Assessment of coastal erosion along the Indian coast on 1 : 25,000 scale using satellite data of 1989–1991 and 2004–2006 time frames

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The long stretch of coastline on either side of the Indian peninsula is subjected to varied coastal processes and anthropogenic pressures, which makes the coast vulnerable to erosion. There is no systematic inventory of shoreline changes occurring along the entire Indian coast on 1 : 25,000 scale, which is required for planning measures to be taken up for protecting the coast at the national level. It is in this context that shoreline change mapping on 1 : 25,000 scale for the entire Indian coast based on multidate satellite data in GIS environment has been carried out for 1989–1991 and 2004–2006 time frame. The present communication discusses salient observations and results from the shoreline change inventory. The results show that 3829 km (45.5%) of the coast is under erosion, 3004 km (35.7%) is getting accreted, while 1581 km (18.8%) of the coast is more or less stable in nature. Highest percentage of shoreline under erosion is in the Nicobar Islands (88.7), while the percentage of accreting coastline is highest for Tamil Nadu (62.3) and Goa has the highest percentage of stable shoreline (52.4). The analysis shows that the Indian coast has lost a net area of about 73 sq. km during 1989–1991 and 2004–2006 time frame. In Tamil Nadu, a net area of about 25.45 sq. km has increased due to accretion, while along the Nicobar Islands about 93.95 sq. km is lost due to erosion. The inventory has been used to prepare a *Shoreline Change Atlas of the Indian Coast*.

Keywords: Accretion, coastal erosion, shoreline changes, high and low tide lines, satellite data.

ISSUES related to coastal erosion can be viewed in two different aspects; one where the erosion rates are low but the threat of coastal erosion is for a longer timescale and while the second one is an ephemeral process, mostly concurrent with sporadic events and usually the loss is regenerated with the withdrawal of the event. The permanent loss of land, even though a slow process, poses a significant threat to valuable land, property and natural coastal resources, including vital habitats. Anthropogenic pressures along the region have significant contribution towards the incessant coastal erosion. Inevitable development activities along the coast and in the catchment areas of the river have induced changes in the equilibrium of the sediment transport which cause undesirable accretion and erosion along the coast. The rise in sea level and local coastal subsidence also lead to changes in the coastal processes[1]. Coastal erosion during storm surge, tsunami or even monsoonal high wave period usually evolves into disaster, but the impact on coastal erosion will be for a shorter period[2,3]. A schematic diagram involving the coastal erosion processes is shown in Figure 1.

Coastal erosion, as in other maritime countries, is a serious problem along the Indian coast. India, as it forms a peninsula, has a long coast on its east and west regions with varied coastal processes dominating the coastal dynamics. These include tide-dominated regions along the northern parts of the west coast, open coast with high wave energy along the southern parts of the west coast, strong longshore sediment transport along the southern parts of the east coast and the coast strongly influenced with river discharges along the northern parts of the east coast. The coastal geomorphology and the land-use pattern along the Indian coast also show a varied range, which includes coral reefs, mangrove belts, tidal mudflats, rocky coasts, wide sandy beaches and deltaic and bay environments.

The Indian coast is relentlessly modified by the mounting development activities along the coastal region, which under improper management at times leads to severe coastal erosion. Management plans with proper understanding of the coastal processes and coastal dynamics are needed to achieve sustainable development along the coastal region, where planning measures have to be taken up at the national level. Inventory related to coastal erosion are a pre-requisite in understanding the coastal dynamics of the region. Even though there are studies and inventory of coastal erosion and littoral sediment transport along the Indian coast, they are region-specific[4–10] and inadequate for planning-level requirements at the national level.

