Estimation of Chlorophyll-a, SPM and Salinity in Mangrove Dominated Tropical Estuarine Areas of Hooghly River, North East Coast of Bay of Bengal, India Using Sentinel-3 Data

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Abstract

This study aims to explore the variations in spatial/Spatio-temporal characteristics of water quality parameters of three estuaries in the western part of the Indian Sundarbans. Reliable retrieval of near surface concentrations of parameters such as Chlorophyll-a, SST & TSM in various aquatic ecosystems with broad ranges of trophic needs has long been a complex issue. In this study the C2RCC processor has been applied that has been tested for its accuracy across different bio optical regimes in inland & coastal waters. Satellite images for the same period were also collected and analysed using the C2RCC processing sequence to retrieve values of parameters such as the depth of water, surface reflectance, water temperature, inherent optical properties (IOPs), salinity, chlorophyll-a and total suspended matter (TSM) using the SNAP software. During the 2017-2020 season, in situ sampling from specific locations and laboratory water quality analysis were carried out. The OLCI retrieved results were then trained and validated using the in situ datasets. It was observed that the highest amount of TSM was recorded in Diamond Harbour during the pre-monsoon, in the year 2018 (301.40 mg L^{-1} in-situ value, and 308.54 mg L^{-1} estimated value). Similarly, chlorophyll-a had higher concentrations during the monsoon season (3.03 mg m^{-3} , in-situ, and 2.96 mg m^{-3} , estimated) in Fraserganj and Sagar south points. Very good fitted correlation results for all seasons between Chl-a, $r = 0.829$ and TSM, $r = 0.924$ were found during the comparisons of OLCI and in situ results. The high level of correlation highlights the importance of both primary and secondary data in understanding any dynamic system properly. Finally, the result shows that the water quality model outperforms conventional techniques and OLCI chl-a and TSM products. This paper empirically investigates a reliable remote sensing method for estimating coastal TSM and chl-a concentrations and supports the use of OLCI data in ocean colour remote sensing.

1. Introduction

The first satellite mission to measure coastal water quality and ocean productivity from space was the Coastal Zone Color Sensor (CZCS), which was launched in October 1978 (Acker, J. 2013, Mondal et al., 2014; Kyriliuk, et al., 2019). This sensor has been used for estimating worldwide productivity, and has led to our increasing understanding of the significance of marine and coastal phytoplankton production (Longhurst et al., 1995; Behrenfeld et al., 2006). Chlorophyll-a is one of the standard water quality parameters monitored in water bodies. It is measured by water sampling and laboratory analysis and through in situ measurements using a water quality checker. However, the CZCS has had difficulties in distinguishing between chlorophyll-a (Chl-a) and Total Suspended matter (TSM). Successive operations by the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA) have aimed to increase the accuracy of the retrieval of various water ingredients from space technology. The launch of OLCI (Ocean and land colour Instrument) on board the Sentinel 3A by the European Space Agency (ESA), in 2016 has enabled better management of the environment and to appreciate and improve data collection influenced by the effects of climate change (Donlon et al., 2014; Bonekamp et al., 2016; Mondal et al., 2019; 2020). OLCI is a follow up to the MERIS mission (2002–2012) (Pavel et al., 2011) with improved capabilities as its spectral configuration is designed for optically complex coastal

and inland waters (Mondal et al., 2018; ESA, 2019; Kyryliuk, et al., 2019). Many studies have demonstrated that the OLCI is currently the most suitable satellite sensor for water color remote sensing in inland waters (Mograne et al., 2019; Xue et al., 2019).

The Hooghly estuary and its tributaries are an extraordinarily complex study object for ocean colour remote sensing. The very high amount of coloured dissolved organic matter (CDOM) received from the Sundarban mangrove forest in the catchment area along with anthropogenic inputs (Thakur et al., 2019) makes the water darker. As a result, the water loss signal is very small, necessitating the use of highly sensitive remote sensing devices as well as extremely precise atmospheric correction. In addition, due to fresh water input in the upper reaches and differential tidal influences, low salinity (psu) is common in some areas, while it is much higher in others. Similarly, there are stark differences in the TSM values along different stretches of the estuaries. This necessitates the need for a good algorithm to study the entire network of estuaries criss-crossing and crossing through the Indian Sundarbans. Eutrophication and hypoxia are regular phenomena in the Indian Sundarbans and, thus, environmentalists have been working to decrease the environmental pollution of runoff. Monitoring of chlorophyll concentrations is a very imperative contribution to evaluating these endeavours. Similar conditions have been reported in the OLCI images, with very good accuracy.

Most of the studies employing the OLCI images have been taken up in Europe and South East Asia. Studies along the eastern coast of India are very limited and, although the Sundarbans is one of the most studied areas in the world, no study using OLCI images has been attempted yet. Because of the fragility of water and the need for continuous monitoring, there is a need for real-time, surface-based studies of water quality parameters. However, due to accessibility and other logistics, that target has not been achieved on a regular basis. This study is an attempt to bridge the gap by using OLCI images from the Sentinel-3 to study a select few parameters of the Hooghly, Saptamukhi and Muri Ganga estuaries.

