determined within an expanded zone with an area 2.5 times that of the water area, including the water body and a buffer zone surrounding it. In addition, in order to avoid the effect of mixed pixel and land adjacency, a 20-m (2-pixel) buffer inside the water boundary was removed from each water body.

2.6. Z_{SD} Estimation Using a Modified Semi-Analytical Model Z_{SD} -QAAv6m

In this study, the semi-analytical Z_{SD} model based on Quasi-Analytical Algorithm (QAA v6) proposed by Lee et al. [16] was modified to adapt the water clarity retrieval of inland water bodies on Hainan Island.

The modified semi-analytical algorithm for the Z_{SD} estimation was established with three main steps: first, the water was classified into clear and turbid water types with a threshold of $R_{rs}(665)$; second, the total absorption coefficient a (m^{-1}) and the backscattering coefficient b_b (m^{-1}) for the two types of water were estimated based on QAAv6; and third, the diffuse attenuation coefficient K_d (m^{-1}) was estimated and then fed to the semi-analytical model of Z_{SD} (Figure 3). In the first step, a new threshold value of $R_{rs}(665)$, i.e., 0.005, was proposed for distinguishing the clear and turbid waters through analysis of the in situ measured and matched Sentinel-2 MSI data from Hainan Island (Figure 4). By changing this threshold value from 0.0015 to 0.005, the water samples in Dalong Reservoir and Shuiyuanchi Reservoir could be classified into the clear water type, enabling the retrieved Z_{SD} to be no longer underestimated for moderately clear waters. The moderately clear water type indicates the inland waters with Z_{SD} above 2 m but $R_{rs}(665)$ between 0.0015 and 0.005 sr^{-1} . In the second step, QAAv6, which is the latest version of QAA, was applied to derive the a and b_b from the Sentinel-2 $R_{rs}(\lambda)$ data with the updated thresholding value to classify the clear and turbid water types. In the third step, K_d at the transparent window of the water (K_d^{tr}) was calculated with the derived a and b_b based on the radiative transfer model [33]; then, Z_{SD} was estimated with K_d^{tr} and R_{rs}^{tr} based on the semi-analytical model of Z_{SD} [10,16], where R_{rs}^{tr} is the remote sensing reflectance at the transparent window of water. The transparent window of water indicates the wavelength at which the water is mostly penetrative by visible light, and it can be determined by the location of the minimum K_d in the visible domain [16].

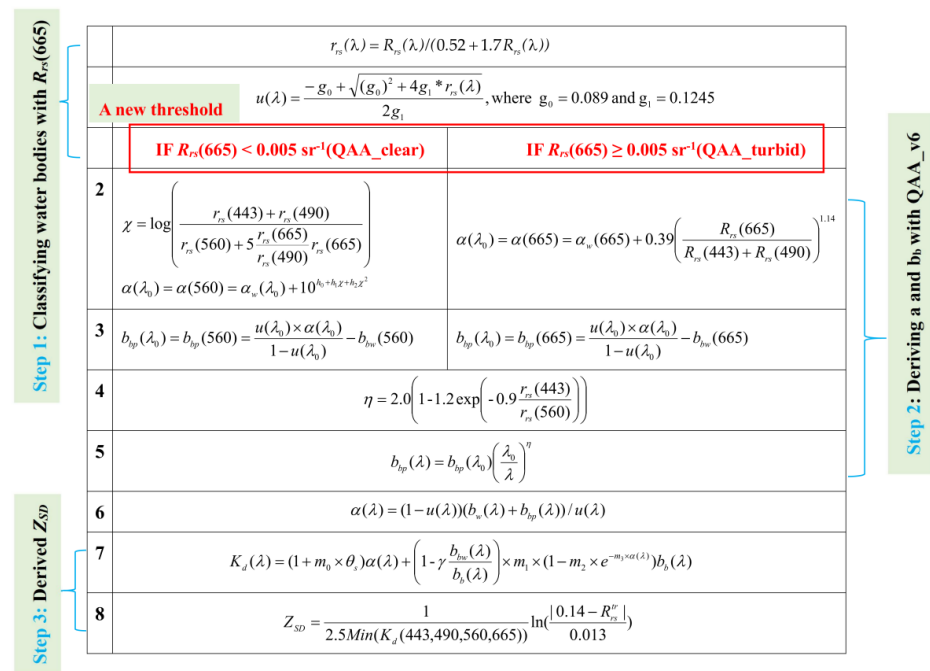


Figure 3. Overall flowchart of the approach to semi-analytically deriving Z_{SD} .

