Simulation of suspended sediment transport initialized with satellite derived suspended sediment concentrations

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Suspended sediment transport in the Gulf of Kachchh is simulated utilizing the suspended sediment concentration (SSC) derived from Oceansat OCM imagery, as the initial condition in MIKE-21 Mud Transport model. Optimization of the model mud parameters, like settling velocity and critical shear stress for erosion are realized with respect to the sediment size distribution and the bottom bed materials observed in the Gulf. Simulated SSCs are compared with alternate OCM derived SSC. The results are observed to be impetus where the model is able to generate the spatial dynamics of the sediment concentrations. Sediment dynamics like deposition, erosion and dispersion are explained with the simulated tidal currents and OCM derived sediment concentrations. Tidal range is observed as the important physical factor controlling the deposition and resuspension of sediments within the Gulf. From the simulation studies; maximum residual current velocities, tidal fronts and high turbulent zones are found to characterise the islands and shoals within the Gulf, which results in high sediment concentrations in those regions. Remarkable variability in the bathymetry of the Gulf, different bed materials and varying tidal conditions induces several circulation patterns and turbulence creating the unique suspended sediment concentration pattern in the Gulf.

1. Introduction

Monitoring and understanding the sediment dynamics and suspended sediment transport is an important issue for coastal engineering related activities. A study on the transport mechanism of suspended sediments in marine environment is essential not only for the safeguard of marine installations or navigational channels but also to make out an assessment on the pollutants and other biological activities in the region.

Conventional methods of monitoring suspended sediment concentration (SSC) through *in-situ*

measurements are difficult, expensive and are point observations whereas remote sensing-based data provide large area coverage and are repetitive observations which are more reliable and quick to obtain. Satellite-derived SSC data provided by IRS-P4 Ocean Color Monitor (OCM) have been found to be useful for Indian region, due to its high spatial and spectral resolution, good temporal resolution and a local pass at 12:00 hrs IST. In spite of 2-day revisit period, OCM observations are inadequate to understand the sediment dispersion by the alternating tidal currents in regions like Gulf of Kachchh, while numerical

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simulation of sediment transport has the advantage of continuous observation of sediment dynamics and understanding the sediment behaviour in the alternating tidal currents.

Numerical simulation of sediment transport is achieved by hydrodynamic-transport coupled models. The simulation of sediment transport models by Liang *et al.* (2007), Cancino and Neves (1999) and Ulses *et al.* (2008) were based on field observations whereas Zhang and Hua (2007) and Douillet *et al.* (2001) have resorted to the theoretical values and lab measurements to validate the transport model. Quillon and Caussade (1991) have described the effective use of satellite remote sensing data in modelling sediment transport. Quillon *et al.* (2004) have coupled remote sensing data with *in situ* measurements to simulate suspended sediment transport in New Caledonia Lagoon.

Initial distribution of sediment concentrations are of critical importance for sediment transport modelling (Lee *et al.* 2007). Often, the initial concentrations are assumed to be constant for the entire model domain or uses field observations which are rather scattered point observations. The present study utilises the sediment concentration values derived from OCM as initial sediment concentrations for a numerical model to simulate its transport under the hydrodynamics prevailing in Gulf of Kachchh.

1.1 Study area and environmental setting

Gulf of Kachchh ($68^{\circ}20'E-70^{\circ}40'E$; $22^{\circ}15'-23^{\circ}40'N$) is an east-west oriented; macro-tidal region in the west coast of India (figure 1). The Gulf is a high energetic system where the highest high tide reaches about 6.6 m at Kandla and 7.2 m at Navalakhi. Studies have reported that the natural period of the Gulf is close to 10 hours (Unnikrishnan and Luick 2003), causing amplification of the constituents, whereas Shetye (1999) has observed an additional amplification of constituents due to the funnel-shaped geometry of the Gulf.

