

Seasonal variations of total suspended matter (TSM) in the Gulf of Khambhat, west coast of India

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Total Suspended Matter (TSM) is an important parameter for determining the water quality in coastal regions as it is responsible for the reduction in the light available to the aquatic vegetation which subsequently alters the health and quality of the water body. In the present study, total suspended matter (TSM) was derived from multi-temporal MODIS (Moderate Resolution Imaging Spectrometer) Terra images. Red-band reflectance with a spatial resolution of 250 m was used to study the sediment dynamics of the macro-tidal region of the Gulf of Khambhat for 2009 (drought year) and 2010 (rain fed year). This has been done after establishing a significant correlation of 0.8 with in-situ TSM data. Through this study, the relative contribution of the physical factors (rainfall and tides) in the spatial and temporal distribution of total suspended matter concentrations of Gulf of Khambhat has been demonstrated.

[Keywords: Total Suspended Matter (TSM), MODIS, Khambhat, Tides, Rainfall]

Introduction

The Gulf of Khambhat, formerly known as Gulf of Cambay (GOC), is a strong converging channel located on the west coast of India. This region experiences strong currents (upto 4 m/s) and large tidal elevations (varying in range between 8 and 11 m). The GOC harbours several major and minor ports and is subject to intensive industrial activities and urban growth. Thus, as many other coastal regions, this bay is highly affected by inland processes including sediment, nutrient fluxes (riverine flux and sea-bed re-suspension) and anthropogenic derived discharges. High concentration of suspended sediment (both organic and inorganic) in the water directly affects the light penetration through the water column, and subsequently, affects the productivity of the phytoplankton, corals and other aquatic vegetation. Many researchers have ascertained the importance of distribution of TSM in transport of pollutants, pathogens, etc¹⁻³, thereby making the study of sediment dynamics immensely important for evaluating the water quality and understanding the condition of a coastal system. Forces such as tides, waves, river discharges, and wind stress and turbidity currents alter the transport and distribution of suspended sediments. Tides in particular, play an

important role in the movement of total suspended matter. In the GOC, large tidal range gives rise to strong tidal currents which enable transport of sediments. The mudflats along the coastline suggest a net movement of sediments towards the land. Nayak and Sahai⁴ suggested that rivers bring with them sediments which remain in suspended form and start settling during the onset of winter. Thus, riverine flux during monsoon is an important source of sediment for this region.

However, the distribution and flux of sediments are highly variable in the coastal environment in terms of their spatial gradients and temporal scale, which renders the traditional field sampling method inadequate in studies pertaining to sediment transport. This limitation has been considerably reduced by incorporating remote sensing data from various sensors. Satellite imageries characterized by synoptic view, higher repeat cycles provide excellent opportunities to map suspended sediments in coastal waters⁵. A number of studies have been carried out which demonstrate the use of satellite imageries in suspended sediment studies⁶⁻¹⁰.

A few studies have been carried out along the Indian Coast. Chauhan *et al.*¹¹ used remote sensing to study suspended sediments along the Tamil Nadu coast.

Rajawat *et al.*¹² used IRS - P4 OCM data to generate Suspended Sediment Concentration (SSC) maps for select coasts around the Indian Sub continent. Kunte¹³ used IRS P4 OCM data to estimate the SSC and understand their dispersal pattern in the Gulf of Khambhat. Sediment concentration and distribution dynamics have also been extensively analyzed for the neighbouring Gulf (Gulf of Kachchh)¹⁴⁻¹⁷. In most of these studies, OCM datasets have been used for the estimation of SSC.

Although numerous studies have been carried out, there are several factors, which limit the application of remote sensing to coastal waters. These include the characteristics of the sensor and the spatial and temporal resolution. From this perspective, the Moderate-resolution Imaging Spectro-radiometer (MODIS) instrument On Terra (NASA Earth Observing System (EOS) provides good temporal resolution (1 day) and is freely available. Another EOS spacecraft, Aqua carries the second MODIS instrument. The MODIS instrument collects reflected and emitted energy in 36 spectral bands (0.4 -14.4 μm) in different spatial resolution (250m: bands 1-2, 500m: bands 3-7, 1000m: bands 8-36). The instrument has been providing satellite datasets since February 2000 on the Terra and June 2002 on the Aqua. MODIS 250m resolution has been used by several researchers in studies related to TSM along various coastal regions. Hu *et al.*¹⁸ showed a simple relationship between in situ TSM and surface reflectance at 645 nm to derive time series of water quality in Tampa Bay using an empirical algorithm. Miller and Mckee²³ established a robust linear relationship between MODIS band 1 and in-situ measurements. Guzman and Santaella¹⁹ developed and validated an algorithm to estimate TSM based on MODIS 250 m reflectance. Chen *et al.*²⁰ analyzed the effect of rainfall on the sediment plume in the coastal waters of Apalachicola Bay by devising an enhanced remote sensing model using MODIS dataset. Shi and Wang²¹ quantified the seasonal and inter-annual variability of an offshore plume in the Central East China Sea using MODIS Aqua data. Son and Wang²² measured water properties in Chesapeake Bay also using MODIS ocean colour data. It is evident from the above literature that MODIS data sets have been used extensively for TSM related studies. This is because of the characteristic of MODIS band 1, such as its resolution, red band reflectance, and near daily coverage, which makes it very suitable for studying

