Modeling and remote sensing of suspended sediments in the Gulf of Kachchh, India

Mukesh Gupta1,2

1 Earth Sciences and Hydrology Division, Marine and Water Resources Group, Space Applications Centre (SAC), Indian Space Research Organisation (ISRO), Ahmedabad, 380 015, Gujarat, India
2 Meteorological Research Division, Data Assimilation and Satellite Meteorology Research Section, Science and Technology Branch, Environment Canada, Dorval H9P 1J3, Quebec, Canada

Corresponding author, e-mail address: guptm@yahoo.com

Abstract
This paper presents a comprehensive analysis of OCEANSAT-1 OCM (Ocean Color Monitor)-derived suspended sediment concentration (SSC), MIKE 21-simulated SSC, bathymetry, and tidal current speed and direction using tidal harmonic analysis to study the suspended sediments in the Gulf of Kachchh in the Arabian Sea for tidal and monsoonal changes. The spring tide and bathymetry predominantly control the sediment dynamics at Okha and Navlakhi ports as shown by the time series data. The sequential high temporal resolution of OCM-derived SSC images is near-ideal means for monitoring the Gulf. The abrupt OCM-derived SSC values were due to the combined influence of deficient monsoon in 2004, prevailing winds, and the re-suspension of bottom sediments.

Keywords: MIKE 21, monsoon, OCEANSAT-1 OCM, sediment dispersal, simulation, SSC.

Introduction
Coastal sediment transport is a process by which sediments that are in suspension or at the bottom get transported to other geographic locations under the influence of physical forces such as coastal currents, waves, wind, tides, etc. Suspended sediments have a direct impact on the underwater light availability for primary production, coastal erosion, accretion, and transport of minerals and pollutants to the oceans [Eisma, 1981]. The usage of satellite remote sensing data for monitoring the dispersal and distribution of suspended sediments has proven to be useful because of high-temporal images (every alternate day) at spatial resolution of as high as 360 m available from the Ocean Color Monitor (OCM) [Pradhan et al., 2004; Rajawat et al., 2005; Ramakrishnan and Rajawat, 2012]. Satellite-based monitoring of suspended sediments is of significance because of its greater spatial and temporal coverage as compared to sea- or ground-truth observations. Ocean color satellite sensors (SPOT - Satellite Pour l’Observation de la Terre, SeaWiFS - Sea-viewing Wide Field-of-view Sensor, MODIS - MODerate-resolution Imaging Spectroradiometer) provide a wealth of information in different spectral channels about the various constituents
Remote sensing modeling of suspended sediments

of seawater for both Case 1 and Case 2 waters [Doxaran et al., 2002; Myint and Walker, 2002; Miller and McKee, 2004]. Ocean color imagery-derived products of suspended sediment concentration (SSC) have further utility in estimating dispersal, extent, and quantification of suspended sediments in the Gulf of Kachchh (GK). OCM data have demonstrated its widespread utility in sediment dispersal dynamics studies [Pradhan et al., 2004], underwater bed forms, and sediment plume [Kunte et al., 2003]. OCM-derived SSC products can also be input to simulate and predict SSC in the GK [Ramakrishnan and Rajawat, 2012]. Chauhan et al. [2007] used the improved spatial resolution of OCM data to find sources, sinks, and dispersal pathways of suspended sediments in the GK. It is possible to retrieve SSC from satellite-detected water-leaving radiance in the electromagnetic channels, which are sensitive to reflection/absorption from suspended sediments. The contribution to spectral reflectance comes from the water column. Water-leaving radiance as detected by the satellite sensor has contributions from the water constituents (e.g., chlorophyll, colored dissolved organic matter, and mineral sediments), particle size distribution, and light scattering/absorption from each constituent [Nanu and Robertson, 1993]. These constituents and available light modify the depth up to which remote sensors can detect the SSC. A typical range of this depth could be from a few centimeters (highly turbid: Case 2 waters) to several meters (open ocean: Case 1 waters) [Forget et al., 2001; Ouillon, 2003]. Ouillon [2003] has reported underwater (at a depth of ~3 m) total suspended matter concentration of 6 mg/l. Tassan [1994] derived an empirical relationship to estimate SSC (up to 4.6 mg/l) based on radiometric observations of the reflectance of suspended sediments. SAC Report [2003] derived SSC up to 40.0 mg/l using satellite remote sensing (OCEANSAT-1 OCM) data. Other algorithms are also available to retrieve SSC up to 4.6 mg/l from SeaWiFS data [Kunte et al., 2005]. Pradhan et al. [2003] proposed an algorithm for SSC (up to 200 mg/l) retrieval using apparent optical properties such as diffuse attenuation coefficient.

OCEANSAT-1 (also known as IRS-P4) was the first Indian satellite primarily built for ocean applications. The PSLV (Polar Satellite Launch Vehicle)-C2 rocket placed the 1,050 kg satellite in a polar Sun-synchronous orbit at an altitude of 720 km, from Satish Dhawan Space Centre (SDSC), Sriharikota, India on 26 May 1999. The satellite carried OCM among others for oceanographic studies. OCM acquired imageries in eight different spectral channels (404–882 nm) every alternate day (see Chauhan et al. [2003] for sensor specifications). The mission ended on 08 August 2010 after serving for 11 years and two months. The GK (also spelled as Kutch, Cutch, or Kachh) is a seismically active, funnel-shaped, macro-tidal (mixed semi-diurnal) environment with tidal height variations of 3-7 m [Chauhan and Vora, 1990; Shetye, 1999]. The coastal region of the GK encompasses a variety of landforms such as tidal flats, sand spits, salt pans, river inlets, and alluvial plains [Patel and Desai, 2009]. The major and only source of sediments and minerals in the GK is Indus River (~100 km further Northwest), which brings nearly 435 million tons of suspended sediments load every year [Kunte et al., 2003; Chauhan et al., 2006; Trivedi et al., 2012]. The GK is highly turbid with SSC during October–November up to 674 mg/l [Ramiaswamy et al., 2007]. The GK experiences strong coastal currents discernible through sediment dispersal patterns observed by OCM [Pradhan et al., 2004]. The tidal current velocity distributions control the seasonal sediment dispersal patterns. The natural period of tidal oscillation in the GK is ~10 hours [Unnikrishnan and Luick, 2003]. Also, the channel geometry further enhances the strength of tidal currents in the GK [Shetye, 1999].
Figure 1 - RESOURCESAT-1 AWiFS standard false color composite (FCC) (B2: blue, B3: green, B4: red) image of the GK acquired on 26 December 2004. Various port locations (for tide measurements) shown in solid squares are: (1) Jakhau, (2) Mandvi, (3) Mundra, (4) Kandla, (5) Navlakhi, (6) Jodiya, (7) Sikka, (8) Kalubhar and (9) Okha.

