

## **10. Vulnerable Areas and Adaptation Measures for Sea Level Rise along the Coast of India**

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### **Abstract**

India has a coastline of about 7500 km with contrasting geological setting. Based upon the available models, global sea level rise of 10-25 cm per 100 year has been predicted due to emission of green house gases. To separate out the influences due to the global climatic changes, the available historical mean sea level data between 1920-1999 at 10 locations was evaluated. There is a large contrast in the deduced sea level changes. The sea level rise along the Gulf of Kachchh and the coast of West Bengal is the highest coast. However, along the Karnataka coast, there is a relative decrease in the sea level.

Shoreline morphologies respond to prevalent hydrography and changes in the shoreline have been estimated and categorised broadly as erosive, dynamic, and depositional. The magnitude of tides has been predicted at 121 stations, which has high correlation with observed tides.

Identification of most vulnerable areas of the Indian coastline determined from the risk assessment—carried out from the integration of physiographic evaluation, site-specific sea level changes, tidal environment and hydrography data—are schematically presented.

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### **Introduction**

Sea level changes are natural phenomenon related to magnitude of insolation received on the earth vis-à-vis locking of water in ice sheets through processes of glaciations (Fairbridge, 1961; Nigam et al., 2002 and references cited therein). However, industrialisation related emissions of green house gases in the past century may have repercussions in altering these natural processes (JNU, 1993, Mitra et al., 2002 and references cited therein). Evaluation of sea level changes, related with the global climatic changes, began during the last three decades of the 20th Century. Prediction models developed by the IPCC (IOC-UNEP Workshop, 1992; IPCC 2001, 2001) derived from the projected magnitude of emission level of green house gases suggest a global warming of 1.5–2 °C. According to IPCC (IOC-UNEP Workshop, 1992) the estimated global sea level rise is of the magnitude of 10-25 cm per 100 year. Studies from the GCM models for the period 1990-2100, have, however, predicted a much higher sea level increase (0.09-0.88 m) attributed to thermal

expansion and melting of ice for varied scenarios detailed in IPCC reports (IOC-UNEP Workshop, 1992; IPCC 2001, 2001).

The coastal zone is a dynamic boundary between land and sea responding to the changes in the physical, geological, and biological processes. A higher influx and deposition of sediments, particularly in an accretionary low energy environment, progrades a shore. Reduced influx or high-energy environment erodes a coast in response to the prevalent hydrography. Because supply of terrigenous detritus is climate regulated, the shoreline changes are thought to be related with the prevalent global climatic changes with (Rajamanickam et al., 2001 and references cited therein). Because shoreline is the dynamic line representing the equilibrium state of these processes with (Chauhan, 1995), the effects of sea level changes on the shore, therefore, are, not de facto changes in the level of the sea, but are closely related to the tectonics of the region with (Fairbridge, 1961). A tectonically active shore may have shoreline changes depending upon the uplift or sinking of the land, even when

the sea level is at a standstill; and as such, it would be necessary to take into consideration, the local parameter controlling isostatic changes whilst evaluating the predicted changes in the sea level due to global climatic variation. The predicted global or regional sea level estimation would therefore be less meaningful while determining site-specific influences of sea level rise if the localised isostatic changes are not profoundly understood.

The changes associated with global ice volume on sea level, therefore, normally have an effect on the tectonically stable or subsiding coast. An uplifted coast will absorb the natural sea level rise, and shall stand unaffected to any adverse effects like submergence or tidal ingress into the land due to the relative higher uplift. Hence, for an overall evaluation of the effects of the sea level rise on the coastal zone, consideration of varied components is needed. The micro level studies of the characteristics of shoreline changes are needed to be evaluated to provide meaningful input for managing the adverse effects of the sea level rise. Based upon analysis of available data, this paper presents initial identification of the most vulnerable areas which need to be considered for undertaking adaptation measures along the Indian coastline

## Methodology

In order to meaningfully estimate shoreline changes, observations on time series variations in physiography for decadal – century level are sine qua non. Such data set is rare, and mostly confined to determination of decadal changes comparing the shoreline determined by land surveys with that of satellite data (Rajamanickam et al., 2001; Chauhan, 1995, 2000; Chauhan et al., 1990, 1994; Chandramohan et al., 1993; Chavadi et al., 1989; Firouzabadi et al., 2000; Jog et al., 2001; Karlekar et al., 2001; Kumar et al., 1989; Kunte, 1994; Loveson et al., 1988; Mani et al., 1997; Mukherjee et al., 2001; Narayana et al., 2001; Natesan et al., 1993; NIO, 1972; Rao, P.B. et al., 1985; Sinha et al., 1997; Sreekala et al., 1998; Subramanya et al., 1989; Sudareran et al., 1993; Land use and Shoreline changes Maps of India: Immandar et al., 2000; Nayak et al., 1992; Rao, R.S. et al., 1994; Ramanujam et al., 1996; Adiga, 1994; Ahmad, 1972; Bruckner, 1988; Hanamgond et al., 1993; Jayappa et al., 1984; Joshi, 1995; Kaliasundaram et al., 1991; Krishnakumar et al., 1994; Kurup, 1972; Mallik et al., 1984, 1987; Paul, 1997, 1996; Ramaiyan et al., 1996; Rao, T.A. et al., 1971; Sanjeev et al., 1996; Tatavarti et al., 1999; Wadia, 1961; Wagle, 1987). Even with the limitation of incomparable methodologies of these techniques, such studies may be considered as a good beginning for initial estimations. Based upon available data (Jog et al., 2001; Karlekar et al., 2001; Kumar et al., 1989; Kunte, 1994; Loveson et al., 1988; Mani et al., 1997; Mukherjee et al., 2001; Narayana et al.,