suspended sediments in the coastal region²³.

In this study, we have assessed the use of Miller and Mckee (2004) algorithm for the TSM estimation of Gulf of Khambhat, which is one of the highest sediment rich regions in the tropical region. Available in-situ data was checked with algorithm derived TSM values. On attaining a good correlation (Fig. 2), we have further applied this algorithm for estimating TSM during 2009 (drought year) and 2010 (rain fed year). The objective of this study is to understand the contribution of monsoon derived riverine flux and its contribution to the sediment dynamics of this region and also the influence of tides on the TSM distribution as this region is a prominent macro-tidal region on the west coast of India.

Materials and Methods

The GoC is about 70 km wide and 130 km long²⁴ with a mid-depth of 30 m. The gulf receives many rivers, including the Sabarmati, Mahi, Narmada, Tapti and Shetrunji and is characterized by a number of estuaries, islands, mudflats, cliffs and mangroves. These rivers contribute large amount of sediments as sediment load into the Gulf and the average monthly discharge exceeds 2000 m³/s. The strong flood and ebb tidal currents lead to high turbidity with high bed and suspended sediment loads. The gulf experiences high-energy hydrodynamic conditions; however, the seabed in most part of the Gulf remains in quasi steady state and moves as sand bars with tides²⁵. The wind is mainly seasonal, being southwesterly during June to September and northeasterly during December to March. The moving mudflats, tidal flats, oscillating shoreline features pose a huge limitation to the coastal studies. Moreover, the formation of shoals and sandbanks are treacherous to navigation. Many ports (Bhavnagar port) and industrial establishments are located along this coast. The ports suffer from intense silting caused by the action of tides and flood torrents from the rivers. Thus, it becomes imperative to study the sediment dynamics in this region in order to ensure better coastal management in this area. Fig. 1 shows the study area, location of in-situ data points, the boundary of the extent considered in this study and the transects (T1, T2, T3) along which the TSM values have been analyzed.

In-situ measurements

Water samples in duplicate were collected at surface using Niskin water samplers at varied times during the period October 2000 to July 2010.

Suspended solids in the Gulf of Khambhat was

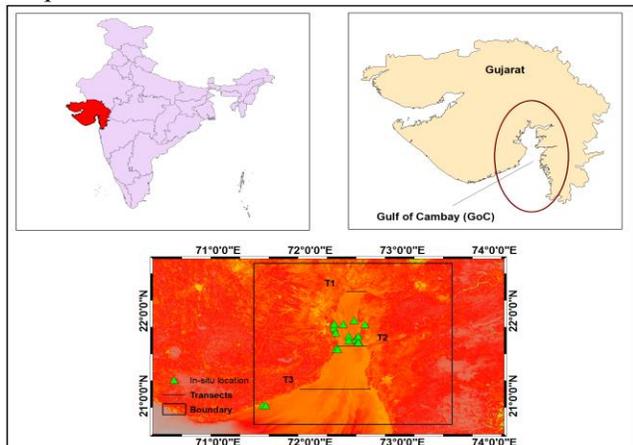


Fig. 1—Study area and sampling locations

determined by filtering 500 ml of water through pre-weighed 0.45 μm Millipore polycarbonate filters, dried and weighed again. Polycarbonate filter papers have low and stable weights (~ 15 mg), and hence SS values determined using these filters are reliable down to 0.5 mg/l^{26} . Only samples which matched the MODIS Terra (good quality) dataset, date of pass were used in this analysis and hence 20 data points were obtained.