Babu et al. [2005] simulated tide-driven currents in the GK using MIKE 21 hydrodynamic model, but did not use any satellite data for model assimilation. To further satellite-based modeling and suspended sediment dynamics in the GK, the following two objectives of the present study are identified as follows:
1. To investigate the control of tidal currents on the SSC in the GK during pre-monsoon and post-monsoon for full tidal cycles based on remote sensing estimates;
2. To exploit the sequential and high-temporal ocean color remote sensing data for monitoring the dispersal, and the dynamics of suspended sediments in the GK.

Study area
The study area lies in the West coast of Indian state of Gujarat, in the northeastern stretch of Arabian Sea, between 68°20'-70°40'E and 22°15'-23°40’N covering an area of ~7,300 km² (Fig. 1). It sprawls ~180 km in length in east-west direction, and ~70 km at the mouth to 1–2 km at the creeks in the East [Ramaswamy et al., 2007]. The depth varies from 60 m near the mouth to 20 m at the eastern end of the GK. The GK has major ports of Kandla, Mandvi, Mundra, Navlakhi, and Okha. There are no rivers, tributaries, or any fresh water source to the GK except the Indus River, which lies ~100 km Northwest from the mouth of the GK.
Methods

Data used

This paper makes use of an aggregate of 38 sequential OCM images for pre-monsoon (March and April 2004) and post-monsoon (November and December 2004) analysis of sediment dynamics in the GK depending on low and high tide conditions (Tab. 1). National Remote Sensing Centre (NRSC), Hyderabad, India provided the satellite imageries. The imageries were raw radiance image files, which were geo-corrected for SSC retrieval after atmospheric correction in Geographic Latitude/Longitude coordinate system and Modified Everest datum. The computation of SSC in response to full month tidal cycle required four images (11, 13 March; and 16, 26 April) in the pre-monsoon and four images (10, 12 November; and 12, 14 December) in the post-monsoon. The selection of these eight cloud-free images matched the high or low tide conditions during a month with a pre-determined satellite pass. The analysis of the suspended sediment dispersal patterns, as observed through sequential satellite images and MIKE 21 modeling, required the remaining 30 SSC images.

Atmospheric correction

It is well known in ocean remote sensing that the radiance contribution from atmospheric scattering processes dominates the aggregate signal received at the satellite sensor and only ~8–10% signal corresponds to the oceanic reflectance [Chauhan et al., 2003]. The atmospheric correction is required before processing imageries for SSC estimation. Therefore, the raw imageries before preparing SSC products were corrected for atmospheric variability [SAC Report, 2003]. The water-leaving radiance is approximately equal to zero at near-infrared channels for Case 1 waters [Chauhan et al., 2003]. The top of the atmosphere radiances in OCM wavelengths, 765 and 865 nm, mainly correspond to a contribution coming only from the atmosphere [Chauhan et al., 2003]; therefore, the water-leaving radiance at 765 and 865 nm channels is nearly zero. Chauhan et al. [2003] obtained a relationship for the spectral behavior of the aerosol optical depth (AOD) using wavelengths 765 and 865 nm using OCM data. However, the water-leaving radiance in near infrared is not zero in Case

| March | April | November | December |
|-------|-------|----------|----------|
| 9     | 6     | 8        | 2        |
| 11    | 8     | 10       | 6        |
| 13    | 12    | 12       | 12       |
| 15    | 14    | 20       | 14       |
| 17    | 16    | 22       | 16       |
| 19    | 18    | 24       | 18       |
| 21    | 20    | 26       | 22       |
| 23    | 24    | 28       | 24       |
| 25    | 26    |          | 26       |
| 27    |       |          | 28       |
| 29    |       |          |          |
2 waters [Chauhan et al., 2003; Dash et al., 2012]. The atmospheric correction procedure was further modified for Case 2 waters [SAC Report, 2003]. The atmospheric correction algorithm uses an exponential relationship for spectral behavior of AOD. The extrapolation of aerosol optical thickness to visible channels using this exponential relationship provides the required values [Mohan and Chauhan, 2003; SAC Report, 2003]. The atmospheric correction of OCM images was performed using the software code generated at the SAC (ISRO), Ahmedabad, India. 

The atmospheric correction procedure used in this paper ignores whitecap correction. As per Gordon and Wang [1994] - whitecap uncertainty sets a lower limit with which aerosol properties can be retrieved from satellite radiances; and for wind speeds ≤10–12 m/s, the water-leaving radiance retrieval is accurate for stated accuracy. The wind speeds in this paper are merely 2–5 m/s; thus, the whitecap correction is not dominant. The out-of-band correction [Gordon, 1995] and the contribution of aerosol path radiance to diffuse transmittance [Gordon and Clark, 1981; McCarthy et al., 2012] are incorporated into the atmospheric correction used in this paper. The AOD at near infrared bands is estimated and then extrapolated to visible wavelengths (490, 555 nm) to include the AOD effect [Chauhan et al., 2003; Mohan and Chauhan, 2003].

Retrieval of SSC

The satellite images were analyzed and geometrically corrected using ERDAS Imagine 8.5 and ENVI 4.1 software on Dell Work Station and IBM Bull machine (AIX). Depending on the requirement and efficient image processing, various software packages were used. SAC Report [2003] estimated SSC up to 40 mg/l from the satellite radiances. The SeaWiFS Data Analysis System (SeaDAS 4.0) was used for color-coding of SSC products. The SSC products were derived using water-leaving radiance at wavelengths 490, 555, and 670 nm. Chauhan et al. [2003] have given a method to convert radiance images into remote sensing reflectance images. Equations [1] and [2] constitute the algorithm used for retrieval of SSC [SAC Report, 2003],

\[
\log(S) = 1.83 + 1.26 \log(X_s) \quad 0.0 \leq S \leq 40.0 \quad [1]
\]

\[
X_s = \left[ Rrs(555) + Rrs(670) \right] \left[ \frac{Rrs(555)}{Rrs(490)} \right]^{0.5} \quad [2]
\]

where \(Rrs(\lambda)\) is remote sensing reflectance at respective wavelengths \(\lambda\), \(S\) is the SSC in mg/l. The retrieval accuracy of SSC using OCM data is within 15% [SAC Report, 2003].