2001; Natesan et al., 1993; NIO, 1972; Rao, P.B. et al., 1985; Sinha et al., 1997; Sreekala et al., 1998; Subramanya et al., 1989; Sudareran et al., 1993; Land use and Shoreline changes

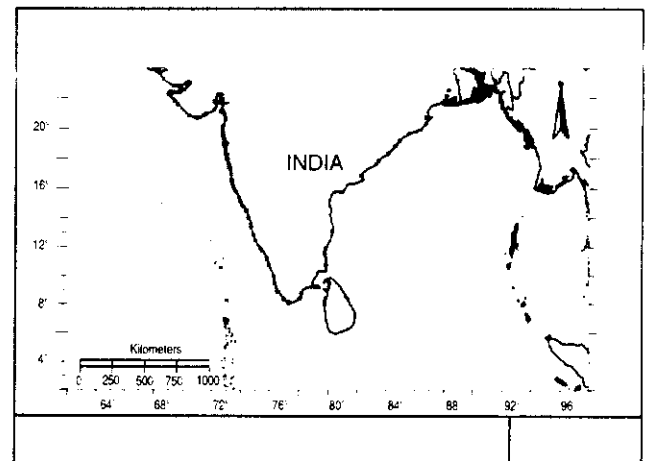


Fig. 10.1 Location of stations where the maximum tidal range was estimated.

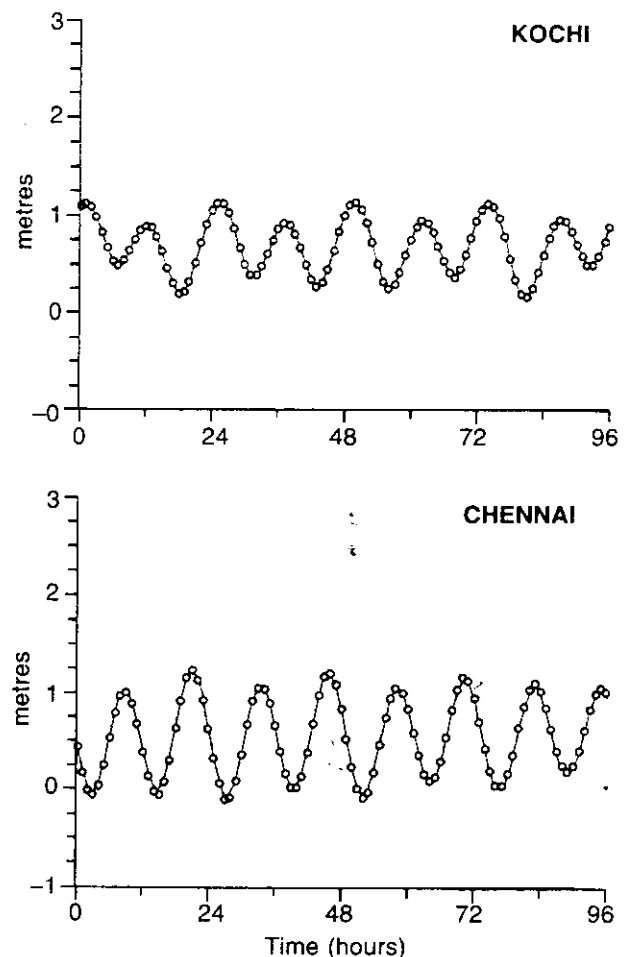


Fig. 10.2 Predicted tides vs observed sea level during 18-2-88 to 21-2-88 (Circle = observed; continuous = predicted) at Chennai and Kochi.

Maps of India) shoreline changes for a span of 10-15 years are estimated along the Indian coastline. However, due to paucity of studies to determine the isostatic characters of the Indian coast, the shoreline changes associated with isostasy still remain unresolved. The data on tidal environment is available mostly for ports only, and by and large, no information is available for site-specific tidal parameters for the entire coastline. In order to understand the overall tidal environment, utilising the working models (Unnikrishnan et al., 2003 and referenced cited therein), the magnitude of tide is estimated at 121 stations shown in Fig. 10.1.

For comparison, the data at selected location have also been compared with available in situ tidal observation. The observed and predicted tides have very good match (Fig. 10.2). The sea level changes along the Indian coastline, determined from time series changes in the tide level at 10 stations (Unnikrishnan et al., 2003; CRZ Maps of the States; Admiralty Tide Tables, Vol 2, 1996; International Hydrographic Bureau, 1930 and references cited therein) are highly variable. It is not possible, however, to ascertain whether these changes are entirely due to eustatic sea level variation.

