

## **Sediment fluxes and the littoral drift along northeast Andhra Pradesh Coast, India: estimation by remote sensing**

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**Abstract:** The littoral-drift regime along the north-eastern coast of India was investigated by analyzing coastal drift indicators and shoreline changes based on multi-temporal satellite images. The study of offshore turbidity patterns and quantitative estimation of suspended sediments was undertaken to understand the magnitude and direction of movement of sediment fluxes. The study revealed that: 1) the character of coastal landforms and sedimentation processes indicate that the sediment transport is bi-directional and monsoon dependant 2) multi-date, multi-temporal analysis of satellite images helps to show the nature of sediment transport along the coast. The dominant net sediment transport is in a NE direction along the eastern coast of India. Finally, this assessment demonstrates the potential of remote sensing technology in understanding the coastal morphometric changes, long term sediment transport, shoreline changes and offshore turbidity distribution pattern and the implications for the transport of sediment associated pollutants.

**Keywords** Andhra Pradesh, India • Pollutants • Remote Sensing • Sediment transport • Suspended particulate matter.

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## **Introduction**

Sediment is a natural component of aquatic systems, derived from physical, chemical and biological inputs in watersheds. It is considered as a discrete form of pollution and harmful when there is excess. Surplus sediment damages environment by smothering benthic (bottom-dwelling) plants and animals. Suspended sediment clouds the water, preventing light penetration to submerged aquatic vegetation and also triggers changes in morphology of the area and its accumulation can clog waterways and ports. Sediments can carry excess nutrients and associated chemical pollutants which can contribute to water quality degradation and constitute a threat to wider ecosystems (James, 2002).

The significance of this process for contaminant transport is largely unknown but within contaminated catchments, a portion of the total contamination is introduced to the riverine surface waters and ground water, and on reaching the estuarine zone can affect coastal waters, often beyond the territorial limits. On entering coastal waters, sediment (and associated contaminant) flux is governed by many coastal transport processes such as alongshore and onshore-offshore sediment transport. The major physical factors, which include current action, tides, waves, turbulence, light, temperature, salinity, bed materials and suspended particles, determine the transport and dispersion of all suspended and dissolved material in the marine system, along with nutrients, and pollutants (James 2002).

The association of pollutants with coastal sediments is well documented. Substances of concern such as polycyclic aromatic hydrocarbons (PAHs) and mercury readily attach to the sediment particles in water. Examples include fossil carbon has been recovered in coastal sediments (Baxter 1980); evidence of recent lead pollution has been obtained from deep north-east Atlantic sediments (Veron et al. 1987) and shelf and slope regions of the East China Sea (Huh and Chen 1999); mercury concentrations observed in marine sediments collected off Southern California (Young et al. 1973), and Chernobyl radionuclides recorded from North Sea sediment traps (Kempe and Nies 1987). The effects of associated contaminants on marine organisms in coastal ecosystems has been widely reported e.g. in the Bay of Bengal (Sarkar 2011) and in bivalves from the northeast coast of China (Yongnu Jin et al. 2008). Shailaja and Sarkar (1992) attributed the high concentration of residues, especially DDT, in the Bay of Bengal to the rapid transport by rivers of their high-suspended sediment load (about 8.1 mg/l) compared to rivers emptying into the Arabian Sea, where suspended particulate loads are 1.6 mg/l. The enrichment of anthropogenic inputs of Pb, Zn, and Cu in the surface sediments of the Godavari estuary is observed especially in the western shallow region (Krupadam et al. 2003, 2007). On the basis of a

chemometric approach to understanding water quality, it was found that at some locations of Godavari R. are under highly influenced by contamination from municipal and industrial effluents, whilst other areas are affected by agricultural contamination (Krishna et al. 2009).

Turbidity is recognized as an effective tool for monitoring suspended sediments in aquatic systems. With recent technological advances, turbidity can be monitored in-situ or remotely, continuously, and at much finer temporal scales than was previously possible. Although turbidity provides an improved method for estimation of suspended-sediment concentration (SSC), there is still significant variability in turbidity-based SSC estimates and in sediment loadings calculated from those estimates (Gao 2008). The study of sediment transport can provide vital clues for the direction of sediment movement, quantity and processes governing transportation. Sediment transport also plays important role in determining areas of coastal erosion and sediment accumulation, in shaping and orienting coastal landforms and in the evolving coastline, responding to climate change. Hence, studies of sediment transport are a prerequisite for coastal protection strategies, designing and maintaining port and harbors, fisheries, marine recreation, pollution assessment and control and land reclamation.

The transport, direction and amount of long-term average shore drift (net sediment transport) are of vital importance when analyzing coastal problems. Net shore drift is the direction in which sediments are transported along the shore over a period of years, in spite of short-term seasonal transport in the opposite direction (Taggart 1989). To ascertain net shore drift directions, the coastline is divided into a set of distinct essentially self-contained, littoral cells (Taggart 1989; Schwartz et al. 1988) which are geographically limited. They consist of sand sources that provide sand to the shoreline; littoral drift that moves sand along the shoreline, and sand sinks where sand is lost from the shoreline. As the direction of net shore drift is the combined drift in all directions, it is necessary to identify drift cells and the shore drift within each drift cell. Since shore drift is variable with respect to direction, time, place, duration and amount, its determination requires a methodology that will take these variables into consideration.