In this research, we presented a novel empirical model for estimating TSM and Chl-a concentrations in the Sundarban coastal waters of the Hooghly Estuary by integrating OLCI data with in situ data. Finally, the model was applied to time-series Sentinel-3 data to map the spatial distribution of TSM and Chl-a concentrations, and then the geographical and temporal distribution features of Chl-a concentration in the Sundarban coastal deltaic waters were analyzed. The main objectives of the study are- to estimate water quality parameters such as salinity, surface temperature, chlorophyll-*a* concentration, and TSM concentration through seasonal field surveys (in-situ data); to use Sentinel-3 OLCI images in estimating salinity, surface temperature, chlorophyll-*a* concentration, and TSM concentration during 2017-19 by C2RCC processor & to validate the results obtained by the OLCI estimations with the in situ data sets through regression equations.

2. Materials And Methods

2.1 Study area

The study area is part of the Sundarbans delta extending from 21°20'N to 22°40'N and 87°0'E to 89°0'E (Fig. 1) and is crisscrossed by many estuaries which are mostly distributaries of the Hooghly estuary (Thakur et al, 2020ab; Mondal, et al., 2016; 2021b; Bag et al., 2019; Bandyopadhyay et al., 2014). The delta is an ecologically sensitive region that is impacted by regular tidal ebb and flow of 12 durations each (Mondal et al., 2021a). Water samples were collected at nine widely dispersed sampling stations along the mangrove-dominated banks of the Mooriganga, Saptamukhi, and Hooghly estuaries, three distributaries of the Ganges. The names of the stations are mentioned in table 1. A map showing the sampling stations along with specific geographical positions has been shown in figure 1.

The area has a monsoonal climate with three main seasons, viz., pre-monsoon, monsoon and post-monsoon. Seasonal field observations were conducted at all the nine sampling stations during the monsoon season (July-Oct), the post-monsoon season (November-January), and the pre-monsoon seasons (March-June) for a period of two years, from November 2017 to January 2020.

Table 1: Name of sampling stations from North to south

SI No	Station Name	Latitude	Longitude	Estuary
1	BabuGhat	88.286329	22.570876	Hooghly
2	Diamond Harbour	88.266451	22.109261	Hooghly
3	Kachubaria Ghat	88.27585	21.762018	Hooghly
4	Beguakhali Village	88.243013	21.497898	Hooghly
5	Sagar South	88.289175	21.451261	Hooghly
6	Namkhana	88.370176	21.644417	Sapatamukhi
7	Fraserganj	88.40682	21.443597	Sapatamukhi
8	Henry	88.455004	21.437648	Sapatamukhi
9	Bakkhali	88.444891	21.418613	Sapatamukhi

2.2. Data and Methodology

2.2.1 *In situ data measurement and procedures*

The all in-situ samples were collected from the above mentioned stations and later analysed in the Marine science laboratory.

2.2.1.1. *In-situ water sample collection*

During this study, in situ biogeochemical data from nine sampling stations spanning a period of 2 years (2017-2019) was used. These stations are unique ecosystems, including coastal estuaries with varying degrees of tidal influences and human activities. The Sentinel-3 satellite passed over the selected sampling area around 09.32 am IST and water sample collection was carried out on 13.06.2018 &

19.06.2019 for the monsoon, 13.12.2017, 10.12.2018 & 2.01.2019 for the post-monsoon, and 21.04.2018 & 24.04.2019 for the pre-monsoon. All water samples were collected using clean plastic buckets from the middle portion of the river using mechanized boats. Both field data and satellite data were collected on the same day and at the same time (9.32 a.m. IST $\pm$ 30 min), irrespective of the tidal conditions in the estuary. Collected water samples were kept in acid cleaned dry polythene bottles and brought to the laboratory for the measurement of suspended particulate matter and salinity. The surface water temperature was measured at each station using a hand-held thermometer. The transparency was measured using a metal Secchi disc of 20 cm in diameter. The mean of three Secchi disc depths was considered as the transparency of water at each station (Preisendorfer 1986; Lee et al. 2015). Soon after collection, all the samples were transported to the laboratory. Every time, triplicate samples were collected and analysed periodically to check the reproducibility of results and to evaluate the precision of measurements. Salinity was measured by argentometric titration following the Mohr-Knudsen method (Grasshoff et al. 1983). Suspended particulate matter was separated by filtering an aliquot of water sample (1-2 liters) through a pre-weighed 0.45 (μ m) Millipore membrane filter under vacuum, and weighing it with an accuracy of (0 ± 0.1 mg) after drying at 60°C or in desiccators in the presence of Conc. H_2SO_4 .