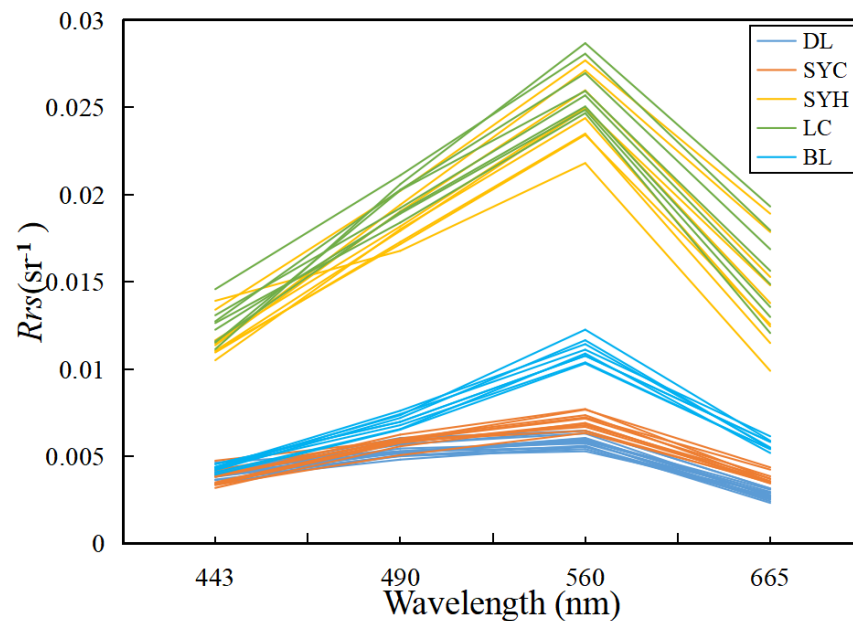


Figure 4. Spectral curve Dataset I at 443, 490, 560, and 665 nm. (DL: Dalong Reservoir; SYC: Shuiyuanchi Reservoir; SYH: Sanya River; LC: Linchun River; BL: Banling Reservoir).

With the derived diffuse attenuation coefficient K_d , the semi-analytical model of Z_{SD} can be expressed as [16]:

$$Z_{SD} = \frac{1}{2.5 \text{Min}(K_d(443, 490, 560, 665))} \ln \left(\frac{0.14 - R_{rs}^{tr}}{0.013} \right). \quad (2)$$

where R_{rs}^{tr} is the remote sensing reflectance of the band corresponding to the minimum diffuse attenuation coefficient K_d .

For brevity, the overall Z_{SD} estimation scheme based on the modified semi-analytical model was called Z_{SD} -QAAv6m, and the Z_{SD} estimation scheme based on the original QAAv6 was called Z_{SD} -QAAv6.

2.7. Accuracy Evaluation

In order to evaluate the performance of the corrected remote sensing reflectance and the Z_{SD} model, this study uses three indicators: the determination coefficient (R^2), the mean relative error (MRE), and the root mean square error (RMSE). The calculation formulas are as follows:

$$R^2 = \frac{\sum_{i=1}^n (y'_i - \bar{y})^2}{\sum_{i=1}^n (y_i - \bar{y})^2}$$

$$MRE = \frac{1}{n} \frac{\sum_{i=1}^n |X - X'|}{X} \quad (3)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^n (X - X')^2}{n-1}}$$

where X and X' are the in situ measured value and model-estimated value, respectively, and n is the number of matched pairs.

3. Results

3.1. Validation of Sentinel-2-Derived Remote Sensing Reflectance

The $R_{rs}(\lambda)$ data corrected from the Sentinel-2 MSI L2A data were validated using the quasi-synchronous in situ measured $R_{rs}(\lambda)$ data. The in situ measured $R_{rs}(\lambda)$ was first converted into the equivalent remote sensing reflectance of the Sentinel-2 MSI band, and then the reflectance-corrected Sentinel-2 MSI L2A data were assessed with the matched in situ data. To demonstrate the feasibility of the matched time window of ± 5 days, the assessment results with a matched time window of ≤ 1 day were also obtained and compared to the results from the matched time window of ≤ 5 days. As shown in Figure 5, with time windows of ≤ 1 day, the $R_{rs}(\lambda)$ derived from the Sentinel-2 data generally had good agreement with the matched in situ $R_{rs}(\lambda)$ data in the four visible bands, where the R^2 was between 0.83 and 0.91, MRE was between 15% and 32%, and RMSE was lower than 0.00005 sr^{-1} . With a time window of ≤ 5 days, the results were generally consistent, with an R^2 between 0.85 and 0.92, MRE between 14% and 27%, and RMSE lower than 0.00004 sr^{-1} (Table 2).

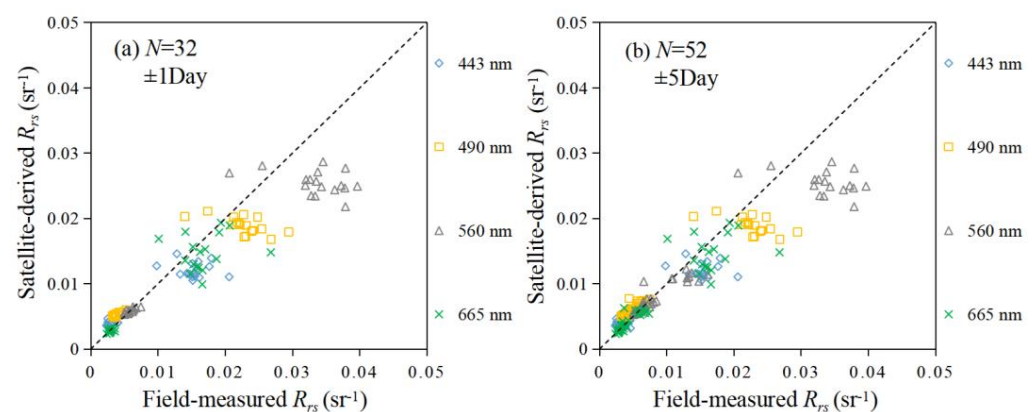


Figure 5. Comparison between the quasi-synchronous in situ measured $R_{rs}(\lambda)$ and Sentinel-2 MSI remote sensing reflectance. (a) ± 1 Day. (b) ± 5 Day.

Table 2. Results of the measured and Sentinel-2 MSI remotely sensed reflectance in four bands.

