

IDENTIFICATION OF BEST-SUITED CHLOROPHYLL ESTIMATION MODEL IN MUMBAI COASTAL WATERS DURING PRE-MONSOON SEASON

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ABSTRACT:

This study attempts to find the best suited *chlorophyll* estimation model for the coastal waters off Mumbai, situated on the western coast of India. These waters are a part of the *Arabian Sea*, highly productive with optical characteristics of case-2 type. There are several diffuse and point sources of domestic and industrial sewage effluent outlets along the coast, apart from two major marine outfalls located around 3.5 km into the sea. The study attempts to use *MODIS* data for the pre-monsoon season and test several existing *chlorophyll* estimation models for their site and season suitability for this area, with the help of synchronous sea-cruise data. The study area has been divided into various subgroups of ambient water quality difference, namely, highly sediment-laden water (outfall zones), high chlorophyll concentration zone and mixed water patches (high sediment + high chlorophyll concentration). The models are tested for each of these regions with the help of in-situ chlorophyll_a data, and their behaviour is analyzed through *regression* based analyses.

1. INTRODUCTION

1.1 General introduction

Pollution of various environments is a consequence of population growth and industrialization. The coastal zone is the most intensively utilised area compared to all other areas in the world of human settlements. Here, population growth is considered to be the driving force of almost all development-management problems, particularly due to conflicting interests. Globally, the number of people living within 100 km of the coast has increased from roughly 2 billion in 1990 to 2.2 billion in 1995 due to population explosion in coastal region; i.e., 39 percent of the world's population (WRI, 2003). High population growth and increased occupation of coastal areas are not limited to developing countries, but are also present in most developed nations. One of the effects of the current population scenarios is that, in the next 30 years, more number of people will live in the coastal zone than that are alive today (NOAA, 1994). For these reasons, coastal resources will continue to be placed under diverse, intensive and often competing pressure.

Therefore, it is essentially important to frequently monitor the change of water-quality in the coastal areas. In the recent years, the ocean science community has become increasingly interested in remote sensing of the complex coastal waters. Airborne or satellite remote sensing is an efficient way to monitor the water-quality by retrieving the chlorophyll-a, yellow substances and suspended matter which are indicators of the ambient water conditions. Remotely sensed data provide rapid and repeated information over large and often inaccessible coastal areas, in comparison to traditional ship and

mooring measurements which are usually biased both seasonally and spatially; not to mention the high costs involved, which is often difficult for a developing nation to bear. Fortunately, satellite remote sensing now provides the oceanographic community with almost daily coverage of the world oceans.

1.2 Need for the Study

The study area under consideration lies on the western coast of India, comprising the coastal and partly offshore waters of the Mumbai coast. These waters are part of a very resource-rich stretch of the Arabian Sea with bi-annual productivity blooms. The area is not only important in terms of natural species richness and fishery resource, but also as the sewage dumping ground of ever-growing metropolis of Mumbai, the economic capital of India. There are several sewage outfalls along the city coast which directly open into the sea, while there are two operational marine outfalls with more in the planning stage. The sewage thus generated has certainly a great effect on the sea-water quality, in terms of turbidity and production. The area also has many natural ports and harbours and thus is very important to the shipping industry, too.

However, studying water quality parameters here through remote sensing techniques is difficult as the coastal waters are optically complex, of case-II type (Morel and Prieur, 1977); at least three relevant ocean colour parameters (Chlorophyll, Suspended Particulate Matter (SPM) and Yellow substances) can vary independently of each other. Because of this inherent variability of the bio-optical constituents, remote sensing algorithms for the retrieval of chlorophyll need to be location and season specific, and relatively complex with respect to

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Case I algorithms where phytoplankton are alone the principal agents responsible for variations in optical properties of the water (Gordon and Morel, 1983).

1.3 Remote sensing of coastal waters

The optical complexity of Case-II waters arises from the fact that the interactions between the optically active constituents are nonlinear, and have spectrally varying effects on the remotely sensed signal. The change in optical signal may be minor with respect to the change in the concentration of a variable component, and moreover, two or more substances may have a similar influence on the signal at some wavelengths. This signal competition makes it difficult to decouple chlorophyll information from the optical contributions of the other two major constituents; yellow substance and suspended particulates (Muller-Krager et al., 2005).