MODIS data processing

Two sets of MODIS data were obtained from the NASA Goddard Earth Science (GES). First, we compared the in-situ data TSM with the MODIS generated TSM values, and then analyzed the contribution of riverine flux during 2009 (IMD declared drought year) and 2010 (rain-fed year). MODIS data are stored as data granules (5 min time of data collection) in the HDF-EOS format. The DAAC data sets MOD02QKM (calibrated radiances level L1b full swath at 250 km) contain reflectance and radiance values of MODIS/Terra 250 m bands 1 and 2 image data. The SDS name for MODIS 250m image data in a MOD02QKM file is EV_250_RefSB. All these images were processed using ENVI (Ver.4.1) processing routines: MODIS Geo-reference and Dark Subtract. The spatial reference system was defined as Geographic lat/long for Gulf of Khambhat region. The dark subtract atmospheric correction involves the selection of the darkest value in band 2 and subtract it to all band 1 data. This value was manually identified in each image and then defined in the "user value" option. Finally, using the band math

function in ENVI we applied the following algorithm which gave TSM values in mg/l .

Table 1—List of MODIS data set used, date and respective tide elevation values

Date of Pass	2009		2010	
	Time of Pass (AM/PM)	Tide elevation (m)	Time of Pass (AM/PM)	Tide elevation (m)
3-Jun	11:55	6.2	11:25	5.27
10-Jun	12:00	1.5	11:30	3.07
18-Sep	11:35	1.56	11:05	5.42
19-Sep	10:40	1.65	11:50	5.41
20-Sep	11:25	1.77	10:55	2.98
25-Sep	11:45	6.47	11:10	2.67
30-Sep	12:00	5.61	11:30	6.67

$$\text{TSM} = -1.91 + 1140.25 * (\text{MODIS band 1 reflectance})$$

TSM values obtained from in-situ measurements were compared with the above algorithm generated TSM values. This was done to check the proficiency of the algorithm for this region. As a significant relationship ($R^2=0.80$) was obtained, we further compared dataset of the same dates in the successive years of 2009 (drought year) and 2010 (rain fed) and obtained profiles to analyze the contribution of rainfall to sediment plume dynamics. This was done by comparing the values along three transect running east to west in the GOC. The transects set were closer to the river mouth to understand the river influence better. We also compared sediment plume profiles during a high tide time and low tide time. The tide values were obtained from the WXTide software. Table 1 lists the MODIS 250 m datasets used, their date of pass and the respective tides during that period.

Results and Discussion

In-situ and Algorithm generated TSM values

In-situ TSM values were plotted against the Miller and McKee's algorithm generated TSM values and a significantly positive relationship ($R^2= 0.80$) was observed. The relationship is consistent over a range of TSM concentrations measured at various stations in the Gulf of Khambhat. Moreover, it is reasonably robust as the TSM data was acquired at different regions by different investigators. The simple atmospheric correction scheme also appears to be effective for a wide range of sky conditions that existed during the sampling dates. Miller *et al.*²⁷ observed that MODIS 250 m band is sufficiently robust in coastal and inland waters because scattering

from suspended material dominates the reflectance spectra in the red region of electromagnetic spectrum when compared to pure water, phytoplankton and CDOM (Colored Dissolved Organic Matter). Daily revisit period, good spatial resolution and large spatial scale makes MODIS a good dataset for the study of large scale dynamics of TSM. Considering the algorithm gave good correlation with *in-situ* data, we further applied this approach to 250 m MODIS data sets for the year 2009 and 2010 to further understand the sediment dynamics of Gulf of Khambhat.

Comparison of sediment plume in 2009 (drought year) and 2010 (rain fed year)

As mentioned earlier, the Gulf of Khambhat is drained by several rivers which bring sediments in huge quantities especially during monsoons. The previous observations suggest that sediments brought to GOC during monsoon by river systems remain in suspension. Past studies from the Arabian Sea have mentioned the dominance of South West Monsoon (SWM) on the magnitude of TSM flux into the Sea²⁸⁻³⁰. Also, tides play a very important role in the movement of suspended sediments and fronts. Kunte (2008) reported the role of flood and ebb tides in the concentration of TSM in the GOC. The tidal currents generate enormous amount of turbulence. There is a period of time between the rising and falling tides when the flow comes to rest and the turbulence is at a minimum. This gives the heavier sediment particles a chance to settle at the bottom. As the tidal current increases again the particles are lifted into the water column again.

