

## **Sediment concentration and bed form structures of Gulf of Cambay from remote sensing**

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### **Abstract.**

The continental shelf on the west coast of India is the widest off Mumbai and leads to a strongly converging channel, the Gulf of Cambay (GoC). Tides in this Gulf are the largest on the Indian coast. The flow-generated bed-forms are significant features in the Gulf of Cambay region, and their presence depends on strong tidal or other currents, capable of moving the sand, and also on the availability of sand. Digital data collected on-board Indian Remote sensing satellites IRS-1C and IRS-P4 OCM (Ocean Color Monitor), covering the GoC region was digitally processed. False Color composite of IRS-1C, was generated and used to map coastal, near shore geomorphic features and underwater flow generated bed form structures. Suspended sediment concentration and their dispersal patterns were studied by processing IRS-P4 data. The impact of high tides on the suspended sediment concentration and sediment flow pattern was studied to understand the mechanism of sediment flow. Based on the suspended sediment concentration, flow structures, geomorphic features and hydrodynamics, it is concluded that fine-grained sediments are transported to the inner Gulf, whereas, sandy sediments are transported southwestwards and outwards of Gulf of Cambay. These sediments, perhaps participate in the formation of bed form structures.

Keywords: Gulf of Cambay, Arabian sea, IRS data, Bed-form structures, sediment concentration.

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## 1. Introduction

The Gulf of Cambay (GoC), also known as Gulf of Khambhat, has acquired greater importance in view of its geographic proximity to two industrially progressive states namely Maharashtra and Gujarat (Figure1). The Gulf provides an easy opening to the sea and means of transportation for the industries situated around it. The presence of different geomorphic features, their location, association and processes, such as sediment transport and concentration has a larger influence on industrial and commercial activities.

The study of suspended matter is of ecological importance as these sediments are the main carriers of various inorganic and organic matters (including pollutants) and become main substrata for biogeochemical processes (Doerffer et al., 1989). The suspended sediments also affect the penetration of light and the transport of nutrients or shoreline morphology among other processes.

The coastal morphology of the Gulf of Cambay region has been studied (Nayak & Sahai, 1985) using visual interpretation of Landsat Multi-spectral scanner (MSS) data. An attempt has also been made (Shaikh et al., 1989) to map coastal landform around the GoC using Landsat TM data. Vora et al., (1980) studied and mapped flow generated bed forms located to the south of the GoC using echo sounder, side scan sonar and shallow seismic profiler etc. Using similar instrumentation, along the central continental shelf of India and to the further south of GoC, two similar studies (Siddiquie et al., 1981 and Siddiquie et al., 1985) were carried out to evaluate the seabed for the purpose of construction of pipelines. All these studies have been attempted either around the Gulf or towards southern side of the GoC. The present study is focused on the estimation of sediment concentration and mapping of features observed using remote sensing within the GoC.

Processes such as tides and waves, river discharge, wind stress and turbidity currents modulate the transport and distribution of suspended sediments

in coastal environment. It has been demonstrated by Klemas et al. (1974), Tassan & Strum (1986), Chauhan et al. (1996), Kunte et al., (2003) etc. that satellite based remote sensing can be effectively used in the detection and quantification of total suspended matters.

Millar and Mckee (2004) established a robust linear relationship between band 1 (620–670 nm) of MODIS Terra 250 m data and in situ measurements of TSM and demonstrates that the moderately high resolution of MODIS 250 m data and the operating characteristics of the instrument provide data useful for examining the transport and fate of materials in coastal environments, particularly smaller bodies of water such as bays and estuaries. Chauhan et al. (2005) analyzed sequential satellite images of Indian Remote Sensing Satellite IRS—P4 ocean color monitor (OCM) to measure total suspended matter (TSM). Along with TSM, synchronous sea truth data, and salinity variations have been used to construct dispersal pathways of the surficial fluvial flux into the northern Bay of Bengal during the NE monsoon. By analyzing the optical properties of estuarine Color components during non-monsoon period using Ocean Color Monitor data suspended sediment and Colored dissolved organic matter (CDOM) were successfully derived by Menon et al. (2006).

The present remote sensing study has been taken up 1) to measure sediment concentration within GoC, 2) to map the coastal, near shore geomorphic features and underwater flow generated bed forms features, 3) to study the pattern of turbidity flow, and 4) to address the mechanism of turbidity flow.

## **2. Study area and environment**

The GoC is a funnel shaped indentation on the western shelf of India, lying between the Saurashtra peninsula and the mainland of Gujarat (Figure 1). The GoC is about 70 km wide and 130 km long (Vora et al., 1980) bounded by

latitudes between 21<sup>0</sup> and 22<sup>0</sup> 20' N and longitudes between 72<sup>0</sup> and 73<sup>0</sup> E. The coast of the GoC is marked by a number of estuaries, islands, mudflats, cliffs, salt marshes and mangrove swamps etc. The inner shelf of GoC is characterized by uneven seafloor topography. Depth ranges from a maximum of about 20 meters at the mouth to less than a meter at the head of the gulf.