In situ data were used to understand the sediment characteristic of the Gulf in their studies by Hashimi *et al.* (1978), Nair *et al.* (1982) and Ramaswamy *et al.* (2007). The complex system of the Gulf is composed with fragile marine ecosystem where, amid the tidal channels, are small shoals and coral islands, controlling the tidal current patterns and sediment dynamics within the Gulf. From the hydrodynamic simulation of tidal currents, the contrast in mixing and transport pattern between the outer and inner Gulf was reported by Kankara *et al.* (2007) which could be probably due to the existence of a dynamic barrier along Sikka–Mundra section, which divides the Gulf into two distinct dynamic systems as reported by Vethamony *et al.* (2005). Babu *et al.*

Figure 1. Location map of Gulf of Kachchh.

(2005) studied the residual eddy currents within the Gulf using numerical modelling of tidal circulations. Hydrodynamic simulation studies alone were found to be ineffective in understanding various sediment dynamics and the use of satellite data in conjunction with the numerical results were opted by Kunte *et al.* (2005) and Chauhan *et al.* (2006, 2007) to comprehend the sediment distribution and source to sink pathways of sediment fluxes.

Babu *et al.* (2003) have studied the sediment transport along Mangalore coast in the Arabian Sea using model results.

In the present study, sediment transport in the Gulf of Kachchh is simulated from the concentration information derived from OCM observations. An attempt is made to understand the relation of tidal currents to the sediment dynamics of the Gulf.

2. Data and methodology

2.1 Satellite image

Remote sensing of oceanic and coastal waters depends upon the interaction of light with optically active water constituent such as phytoplankton, total suspended matter and dissolved organic matter, also known as yellow substance. A large number of sensors are developed by Indian and other space agencies, which are dedicated to determine the ocean parameters optically. OCM onboard Oceansat-1 collects data in eight spectral channels (402–422, 433–453, 480–500, 500–520, 545–565, 660–680, 745–785 and 845–885 nm) with temporal resolution of 2 days at a local time 12:00 hrs. Each OCM scene covers 1420×1420 km ground area.

From the first six channels corresponding to the visible spectrum, water leaving radiance (L_w) is extracted after correcting for the atmospheric constituents. The sensor observed radiance (L_t) can be partitioned into components corresponding to distinct physical processes like Rayleigh scattering by the atmospheric gaseous constituents (L_r), scattering by the aerosol particles (L_a) and the water leaving radiance (L_w) (Doerffer 1992). L_r is computed from its spectral dependency, which leaves L_a as the unknown to be determined to obtain L_w from L_t . L_w at band 7 and band 8 in the near infrared (NIR) region is assumed to be negligible enabling estimates of NIR L_a . L_a at visible bands is obtained by extrapolating the NIR L_a using aerosol model. The detailed descriptions are given in Gordon (1997).

Even though a large number of sediment algorithms have been proposed to quantify total suspended matter (Miller and McKee 2004; Pradhan

et al. 2005; Erico *et al.* 2007), universal sediment algorithms are unavailable (Acker *et al.* 2005). In the current study, from the water leaving radiances, SSC values were derived from algorithm initially proposed by Tassan (1994) and later undergone site specific modification (Chauhan *et al.* 2006):

$$\log(S) = 1.83 + 1.261 \log(X_s) \quad 0.0 \leq S \leq 40.0 \quad (1)$$

where S is the SSC in mg/l and X_s is defined as:

$$X_S = \{R_{rs}(555) + R_{rs}(670)\} \\ \times [R_{rs}(490)/R_{rs}(555)]^{-0.5} \quad (2)$$

where $R_{rs}(\lambda)$ is the remote-sensing reflectance in respective wavelengths.

Chauhan *et al.* (2007) have used the same SSC retrieval algorithm in the Gulf of Kachchh region to obtain the SSC distribution patterns within the Gulf. Their study have compared OCM derived SSC with *in situ*, pass synchronous and random measurements and observed that the OCM SSC are underestimated by $\pm 25\%$. Pradhan *et al.* (2004) have utilized OCM derived sediment inputs to study the impact of tidal propagation on the sediment dynamics of the Gulf. In their study by Chauhan *et al.* (2006), the contribution of sediments from the River Indus into the Gulf of Kachchh was made observed using OCM derived SSC. SSC in the Gulf of Kachchh was derived from SeaWiFS data using Tassan algorithm by Kunte *et al.* (2005) to study the sediment distribution of the Gulf. It is observed that the SSC values obtained from OCM shows rather a relative value than the absolute value of SSC. The acceptability of the satellite derived SSC lays in its ability to preserve the general pattern of sediment distribution (Chauhan *et al.* 2007; Peckham 2008).