Planning measures for sustainable development along the coastal region require a systematic inventory of shoreline changes occurring along the entire Indian coast on 1 : 25,000 scale. It is in this context and according to the recommendations of the Coastal Protection and Development Advisory Committee (apex body concerned with planning of coastal protection measures at the national level in India), that shoreline changes for the time frame 1989–1991 and 2004–2006 are mapped on 1 : 25,000 scale for the entire Indian coast based on multidate remote sensing data in GIS environment. The present communication discusses the salient observations and results

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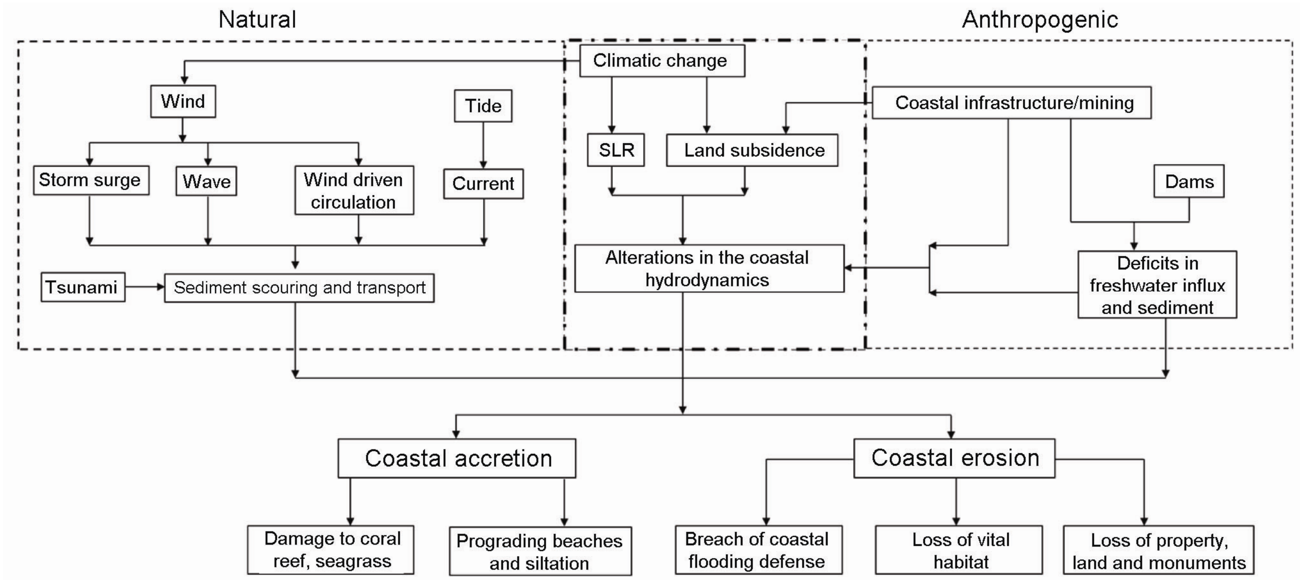

Figure 1. Schematic diagram representing the coastal erosion processes (modified after Eurosion[3]).

Table 1. Salient characteristics of satellite data used

Satellite	Sensor	Bands (nm)	Spatial resolution (m)	Radiometric resolution (bits)	Swath (km)
SPOT 1	HRV	500–590 610–680 780–890	20	8	60
SPOT 2	HRV	500–590 610–680 780–890	20	8	60
IRS-1A	LISS-II	450–520 520–590 620–680 770–860	36.25	7	(2 × 74)
IRS-1B	LISS-II	450–520 520–590 620–680 770–860	36.25	7	(2 × 74)
IRS-P6	LISS-IV	520–590 620–680 770–860	5.8	10	24

obtained from the shoreline change mapping carried out for the entire Indian coast.