The main rivers that drain into the Gulf are the Sabarmati, the Mahi, the Narmada, the Tapti and the Shetrunji. These rivers discharge a large amount of sediments, as suspended load, into the Gulf and the average monthly water discharge exceeds 2000 m<sup>3</sup>/sec. Concentration of sediments in the surface water of GoC is greater than 4 mg/liter and at the bottom more than 8 mg/liter (Vora et al., 1980).

The Gulf comprises an area of high tides (up to 11 meters) and is characterized by domination of strong tidal currents, the largest amplitude on the west coast (Unnikrishnan et al.1999). Tidal currents during flood and ebb tides follow almost identical paths and reflect the bathymetric features of the gulf. The coastal features are also related to the behavior of tides and tidal currents. The amplitude increases as the tide moves into the GoC.

The flow generated bed forms are an integral part of sediment transport and are related to the flow conditions, size and quantity of the sediment input, and their concentration and distribution. Ripples, mega-ripples, sand waves, sand banks, sand ridges, shoals, and sand bars are the best known flow-generated bed forms on the sea floor. Investigations of present day bed form features and simulation of hydrodynamic conditions are useful in interpreting the movements of sediment, bed load and suspended material.

The wind pattern in this area is predominantly seasonal with rare cyclonic disturbances. Predominant wind directions in this area are west southwesterly and north northeasterly during the months June to September and December to

March respectively. Higher wind speeds are likely to occur during June to September with winds up to 74 km/hr from the west and southwest (Srivastava & John, 1977). High tidal amplitude, an extreme amount of temporal-spatial sedimentation, the shifting of bathymetric relief features, changing shoreline, oscillatory movement of mud banks and tidal flats pose as a challenge to working scientists.

### **3. Materials and methods**

Indian Remote Sensing satellite IRS-1C carrying LISS-III payload with spatial resolution of 23 m, digital data (path 93, row 57, dated 30<sup>th</sup> March 1999) in four spectral bands (Plate 1) and IRS-P4 with Ocean Color Monitor (OCM) data with spatial resolution of 360 m of path 9, row 13, for 5 different dates like 2-Jan-2000, 13-Nov-2000, 2-Jan-01, 6-Dec-01 and 1-Jan-02 in 8 bands (Table 1), covering GoC were processed and used for estimation of sediment concentration and visual interpretation.

The OCM data was analyzed using the atmospheric and radiometric correction developed initially for IRS-P3 MOS data (Mohan et al., 1998, Chauhan et al. 2002) and later modified for IRS-P4 OCM data (Chauhan et al., 2001). The estimation of sediment concentration was carried out using OCM data processing software version 1.4 developed at Regional Remote Sensing Service Centre (RRSSC), Nagpur, however, computation algorithms of the software for chlorophyll, yellow substance and suspended sediments were developed at Space Application Centre (SAC), Ahmedabad. A three-components model, initially proposed by Tassan (1994) and later adopted by SAC was applied to case 2 waters of the GoC for estimating and mapping of suspended sediment concentration (hereafter called SSC) from OCM datasets. This algorithm captures the inherent sigmoid relationship between R(490), R(555) and R(670) band ratio (detail model description is given in Tassan, 1994) and computes suspended sediment concentration  $X_s$ , where R is remote sensing reflectance. The water-leaving radiance at different wavelengths is transformed to the

reflectance values at those wavelengths and is used in the algorithm. The final form of optimization routine for suspended sediment concentrations (S) is,

$$\text{Log (S)} = 1.83 + 1.26 \text{ Log } X_s, \quad \text{for } 0.0 < S < 100.0 \quad \text{----- 1}$$

Where S is suspended sediment concentration in mg/l and  $X_s$  is a variable defined as

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

$R_{rs}$  is remote sensing reflectance in respective wavelengths.

IRS-P4-OCM data for five different dates like 2-Jan-2000, 13-Nov-2000, 2-Jan-01, 6-Dec-01 and 1-Jan-02 in eight bands (Table 1), were used as input to the OCM data processing software and SSC were estimated. Using commercial GIS software package, five geo-referenced sediment concentration maps were prepared (Plate 2). In addition to SSC, using same software, chlorophyll, and yellow substances were also estimated. Due to practical hindrance, no sea truth suspended sediment data was collected during satellite passes. However, in the absence of simultaneously collected data, suspended sediment data collected over a decade period (1991-2000), during various projects, available with the data centre, was used as sea truth data (Table 3).