Similarly, global algorithms for estimation of the water colour parameters such as chlorophyll, yellow substance and suspended particulate matter do not work well in the current study area. Hence, a thorough study of the optical characteristics within the scope of remotely sensed data is needed for developing seasonally-suited local algorithms. This study attempts to study the behaviour of global chlorophyll algorithms such as OC-2 V.4 (O'Reilly et al., 2000), Chlor_a_2 (Carder et al., 1999a) and Chlor_a_3 (Carder et al., 1999b) algorithms using pre-monsoon in-situ data. For this purpose, 1 km aggregated spatial resolution MODIS-Terra data is used.

1.4 Study area

The study area lies on the western coast of India, comprising of the coastal and offshore waters off the coast of Mumbai, roughly falling within the latitude-longitude coordinates: 19° 8' 23" N, 72° 39' 54" E and 18° 48' 26" N, 72° 58' 17"E. The area is predominantly hot and humid. The average annual rainfall is 1917.3 mm. About 94 per cent of the annual rainfall in Greater Mumbai District is received during the south-west monsoon months of June to September. The area is rich in natural resources, being a part of the Western Ghats of India, an area of great biological diversity. It is also very important from environmental point of view as it supports a vast area of mangrove forest besides flora and fauna at certain stretches. The study area has several major creeks and river systems. The Thane creek is a major source of silt in the area and a convenient disposal site for treated as well as untreated effluents.



Figure 1. Study area (Mumbai coast with field sampling locations)

Apart from this, there are Mahul creek and Ulhas Estuary, which also contribute significantly to the localized turbid patches in the study area. Hence, the area has great variability in terms of water clarity within this small stretch of about 70 km.

2. MATERIALS

Main requirement of the project was satellite data and satellite pass-synchronous sea-truth data.

2.1 Satellite data

Satellite data used for the project was from the sensor MODIS onboard Terra satellite of EOS NASA. The MODIS Level 1B dataset contains calibrated and geo-located at-aperture radiances for 36 discrete bands located in the 0.4 to 14.4 micron region of electro-magnetic spectrum.

Central Wavelength (nm)	Resolution (m)	Revisit time (days)	Nominal Band Solar Irradiances mW/cm ² /μm
412	1000	2	171.18
443	1000	2	188.76
469	500	2	203.52
488	1000	2	194.18
531	1000	2	185.94
551	1000	2	187.00
555	500	2	183.76
645	250	2	158.74
667	1000	2	152.44
678	1000	2	148.14
748	1000	2	127.60
859	250	2	95.728
869	1000	2	94.874
1240	500	2	45.52
1640	500	2	22.99

Table 1. MODIS sensor description

2.2 Sea-truth data

Sea-truth data collected and used for the project mainly consisted of water quality parameters, which included biological parameters such as photosynthetic pigments (chlorophyll_a, b, c and total chlorophyll) and primary productivity) and transparency parameters (SPM and Secchi disk depth). For the current communication, chlorophyll_a concentration derived from field data has been used along with satellite data for assessing the algorithms of chlorophyll estimation. Cruise dates for which cloud free satellite data were available were 27th February, 3rd March, and 6th May, 2010 (sampling location are shown in Figure 1).

3. METHODOLOGY

The main thrust areas were sea-truth data collection and analysis, satellite data collection, pre-processing and analysis and further field correlations. Methodology for this work is given in details below.

3.1 Sea truth data collection and analysis

For this study, the most important requirement was satellite synchronous sea-truth data. Most of the observations were carried out on board small mechanised fishing vessels, for the pre-monsoon season. Surface water samples were collected by using cleaned polythene buckets; below surface samples were collected with water sampler. Analytical methods followed are as per Standard Methods of the American Public health Association, 1998.