Coastal land-use/land-cover maps have been prepared for the entire Indian coast on 1 : 25,000 scale using IRS-P6 LISS-IV data of 2004–2006 period[11] and SPOT-1 and 2 multispectral and IRS-1A and IRS-1B LISS-II data of 1989–1991, and considered as a part of the geospatial database created for Coastal Zone Information System (CZIS) developed at Space Applications Centre (SAC), Ahmedabad. These maps also depict High Tide Line (HTL) and Low Tide Line (LTL). Shoreline change mapping for the purpose of demarcating coastal erosion, accretion and stable nature of the coast has considered changes in HTL as these exclude seasonal changes, where HTL represents Highest High Tide Line. HTL has been demarcated using satellite data based on various geomorphologic/land-use features and tonal contrasts like landward berm/dune crest, rocks, headlands, cliffs, seawalls or embankment, permanent vegetation line, landward side of mangroves, salt pans, supra-tidal mud flats, etc.[12,13]. The sensor parameters for the satellite data used are given in Table 1.

In addition, Landsat TM, ETM and Resourcesat-1 AWiFS data of the corresponding time frames were used

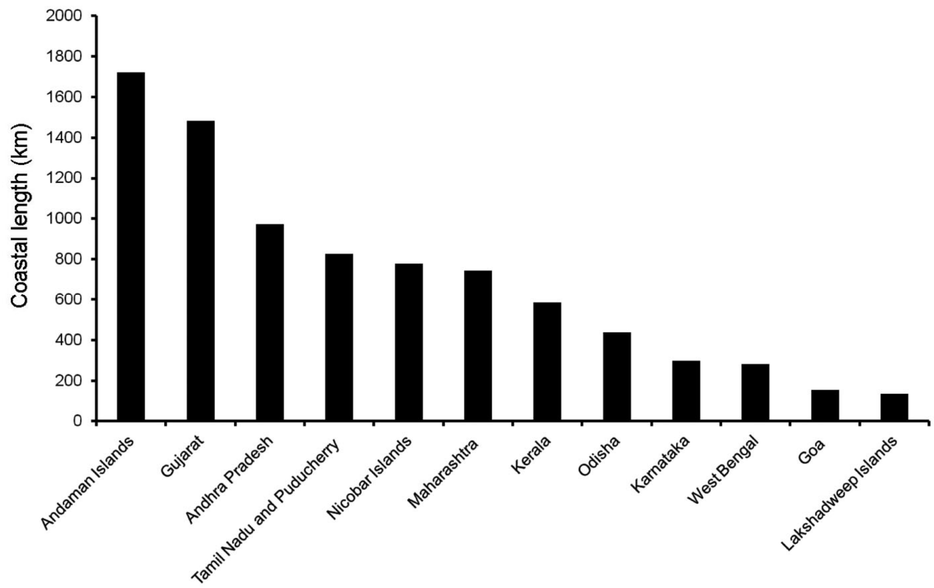

Figure 2. Coastal length of different maritime states and UTs.

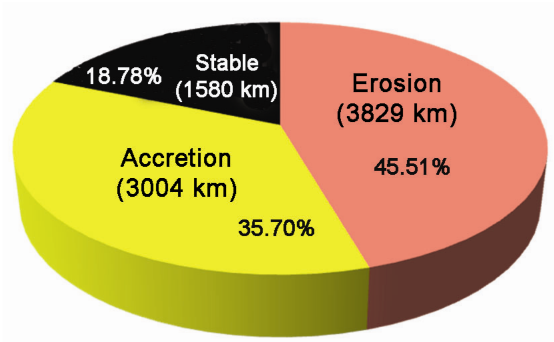

Figure 3. Length of shoreline under erosion, accretion and as stable along the entire Indian coast.

for rechecking and confirming the continuity of HTL in adjoining map sheets. Existing national spatial framework has been used for seamless mosaicing and organizing the database, where one degree consists of 8 × 8 rectangular grid or cell and each grid represents 7.5′ × 7.5′ area on 1 : 25,000 scale.

Shoreline change analysis has been carried out based on spatial displacement of HTL 2004–2006 with respect to HTL 1989–1991. The spatial displacement analysis has been carried out only along the main shoreline, which excludes mouths of rivers, streams, creeks and their inner parts. Area under accretion and erosion and length of shoreline being eroded, accreted and stable were calculated for each 7.5′ × 7.5′ grid. The coastline is considered to be stable where the HTLs of the two different time frames overlap. Field checks were carried out along the entire Indian coast and based on field observations, corrections were incorporated while finalizing the maps. Classification as well as planimetric accuracy of the maps was assessed while carrying out field work. Overall the classification accuracy of these maps ranges from 90% to 95% at 90% confidence level. The planimetric accuracy of these maps is 6.25 m.

