Int. J. Environ. Res., 7(4):841-850,Autumn 2013
ISSN: 1735-6865

An Algorithm for Estimating Suspended Sediment Concentrations in the Coastal Waters of India using Remotely Sensed Reflectance and its Application to Coastal Environments

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Received 30 July 2012; Revised 24 May 2013; Accepted 27 May 2013

ABSTRACT: This study presents an empirical relationship of suspended sediment concentrations (SSCs) in the coastal waters, which is derived from the conventional methods, to radiometer remote sensing reflectance values (R_{rs}) and satellite data in coastal waters of Kerala. An algorithm is then developed to utilize both in situ SSCs measured from conventional methods and R_{rs} values. This algorithm is validated with the SSCs retrieved from Oceansat-2 Ocean Colour Monitor (OCM) data. A significant coefficient of determination (R^2=0.62) is observed between the SSCs measured in situ and satellite derived SSCs. Reflectance values from more than two spectral wavelength bands are also employed to test the accuracy of results. Satellite derived SSCs range from 1- 40 mg/L in the coastal waters off Cochin, southwest India. The regional algorithm developed for the study area gives better results than Tassan’s algorithm, and this algorithm can be used in estimation of SSC for coastal waters of western India.

Key words: Suspended particulate matter, Oceansat-2, Ocean Colour Monitor, West coast of India, Validation of suspended sediment concentrations

INTRODUCTION

Estimating suspended sediment concentration (SSC) over large oceanic areas using in-situ sampling is a lengthy, expensive, and time-consuming process**.** By contrast, remotely sensed spectral radiant energy measured by satellite sensors can provide an alternate, synoptic, speedy, and economic approach for assessing the SSCs in oceans, lakes, rivers and coastal waters (McKim *et al.,* 1984; Curran and Wilkinson, 1985). However, robust algorithms are required to convert radiance or reflectance values into estimates of water constituents. In sediment dominated coastal waters, refined algorithms are particularly needed to estimate accurately the suspended particulate concentrations from remotely sensed ocean color data (Robinson *et al.,* 1998; Moore *et al.,* 1999). Empirical algorithms can be used to derive information about water constituents (optical properties, particulate concentrations) from the estimated radiance from the water surface. Such information is useful for the management of water quality, monitoring of water pollution, modeling of sediment distribution and transportation, and sediment budgeting in coastal environments.Algorithms designed to estimate SSCs in open ocean waters as a function of chlorophyll (CHL) concentration in the deep sea rely mainly on concentrations of plankton and associated organic detrital matter (Morel, 1980; Viollier and Sturm, 1984). The commonly adopted algorithms for CHL and SSC are the reflectance band ratios, characterizing the high absorption of CHL around 440 nm and low absorption at 550 nm. However, CHL and SSC do not co-vary in coastal waters because of the presence of particles that form from re-suspension, shore erosion, or river discharge. Therefore, the algorithm derived from blue: green band

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ratio is considered as unsuitable for SSC retrieval (Tassan, 1993).

Several researchers have attempted to estimate the SSCs in the coastal waters based on the remote sensing reflectance, absorption, and scattering of light by water (Tassan and Strum, 1986; Tassan, 1994; Green and Sosik, 2004; Pradhan *et al.,* 2005; Wang *et al.,* 2010; Chauhan *et al.,* 2012; Avinash *et al.,* 2012). Earlier studies on the relationship between SSC and reflectance values in coastal waters suggest that algorithms derived from single band reflectance values may be adopted, where the SSCs increase with increasing reflectance (Curran *et al.,* 1987; Novo *et al.,* 1989). Empirical calibration of different data sets were carried out using different combinations of wavelength bands for laboratory measured total suspended matter, in situ reflectance data, and satellite-derived reflectance data (Chen *et al.,* 1991; Forget and Ouillon, 1998; Hu *et al.,* 2004; Vilamaliz and Fernando, 2009). The reflectance model of Gordon et al. (1988), used for open ocean water and validated for inland turbid waters by Dekker et al. (1997), has been extensively used to retrieve SSCs in estuarine waters (Stumpf and Pennock, 1989), and in coastal and deep ocean waters (Van Der Woerd and Pasterkamp, 2004; Eleveld *et al.,* 2008). Doxaran et al. (2002, 2003, 2005) used the near-infrared (NIR) band ratio (850 and 550 nm) model to remove the effects of particle size distribution and the bidirectional variation of the remotely sensed reflectance for sediment dominated coastal waters. Some researchers have adopted analytical approaches to solve the reflectance model and considered water constituents as the unknown parameterization of specific inherent optical properties (Forget *et al.,* 1999; Haltrin and Arnone, 2003). Nechand et al. (2010) propose a single band algorithm for total suspended matter retrieval based on reflectance model and calibrated the results using the seaborne reflectance and total suspended matter measurements of the southern North Sea.