3.1.1 Chlorophyll Estimation

Phytoplankton chlorophyll was estimated using UNESCO protocol (1966). The samples were stored in clean bottles and are filtered as soon as possible using 47 mm GF/F filter paper. The suction pressure was below 0.5 atm. After filtration the filter papers were flooded with the 90% acetone and were kept for 24 hours in darkness in refrigerated condition. The extract was centrifuged (~4000 rev/minute, for 10 minutes). 1 cm clean cuvettes were used for spectrophotometric analysis. The absorption spectra in the range 380-750nm was collected. The equation used for chlorophyll_a estimation is from Strickland and Parsons (1968):

$$Ca [mg m^{-3}] = (11.6 D_{665} - 1.31 D_{645} - 0.14 D_{630}) v / V * L \quad (1)$$

Where, Ca = chlorophyll_a concentration, D = Optical Density, v = Volume of acetone [ml], L = Cell (cuvette) length [cm] and V = Volume of filtered water [L].

3.1.2 SPM estimation

For SPM concentration estimation, seawater samples were collected from undisturbed or temporarily disrupted area. A sample volume of 1 Litre was filtered through a pre-washed, pre-dried (at 103-105 °C) 0.45µm filter paper. This was dried

and reweighed to calculate SPM in mg/L. SPM was calculated by using the equation below

$$SPM [mg/L] = ([A-B]*1000)/C \quad (2)$$

Where, A = final dried weight of the filter [mg], B = Initial weight of the filter [mg], C = Volume of water filtered [L].

3.2 Satellite data collection, pre-processing and analysis

MODIS data, synchronous with the sea-cruise dates were downloaded in HDF format from ECHO-WIST web archive (<https://wist.echo.nasa.gov/api/>). The datasets were imported, geo-referenced and subsetted using ENVI 4.2 software. A Bow-tie correction was applied to the images for correcting the swath distortion (which arises as the pixels towards the edges of the scan have increasingly larger coverage on the ground and the coverage of pixels from the subsequent mirror swaths partly overlaps). Dark pixel subtraction was applied to each image, band by band, for a basic atmospheric correction; assuming that the study area being small (around 70 km in length), the aerosol cover over it will not vary significantly on a particular day at a particular time (satellite imaging snapshot time).

Next, radiance is calculated using the gain and bias values for each band given in the metadata. The radiance is converted into remote sensing reflectance (R_{rs}) by using the formula:

$$R_{rs} = nL_w / F_0 \quad (3)$$

Where, nL_w = normalized water leaving radiance (replaced by radiance after dark pixel correction here), and F_0 = Nominal Band Solar Irradiances ($mW/cm^2/\mu m$) as given in Table 1.

There are several global chlorophyll_a retrieval algorithms available for application on MODIS data. Of these, four algorithms were chosen for this study, which are given in the table below:

Algorithm	Empirical equation	Band ratio R)	Coefficients (a)
OC2 V. 4 (O'Reilly et al., 2000)	$C = 10^{(a_0 + a_1 \times R + a_2 \times R^2 + a_3 \times R^3 + a_4)}$	Log (Rrs490/Rrs555)	[0.319, -2.336, 0.879, -0.135, -0.071]
Chlor-MODIS (Clark, 1997)	$C = 10^{(a_0 + a_1 R + a_2 R^2 + a_3 R^3 + a_4/e)}$	log (nLw443+nLw 488)/nLw551	Coefficients when $R > 0.9866$ are: a = [-2.8237, 4.7122, -3.9110, 0.8904, 1] Coefficients when $R < 0.7368$ are: a = [-8.1067, 12.0707, -6.0171, 0.8791, 1]
Chlor-a 2 (Carder et al., 1999)	$C = 10^{(a_0 + a_1 R + a_2 R^2 + a_3 R^3 + a_4 R^4)}$	log [max(r25, r35)] where r25 = Rrs443/Rrs551, r35 = Rrs 488/Rrs551	[0.2830, -2.753, 1.457, 0.659, -1.403]
Chlor-a 3 (Carder et al., 1999)	$C = 10^{(a_0 + a_1 R + a_2 R^2)}$	log(Rrs488/Rrs551)	[0.289, -3.2, 1.2]

Table 2. Chlorophyll algorithm description

Chlorophyll_a concentrations were retrieved from the MODIS images using these four algorithms. Of these, Chlor_MODIS algorithm developed by Clark (1997) uses water leaving radiance instead of remote sensing reflectance.