Orbital images provide a synoptic view of submerged as well as discrete turbid water masses (suspended sediments) in the gulf waters. Depending on the type of particulate matter, stratification, depth of settling and bottom condition, overlying water reflectivity changes in different shades of Color. On the satellite images, the sharp contrast between various sediment-bearing waters is clear and mappable. On the satellite images, the sediment-laden plumes indicate the current direction as they become elongated and pointed towards flow. False color composites were generated from IRS bands - 4, 3, and 2 (RGB) using image processing system (Plate 3). This FCC image was enlarged and properly geo-referenced to locate and to map various coastal geomorphic units, bed flow structures, and nearshore features. False color composites (like Figure 3) were

also generated for five dates of OCM-P4 bands – 8, 7, and 6 (RGB) for feature existence verification during different seasons. Topographic maps (41 C-1-16) and navigation charts (NHC-208) were used for the reference. The coastal and the near shore geomorphic features, and underwater flow features are marked on the FCC image (Plate 3) by assigning letters. The presence of the same geomorphic and bed-form features was confirmed on images of different dates and seasons of OCM data.

## **4. Results**

### *4.1 Quantitative assessment of suspended sediments concentration*

In all the five data sets (Plate 2) images, the pink portion on the northeastern side represents land. A bluish portion on the southwestern side represents very low concentration (1-15 mg/liters) of suspended sediments present over deeper parts of water. The green-yellow color indicates moderate (17-32 mg/liters) concentration of sediments in majority of outer gulf region. Red color indicates turbidity maxima (33-40 mg/liter). Maximum sediment concentration is observed encircling the mouth of the Gulf. The sediment concentration is more along eastern border than along Saurashtra coast. Moderate sediment concentration is occupying much of the outer Gulf and is bordering high turbidity. The inner gulf is occupied by black color representing null values. The time of data collection and that of lowest low tide in the region (Table 2) have coincided or are very near by. The blacked out region in the Gulf of Cambay (Plate 2) is the region, where suspended sediments could not be estimated due to very low water level. A Close observation of images in plate 2, indicates that sediment concentration (SC) near mouth is least in a & b images and moderate in the image e, whereas it is higher in image d and highest in image c. Adopting similar procedure (Tassan 1994), and same software, the chlorophyll concentration was estimated between 0.01 to 63 mg/liters and yellow substance was found to be between 0.01 to 10 mg/liters. As date, time and season for sea truth data (Table 3) and remote sensing data are different,

suspended sediment concentrations derived from the satellite image could not be properly validated using in-situ measurements as shown in Figure 2. Although SSC patterns derived from the imageries in the study area may have limitation for the accurate quantification of fluxes, the patterns are used to reconstruct the regional dispersal patterns of the fluvial flux.

Due to high tidal effects, the sediments are suspended and re-suspended at the mouth without indicating specific direction of sediment movement. High turbidity pattern observed near the mouth and just outside the Gulf, follows ebb tide current (Plate 3) & (Table 2). During high flood tide, moderate to high sediment concentration enters the Gulf from the mouth and spreads right up to the head of the Gulf. The study of OCM – P4 data collected prior to and after the Gujarat earthquake (which took place on 26<sup>th</sup> Dec 2001) showed that, just prior to an earthquake, (plate 2), the sediment concentration was maximum (Image c), whereas it was reduced after the earthquake (Image e).

#### *4.2 Qualitative assessment of sediment dynamics*

From a close observation of IRS 1C imagery it appears that band 1 & 2 are strongly related to suspended sediments, whereas, submerged sediments (forming bedforms) shows relation with band 3. Water and mudflats are well visible in band 4 (Plate 1). In IRS FCC (Plate 3) image, backscattering from bedload sediments and that from suspended sediments is distinguished based on the image information gathered from individual IRS 1C bands. It was noted from the visual interpretation that Mudflats with intervening sandy ridges mainly cover the northern most part of the Gulf. The mudflats situated to the northward part of the GoC as well as between the Mahi and the Narmada estuaries, lying above the high tide flats are recognized as paleo-mudflats. They are irregular in shape and show rough texture (denoted as 'Mp' in Plate 3). Paleo-mudflats are much above the waterline and occasionally cover the sand ridges. They are rounded in shape and vary in size. The intertidal mudflats (denoted as 'Mi' in



Plate 3) are irregular in shape, have smooth texture, and are found in the area, where the tidal influence is not too strong. The sub-tidal mudflats (denoted as 'Ms' in Plate 3) have smooth texture and are found in the areas where waterline is very low, and is associated with low energy coast. They are made up of clayey and silty material.

The bed forms are relief features generated by flowing water over a sea bottom of movable materials. The mainland coast is mainly muddy in nature, while the Saurashtra coast is muddy in the north and sandy to rocky in the south. The longitudinal bars occupy about one-third of northern gulf and are aligned more towards the mainland. Sandbars (Sb) are longitudinal to the coast and are found singly or together and are formed due to the movement of waves and currents. As the depth increases towards the mouth of the gulf, the height of the sand bars also increases. Many sandy shoals (Ss) are present in the Gulf, especially near the mouth of the estuaries. They are irregular in shape with smooth texture, and remain submerged under water. In the central part of the Gulf, channels are observed intervening the sandbars, which are lenticular in shape, tapering due north and south and are running in the direction of the tidal currents. Sandbars are mostly filled with clay. While in the southern gulf, the channels are seen bifurcated, and the sand waves narrowing, crowded and longitudinal. Sand wedges (intermingling sand bars) are observed, which are formed due to the interaction between tides and the flow of the sediments. In the southernmost part of the Gulf, sand waves and ripples have superimposed wide sandbars. From the orientation of sand waves, it is deciphered that they are tide dominated. Further south, the sand waves are seen bifurcated. Bedform structures like sand dunes or mega ripples are not visible on the image probably due to the high attenuation and depth. Eddy structures ('Es') are present which are formed due to tides prevailing in the Gulf (Plate 3). These features were compared with available navel hydrographic chart (No. 208, Year-1970). As changes are numerous over time, feature verification was partial.