The basis to determine the nature of coast is to organise a chart of shoreline changes prepared comparing the survey and satellite data for the past 10-15 years (Land use and Shoreline changes Maps of India; Immandar et al., 2000; Nayak et al., Rao, R.S. et al., 1994; CRZ Maps of the States) and from the available literature. (Rajamanickam et al., 2001; Chauhan, 1995, 2000; Chauhan et al., 1990, 1994; Chandramohan et al., 1993; Chavadi et al., 1989; Firouzabadi et al., 2000; Jog et al., 2001; Karlekar et al., 2001; Kumar et al., 1989; Kunte, 1994; Loveson et al., 1988; Mani et al., 1997; Mukherjee et al., 2001; Narayana et al., 2001; Natesan et al., 1993; NIO, 1972; Rao, P.B. et al., 1985; Sinha et al., 1997; Sreekala et al., Subramanya et al., 1989; Sudareran et al., 1993; Land use and Shoreline changes Maps of India; Immandar et al., 2000; Nayak et al., 1992; Rao, R.S. et al., 1994; Ramanujam et al., 1996; Adiga, 1994; Ahmad, 1972; Bruckner, 1988; Hanamgond et al., 1993; Jayappa et al., 1984; Joshi, 1995; Kaliasundaram et al., 1991; Krishnakumar et al., 1994; Kurup, 1972; Mallik et al., 1984, 1987; Paul, 1997, 1996; Ramaiyan et al., 1996; Rao, T.A. et al., 1971; Sanjeev et al., 1996; Tatavarti et al., 1999; Wadia, 1961; Wagle, 1987; Wynne, 1966). The coastline is categorised under five categories between accretions – erosion for each state.

## Results and Discussions

The physiographic settings and tidal regime are important parameters to determine the resilience of an area to the influence of sea level rise. The estimated tidal environment at 121 stations is determined and presented in Table 1. The

mean spring tide ranges show a progressive increase towards north along the east coast. Similar trend is also observed along the West Coast of India. Some of the highest tidal ranges are measured at stations in the Gulf of Kachchh and in the Gulf of Khambhat (Table 1). From the time series mean spring tide amplitude, it is deduced that the northern areas along the east as well as west coasts are mostly having a higher tidal range and very wide intertidal and supratidal zone.

**Table 10.1** Maximum Tidal Ranges at different stations along the Indian Coastline. Refer Fig for the location of the stations.

Location	Tidal range (cm)
Lakhpat	469.8
Vengurla	244
Bombay (Apollo Bandar)	466
Koteshwar	458.6
Marmagao	246
Bombay Prince's Dock	471.2
Godia Creek	365.2
Betul	222
Trombay (Bombay)	500.8
Mandvi	454
Karwar	230
Mora Bandar (Uran)	476
Navinal Point	618.6
Tadri	234.4
Revas Bandar	470.8
Mundra	614.2
Kumta	222
Revadanda	412.2
Tekra	728
Bhatkal	187.8
Janjira (Dangri Bandar)	400
Khori	750.6
Coondapore (Ganguli)	194.4
Shrivardhan	369.6
Kandla Harbour	748
Malpe	202
Bankot	337.2
Navi Wat	722.4
Mangalore	170
Harnai	343.6
Hansthal Point	672.6
Kasargod	167.6
Dabhol	315.8
Navlakhi	782
Azhikal	148
Palshet	309.4
Rozi	694.6
Cannanore	170

Location	Tidal range (cm)
Boria Bay	309.4
Sikka	602.8
Tellicherry	154.8
Jaigarh	310.6
Salaya (Sykes Point)	559.2
Calicut	137.4
Ratnagiri	286.4
Okha	423.6
Beypore	148
Muskazi	278.2
Dwarka (Rupen Bandar)	342
Ponnani	138
Vijjadurg	284
Miani	185.8
Kochi	106
Devgarh	261
Porbandar	282
Alleppey	128
Achra	248.4
Veraval	256
Nindakara	90.8
Malvan	246.4
Kotra	247.2
Quilon	113.4
Pondichery	104.2
Nawabandar	273.8
Trivandrum	106.4
Chennai	117.4
Jafarabad	309.6
Vilinzam	97.4
Surya Lanka	136
Port Albert Victor	386.8
Kolachal	93.4
Sacramento Shoal	150
Pipavav Bandar	392
Muttam	74.6
Kakinada	161
Bhavnagar I	1040
Kavaratti (Lakshadweep)	161.4
Vishakhapatnam	167.6
Bhavnagar 2	1041.6
Minicoy	136.4
Bhimunipatnam	158.2
Dahej Bandar	539.4
Lee Puram	75.2
Kalingapatnam	167
Ambheta	882.6
Diego Garcia	170
Baruva	158.8
Suvali	720

Location	Tidal range (cm)
Ihavandhoo	124
Gopalpur	130
N.W. Hazira (Tapi River)	516
Egmont Island	132
Chilka Mouth	102
Hazira (2nd)	754.6
Eagle Island	124
Kushbhadra River	177.8
Bulsar	713.8
Peros Banhos	136
Devi River Entrance	184
Umbargaon	566.4
Solomon Islands	132
Paradip	214.8
Dahanu	565.2
Kulasekarapatna	86.4
False Point	234.4
Satpati	503.2
Tuticorin	94.4
Short Island	299.6
Kelve (Mahim)	491.6
Pamban Pass	82
Dhamra	290.6
Arnala	475
Nagapatnam	73
Chandbali	232
Vasai	467
Porto Novo	94.6
Diamond Harbour	495.2
Bandra	440.4
Cuddalore	96.4
Calcutta-Kidderpore Docks	396
Sagar Roads	452

### Physiographic characteristics of the coast

The Indian coastline can be categorised into three classes

- Coast of emergence
- Coast of submergence
- Neutral

The shoreline off the mouth of all major rivers the Ganga, the Mahanadi, the Krishna, the Godavari and the Cauvery is neutral and is highly dynamic due to a large influx of sediments. The shoreline along the northern east coast (130° N Latitude), by and large, is marked with sand dunes and prograding deltas of the perennial rivers, and mostly falls under the category of emerging coast with no offshore bar. The coastline of the southern part of East Indian Peninsula is moderately characterised by the offshore reefs, inland creeks, and extensive long beaches. The coastline is protected

by reefs, along Rameswaram sector, from wave action. After the Holocene transgression, most of the coastline along the southeastern India has characteristics of "Emergent with offshore bar and Lagoon".