2.2.2.2 Estimation of Salinity and Temperature

Salinity was estimated through the argentometric titration method, following Strickland & Parsons, 1972. Samples of waste-water (15 ml) were titrated against a standard AgNO_3 solution, using a K_2CrO_4 solution (3.5 g l^{-1}) as an indicator. Silver nitrate solution was previously standardized against standard seawater solution (3.5 g NaCl in 96.5 ml distilled water), having chlorinity 19.375 ppt and salinity 35‰. The salinity and chlorinity were related by Knudsen's equation; $S_{\text{‰}} = 0.03 + 1.805 \text{ Cl}_{\text{‰}}$. This method is accurate up to 0.05 to 0.1 ‰ of salinity. The water temperature was recorded during each sample collection using a laboratory thermometer.

2.2.2.3 Chlorophyll measurement

For the validation of water parameters, we collected around 15–20 cm under the river surface using Niskin bottles, and samples have been transported to the laboratory for further analysis. Water samples were filtered through 0.7 μ m Whatman glass fiber filter (GF/F) paper under low vacuum and kept in acetone of 90% concentration at 0°C for 24h in the dark for the complete extraction. The extracted solution was centrifuged at 10000 rpm for 10min and the solvent was used to estimate Chl-*a* concentration using a Shimadzu UV-vis 2450 spectrophotometer following the method described in Strickland and Parsons (1972). The precision of Chl-*a* estimation is at the 5 μ g level, the correct value lies in the range:

Mean of n determinations $\pm 0.26/n^{1/2}$ μ g Chl-*a*

2.2.2.4 TSM measurement

The organic and inorganic section of (TSM in mg L^{-1}) has been measured using the gravimetric method detailed by Toming (2017) and also the MERIS protocols. Whatman Glass Fiber Filters (GF/F) are washed with ultrapure water to remove any drop filter bits, and they now combust at 480°C with an instruction to burn off any conceivable organic contamination (Doerffer et al., 2002). The weighted clean filters and they are kept in a folded square of aluminum foil paper ($0.020 * 100 * 100 \text{ mm}$) through counted numbers up to their percolation. In accumulation, the amount of water samples (1–2 L) has been filtered in triplicates over and done with the pre-weighed and also pre-combusted filter methods (Kratzer et al., 2018). The funnel and filter wash the clean water, then add 50mL of ultrapure water to take out any residual salt. The filters were dried up overnight at 60°C and preserved in a desiccator prior to consideration by a microbalance ($\pm 1\mu\text{g}$). TSM was obtained through the dissimilation of both the tare and the dry weight. Then, the sample data is combusted at 480°C in an incinerator, monitored by an alternative weighing stage. The weight of the inorganic TSM was then equal to the weight of the combusted filters (modified tare weight), and the organic segment was the variance of the entire and the inorganic TSM.

2.2.3. Sentinel-3 Satellite data processing

2.2.3.1. Image pre-processing

The Sentinel-3 Ocean and Land Colour Instrument (OLCI) has a specification sensor as per its precursor Medium Resolution Imaging Spectrometer (MERIS) on ENVISAT with the capability to achieve an analysis of bio-optical ingredients in global coastal and inland regions (Doerer et al., 1999, Moore et al., 1999; Merheim-Kealy et al., 1999). The Sentinel-3 OLCI bands (Table 2) are an inheritance of MERIS and are supplemented to improve the quality of the measurement of ocean colour remote sensing. The Sentinel 3 OLCI instrument swath area covers around 1270 km and it's tilted across by a track of 2.6 in the opposite track to the sun's angle in direction to minimize the potential effect of sun glint (ESA, 2019). Cloud free images for the period 2017-2020, viz. the monsoon (June), post-monsoon (November), and pre-monsoon (April) were downloaded and used in the study. The Sentinel-3 satellite passed over the selected sampling area around 9.32 am and satellite images with a ± 6 -hour time lag from water sampling timings were collected on the following dates: 13.06.2018 & 19.06.2019 for the monsoon, 13.12.2017, 10.12.2018 & 2.01.2019 for the post-monsoon, and 21.04.2018 & 24.04.2019 for the pre-monsoon. Using the SNAP software, the images were corrected for atmospheric effects. The Case-2 Regional/coast colour (C2RCC) processor was used for atmospheric correction (Brockmann et al., 2016). The C2RCC processor is a processing chain that helps in retrieving water quality parameters such as Chl-a, TSM, SST and salinity. The processor consists of two neural nets. One net removes atmospheric and water surface effects (such as glint), while the other net retrieves absorption and scattering coefficients from which optically active substance concentrations (such as Chl-a) are calculated. The processor is available freely through the SNAP (Sentinel Application Platform) software. Finally, we have used the cloud-free pixel values relating to each sampling station's location were extracted from each thematic layer and verified against ground truth data. The extraction multi-layer values to points tool in Arc GIS was used to extract the Chl-a and TSM indices from the images at locations specified in a point feature class. For each input raster cluster

value, a new field containing the cell values for each input raster is added to the input particular point feature class, and each pixel that covered the geographic location of the station value is extracted. After that, an attribute table was exported to Microsoft Excel to build a connection between both the radiometric values and in-situ Chl-a and TSM concentration, as well as an analysis of the models produced. Figure 2 shows a summary of the methods used in this study.