Geometric correction is applied separately on individual datasets to remove image distortion and bring them to a standard geographic projection. Image to image rectification is done among the sequential satellite data to obtain an error limit restricted to one pixel (360 m). Cloud free OCM scenes for January 2005 are selected to understand the spatial distribution of the suspended sediment in the Gulf.

2.2 Simulation of tidal currents

Simulation of tidal currents in Gulf of Kachchh is done using Hydrodynamic (HD) module of MIKE-21. MIKE-21, developed by the Danish Hydraulic Institute, Denmark, is a software package

containing a comprehensive modelling system for 2D free-surface flows. The flow field is calculated from the solution of depth integrated equations of conservations of volume and momentum in x and y directions (Abbott 1979) given as:

x-momentum:

$$\begin{aligned} \frac{\partial p}{\partial t} + \frac{\partial}{\partial x} \left[\frac{p^2}{h} \right] + \frac{\partial}{\partial y} \left[\frac{pq}{h} \right] + gh \frac{\partial \eta}{\partial x} \\ + \left[g \frac{\sqrt{\frac{p^2}{h^2} + \frac{q^2}{h^2}}}{C^2} \right] - fVV_x - \frac{h}{\rho w} \frac{\partial P_a}{\partial x} \\ - \Omega q - E = S_{ix} \end{aligned} \quad (3)$$

y-momentum:

$$\begin{aligned} \frac{\partial q}{\partial t} + \frac{\partial}{\partial x} \left[\frac{pq}{h} \right] + \frac{\partial}{\partial y} \left[\frac{q^2}{h} \right] + gh \frac{\partial \eta}{\partial y} \\ + \left[g \frac{\sqrt{\frac{p^2}{h^2} + \frac{q^2}{h^2}}}{C^2} \right] - fVV_y - \frac{h}{\rho w} \frac{\partial P_a}{\partial y} \\ - \Omega q - E = S_{iy} \end{aligned} \quad (4)$$

the equation of continuity:

$$\frac{\partial \eta}{\partial t} + \frac{\partial p}{\partial x} + \frac{\partial q}{\partial y} = S - e \quad (5)$$

P and q =the flux in the x and y directions, respectively, h =water depth, t =time, P_a =atmospheric pressure, ρ_w =density of water, g = acceleration due to gravity, h = surface elevation (m), e = evaporation rate (mm/day), C = Chezy's coefficient, f = wind friction factor, V = Coriolis force, S_{ix} and S_{iy} = source impulse in x and y directions, E = eddy viscosity coefficient, and Ω = Coriolis parameter.

The domain is selected to include the entire Gulf of Kachchh. Available NHO (National Hydrographic Office) hydrographic chart is used to create the bathymetry (figure 2). The resolution of bathymetry is chosen as that of the spatial resolution of OCM, which is 360 m. For the purpose of classification of the Gulf according to the bathymetry, the region deeper than 27 m is termed as tidal scour channel of the Gulf (figure 2).

As river input into the Gulf can be neglected (Ramaswamy *et al.* 2007), eastern part of the Gulf is closed so that water enters the Gulf only through the west (open ocean). The model is forced using the tidal elevation at the open boundary, with Godia creek on the north and Okha on the south. Tidal elevations for the above-mentioned stations are obtained from MIKE-CMAP tidal extraction tool at an interval of 30 min. A constant wind of 5 m s^{-1} and wind friction factor of 0.0026, resistance of $38 \text{ m}^{1/3} \text{ s}^{-1}$ and horizontal eddy viscosity of $0.5 \text{ m}^2 \text{ s}^{-1}$ are given to the model as suggested by Babu *et al.* (2005). The simulation is carried out for January 2005.