In this study, we have tried to analyze these two factors during the SWM period (June - September) of 2009 and 2010. The rainfall as reported by

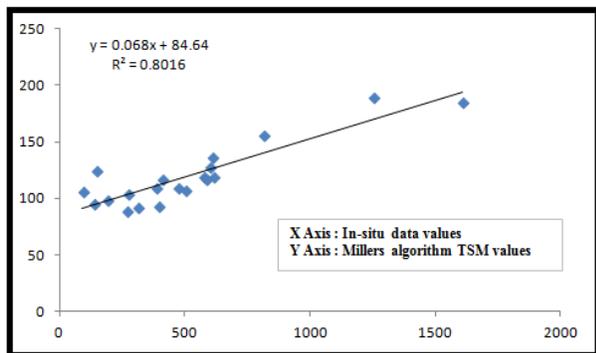


Fig. 2—Comparison between in-situ and Miller & McKee's algorithm derived TSM Values

Indian Meteorological Department (IMD) report was 383.1 mm and 790 mm for 2009 (drought year) and 2010 (rain-fed), respectively. In the following sections, we discuss the TSM profiles obtained for each dataset along three transects (T1, T2 and T3) as well as spatial pattern of TSM in the GOC in June and September (MODIS imagery with least cloud cover were used, as the analysis is for monsoon, limited datasets were obtained).

Spatial Pattern of TSM in June 2009 and 2010

Two dates (3rd June and 10th June) have been considered for both the years. The rainfall in June 2009 is reported as 26.2 mm and 72.5 mm for the year 2010.

The maximum sediment concentration for the 3rd June 2009 is 681.9 mg/l and 999 mg/l in 2010. Although the tidal values are almost similar, the former year corresponds to a rising flood tide and

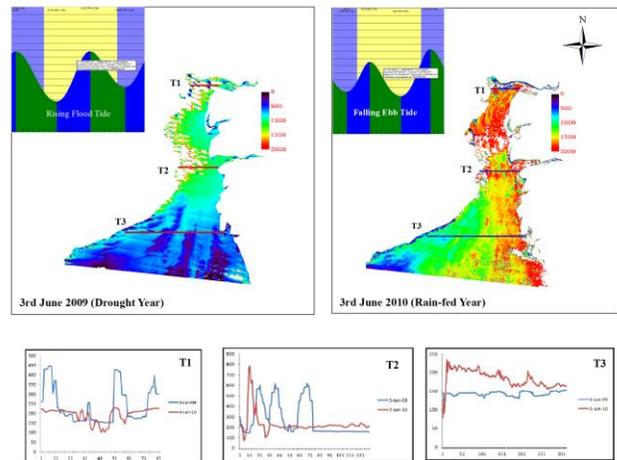


Fig. 3—Spatial map and profiles of TSM for 3rd June

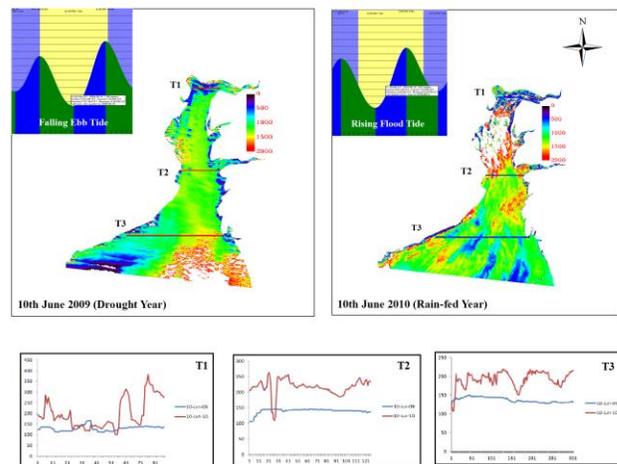


Fig. 4—Spatial map and profiles of TSM for 10 June

the later to a falling ebb tide. The TSM concentration are higher in the central portion of the bay. In case of 2010 higher concentrations can be observed along the eastern coast especially near the river mouths. The transect profile shows high values along the third transects for the year 2010 in comparison to 2009. However, for both transects 1 and 2 the values are almost similar for both the years.

In the case of 10th June, the highest value of TSM observed is 347.6 mg/l in 2010 and 285.6 mg/l in case of 2009. The tidal value for the year is 1.5 m (falling ebb tide) and 3.07 m (rising flood tide). For all the three transects the year 2010 shows higher value than 2009.

Spatial pattern of TSM in September 2009 and 2010

Five different days (18, 19, 20, 25 and 30) have been studied for both the years. The rainfall in June 2009 is reported as 35.4 mm and 200 mm for the year 2010.

