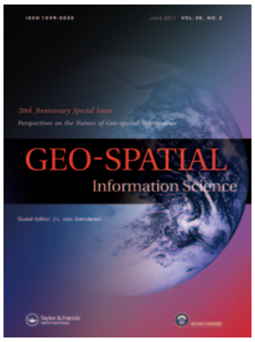

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Coastal zone management in India – present status and future needs

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ABSTRACT

The coastal zone is a region where land, ocean and atmosphere interact and hence it is dynamic in nature. India has a long coastline which was not adequately monitored until the advent of the satellite remote sensing era in the 70s. India has a very robust remote sensing program that the Indian Remote Sensing Satellite (IRS) series of satellites were effectively used to monitor coastal habitats, landforms, shoreline, water quality, etc., and changes were identified during the last 40 years. The classification system for coastal habitats and the classification and geometric accuracies of products were standardized. Detailed information for mangroves communities and characteristics of coral reefs were generated. The high and low tide lines were delineated seamlessly for the entire coastline using satellite data. All these data were organized in a GIS and the coastal database for the entire country was created. Impacts of various hazards on such as cyclones, tsunami and sea level changes on coastal habitats were documented. Based on topography, shoreline changes and tides, coastal multi-hazard vulnerability maps were characterized by employing the elevation data derived from satellite data and were prepared for the coastline of India. The information on ocean color and sea surface temperature was used to generate potential fishery advisories, which are provided daily to fishermen. The coastal database was utilized effectively to identify coastal regulation zones, marine protected areas, vulnerable zones, etc. Various services for tsunami, fishery and coral reef bleaching were generated for societal benefits. It is planned to develop models for the coastal zone, so that impeding dangers and likely changes in the coastal zone can be predicted and suitable actions can be undertaken. It is necessary to integrate socio-economic data with the knowledge database of coastal zone to understand the impact of anthropogenic activities and the changing climate on the coastal zone.

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Coastal zone; India; habitats; processes; water quality; living resources; coastal management

1. Introduction

The Indian coast is about 7500 km long and characterized by varied landforms and ecosystems. In the context of India, the coast is a place where geosphere, ocean, biosphere, and atmosphere interact. Mass and energy are continuously exchanged among these components and thus, such interactions created a unique ecosystem. In view of such exchanges, coastal regions are of remarkable biological productivity and diversity and hence, have become center of human activities. Coastal regions provide fish, shellfish, seaweeds, and host ports for trading and commerce. In addition, many biota are sources of fertilizer, drugs, cosmetics, and household products. Coastal wetlands also store and cycle nutrients, filter pollutants and help to protect the shoreline from erosion and storms. People are attracted to coasts because of their beauty, and thus, provide recreation and facilitate tourism. These products and services support human life and thus, impact the economy of a country and in turn its socio-economic conditions. Hence, we need to ensure robust health of coastal ecosystems through sustainable management, so that they continue to provide various goods and services for future generations, as well.

The information requirement for managing the coastal zone comprises up-to-date and comprehensive data on coastal habitats, ecosystems, landforms, shoreline conditions, water quality, living resources as well as impacts of natural hazards and anthropogenic activities on coastal environment. Remote sensing has greatly enhanced our knowledge on spatial pattern, extent, physical structure, and conditions of coastal habitats and on rates of changes in coastal landscape. Satellite remote sensing data for high spatial resolution (CARTOSAT, IRS LISS IV, and IKONOS), temporal resolution (OCEANSAT, OCEAN COLOUR MONITOR (OCM), MODIS, and SEAWiFS), multispectral (IRS LISS II, III, SPOT, LANDSAT MSS, and TM) and hyper-spectral (HYPERION) have been utilized to derive physical, geological, and ecological parameters. It is very important to understand the characteristics of each satellite data sets and spectral behavior of the targets, so that accurate information can be derived.