## 5. Discussion

In the earlier study (Vora et al., 1980), the presence of major (mega) sand waves is reported from further south of the Gulf, off Daman. These sand waves are nearly symmetrical, less than 2 m height and of 100-200 m wavelength in the southern part, whereas in northern part sand waves are asymmetrical, 3-4 m high and of 300-400 m wavelength (Vora et al., 1980). From present study, it is inferred that these sand waves are an extension of bedform structures reported in the present study.

The tides play an important role in the movement of suspended as well as bed load sediments. It is observed on the satellite images that during the flood tide, the sediments cover almost the entire Gulf and the concentration is more along the coast than in the central portion of the Gulf. The concentration towards the mainland coast is more than that of the Saurashtra coast side. During the ebb period, the central part of the Gulf contains suspended sediments, while the coastal region contains a relatively less. During the slack period, sparse suspended sediments are seen in the deeper central region of the Gulf. This probably indicates a period of settling. Coastal region contain relatively smaller amount of suspended sediments.

The gulf is a site of high tidal range, arising from a combination of many factors such as, convergence of shorelines, river water input, shallowness of gulf and predominate action of south westerly wind. Based on visual interpretation, it has been hypothesized that during the flood period, the strong tidal surface currents push suspended (muddy) particles towards the coastal and towards the head of the gulf - resulting in accumulation of mud. Whereas, during the ebb period, the bottom currents pull sediment (sand) particles supplied by major and minor rivers, rolling along the gulf bed. These sediments perhaps participate in the formation of bed form structures.

The topography of the gulf bottom comprises of numerous underwater ridges, deep channels, pinnacles and shoals. These features are the reflections of the earlier presence of graben faults that were subsequently modified by sediment accumulation by tidal currents. The continuous supply of sand size particles to the high energy, tide dominated GoC, by major rivers is decreasing due to the construction of dams across the rivers like the Narmada and the Mahi. Considerable reduction in the supply of sediments will aggravate the erosion along the coast and/or will erode of flow structures.

From all OCM and IRS FCC, direction of sediment transport is inferred as either towards north or south. Incidentally, sediment transport directions match well with the seasonally changing wind pattern and thereby along shore currents (Kunte et al., 2001). Hence, for the present study, OCM data that have been collected during December & January months are showing sediment contributions from south as well as from north. Seasonally changing along-shore currents and tidal currents guide the sediment transport in GoC region. Since the generation and maintenance of the underwater flow structures depends considerably on coupled system of hydrodynamics, sediment transport and morphology, there thus appears to be a wide scope for modeling the generation, evolution and stability of flow structures under the scenario of rising sea level and coastal retreat.

The study concludes that OCM and IRS data can help in recognizing and locating of underwater bedforms, sediment plumes, and other geomorphic features situated in the high-energy tide dominated Gulf. Before claiming that satellite data have potential to improve the charts, study needs refinement and needs to be tested at several different places. By studying turbidity distribution patterns and sediment transport indicators, sediment distribution and dispersion can be well inferred. Sediments are contributed to the Gulf from the north as well as the south and are season dependent.

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**Table 1.**

a) OCM spectral bands and their sensitiveness to different Ocean Parameter.

<b>Bands</b>	<b>Wavelength</b>	<b>Application</b>
C1	402-422	Yellow substance and turbidity
C2	433-453	Chlorophyll absorption maxima
C3	480-500	Chlorophyll and other pigments ( $\leq 1.5$ mg/m <sup>3</sup> )
C4	500-520	Chlorophyll and other pigments ( $\geq 1.5$ mg/m <sup>3</sup> )
C5	545-565	Suspended sediments (away from chlorophyll and Gelbstoff)
C6	660-680	Second chlorophyll absorption , maxima
C7	745-785	O <sub>2</sub> absorption R-branch
C8	845-885	Aero optical thickness

b) LISS-III Sensor Characteristics

<b>Parameters</b>	<b>B1 B2B3</b>	<b>B4</b>
Spectral bands	0.52-0.59(green) 0.62-0.68(red) 0.77-0.86(NIR)	1.55-1.70 (SWIR)
Resolution (m)	23.5 (for bands B2,B3,B4)	70.5 (for b5)
CCD devices	6000 elements	2100
Swath (Kms)	141	148
Equi focal length (mm)	347.5	301.2
Number of grey levels	128 (7 bits)	128