Band	R^2	MRE	RMSE (sr^{-1})
443 nm	0.90	23.4%	0.0000063
490 nm	0.91	26.3%	0.000012
560 nm	0.92	15.4%	0.000033
665 nm	0.85	14.5%	0.0000069

3.2. Validation of ZSD-QAAv6m Model

This study first used the in situ measured $R_{rs}(\lambda)$ and Z_{SD} data obtained for Hainan Island to evaluate the performance of the Z_{SD} -QAAv6 and Z_{SD} -QAAv6m models. Figure 6 shows the comparison between the Z_{SD} obtained by Dataset I in situ measurements and the matched estimated Z_{SD} via the Sentinel-2 satellite based on the Z_{SD} -QAAv6 model and the Z_{SD} -QAAv6m model. It was found that the Z_{SD} -QAAv6m model performed better ($R^2 = 0.93$, MRE = 12.8%, RMSE = 0.13 m), which could solve the underestimation in Z_{SD} -QAAv6 model when Z_{SD} is above 2 m. The performance evaluation can be explained in that, with the original threshold of $R_{rs}(665)$, QAAv6 identified all samples in Dataset I as turbid water bodies, which consequently led to underestimations in the high-value ranges.

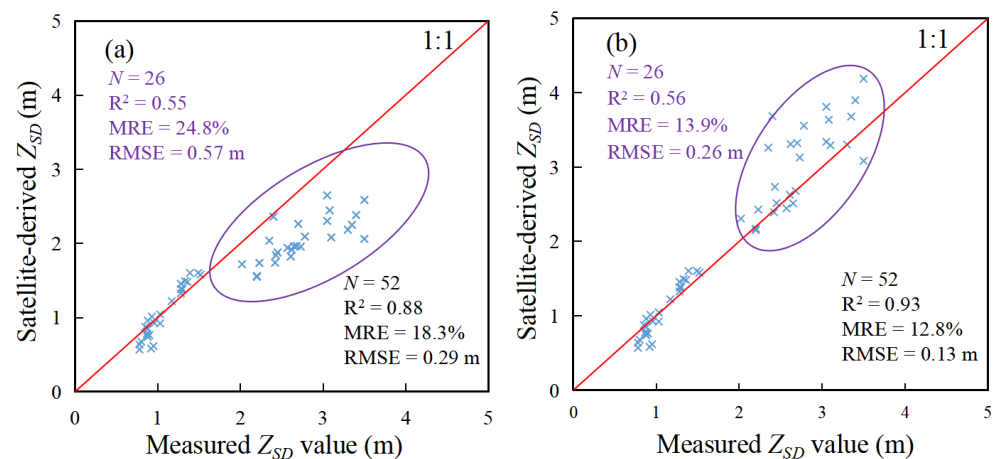


Figure 6. Validation of the model using Dataset I and matched Sentinel-2 data. (a) The Z_{SD} -QAAv6 model, (b) the Z_{SD} -QAAv6m model.

With the recalibrated thresholding value of $R_{rs}(665)$ for distinguishing clear and turbid waters, the underestimation could be avoided, while MRE and RMSE were lowered from 24.8% and 0.57 m to 13.9% and 0.26 m for moderately clear waters, that is, if Z_{SD} was above 2 m but $R_{rs}(665)$ was larger than the original threshold of 0.0015 sr^{-1} . To further test the performance of the Z_{SD} -QAAv6m model, the satellite earth synchronization data of Dataset II were used to test the model. Figure 7 shows the comparison between the measured Z_{SD} data of Dataset II and the Z_{SD} estimated by the matched Sentinel-2 satellite. The results illustrate that the overall performance of the Z_{SD} -QAAv6m model is good for inland waters across Hainan Island ($R^2 = 0.58$, MRE = 27.7%, RMSE = 0.55 m).

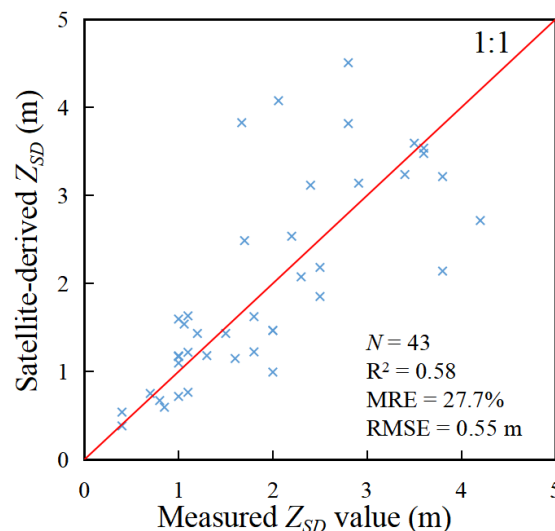


Figure 7. Validation of the Z_{SD} -QAAv6m model using Dataset II for Hainan Island.

3.3. Model Comparison

To demonstrate the applicability of the modified Z_{SD} -QAAv6m model, this semi-analytical model was compared with four published Z_{SD} empirical models based on in situ datasets and matched Sentinel-2 data for Hainan Island. These empirical models included band-ratio algorithms: the Red–Blue ratio model, Red–Green ratio model, and two CIE color-based algorithms, that is, the FUI & Hue-angle model and Hue-angle model [12,14,34–37]. The models were tuned and optimized using Dataset I in situ measurements and then tested using in situ measurements of Z_{SD} in Dataset I and Dataset II and the matched Sentinel-2 data. As shown in Figure 8, the CIE color-based models generally achieved better performance than the band-ratio models, but MRE for the CIE color-based models was generally larger than 30%, and MRE for the modified Z_{SD} -QAAv6m model was less than 30%. These results indicate that the modified Z_{SD} -QAAv6m semi-analytical model outperformed the empirical models in Z_{SD} retrieval for inland waters on Hainan Island using Sentinel-2 data. Thus, the Z_{SD} -QAAv6m model was applied to map the spatiotemporal patterns of water clarity across Hainan Island.