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Coastal landforms and shoreline are the results of geomorphic processes such as erosion, sediment transport and deposition as well as sea level changes. Satellite data provided an excellent record of landforms and changes due to their repetitive nature. Such data also help us to understand changes occurring due to natural and anthropogenic activities. Coastal vulnerability maps showing likely areas to be inundated have been prepared for the entire coastline using both satellite and ground-based data. Coastal quality is an important parameter and monitored at 24 locations along the Indian coast.

Coastal ecosystems, such as mangroves and coral reefs, have been classified based on community- and geomorphology, respectively. The long length of records of satellite data allowed to effectively monitor such ecosystems and the changes were detected and mapped. However, such information on changes may not be sufficient to interpret as a climate signal.

The information on marine species is collected to understand ecosystem structure and function. In order to facilitate fishermen searching for fishing grounds efficiently, an advisory service for locating potential fishing zones has been provided.

The timely and accurate information provided by remote sensing and along with developments of GIS and GPS systems, has paved a way to develop an effective strategy for the selection of brackish water aquaculture sites, regulation zones, warning systems for hazards and ultimately sustainable management practices. In India, the application of remote sensing for the coastal environment has matured during the last 40 years, and been effectively used to manage the coast. A review of the same is presented in this article.

2. Coastal and marine habitats and biodiversity

The baseline information on coastal and marine habitats is vital. The first inventory of coastal habitats in India, with emphasis on coral reefs and mangroves, was carried out using IRS LISS II and LANDSAT TM data (1989–1991) at 1:250,000 and 1:50,000 scales (Jagtap, Naik, and Nagle 2001; Nayak et al. 1991, 1992). These maps show high tide line and low tide line (HTL and LTL) and landform/wet land features such as mudflats, beach, mangroves, coral reefs (as shown in Figure 1). Coastal land use maps showing HTL and LTL and land use features were also prepared at a scale of 1:25,000. The details of methodologies have been given by Nayak (1994a, 2009). The distinctive patterns of ecological and morphological zones of these two ecosystems were identified using IRS LISS III and Panchromatic (PAN) merged data (Bahuguna and Nayak 1998; Nayak et al. 1996; Shah et al. 2005). All the thematic maps related to coastal land use, wetland, mangroves, coral reefs, and shoreline changes have been organized in a GIS and Query Shell has been developed to create a database and generate output maps (Gupta, Krishnarajan, and Nayak 2001; SAC 2011). All these maps and outputs can be downloaded from www.vedas.sac.gov.in. The classification accuracy of these maps was 85% at 90% confidence level. In many regions, mangroves and coral reefs have degraded and as well as reclamation of lagoons and mudflats have been observed (Desai et al. 1991; Nayak et al., 1992).

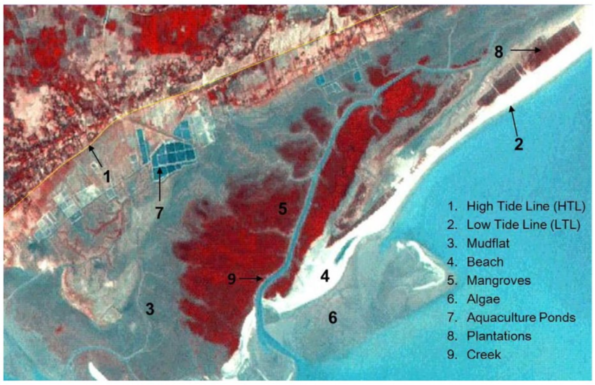

Figure 1. Various coastal landforms in East Coast of India (IRS LISS III and PAN merged Image of the Subarnrekha Estuary).