Figure 2. Model domain and the bathymetry of the region. (For comparison, the SSC from OCM and model is extracted along the line drawn from mouth to head.)

2.3 Integration of satellite-derived SSC into the sediment transport model

Coupling of remote sensing and numerical models were reported by Quillon *et al.* (1998) where the applicability of remote sensing to provide initial data or boundary forcing to a numerical model was detailed. In the present study, the synoptic distribution of SSC derived from OCM for 1 January 2005 (figure 3) is taken as the initial condition of sediment concentration in a numerical model to simulate the suspended sediment transport. Geometrically corrected OCM scene is brought to geographic projection as that of bathymetry file prepared for the numerical simulation. The error limit was restricted to one pixel which made sure that the SSC maps derived from OCM exactly fits over the bathymetry file. These sediments (OCM derived) are then advected with the tidal currents (simulated from MIKE-21 HD) imparting dispersion and settling of the sediments. The sediment transport models are configured to run in conjunction with the hydrodynamic model. MIKE-21 Mud Transport (MT) model is used to simulate suspended sediment transport within the Gulf of Kachchh. The MT module describes erosion, transport and deposition of silt, mud and clay particles under the action of currents and waves.

The governing equation for the suspended sediment transport model is:

$$\frac{\partial C}{\partial t} + u \frac{\partial C}{\partial x} + v \frac{\partial C}{\partial y} = K_x \frac{\partial^2 C}{\partial x^2} + K_y \frac{\partial^2 C}{\partial y^2} + \frac{\varphi_r - \varphi_s}{h} \quad (6)$$

where C = depth-averaged concentration of suspended sediment, u , v = x and y components of depth-averaged of current velocity derived from the hydrodynamics model, K_x , K_y = depth mean dispersion coefficients in x and y directions, φ_r = re-suspension flux, φ_s = sedimentation flux, and h = total depth.

Settling velocity and critical shear stress of erosion are two important mud parameters of the model. For grains to get deposited from the suspended load, the settling velocity w_s of the grains in suspension should be greater than the upward turbulent component of velocity. The settling velocity of grains is calculated according to the suspended sediment size distribution maps within the Gulf compiled from the field observations of Ramaswamy *et al.* (2007).

Settling velocity is calculated from the equation given by Soulsby (1997)

$$w_s = \frac{\nu}{d_{50}} \left[(10.36^2 + 1.049 D_*^3)^{1/2} - 10.36 \right] \quad (7)$$

where d_{50} is the grain size diameter, ν is the kinematic viscosity of water = $1.36 \times 10^{-6} \text{ m}^2/\text{s}$, and D_* is the dimensional size parameter.

$$D_* = \left[\frac{g(s-1)}{\nu^2} \right]^{1/3} d_{50} \quad (8)$$

where g is the gravity, and s is the ratio of densities of sediment and water.

For very slow flow over a sand bed, the sand remains immobile, but as the flow velocity is increased slowly, a velocity is reached at which a

Figure 3. SSC for 1st January 2005 in mg/l (initial concentration for simulation of sediment transport model).

Figure 4. Comparison of simulated and predicted tidal elevation for Navalakhi.

Figure 5. (a) Flood current pattern in Gulf of Kachchh, (b) ebb current pattern in Gulf of Kachchh, (c) current pattern in Gulf of Kachchh during reversal of tide and (d) residual current in Gulf of Kachchh computed for four tidal cycles.

few grains begin to move. This is called threshold of motion. The bed shear stress associated with the threshold of motion is called critical bed shear stress τ_{cr} . The spatial variation of critical shear stress within the Gulf is evaluated according to the bed form distribution of Gulf of Kachchh compiled by Kunte *et al.* (2003).

$$\tau_{cr} = \theta_{cr} g d_{50} (\rho_s - \rho) \quad (9)$$

where ρ is the water density = 1027 kg/m³, ρ_s is the sediment density, and θ_{cr} is the shield parameter.

$$\theta_{cr} = \frac{0.30}{1 + 1.2D_*} + 0.055 [1 - \exp(-0.020D_*)] \quad (10)$$

Winter (2007) has described the significance of statistical parameters for the evaluation of

sediment transport model. SSC derived from subsequent OCM images for 3rd, 5th and 7th January 2005 are used for the statistical evaluation of the model results.