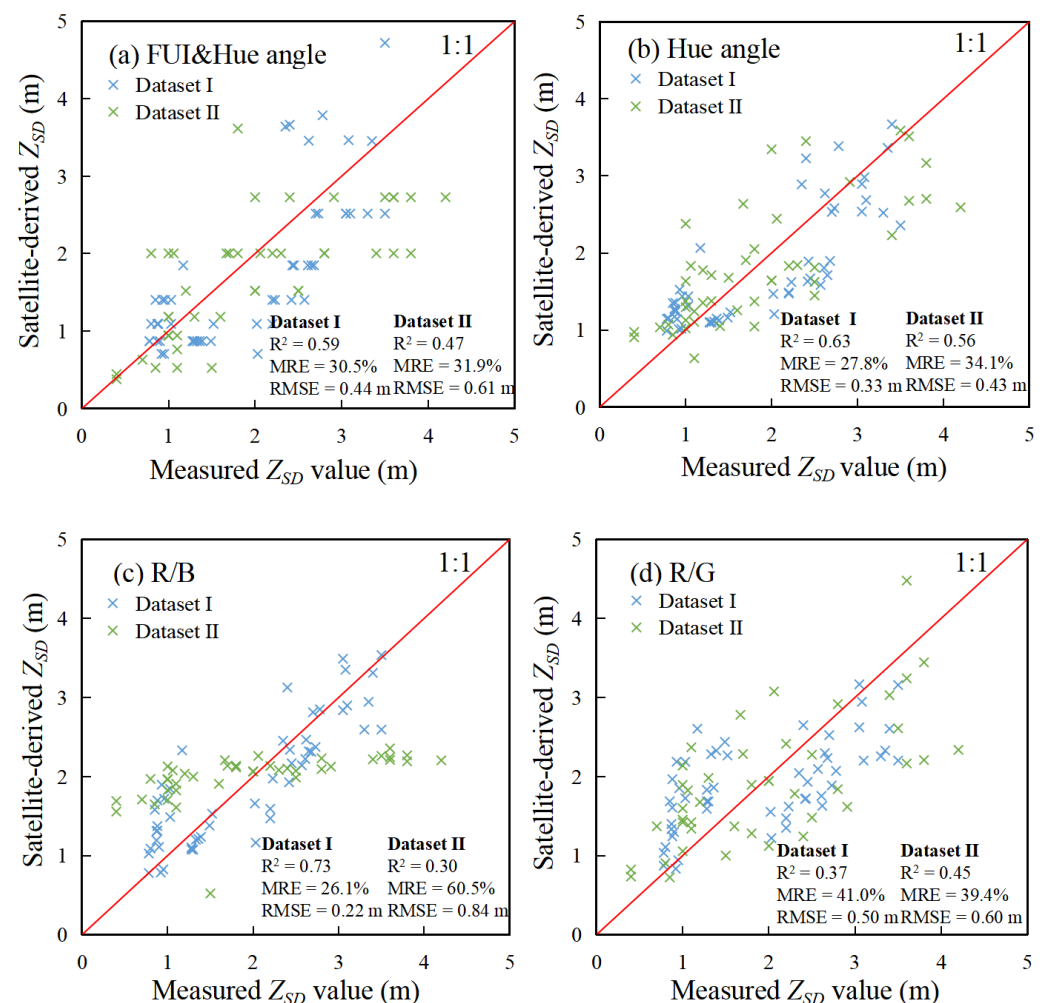


Figure 8. Model comparisons of the (a) FUI and Hue-angle model, (b) Hue-angle model, (c) Red–Blue ratio model, and (d) Red–Green ratio model in Datasets I and II.

3.4. Spatiotemporal Dynamics of Lake Clarity on Hainan Island during 2017–2021

With the available Sentinel-2 MSI data from 2017–2021 on Hainan Island, the water clarity of 61 inland water bodies across the island were mapped using the proposed Z_{SD} -QAAv6m model. To evaluate the seasonal variations, the year was divided into two seasons: wet (May–October) and dry (November to April), according to the tropical climate type of Hainan Island, where frequent rainfall occurs in the wet season and less rainfall occurs

in the dry season. The climatological mean Z_{SD} in the wet and dry seasons between 2017 and 2021 for inland waters across Hainan Island are shown in Figure 9. The results showed that 87.1% of inland water bodies on Hainan Island had higher water clarity in the dry season than in the wet season. In particular, in the northeast coastal areas (Haikou city and Wenchang city), the water clarity in the dry season is significantly higher than that in the wet season. Moreover, the proportions of water clarity across Hainan Island in dry and wet seasons from 2017–2021 were plotted and the results are shown in Figure 10; the water clarity of inland water bodies is generally higher in the dry season than in the wet season. Meanwhile, the average water clarity of water in the wet season was 1.1 m, and that in the dry season was 1.3 m. In addition, it is also shown in Figure 10 that the proportion of water bodies with higher Z_{SD} (≥ 1.5 m) significantly increased, and the proportion of water bodies with lower Z_{SD} (< 0.5 m) significantly decreased from 2017 to 2021. This indicates that the water clarity in inland waters across Hainan Island improved in recent years, although the water clarity in Hainan is lower in the wet season compared with that in the dry season every year.