Coral reef, a keystone ecosystem of tropical region, is a highly productive area and exhibits distinctive ecological and geomorphological patterns. Such zones were mapped for all coral reef areas of the country. It was possible to identify types of reefs, characteristics of reef flats, lagoon, etc. (Deshmukh et al. 2005). Submerged coral reef features were identified using OCEANSAT OCM and RESOURCESAT LISS III data (Chauhan and Nayak 2005; Mahendra et al. 2010a). The extent of live corals was delineated only in a few cases. This is the limitation of these datasets. Hyperion hyper-spectral data in VNIR region are able to distinguish morphological features such as healthy (live) and degraded corals, reef flat, algal cover, algal ridges, sea grass, lagoon, knolls, and sandy areas (Velloth, Mupparthy, and Nayak 2012; Velloth et al. 2014). An approach, Coupled Ocean Atmosphere Radiative Transfer (COART) to correct for atmospheric and oceanic effects has been developed and applied to correct Hyperion data (Velloth et al. 2014). Fusion of high spatial resolution images from IRS LISS IV, IKONOS, QUICK BIRD, etc. can further improve classification of coral reefs (Velloth, Mupparthy, and Nayak 2015).

It was observed that coral reefs are generally in good condition, except those in the Gulf of Kachchh, Western India. This unique system is facing both natural and anthropogenic stress. The high suspended sediment load in the Gulf of Kachchh and anthropogenic activities have adversely affected coral reefs (Bahuguna and Nayak 1998; Sharma et al. 2008). The tsunami of 2004 destroyed almost 400 km^2 of coral reef areas and 130 km^2 of reef were covered with backwash in the Andaman and Nicobar Islands (Nayak and Bahuguna 2008). However, it was observed that coral reefs have been recovering slowly and showing its resilience capacity (Bahuguna, Nayak, and Roy 2008). Mesoscale processes such as cyclonic eddy can affect coral reefs. It is inferred based on model outputs that cyclonic eddy observed in Southwest (SW) of Sumatra, though it generally enhances primary productivity, it can significantly damage corals through asphyxiation caused by massive phytoplankton blooms (Reddy et al. 2010).

Incidences of coral bleaching have increased during the last two decades, especially in 1998 and 2010, due to warming of the sea. Coral reefs are made of many species of corals, each of which has a symbiotic relationship with algae living in their tissues. These algae supply vital nutrition to the host but are sensitive to environmental changes including increase in seawater temperature. However, we know that in the Persian Gulf, corals withstand high temperature, probably because of high thermal tolerance by algae (Hume et al. 2013). In view of increased warming of sea, corals may be quite different in the future (Normile 2010). The associated loss of algae is known as coral bleaching. Hence, monitoring the health of order coral reefs is very vital. NOAA AVHRR Sea Surface Temperature (SST) data were used to identify cumulative temperature anomalies and thermal stress over coral reef regions. These two products were used to identify probable areas of bleaching (Mohanty et al. 2013). It was observed that soft corals such as *Acropora* are affected significantly, unlike hard corals such as *Porites*. Using this concept, Coral Bleaching Alert System (CBAS) has been introduced and regular bulletins are issued for coral reef areas (www.incois.gov.in).

The estimate for mangroves based on satellite data was 4460 km^2 (Nayak and Bahuguna 2001). The identification of dominant communities, viz. *Avicenna, Rhizophora, Ceriops, Heritiera, Excoecaria, Sonneratia, Xylocarpus,* etc. was accomplished using a combination of red, infrared, and middle-infrared bands of IRS 1C LISS III data (Nayak et al. 1996). The community-wise classification of mangroves for the entire Indian coast was carried out (Ajai et al. 2013; SAC 2011). The mangrove area along the Indian coast has increased to 4956 km^2 (SAC 2011). The increase in mangrove extent was observed on the coasts of Maharashtra, Goa, Tamil Nadu, Orissa, and West Bengal, essentially due to conservation measures. The major decrease in mangroves was noticed on the Gujarat coast. In most cases the degradation in mangrove habitat was due to their conversion for agriculture, aquaculture or industrial use. Significant decrease in mangrove areas (150 km^2), on the Andaman and Nicobar Islands was due to the damage caused by the tsunami in 2004 (Nayak and Bahuguna 2008). Cyclones do damage mangroves and such damage is visible in NDVI images generated from OCEANSAT-1 OCM and IRS WIFs (Nayak, Sarangi, and Rajawat 2001). It can also be observed in subsequent NDVI images that mangroves are very resilient and they recover within six months. A model for assessing the health of mangroves has been developed based on canopy cover, floral diversity, fragmentation and hydrological parameters and applied in the selected areas to assess the health of mangroves (SAC 2011). This model is yet to be applied for the coastline of the entire country.