In general, the optics of water–sediment mixtures is highly nonlinear, and many factors such as suspended particle size, shape, and colour can influence the water–sediment optics (Baker and Lavelle, 1984; Curran and Novo, 1988; Stumpf and Pennock, 1989; Sydor and Arnone, 1997). Because of these optical complexities, it is difficult to propose an universal algorithm for estimation SSCs. Further, various other parameters such as coastal geomorphology, river input, local coastal circulation influence the SSCs and hence the algorithm developed for one region may not be applicable to another region. Against this background, we have attempted to develop a regional algorithm for coastal waters of southwest coast of India, using combinations of linear reflectance bands 490, 555 and 620 nm and in situ SSCs measured by the conventional methods. The present study is carried out with an objective of developing a regional algorithm for estimation of SSCs using in situ reflectance values and in situ measured SSCs in the coastal waters of southwest coast of India. Further, satellite derived SSCs are validated using in situ SSCs and checked for the robustness of the regional algorithm developed in the present study.

MATERIALS & METHODS

Field measurements of in situ SSCs and reflectance values of coastal waters off Cochin, southwest of India (9° 24'- 10° 18' N; 76° 5' – 76° 15'E) (Fig. 1) were carried out during the periods of October & November 2010 and January & February 2011. Surface water samples from the coastal sea were collected using a Niskin sampler from subsurface depth of 0.5 m in the water column at 8 stations (Sr. No. S1 - S8; Fig. 1. Table.1) onboard the research vessel of Central Institute of Fisheries Technology (CIFT, Cochin, India) for estimation of SSCs by conventional methods. Global Positioning System (GPS) was used to fix the sample stations. Suspended particulate matter (dry weight in mg/L) for each station was gravimetrically measured following the procedure of Strickland and Parsons (1972). Samples were filtered through pre-weighed 0.4 μm Whatmann glass fiber filter paper, oven dried at 75° C for 48 hours, and then reweighed in the laboratory using an electronic balance. Remote sensing reflectance (R_{rs} in sr^{-1}) values were obtained at an average depth of 3 m with the help of a Satlantic™ hyperspectral ocean colour radiometer (HyperOCR) during the study period in the coastal waters off Cochin and these values are employed in the development of regional algorithm.

The Satlantic™ hyperspectral ocean colour radiometer (HyperOCR) effectively measures the down-welling irradiance (Ed (λ, z)), and upwelling radiance (Lw (λ, z)), which captures the optical properties of sea water. Measurements are made with 255 channels with wavelengths ranging from 300 to 1200 nm (350 to 800 nm standard) with a bandwidth of ± 10 nm in visible bands and ± 20 nm in NIR bands. Field measurements of the water leaving radiance signal (L_w), and down-welling irradiance signal just above the water surface E_d (0+) lead to the determination of $R_{rs}(\lambda)$ as defined below (Mobley, 1994):

$$R_{rs}(\lambda) = \frac{L_w(\lambda)}{E_d(\lambda, 0+)}$$ where λ (in nm) is the wavelength

The Remote Sensing Reflectance (R_{rs}) signal is related to the total suspended sediment concentration and dissolved organic matter in the surface waters.

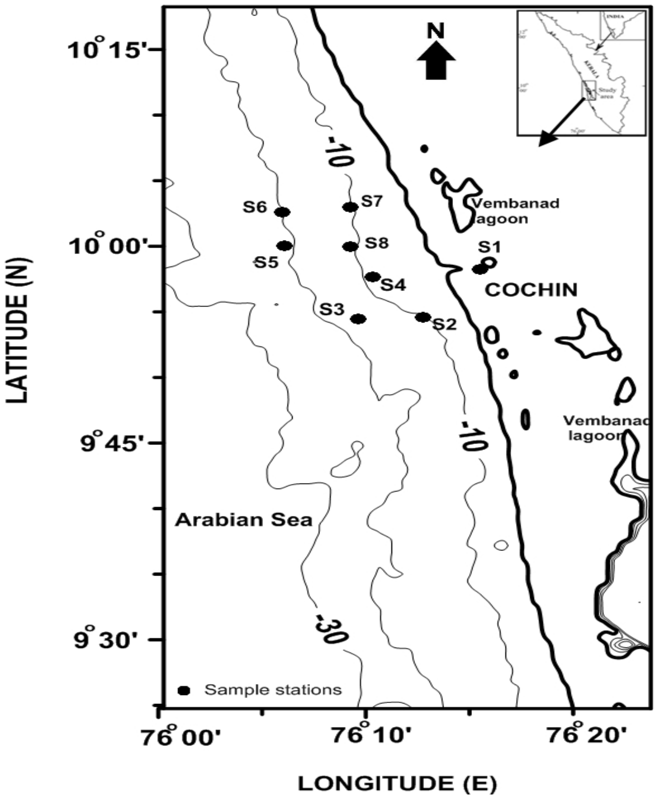


Fig. 1. Map showing the study area off Cochin, southwest coast of India. Sample stations for in situ suspended sediment concentrations (SSCs) and reflectance measurements are also shown. (Referred in Materials and Methods Section, Line number 77; 80 Pl delete this