SWIR – Short Wave Infra red, NIR – Near Infra red

**Table 2.**

Tidal phase information during satellite data collection

<b>Satellite Data collection</b>	<b>Tide information at Veraval (outer gulf)</b>		<b>Tide information at Bhavnagar (inner gulf)</b>		
	<b>Time in hrs</b>	<b>Tide</b>	<b>Time in hrs</b>		<b>Time in hrs</b>
02-Jan-2000	7:23	Lowest low tide (2m)	7:21	Highest high tide (4m)	8:40
13-Nov-2000	7:23	Lowest low tide (1.1m)	6:25	Highest high tide (11m)	5:22
02-Jan-2001	7:23	Lowest low tide (1.2m)	10:54	Highest high tide (9m)	9:09
06-Dec-2001	7:23	Lowest low tide (1.4)	9:46	Highest high tide (8m)	10:31
01-Jan-2002	7:23	Lowest low tide (1.3)	7:12	Highest high tide (11m)	5:52

**Table 3**

Details of sea truth data shown in figure 2.

Date	Time	Latitude	Longitude	Depth	SSC in mg/l
02/22/91	11:15	21.067	72.55	0	49
02/28/91	5:00	20.415	72.567	0	36
02/28/91	7:15	20.608	72.69	0	42
02/28/91	9:15	20.415	72.775	0	46
03/23/91	8:10	20.884	72.355	0	19
02/04/92	12:45	20.884	72.355	0	29
02/26/92	8:00	20.415	72.775	0	57
03/19/93	14:00	20.957	72.581	0	61
02/01/95	7:00	21.681	72.845	0	25
02/01/95	7:00	21.681	72.845	0	31
02/01/95	7:00	21.681	72.845	0	36
02/01/95	7:00	21.681	72.845	0	39
02/01/95	7:00	21.681	72.845	0	43
02/01/95	7:00	21.681	72.845	0	48
02/02/95	13:30	21.676	72.593	0	26
02/02/95	13:30	21.676	72.593	0	32
02/02/95	13:30	21.676	72.593	0	37
02/02/95	13:30	21.676	72.593	0	40
02/02/95	13:30	21.676	72.593	0	44
02/02/95	13:30	21.676	72.593	0	49
02/03/95	7:30	21.661	72.569	0	27
02/03/95	7:30	21.661	72.569	0	33
02/03/95	7:30	21.661	72.569	0	41
02/03/95	7:30	21.661	72.569	0	45
02/03/95	7:30	21.661	72.569	0	50
02/04/95	8:00	21.623	72.556	0	34
02/04/95	8:00	21.623	72.556	0	42
02/04/95	8:00	21.623	72.556	0	46
02/04/95	8:00	21.623	72.556	0	51
02/04/95	20:30	21.64	72.551	0	35
02/04/95	20:30	21.64	72.551	0	47
02/04/95	20:30	21.64	72.551	0	52
02/06/95	9:30	21.624	72.506	0	53
04/22/95	6:45	21.098	72.819	0	60
03/12/97	13:00	21.674	72.486	0	36
04/28/97	6:30	21.098	72.819	0	42
11/25/97	7:00	21.417	72.576	0	10.5
11/25/97	8:00	21.417	72.583	0	13.2
11/25/97	9:00	21.4	72.583	0	6.8
11/25/97	10:00	21.409	72.569	0	11.3
11/25/97	11:00	21.418	72.557	0	7
11/25/97	12:00	21.433	72.571	0	2.5
11/25/97	13:00	21.437	72.583	0	2.7