The extent and condition of coral reefs and mangroves, mapped by using satellite data, is useful as an input to identify boundaries of the protected areas and biosphere reserves as well as to monitor them to detect changes, if any. About 128 marine protected areas have been identified, and monitored using IRS LISS III and IV data. It is demonstrated that the degradation of mangroves and coral reefs can be halted and the recovery of these ecosystems can take place by suitable conservation measures as observed in marine protected areas in the Gulf of Kachchh (Nayak et al. 1989). The sustained conservation measures in the Gulf of Kachchh led to substantial increase in both density and extent of mangroves despite increased industrial activities (SAC 2011). However, degradation of these two key ecosystems was observed in many other protected areas.

The degradation of coastal habitats also results in loss of biodiversity. The information on biodiversity is very crucial, and is likely to be affected by anthropogenic activity and impact of global warming of sea. The impact of the loss of marine biodiversity on other processes needs to be understood. The detailed records of marine life and changes need to be meticulously recorded. The Indian Ocean Biogeographic Information System (IndOBIS) and Census of Marine Life programs have been launched to pool all the information, which made it available through a portal and internationally accepted data protocol. At present, IndOBIS has records of over 122,000 species, including new records of several species (www.indobis.org), for the Indian Ocean. The focus is on the understanding of the structure, function and vulnerability of ecosystems. We need to ensure a healthy ocean environment for the sustained benefit of our successive generations. Similar information systems for coastal areas need to be developed.

Brackish water aquaculture is one of major activities along most coastal regions of India. The selection of suitable sites is an important step towards efficient management and reducing environmental impacts. The coastal habitat data created for the entire coast were utilized to select the probable areas. Coastal habitat, drainage, transportation network, salinity, pH and other parameters were used to develop a criteria-based GIS model to prioritize sites (Gupta, Krishnarajan, and Nayak 2001).

3. Coastal processes and natural hazards

Geomorphic processes of erosion, sediment transport, deposition and sea level changes continuously modify the shoreline. The understanding of coastal processes is vital to plan effective coastal protection measures. It is also vulnerable to various natural hazards such

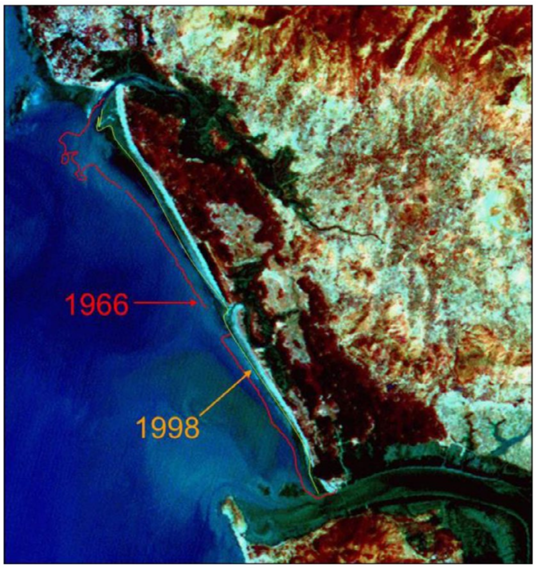

Figure 2. Erosion between 1966 and 1998 in IRS LISS III Image of the West Coast of India.

as cyclones, storms, tsunamis which impact the coast. Multi-date high-resolution satellite data were used to detect long-term changes in shoreline and landforms. The information on shoreline changes along with near-shore water flow provide important insight into causes of shoreline changes. The shoreline-change maps using topographical maps (1966–1968) and satellite data of 1985–1989, 1990–1992, and 2004–2006 were prepared (Nayak et al.1992; SAC 2011). The areas under erosion, deposition and relatively stable areas were mapped (as shown in Figure 2). The construction of breakwaters and jetties for ports have increased erosion, generally in the direction of the long-shore currents as witnessed on the east coast of India (Chauhan et al. 1996; Nayak et al. 1992, 1997). Similarly, the construction of dams on rivers also introduces erosion, immediately after commissioning of dams (Nayak and Sahai 1985). It is observed that the coast stabilizes after few years. The role of sea level changes, neotectonics, and sediment transport was evaluated because they are shaping the present landforms in the Gulf of Khambhat, Western India (Shaikh et al. 1989). Shoreline change and landform maps for the coastline of the entire country are now available (www.vedas.sac.gov.in).