Table 1. Field measurements of in situ suspended sediment concentrations (SSCs) along the Cochin coast, India. Locations of sample stations and suspended sediment concentrations in surface waters during the field season are given. (Referred in Materials and Methods Section, Line number 80) Please delete these words

Station. No	Lat (N) Long (E)	In situ SSC values (mg/L) measured during sampling days				Remarks
		17 Oct 2010	21 Nov 2010	21 Jan 2011	22 Feb 2011	
S1	9° 58' 16" 76° 15' 32"	23.28	14.6	29.5	32.82	Cloud sky was observed on 17 October & 21st November 2010.
S2	9° 54' 34" 76° 12' 47"	19.06	15.93	18.4	17.79	
S3	9° 54' 28" 76° 09' 40"	16.12	14.27	14.78	16.35	
S4	9° 57' 40" 76° 10' 10"	19.17	20.56	22	21.58	
S5	10° 00' 02" 76° 06' 05"	16.62	10.61	8.56	12.66	Clear sky was observed on 21 January & 22 February 2011.
S6	10° 02' 37" 76° 05'58"	15.59	10.11	8.1	13.61	
S7	10° 02' 58" 76° 09' 15"	16.8	9.2	7.05	5.4	
S8	9° 59' 57" 76° 09' 15"	28.13	12.72	14.14	13.53	

The R_{rs} values recorded from radiometers at different stations and their respective wave lengths for different SSC values are shown in Fig. 2. A progressive increase in reflectance can be seen in the visible region as sediment concentrations increase. Measured reflectance values, at different wavelength bands 490, 555, 620 nm, in coastal waters of the study area are presented in Table 2. In this study, we have analyzed the relationship between in situ SSCs and R_{rs} values derived from single wavelengths and from combinations of different wavelength bands viz., 490, 555 and 620 nm (Fig. 3 & 4; Table 3).

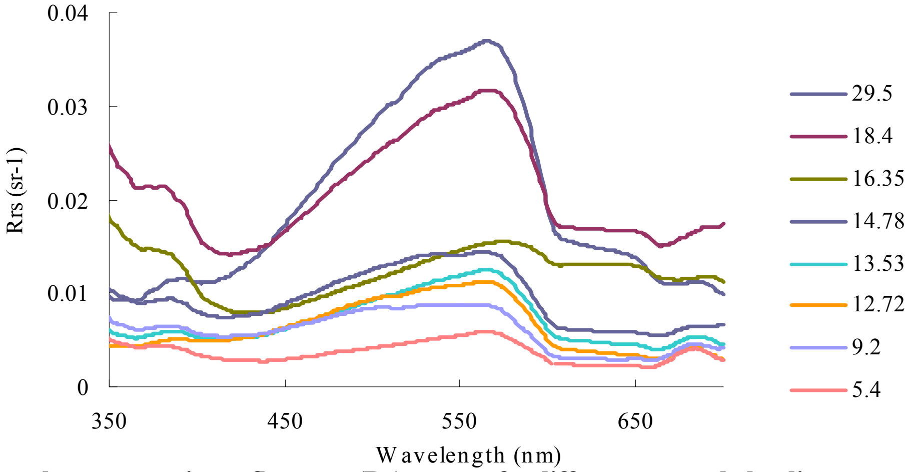


Fig. 2. Measured remote sensing reflectance (R_{rs}) spectra for different suspended sediment concentrations (SSCs): (a) 5.4 mg/L; (b) 9.2 mg/L; (c) 12.72 mg/L; (d) 13.53 mg/L; (e) 14.78 mg/L; (f) 16.35 mg/L, (g) 18.4 mg/L; (h) 29.5 mg/L. (Referred in Materials and Methods Section, Line number 100) Pl delete these words, and see original figure and mark a, b, c, d, e, f on the corresponding spectral lines