A standard map composition and layout was finalized and used for final composition of each map. The type and spatial extent of coastal protection measures taken up by the respective Maritime states and Union Territories (UTs) were also considered as a part of the geospatial database and are shown in the respective shoreline change maps. Other necessary spatial-information like rail, road and habitation are also depicted in each map. The inventory has been used to prepare A-3 size *Shoreline Change Atlas of the Indian Coast*, brought out as six volumes for the entire Indian coast[14].

According to the inventory, the total length of the main shoreline, which excludes the length of the mouth of estuaries, rivers, creeks and the inner part is 8414 km. Figure 2 shows the Maritime state/UT-wise distribution of coastal length. Andaman Islands has the longest coastal length ~1722 km and Lakshadweep Islands has the smallest coastal length of about ~136 km. Out of the 8414 km length of the Indian shoreline, around 45.5% (3829 km) is observed to be under erosion (Figure 3).

Accretion has occurred along 35.7% (3004 km) of the shoreline while 18.8% (1581 km) of it is observed to be more or less stable. The Maritime state-wise distribution of shoreline length under erosion, accretion and as stable is given in Table 2 and Figure 4. The length of shoreline under erosion is longest for Andaman Islands (740.34 km) and it is shortest for Goa (27.03 km), while the shoreline length that has accreted is also maximum for Andaman Islands (944.84 km) and minimum for West Bengal (19.46 km).

Table 2. Coastal length under erosion, accretion and as stable in different Maritime states/Union Territories of India (excluding mouths of rivers/streams/creeks and their inner parts)

Maritime states and Union Territories*	Erosion length (km)	Accretion length (km)	Stable length (km)	Total length (km)	Area under accretion (sq. km)	Area under erosion (sq. km)	Net gain/loss (sq. km)
Gujarat, Daman* and Diu*	486.43	297.99	697.71	1482.1	43.45	27.28	16.17
Maharashtra	449.5	244.47	48.29	742.26	5.08	7.83	–2.75
Goa	27.03	46.98	81.38	155.39	1.53	0.771	0.759
Karnataka	106.12	118.65	73.31	298.08	6.26	5.16	1.1
Kerala	218	294	73.6	585.6	9.54	5.31	4.23
Tamil Nadu and Puducherry*	281.56	514.11	29.25	824.92	42.64	17.19	25.45
Andhra Pradesh	443.88	186.94	340.45	971.27	25.14	46.89	–21.75
Odisha	199	205	32.1	436.1	13.3	13.8	–0.5
West Bengal	115.06	19.46	147.68	282.2	1.52	11.63	–10.11
Lakshadweep Islands*	72.03	63.24	1.01	136.28	0.83	1.7	–0.87
Andaman Islands*	740.37	944.84	36.83	1722	27.09	17.93	9.16
Nicobar Islands*	690.1	68.3	19.23	777.63	0.77	94.72	–93.95
Total	3829.1	3004	1580.8	8413.9	177.15	250.211	–73.061