The shoreline of Kerala is highly indented, marked with bays, backwaters with headlands and pocket beaches, and has been categorised as submergence type (Ahmad, 1972).

The shoreline of Karnataka, Goa, and Maharashtra is characterised by a network of small coastal rivers, inland creeks and backwaters. The shore is rocky with headlands and pocket beaches, and is categorised as coast of submergence.

The coast of Gujarat, characterised by creeks and inland waters is also classified as submergence type. It may be noted that "submergence type" coastlines are more prone to the effects of sea level rise.

Based on the comparisons of satellite data and hydrographic charts, the shoreline changes along the Indian coastline were examined for 10-15 year span (Land use and Shoreline changes Map of India; Immandar et al., 2000; Nayak et al., 1992; Rao, R.S. et al., 1994; CRZ Maps of the States). The state wise characteristics of the shoreline for the Indian coast are schematically shown in Figures 3-4. The characteristics of coast are briefly described hereunder.

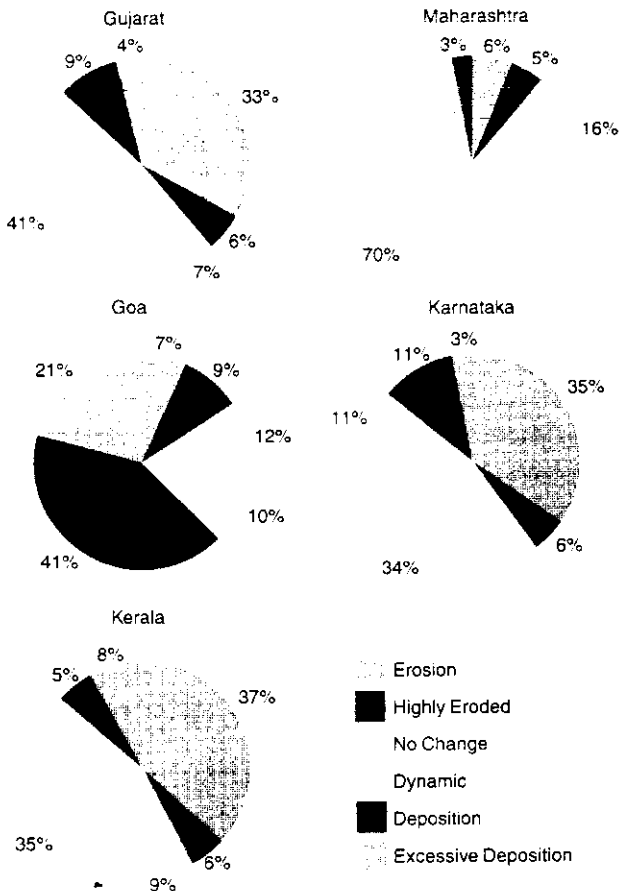


Fig. 10.3 Percent area for erosion and depositional segments of the coastline of the states along the West Coast of India.

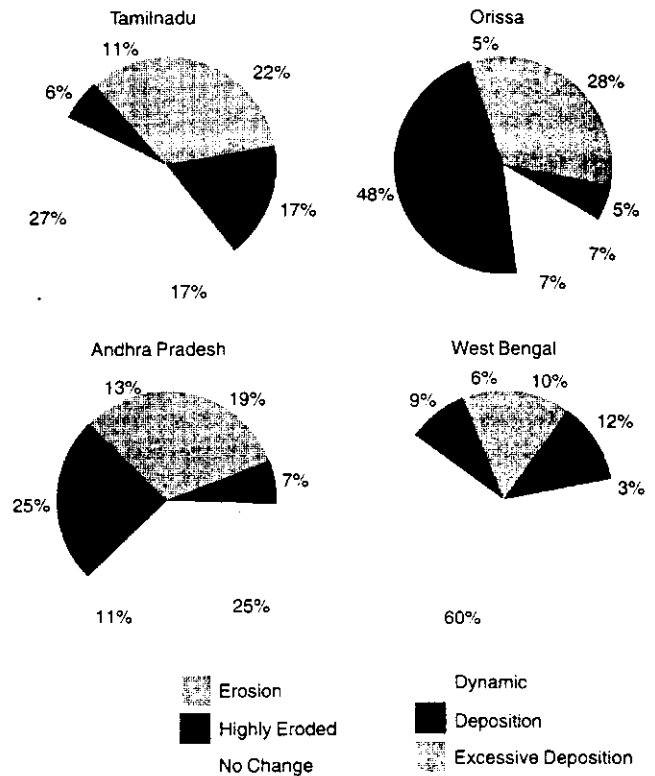


Fig. 10.4 Percent area for erosion and depositional segments of the coastline of the states along the East Coast of India.

**Gujarat:** The results suggest that the Gulf of Kachchh has a highly dynamic coastline. The Gulf of Khambhat is a potential site for shoal migration. Large shoreline changes occur due to the prevalent macro-tidal regime here. Southern coast of Gujarat has a highly dynamic coastline with erosional tendency.

**Maharashtra:** The northern coast of Maharashtra has an indented coastline with many creeks, inland waters, and pocket beaches. The coastline, though mostly rocky along the coast due to presence of the Sahyadri Range, is under threat at many locations due to reduced fluvial input.