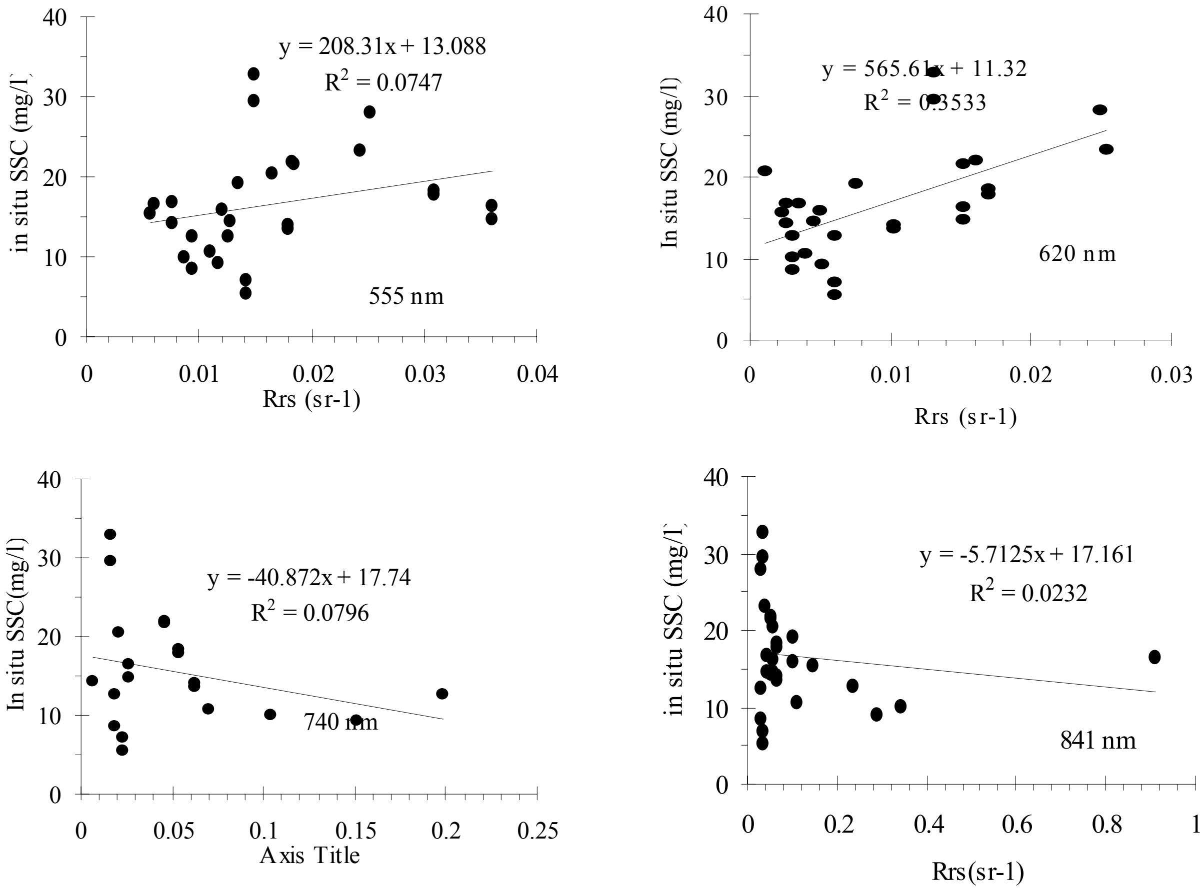


Fig. 3. Remote sensing reflectance (R_{rs}) values at different wavelength bands 555, 620, 740 and 841 nm plotted against in situ suspended sediment concentration (SSC). The coefficients of determination (R^2) values for respective spectral bands are 0.074, 0.353, 0.018, and 0.023. (Referred in Materials and Methods Section, Line number 104)Pl delete