Geomorphic processes of erosion, sediment transport and deposition in the vicinity of river mouths on the West coast of India were studied by using satellite data as well as ground observations and sediment analysis. The sedimentation in the river mouth essentially takes place during pre-monsoon period (April–May), while beaches grow during post-monsoon (October–December) period (Nayak et al. 2010). On the same coast, OCEANSAT-1 OCM data showed the northward and southward movement of suspended sediments along the coast during monsoon (June–September) and post-monsoon (October–December) period. The net suspended sediment movement towards estuarine mouths resulted in the formation of mudflats (Nayak et al. 2012). In the same region, the presence of all types of spits, viz. paired, single and wing like, suggested that the role of sea level changes and tectonics along with long-shore currents in their formation (Hegde et al. 2012). The presence of submerged bars is also very critical in formation of spits. The divergent spits are formed due to reversal in a long-shore drift and wave divergence which favor the movement of sediment in opposite directions (Hegde et al. 2015).

An artificial mouth was created on the Chilika lagoon in 2000. Remote sensing data were effectively used to assess the impacts of such an artificial mouth on the Chilika lagoon in the East of India (Rajawat et al. 2007). The original 80 m-wide mouth was widened to 680 m over a period of time and erosion of the coast occurred. However, there was an improvement in tidal flux and mixing resulted in increased salinity levels and reduced weeds. This ultimately improved brackish water fishery in the lagoonal area. The repetitive satellite data proved to be quite useful in monitoring the impacts of engineering structures.

The coastal regions are regularly affected by cyclones and storm surges and occasionally by tsunamis. We must live with such hazards, and prepare ourselves to respond to hazards to save lives. It is essential to identify vulnerable areas, so that associated risks can be recognized and necessary mitigation measures can be taken up.

Coastal topography is one of the critical factors in defining vulnerability because its characteristics significantly affects the inundation due to storm surge or tsunami. The accurate information on topography improves the estimation of inundation. The evaluation of elevation data derived from CARTOSAT and Airborne Laser Terrain Mapper (ALTM) was carried out (Nayak et al. 2013). It was observed that the elevation accuracies of CARTOSAT and ALTM are ±2 m and ±0.6 m, respectively. This inaccuracy affects the extent of inundation up to a certain extent. Considering the cost and time required for acquiring and analyzing ALTM data, its use may be restricted to urban areas. CARTOSAT data are quite suitable to be used in coastal regions.

Coastal vulnerability maps (cyclone, tsunami, and sea level rise) for the entire Indian coast, based on projected long-term rise in sea level, and climatological data on tidal range and wave height, coastal elevation and slope, long-term shoreline changes (rate of erosion and accretion) along with geomorphological setting have been produced (Kumar et al. 2010). The vulnerability has been defined in terms of an index indicating likelihood of physical changes that may occur and the natural ability of coastal system to change environmental conditions. Such maps can provide base level information for coastal management. Vulnerability maps of the entire country have been prepared (www.incois.gov.in). In another project, a slightly different approach was used to prepare the multi-hazard and risk maps for part of the tsunami-affected area on the East coast of India (Mahendra et al. 2011, 2010b).