**Goa:** The state has many pocket beaches. Till recently the beaches were accreting with a strong dune formation. However, owing to pressure from tourism related anthropogenic activities, some of the beaches are destabilised.

**Karnataka:** The shoreline of Karnataka is indented with hills, creeks, and small estuarine rivers, the mouths of which have dynamic shoaling. In the southern region, the shore is more dynamic compared to the north. The mouths of the small coastal rivers and backwaters at many places are undergoing erosion.

**Kerala:** The shoreline of Kerala by and large is dynamic with high erosional tendency.

**Tamil Nadu:** High erosion has been observed in the Manar and Tuticorin area. There are pockets of high erosion located all along the coast.

**Andhra Pradesh:** The southern coast of AP is more dynamic than the northern coast. The coasts along the mouth of all major rivers are highly dynamic. The mouths of many perennial rivers are migratory. The area is also frequented by cyclones, and the shoreline is highly sensitive to such extreme natural processes.

**Orissa:** The shoreline is dynamic due to high fluvial input and is metastable in the creeks and backwaters. The shoreline is subjected to severe erosion during cyclones and depression.

**West Bengal:** The shoreline is very dynamic due to a large fluvial flux from the Ganga and the Brahmaputra. At many places, shoreline is erosional (Digga Beach), and large changes in the island geomorphology have been observed. The Sundarbans is prone to erosion. Significant site-specific features of the shoreline are presented in Table 2

**Table 10.2** Significant sites of major shoreline changes along the Indian coastline (data sources: Rajamanickam et al., 2001; Chauhan, 1995, 2000; Chauhan et al., 1990, 1994; Chandramohan et al., 1993; Chavadi et al., 1989; Firouzabadi et al., 2000; Jog et al., 2001; Karlekar et al., 2001; Kumar et al., 1989; Kunte, 1994; Loveson et al., 1988; Mani et al., 1997; Mukherjee et al., 2001; Narayana et al., 2001; Natesan et al., 1993; NIO 1972; Rao P.B. et al., 1985; Sinha et al., 1997; Sreekala et al., 1998; Subramanya et al., 1989; Sudareran et al., 1993; Land use and Shoreline changes Maps of India; Immandar et al., 2000; Nayak et al., 1992; Rao, R.S. et al., 1994; Ramanujam et al., 1996; Adiga, 1994; Ahmad, 1972; Bruckner, 1988; Hanamgond et al., 1993; Jayapaa et al., 1984; Joshi, 1995; Kaliasundaram et al., 1991; Krishnakumar et al., 1994; Kurup, 1972; Mallik et al., 1984, 1987; Paul, 1997, 1996; Ramaiyan et al., 1996; Rao, T.A. et al., 1971; Sanjeev et al., 1996; Tatavarti et al., 1999; Wadia, 1961; Wagle, 1987; Wynne, 1966). Site-specific features at the specific locations are given for different sectors.

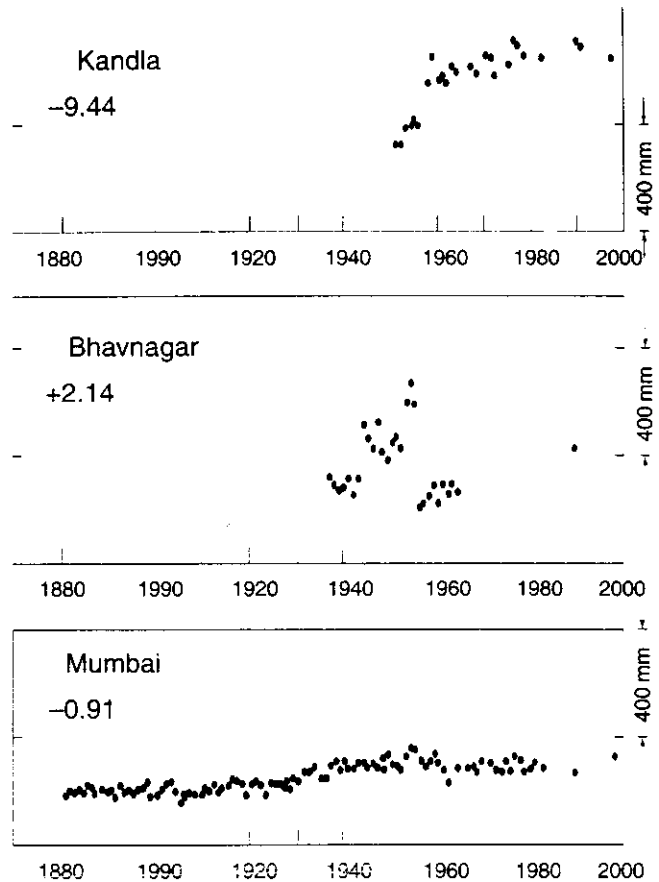
Area	Erosion/special feature	Deposition/ special features
Gujarat		
Gulf of Kachchh	Creeks: Water has moved landwards from Mandvi to Mundra coast	
Gulf of Khambhat	Erosion at Mahi estuary	
South of Gujarat coast	Erosion at the mouth of Purna, the Ambier & the Damanganga rivers	Shoals of deposition at Umargan with highly dynamic characteristics
Maharashtra		
Maharashtra coast	Rocky cliffs and pocket beaches	