4. RESULTS AND DISCUSSION

Concentrations of chlorophyll_a derived from the satellite images were correlated with the field data. As described above, the study area happens to be very diverse in terms of water clarity and composition. Hence, the sampling locations were sequestered into classes such as highly sediment-laden water (outfall zones), high chlorophyll concentration zone (deep sea point) and mixed water patches with high sediment and chlorophyll concentration (Southern Tip point, stations 4 and 5). These classes were basically derived from field knowledge and literature. The results are given below:

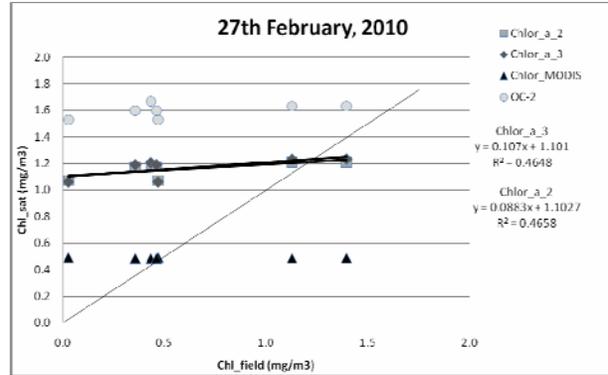


Figure 2. Variation of algorithm output on 27th Feb, 2010

The variation of modeled chlorophyll_a concentration (Chl_sat) values are compared against the observed chlorophyll concentration in field (Chl_field). The central line denotes the 1:1 correlation line to emphasize the deviation from ideal. As seen from figure 2 and 4, all algorithms fail to depict the actual chlorophyll concentration scenario for two dates (27th Feb and 6th May, 2010); however, Chlor_a_2 and Chlor_a_3 perform very close to each other. The reason for this may be the poor data quality of the satellite images for these two dates, and insufficient atmospheric effect correction.

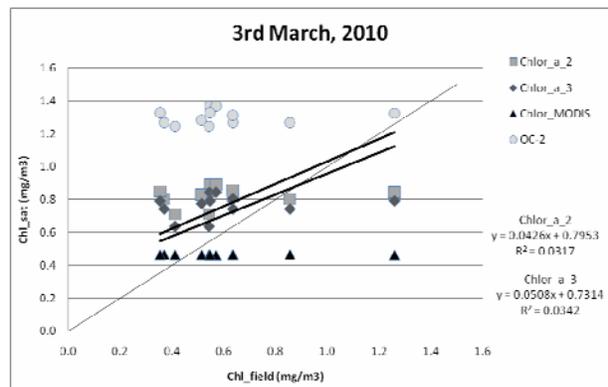


Figure 3. Variation of algorithm output on 3rd Mar, 2010

However, as can be seen from Figure 3, on 3rd March, 2010 Chlor_a_2 and Chlor_a_3 algorithms have good correlation with field data. In this case Chlor_MODIS significantly underestimated the Chl_a concentration, whereas OC-2 Overestimated it.

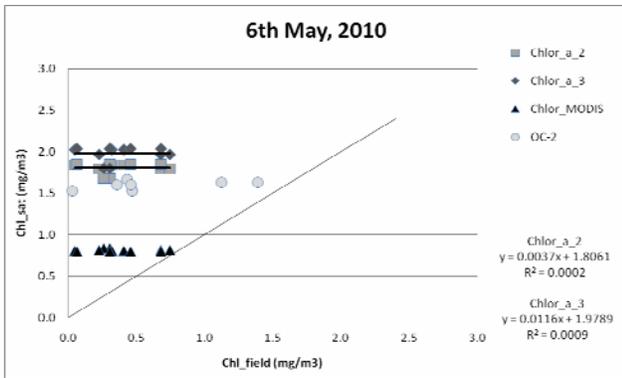


Figure 4. Variation of algorithm output on 6th May, 2010

It was also noted that the algorithm output significantly deviated from field data in the presence of high sediment content. Therefore, the variation in the study area for location rather than sampling day was studied. From this it was found that in the outfall locations, output from all the algorithms were negatively correlated to the field values; yet if only data of 3rd March is considered, Chlor_a_2 and Chlor_a_3 give the most significant correlation.