Rising sea levels are already eroding shorelines, slowly drowning low-lying areas, and changing shoreline configuration of the coast. These changes in sea level coupled with high tides and waves and storm surges can cause excessive episodic flooding. Such flooding affects the ecosystems, settlements, and port operations, and ultimately the livelihood of coastal communities as well as leads to migration of local people to other areas (Nayak 1994b). Human modification of the shoreline has altered currents and sediment delivery, resulting in the advancement of the coast in some areas and eroding beaches in others regions. We know that the evolution of coast depends on regional tectonics, sea level rise, vegetation, and wave activity. One view is that the slow rise in the sea level will advance the coasts while rapid rise will erode them (Stutz and Pilkey 2011). Recently, a distinct reversal of the Northern Indian Ocean (North of 5°S) sea-level decadal trend between 1993 and 2013 by using satellite and *in situ* observations, ocean analysis products and model simulations was reported (Srinivasu et al. 2017). We need to model the impact of such changes in sea-level rise on coasts and islands. We should make people aware of the changing environment and take adaptive and mitigation measures. Healthy mangrove and coral reef ecosystems can significantly mitigate the impact of sea-level rise on coastal areas (Baba and Nayak 2002).

Cyclones over the oceans trigger strong biological response and induce phytoplankton blooms (Vinay Chandran and Mathew 2003). In the Bay of Bengal, cyclones are very frequent and cause lots of damage to infrastructure and life. The super cyclone which occurred during October 1999 in the Bay of Bengal, induced meso-scale phytoplankton bloom as evidenced from satellite data and persisted for over a month (Reddy, Salvekar, and Nayak 2008). It was observed that productivity increases substantially along the track of a cyclone. Such blooms were observed during subsequent cyclones as well. However, the magnitude of productivity varies during such events (Lotlikar et al. 2014; Masuluri 2009). Since phytoplankton plays a very significant role in the global carbon cycle, it is necessary to compute the uptake of carbon dioxide during such blooms.

A tsunami is a system of ocean waves formed as a result of large scale disturbances of the ocean floor. A state-of-the-art tsunami warning system has been designed around GIS and implemented after the devastating tsunami in December 2004 (Nayak and Kumar 2008, 2009, 2011). The system is capable of receiving and analyzing seismic and sea level, both on coast and deep sea, received from the Indian and global stations, in real time. It provides advisories about travel time, and run-up-height at 1800 coastal forecast points within 10 min to all concerned within India and the Indian Ocean Rim countries through web-based services. The performance of the tsunami warning system is as per design specifications (Kumar et al. 2012a, 2012b). The system has provided very useful advisories during last ten years. It is now recognized as the Regional Tsunami Service Provider for the Indian Ocean.

The prediction of cyclone tracks and landfall, 24 h before the event, has been improved to 140 km and 70 km, respectively (Mohapatra et al. 2013, 2015). The assimilation of OSCAT data improved the location of the center and track predictions (Prasad et al. 2013). The information on storm surges and associated inundation is very important for disaster management authorities. A simulation of both these aspects was carried out using the ADCIRC model (Kumar et al. 2015). The simulated and observed surge heights matched well, but were underestimated. The extent of inundation matched reasonably well but an improved topographic model using CARTOSAT and ALTM data can further enhance the accuracy of delineation of inundation boundaries.

4. Water quality

Many national and regional monitoring programs exist for monitoring a variety of pollutants. In India, coastal water quality is being monitored for last 25 years at 24 priority sites. Various physical, chemical and microbiological parameters (total 54) for water and sediments are measured seasonally. Increased nutrient inputs to coastal waters due to rise in coastal population and agriculture intensification have been observed at many sites. This led to decreased levels of dissolved oxygen in coastal waters, although they are not at the alarming levels. This data helped to take mitigating action wherever pollution levels crossed threshold values. The data is available on www.incois.gov.in/portal/comaps/home.jsp.

Suspended sediments movement along with shoreline change information helps to understand relationships between sediment input, transport, and deposition (Nayak 2009). In tide-dominated areas, such as the Gulf of Khambhat and the Hooghly estuary, tides play very critical role in movements of sediments and fronts (Nayak and Sahai 1985; Nayak et al. 1996). OCEANSAT-1 Ocean Colour Monitor (OCM) provides extremely useful information on decay of fronts, eddies, gyres, plumes, etc. Due to its high temporal resolution (as shown in Figure 3), OCM data were used to compute the advective velocity of surface currents and thus, to understand movement of sediments (Nayak 2009; Prasad et al. 2002). Such information is very useful in modeling the path of waste effluents.