2.2.3.2. Methods

The water pixels are processed exclusively by the Sentinel 3 OLCI data processing system. A part of it is based on atmospheric correction, which produces water-leaving reflectances and, as a by-product, the aerosol load above it, and the other part is based on ocean colour processing, which is the derivation of the colour of the water body itself from the water-leaving reflectance's of the suite of products describing it.

Table 2: OLCI bands with MERIS heritage bands and additional highlighted in bold (source: ESA)

Band Number	Central Wavelength (nm)	Bandwidth (nm)	Function
Oa1	400	15	AC, improved water constituent retrieval
Oa2	412.5	10	CDOM and detrital pigments
Oa3	442.5	10	Chl absorption maximum
Oa4	490	10	High Chl and other photosynthetic pigments
Oa5	510	10	Chl, TSM, turbidity and red tides
Oa6	560	10	Chl reference (minimum)
Oa7	620	10	TSM
Oa8	665	10	Chl (2nd absorption maximum), TSM and CDOM
Oa9	673.75	7.5	Improved fluorescence retrieval
Oa10	681.25	7.5	Chl fluorescence peak
Oa11	708.75	10	Chl fluorescence baseline
Oa12	753.75	7.5	O ₂ (oxygen) absorption and clouds
Oa13	761.25	2.5	O ₂ absorption band and AC aerosol estimation
Oa14	764.375	3.75	AC
Oa15	767.5	2.5	O ₂ A-band absorption band used for cloud top pressure
Oa16	778.75	15	AC aerosol estimation
Oa17	865	20	AC aerosol estimation, clouds and pixel co-registration, in common with SLSTR
Oa18	885	10	Water vapour absorption reference band
Oa19	900	10	Water vapour absorption
Oa20	940	20	Water vapour absorption, linked to AC
Oa21	1020	40	AC aerosol estimation

2.2.4. Data integration

The results of the laboratory analysis were then arranged in a systematic manner. Cloud free OLCI C2RCC processed pixel values corresponding to the sampling location points were extracted. These values of data sets giving chl-a, TSM, SST and Salinity were also added to the database (Table 1; Fig. 2).

2.2.5. Statistical analysis

The validation operations took place between 2017 and 2020 in the Hooghly estuary of the Bay of Bengal. In different seasons of the year, marine, coastal, and inland water bodies have been covered, including in situ measurements of parameters such as chlorophyll-a, TSM, salinity, and sea surface temperature. After the datasets were assembled in one database, they were subjected to statistical analysis, and finally, the OLCI retrieved data validated with the in situ results by applying regression and correlation analysis using Matlab software.

3. Results

The physico-chemical and biological characteristics of a flowing river system largely depend on the tidal impacts, the intensity of contribution from point and non-point sources contributing on both sides of the banks, and the anthropogenic activity in and around the riverine system. Thus, the variations of the studied components are ascribed to tidal variations, spatial variations, and seasonal and annual variations. In this research, we have estimated the water quality parameters from Sentinel-3 images along with multi-seasonal in-situ field data and have tried to validate and analyse the findings.

3.1 Variation of Sea Surface Salinity

Salinity, being the primary differentiating characteristic between freshwater and seawater, has shown significant variation in our study zone. In all seasons, Babughat station has recorded the lowest values, while Henry's island has had the highest salinity values. During the monsoon season, salinity is at its lowest, and at its highest during the pre-monsoon season. During the monsoon, mean salinity varied from 0.25 ± 0.07 at Babughat to 21.28 ± 3.08 at Bakkhali with small lower values of 20.86 ± 2.06 at Henry's island and of 20.93 ± 1.80 at the Sagar south sampling points. Another major contributor to mean monsoonal mean salinity was Fraserganj with 20.55 ± 2.55 . During post-monsoon highest salinity of 24.36 ± 0.97 was recorded at Henry's island and the lowest of 0.55 ± 0.05 at Babughat. Other major observations of higher post monsoonal salinity were Kachubaria Ghat with 15.07 ± 3.66 , Sagar south with 23.76 ± 2.60 , Namkhana with 20.41 ± 1.82 , Bakkhali with 23.79 ± 1.17 , and Fraserganj with 24.06 ± 1.55 . Babughat, being dominantly freshwater, also showed the lowest mean salinity of 0.61 ± 0.41 during the pre-monsoon season, whereas Henry's island showed the highest value of 27.89 ± 0.61 salinity. Other stations with higher salinity observed were Sagar south with 27.45 ± 0.28 , Bakkhali with 27.16 ± 0.33 , Fraserganj with 26.14 ± 0.21 , and Namkhana with 25.87 ± 0.35 . Though Diamond Harbour is a major point on the Hooghly River, being situated in the upstream region has comparatively lower levels of mean

salinity in all seasons. The mean salinity observed here was about 1.18 ± 0.45 during the post-monsoon, 1.43 ± 0.66 during the pre-monsoon, and 0.78 ± 0.60 during the monsoon season (Fig. 3).