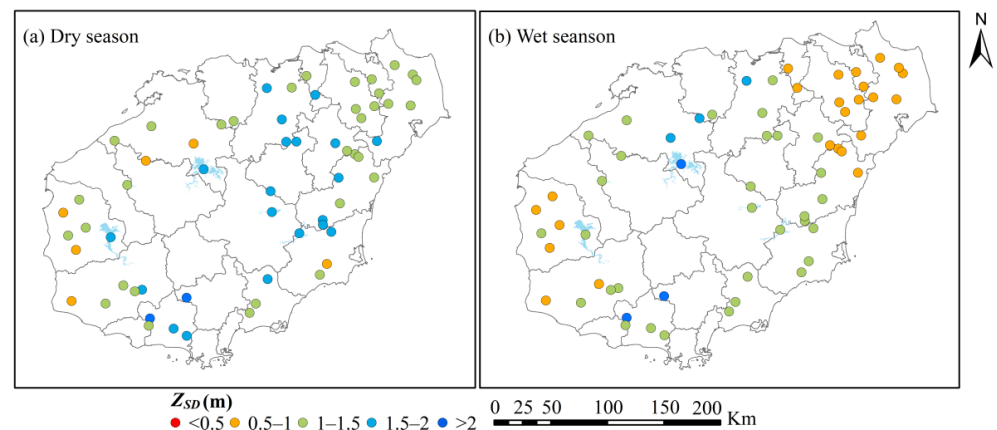


Figure 9. Climatological mean Z_{SD} of inland water bodies on Hainan Island in the (a) dry and (b) wet seasons during 2017–2021.

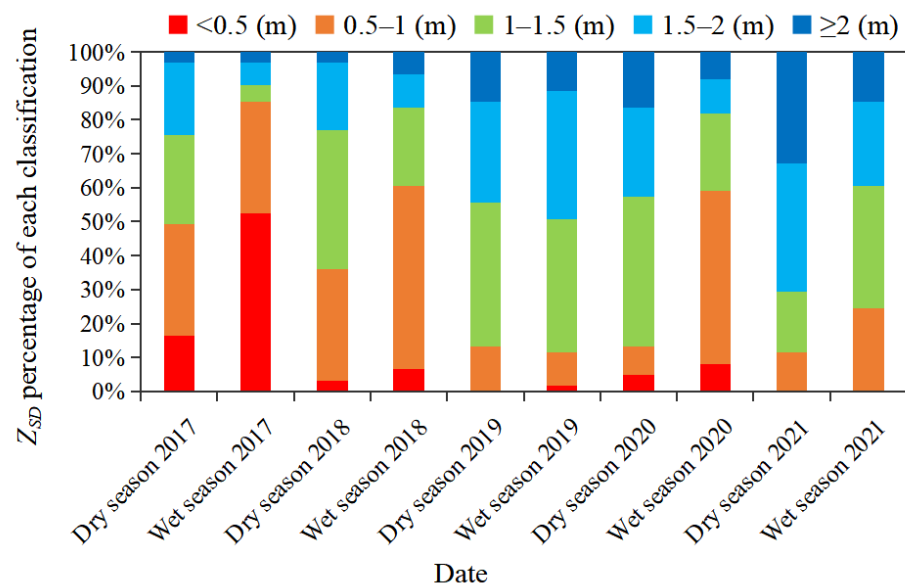


Figure 10. Z_{SD} distribution in the dry and wet seasons from 2017 to 2021.

The spatial variation of water clarity was analyzed according to the administrative divisions of Hainan Island as follows: Baisha Li Autonomous County (BSLZ), Baoting Li and Miao Autonomous County (BTLZ), Changjiang Li Autonomous County (CJLZ), Chengmai County (CMX), Danzhou City (DZS), Ding'an County (DAX), Dongfang City (DFS), Haikou City (HKS), LinGao County (LGX), Ledong Li Autonomous County (LDLZ), Lingshui Li Autonomous County (LSLZ), Qionghai City (QHS), Qiongzong Li and Miao Autonomous County (QZLZ), Sanya City (SYS), Tunchang County (TCX), Wanning City (WNS), Wenchang City (WCS), and Wuzhishan City (WZSS). Among them, BSLZ, QZLZ, WZSS, BTLZ, DAX, and TCX are located in the central region, while the remaining are in coastal regions. As shown in Figure 11, the higher water clarity was observed in the central region of Hainan Island and lower water clarity was found in the coastal regions. The average clarity of the central regions and coastal cities is respectively 1.4 m and 1.2 m. And the proportion of water bodies with clarity greater than 1 m in the northeast coastal area of the Hainan Island in the dry season is higher than that in the wet season; in the wet season, the average clarity of the water bodies in the coastal areas is basically below 1.5 m. In particular, the water clarity of Wenchang City and Haikou City is below 1 m. This may be related to the increase in rainfall in the wet season and the short-term strong rainfall brought by typhoons and land cover type.

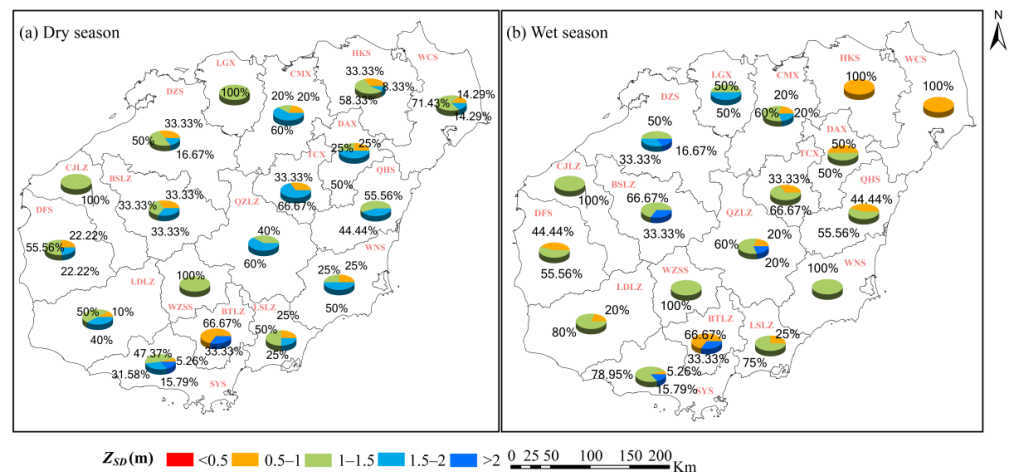


Figure 11. Average proportion of annual Z_{SD} water bodies in the (a) dry and (b) wet seasons for inland water bodies on Hainan Island from 2017–2021.