Fig. 5 shows the effect of a combination of riverine

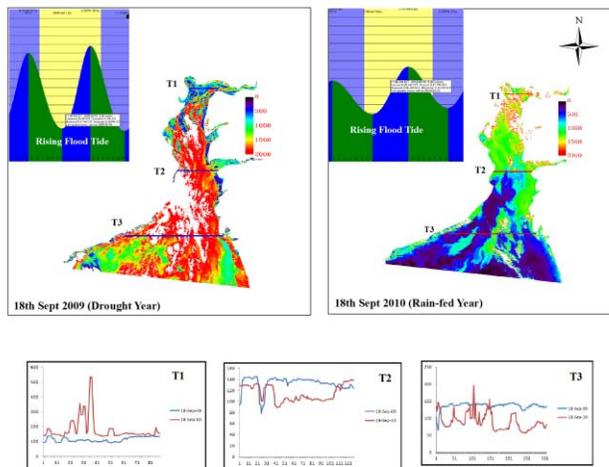


Fig. 5—Spatial map and profiles of TSM for 18 September

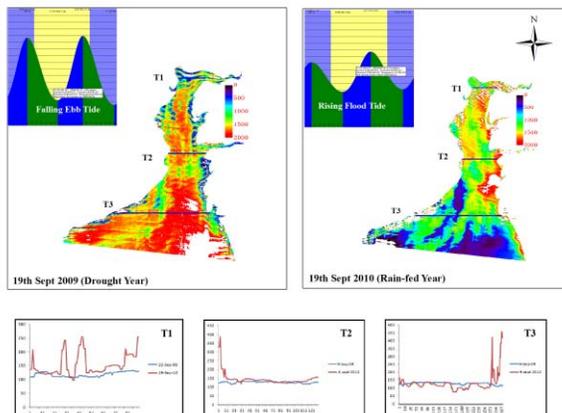


Fig. 6—Spatial map and profiles of TSM for 19 September

flux as well as tidal changes. The 2010 dataset depicts very high turbidity condition with concentration as high as 1058.1mg/l. However, these high values are mainly concentrated near the river mouths. The highest concentration for 2009 is 620.3 mg/l spread from the mouth across the central portion of the bay. For 2009, the rising flood tide value is 1.56 m and for 2010 the value is 5.42 m (rising flood tide). It is because of the tides that higher values can be seen for transects 2 and 3.

The highest TSM concentration observed on 19 September of 2009 is 275.3 mg/l and 711.8 mg/l for 2010. The profiles of transects 2 and 3 almost show similar trend of concentration, whereas higher values are observed along transect 1 for the year 2010. The year 2009 follows the falling ebb tide condition and 2010 a rising flood tide condition. The TSM distribution can be observed to be relatively uniform in case of both years.

The 20 September 2009 TSM imagery coincides with ebb tide of 1.77 m whereas that of 2010 coincides with a rising flood tide of 2.98 m. The maximum concentration is 352 mg/l for 2009 and 726.9 mg/l for 2010. For all the three transects the 2010 values are higher than 2009 values.

Fig. 8 shows high turbid condition with the highest concentration being 1198.6 mg/l in 2010. In case of 2009 the high concentration is 648.7 mg/l which almost half of the concentration of the former. The turbidity in case of 2010 is distributed throughout the bay. In terms of tidal conditions both the images coincided with falling ebb tide conditions. The TSM profiles at all the three transect showed greater TSM values for the year 2010.