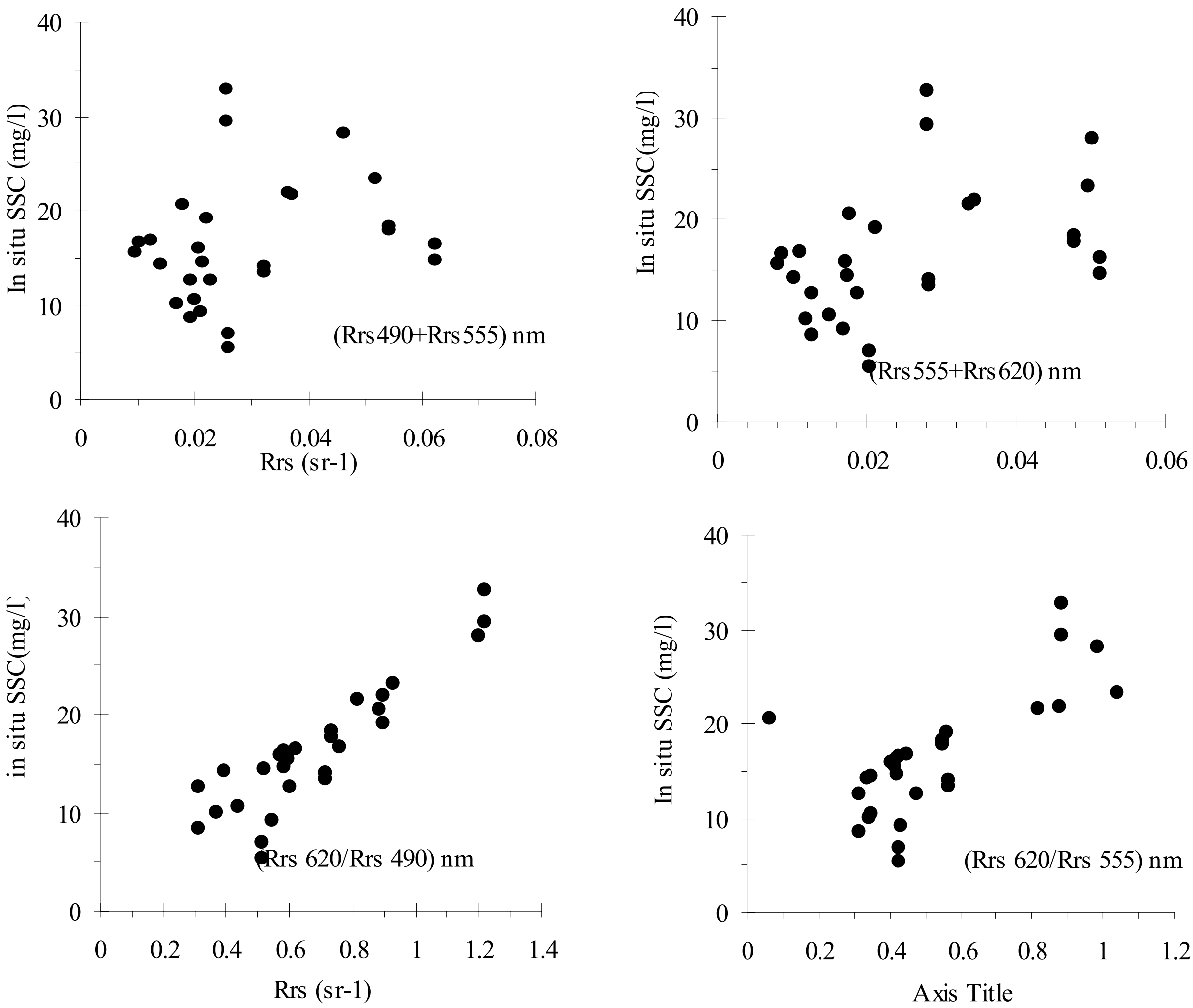


Fig. 4. Different wavelengths band combinations of remote sensing reflectance (R_{rs}) plotted against in situ suspended sediment concentration (SSC). See the Table 3 for corresponding equations and coefficients of determinations of linear regressions. (Referred in Materials and Methods Section, Line number 104)Pl delete

Table 2. Statistics of reflectance values at different wavelengths 490, 555, and 620 nm measured in coastal waters off Cochin, southwest coast of India. These wavelength bands are used for the development of regional algorithm. (Referred in Materials and Methods Section, Line number 102)Pl delete

Wavelength bands (nm)	Remote sensing reflctance (sr^{-1})			
	Min	Max	Average	St.Dev
490	0.0012	0.0272	0.0128	0.0073
555	0.0056	0.0361	0.0164	0.0086
620	0.0010	0.0253	0.0092	0.0069

An empirical regression relation between R_{rs} values of 490, 555 and 620 nm and in situ SSC has been estimated using the equation

$$Y=14.92X+8.22 \text{ ——————— } (1)$$

where Y is the SSC in mg/L, $X = \{[R_{rs}(555) + R_{rs}(620)] + [R_{rs}(620) / R_{rs}(490)]^2\}$, $R^2= 0.84$, $t>2$ and $p<0.05$. The above equation passed the t-test at significance level 0.05 (n=28). The linear regression fit between in situ SSC and R_{rs} measurements are employed for the development of the regional algorithm is shown in Fig. 5.

We have applied the developed algorithm for the retrieval of SSCs from ocean color monitor (OCM) of Oceansat-2. The OCM of the Indian Remote Sensing Satellite Oceansat-2 is optimally designed for the

Table 3. Coefficient of determination (R^2) and Root Mean Square Error (RMSE) of different regressions for various combinations of the wavelength bands. The highest coefficient of determination values (>0.60) are shown in bold. (Referred in Materials and Methods Section, Line number 104; 151)Pl delete