The peninsular part of the Indian subcontinent is traversed by a number of rivers most of which flow from west to east and carry a large amount of sediment, building large deltas at their mouths. These peninsular deltas have been investigated extensively during the past few decades (Mahadevan and Prasada Rao 1958; Sambasiva Rao and Vaidyanadhan 1979a, b; Krishna Rao and Swamy 1991; Srinivasa Rao et al. 2001; Behera et al. 2002; Gamage and Smakhtin 2009; Sarkar et al. 2009). Whilst minimal pollution burden in the context of trace elements has been indicated (Alagarsamy 2006;

Alagarsamy and Zhang 2010; Ray et al. 2006), the effects of seasonal disturbance from Monsoons can enrich mobile sediment fractions in trace metals (Krupadam et al. 2003), with implications for wider dispersal in the region. However, no significant systematic study of the alongshore littoral drifts system has been carried out to date. This is a critical issue, for coastal engineering (Patsch and Griggs 2008), pollution assessment, and in the morphodynamic maintenance of the deltas.

#### Physiographic setting of the study area

The 290-km-long NE Andhra Pradesh coast, India ( $16^{\circ}26'24''$ -  $17^{\circ}43'45''$  N;  $81^{\circ}42'17''$ -  $83^{\circ}18'23''$  E) is dominated by the Godavari delta, Kakinada bay, and an open coast from Uppada to Vishakhapatnam in the north (Fig. 1).

Geomorphologically, the sub-aerial sections of the Godavari delta have been divided into the upper fluvial plains with a number of abandoned/buried channels and natural levees, while the lower coastal strand plains are characterized by a series of beach/dune ridges and swales, mudflats, lagoons, mangrove swamps, tidal channels, spits and barriers, etc. The coastal plain has a very gentle gradient that ranges from 10-20 cm/km towards the sea. The beach sands, modern dunes, and sand ridges overlie the bed sediments. Whilst khondalites, granites, charnokites, pegmatites and quartz veins constitute the hill ranges of the Vishakhapatnam coast, the Godavari deltaic region consists of Holocene-Pleistocene sediments.

Fed by a large  $312,812 \text{ km}^2$  drainage basin, the delta spreads over an area of about  $5,100 \text{ km}^2$  at the mouth of the second largest river in the country (1,465 km). At about 10 km downstream of Rajamundry near the Dowlaiswaram barrage, the river bifurcates into two distributaries, the Gautami and the Vasishta (Fig. 1). A third tributary, the Vainateyam, splits from the Vasishta farther downstream. Terminal branching of Gautami results into a fourth tributary, the Nilarevu.

During 16-year period from 1988 to 2003, the average discharge of the Godavari trunk river was  $96.5 \text{ km}^3/\text{yr}$  of which  $64.6 \text{ km}^3/\text{yr}$  (67%) flowed through Gautami tributary, while  $31.9 \text{ km}^3/\text{yr}$  (33%) flowed through Vasishta branch (Nageswara Rao et al. 2005). The average, Vasishta/Gautami discharge ratio is 0.49 during the 16-year period, with some annual fluctuations (Nageswara Rao et al. 2005). The mean annual water flow (Bikshamaiah and Subramanian 1988) and sediment transport of the Godavari River are estimated to be  $92 \text{ km}^3$  and  $170 \times 10^6 \text{ ton (t)}$ , respectively. Reddy et al. (1994) studied seasonal changes in suspended sediment load in the Gautami-Godavari estuary and concluded that higher

concentration of suspended matter (270 mg/l) at the Gautami estuarine mouth compared to the Nilarevu (95 mg/l) estuarine mouth could be due to the turbulence caused by wave action and tides.

Tide gauge data from 1990 to 2001 recorded at Kakinada port shows that the mean annual high tide is about 1.3 m and the low is 0.3 m. Tides are semidiurnal with a slight variation in the amplitude of the spring and neap tides (Nageswara Rao et al. 2005). As a result of the seasonally reversible monsoon wind systems, bidirectional surface circulation patterns prevail over the Bay of Bengal, under the influence of which the surface currents move northeastward during the southwest monsoon, whereas, weaker southwestward currents prevail during retreating monsoon (Lafond and Lafond 1968).

The air temperature in the study area reaches a maximum of 48<sup>0</sup> C during April to June and is moderate during the rest of the year. The average rainfall is around 1280 mm. More than half of the rainfall is from southwest monsoons (June-September) and the rest is from the northeast monsoon during the months (October- December). The fetch of the northeast monsoon that affects the east coast is about 1,500 km.

Several studies on the nature of coastal landforms along the delta front indicated an increase in the sediment flow through the Godavari River during the nineteenth century and even over a major part of the twentieth century. Based on an analysis of multi-date maps of 100 years, Mahadevan and Prasada Rao (1958) traced a 21-km-long sand spit growth at the delta, east of Kakinada. Overall accretion of land due to development of several other sand spits at the tributary mouths of the Godavari during the period between 1937 and 1977 was reported by Sambasiva Rao and Vaidyanadhan (1979a). However, field study revealed a predominance of erosion rather than deposition along the estuarine banks and delta front shoreline (Malini and Rao 2004).