In the present study, it is safe to assume that the scattering from suspended sediments is predominantly near surface as the GK is highly turbid with SSC > 40.0 mg/l with little light penetration into the water column. This paper does not use any \textit{in situ} SSC data for validation of algorithm reported in SAC report [2003], thus no information is available about SSC in the water column.
**MIKE 21 simulation**

MIKE 21, developed by Danish Hydraulic Institute (DHI), Hørsholm, Denmark, has been used to simulate SSC maps of the GK for same date and time as the satellite images. To simulate the actual SSC conditions, three different modules of MIKE 21 are used in conjunction. The sequence of simulations using various modules of MIKE 21 is the following: hydrodynamic module (HD)-advection-dispersion module (AD)-mud transport module (MT). The OCM-derived SSC value of 10.0 mg/l at the open boundary (the open sea side) is assimilated into the model to initiate the simulation. The role of each module in the simulation process is described in the following sections.

After the simulated maps are obtained, these are studied date-by-date with the corresponding satellite-derived SSC image. MIKE 21 has also been used to simulate tidal current vectors in the GK for the same date and time as satellite images, to study the sediment dispersal patterns as it relates to tidal currents in two different seasons (pre- and post-monsoon).

**HD module**

The HD module (hydrodynamic equations) simulates the unsteady two-dimensional flows in one-layer (vertically homogenous) fluids. The water depth and fluxes obtained are used in MT and AD modules to compute sediment transport and advection-dispersion of suspended sediments. The Equations [3]-[5], the conservation of mass and momentum, integrated over the vertical, describe the flow and water level variations to simulate tidal flow in the GK [DHI, 2011].

\[
\frac{\partial \zeta}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = \frac{\partial d}{\partial t} \quad [3]
\]

\[
\frac{\partial p}{\partial t} + \frac{\partial}{\partial x}\left(\frac{p^2}{h}\right) + \frac{\partial}{\partial y}\left(\frac{pq}{h}\right) + gh\frac{\partial \zeta}{\partial x} + \frac{gp\sqrt{p^2 + q^2}}{C^2h^2} - \frac{1}{\rho_w}\left[\frac{\partial}{\partial x}(h\tau_{xx}) + \frac{\partial}{\partial y}(h\tau_{xy})\right] \\
\Omega q - fVV_x + \frac{h}{\rho_w} \frac{\partial}{\partial x}(p_a) = 0 \quad [4]
\]

\[
\frac{\partial q}{\partial t} + \frac{\partial}{\partial x}\left(\frac{q^2}{h}\right) + \frac{\partial}{\partial y}\left(\frac{pq}{h}\right) + gh\frac{\partial \zeta}{\partial y} + \frac{gq\sqrt{p^2 + q^2}}{C^2h^2} - \frac{1}{\rho_w}\left[\frac{\partial}{\partial y}(h\tau_{yy}) + \frac{\partial}{\partial x}(h\tau_{xy})\right] \\
\Omega p - fVV_y + \frac{h}{\rho_w} \frac{\partial}{\partial y}(p_a) = 0 \quad [5]
\]

The symbols used in above equations are:

- \(h(x,y)\) water depth = \(\zeta - d\), m;
- \(d(x,y,t)\) time varying water depth, m;
- \(\zeta(x,y,t)\) surface elevation, m;
$p, q(x, y, t)$ flux densities in $x -$ and $y -$ directions $= (uh, vh)$, m$^3$/s/m;

$(u, v)$ depth averaged velocities in $x -$ and $y -$ directions;

$C(x, y)$ Chezy resistance, m$^{1/2}$/s;

$g$ acceleration due to gravity, m/s$^2$;

$f(V)$ wind friction factor;

$V_x, V_y(x, y, t)$ wind speed and components in $x -$ and $y -$ direction, m/s;

$\Omega(x, y)$ Coriolis parameter, latitude-dependent, /s;

$p_a(x, y, t)$ atmospheric pressure, kg/m/s$^2$;

$\rho_w$ density of water, kg/m$^3$;

$x, y$ space coordinates, m;

$t$ time, s;

$\tau_{xx}, \tau_{yy}, \tau_{yy}$ components of effective shear stress.

The HD module makes use of alternating direction implicit (ADI) method to integrate the equations for mass and momentum conservation in the space-time domain. The Coriolis parameter (being dependent only on Earth’s angular velocity and latitude) can be treated as constant on given latitude ($22^\circ$N) for the GK. The surface stress terms, as that effect is very small on the tidal circulation in the GK, are assumed negligible. The astronomical tide of the adjacent Arabian Sea causes the main forcing in the GK. The model has an open boundary to the mouth of the GK. Prescribing temporal variation of the sea surface elevation across the western open ocean boundary extending in the north-south direction simulates the oscillatory flow in the GK. The surface elevation and bathymetry used in the model is taken from the MIKE C-MAP, a bathymetry retrieval module. The initial and boundary conditions used in HD module are as follows: the surface elevation of water at the open boundary (open sea) for March, April, November, and December were input as 2.2, 2.6, 2.1, and 1.9 m. Other simulation parameters were Smagorinsky factor ($C_s$), 0.2 [Smagorinksy, 1963]; and the Manning Number (bed resistance), 48 m$^{1/3}$/s.

**AD module**

AD module is required to simulate sediment dispersal in combination with the HD module. Simulated SSC maps are generated combining all three modules. The AD module uses OCM-derived SSC at the open boundary (the open sea side) to initiate the simulation. The advection and dispersion of suspended sediments at the surface (zero depth) are simulated using this module (Eq. 6). Sediment transport formulas are built into the AD module, which solves the advection-dispersion equation [DHI, 2011]
\[ \frac{\partial (hc)}{\partial t} + \frac{\partial (uhc)}{\partial x} + \frac{\partial (vhc)}{\partial y} = \frac{\partial}{\partial x} \left( hD_x \frac{\partial c}{\partial x} + hD_y \frac{\partial c}{\partial y} \right) + \frac{\partial}{\partial y} \left( hD_y \frac{\partial c}{\partial y} \right) - Fhc + S \quad [6] \]

where,

- \( c \) compound (depth-averaged) concentration, arbitrary units;
- \( u, v \) horizontal velocity components in the \( x, y \) directions, m/s;
- \( h \) water depth, m;
- \( D_x, D_y \) dispersion coefficients in the \( x, y \) directions, m\(^2\)/s;
- \( F \) linear decay coefficient, /s. (The decay in motion is considered linear, not due to heat dissipation, in this model);
- \( S = Q_s(c_s - c) \) (It is the source or sink term);
- \( Q_s \) source/sink discharge, m\(^3\)/s/m\(^2\). (It represents the discharge from one point to another, i.e. from source to sink);
- \( c_s \) concentration of compound in the source/sink discharge.