Area	Erosion/special feature	Deposition/ special features
Thane creek	Erosion	
Goa		
Goa beaches		Deposition/ dynamic
Karnataka		
Mangalore	Erosion	
Kahlinadi creek near Karwar		Deposition (Siltation)
Kerala		
Kerala coast	Backwater under dynamic changes/coast dynamic with cell circulation	Reclaimed land
Manjeshwar	Erosion	
Kumbala	Erosion	
Kasaragod	Erosion	
Payyannur	Erosion	
Calicut	Erosion	
Kochi	Erosion	
Karti Kapalli	Erosion	
Tellicherry		Marginally dynamic
Mahe		Marginally dynamic
Badagara		Marginally dynamic
Quilandi		Marginally dynamic
Ponnani		Marginally dynamic
Irinjalakuda		Depositional
Sheratallai		Depositional
Alleppey		Depositional
Tamil Nadu		
Near Rameswaram	Fringing and patch reefs	
Gulf of Mannar	Fringing and patch reefs	
Pichavaram	Mangrove forest dynamic	
Vedaranyam	Mangrove forest dynamic	
Pt. Calimere	Mangrove forest dynamic	Coast dynamic
Nagapattinam		Deposition
Pattukkotlai		Deposition
Kilakkarai		Deposition
South of Chennai		Deposition
Ovari	Erosion	
Paravarnattam		
North of Chennai	Erosion	
Andhra Pradesh		
North of Godavari delta	Spits (at the mouth of the river)	
Kakinada	Spit is dynamic	
Krishna delta	Front has been dynamic through spits & barrier bars.	

Area	Erosion/special feature	Deposition/special features
Tutipalan	Spit under dynamic changes	
Mouth of Penner	Spit (breached in 1986 cyclone)	
Vishakhapatnam (south)		Accretion
Vishakhapatnam (north)	Erosion	
Between Vinatayam & Vashishta	Erosion	
Godavari		
Machilipatnam	Erosion	
South of Polakayatippa	Erosion	
Pulicat Lake	Shrinking	Reclaimed land
Orissa		
Chilka region	Mud flats	
Bhitar kanika	Mangrove forest region undergoing erosion	
Hatamunidia	Mangrove forest region undergoing erosion	
Karanjmal	Dynamic	
Near Paradip Port (Mahanadi River)	River mouth dynamic	
Sabarnarekha Mahanadi	River mouth dynamic	
Mahanadi River and its distributaries	Erosion : Delta formed by the river is prone to erosion under the cyclonic storms	
West Bengal		
Hoogly	Estuarine delta	
Sundarbans	Highly dynamic	
Lakshadweep Islands	Corals: Lagoons are affected due to death of corals at many locations	
Andaman Nicobar Islands	Corals are under threat due to anthropogenic activities. Large-scale deforestation may cause silting of lagoon and adjacent seas.	

**Sea level changes**

Tide gauge records are useful for analysis of changing relative sea level. Hourly measurements of tides from the available records between 1920-1999 were obtained (Unnikrishnan et al., 2003; Emery et al., 1989; Das, 1991; Admiralty Tide Tables, Vol 2, 1996; International Hydrographic Bureau, 1930). (Unpublished data of Michael, G.S. et al. NIO, Goa, and the data of Survey of India) and averaged for a full year to obtain the mean annual relative sea level changes. A time series data set for 10 stations that was continuous was statistically analysed to obtain regression trends at each location. The basis of sea level estimation (Emery et al.,



**Fig. 10.5** Time series variations in the mean sea level at Kandla, Bhavnagar and Mumbai. Refer (Emery et al., 1989) for methodology. The values on the left side corner indicate sea level variations per year. Minus indicates relative increase in mean sea level with respect to the land.

1989; Das, 1991; Admiralty Tide Tables Vol. 2, 1996; International Hydrographic Bureau, 1930) is the time series changes in the mean annual sea level for the specific period for a given location (Figs 10.5-10.7).

The estimated sea level variations are site specific and are given in Table 3. The mean sea level data has not been corrected for possible isostatic changes due to the location of these stations in tectonically unstable regions. The estimated changes are, therefore, a sum total of an increase in the sea level and/or sinking of land and may be locally biased. Analyses at Kandla, Diamond Harbour and Kolkata do not have sufficient statistical significance, and hence are not presented in Table 10.3.

**Likely vulnerable region along Indian coastline due to future climate changes and associated sea level rise**

The shoreline is a dynamic boundary resulting from the

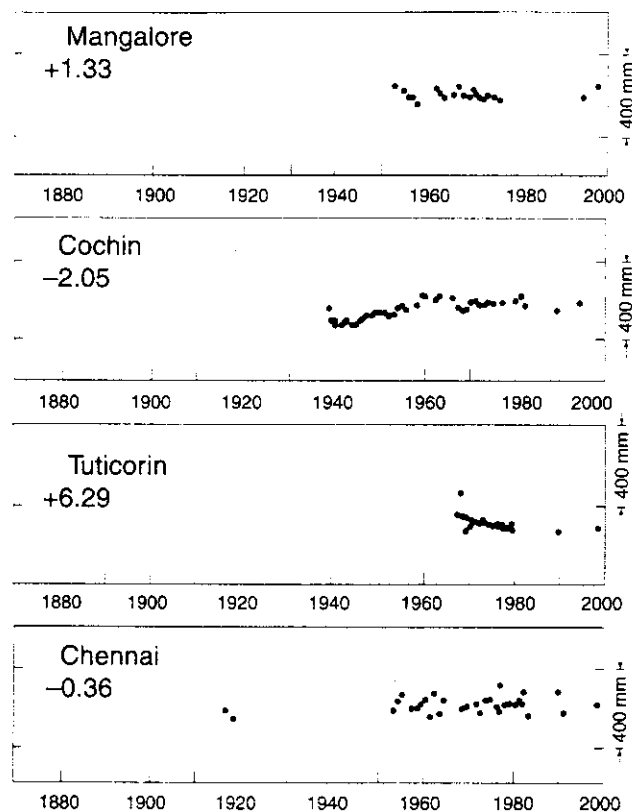


Fig. 10.6 Same as Fig. 5 but for Chennai, Tuticorin, Kochi and Mangalore.