The study reported here analyzes the littoral-drift regime along the coastal stretch between Narsapur and Vishakhapatnam, north-eastern coast of Andhra Pradesh, India, which is dominated by the Godavari Delta and an open coast. Here, the intention is to use remote sensing data understand the single decade morphometric changes and long term net shore drift to determine sources, sinks, dispersion and distribution of sediments and implications for transport of associated pollutants. The direction of net shore drift is determined by studying coastal landform indicators and identifying changes in coastal landforms. The study of the distribution pattern of offshore turbidity and quantitative estimation of suspended sediments has been carried out to understand quantum and dynamics of suspended sediment fluxes.

## Materials and methods

Two scenes of Landsat Enhanced Thematic Mapper (ETM dated 2000) data, two scenes of Landsat Thematic Mapper (TM dated 1988, 1989) data and three scenes of Landsat MSS imagery covering study area were downloaded from the Global land cover facility (<http://glcfapp.glcfc.umd.edu:8080/esdi/index.jsp>). Acquisition and radiometric characteristics are provided in table 1 and 2. Optical sensor data from MODIS (technical specifications <http://modis.gsfc.nasa.gov/aboutspecs.html/>) onboard Aqua and SeaWiFS data (for more detail <http://oceancolor.gsfc.nasa.gov/seaWiFS/SEASTAR/SPACECRAFT.html>) onboard the SeaStar spacecraft over the study area have been used to estimate suspended sediment concentration. To study water turbidity variation, black/white Landsat Images have been used.

### *Quantitative estimation of suspended sediments*

Using geometric and atmospheric correction algorithm provided by SeaWiFS group, the reflectance values were calculated from radiance values. The reflectance values were then employed to estimate suspended sediment concentration by using Tassan's approach (Tassan, 1994) to study 'case II water' along the study region. This algorithm captures the inherent sigmoid relationship between R(490), R(555) and R(670) band ratio. A script (program) based on equations 1 and 2 using SEADAS software computes suspended sediment concentration  $X_s$ , where R(B) is remote sensing reflectance in respective wavelength band B. The final form of optimization routine for suspended sediment concentration (S) is,

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

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

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

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

Results for two days 11<sup>th</sup> November 2000 (SeaWiFS data of post-monsoon season) and 22<sup>nd</sup> March 2003 (MODIS data of pre-monsoon season) have been presented as Fig. 2a & 2b respectively.

### *Qualitative Study by Image Processing*

Using image processing software, TM and ETM data for three scenes were digitally processed and a mosaic covering the Northeast Andhra Pradesh coast was prepared. The TM and ETM data sets, with ten years difference in coverage, were collectively studied and analyzed after enlarging.

### *Distribution of Turbidity patterns*

Shore drift causes churning and transportation of clay-size sediment particles along with the fluxes of associated organic matter, nutrients, toxic chemicals and other pollutants received from rivers, creating turbidity in coastal waters. The first band of TM imagery (Fig. 3) provides a synoptic view of turbid water masses which helps to understand the distribution, variation and dispersion of suspended sediments and associated pollutants. On satellite images, the sharp contrast between various sediment laden waters is noticeable. Tonal variation is considered as a measure of turbidity concentration (Kunte and Wagle 1993 a, b). Texture and pattern help in monitoring distribution and movement of turbid water masses. Current directions are indicated by the sediment laden plumes as they become elongated and pointed in the direction of flow. Based on tonal and textural variation, five distinct types of water masses are identified in the region (Fig. 3). The higher concentration of suspended sediment occurs in the highly turbid water, while minimal concentration is reflected by clear water.

### *Determination of the direction of Littoral drift*

Since coastal landforms are affected by all the variables of shore drift during their formation, they can be considered as the most reliable long-term shore drift indicators. Their shape, size, form, pattern, development and their location, orientation and association with respect to other landforms are important when determining the direction of shore drift.

Several shore drift indicators like beach width, sediment size gradation, beach slope, bluff morphology, headland-bay beaches, structures interrupting shore drift, stream mouth diversions, inlet migrations, spit growth, identifiable sediment, plan configuration of delta and inlet fans, beach pads and near shore bars are reported in the literature (Schwartz et al. 1985; Taggard 1989; Frihy and Dewidar 2003; Peterson et al. 2010). As this study was carried out with remote sensing technique, a limited number of landform indicators were considered. These are river mouth deflection, spit growth, tombolo, beach width, paleo beach ridges and man-made structures interrupting shore drift, all of which can be clearly mapped by remote sensing technique (Kunte 1994).

### *Landform change analysis*

The sediment transportation pattern along the area was studied using TM (dated 1988, 1989) and ETM (2000) images by detecting the landform and shoreline changes during the decade (1988/89 to 2000). The multi-date color composite for each sector was generated by assigning red color to a band of ETM

data and green and blue color to the corresponding band of TM data. In multi-date color composite images, red colored features indicate growth of the feature during the period 1989 to 2000, whereas, green-blue features indicates the earlier existence of landform, while white colored features have remained unchanged. To understand shoreline changes along the study area over a decade period, shoreline digitized from TM and ETM were overlaid using Geographic Information System (GIS) and shoreline changes mapped (Fig. 4).