An explicit, third order finite difference scheme, known as the ULTIMATE scheme, solves the advection-dispersion equation [Leonard, 1991]. The well-known QUICKEST scheme lies at the basis of this scheme [Leonard, 1979; Ekebjaerg et al., 1991].

**MT module**

While the AD module incorporates advection and dispersion of suspended sediments, the MT module describes erosion, transport, and deposition of mud, or sand/mud mixtures under the action of currents and waves [Eq. 7]. The HD (hydrodynamic equations) and AD (advection-dispersion equations) output results serve as input to the MT module. Since the GK carries much mud and sand mixtures along with the presence of tidal muddy flats, the MT module is the most appropriate [DHI, 2011]. The MT uses sediment transport equation [Teisson, 1991]. The sediment density and the density of bed layer in the GK are taken as 2,650 kg/m\(^3\) and 180 kg/m\(^3\). The fall (or settling) velocity can be constant if the SSC is below a certain level when flocculation may be negligible. The sedimentological processes of flocculation, hindered settling, and re-suspension are accounted for in this model. The concentration of flocculation is 0.01, the concentration of hindered settling is 10, and constant settling velocity is taken as 0.0005 m/s. The anisotropic eddy viscosity has been considered to account for the three-dimensional flow effects, as the SSC is highly variable in the GK. For a very low SSC, the mud effect on the density and viscosity can be neglected. The model-simulated pre-monsoon SSC images filled the gaps for dates when satellite imageries were not available in March.
\[
\frac{\partial c^i}{\partial t} + \frac{\partial uc^i}{\partial x} + \frac{\partial vc^i}{\partial y} + \frac{\partial wc^i}{\partial z} = \frac{\partial}{\partial x} \left( \frac{v_{Tx}}{\sigma_{Tx}} \frac{\partial c^i}{\partial x} \right) + \frac{\partial}{\partial y} \left( \frac{v_{Ty}}{\sigma_{Ty}} \frac{\partial c^i}{\partial y} \right) + \frac{\partial}{\partial z} \left( \frac{v_{Tz}}{\sigma_{Tz}} \frac{\partial c^i}{\partial z} \right) + S^i \quad [7]
\]

where,

- \( t \) time, s;
- \( x, y, z \) Cartesian coordinates;
- \( u, v, w \) flow velocity components, m/s;
- \( c^i \) the \( i \) th scalar component;
- \( w_s \) fall velocity, m/s;
- \( \sigma_{Tx} \) turbulent Schmidt Number;
- \( v_{Tx} \) anisotropic eddy viscosity, m\(^2\)/s;
- \( S^i \) source term.

Figure 2 - Tidal variations at Okha port during March and April 2004 using Survey of India (SOI) Tide Table and WXTide32 software.

To investigate the SSC patterns with respect to bathymetry, three profiles A-A, B-B, and C-C across the GK from the south extending to the north were taken. The three profiles covering inner, middle, and mouth of the GK are representative of the variability in SSC with bathymetry. The OCM-derived SSC and MIKE 21-simulated SSC were correlated and interpreted along these profiles alongside bathymetry. The AD module provides advection and dispersion of the SSC at the surface (zero depth) assisted with the sediment transport...
computation using MT module. Thus, the space-based surface SSC and model-simulated surface SSC are correlated. The selection of profile B-B for discussions is preferable as it lies in the most dynamic region of the GK with regards to variability in bathymetry and SSC.

**Tidal analysis**
Tide data, from Survey of India (SOI), of March at Okha port were fed as input to the MIKE 21 Toolbox to predict the tidal harmonic coefficients (amplitude and phase) using the IOS (Institute of Ocean Sciences) method [Foreman, 1977]. The time series of water level at 3600 sec interval was selected. Figure 2 shows a comparison of SOI Tide Tables (ground-truth data) with predicted tides (astronomical tide data) using WXTide32 software ([http://www.wxtide32.com](http://www.wxtide32.com)) for March-April, and November-December (not shown in the figure). The surface winds (meteorological, not the surface currents) in the GK are reported to be 2-5 m/s, which can go up to 10 m/s [Pradhan et al., 2004].

Figure 3 - OCM-derived (left panel) and MIKE 21-simulated (right) SSC images on 11 and 13 March; 16 and 26 April; 10 and 12 November; and 12 and 14 December 2004.

Table 2 - The linear correlation (Pearson’s $r$) between OCM-derived and MIKE 21-simulated SSC at different profiles. The plots of comparison for profile B-B are provided in Figure 5.

| Month (2004) | Profile A-A | Profile B-B | Profile C-C |
|--------------|-------------|-------------|-------------|
| Mar          | 0.73        | 0.67        | 0.67        |
| Apr          | 0.60        | 0.71        | 0.69        |
| Nov          | 0.71        | 0.82        | 0.88        |
| Dec          | 0.82        | 0.81        | 0.64        |
Results and discussion

**OCM- and MIKE 21-derived SSC comparison for different seasons**

The OCM data were available for odd dates in March (Tab. 1). Figure 3 shows the OCM-derived SSC images of March, April, November, and December vis-à-vis MIKE 21-simulated maps (using HD and MT modules). The interdependence between the simulated and OCM-derived SSC is measured using linear correlation (Pearson’s $r$ varying between 0.60–0.88) between the two (Tab. 2). As both variables are SSCs, therefore, a statistical hypothesis testing for difference in methods is not preferable in this case. Pearson’s correlation shows the interdependence between the same variable obtained by two different methods, i.e. OCM and MIKE 21. In the pre-monsoon period (March and April), the correlation coefficient is lower than that in post-monsoon period (November and December). This is likely because of the increased sediment flux of Indus River during pre-monsoon [Gupta, 2015]. The snowmelt initiates in the Himalayas in the spring season during March-April. It augments the aggregate sediment flux of Indus River leading to the enhanced SSC in the GK. Highly concentrated suspended sediments behavior involves complex and difficult model computation as compared to the modeling of lower SSC. Therefore, there is a good correlation between the lower SSC in pre-monsoon and the SSC in the post-monsoon. Also, the monsoon in 2004 was a deficit [Rajeevan et al., 2007; Dutta et al., 2012], which resulted in lower SSC in post-monsoon. The paired samples $t$ test for the statistically significant difference between pre-monsoon and post-monsoon SSC data shows the $P$ value < 0.008. This indicates that pre-monsoon and post-monsoon SSCs were significantly different from each other.