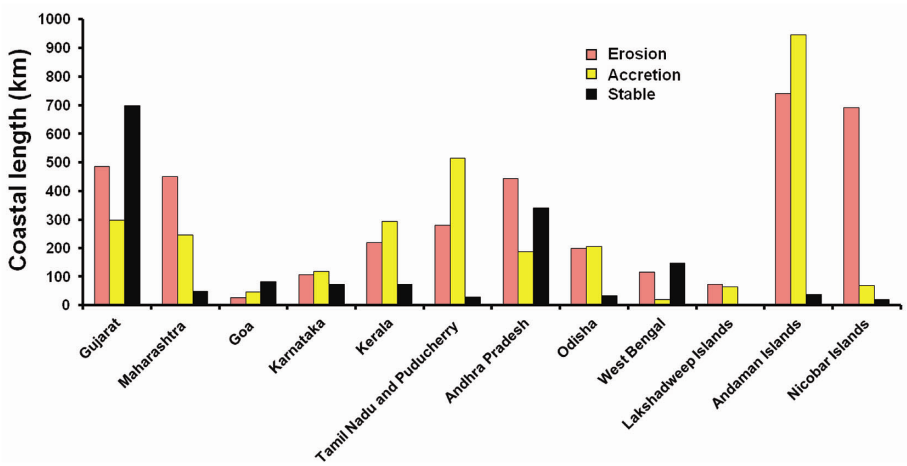

Figure 4. Coastal length under erosion, accretion and as stable in different Maritime states/UTs (excluding mouths of rivers/streams/creeks and their inner parts).

While assessing the percentage-wise distribution of shoreline length under erosion, accretion and as stable for individual Maritime states and UTs, Nicobar Islands show the highest percentage of shoreline under erosion (88.7), followed by Maharashtra and Lakshadweep (Figure 5 *a*). For the remaining Maritime states, the eroding shoreline length is less than 50% of their total respective shoreline lengths. Percentage of accreting coastline is highest for Tamil Nadu, which is around 62.3% of its total shoreline (Figure 5 *b*), followed by Andaman Islands, while least accretion is observed for West Bengal coast. Goa has the highest percentage of stable shoreline, which is about 52.4% of its total shoreline (Figure 5 *c*), followed by West Bengal, Gujarat, Andhra Pradesh and Karnataka coasts having around 20–40% as stable coast with respect to their total coastal length. The coast along Kerala, Odisha, Maharashtra, Tamil Nadu, Puducherry, Nicobar Islands, Andaman Islands and Lakshadweep Islands shows less than 10% as stable in general.

Among various Maritime states and UTs, Tamil Nadu has the highest net increase of its coastal area which is about 25.45 sq. km (Table 2), while net loss of coastal area is maximum for the Nicobar Islands, which is around 94 sq. km. Maharashtra, Andhra Pradesh, Odisha, West Bengal, Lakshadweep Islands and Nicobar Islands have a net loss of area, while the other Maritime states and UTs have a net gain along their coastal regions. The analysis also shows that the Indian coast has lost a net area of about 73 sq. km during 1989–1991 and 2004–2006 time frames.

The results from the shoreline displacement analysis are a major contribution towards the proper understanding of shoreline dynamics along the Indian coastal region. As India has a long shoreline with a varied range of coastal processes and coastal geomorphology, the shoreline displacement also shows a varied response along the different segments of the coast. The rocky coastal stretches along the Saurashtra and central western coast show more