4. Discussion

4.1. Z_{SD} Estimation Uncertainty

Previous studies have shown that the Z_{SD} inversion algorithm has good performance in open oceans and coastal areas (the Z_{SD} range is 0.1–30 m) [10,16]. However, due to the complex components and bio-optical properties of inland water bodies, the application of semi-analytical algorithms to large-scale inland water bodies is still a challenge, and regional differences must also be considered [12,38]. Meanwhile, the QAAv6 algorithm, which uses the red-band threshold method to distinguish turbid and clean water bodies, has rarely been applied to large-scale inland water bodies and needs further verification and calibration [21,25]. In this study, by modifying the Z_{SD} -QAAv6 model parameters, the Z_{SD} -QAAv6m model showed good adaptability in diverse types of inland water bodies, thereby improving the original model's retrieval capabilities of water clarity in moderately clean water bodies, and ultimately enhancing the performance of water clarity inversion over regional inland water bodies. However, it is noted that the in situ data acquired in this study is limited and the Z_{SD} in this dataset is generally covarying with the total suspended matter in water. For a broader application of the semi-analytical model to inland waters, additional field data collection may help to calibrate and improve the proposed model of this study.

Another limitation is that the atmospheric correction of Sentinel-2 data may introduce some uncertainty to the retrieval of Z_{SD} . First, this is because a more stable atmospheric correction algorithm is needed for an extensive range of complex inland water bodies. Research shows that Sen2Cor has been widely used for complex inland waters [39–42] and has shown good performance in retrieving the water reflectance of inland waters, specifically of Hainan Island (Figure 5), so the Sen2Cor algorithm was another reasonable choice for this study. However, Sen2Cor is not designed specifically for inland waters. In contrast, the Z_{SD} retrieved by QAAv6 depends on the attenuation coefficient $K_d(\lambda)$ as well as $R_{rs}(\lambda)$, while the value of the $K_d(\lambda)$ depends on a and b_b calculated by QAA. The QAA algorithm for water bodies with different turbidity levels needs to change the reference wavelength to obtain more accurate a and b_b . For clean water bodies with low absorption coefficients, QAAv6 is suitably applicable; however, for the more turbid inland waters, due to the high absorption coefficient, QAAv6 will lead to the estimated value of $a(\lambda)$ for turbid water being too small, resulting in an error in water clarity [43]. The atmospheric correction affects the longer wavelength band, thus causing uncertainty in the retrieval of water clarity by the QAAv6 algorithm. Therefore, a more detailed atmospheric correction of Sentinel-2 data for inland waters remains to be identified in the future [40,44].

Finally, due to the frequent occurrence of cloudy weather over Hainan Island, the availability of cloud-free Sentinel-2 data is limited, which makes it difficult to accurately calculate the interannual variation Z_{SD} from satellite data. In future studies, the uncertainties of water clarity inversion will be introduced into the spatiotemporal analysis. Consequently, by utilizing multi-source satellite data, the reliability of water clarity inversion can be improved, thereby enhancing the time-series analysis.

4.2. Environmental Factors Related to the Water Clarity Variations in the Hainan Island

The results illustrated that the water clarity tends to be high in the middle regions of Hainan Island and low in the coastal zone. In previous studies, land cover has been recognized as a significant influencing factor to the regional water quality [45–47] and high vegetation cover can reduce the sediments taken by runoff to the water bodies [48,49]. Studies have shown that the land-cover type of Hainan Island is dominated by tree cover, of which tree cover area accounts for more than 93%, and the vegetation cover in central mountainous cities and counties is higher than that in coastal cities and counties [3,50]. Therefore, the correlation between vegetation cover and regional average water clarity was analyzed using the ESA land-cover product in 2021 derived from GEE [51,52]. As shown in Figure 12, the vegetation cover in the central mountainous area was over 95% and the water clarity was significantly and positively correlated with the regional vegetation cover ($p < 0.05$). This confirms the contribution of high vegetation cover, especially the high tree cover, to the regional water clarity on Hainan Island.

Climate factors are widely recognized as the primary driver of clarity in lakes and reservoirs. As a typical island water system, the inland water bodies of Hainan Island can be largely impacted by rainfall in the region. With heavy rainfall in the wet season, suspended matter and nutrient substances would be brought into water bodies with surface runoff [53–55]; therefore, the water clarity can be relatively low in this season. In contrast, the water clarity can be higher in the dry season when there is little rainfall and runoff. Moreover, due to the typical tropical island climate, the heavy rainfalls are usually accompanied by strong winds and even typhoons in the coastal regions [56]. Therefore, the inland water bodies in the surrounding coastal regions seem to be more vulnerable to rainfall, typhoons, and other climatic factors. In order to further explain the impact of typhoons on water clarity, this study analyzed the changes in water clarity before and after a typhoon. On 13 October 2021, typhoon “Kompasu”, the strongest typhoon to make landfall in Hainan Province in the last 5 years, made landfall in Qionghai City on Hainan Island. Given the typhoon path released by the Hainan Meteorological Information Service Website, the Daguangba Reservoir was used as an example to show the spatial variation of the water clarity in this reservoir before and after the typhoon. As shown in Figure 13, the water clarity of the Daguangba Reservoir decreased significantly after the typhoon. By mixing the

water body and bringing in sediments through heavy rainfall, the typhoon caused an obvious decrease in water clarity of the water body.

