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Letter

A technique for estimation of suspended sediment concentration in very high turbid coastal waters: An investigation from Gulf of Cambay, India

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ABSTRACT

This paper presents a technique to estimate the suspended sediment concentration (SSC) in Case-2 waters based on spectral similarity between satellite images and library spectra. Average Weighted Spectral Similarity (AWSS), a measure of spectral matching, is used to estimate SSC ranges in ocean color monitor (OCM) data of Gulf of Cambay (GC), India. For this, a spectral library comprising field and laboratory measured data representing diverse sediment mineralogy and grain sizes was generated. Results estimated by AWSS were compared with other published procedures and observed to be more accurate ($R^2 = 0.95$ at 99% significance). Further, in Case-2 waters reflectance in bands centered at 743 and 835 nm is more sensitive to SSC changes. Sediment concentration and grain size significantly affect reflectance of water.

1. Introduction

Understanding the distribution and movement of SSC is necessary in addressing many coastal problems such as siltation of ports, modification of coastal morphology, scouring, and variation of underwater topography. Spatial data on SSC collected by field-based techniques are often spatially limited and the procedures involved in collecting such data are tedious and costly. Satellite data in conjunction with quasi-synchronous field data such as reflectance, Secchi disk compensation depth, and turbidity have been extensively used for successful estimation of sediment flux and its dispersion (Doerffer and Fischer, 1994; Forget and Ouillon, 1998). These procedures require elaborate field and laboratory analyses to estimate the SSC and are therefore better suited for microscale applications.

However in recent studies, interrelationship between sediment concentration and spectral reflectance of water is proven to be an easy, cost effective and accurate alternative for estimating the SSC (Dekker et al., 2001; Doxaran et al., 2002; Deng and Li, 2003; Miller and McKee, 2004; Han et al., 2006; Chen et al., 2007). This understanding led to the development of inversion algorithms based on the interrelationship between SSC and spectral reflectance with measurements ranging from laboratory to satellite scales (Lira et al., 1997; Miller and McKee, 2004). Though satellite based estimates are advantageous, adequate care is necessary to calibrate satellite-reflectance with field measurements (Chauhan et al., 2005; Kunte, 2008). This requires an efficient SSC retrieval algorithm and good understanding of vital reflectance-influencing parameters such as angular distribution of light, mineralogy, grain size, abundance of organic detritus, and phytoplankton (Yanjiao et al., 2007). Prevailing retrieval algorithms can be broadly grouped into three major categories such as empirical based (Tassan, 1993; Deng and Li, 2003; Miller and McKee, 2004; Han et al., 2006; Chen et al., 2007), radiative transfer based (Doerffer and Fischer, 1994), and semi-analytical procedure based (Dekker et al., 2001; Doxaran et al., 2002; Warrick et al., 2004).

In this study, we developed a semi-analytical SSC inversion model for very high-turbid waters of the Gulf of Cambay region, India using field, laboratory, and satellite based spectral measurements. The study area is one of the best sites in the world to study reflectance–SSC relationship of very high turbid coastal waters (Nambiar and Rajagopalan, 1995). We used OCM satellite data onboard Indian Remote Sensing Satellite (IRS) P-4 for achieving the above objectives.

2. Study area

The GC is situated between the mainland Gujarat and Saurashtra peninsula in the west coast of India. It is bounded by northern latitudes 21°00′ and 22°16′ and eastern longitudes 72°00′ and 73°00′ and encompasses estuaries of seven major rivers including Sabarmati, Mahi, Dadar, Narmada, Tapti, Ambika and Shetrunji that debouch very high sediment loads (6×10^7 metric tons/year). These rivers discharge a large amount of sediment as suspended load into the Gulf with an average monthly water discharge exceeding 2000 $m^3 s^{-1}$ (Kunte, 2008). The GC is also known for strong tidal currents with high tides often rising up to 11 m from the normal waterline (Jervis, 1838; Unnikrishnan et al., 1999).

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3. Materials and methods

3.1. Field data collection

A field cruise was carried out between 26th and 30th of December, 2006 in the GC and estuaries of Mahi, Narmada, and Purna with an aim to obtain spectral reflectance, water and sediment-samples, and Secchi disk compensation depth. Acid-leached 1000 mL Teflon bottles were lowered into the water to 20 cm sampling depth, allowed to fill, retrieved, capped tightly, and packed for further analysis. Samples from the fresh mudflats and sand bars (representing the suspended and saltation sediment loads) were collected for mineralogical and additional laboratory based studies on water leaving reflectance. Since the light does not penetrate beyond 4 cm in all cases, in situ above water surface reflectance was collected using GER 1500 field spectroradiometer following the procedures of Doxaran et al. (2002). The reflectance spectra were collected between 10 a.m. and 2 p.m. with nadir looking sensor setup to minimize the adverse effects of geometry (Novo et al., 1989) and glint (Mobley, 1999). In all, 39 spectra and corresponding number of sediment samples were collected with GPS co-ordinates.

3.2. Laboratory analyses and spectral library generation

The SSC concentrations were determined by filtering 1000 mL of the collected water samples on pre-weighed 8 μm filter paper. The filter papers were then dried at 100 °C and re-weighed for estimating the sediment concentration. Mineral composition of the filtrates was determined using a Philips (PW2404) X-ray diffractometer with CuKα source. The mineral identification and qualitative abundance estimation were carried out following the method of Carrol (1970). The grain size of samples representing various estuaries and Gulf was carried out by mechanical sieving and laser particle size analysis techniques.