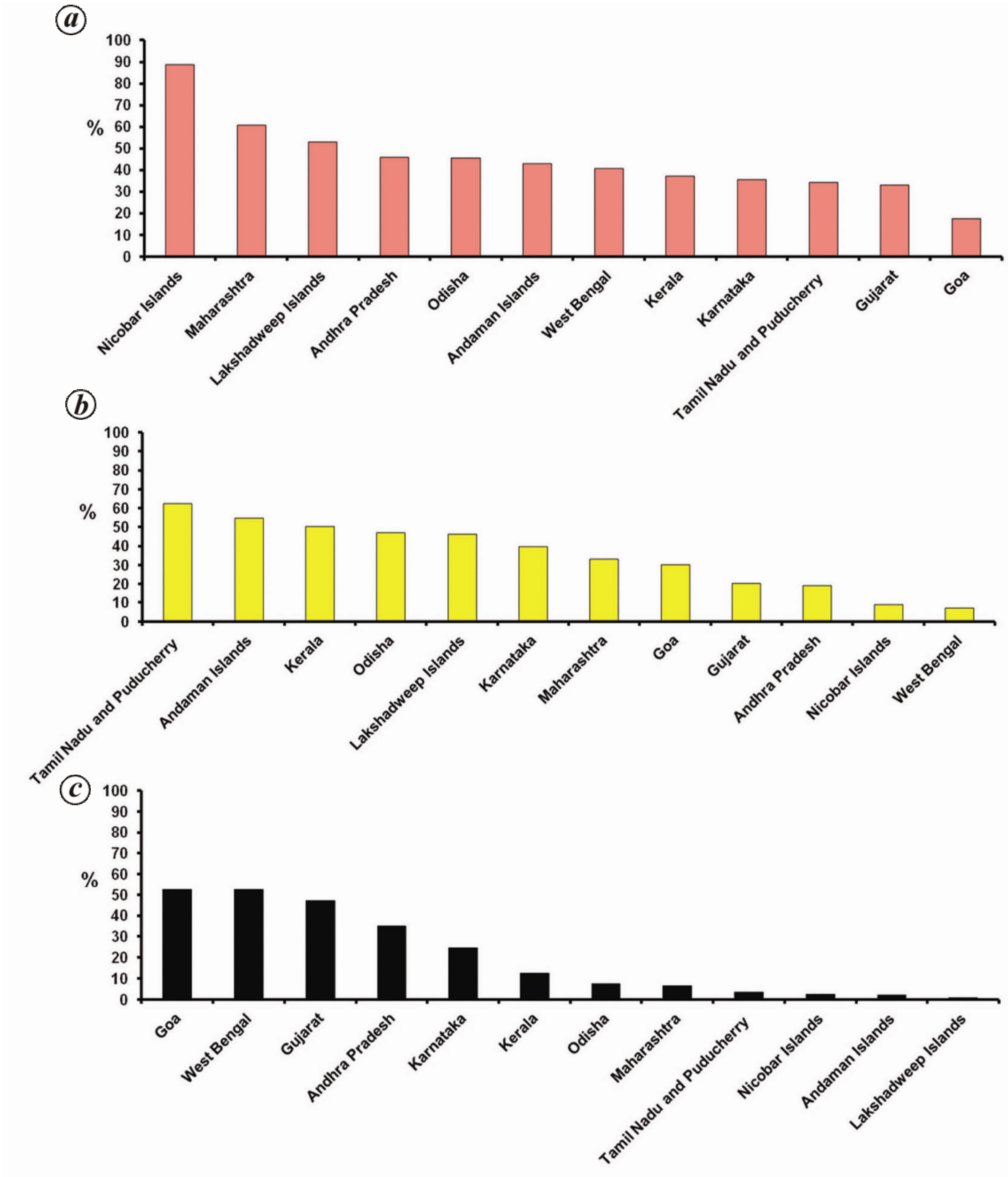

Figure 5. Percentage wise distribution of coastal length under erosion (***a***), accretion (***b***) and stable (***c***) in different Maritime states/UTs.

or less stable shoreline, where local shoreline dynamics is observed along pocket beaches within these stretches.

Coastal habitats such as mangroves, coral reefs and lagoons are recognized as the best defence against sea storms and erosion, deflecting and absorbing much of the energy of sea storms. Therefore, it is important to maintain these natural habitats for shore protection as well as for environmental conservation. Human activities that remove or degrade protective landforms – removing beach sands, weakening coral reefs, bulldozing dunes or destroying mangrove swamps, diminish the degree of natural protection. Human interference with natural coastal processes such as the building of groins, jetties, breakwaters, sea walls, artificial dunes and other structures is occasionally successful, but in some cases it causes considerable coastal erosion. These have had mixed success, and often cause additional problems in adjacent areas.

Figure 6 shows LISS IV images of 2011–2012 covering certain hotspots along the Indian coast overlaid with the HTL of 1989–1991 and 2004–2006, except for Figure 6 *a*, where LISS III image of 2006 has been shown. The figure elucidates the different aspects of coastal issues along the Indian coast. The major natural processes involved in the shoreline dynamics are wave-induced erosion (Kosamba, Gujarat; Figure 6 *a*) and littoral drift.