Remote sensing reflectance (R_{rs} (λ))	Regression equation	R^2	RMSE	t	P
555	Y= 203 X+13.08	0.074	6.19	1.45	0.159
620	Y=565.6 X+11.32	0.353	5.18	3.77	0.0009
740	Y= -10.07 X+17.15	0.018	6.38	-0.69	0.494
841	Y= -5.71 X+ 17.16	0.023	6.36	-0.78	0.438
490+555	Y=110.45 X+13.28	0.068	6.21	1.38	0.1787
555+620	Y=198.04 X+11.44	0.194	5.78	2.51	0.0187
(555+620)/(555+490)	**Y=48.35 X-25.04**	**0.779**	**3.02**	**9.57**	**5.1E-10**
620/490	**Y=23.26 X+ 0.61**	**0.81**	**2.77**	**10.69**	**5.2E-11**
620/555	Y=19.95 X+6.08	0.507	4.52	5.17	2.16E-05
840/490	Y=-0.095 X+17.5	0.037	6.43	-0.98	0.3332
840/555	Y= -0.248 X+18.3	0.119	6.40	-1.83	0.0777
840 -740	Y= -5.906 X+16.8	0.007	6.35	-0.43	0.6727
$(620/490)^2$	**Y=15.15X+8.48**	**0.839**	**2.58**	**11.67**	**7.8E-12**

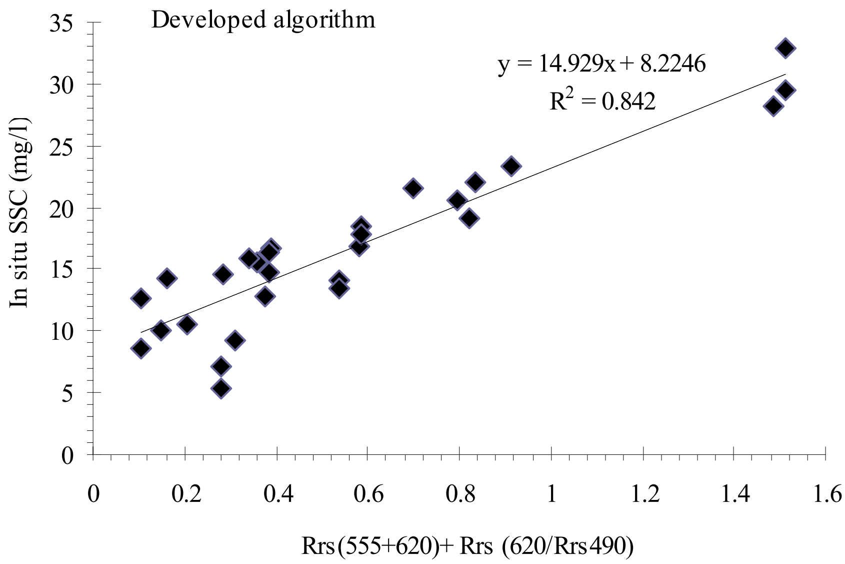


Fig. 5. Linear regression fit between in situ suspended sediment concentration (SSC) and remote sensing reflectance (R_{rs}) measurements used for the development of the regional algorithm. (Referred in Materials and Methods Section, Line number 111)Pl delete

estimation of SSC. The high resolution OCM sensor is a push broom linear charge coupled device with eight spectral bands in visible and NIR region (with central wavelength bands of 412, 443, 490, 510, 555, 620, 740, 865 nm). The OCM provides an instantaneous Geometric Field of View of 360 m, radiometric resolution of 12 bits, and swath of 1420 Km, and repeats at two-day time interval for any given area. Oceansat-2 OCM data covering the coastal regions off Cochin (path 10 and row 14) were used to derive suspended sediments concentration. The derivation of ocean color parameters for estimating SSC in the near-shore water involves three major steps - (i) the application of an atmospheric correction of visible channels to obtain normalized water leaving radiances (nLw), (ii) the calculation of remote sensing reflectance R_{rs} (λ), and (iii) the retrieval of SSC. The satellite sensors capture the reflected energy from the sea surface water constituents. Depending upon the constituents of the atmosphere layers, the energy may also be reflected or refracted by the objects in the atmosphere. Thus, the energy absorbed by sensor may not accurately represent the reflectance characteristics of the suspended matter in the ocean. Therefore, the OCM data needs to be corrected for atmospheric effects of Raleigh and aerosol scattering. The algorithm developed by Ramana et al. (2000) for case-II water (inner shelf) is used in the present study for carrying out atmospheric correction. Aerosol scattering is computed using a long wavelength atmospheric correction method. SSCs in the study area have been derived using water-leaving radiance at spectral bands 490, 555, and 620 nm. The regional algorithm that has been used to compute SSCs from OCM data is given above in equation 1. Geometric correction for the satellite data are carried out with help of ERDAS Imagine 9.1 software.