3.2 Variation of Sea Surface Temperature

Water temperatures are generally higher during the monsoon and pre-monsoon seasons than during the post-monsoon season. During the post-monsoon, mean water temperatures have varied from 19.97 ± 3.32 °C at BabuGhat to 24.43 ± 0.25 °C at Henry's island. During this season, mean water temperatures at other stations were 22.40 ± 2.97 °C at Diamond Harbour, 20.10 ± 0.52 °C at Sagar south, and 24.38 ± 0.16 °C at Bakkhali. During the monsoon, the same parameter has varied from 28.75 ± 2.47 °C at Kachubaria to 33.90 ± 3.54 °C at Diamond Harbour. The mean water temperatures at some other stations were 31.35 ± 0.21 °C at Beguakhali, 31.48 ± 0.39 °C at Fraserganj, and 31.50 ± 0.57 °C at Bakkhali. Summer has dominated the pre-monsoon, resulting in higher mean water temperature values at all sampling stations. In this season it varied between 34.65 ± 0.64 °C at Sagar south and 30.05 ± 0.07 °C at Beguakhali and Henry's island and 30.05 ± 0.35 °C at Bakkhali. In the same season, the mean water temperature at BabuGhat was 32.90 ± 2.69 °C and at Diamond Harbour it was 33.90 ± 0.14 °C (Fig. 4). A point to be mentioned is that the water temperature variation majorly depends on tidal circulation and the sample collection time. Hence, from its variation, no important conclusion can be drawn directly.

3.3 Mapping Chl-a Concentration from the OLCI Images

Chlorophyll content of water is an excellent indicator of biotic production in any aquatic system. In estuaries like Hooghly, chlorophyll-*a* concentrations significantly describe water circulation and dilution patterns. It is sometimes also an important indicator of anthropogenic input of nutrients into the nearshore areas. In our study, the monsoonal concentration of in-situ (field survey) Chl-*a* was lower than in the other two seasons. During the monsoon, the mean Chl-*a* concentration varied from 1.16 ± 0.10 mg m⁻³ at Henry's Island to 2.47 ± 0.36 mg m⁻³ at Diamond Harbour. Among other stations, Namkhana had exhibited 1.42 ± 0.16 mg m⁻³, Sagar south had exhibited 1.86 ± 0.31 mg m⁻³, Babu Ghat had exhibited 1.72 ± 0.68 mg m⁻³, Beguakhali had exhibited 1.73 ± 0.22 mg m⁻³ and Bakkhali had exhibited 1.40 ± 0.10 mg m⁻³ (Fig. 5). During the same season, the estimated (Sentinal-3) Chl-*a* values were lower than the in-situ values. The estimated values varied from 0.68 ± 0.03 mg m⁻³ at Namkhana to 1.47 ± 0.29 mg m⁻³ at Fraserganj (Fig. 6a).

During post-monsoon the estimated Chl-*a* values were higher compared to the monsoon, with a highest of 1.96 ± 0.80 mg m⁻³ at Sagar South and a lowest of 1.05 ± 0.28 mg m⁻³ at Henry's Island. Other major contributors to the in-situ mean Chl-*a* concentration in the post-monsoon season were 1.13 ± 0.05 mg m⁻³ at Babu Ghat, 1.22 ± 0.27 mg m⁻³ at Diamond Harbour, 1.16 ± 0.83 mg m⁻³ at Namkhna point, and 1.53 ± 0.40 mg m⁻³ at Bakkhali point (Fig. 6b).

During the same season, the in-situ Chl-*a* levels were higher than the estimated levels. The in-situ Chl-*a* varied from 2.28 ± 0.70 mg m⁻³ at Sagar South to 1.26 ± 0.04 mg m⁻³ at Babu Ghat (Fig. 5) When

compared to the other two seasons, pre-monsoon concentrations of in-situ Chl-*a* were highest. During the pre-monsoon, the mean in-situ Chl-*a* concentration has varied from $2.45 \pm 0.50 \text{ mg m}^{-3}$ at Bakkhali to $1.23 \pm 0.14 \text{ mg m}^{-3}$ at Namkhana. Higher mean in-situ Chl-*a* concentrations were also observed on Henry's Island, i.e. of $2.15 \pm 0.52 \text{ mg m}^{-3}$, in Diamond Harbour, i.e. of $1.80 \pm 0.31 \text{ mg m}^{-3}$, in Babu Ghat, i.e. of $1.72 \pm 0.14 \text{ mg m}^{-3}$ and in Sagar South, i.e. of $2.07 \pm 0.24 \text{ mg m}^{-3}$ in this season (Fig. 5).