**SSC profiles**

The analysis of suspended sediment dispersal patterns using OCM and model simulation along with the bathymetry data show that the entire northern region exhibits higher SSC as compared to southern region during all months of March, April, November, and December (Fig. 3). Figure 4 shows the water depth and maps of simulated tidal current vectors during different dates in March and April. It shows that suspended sediments in the GK respond to the propagation of tidal currents. All stations show a variable response to the tidal currents and SSC. The source of sediments lies in the northwestern parts of the GK. The sediment transport occurs into the GK along the northern shore during flooding phase with eastward current direction (Fig. 4). The profile B-B shows good agreement with the OCM-derived SSC (Tab. 2, Fig. 5, right panel). In profile B-B, bathymetry is shallow near to the southern and northern part and it is deep at a distance of 15 km from southern part and shallow at central part at ~18 m depth. In the central part, the suspended sediments come in suspension because of high tidal currents. Tidal currents vary from 1.2-2.3 m/s at the mouth to 3.0-5.0 m/s in the central portion of the GK (Fig. 4).

The sediment transport is very low near Kalubhar port (box 8 in Fig. 1) in post-monsoon; however, the suspended sediments appear along the southern part of the GK because of shallow bathymetry. Bottom sediments may lead to re-suspension because of tidal currents. The plots of SSC along profile B-B use the MT module and OCM-derived SSC images assisted with the bathymetry at the same profile location for March and November (Fig. 5). It is observable that near the Mundra port (box 3 in Fig. 1) as the bathymetry becomes shallow the SSC increases (Fig. 3). This is likely the result of the re-suspension of bottom sediments.
Figure 4 - MIKE 21-simulated current vectors overlaid on the water depth depicted in color on 11, 13, 15, 17, 19, 21, 23, 25, 27, 29, and 31 March 2004.

Figure 5 - Left panel: Bathymetry of the GK and geographic locations of profiles A-A, B-B and C-C. Right panels: SSC profiles (MIKE 21 and OCM) at B-B for (a) March, (b) November 2004, and (c) Bathymetry along the profile B-B (north-south). Please see Table 2 for quantified information.
The OCM and MIKE 21-derived SSC for profiles A-A (not plotted), B-B, and C-C (not plotted) show a good correlation for different seasons (Tab. 2, Fig. 5). The low SSC, as seen from the time series, on 14 March at Okha (box 9 in Fig. 1) is consistent with the OCM image and tide data (Fig. 6). For the period of six hours in a day, the SSC pattern at Navlakhi (box 5 in Fig. 1) is more uniform than the SSC patterns observed at Okha. This may be because Navlakhi lies in the interior of the GK, and the tidal current velocity is comparatively low (Fig. 4).

Table 3 - Averaged SSC at profiles A-A, B-B, and C-C during pre-monsoon and post-monsoon corresponding to tidal heights during spring tide.

| Time of Tide (IST) | OCM Time (IST) | SSC (OCM) (mg/l) | SSC (MIKE 21) (mg/l) | Water Height (m) |
|--------------------|----------------|------------------|---------------------|-----------------|
|                    |                |                  |                     |                 |
| **Full Moon**      |                |                  |                     |                 |
| 3 Mar 04:44        | -              |                  |                     |                 |
| 5 Apr 16:33        | 6 Apr 12:00    | 30.5             | 30.7                | 3.47            |
| 27 Nov 01:37       | 28 Nov 12:00   | 23.6             | 19.1                | 2.87            |
| 26 Dec 00:36       | -              | -                | -                   | -               |
| **New Moon**       |                |                  |                     |                 |
| 21 Mar 04:11       | 21 Mar 12:00   | 27.0             | 22.3                | 3.32            |
| 19 Apr 18:51       | 18 Apr 12:00   | 33.9             | 24.4                | 3.28            |
| 12 Nov 09:57       | 12 Nov 12:00   | 19.9             | 19.4                | 3.33            |
| 12 Dec 06:29       | 12 Dec 12:00   | 19.8             | 20.6                | 3.30            |

*IST, Indian Standard Time.
**Tidal currents simulation**

The role of tidal currents in sediment dispersal in the GK is dominant as discernible from the simulated images. Figure 7 shows rose plots of the direction and magnitude of MIKE 21-simulated tidal currents in the GK. The magnitude of tidal currents progressively increases from 0.2-1.2 m/s for March at Okha port. During the pre-monsoon period, the average water height (3.47 m) at full Moon is greater than that during post-monsoon period (average water height is 2.87 m) (Tab. 3). This is attributed to greater sediment flux of Indus River due to Himalayan snowmelt in pre-monsoon months (February-April). The OCM-derived SSC images also substantiate this observation (Fig. 3). Figure 8 and Table 4 respectively show the tidal current vectors (generated using MIKE 21) and water height during equinox (21 March) and solstice (21 December), which also correspond to pre-monsoon and post-monsoon. The tidal currents reduce in the solstice likely resulting from lower water input into the GK. Tidal harmonic analysis in the GK shows that principal lunar (M2 and O1), principal solar (S2), larger elliptical lunar (N2), and lunisolar declinational (K1) are the major constituents that account for ~83% of the aggregate tide generating force [Doodson, 1941]. M2, S2, and N2 are semi-diurnal whereas K1 and O1 are diurnal constituents (Tab. 5).

![Figure 7 - Direction and magnitude of tidal currents at Okha port during (a) 11-17 March (b) 17-23 March, and (c) 23-31 March 2004.](image-url)
Figure 8 - Current vectors overlaid on the water depth image for Equinox (top panel) and Solstice period (bottom panel) (21 March and 21 December 2004).