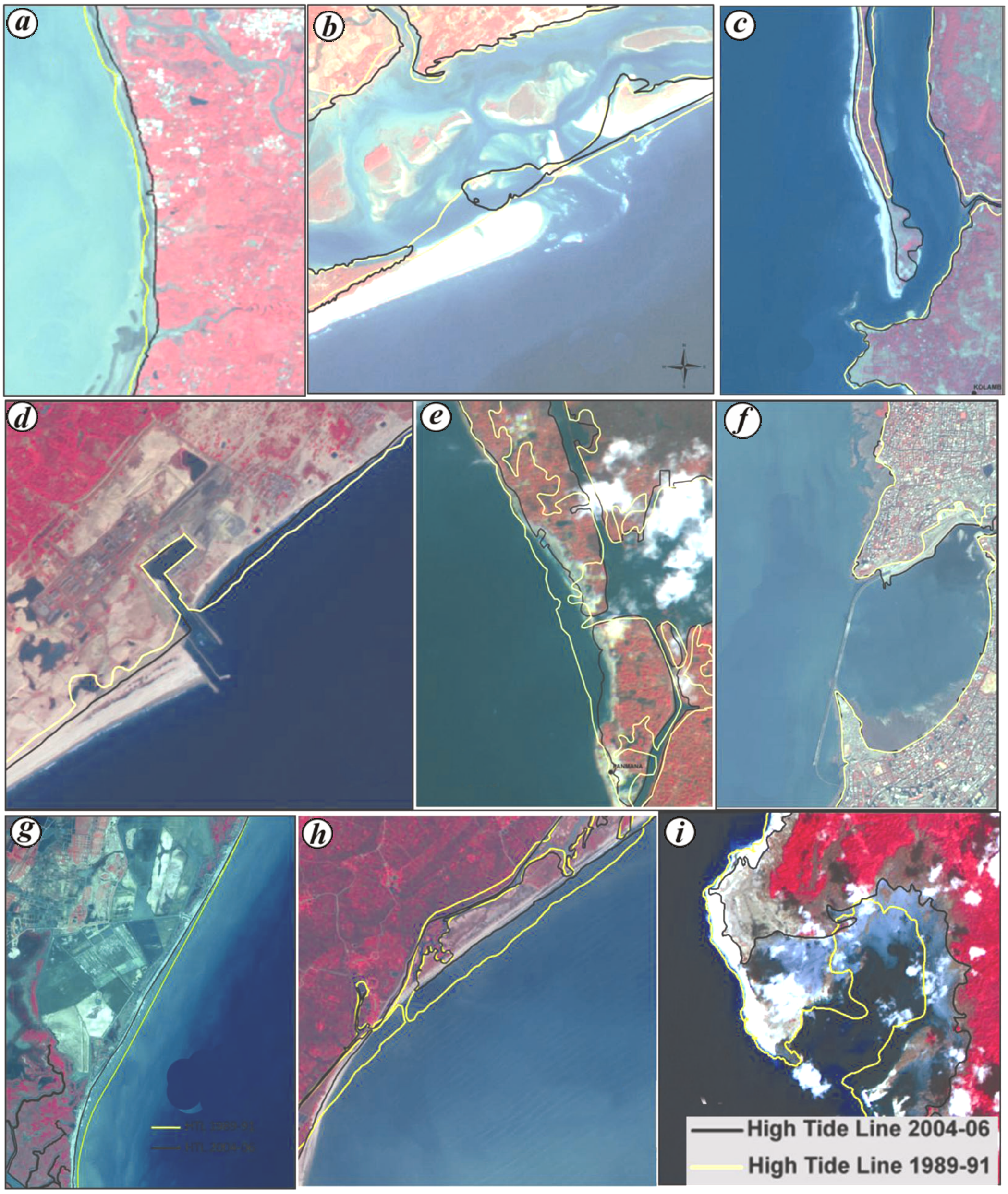

Figure 6. IRS LISS-IV images of 2011–2012/2006 overlaid with high tide line of 1989–1991 and 2004–2006: ***a***, Kosamba, Gujarat (LISS-III, 2006); ***b***, Chilika, Odisha; ***c***, Kalavali creek, Maharashtra; ***d***, Gopalpur, Odisha; ***e***, Panmana, Kerala; ***f***, Mumbai, Maharashtra; ***g***, Palletummalapalem, Andhra Pradesh; ***h***, Pentha, Odisha; ***i***, Katchall Island, Nicobar Islands (LISS-III, 2006).

Alterations of coastal geomorphic features by the littoral drifts are evident from the dynamics of Chilika inlet mouth, Odisha (Figure 6 *b*) and chocking of river/inlet mouths (Kalavali creek mouth, Maharashtra; Figure 6 *c*). The processes of longshore sediment transport occurring naturally along the coasts are highly altered by the constructions of breakwaters and have triggered coastal erosion due to obstruction of the littoral drift[6].

Figure 6 *d* is an example of obstruction of littoral drift at the Gopalpur Port, Odisha inducing coastal erosion towards its north. Sand mining (Panmana, Kerala; Figure 6 *e*) and land reclamation (Mumbai, Maharashtra; Figure 6 *f*) along the coast of India are also crucial anthropogenic activities altering the sediment dynamics and triggering coastal erosion. Coastal erosion induced by the changes in equilibrium of sediment transport along the coast resulting due to dam construction in the catchment areas of rivers[8] is evident along Palletummalapalem, Andhra Pradesh (Figure 6 *g*). Significant erosion is observed along the coastal stretch of Pentha, Odisha (Figure 6 *h*), possibly due to land subsidence, which requires imperative study. Natural disasters like the December 2004

Indian Ocean tsunami have resulted in permanent loss of vital habitat and coastal features along the Katchall Island in Nicobar (Figure 6 *i*).