RESULTS & DISCUSSION

In this study, we have developed an empirical algorithm based on a statistical relation between SSC and R_{rs} to estimate SSCs from spectral reflectance, and we also improved it using a combination of visible and near IR bands, as the combination of these bands gives better accuracy of estimated SSCs (Doxaran *et al.,* 2002; Ma and Dai, 2005). Wang et al. (2010) have observed a significant improvement in the relationship between in situ SSCs and the difference in spectral values of wavelength bands 2 and 5 of MODIS data over the relationship between the in situ SSCs and single band spectral values. Further, combination of in situ reflectance wavelength bands employed in global Tassan's (1994) algorithm ($Log_{10}S=1.83+1.26\ Log_{10}X_s$; where S is the SSC in mg/L and $X_s = \{[R_{rs}(555)+R_{rs}(620)] \times [(R_{rs}(555)/R_{rs}(490)^{-1.2}]\}$), has been tested with in situ SSC data acquired in this study. However, no significant relation (R^2=0.16) is observed between the results derived from Tassan's algorithm and in situ SSC measured by conventional methods in our study area.

Our results suggest a weak correlation between single wavelength band R_{rs} values and in situ SSCs. However, a strong correlation is observed between the square of ratio of $R_{rs}(620)$ and $R_{rs}(490)$ and in situ SSCs, but only a weak correlation between the ratio of $R_{rs}(841)$ and $R_{rs}(555)$ and in situ SSC values obtained by conventional methods. Further, a robust linear relationship is observed between in situ SSC and the combination of wavelength bands $\{[R_{rs}(555) + R_{rs}(620)] + [R_{rs}(620)/ R_{rs}(490)]^2\}$, much more robust than the relationship between single wavelength band and in situ SSC. We have tried to derive relationships with other wavelength bands as shown in Table 3, but no significant relationship was observed.

Doxaran et al. (2005) have established a linear relationship between the band ratios of reflectance in the near IR (e.g.850 nm) and visible wavelength (e.g. 550 nm) bands, and their relationship follows a power law in the sediment dominated coastal waters (D'Sa and Miller, 2003). Avinash et al. (2012) modified Tassan's algorithm with regression coefficients, in which these authors replaced global coefficients of Tassan's algorithm for estimation of SSCs in the coastal waters of west coast of India. These authors have recorded low values with the application of Tassan's algorithm, and hence, they have employed the algorithm developed by SAC (2004).

SSCs retrieved from OCM data using the regional algorithm developed for the study area and their spatial distribution on 20th January 2011 are shown in Fig. 6. SSCs in the study area vary from 1 to 40 mg/L. High concentrations (25 mg/L) are recorded very close to the shore, and low values (2 mg/L) of SSC characterize the deeper shelf region. Oceansat-2 OCM data were processed to estimate the remote sensing reflectance values at 490, 555, 620 nm wavelength bands. The regional algorithm has been implemented for retrieval of SSCs from OCM sensor onboard Oceansat-2 satellite. This regional algorithm is validated for OCM data of southwest coast acquired on 20th January 2011 and of east coast of India acquired on 7th, 9th and 11th of February 2011. The SSCs at 30 stations retrieved from satellite data using the algorithm developed here are used for validation of in situ SSCs. It can be observed from the Fig. 7 that the coefficient of determination (R^2=0.62) is significant and valid for retrieval of SSCs in coastal waters.

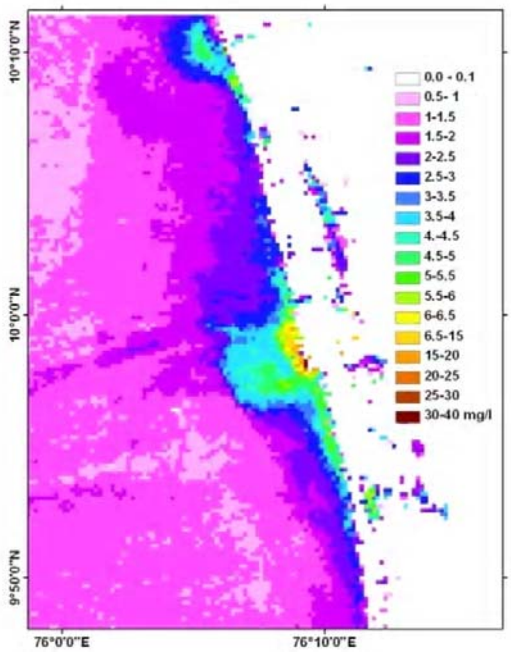
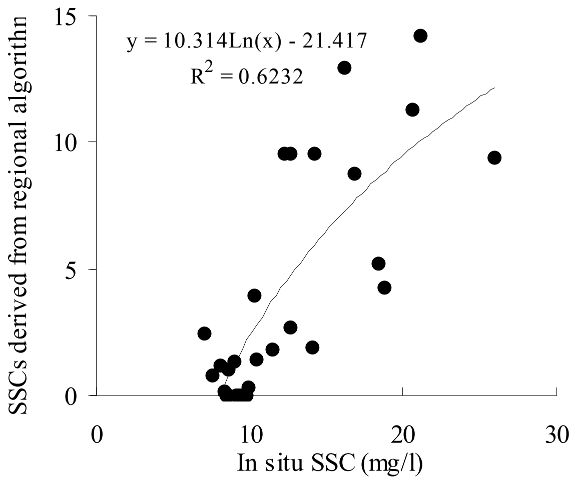