## **Results**

### *Quantitative estimation of suspended sediment concentration*

In images (Fig. 2a & 2b), the black portion represents landmass, whereas black patches within data represent no-data region. The suspended sediment concentration (SSC) along the coast varies between 5 to 100 milligrams per liter (mg/l). Maximum sediment concentration (100 mg/l) was observed encircling Godavari delta. In the SeaWiFS image (Fig. 2a), sediment plumes point southwestwards, indicating the drift of sediment southwestward during the northeast monsoon. In the MODIS image (Fig. 2b) sediment plumes point southwestwards in the northern part and northeastwards in the southern part, resulting in convergence of coastal currents during the inter-monsoonal period (February–April). The sediment plume trajectory off Godavari delta has extended eastward to a distance of about three hundred kilometers from the delta coast and gradually diminishes after around forty-five days. The Bay of Bengal is a semi-enclosed, tropical basin driven by seasonally reversing monsoons. Hydrographic studies have revealed the presence of basin-scale gyral flows with adjacent meso-scale eddies rotating in the opposite direction (Sridhar et al. 2008). The jet is sandwiched between the cyclonic and anti-cyclonic circulation (Fig. 2b). As a result, a water-jet turns eastward and carried along sediments from the Godavari delta. The same sediment plume trajectory (Fig. 2b) was observed (Sridhar et al., 2008) while processing Ocean Color Monitor data collected on-board Indian Remote Sensing satellite-P4 for the region.

As per Ambient Water Quality Guidelines (Criteria) for Turbidity, Suspended and Benthic Sediments issued by Government of British Columbia (Caux et al. 1997), marine environment for aquatic life is considered as polluted by sediments, if there is a significant change from a background of 10 mg/l at any time or when the background is 25 - 100 mg/l during high flows or in turbid waters. Hence, along the coast, where SSC is measured between 80 and 100 mg/l, establishes the region as polluted due excess sediments.



### *Distribution pattern of offshore turbidity*

Major suspended sediment movement is seen off the Godavari delta coast. Large volumes of sediment brought in by four tributaries of the Godavari River are dispersed by river drift as well as alongshore drift. Hence highly turbid water is observed at the mouth of all four tributaries. Suspended sediments moved seaward and then southwestwards. For south westward moving suspended sediments, Kakinada spit and bay are major sinks and hence the majority of sediments are trapped within the Godavari delta.

Suspended sediments emerging from the Vasishta tributary are transported seawards and then westwards and finally are pushed eastwards. Sediments flow outwards and then along the coast during the month of November. Wave crest approaches perpendicular to the shore and hence suspended sediments move seawards and then form a belt along the coast. Suspended sediments emerging out from the Nilarevu tributary have moved seaward and then southwards (Fig. 3) resulting high to moderately high turbid water.

### *Landform Change Analysis*

The tail of a spit on the western bank of Vainateyam R. shows marginal erosion (in green-blue), whereas on the east bank accretion occurs (in red). Both the spits show accretion (in red) and erosion (in green-blue) at different locations (Fig. 5a). Portions of spits situated on banks of the Gautami R., show erosion in green-blue and growth in red (Fig. 5b). A Lagoon formed between the new and old spit on the south bank is filled with recent deposits. Sediment accumulation has dominated this coastal segment (Fig. 5b). The spit on the southern bank of the Nilarevu R. has shown significant growth along its tail in the past ten years and growth (shown in red) on seaward portion of the spit is also evident (Fig. 5c). The spit on northern bank and the riverward portion of the southern bank shows erosion (in green-blue color). The unchanged nature of spit is shown in white.

The 21-km-long Kakinada spit, which is prominent among all such sand bodies, had even deflected the course of the Gautami R. in the initial stages of its growth under the influence of a strong unidirectional northeastward alongshore drift (Fig. 5d). The back barrier Kakinada Bay continued to fill with fine sediments. Mangroves colonized the abandoned delta lobe and the emerging floor of the bay, especially in the bay head zone.

The open coast between Kakinada and Padimadaka has a narrow lining of sandy beaches (Fig. 6a). The shoreline changes along this coast are marginal but apparent in red (accretion) and green-blue

(erosion) color respectively. From Padimadaka to Vishakhapatnam shoreline is mostly covered with beaches with less sand deposition. Accretion (Red) and erosion (green-blue) has taken place alternatively all along the coast (Fig. 6b). Vishakhapatnam beach shows accretion.

Along the open coast between Kakinada and Vishakhapatnam, little or no shoreline change has been detected (Fig. 6c), whereas along Godavari delta, distinct shoreline changes in terms of accretion and erosion have been noted and mapped. Along Godavari delta coast, net shore drift is predominantly towards the northeast; with divergent drift between the Gautami and Vainateyam R. mouths; and cusped convergence at the Vasishta R. mouth. Along the open coast, net shore drift is predominantly towards the northeast, with some short reversals.

#### *Description and demarcation of drift cells*

In the southern sector, two converging drift cell (DC-1 & DC-2) are identified based on the growth of two spits (S1, S2 in Table 3) from either flank of Vasishta R. Two converging spits (S3 & S4) at the mouth of Vainateyam R. form two drift cells DC-3 and DC-4. Drift direction is decided based on spit growth, diversion of river mouth and converging or diverging stacked strand lines (Taggart and Schwartz 1988). Two drift cells DC-5 and DC-6 are identified at Gomati R. mouth. A Northeasterly extending long spit, S5, forms drift cell 5 with drift cell direction towards northeast. DC-6 is a short cell with drift direction towards southeast. DC-7 and 8 are two converging drift cells identified at the mouth of Nilarevu R. Spit S7 initially diverted Nilarevu tributary towards north indicating northward drift direction. DC-9 is represented by a long narrow spit with a curved form which encloses Kakinada bay. Spit growth towards the east indicates drift direction is towards the northeast (Fig. 5d).