3. Results and discussion

3.1 Tidal simulation

Simulation is carried out to obtain the tidal current within the Gulf of Kachchh for January 2005.

In the absence of synchronous current measurements, the simulation is validated with predicted tidal elevation for Navalakhi in the eastern side of the domain (closed boundary). The comparison of the model and predicted tidal elevation (figure 4) confirms that the model reproduces the phase and amplitude with the predicted tide. Figure 5(a) depicts the surface current distribution during high tide time. During the high tide, the current enters the Gulf with a maximum speed of 2.8 m/s. The distribution of ebb current is shown in figure 5(b), with a maximum speed of 2.47 m/s.

Figure 6. Comparison of simulated SSC with OCM derived SSC (mg/l).

Figure 5(c) shows the current pattern during the reversal of current from flood to ebb. Co-tidal line from figure 5(c) indicates that tide in the Gulf is ebb, but the currents in the tidal scour channel (shown in figure 2) are observed to flow eastwards (characteristic of a flood tide), that is, currents in the tidal scour channel lag behind the tidal elevation. In the tidal scour channel, currents have large

velocity and momentum and thus a lower response to the change in tide. Towards the coast, the current velocities are small with smaller momentum and follow the tidal elevation without any significant time lag. Tidal fronts are formed at the conjunction of these opposing currents which are characterized by high turbulence. Eddies are also observed during the reversal of the tide (figure 5c).

The residual currents are calculated by taking average of the velocities for a period of four tidal cycles (figure 5d). Several clockwise and anticlockwise eddies are observed within the Gulf confined to the islands and shoals where a sudden change in the depth occurs.

3.2 Simulation of suspended sediment transport

Simulation of suspended sediment transport is carried out by optimizing the model control parameters like settling velocity and critical shear stress for erosions. The settling velocity given is 0.0002 m/s and the critical shear stress for erosion is obtained in the range of 0.05–2.00 N/m², where the low value coincides with region of soft sediment bed and larger value corresponds to

Figure 7. Scatter plot showing the comparison of simulated SSC with OCM SSC.

Figure 8. Comparison of simulated SSC and OCM SSC extracted along the line.

Figure 9. OCM-derived SSC (mg/l) for January 2005.

area with hard sediment bed forms. Simulation of sediment transport is carried out from 1st January 2005 12:00 hrs by taking OCM-derived SSC as the initial concentration.

SSC obtained from the model at 12:00 hrs for 3rd, 5th and 7th January 2005 is visually compared with the corresponding OCM derived SSC (figure 6). A statistical comparison is done from the scatter plot shown in figure 7. The RMS error is found to be 5.8 and 5.5 mg/l for 3rd and 5th January 2005 and for 7th January 2005 the RMS error was 7.5 mg/l.

From OCM and corresponding simulated results, SSC is extracted along the line shown in figure 2. From the comparison of the SSC extracted along the line, it is observed that the model is able to simulate the general trend in the spatial variation of SSC (figure 8). The correlation coefficient for 3rd January 2005 is 0.95 which got declined to 0.85 and 0.74 for 5th and 7th January 2005.

The simulation result shows an increase in SSC near the islands and shoals within the Gulf when the current velocity is higher. The swift action of the tidal current scours the bottom sediment in these regions and brings it to suspension. The model results and OCM show a gradual decrease in SSC from January 1st to 7th.