Spatial inventory of shoreline changes using satellite data of 1989–1991 and 2004–2006 time frame in GIS environment has been created for the entire Indian coast on 1 : 25,000 scale. The results show that 3829 km (45.5%) of the coast is under erosion, 3004 km (35.7%) is getting accreted, while 1581 km (18.8%) of the coast is more or less stable in nature. Highest percentage of the shoreline under erosion is in Nicobar Islands (88.7), while percentage of accreting coastline is highest for Tamil Nadu (62.3) and Goa has highest percentage of stable shoreline (52.4). The cause of severe erosion along Nicobar coast is probably due to the Indian Ocean tsunami of December 2004. In many other parts of the Indian coast, coastal erosion occurs due to the construction of dams in catchment areas of rivers and developmental activities such as construction of ports/fishing harbours/jetties. The analysis shows that the Indian coast has lost a net area of about 73 sq. km during 1989–1991 and 2004–2006 time frame. In Tamil Nadu, a net area of about 25.45 sq. km has increased due to accretion, while along Nicobar Islands about 93.95 sq. km has been lost due to erosion. The inventory along with current status of coastal protection measures taken up by concerned state departments has been used to prepare a *Shoreline Change Atlas of the Indian Coast*. The baseline data are aimed towards initiating appropriate action for protecting the Indian coast by concerned Maritime states and UTs besides use by the scientific community as well decision-makers of the country.

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Heavy rainfall in the Kedarnath valley of Uttarakhand during the advancing monsoon phase in June 2013

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During the monsoon season of 2013, the advance of monsoon over northwest (NW) Indian region showed large abnormality as arrival of rainfall over Punjab, Himachal Pradesh (HP), Uttarakhand, Haryana and Delhi occurred between 13 and 16 June 2013, nearly twice the standard deviation earlier than normal. Such an early arrival by mid-June has been exceptional. The event was marked by unprecedented very heavy rainfall between 14 and 18 June 2013 over different meteorological sub-divisions of NW India. The event also led to human tragedy in Uttarakhand,

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