In the northern sector, six drift cells are identified and mapped along the open coast between Uppada and Padimadaka (Fig. 6a & 6b). These drift cells are mostly composed of sand bars which have been stacked along the coast over several centuries. Sandy beaches of variable length and breadth are located all along these drift cells. When carefully observed on remote sensing images and subsequently on topographic maps, it was noted that beach widths are wider on either ends of the beaches compared to the middle portion. These observations indicate that the shore drift is both to the north and to the south, as beach width increases through a drift cell in the down drift direction (Taggart and Schwartz 1988).

The last four drift cells between the Padimadaka and Vishakhapatnam shores are identified on the basis of a large rocky mass which obstructs the alongshore drift (Fig. 6c) and form a tombolo (as

marked by a circle in Fig. 6) in DC-17 and DC-18. The formation of two tombolos indicates drift cells and direction towards the NE in both cases. It is observed that sand accumulates initially in the shadow zone of wave fronts (Fig. 6d, DC-18), between large rock boulders and the coast, to form a cone-shaped accumulation where the alongshore drift is obstructed (Kunte and Wagle 1993a). The cone points in the direction of net shore drift. At an advanced stage, this accumulation joins the island to the coast, thus forming tombola. All four drift cells show drift direction towards the northeast. The DC-10, which is off Kakinada town, is represented by a south-growing spit and two jetties (Fig. 6d). Such man-made structures obstruct shore drift and sediment accumulates on the up drift side, whereas, the down drift side experiences sediment starvation and subsequent erosion (Taggart and Schwartz 1988). Accumulated sediment deposit on the northern side, clearly indicates drift direction to be towards the north-east (Fig. 6d).

DC-10 to DC-20 is situated along rocky shores which are skirted by sand accumulations from long shore drift. As no major river is debouching along this sector of the coast, sediment movement is less. Based on the analysis of shoreline change and the landform indicator study, shore drift and net shore drift direction were determined and indicated on a map overlain on the TM imagery. Twenty drift cells (DC-1 to DC-20) are identified in the study area. Out of twenty drift cells, eleven drift cells have a north or north-eastward drift direction, whereas, nine drift cells have drift direction pointing south or southwest (Fig. 7).

## **Discussion**

Evidence obtained from the study of landform drift indicators, the pattern of distribution of off-shore turbidity and the detection of shoreline change suggests that sediment transport direction is towards both the northeast and southwest direction within the drift cells coinciding with the monsoon pattern and influenced by monsoonal winds. In TM and ETM data collected in November, the sediment transport direction shown by suspended sediments is in a NE or SW direction.

Each drift cell indicates sediment transport direction either towards the northeast or southwest, based on the orientation of palaeo-beach ridges, shifting of Godavari R., spit growth direction, beach width and plan view of delta. Those drift cells which have a northeasterly drift direction, are much larger and are more prominent; hence, net sediment transport direction is confirmed as towards the northeast. However, in adjoining Krishna delta region, net sediment transport direction is towards southwest (Kunte and Wagle 1993b).

The longshore sediment transport study (Chandramohan et al. 1988) also showed that the general direction of longshore transport is towards the northeast during March to October and southwest during November to February. The longshore transport rate is high during the southwest monsoon period from June to September. Based on the measured data, wave height and current speed, longshore sediment transport rates were estimated (Sanilkumar et al. 2006). Along the east coast, longshore transport is southerly from November to February, northerly from April to September and variable in March and October. However, the net sediment transport along the east coast of India is towards the north, supporting the present investigation.

As indicated by the Central Pollution Control Board (CPCB), India, the water quality monitoring of major rivers indicates that organic pollution is predominant (CPCB 2003). The rivers with grossly polluted stretches (Table 4) include Sabarmati, Godavari, Satluj, Yamuna, Cauvery, Ganga, Krishna, Tapi, Mahanadi and Brahmani whereas relatively clean rivers include Mahi, Narmada, Brahmaputra and Beas with respect to organic and bacterial pollution (Bhardwaj 2005). The Pennar river estuarine sites in the east coast of India are affected by metal pollution (Co, Cr, Fe, Mn, Pb, Zn, Cu, Se, Sb and Ni) due to human activities like aquaculture, industry (Sundara Raja et al. 2009). The east coast, on average, is found to be much more contaminated than the west coast, which might be attributed to residues carried by the major rivers along the former coast (Sarkar et al. 2008).

The large rivers on the east coast play an important role in confining along-shore pollutant transport. Their high run-off act as barriers to the transport of sediment and associated pollutants close to the coastline. It is important to understand shelf and estuarine circulation in the region as the large number and wide range in size of discharge points, add complexity to the system, so that through effective modeling, information on the mixing of pollution sources, sediments and offshore hazards (oil spills) is available to decision makers for effective coastal management. In addition, the large volume of flushing through the river systems during the Monsoon has a twofold effect of purging stored sediment and associated pollutants and dilution and mixing of anthropogenic pollution (Alagarsamy 2006). The higher mean Enrichment Factor for Pb, Cd, Zn and Cr reveals significant contamination of sediments by these metals from external sources such as industrial sites and the expanding modern population activities in the east coast (Selvaraj et al. 2004) and warrants further study to gain detailed understanding of sediment and associated pollutant dynamics in the region.