3.3 OCM Observations and the sediment dynamics

SSC is derived from cloud free OCM scenes for the month of January 2005 (figure 9). The mean SSC is calculated for each scene (figure 10a). A gradual decrease in the mean SSC is seen from 1st to 9th January 2005. On 13th January 2005 SSC values are high, which decreased gradually for the subsequent images. The temporal variations in SSC within the Gulf are associated with the variations in tide range. Figure 10(b) shows the tide range in Gulf of Kachchh during the observations. From 1st to 8th January 2005, the tide in the Gulf is neap where the tidal range is between 2.6 and 2.8 m. From simulation results the current velocity was found to be in the range of 0.7–0.9 m/s. Low current velocities during the neap tide caused deposition of suspended sediments within the Gulf. The spring tide that followed (from 10th to 16th January 2005) is having a tide range of 3.0–3.32 m and from the simulation, current velocity obtained is in the range 2.2–2.8 m/s. The high velocity currents triggered the re-suspension of the deposited sediments resulting in high values of SSC on 13th January 2005.

The relation between residual current and the turbidity was shown by Kunte *et al.* (2005) and

Figure 10. (a) Mean SSC during the observation (data gap shows non-availability of OCM for 11th and 15th January 2005) and (b) the tide range in Gulf of Kachchh during the observations.

similarly high residual velocities are observed (figure 5d) near the islands and shoals which corresponds to high value for SSC from OCM observations. High SSC values in these regions are also attributed to the tidal fronts. The opposing currents (figure 5c) formed during the reversal of tide produces the tidal fronts which are characterized by high turbulence that keeps the sediments in suspension.

In the southern coast near to Pindhara, a strip of high SSC is observed from OCM for almost all scenes but the model is unable to produce this high SSC strip. The possible reason could be that the sediment influx from adjoining creek that opens into the Gulf causing high SSC values in the region. In figure 11, OCM-derived SSC of 3rd January 2005 is overlaid with the corresponding simulated tidal current. It can be seen from the figure that the dispersion pattern of the current and sediment along Pindhara coast is across shore (perpendicular to the coast) whereas the current and sediment dispersion in the northern coast is along shore (parallel to the coast).

Patches of high SSC are also seen at the head (eastern side) of the Gulf in both the OCM scenes and in the simulation results. The soft sediments in these shallow regions are subjected to deposition and erosion owing to the variations in the velocity of the tidal currents. In the mid Gulf, a

Figure 11. OCM-derived SSC for 3rd January 2005 overlaid with simulated current.

region of low concentrations of SSC is observed from both OCM and simulation results. A possible reason for low SSC region might be that a dynamic barrier exists across the Sikha–Mundra section Vethamony *et al.* (2005); Kankara *et al.* (2007). Existence of this barrier could make the portion of Gulf to the right of this barrier devoid of sediment inputs from the river Indus. The region corresponding to low SSC values in the mid Gulf is also the deeper portion of the tidal channel, which makes the re-suspended sediments from the bed difficult to be observed by the OCM.

4. Conclusions

The viability of utilizing satellite derived sediment concentrations for simulating sediment transport within the Gulf of Kachchh is shown in the present study. The statistics obtained from the comparison of model simulated SSC and OCM-derived SSC is conducive for the explanations of sediment dynamics in the Gulf using the model results. When compared with OCM, the model results showed a gradual increase in RMSE with time. Due to the

lack of wind data, effect of varying winds are not included in the simulation. It is also expected that with the development of improved algorithms for Case-2 waters to retrieve suspended sediments, such simulations shall provide near-real quantification of suspended sediments. The simulation results can also be further improved by including the sediment influxes from the creeks and smaller rivers that open into the Gulf.

There is a significant deposition and re-suspension processes within the estuary controlled by the varying tidal ranges. The complexity in bathymetry and the coastline plays vital role in influencing the tidal currents and sediment distribution patterns in the Gulf region. Region of high turbulent zone with eddy formations and maximum residual velocities are obtained near the shoals and islands which coincide with high sediment concentrations. Deep tidal scour channels in the mid Gulf are found to be devoid of high suspended sediment concentrations throughout the observations. The distinct variability in the bathymetry leads to spatial variation in tidal velocities which controls the disparity in the suspended sediment distributions in the Gulf.

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