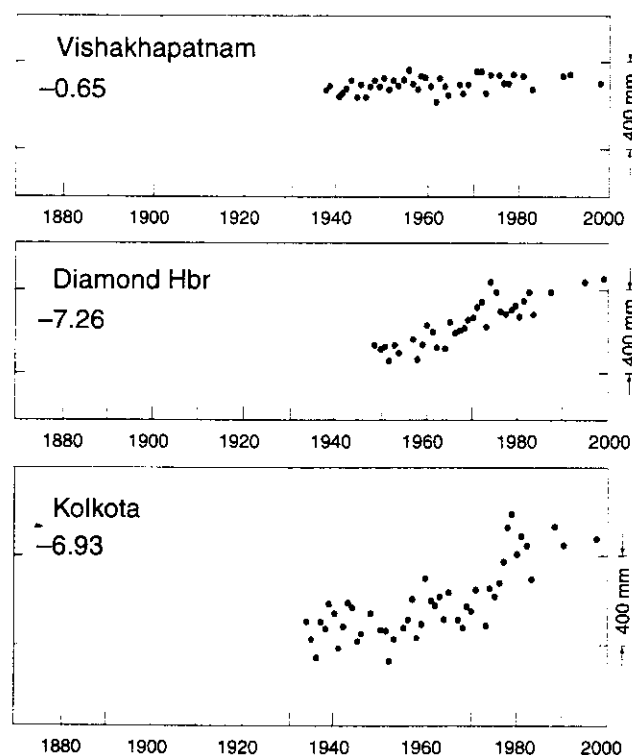


Fig. 10.7 Same as Fig. 5 but for Kolkota, Diamond Harbor, and Vishakhapatnam.

**Table 10.3** Estimated sea level rise at selected locations along the Indian Coastline (Emery et al., 1989; Das, 1991; Admiralty Tide Tables, Vol 2, 1996; International Hydrographic Bureau, 1930). Minus indicates increase in sea level with respect to the land.

Location	Estimated sea level rise (mm) y <sup>-1</sup>
Bhavnagar	2.14
Mumbai	-0.91
Mangalore	1.33
Kochi	-2.05
Chennai	-0.36
Vishakhapatnam	-0.65

fragile equilibrium among the hydro-meteorological parameters vis-à-vis supply of the sediments (Chauhan, 1995). The sediment dynamics play an important role for evaluating and determining the influences of tidal regime, wave climate, and sea level changes. For overall evaluation of the site-specific impact of sea level changes, sea truth data needs to be generated for these parameters. The present work has its limitation as it stems from the compilation of available data, which many a time uses different and non-comparable methodologies. For example, time series observation on littoral currents, hydrography and beach profile changes are rare and use variable methodologies (Chauhan, 1995, 2000; Chauhan et al., 1990, 1994; Chandramohan et al., 1993; Chavadi et al., 1989; Firouzabadi et al., 2000; Jog et al., 2001; Karlekar et al., 2001; Kumar et al., 1989; Kunte, 1994; Loveson et al., 1988; Mani et al., 1997; Mukherjee et al., 2001; Natesan et al., 1993; NIO, 1972; Rao, P.B. et al., 1985; Sinha et al., 1997; Sreekalal et al., 1998; Subramanya et al., 1989; Sudareran et al., 1993; Land use and Shoreline changes Maps of India; Immandar et al., 2000; Nayak et al., 1992; Rao R.S. et al., 1994). Similarly, for shoreline changes, the satellite-derived shorelines are compared with the hydrographic charts, which have different degree of accuracy due to adopted methodologies (Land use and Shoreline changes Maps of India; Immandar et al., 2000; Nayak et al., 1992; Rao R.S. et al., 1994; Ramanujam et al., 1996; CRZ Maps of the States). No GPS data is available for Indian coastline to determine its tectonic characteristics. Many a time it is not possible to ascertain whether standard correction for chart datum is applied to the soundings and satellite data. Moreover, for planning purpose, the inventory work of the physiography, and shoreline changes will only be meaningful if presented on the much-reduced scale maps incorporating time series data.

From the available data, however, it can be deduced that the coastline of the Gujarat is highly susceptible to sea level changes. Kandla has the highest sea level rise (9.44 mm). This estimation, however, has low statistical significance, and may also be biased due to isostatic nature of the region. This region is semi arid with little fluvial input, and is a



macrotidal site with large inter-tidal area. Besides, the area lies in active seismic zone with historical records of occurrence of the earthquakes. Sindre town is known to have sunk about 1.5 m during the earthquake of 1918. Considering these aspects, this area is most vulnerable to the sea level changes.

The southern region of Gujarat is relatively less unstable. However, shifting shoals of the Rivers Tapi and the Narmada, and a large intertidal zone with dynamic shoreline of this region makes it a vulnerable zone even for moderate sea level rise.

The coastline of Maharashtra is also prone for erosion at many places. The entire area has extensive backwaters and creeks. Along most part of the coast of the Maharashtra, the Sahyadri Range is very close to the sea, and therefore the coastal space is rather narrow. The area has mostly pocket beaches that are sustained by cliff erosion. The west coast fault (a N-S trending regional tectonic feature) and the submergence characteristics add to the vulnerability of these regions.