On the eastern coast, wave activity is significant during monsoons. Extreme wave conditions occur under severe tropical cyclones (Mascarenhas 2004), which are frequent in the Bay of Bengal during the northeast monsoon period. In spite of frequent storms, steep shore gradient, narrow shelf break; bi-directional season dependent littoral drift along the study area has influenced the management and maintenance of the coast and in forming several depositional features such as long spectacular spits, bars, and delta fronts. These littoral-drift characteristics along the northeast Andhra Pradesh coast indicate a shoreline configuration that has clearly adjusted to the present ambient wave conditions.

The transport routes and transport rates of the different sediment classes are likely to play a significant part in the dispersal of attached pollutants. For instance, while Cd and Cu tend to exhibit an inverse relationship with salinity, suggesting that these metals behave like dissolved tracer, the more 'particle reactive' Hg becomes rapidly associated with particulate matter. Coastal sediments act as temporary or long-term sinks for many classes of anthropogenic contaminants and consequently act as the source of these substances to the ocean and biota. Pesticides applied on land can be transported through surface run-off, leaching and vapor phase and ultimately accumulates and settles in the bottom sediments. Hence bottom sediments represent an archive of particle bound contaminants deposited over a longer period of time (Sarkar et al. 2008).

Detailed geomorphic study of the area demonstrates the importance of rivers as major sources of sediment for littoral drift. Substantial quantities of sediment are also derived from offshore, particularly during extreme events (Mascarenhas 2004), and are added to littoral zones. Beach and cliff erosion contribute partially as sources while other geomorphological features such as lagoons, deltas, estuaries, beach storage, sand spits and offshore slopes are sediment sinks for marine sand (Chandramohan et al. 2001). Protruding river deltas, constant elongation and stabilization of spits, filling of lagoons by sediment deposits, seaward coastal accretion and formation of dunes are clear indicators of positive sediment balance along the Orissa coast except in the south-central part of the Baleshwar Bay region. Thus, sedimentological functioning of these geomorphic units helped understanding the propagation of anthropogenic pollutants in the coastal environment.

## **Conclusions**

The study reveals that: 1) multi-date, multi-temporal satellite images help in understanding the nature of sediment transport along the coast, 2) the character of coastal landforms and sedimentation processes in the study zone indicate that the sediment transport is bi-directional and monsoon dependant. However,

the prominent net sediment transport is from SW towards NE along the eastern coast of India, 3) sediment transport characteristics along the northeast Andhra Pradesh coast indicate that littoral drift regime adjusts with the changing wave climate along the coast, and 4) a positive sediment balance along the coast is reflected in the development of large spits and delta growth.

Finally, we have demonstrated the usefulness of remote sensing technology in understanding the coastal morphometric changes, long term sediment transport, shoreline changes and offshore turbidity distribution pattern to determine sources sinks and the dispersion of sediment associated pollutants in sensitive coastal regions.

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**Table 1** Data acquisition details

Area covered	Sensor	Path	Raw	Date
North	TM	139	48	12 Oct. 1988
South	TM	141	49	31 <sup>st</sup> Oct. 1989
North	ETM	141	48	8 <sup>th</sup> Dec 2000
South	ETM	141	49	8 <sup>th</sup> Dec. 2000
North	MSS	152	48	8 <sup>th</sup> Jan 1977
Central	MSS	151	48	24 <sup>th</sup> Feb 1973
South	MSS	152	49	1 <sup>st</sup> June 1977

**Table 2** Radiometric Characteristics of TM and ETM

Satellite	Sensor	Spectral Resolution ( $\mu$ )	Band	Spatial Resolution	Altitude (km)	Revisit (days)
Landsat 5	TM	Band 1: 0.45 - 0.52	Blue	30	705	18
		Band 2: 0.52 - 0.60	Green	30		
		Band 3: 0.63 - 0.69	Red	30		
		Band 4: 0.76 - 0.90	Near IR	30		
		Band 5: 1.55 - 1.75	Mid IR	30		
		Band 6:* 10.4 - 12.5	Thermal	120		
		Band 7: 2.08 - 2.35	Mid IR	30		
Landsat 7	ETM	Band1: 0.450 - 0.515	Blue	30	705	16
		Band 2: 0.525 - 0.605	Green	30		
		Band 3: 0.630 - 0.690	Red	30		
		Band 4: 0.760 - 0.900	Near IR	30		
		Band 5: 1.550 - 1.750	Mid IR	30		
		Band 6: 10.40 - 12.5	Thermal	60		
		Band 7: 2.080 - 2.35	Mid IR	30		
		Panchromatic				
Band 8: 0.52 - 0.92	Pan	15				

\* Band 6 on Landsat 7 is divided into two bands, high and low gain

**Table 3** Location and description of spits of the study area. Out of 9 spits, 6 spits grown E or NE side, whereas, 3 spits are pointing W or SW direction. Out of 6 NE/E pointing spits, 5 spits shows accretion whereas only one spit is eroded. All 3 spit pointing SW/W shows accretion. Spit length change clearly indicates net shore drift direction towards NE.