Again, in the pre-monsoon season, the estimated Chl-*a* concentration was lower than the in-situ values. The highest estimated Chl-*a* concentration was recorded at Bakkhali, i.e. $1.82 \pm 0.44 \text{ mg m}^{-3}$ and the lowest was at Namkhana, i.e. $0.80 \pm 0.16 \text{ mg m}^{-3}$ in this season during 2018 – 19 (Fig. 6c). This trend of mean Chl-*a* concentration variation has indicated that as the river flows downstream towards the Bay of Bengal, the parameter gets diluted and so the productivity drops lower.

3.4 Mapping of Total Suspended Matter (TSM) from the OLCI Images

The weight of total suspended matter (TSM) is dependent upon a number of factors present in the water column, e.g. turbidity, chlorophyll concentration, waste water dilution, and tidal fluctuations. Because of massive anthropogenic inflows, the upstream parts of the Hooghly estuary have shown higher values. TSMs concern their Bay of Bengal ward counterparts, with Beguakhali as an exception during the post-monsoon and monsoon seasons. During the post-monsoon season, the mean weight of in-situ TSM was the highest, $129.24 \pm 27.08 \text{ mg L}^{-1}$ at Diamond Harbour, and the lowest, $25.53 \pm 9.48 \text{ mg L}^{-1}$ at Babu Ghat. Other major contributors to the post monsoonal mean weight of in-situ TSM were Namkhana with $57.97 \pm 23.01 \text{ mg L}^{-1}$, Kachubaria with $101.71 \pm 32 \text{ mg L}^{-1}$, Henry's Island with $82.65 \pm 18.21 \text{ mg L}^{-1}$ and Bakkhali with $69.87 \pm 25.44 \text{ mg L}^{-1}$ (Fig. 7).

The estimated TSM was higher compared to the in-situ values for this season. The highest estimated TSM concentration was recorded at Diamond Harbour, i.e. $134.61 \pm 30.55 \text{ mg L}^{-1}$ and the lowest was at Babu Ghat, i.e. $41.86 \pm 22.24 \text{ mg L}^{-1}$ (Fig. 8a). During the pre-monsoon, the scenario changes. With a mean weight of estimated TSM of about $114.06 \pm 30.61 \text{ mg L}^{-1}$, Babu Ghat had exhibited the lowest and, with about $281 \pm 26.95 \text{ mg L}^{-1}$, Kachubaria had acquired the highest position. Among other upstream sampling stations, Diamond Harbour had exhibited $180.58 \pm 25.83 \text{ mg L}^{-1}$ and Namkhana had exhibited $102.93 \pm 84.48 \text{ mg L}^{-1}$. Among downstream points, Sagar south had exhibited $119.26 \pm 11.39 \text{ mg L}^{-1}$ and Henry's Island had exhibited $179.99 \pm 18.68 \text{ mg L}^{-1}$ (Fig. 8b). This season, the highest in-situ TSM was measured at Kachubaria ($273.05 \pm 28.35 \text{ mg L}^{-1}$) and the lowest at Babu Ghat ($108.03 \pm 27.72 \text{ mg L}^{-1}$) (Fig. 7).

During the monsoon season at Fraserganj, the highest mean weight of estimated TSM, i.e. $150.41 \pm 26.17 \text{ mg L}^{-1}$ was observed, and at Babu Ghat, the lowest value of $26.30 \pm 2.49 \text{ mg L}^{-1}$ was observed. Similar to this, the weight of in-situ TSM was also highest at Fraserganj, i.e. $148.96 \pm 25.36 \text{ mg L}^{-1}$ and

was lowest at Babu Ghat at $24.64 \pm 2.77 \text{ mg L}^{-1}$. Among other downstream points, Kachubaria has exhibited a $76.35 \pm 2.97 \text{ mg L}^{-1}$ estimated and a $72.38 \pm 2.33 \text{ mg L}^{-1}$ in-situ TSM concentration. Bakkhali had an in-situ TSM concentration of $130.52 \pm 6.35 \text{ mg L}^{-1}$ and an estimated TSM concentration of $95.75 \pm 44.28 \text{ mg L}^{-1}$. Whereas among upstream points, Diamond Harbour has exhibited an $89.80 \pm 39.27 \text{ mg L}^{-1}$ estimated and a $95.50 \pm 6.50 \text{ mg L}^{-1}$ in-situ TSM concentration. Namkhana had an in-situ TSM concentration of $45.63 \pm 14.77 \text{ mg L}^{-1}$ and an estimated TSM concentration of $47.20 \pm 11.19 \text{ mg L}^{-1}$ (Fig. 7; 8c).

Though Beguakhali is a major point in the downstream part of the Hooghly estuary, it has been shown to have lower values of the mean weight of the in-situ and estimated TSM in all seasons. It has shown a weight of an estimated TSM of $64.79 \pm 19.19 \text{ mg L}^{-1}$ during the post-monsoon, $136.49 \pm 27.82 \text{ mg L}^{-1}$ during the pre-monsoon, and $57.53 \pm 18.21 \text{ mg L}^{-1}$ during the monsoons.