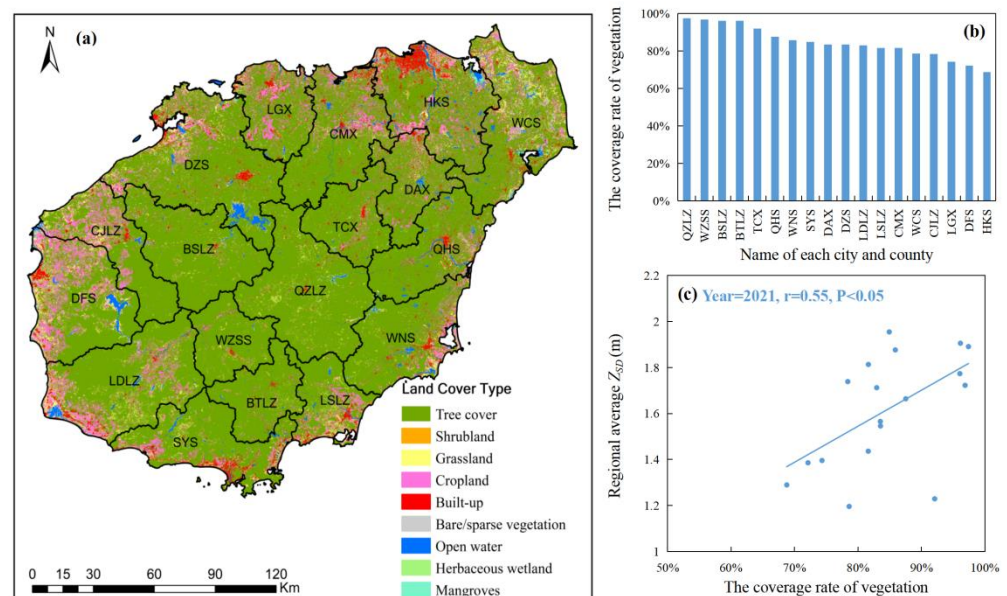


Figure 12. Land-cover types on Hainan Island and their correlation with regional water clarity. (a) The land-cover type of Hainan Island in 2021, (b) the coverage rate of vegetation (including tree cover, shrubland, grassland, and cropland) in regions of Hainan Island, (c) correlations between the Sentinel-2-derived water clarity and vegetation cover in regions of Hainan Island.

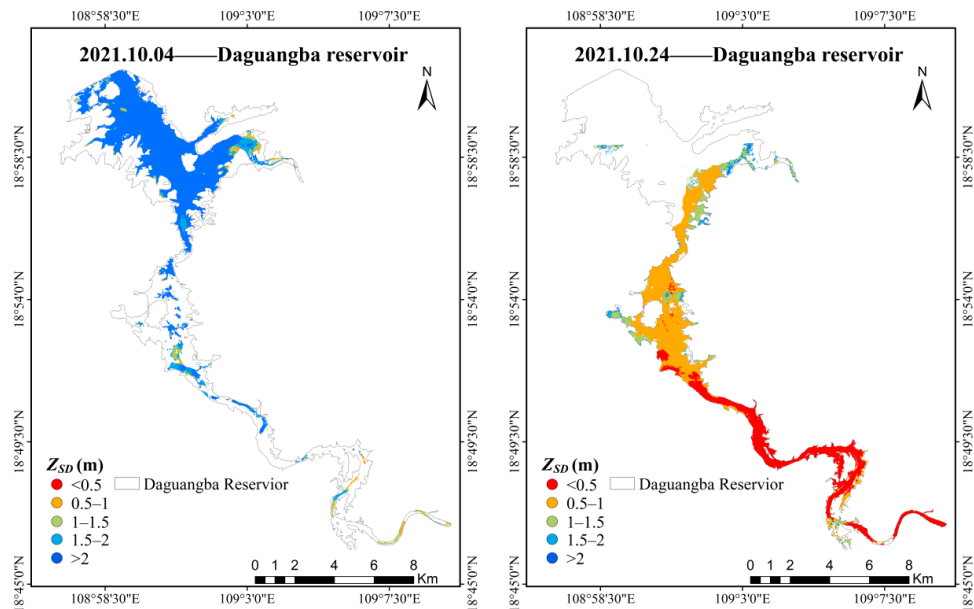


Figure 13. Change in water clarity in the Daguangba Reservoir before and after the heavy rainfall of typhoon “Kompasu” (the blank space within the boundary of the water body indicates the area not covered by the water body or an area in which there are no effective observations).

In terms of the yearly pattern, this study found that the water clarity of inland water bodies on Hainan Island gradually increased between 2017 and 2021. This result is consistent with the results from the Hainan Ecological and Environment Bulletin (http://hnsthb.hainan.gov.cn/hjzl/hjzlx/hjzkgb_51008/, accessed on 15 September 2022). But there was no obvious change in meteorological factors (precipitation, temperature, wind speed) during that period. However, it is noted that Hainan Province has intensified

the efforts to protect the water environment in recent years, particularly after 2018 [57,58]. In this case, human activities may have played an important role in impacting the water clarity change of inland water bodies on Hainan Island during the past 5 years. The monthly water quality report of urban rivers and lakes in Hainan Province also confirmed the positive effect of the relevant policies issued by Hainan Province since 2018 in strengthening the environmental protections and surface water treatments, such as the "Three Year Action Plan for the Treatment of Polluted Water Bodies".