No	Spit name	Central location		Spit description	Distal end Pointing	Spits length in meters		Name of diverted river	Diverted Towards
		Latitude	Longitude			TM*	ETM+		
						Year88-89	Year2000		
S1	Vasista-west-spit	16° 23' 36"	81° 39' 31"	Long, narrow, curved tail	NE	14.10	14.20	Vasista	NE
S2	Vasista-east-spit	16° 20' 00"	81° 46' 33"	Thick, blunt, triangular	SW	117.08	17.31	Vasista	SW
S3	Vianateyama West-spit	16° 23' 36"	81° 55' 33"	Thick blunt triangular	E	110.28	10.23	Vianateyama	E
S4	Vianateyama East-spit	16° 25' 16"	81° 59' 56"	Thin long, two wings spit	W	009.19	10.25	Vianateyama	W
S5	Gautami West-spit	16° 32' 52"	82° 15' 42"	Thin, long, curved tail	E	113.17	15.32	Gautami	E
S6	Neelarevu West-spit	16° 42' 12"	82° 21' 09"	Short, hook tail	NW	112.63	14.98	Neelarevu	NW
S7	Kakinada spit	16° 54' 9"	82° 21' 55"	Long narrow, tail curved	N	220.87	20.99	Kakinada bay	N
S8	Tuni west-spit	17° 24' 39"	82° 51' 22"	Short, tail curved landward	NE	005.89	05.93	Perennial river	NE
S9	Padimadaka spit	17° 26' 54"	82° 59' 55"	Small narrow, curved tail	SW	55.25	05.29	Perennial river	SW

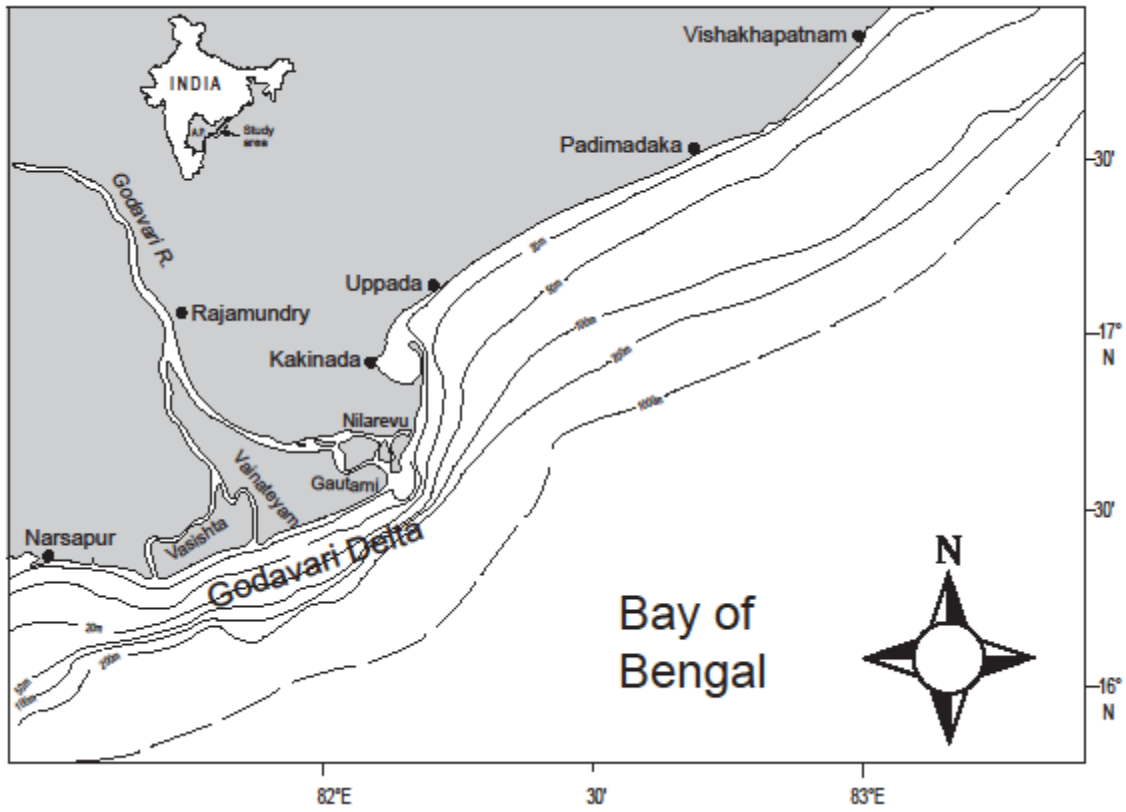
\*TM—Thematic Mapper and +ETM – Enhanced Thematic Mapper