SSC – Suspended Sediment Concentration



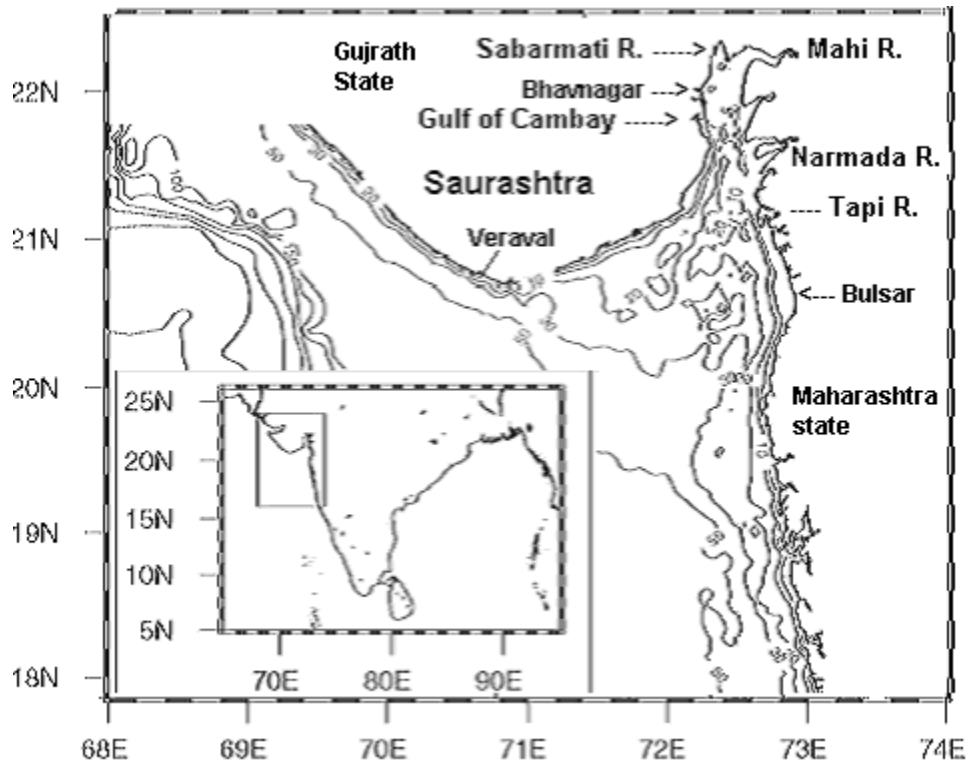


Figure 1 Location map of the study area with bathymetric contours and river mouths.

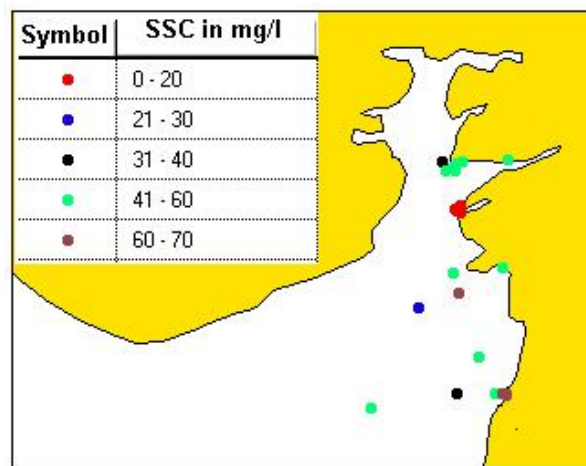
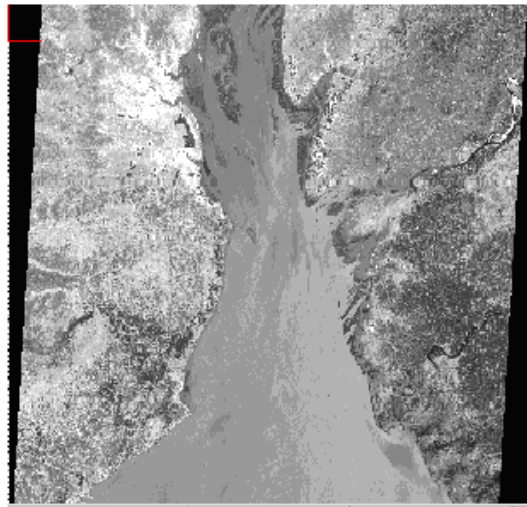


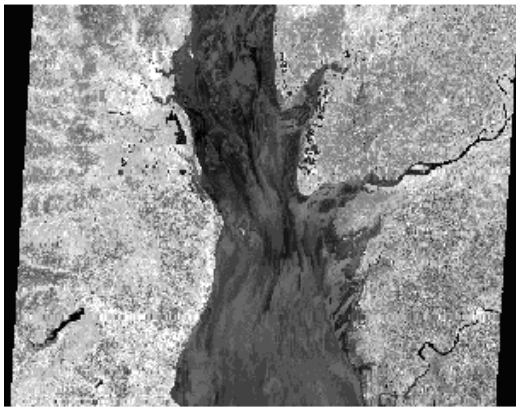
Figure 2. Map showing location and range of sea-truth suspended sediment data (see table 3 for more details).



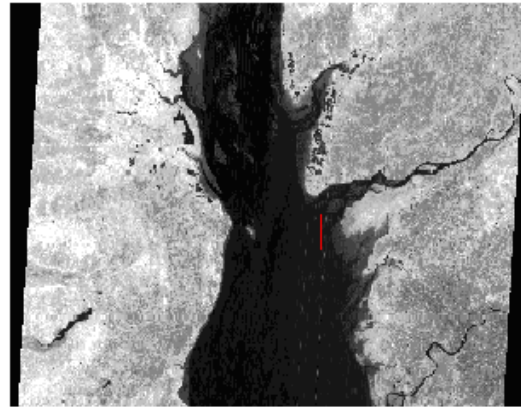
IRS Band 1



IRS Band 2



IRS Band 3



IRS Band 4

Plate 1. IRS 1C LISS-III bands.