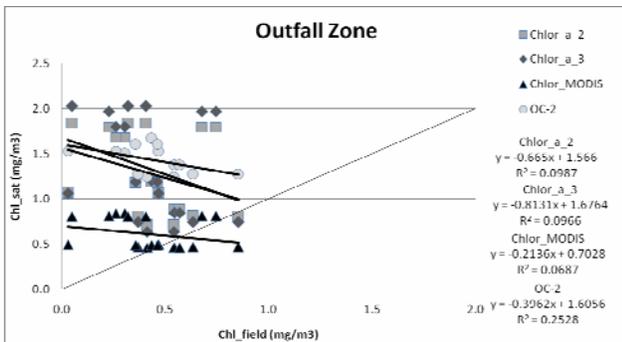


Figure 5. Algorithm behaviour in the outfall area for 3 cruise dates

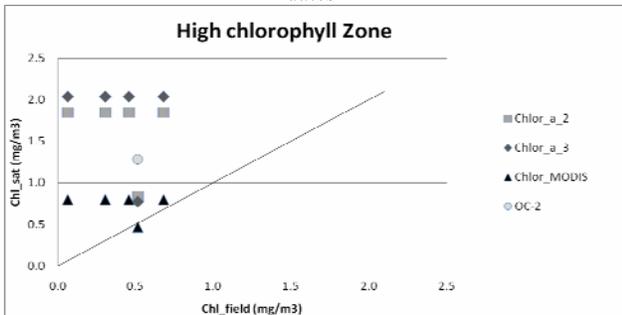


Figure 6. Algorithm behaviour in the high chlorophyll concentration zone for 3 cruise dates

In the characteristically high Chlorophyll zone (deep sea point, away from coastal sediment plumes) the analysis is once more limited by the poor quality of satellite data for two days mentioned above. Interestingly, OC-2 algorithm gave very high number of negative pixels values for chlorophyll_a concentration, but yielded good correlation for 3rd March data.

It is found that, Chlor_a_3 algorithm gave the best result for the 3rd March data in this region.

For the third type of ambient water which has high Chlorophyll concentration along with high SPM (from field observation; it was noted that the Chl_a and SPM do not co-vary at these locations), once again the best choice seemed to be Chlor_a_2 and Chlor_a_3 algorithms.

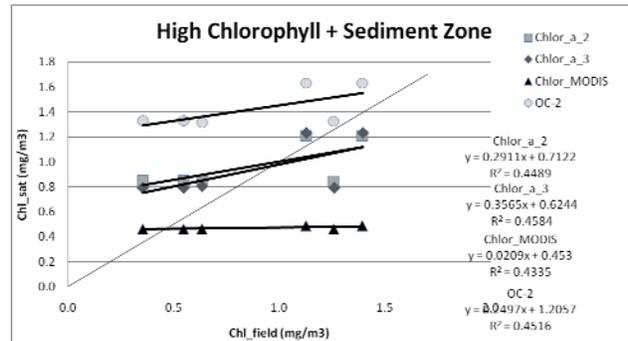


Figure 7. Algorithm behaviour in the high chlorophyll + sediment concentration Zone for 3 cruise dates

To summarise, 4 existing chlorophyll algorithms were tested against satellite-synchronous field data for 3 dates in the pre-monsoon season. Of these, the performance of the Chlor_a_2 and Chlor_a_3 algorithms were found to be of some significance over the other two (Chlor_MODIS and OC-2). It is also observed that, from over-all performance, Chlor_a_3 has yielded better results in the study area than Chlor_a_2, which slightly over-estimates the Chl_a concentration than the other.

The study is limited by the lack of cloud-free data for the study area. For the clear-sky day these two algorithms have yielded good results, and can be used with slight localized modifications of the coefficients, which is not attempted here due to the data shortcomings. Hence, further study is proposed for the post-monsoon season to arrive at a more stable relationship between the algorithm output and field reality.

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