3.5 Correlation between estimated in-situ field data and Sentinel-3 OLCI data

Aside from the chlorophyll-a and TSM, statistical regression analysis of Sentinel-3 reflectance data is an experimental method for obtaining algorithms for the interpretation of blue ocean color and inland water bodies. For ease of understanding of statistical variations, we have abbreviated the chlorophyll-a and TSM data in the following way:

Sentinel-3 estimated chlorophyll concentration – $X_{\text{Chl.a}}$ Sentinel-3 estimated TSM amount – X_{TSM} , Field in-situ chlorophyll concentration – $Y_{\text{Chl.a}}$, & Field in-situ TSM amount – Y_{TSM} .

The figures, 9a & 9b, represent the best-fitted line plots for both Chl-a and TSM. This plot was created using all of the season values. This indicates the significant linear relationship between the sentinel-3 data and field data. When studied for individual seasons, the regression equations are different. The values for chlorophyll-a were well distributed and represented the statistical variability. But for TSM, some biased readings towards the lower representatives were observed. This may be attributed to location-specific biotic environmental interactions and pollution.

During pre-monsoon individual regression equations turned out as $Y_{\text{Chl.a}} = 0.3548 + 1.042 X_{\text{Chl.a}}$ ($R^2 = 0.823$) and $Y_{\text{TSM}} = 36.10 + 0.7905 X_{\text{TSM}}$ ($R^2 = 0.866$) for Chl-a and TSM respectively. This scenario further changes during the monsoon season.

During the monsoon, the linear relationships were $Y_{\text{Chl.a}} = 0.5736 + 1.023 X_{\text{Chl.a}}$ ($R^2 = 0.613$) and $Y_{\text{TSM}} = 28.94 + 0.7172 X_{\text{TSM}}$ ($R^2 = 0.628$) for Chl-a and TSM respectively.

But during post-monsoon the relationship normalizes and the equations turned out as $Y_{\text{Chl.a}} = 0.4900 + 0.9300 X_{\text{Chl.a}}$ ($R^2 = 0.847$) and $Y_{\text{TSM}} = 10.79 + 0.7658 X_{\text{TSM}}$ ($R^2 = 0.774$) Chl-a and TSM respectively. These inferential statistical analyses helped to determine that our acquired objective for comparing

ground data and satellite data is significantly viable for larger populations and varied hydrological parameters. This could be bolstered further by a correlation study between the two.

Table 3. Table showing Seasonal correlation between Sentinel-3 observed data and field data of Chl-a and TSM

Season	Parameter	r value	p value
Monsoon	$Y_{\text{Chl.a}} \text{ vs. } X_{\text{Chl.a}}$	0.619	0.006
Post Monsoon		0.920	0.000
Pre Monsoon		0.907	0.000
Monsoon	$Y_{\text{TSM}} \text{ vs. } X_{\text{TSM}}$	0.792	0.000
Post Monsoon		0.880	0.000
Pre Monsoon		0.931	0.000

A significant correlation was observed between field data and Sentinel-3 data in all seasons along the Hooghly River for both parameters, i.e. Chl-a and TSM (Table 3). All r values for individual seasons were > 0.5 , which indicates a significant relationship. This may further be supported by p values, i.e. all values ≤ 0.05 . This validates the level of accuracy of field sampling and also states the importance of both primary and secondary data in understanding any dynamic system properly. When studied for all seasons, for Chl-a, $r = 0.829$ and $p = 0.000$ and for TSM, $r = 0.924$ and $p = 0.000$. Both these were again significantly supported by the strength of satellite data and field data variables. Although there is an ongoing debate among researchers about the reliability of primary field data versus secondary satellite data, this type of comparative study may serve as a bridge between the two and will have a futuristic application of interpretation in oceanic research.

The study's findings indicate that there is a strong need to develop an algorithm specific to the Hooghly estuary, particularly for the C2RCC processor, because the current ones only provide sensible reflectance outcomes in Chlorophyll and TSM circumstances and correlation with in-situ data.

4. Discussion Of The Study

In the present scenario, the spectral and temporal resolution of OLCI makes it ideal for mapping and collecting water quality parameter information for large-scale coastal waters. The OLCI data has been acquired nearly daily using the Sentinel-3A and Sentinel-3B satellites' ocean monitoring programme. However, image quality is constantly affected by the weather, particularly in cloudy and rainy subtropical coastal regions such as the Sundarban delta. This limits the usefulness of the OLCI images for studying

ocean colour, yet this climatic factor is unavoidable in optical remote sensing. To acquire additional ocean colour information in the future, we should explore combining multi-source satellite data. Furthermore, the atmospheric adjustment is important for retrieving ocean colour. The quality of the atmospheric adjustment has a significant impact on the remote sensing inversion outcome. For ocean colour modelling, a good atmospheric correction technique can provide high-quality reflectance data.