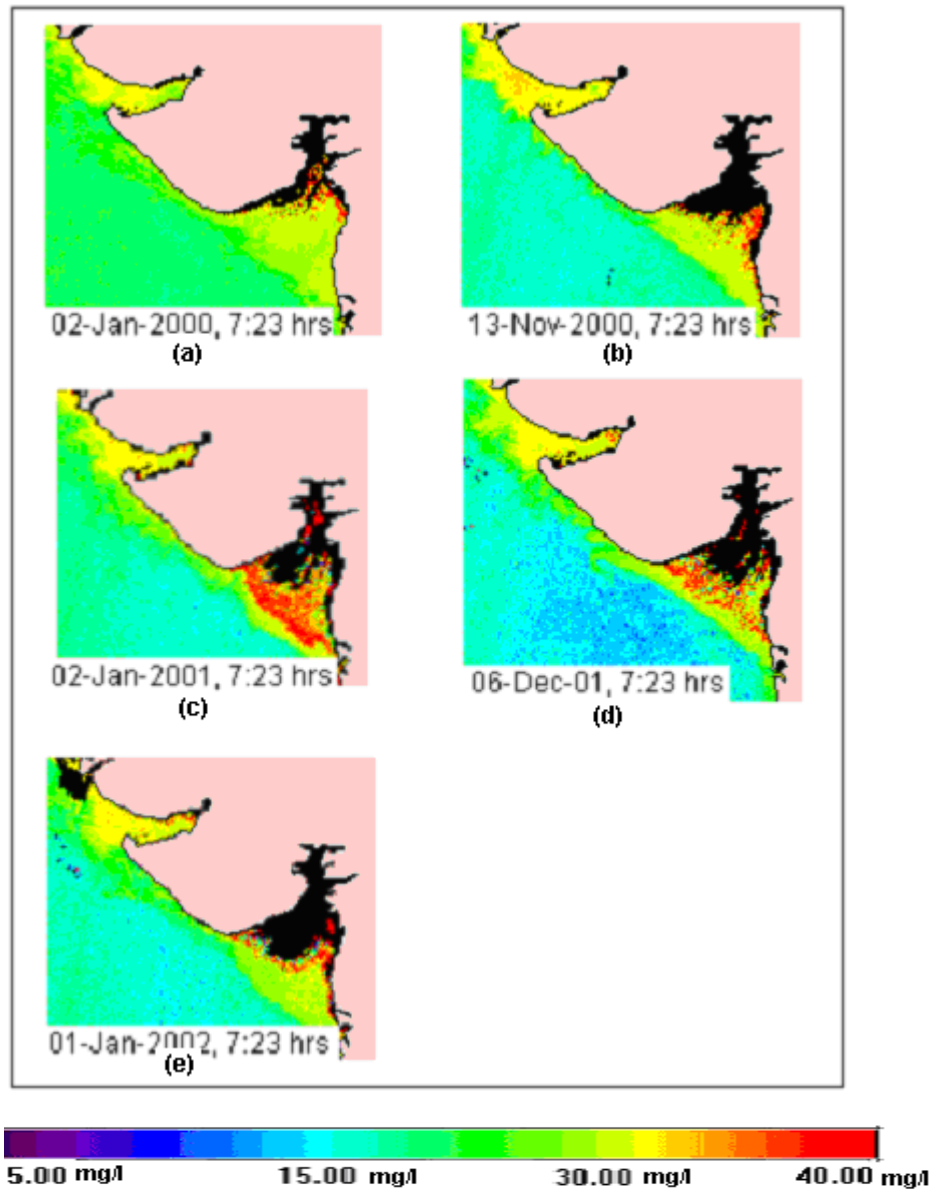


Plate 2. Quantitative estimation of suspended sediment of Gulf of Khambhat derived from OCM P4 data sets of different date