The frequency of Harmful Algal Blooms, resulting in mass mortality and morbidity of marine organisms, has increased significantly. In the North Arabian Sea, we have observed the shift from diatom to green dinoflagellates (Gomes et al. 2008). The increase in extreme rainfall also increases river run-off, polluting coastal

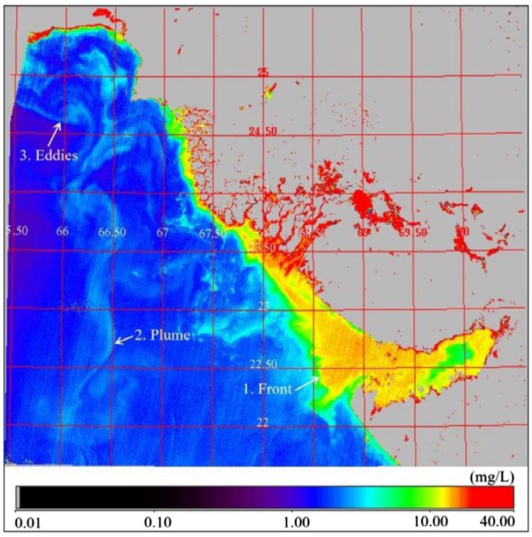

Figure 3. Suspended concentration in Oceansat-1 OCM Image of the North Coast of India.

waters with more nitrogen and phosphorus, sediments and other contaminants. Increased direct monitoring of water quality parameters, coupled with satellite data, will improve our knowledge of health of coastal and ocean waters.

5. Living resources

Marine fishery catch in India is about 3.5–4.0 million tonnes. Fishermen used to spend considerable time in locating fish schools and thus, cost-per-unit efforts were high. A satellite-based technique was developed to locate potential fishing grounds using NOAA AVHRR SST (Narain et al. 1990). This system was based on the detection of oceanographic features such as upwelling, divergent fronts, eddies, gyres, rings, meanders. Because the temperature variation in tropical waters is only about 3 °C, this technique was not very successful. During late 90s, the availability of satellite-derived chlorophyll information and its integration with SST further improved forecasts (Solanki, Dwivedi, and Nayak 1998). A successful GIS-based fishery forecast system was developed by integrating chlorophyll, SST, surface currents and bathymetry (Nayak, Kumar, and Nagarajakumar 2007). Daily advisories for more than 350 fishing harbors are being generated and disseminated through electronic boards at fishing harbors, web (www.incois.gov.in), and e-mails. At present, about 93% of fishermen are adopting these advisories, which direct fishermen to the productive areas and hence avoid exploitation of fishery in low to moderately productive areas. This technique helped fishermen to reduce catch-per-unit effort and hence brought economic benefits to fishermen.

Overfishing caused degradation of coastal and marine ecosystems, and destructive trawling techniques led to loss of nursery areas of commercial fishery in some regions. Hence, loss of coastal habitats affected the capacity of producing fish for human consumption. It was also discovered that populations of phytoplankton and copepods are also changing, threatening food supply of fishes as well as many marine mammals that in turn prey on fish (Sanjeevan, Smitha, and Padmakumar 2014). Such a shift can transform the biodiversity and functioning of marine ecosystems. There are many examples where changes in ocean climate contribute to shifts in abundances and seasonal cycles of variety of species. The increased availability of Sardines on the East coast and on the Maharashtra coast while reduced supply on the Kerala coast is an example (Sanjeevan, Smitha, and Padmakumar 2014). Annual stock assessments of fish are necessary to identify Maximum Sustainable Yield (MSY) for various commercially important species. This assessment will help to manage fishery for sustainable yield.