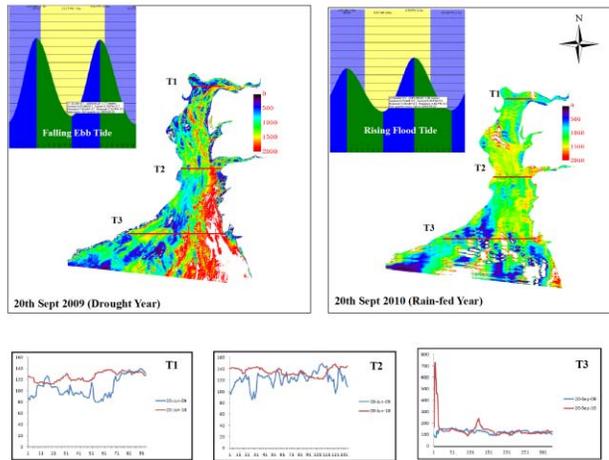


Fig. 7—Spatial map and profiles of TSM for 20 September

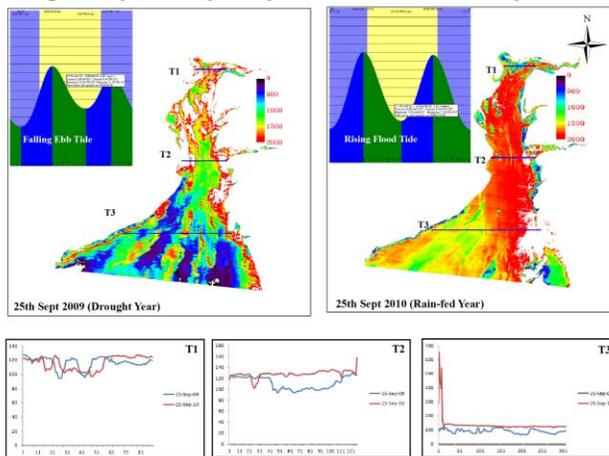


Fig. 8—Spatial map and profiles of TSM for 25 September

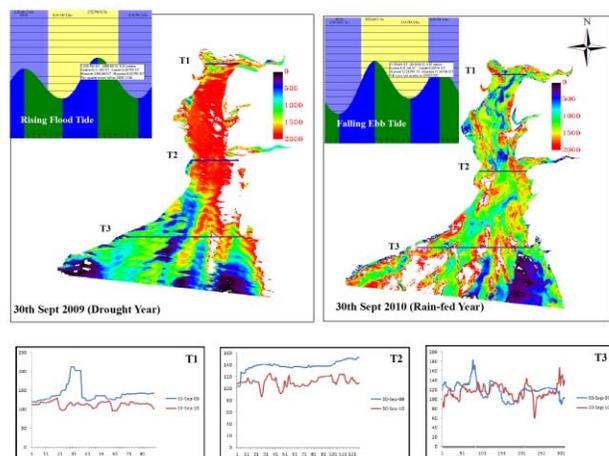


Fig. 9—Spatial map and profiles of TSM for 30 September

An interesting observation in case of 30 September is the trend of TSM values along the transect is totally opposite to those in previous datasets. Nevertheless, the maximum turbidity observed is 347.6 mg/l during ebb tide in 2010 and 285.6 mg/l during rising flood tide in 2009.

From the above observations, it is evident that during SWM period there is a dominance of river influx which contributes to the TSM value in the Gulf of Khambhat. As evidenced from the study, it can be suggested that during SWM offshore supply of TSM increases leading to appreciation in TSM values by virtue of riverine flux. However, we also observe the role of tides in modulating the distribution of TSM. Also, we find that concentration along the eastern coast is more than that along the western coast. The variation of suspended sediments with tide was studied by³¹ for Northern Andaman Sea and the Gulf of Martaban and they concluded that tide is the dominating factor for this region. Chauhan *et al*³² suggested that tidal currents feed the River Indus flux in the Gulf of Kachchh. Sinha *et al*²⁵ modelled the tidal variation and suspended sediment concentration for the Gulf using numerical models. They reported that currents during ebb range upto 2.21 m/s and during flood upto 2.0 m/s. They also estimated suspended sediment concentration: 100 mg/l to 800 mg/l during flood and 120 mg/l to 920 mg/l during ebb. It is generally observed that during flood tide the concentrations are lesser than those during ebb tide. Kunte¹³ mentions that during the flood period, tidal currents push suspended particles towards the coast and the gulf head whereas during ebb, the bottom currents pull the sediment particles supplied by rivers. This can be clearly observed in Fig. 6 where transect 1 in case of the year 2010 shows high concentration at the head of gulf. Fig. 5 gives a good example of the influence of flood tide and ebb tide, where the combined effect of ebb tide and river influx results high turbidity condition in the bay in 2010 in contrast to the flood tide of 2009. Thus, it can be suggested that during monsoon, TSM dynamics in the Gulf is governed largely by the rivers that drain into the Gulf, and the high tidal ranges aid in the redistribution of sediments.

Conclusion

This quantitative study attempted to find out the spatial and temporal variation of TSM in the Gulf of Khambhat. In terms of observations, it can be inferred

that the large tidal range as well as the presence of rivers like Sabarmati, Mahi and Narmada greatly influences the TSM dynamics in this region. The fact that the TSM concentration was lesser in 2009 (drought year) than in 2010 (rain-fed year) suggests the effective role of rainfall and subsequently increased riverine influx. Finally, it is worth mentioning that this kind of study is an essential step in understanding the environmental condition in the Gulf of Khambhat, which is facing immense anthropogenic impact by virtue of the ports and industries located here.

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