Table 4 - Water heights at different ports on equinox (21 March) and solstice (21 December) in 2004.

| Date     | Water Height (m) | Date     | Water Height (m) |
|----------|------------------|----------|------------------|
|          |                  |          |                  |
| **Equinox** |                 |          |                  |
| Okha     | 21 Mar 01:00    | 3.67     | 21 Mar 06:57     | 0.56  |
| Kandla   | 21 Mar 03:00    | 6.62     | 21 Mar 09:42     | 0.90  |
| Navlakhi | 21 Mar 03:28    | 7.22     | 21 Mar 10:23     | 0.57  |
| **Solstice** |                |          |                  |
| Okha     | 21 Dec 22:26    | 3.38     | 21 Dec 15:11     | 0.64  |
| Kandla   | 21 Dec 23:48    | 6.05     | 21 Dec 17:24     | 1.05  |
| Navlakhi | 21 Dec 23:54    | 6.66     | 21 Dec 17:50     | 0.51  |

*IST, Indian Standard Time.
Table 5 - Harmonic coefficients obtained from the analysis: principal lunar (M2 and O1), principal solar (S2), larger elliptical lunar (N2), and lunisolar declinational (K1).

| Constituent Name | Amplitude (m) | Phase (°) |
|------------------|---------------|-----------|
| O1               | 0.2113        | 57.55     |
| K1               | 0.3459        | 74.57     |
| N2               | 0.1994        | 334.80    |
| M2               | 1.1417        | 2.79      |
| S2               | 0.4560        | 48.59     |

SSC in pre-monsoon is greater than that in post-monsoon during full Moon phase. The same is also observable from the simulations and OCM image (Tab. 5, Fig. 3). During neap tide, variation in the SSC is less as compared to the SSC during the spring tide and the average height of water during neap tide is less than that during spring tide (Tab. 6, Fig. 2). The SSC is very high during pre-monsoon period as compared to that during post-monsoon period (Tabs. 3 and 6). Generally, the spring tide causes flooding in the GK (Figs. 4 and 9).

Table 6 - Averaged SSC along profiles A-A, B-B, and C-C during pre-monsoon and post-monsoon in 2004 corresponding to tidal heights during neap tide.

| Time of Tide (IST) | OCM Time (IST) | SSC (OCM) (mg/l) | SSC (MIKE 21) (mg/l) | Water Height (m) |
|-------------------|----------------|------------------|----------------------|------------------|
| Last quarter      |                |                  |                      |                  |
| 14 Mar 02:31      | -              | -                | -                    | -                |
| 12 Apr 09:16      | 12 Mar 12:00   | 24.7             | 27.6                 | 0.43             |
| 5 Nov 11:23       | 8 Nov 12:00    | 18.8             | 16.5                 | 2.28             |
| 5 Dec 06:23       | 6 Dec 12:00    | 19.2             | 16.4                 | 1.50             |
| First quarter     |                |                  |                      |                  |
| 29 Mar 05:18      | 29 Mar 12:00   | 17.4             | 14.9                 | 0.91             |
| 27 Apr 23:02      | 26 Apr 12:00   | 23.1             | 23.1                 | 1.12             |
| 19 Nov 11:20      | 20 Nov 12:00   | 23.1             | 21.8                 | 1.34             |
| 18 Dec 22:10      | 18 Dec 12:00   | 20.3             | 21.3                 | 1.30             |

*IST, Indian Standard Time.

Simulated results of the HD module show that the currents resulting from spring tide are very large ~3.0-4.0 m/s on 12 November (Fig. 9). The simulated SSC image and OCM-derived SSC image show that the amount of SSC is also high on 12 November (Fig. 3). Low current velocity persists during the neap tide on 29 March in the pre-monsoon period (Fig. 4). This results in ebb tide condition, which transports the sediments at the mouth outside the GK. This dynamics is also discernible on 8 November during the post-monsoon period (Figs. 3 and 9).
Conclusion
This paper presented a comprehensive analysis of OCM-derived SSC, MIKE 21-simulated SSC, to provide insights into the fate of suspended sediments in the GK for tidal variations and seasonal (pre-monsoon and post-monsoon) changes. The conclusions based on the analysis are as follows:

Toward objective-1, the suspended sediment dispersal in the GK is highly dependent on the tidal conditions prevalent in a given time and space domain. The underlying bathymetry (>27 m termed tidal scour channel by Ramakrishnan and Rajawat [2012]) controls the spatial behavior of suspended sediments to a greater extent. The SSC was high in all those regions where water depth was shallow in the GK. The tide is very influential in bringing the suspended and bottom sediments into motion in shallow areas. The spring tide has stronger influence (than neap tide) on the SSC in the GK. It is important to advert to that the GK undergoes tremendous water level variations throughout the year. The water level variations are higher during pre-monsoon likely attributable to the increased sediment flux of Indus River due to Himalayan snowmelt during pre-monsoon (February-April). This is evident on the equinox and solstice simulations of tidal current vectors and OCM-derived SSC images during full and new Moon (spring tide), and first and last quarter (neap tide). The time series of SSC at Okha and Navlakhli ports show that the SSC at these locations closely follow the tidal energy and the bathymetry. A sensitivity analysis regarding the roles of tides on the SSC patterns by adding and removing tidal component from the model is suggested as future research. Shear stress can be mapped in the model to quantify the roles of bathymetry and re-suspension of sediments.

Toward objective-2, the sequential high-temporal-resolution (two days) OCM-derived SSC images have demonstrated near-ideal means for monitoring of a tide-dominated Gulf. The sporadically inconsistent and abrupt SSC values, observed from OCM images, result from the combined influence of the deficient monsoon in 2004 [Rajeevan et al., 2007; Dutta et al., 2012], prevailing surface winds, and re-suspension of bottom sediments because of
tidal currents in the GK. Strong or even normal monsoon conditions have the potential in changing the suspended sediment loads in the GK. The pre-monsoon and post-monsoon analysis of the data show that the GK seems to be more affected by the tidal energy (mainly spring tides) than the monsoonal changes. A geo-statistical study using satellite data and numerical modeling would be an interesting validation exercise. This study showed that without extensive ground-truth data collection in a Gulf, it is possible to understand the suspended sediment behavior and dispersal patterns. *In situ* measurements of SSC and its surface extents can be a future validation exercise. However, very high SSC (>$40.0$ mg/l) poses problems in satellite retrieval of SSC because of radiance saturation at the sensor, but complex mathematical modeling can provide better solutions. Higher temporal (<two days) and spatial (<360 m) resolution of future ocean color satellite sensors can provide an improvement in the modeling of suspended sediments in a tide-dominated Gulf. An analogous study for multiple and consecutive years is likely to generalize the findings of this paper. The present atmospheric correction procedure used AOD only due to marine aerosols. The consideration of other types of aerosols, e.g., terrestrial and urban [Bassani et al., 2014], for computation of AOD, provides a good avenue for future research for remote sensing SSC estimation.