To augment the spectral database, laboratory experiments were conducted in a test tank with similar field of view (FOV) and sun-sensor geometry to acquire spectral information with contiguous increase in sediment concentration. The experimental setup contains an acrylic water tank (of 1 m^3 capacity), a turbo stirrer to maintain the sediments in suspension and a spectroradiometer to measure reflectance. The sediments collected from the field were dried, weighed, sieved, and mixed to match the grain sizes of the suspended sediment load. Irradiance and upwelling radiances were collected with the aid of GER 1500 field portable spectroradiometer and spectralon panel for the wavelength region from 350 to 1050 nm. Using this setup, contiguous reflectance spectra representing the sediment load from 1 ppm to 6000 ppm (at an interval of 500 ppm) were generated and archived as spectral library for each estuary and Gulf separately.

3.3. Image processing and spatial mapping of SSC

In this study, OCM data for 26th December, 2006 was procured from National Remote Sensing Agency (NRSA), India and processed. OCM collects data in eight narrow spectral channels (402–422, 433–453, 480–500, 500–520, 545–565, 660–680, 745–785, 845–885 nm) with spatial resolution of 360 m and radiometric resolution of 12 bits. Prior to retrieval of SSC, the OCM data was corrected for radiometric, geometric, and atmospheric effects. Geometric correction of the data was carried out with the aid of ground control points (GCPs) collected during the field campaign. Conversion of Top of Atmosphere (TOA) radiances to surface reflectance was carried out following the atmospheric correction procedures of Mohan and Chauhan (2003). Spatially coherent noise in the reflectance image was reduced by using the Minimum Noise Fraction (MNF) algorithm (Green et al., 1988).

Subsequently three different approaches, namely, Total Suspended Matter (TSM), Suspended Sediment Matter Retrieval (SSMR), and spectral similarity based AWSS algorithms were used to map SSC. The TSM algorithm (Sathyendranath et al., 1989) creates a large set of remote sensing reflectance (Rrs) values by independently varying the concentration of chlorophyll-a, suspended matter and yellow substance. The exponential relationship between TSM and reflectance (at 555 and 620 nm) (Eqs. (1) and (2)) is used to predict concentrations.

$$\mathrm{Log(S)} = 266.23 \times \mathrm{Rrs}\,555 - 1.025 \text{ for } 1.0 < \mathrm{S\,(mg/L)} < 250 \tag{1}$$

$$\mathrm{Log(S)} = 164.39 \times \mathrm{Rrs}\,620 - 1.13 \text{ for } 1.0 < \mathrm{S\,(mg/L)} < 250 \tag{2}$$

The SSMR (Ramaswamy et al., 2004) uses reflectance band ratios involving 490, 555, and 670 nm regions (Eqs. (3) and (4)).

$$\mathrm{S} = 25 \times \exp(2.16 + 0.991 \times \mathrm{LogXs}) \tag{3}$$

where, S is suspended sediment concentration in mg/L and Xs is variable defined as,

$$\mathrm{Xs} = [\mathrm{Rrs}(555) + \mathrm{Rrs}(670)] \times [\mathrm{Rrs}(490)/\mathrm{Rrs}(555)] - 1. \tag{4}$$

Ramakrishnan et al. (2012) observed that even SSMR based estimates yielded inaccurate sediment concentrations in GC. It was also evident from our earlier study that in addition to reflectance at 490, 555, and 670 nm, absorption depths at 740 and 835 nm are very sensitive to changes in SSC. Hence, we used a spectral similarity based approach involving all OCM wavelength regions for estimating the SSC. For this purpose, AWSS was derived by scaling the outputs of Spectral Angle Mapper (SAM — Kruse et al., 1993), Spectral Feature Fitting (SFF — Clark et al., 1990), and Binary Encoding (BE — Mazer et al., 1988) into a measure ranging between 0 and 100% and then each weighted by 33% (i.e. equal-weighting). Since AWSS involves similarity estimation between library (reference) and image spectra (target) based on spectral angle of similarity (SAM), continuum-removed fits (SFF), and average correlation fits (BE), the results are expected to be more accurate than the band ratio based approaches. Typically, AWSS score ranges between 0 and 100% corresponding to least and best correlation between image and library spectra. In this study, AWSS scores exceeding 85% were used to classify the satellite imagery.

4. Results

4.1. SSC and spectral reflectance

It is evident from field (Fig. 1a) and laboratory (Fig. 1b and c) spectra that reflectance of water increases at all wavelengths with increase in SSC. Typical reflectance spectra have three distinct peaks in 400–1000 nm region. The first peak is centered at 590 nm, the second at 700 nm, and the third at 810 nm. At lower SSC (<1000 ppm), the spectra have a characteristic plateau in 590–690 nm window. With progressive increase in SSC (1000–4000 ppm), this plateau disappears and at very high concentrations (>4000 ppm), absorption features at 740 and 835 nm are significantly subdued. To understand wavelength dependent reflectance changes, scatter plots between sediment concentration and reflectance in 490, 555, and 670 nm were analyzed. It is observed that reflectance in higher wavelengths has poor correlation ($R^2 = 0.43–0.63$) with SSC. The error in SSC estimates retrieved using reflectance at 490, 555, and 670 nm are ±1235 ppm, ±1062 ppm and ±939 ppm, respectively.

However, spectral absorption features centered at 480, 743 and 835 nm in the convex hull normalized spectra are very sensitive to changes in SSC ($R^2 = 0.97–0.99$) at high statistical significance (99%) (Fig. 2). The error in SSC estimate using 743 and 835 nm reflectance values is ±477 ppm and ±447 ppm respectively. With increase in SSC, absorption depth at these wavelengths decreases.