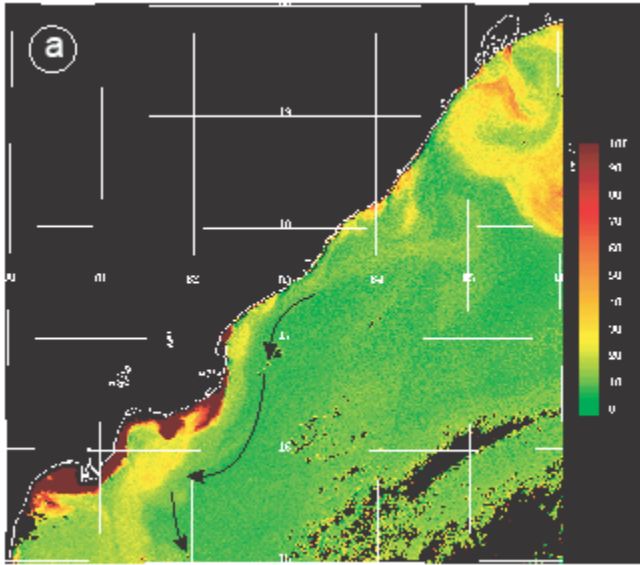
Table 4 Water Quality of Rivers draining the study area – 2002  
(Observed Range of Water Quality Parameters) (modified from Bhardwaj, 2005)

River name	Length (km)	Temperature degree C	pH	DO (mg/l)	BOD (mg/l)	COD (mg/l)	Total Coliform (MPN/100 ml)
Godavari	1465	22-35	7.0-9.0	3.1-10.9	0.5-78.0	3-96	8-5260
Krishna	1401	18-33	6.8-9.5	2.9-10.9	0.2-10.0	3-88	17-33300
Mahanadi	851	18-38	7.3-8.9	1.3-10.4	1.0-7.6	7-39	15-30000
Brahmani	799	20-38	7-8.4	5.2-9.8	1.5-6.0	8-13	80-90000
Baitani	--	24-36	7.3-8.3	6.8-9.3	2.0-6.8	7	900-22000
Subarnrekha	395	18-36	6.5-8.0	5.2-8.5	0.2-12.0	4-96	150-1800

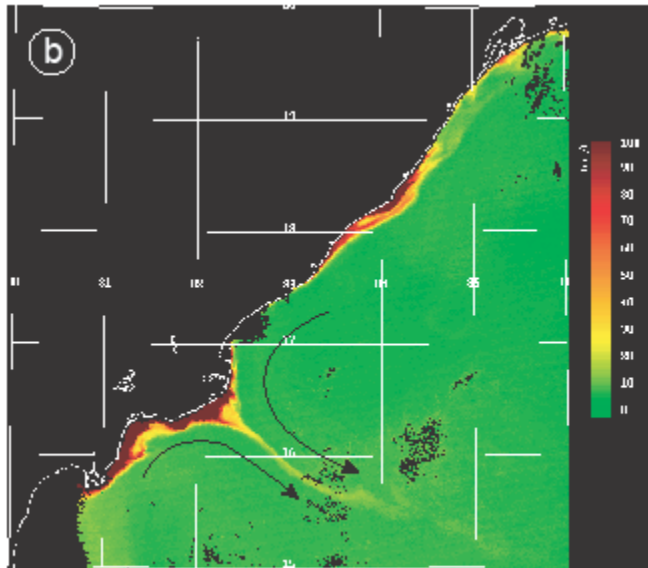
### Figure captions

- Fig. 1** Map showing study area covering Godavari delta and open coast between Uppada and Vishakhapatnam in NE region of Andhra Pradesh.
- Fig. 2** Suspended sediment estimation (in mg/l) using SEADAS software and SeaWiFS and MODIS data. Suspended sediment movement is shown by arrows. Black color within ocean indicates no-data region.
- Fig. 3** B/W Composite of ETM bands 1, 3, 4 showing distribution and dispersion of suspended sediment along NE Andhra Pradesh coast. Suspended sediment movement is towards SW during November month.
- Fig. 4** A decade shoreline change deciphered using GIS coupled with remote sensing images of ETM and TM. Note shoreline changes along Godavari delta.
- Fig. 5** Multi-date TM-ETM composite images. Red colored features indicate growth during the past 10 years, whereas, green-blue color indicates earlier existence of the landform. White colored features have remained unchanged. (a) Image overlay showing Vainateyam distributary mouth and spits on either bank of Vainateyam distributary. (b) Image overlay showing Gautami distributary mouth and spits attached to either bank of Gautami distributary. Note erosion (in blue) and accretion (in red). (c) Observe the changes at the Nilarevu delta mouth. Overlay showing Nilarevu distributary and curved spits on right bank (DC 7). (d) Growth of spit has migrated Nilarevu river mouth. Deposition pattern is visible. Kakinada spit and Kakinada bay are visible in northern part of the figure (DC 9).
- Fig. 6** Multi-date TM-ETM composite image overlay showing parts of open coast from Padimadaka to Vishakhapatnam. a) Image overlay showing open coast off Kakinada and Uppada. Drift directions in drift cells 10 & 11 are identified as towards southwest based on beach width and man-made structure as in Fig. 6d. b) Image showing drift cells along open coast from Tuni to Padimadaka. c) Port in DC 20 and tombola formation in DC-18 is visible. d) The sand accumulation at man-made structures (Jetty) off Kakinada town is formed due to along shore drift obstruction. Northward accumulation of sand at the jetty clearly indicates drift direction towards south. (Figure extracted from Google).
- Fig. 7** Map showing extent and directions of drift cells and net shore drift direction. Arrows along the shore indicates extent and direction of littoral drift cell (Numbered). Net shore drift direction is shown with double line arrow.





SeaWiFS image 11th Nov 2000 Time:06:16



MODIS image 22nd March 2003 Time:07:55