**Acknowledgements**
The author expresses deep gratitude to Dr. Shailesh R. Nayak for his leadership and institutional support during this project. I gratefully acknowledge Mr. J. Girishkumar for processing of OCM images and assistance with modeling.

**References**
Babu M.T., Vethamony P., Desa E. (2005) - *Modelling tide driven currents and residual eddies in the Gulf of Kachchh and their seasonal variability: A marine environmental planning perspective*. Ecological Modelling, 184: 299-312. doi: [http://dx.doi.org/10.1016/j.ecolmodel.2004.10.013](http://dx.doi.org/10.1016/j.ecolmodel.2004.10.013).

Bassani C., Manzo C., Braga F., Bresciani M., Giardino C., Alberotanza L. (2014) - *Impact of the aerosol type on HICO™ atmospheric correction in coastal waters*. Atmospheric Measurement Techniques Discussions, 7: 5147-5172. doi: [http://dx.doi.org/10.5194/amtd-7-5147-2014](http://dx.doi.org/10.5194/amtd-7-5147-2014).

Chauhan O.S., Jayakumar S., Menezes A.A.A., Rajawat A.S., Nayak S.R. (2006) - *Anomalous inland influx of the River Indus, Gulf of Kachchh, India*. Marine Geology, 229: 91-100. doi: [http://dx.doi.org/10.1016/j.margeo.2005.12.003](http://dx.doi.org/10.1016/j.margeo.2005.12.003).

Chauhan O.S., Menezes A.A.A., Jayakumar S., Malik M.A., Pradhan Y., Rajawat A.S., Nayak S.R., Bandekar G., Almeida C., Talaulikar M., Ramanamurty M.V., Subramanian B.R. (2007) - *Influence of the macrotidal environment on the source to sink pathways of suspended flux in the Gulf of Kachchh, India: evidence from the Ocean Colour Monitor (IRS-P4)*. International Journal of Remote Sensing, 28: 3323-3339. doi: [http://dx.doi.org/10.1080/01431160600962756](http://dx.doi.org/10.1080/01431160600962756).

Chauhan P., Mohan M., Nayak S. (2003) - *Comparative analysis of ocean color measurements of IRS-P4 OCM and SeaWiFS in the Arabian Sea*. IEEE Transactions on Geoscience and Remote Sensing, 41: 922-926. doi: [http://dx.doi.org/10.1109/TGRS.2003.813551](http://dx.doi.org/10.1109/TGRS.2003.813551).

Chauhan O.S., Vora K.H. (1990) - *Reflection seismic studies in the macrotidal Gulf of*
Kachchh, India: evidence of physiographic evolution. Continental Shelf Research, 10: 385-396. doi: http://dx.doi.org/10.1016/0278-4343(90)90058-T.

Dash P., Walker N., Mishra D., D’Sa E., Ladner S. (2012) - Atmospheric correction and vicarious calibration of Oceansat-1 Ocean Color Monitor (OCM) data in coastal case 2 waters. Remote Sensing, 4: 1716-1740. doi: http://dx.doi.org/10.3390/rs4061716.

DHI (2011) - MIKE 21 Manuals, Danish Hydraulics Institute, Hørsholm, Denmark.

Doodson A.T., Warbrug H.D. (1941) - Admialty manual of tides. Her Majesty’s Stationery Office, London.

Doxaran D., Froidefond J.M., Lavender S., Castaing P. (2002) - Spectral signature of highly turbid waters: Application with SPOT data to quantify suspended particulate matter concentrations. Remote Sensing of Environment, 81: 149-161. doi: http://dx.doi.org/10.1016/S0034-4257(01)00341-8.

Dutta S., Narkhedkar S.G., Devi S., Sikka D.R. (2012) - A composite energetics study for contrasting south west monsoon years in the recent decade. Atmosfera, 25: 109-126.

Eisma D. (1981) - Suspended matter as a carrier for pollutants in estuaries and the sea. In: Marine Environmental Pollution, Dumping and Mining, 2: 281-295. Geyer R.A. (Ed.), Elsevier Oceanographic Series 27B, Amsterdam.

Ekebjaerg L., Justesen P. (1991) - An explicit scheme for advection-diffusion modelling in two dimensions. Computer Methods in Applied Mechanics and Engineering, 88: 287-297. doi: http://dx.doi.org/10.1016/0045-7825(91)90091-J.

Forget P., Broche P., Naudin J.-J. (2001) - Reflectance sensitivity of solid suspended sediment stratification in coastal water and inversion: A case study. Remote Sensing of Environment, 77: 92-103. doi: http://dx.doi.org/10.1016/S0034-4257(01)00197-3.

Foreman M.G. (1977) - Manual for tidal heights analysis and prediction. Pacific Marine Science Report 77-10, Institute of Ocean Sciences, Canada.

Gordon H.R. (1995) - Remote sensing of ocean color: a methodology for dealing with broad spectral bands and significant out-of-band response. Applied Optics, 34: 8363-8374. doi: http://dx.doi.org/10.1364/AO.34.008363.

Gordon H.R., Clark D.K. (1981) - Clear water radiances for atmospheric correction of coastal zone color scanner imagery. Applied Optics, 20: 4175-4180. doi: http://dx.doi.org/10.1364/AO.20.004175.

Gordon H.R., Wang M. (1994) - Influence of oceanic whitecaps on atmospheric correction of ocean-color sensors. Applied Optics, 33: 7754-7763. doi: http://dx.doi.org/10.1364/AO.33.007754.

Gupta M. (2015) - Analysis of pre- and post-monsoon suspended sediments in the Gulf of Kachchh, India using remote sensing. arXiv:1503.08369 [physics.ao-ph].

Kunte P.D., Wagle B.G., Sugimori Y. (2003) - Sediment transport and depth variation study of the Gulf of Kutch using remote sensing. International Journal of Remote Sensing, 24: 2253-2263. doi: http://dx.doi.org/10.1080/01431160210164316.