6. Summary and outlook

Coastal zone management depends on the information available on varied aspects of coastal habitats, coastal processes, natural hazards and their impacts, water quality, and living resources. The effective management practices depend on such knowledge and suitable response by concerned government agencies.

The loss of coastal habitat areas reduces key ecological services. Fish and shell fish stocks may decline and shoreline may be destabilized. The relationship between health of wetlands and fish stocks is generally linear. The ecological services are provided by wetlands, i.e. the wave attenuation service that protects coasts from storms and tsunamis. The relationship between this service and wetland area is non-linear (Barbier et al. 2008). Such relationships have consequences for management and should be taken into account. Hence, the optimal land use option should include the integration of development and conservation activities and should be consistent with ecosystem-based coastal zone management goals.

The identification of areas suitable for brackish water aquaculture was accomplished based on coastal landforms and land use derived from satellite images for the coastline of the entire country. The movement of sediments along the coast, onshore–offshore sediment transport, impact of tides on sediment movement, and impact of engineering structures on sediment movement and areas under erosion and deposition, were studied using high temporal resolution satellite data. Based on this information, the alternative methods to restore beach such as beach nourishing and construction of an artificial reef are being attempted.

In order to preserve coastal ecosystems, the Government of India has declared areas between high and low tide lines (HTL, LTL) and 500 m from HTL as the Coastal Regulation Zone (CRZ) and prohibited or restricted construction and industrial activities. The accurate delineation of HTL and LTL is very critical. They have been delineated based on tonal discontinuity on satellite images (Nayak 2009). This regulation has undergone too many changes over last 25 years, mainly due to incorrect interpretation of HTL and conflicting laws of state and central governments. In view of this, it was suggested that such anomalies should be removed. CRZ regulation needs to focus on protecting ecologically sensitive areas, while urban and rural areas are governed by existing laws of state and central governments with few conditions (Nayak et al. 2015). Local communities may be allowed to take up traditional aquaculture, ornamental fisheries, etc. In a separate report, it was also suggested to draw HTL using ALTM and high-resolution satellite data for the coastline of the entire country and use it as a construction setback line to draw boundaries of CRZ. However, these suggestions are yet to be implemented. Despite these limitations, this regulation has helped to conserve most of the protected areas, ensure livelihood security of fishermen, provide resilience to impacts of hazards and promote socio-economic development based on scientific principles.

The effects of anthropogenic activities on ecosystems have not been well-understood. We need to carry out predictive modeling, using existing climatic, coastal, and topographic data combined with ecological information, where historical data is available. We also know that the current climate impact models have been showing very large uncertainty. We need to improve the understanding of likely impact of anthropogenic activities on the coastal environment.

The advisory services for the cyclone and tsunami have been provided to all stakeholders. The response of the government to such events at the local, state and national levels has been exemplary. In the last century, a super cyclone struck the Orissa coast and more than 10,000 people died. During the last 10 years, loss of lives has been minimized because of the availability of accurate and timely information on track, landfall point, velocity of wind, storm surge, etc. (Mohapatra et al. 2013, 2015), the suitable response and actions of the government and the trust of local people in the forecast and government. The tsunami warning center has performed very well (Kumar et al. 2012a) and there has been no false warning during the last 10 years. Such systems have definitely helped to reduce risk from these hazards. Though coral reef bleaching alert bulletins have been issued, it is not clear how one can respond to such an event. We need to address the issue of developing a response mechanism.

The sustainable management also depends on the nature of the social system, comprising political economic and industrial infrastructure and its linkages, with the knowledge about coastal systems as well as local communities. We have noted that economic growth and technological advancement during last two centuries have significantly affected our coastal environment and have also become major driver of influencing the earth system. The earth system processes, especially carbon cycle, ocean acidification, sea level changes, loss of biodiversity, and modern agriculture-induced pollution of reactive nitrogen and phosphorous, have reached a level at which they can cause damage to the entire earth system (Rockström et al. 2009). We need to model impacts of these processes and design adaptive and mitigation strategies for the sustainable development of the coastal zone. Geospatial information technology can contribute greatly to develop such models.

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