Fig. 6. Distribution of suspended sediment concentrations (SSCs) derived from the ocean colour monitor (OCM) sensor onboard Oceansat-2 (acquired on January 20, 2011) along the southwest coast of India, employing the developed regional algorithm. (Referred in Results and Discussions, Line number 162)Pl delete



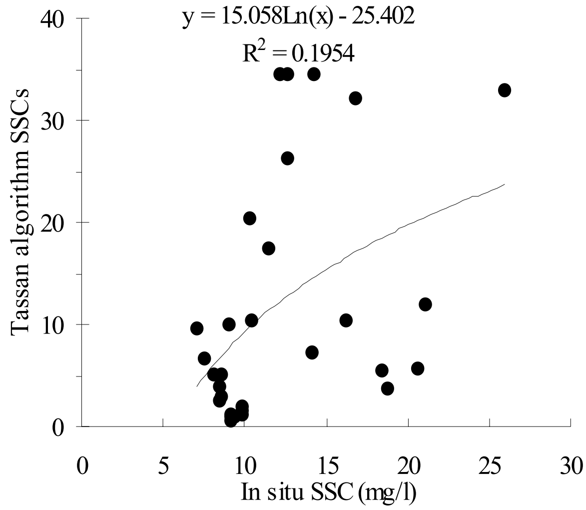


Fig. 7. Validation of developed regional algorithm employing satellite derived suspended sediment concentrations (SSC) and in situ suspended sediment concentrations (SSCs). Strong coefficient of determination (R^2=0.62) is noted. (Referred in Results and Discussions, Line number 170; 178)Pl delete

In addition, we have also compared the in situ SSC measurements with satellite derived SSCs using the Tassan's algorithm. It is found that the SSCs retrieved from the satellite data using the Tassan's algorithm are lower than the in situ SSCs values, and the corresponding coefficient of determination (R^2=0.195) is insignificant. We have attempted to establish a statistical relationship between the in situ SSC and R_{rs} at different wavelength bands such as 490, 555 and 620 nm for improving the accuracy of SSC retrieval. A good correlation (R^2= 0.62, n=30) was observed between the in situ SSCs and retrieved SSC values from satellite data using the regional algorithm (Fig. 7). Further, these results indicate that the best wavelength bands for estimating SSCs are 490, 555 and 620 nm in the present study. The results derived from these wavelength bands are more accurate and precise than the results achieved from the customary use of single wavelength band. No in situ measurements could be carried out during the southwest monsoon (because of hostile weather during monsoon period), but validated SSC values for non-monsoonal season establish that regional algorithm developed in this study provide accurate estimates of SSCs in coastal waters off southwest India.

CONCLUSION

In this study, a regional algorithm for estimation of SSCs in coastal waters of southwest of India has been developed by employing measured in situ SSCs by conventional methods and radiometer reflectance values and SSCs retrieved from Oceansat-2 satellite data. An empirical relationship has been established between R_{rs} values and concentrations of suspended sediments for the coastal waters off Cochin, southwest India. A good correlation (R^2=0.84; linear regression) was obtained between the R_{rs} values derived from band combinations of 490, 555 and 620 nm and in situ SSCs. The suitability of this algorithm with respect to the SSCs retrieved from satellite data has also been tested. For this purpose, the regional algorithm developed by us has been implemented for retrieval of SSCs from Oceansat-2 OCM sensor data and these results were validated. The regional algorithm has been validated with in situ measurements of SSCs and concentrations of suspended sediments were quantified. A good correlation (R^2=0.62) is observed between in situ SSCs and retrieved SSCs from satellite data using the regional algorithm developed in this study. Suspended sediments, retrieved employing the regional algorithm, vary in concentration from 1 to 40 mg/L in the coastal waters off Cochin, southwest India.High concentrations (> 20 mg/L) were recorded very close to the shore and lower values (< 2 mg/L) of suspended sediments are recorded toward the offshore area. Suspended sediments are dominant near the river mouths and in embayments (>15 mg/L) along the southwest coast of India. The present study helps in understanding the amounts and dispersal patterns of the suspend sediments in the coastal waters of India, which in turn will help in coastal zone management and maintenance of navigational channels.

ACKNOWLEDGMENTS

ACN thanks the Naval Research Board, DRDO, Govt. of India, for financial support through a research project (No. DNRD/05/4003/NRB/96). Authors thank Dr. T. Srinivas Kumar, INCOIS, Ministry of Earth

Sciences, Hyderabad, for his support and help extended during the study. Authors thank Prof. Peter Molnar, University of Colorado, Boulder, for his help in improving the English language.

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