Kunte P.D., Zhao C., Osawa T., Sugimori Y. (2005) - Sediment distribution study in the Gulf of Kachchh, India, from 3D hydrodynamic model simulation and satellite data. Journal of Marine Systems, 55: 139-153. doi: http://dx.doi.org/10.1016/j.jmarsys.2004.09.008.

Leonard B.P. (1979) - A stable and accurate convective modelling procedure based on quad- ratic upstream interpolation. Computer Methods in Applied Mechanics and Engineering, 19: 59-98. doi: http://dx.doi.org/10.1016/0045-7825(79)90034-3.
Leonard B.P. (1991) - *The ULTIMATE conservative differential scheme applied to unsteady one-dimensional advection*. Computer Methods in Applied Mechanics and Engineering, 88: 17-74. doi: http://dx.doi.org/10.1016/0045-7825(91)90232-U.

McCarthy S.C., Gould R.W., Richman J., Kearney C., Lawson A. (2012) - *Impact of aerosol model selection on water-leaving radiance retrievals from satellite ocean color imagery*. Remote Sensing, 4: 3638-3665. doi: http://dx.doi.org/10.3390/rs4123638.

Miller R.L., McKee B.A. (2004) - *Using MODIS Terra 250 m imagery to map concentrations of total suspended matter in coastal waters*. Remote Sensing of Environment, 93: 259-266. doi: http://dx.doi.org/10.1016/j.rse.2004.07.012.

Mohan M., Chauhan P. (2003) - *Atmospheric correction for ocean color remote sensing*. ISRO Scientific Report, IRS-P4/SATCORE/SAC/RESIPA/MWRG/SR/22/2003, Ahmedabad, India, 22 pp.

Myint S.W., Walker N.D. (2002) - *Quantification of surface suspended sediments along a river dominated coast with NOAA AVHRR and SeaWiFS measurements: Louisiana, USA*. International Journal of Remote Sensing, 23: 3229-3249. doi: http://dx.doi.org/10.1080/01431160110104700.

Nanu L., Robertson C. (1993) - *The effect of suspended sediment depth distribution on coastal water spectral reflectance: theoretical simulation*. International Journal of Remote Sensing, 14: 225-239. doi: http://dx.doi.org/10.1080/01431169308904334.

Ouillon S. (2003) - *An inversion method for reflectance in stratified turbid waters*. International Journal of Remote Sensing, 24: 535-558. doi: http://dx.doi.org/10.1080/01431160304986.

Patel S.J., Desai B.G. (2009) - *Animal-sediment relationship of the crustaceans and polychaetes in the intertidal zone around Mandvi, Gulf of Kachchh, Western India*. Journal of Geological Society of India, 74: 233-259. doi: http://dx.doi.org/10.1007/s12594-009-0125-6.

Pradhan Y., Rajawat A.S., Nayak S. (2004) - *Application of IRS-P4 OCM data to study the impact of tidal propagation on sediment dynamics in the Gulf of Kachchh*. Indian Journal of Marine Sciences, 33: 129-137.

Pradhan Y., Rajawat A.S., Thomaskutty A.V., Gupta M., Nagur C.R.C., Nayak S. (2003) - *An improved regional algorithm to retrieve total suspended particulate matter using IRS-P4 OCM data*. International Archives of Photogrammetry Remote Sensing and Spatial Information Sciences, 34 (7/B): 1432-1436.

Rajawat A.S., Gupta M., Pradhan Y., Thomaskutty A.V., Nayak S. (2005) - *Coastal processes along the Indian coast- Case studies based on synergistic use of IRS-P4 OCM and IRS-1C/1D data*. Indian Journal of Marine Sciences, 34: 459-474.

Rajeevan M., Pai D.S., Kumar R.A., Lal B. (2007) - *New statistical models for long-range forecasting of southwest monsoon rainfall over India*. Climate Dynamics, 28: 813-828. doi: http://dx.doi.org/10.1007/s00382-006-0197-6.

Ramakrishnan R., Rajawat A.S. (2012) - *Simulation of suspended sediment transport initialized with satellite derived suspended sediment concentrations*. Journal of Earth System Science, 121: 1201-1213. doi: http://dx.doi.org/10.1007/s12040-012-0222-6.

Ramawat V., Nath B.N., Vethamony P., Illangovan D. (2007) - *Source and dispersal of suspended sediment in the macro-tidal Gulf of Kachchh*. Marine Pollution Bulletin, 54: 708-719. doi: http://dx.doi.org/10.1016/j.marpolbul.2007.01.026.
SAC Report (2003) - IRS-P4 OCM/SATCORE Project Report, Volume 3, Report N. IRS-P4/SATCORE/SAC/RESIPA/MWRG/SR/22/2003, Space Applications Centre, Ahmedabad, India, 120 pp.

Shetye S.R. (1999) - Tides in the Gulf of Kutch, India. Continental Shelf Research, 19: 1771-1782. doi: http://dx.doi.org/10.1016/S0278-4343(99)00038-2.

Smagorinsky J. (1963) - General circulation experiment with the primitive equations. Monthly Weather Review, 91: 99-164. doi: http://dx.doi.org/10.1175/1520-0493(1963)091<0099:GCEWTP>2.3.CO;2.

Tassan S. (1994) - Local algorithms using SeaWiFS data for the retrieval of phytoplankton pigments, suspended sediment, and yellow substance in coastal waters. Applied Optics, 33: 2369-2378. doi: http://dx.doi.org/10.1364/AO.33.002369.

Teisson C. (1991) - Cohesive suspended sediment transport: feasibility and limitations of numerical modelling. Journal of Hydraulic Research, 29: 755-769. doi: http://dx.doi.org/10.1080/00221689109498957.

Trivedi D., Raicy M.C., Devi K., Kumar D., Buynevich I., Srinivasan P., Iyer N.R., Guin R., Sengupta D., Nair R.R. (2012) - Sediment characteristics of tidal deposits at Mandvi, Gulf of Kuchchh, Gujarat, India: geophysical, textural and mineralogical attributes, International Journal of Geosciences, 3: 515-524. doi: http://dx.doi.org/10.4236/ijg.2012.33054.

Unnikrishnan A.S., Luick, J.L. (2003) - A finite element simulation of tidal circulation in the Gulf of Kutch, India. Estuarine, Coastal and Shelf Science, 56: 131-138. doi: http://dx.doi.org/10.1016/S0272-7714(02)00135-X.

© 2015 by the authors; licensee Italian Society of Remote Sensing (AIT). This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution license (http://creativecommons.org/licenses/by/4.0/).