Despite the fact that ocean colour missions have given us with a plethora of ocean colour products, their suitability for use in local environments has not been determined. In this study, we compared the Chl-a and TSM with a correlation matrix-based model on in-situ measurement with the inherent optical properties (IOPs) product. While the spatial distribution of TSM and Chl-a concentrations from various techniques is usually comparable, the TSM and Chl-a values from each method have vastly different ranges. The primary reason for this is that field measurement data for other ocean colour models has been gathered from different ocean areas throughout the years, while field survey data for the correlation matrix-based model is collected from the Hooghly estuary's coastal waters (Fig. 10). According to our result shows the Sentinel-3 products are suitable for ocean color monitoring in Hooghly estuary of Sundarban coastal waters. Although the correlation matrix-based technique has shown positive results in the coastal waters of the Hooghly estuary, for the spatial application of this method. Finally, our approach, on the other hand, offers significant reference value for the study of ocean colour in other coastal regions.

5. Conclusions And Outlook

The retrieval of the estuarine water quality parameters and its subsequent validation was generally successful with moderately consistent results (comparatively stumpy bias and scatter) for the Chl-a, TSM, salinity, and water temperature. In general, the C2RCC does well in recovering a remote sensing spectrum with a distinctive deltaic shape for estuary waters with a reflectance peak at 560 nm. Results showed that the highest concentration of chlorophyll-a was observed during the post-monsoon period (2.96 mg m^{-3} , estimated and 3.17 mg m^{-3} , in-situ) on Sagar Island South. The amount of chlorophyll-a belongs moderately in the continental shelf zone than continental slope because of the abundance of phytoplankton. That is why the continental shelf zone is better for fishing activities. The in-situ results total amount of TSM has decreased progressively into land towards the sea completely over the year (2017-2020). The amount of TSM is very low at the most upstream sampling point, i.e. Babu Ghat. It has shown a mean of 36.76 mg L^{-1} in-situ and 58.04 mg L^{-1} estimated TSM in all seasons of our study period. The study results have also shown the highest amount of in-situ TSM at Fraserganj during the monsoon time in 2019 (174.32 mgL^{-1}), much more in the monsoon period than in the post-monsoon period in the Hooghly estuaries.

The aim of this study was to test the performance of Sentinel 3A OLCI in coastal waters by evaluating the results of atmospheric correction ocean colour products produced by a standard processor (C2RCC) and the results point to very good performance in the test. Very good fitted correlation results for all seasons between Chl-a, $r = 0.829$ and TSM, $r = 0.924$ were obtained during the comparisons of OLCI with the in

situ results. The high level of correlation highlights the importance of both primary and secondary data in understanding any dynamic system properly. This research could pave the way for future research into the estuarine waters of the Indian Sundarbans, which are difficult to access for laboratory-based studies. Real-time monitoring using OLCI images and the application of different algorithms could bring about a very good chance in the environmental monitoring programs of the Indian Sundarbans.

Declarations

Ethical Approval: Not applicable

Consent to Participate: Not applicable

Consent to Publish: Not applicable

Authors Contributions:

Aakash De: Conceptualization, **Ismail Mondal:** Conceptualization, Writing- original draft, Software, Formal analysis, Visualization. **Subhanil Nandi, Sandeep Thakur,** Data curation, Formal analysis; Writing- original draft, Visualization. **Mini Raman, and Tarun Kumar De:** Writing, Review and editing, Supervision.

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Competing Interests:

This manuscript has not been published or presented elsewhere in part or in entirety and is not under consideration by another journal. There are no conflicts of interest to declare.

Availability of data and materials:

The data that support the findings of this study are available from the author, [**Ismail Mondal, ismailmondal58@gmail.com**], upon reasonable request.

Declarations:

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Figures

Figure 1

Location map of the study area

Figure 2

Flowchart showing the Methodology of Water Quality Modelling using Sentinel-3 images

Figure 3

Seasonal Variation of In-situ Salinity at the different stations

Figure 4

Seasonal Variation of In-situ Water Temperature (°C) in different stations

Figure 5

Seasonal Variation of In-situ Chlorophyll-*a* (mg m⁻³) at the different stations

Figure 6

(a) Chlorophyll-*a* distribution during the monsoon season (2018 & 2019). **(b)** Chlorophyll-*a* distribution during the post monsoon season (2017, 2018, 2019). **(c)** Map showing the distributions of Chlorophyll-*a* during the post monsoon season (2018 & 2019)

Figure 7

Seasonal Variation in Weight of TSM (mg L^{-1}) at the In-situ stations

Figure 8

(a). Map showing distribution of TSM during the Post Monsoon season (2017, 2018 & 2019). **(b).** Map showing distribution of TSM during the Pre- Monsoon season (2018 & 2019). **(c).** Map showing distribution of TSM during Monsoon (2018 & 2019)

Figure 9

(a). Regression plot for Chlorophyll-a (Y Chl. a is the in-situ value and X Chl. a is the Sentinel 3 estimated value). **(b).** Regression plot for TSM (Y TSM a is the in-situ value and X TSM. a is the Estimated value)

Figure 10

In-situ Measurement of Water Quality Estimation in the Hooghly Estuary

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