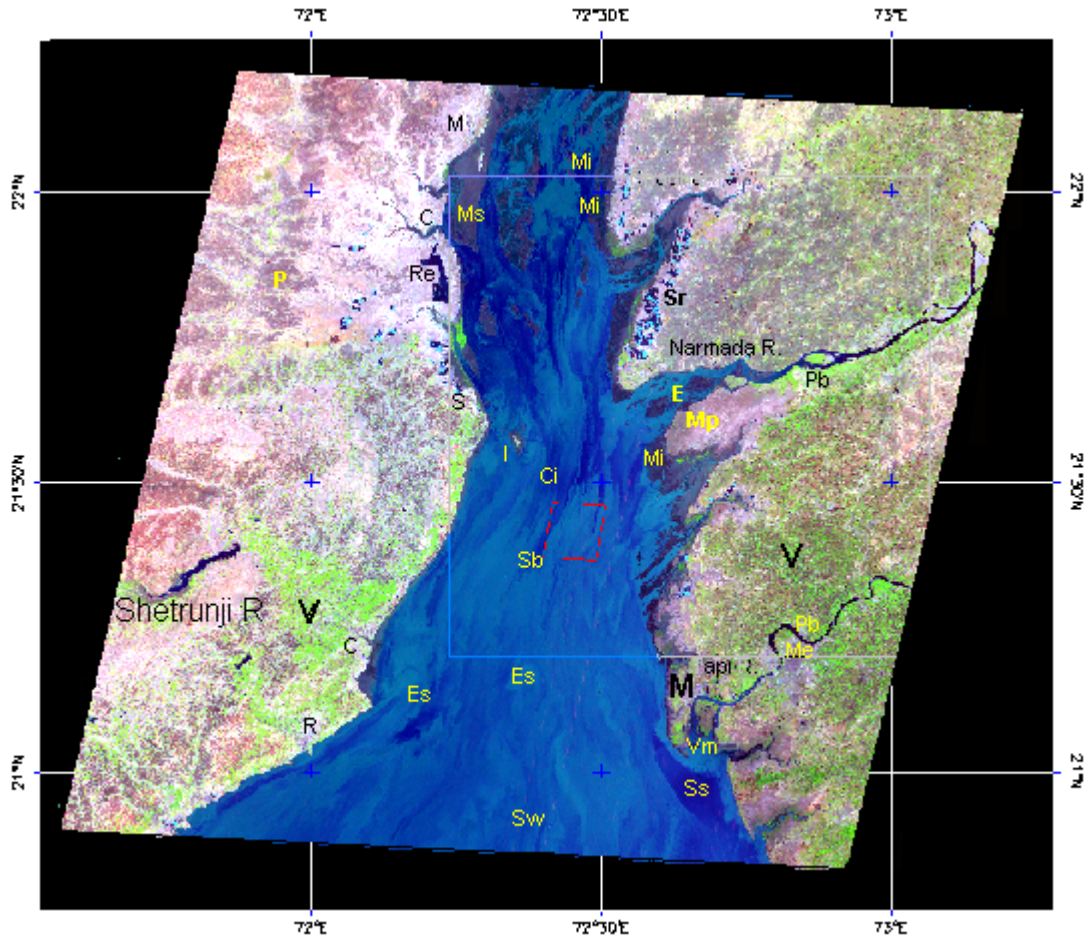


Plate 3. False color composite of IRS 1C LISS-III data from bands 2,3,4 (RGB) showing following geomorphic features.

Rocky coast	R	Island	I
Sandy coast	S	Estuarine island	E
Muddy coast	M	Sand bars	Sb
Vegetation	V	Sandy shoals	Ss
Mangroves	Vm	Sand waves	Sw
Reservoir	Re	Intervening channels	Ci
Rivers	R	Palaeo-mudflats	Mp
Creeks	C	Intertidal mudflats	Mi
Palaeo-channels	P	Sub tidal mudflats	Ms
Meander	Me	Eddy structures	Es
Abandoned river	A	Point bars	Pb
Sandy ridge	Sr		

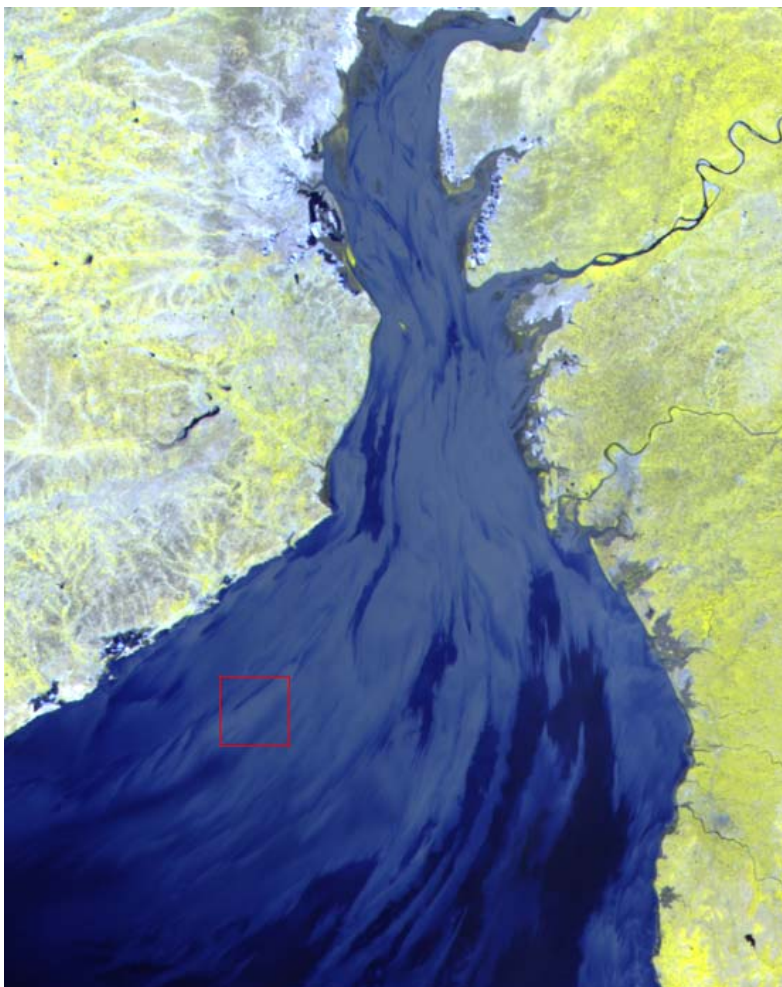


Figure 3. OCM FCC 876 (RGB) of 6<sup>th</sup> Dec 2001, 7:23 hrs.