4.3. Implications for the SDG 6.3.2 Evaluation

Z_{SD} is an important and comprehensive optical water quality parameter, which reflects the cleanness of water bodies and the overall water quality to a certain extent [59,60]. In the UN SDG 6, the indicator of SDG 6.3.2 is "the proportion of water bodies with good ambient water quality" [6]. Therefore, the water clarity retrieved by Sentinel-2 data can be used to evaluate water quality, as it can be satisfactorily estimated with satellite data [11,37]. Here, water bodies with average water clarity larger than 0.5 m were identified as having good ambient water quality, because that value is usually regarded as a simple criterion for assessing eutrophic state in inland waters [61]. Therefore, the proportion of water bodies with good water quality in the Hainan Island was evaluated from 2017–2021 using the satellite-derived water clarity data. As shown in Figure 14, the results indicate that the proportion of water bodies with good water quality on Hainan Island was relatively low in 2017 (~75% in the dry season and ~45% in the wet season). After 2018, there was a significant increase in the proportion of water bodies with good water quality on Hainan Island. By 2021, the proportion of water bodies with good water quality in the dry and wet seasons had reached 100%. This indicates that the overall water quality of inland water bodies on Hainan Island improved from 2017–2021.

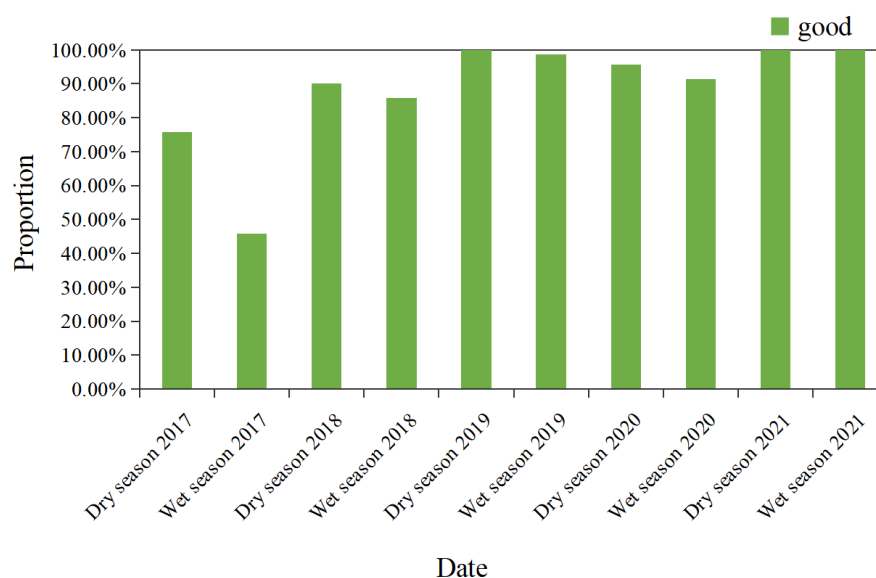


Figure 14. Proportion of inland waters with good quality indicated by water clarity ($Z_{SD} > 0.5$ m) on Hainan Island in the dry and wet seasons, 2017–2021.

5. Conclusions

In this study, the water clarity of lakes and reservoirs larger than 1 km² on Hainan Island was derived using Sentinel-2 MSI data. First, the Sentinel-2 MSI Level-2A data were corrected and evaluated to derive the R_{rs} over inland waters in the Hainan Island. Then, the semi-analytical Z_{SD} model based on QAAv6 was tested and calibrated to cope with the underestimations in moderately clear waters. A modified semi-analytical Z_{SD} retrieval scheme, named Z_{SD} -QAAv6m, was proposed, where the threshold value of $R_{rs}(665)$ in the QAAv6 model for classifying turbid and clear waters was changed to 0.005 from 0.0015 sr⁻¹. With the new scheme, Z_{SD} was better retrieved with Sentinel-2 MSI data with

MRE values less than 30%. Furthermore, compared with other empirical Z_{SD} models, the Z_{SD} -QAAv6m model produced superior performance and demonstrated the capacity of the semi-analytical model to retrieve water quality parameters for regional inland water bodies. Finally, the water clarity of more than 60 inland water bodies on Hainan Island from 2017–2021 was derived and analyzed. The water clarity generally improved from 2017–2021, with the quality lower in the wet season and higher in the dry season. Spatially, it was found the water clarity of Inland waters in central regions was generally higher than that in the coastal regions. The spatiotemporal variations in water clarity are likely related to the distinct climate type and water system distribution of the island and can also be attributed to strengthened water protection measures recently applied in the Hainan Province. In addition, the satellite-derived water clarity results were further applied in the evaluation of SDG 6.3.2 for the past 5 years on Hainan Island.

This paper is the first to use satellite remote sensing data from Sentinel-2 MSI and a semi-analytical algorithm to approach water quality studies and SDG indicator evaluation in island regions. In spite of the advantages, there are still some limitations with respect to using clarity to assess the water quality of inland water bodies. As the single indicator of water clarity used to assess water cleanliness, Z_{SD} may not comprehensively reflect the condition of water quality, thus a more integrated water quality assessment using satellite remote sensing technology remains to be explored. In addition, the modified Z_{SD} -QAAv6m model was fitted by using inland water data from Hainan Island, hence there is still a need to optimize the water body classification scheme in the QAAv6 model with a large amount of in situ measured datasets for a wider application.

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