The Sahyadri Range has migrated landwards along the coast of Goa. The coastline is highly dynamic along the open coast. Several pocket beaches, some protected and sheltered by the offshore extension of the basalt, needed to be saved from dune flattening for continually growing need to accommodate demographic pressure and tourism. This unplanned large-scale construction, in the past two decades along the beaches, is likely to be affected severely in the event of sea level rise, particularly when sand dunes, the natural line of defense, are under destruction.

Karnataka coast is indented with creeks and pocket beaches. The fluvial influx into the region is minor, and as such, the coast has characteristics of submergence. Compared to Mumbai, the expected sea level rise is reversed here (+1.33 mm), which is attributed to tectonics of this region 59. The coastal area has pockets of dense population, and has meso-tidal regime. Tidal ingress into the numerous coastal rivers and bar migration off their mouth is observed at many locations. In the event of sea level rise, the coastline at these locations with dynamic and migrating shoaling activities is prone to destruction. Much of the larger inland backwaters areas have a risk of being affected by tidal ingress.

The coastline of Kerala is having a large density of backwaters, creeks and mud flats. The density of the human population is also the highest. The entire coastline is highly dynamic and severe erosion is observed at many locations. The hydrography of the region is complex due to strong littoral currents. The formation of cell circulation at Kochi is a significant example of the dynamic nature of the coast. The observed sea level rise at Kochi is 2.05 mm per year, which is larger than that of Karnataka's. The submergence characteristics of the coast make it further vulnerable to sea level rise. The entire coastline of Kerala is vulnerable to the level rise, and needs special attention.

Tamil Nadu Coast has a varied environment. The coast

has a dynamic as well as depositional component in varied segments. By and large, northern Tamil Nadu has an unsheltered shoreline with a highly dynamic or erosional tendency. The shoreline is retreating at many locations. The shore in Manar-Pamban area is protected by coral reefs. However, due to anthropogenic activities the coral reefs are under threat. Southern Tamil Nadu has localised segments of unstable shoreline.

The coast of Andhra Pradesh has a large influx of fluvial sediments. The shoreline is highly dynamic. The area has a very high probability of the occurrence of cyclones/depression, and has migratory shoals at many locations. The coastline, though accreting at many locations and classified as progradational, is still prone to tidal ingress of large fluvial deltas in the event of sea level rise.

The coastline of Orissa is progradational. It has segments of erosional and depositional tendency depending upon prevailing wave environment, littoral currents, and other oceanographic parameters. The coastal area has numerous small and large rivers and their distributaries, which fan out into the coastal region. The area has a high probability of occurrence of cyclone ( $p \approx 1.0$  during October – January) (Chauhan et al., 1988). These rivers are prone to salinity ingress, particularly in the event of sea level rise.

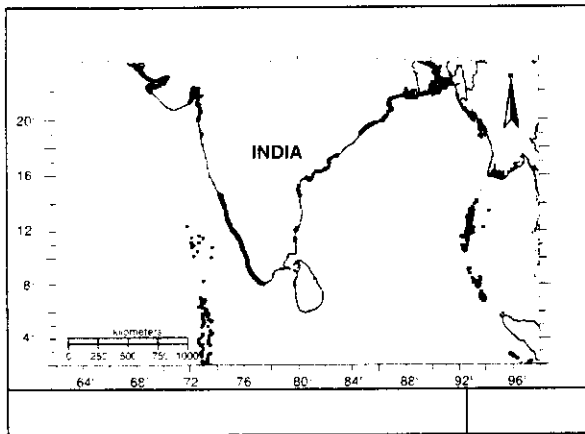
Very high sea level rise (7.26-6.33 mm) has been tentatively deduced for the coast of West Bengal. These estimates, however, have a low statistical significance. The coast has erosional tendency at many locations. The delta region is highly dynamic and the islands located in this region need special consideration. The Sundarban area and Hoogly estuarine regions are two other areas found most vulnerable to the observed sea level rise.

There is no data on the tectonic nature of the Lakshdweep Islands. The islands have damaged coral reefs (on the lagoon sides at many islands). Being located few meters above sea level, islands are likely to be under potential threat due to sea level rise, if the reefs are not protected.

Andaman and Nicobar Islands are known for volcanic activities. It is difficult to establish the nature of these islands. No data is available to evaluate the sea level changes in this area. Many islands are larger compared to Lakshdweep, and have protected reefs and mangroves. Nevertheless, anthropogenic activities have taken a toll on these. More time series observations are needed to evaluate the influences of sea level rise in this region.

The areas of the Indian coastline most vulnerable to the predicted sea level rise, and need special, immediate consideration are schematically shown in Figure 8.

The current assessment, of the sea level rise, shoreline changes and inventory of the physiographic feature, as indicated earlier, is quasi systematic. The dearth of time series observations and their interpretation are some of the major weak links. In order to estimate the sea level rise meaningfully, time series GPS observations of land movement are prerequisites. The current assessment of sea



**Fig. 10.8** Most vulnerable location identified from the predicted sea level changes, tectonics, prevalent hydrography, and physiography of the areas along the Indian Coastline.

level rise on Indian coastline and its influences need further evaluation integrating in situ time series tidal observations, GPS observations, satellite pass synchronous shoreline morphology, synchronous chart datum correction to the sounding data, which is bound to improve the understanding of these complex phenomena.

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