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Assessment of Sea Level and Morphological Changes along Indian Coastal Areas during 1975-2005

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ABSTRACT

Recent studies showed evidences of coastal accretion in many regions because of natural erosion and anthropogenic activities. On the contrary, sea level is rising in almost every coast across the World and leading to inundation. Present study estimated the changes in sea level and land areas along Indian coast during 1975-2005 using onscreen visual interpretation of Landsat images (60m resolution) for 1975 and 2005, and a newly developed sloping method at 615 coastal points from Shuttle Radar Topography Mission (SRTM) images (90m resolution) and the Permanent Service for Mean Sea Level (PSMSL) dataset. The results records sea level rise in the tune of 1.415 mm per year during 1975-2005 along Indian coast and the average slant height of inundated area is 2.136 m during this period. The overall results (considering accretion and inundation) indicate an effective land area increase by ~103.4 sq. km along Indian coast during 1975-2005. However, these estimates can be improved further by providing more reliable slopes and appropriate boundary points using higher resolution images along the coastline.

Keywords: Changes in coastal land area; Sea level rise; On-screen visual interpretation; Remote sensing

INTRODUCTION

Recent studies have argued that coastal areas are accreting in many regions due to various natural phenomenon such as erosion etc. and subsequent transportation of the eroded sedimentary materials to the coast (Manjunatha and Shankar, 1992; Thanh *et al.,* 2004; Angusamy and Rajamanickam, 2006; Mettier *et al.,* 2008; Ramakrishnan and Rajawat 2012; Rajawat *et al.,* 2014). This argument is based on the sediment deposition along the coastline for years, by sea waves, tides and longshore current and result of interaction of river borne sediments to sea waves. Narayanna and Babu (1983) reported that ~29% of the total eroded soil in India is lost permanently to the sea. Similarly, Chandramohan *et al.* (2001) highlighted that the annual discharge of sediments to sea along the Indian coast is about 1.2 × 10^{12} kg. In another study, Kunte and Wagle (2005) reported that the beach ridge of the eastern coast of India stretch has protruded approximately 30-35 km seawards since the beginning of the Holocene period. The morphological changes due to erosion and sediment deposition, growth of corals along the Indian coast are also observed in few studies (*e.g.,* Mergner and Scheer, 1974; Jayappa *et al.,* 2001). Mergner and Scheer (1974) documented that the corals grow in a great profusion along the Indian coast. Jayappa *et al.* (2001) highlighted the morphological

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changes due to erosion and sediment deposition along the coast of Dakshina Kannada and Udupi districts of India during 1985-1999. Waves associated with extreme events such as cyclones, storm surges also crash straight over the top of reef platforms and transport sediment from adjacent reef platforms to beaches. Webb and Kench (2010) reported that low lying Pacific Islands are expanding due to onshore and alongshore transport of sediments to atoll reef platforms. All these studies indicate that the coastal areas in different regions are accreting to some extent.

On the other hand, sea level rise is increasing and leading to the inundation of low-lying coastal regions (Williams *et al.,* 2009). The global average rate of sea level rise in twentieth century is documented as (1.7 ± 0.5) mm per year (Bindoff *et al.,* 2007). According to Unnikrishnan and Shankar (2007) the rate of sea lever rise across Indian coast is in between 1.06-1.75mm per year with a regional average of 1.29 mm per year. In a recent study, Nayak *et al.* (2013) studied the inundation of coastal area along Indian coast and highlighted that 34.906 sq km of Indian coastal area went under the sea in the twentieth century. In another study, Singh and Kambekar (2016) reported that probable sea level rise of 1 m, 2 m, and 3 m along Mumbai coast, India may inundate the coastal land at 3.84 %, 8.79 %, and 14.16 % respectively. However, coastal changes along whole Indian coast in recent decades due to sea level rise are not well documented so far. Our study intends to discuss on this issue to assess the sea level and morphological changes along Indian coast during 1975-2005 by analyzing the sea level and satellite datasets of recent decades. The next section presents the methodology and data used in the study. The results obtained and related discussions and conclusions are presented in subsequent sections.

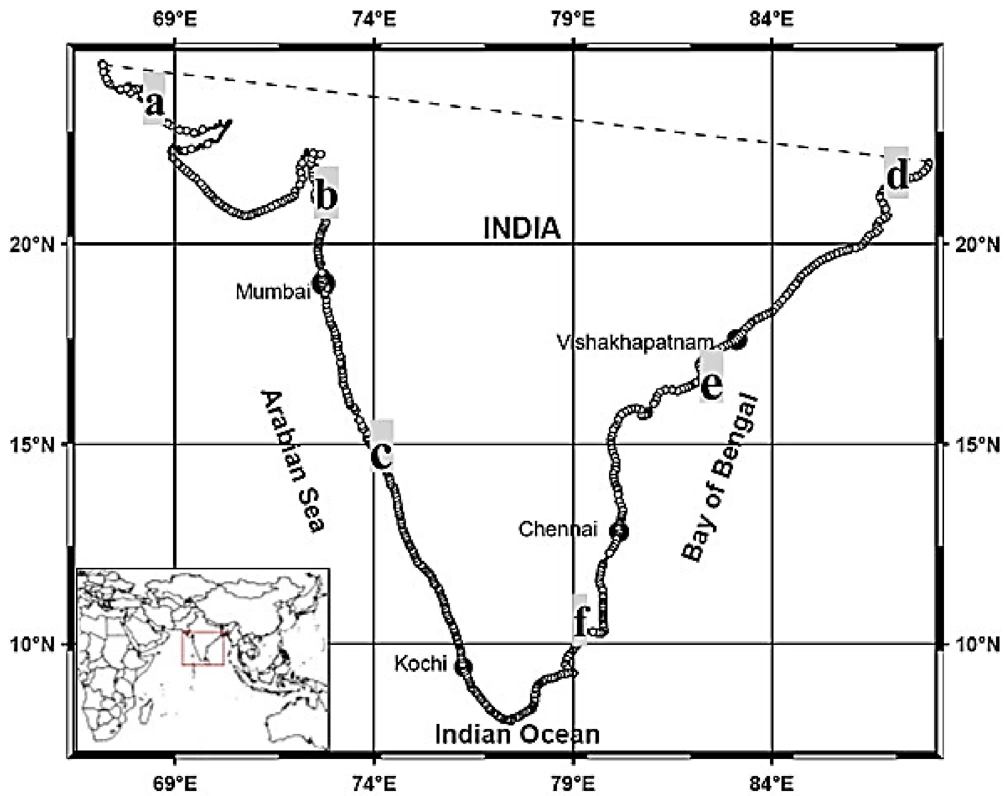


Fig. 1: Location map of Indian coastline with four representative stations and 615 points along the coast at which the slopes have been calculated. The a, b, c, d, e, and f are the places at which the sample pictures are taken for analysis (Fig. 3).

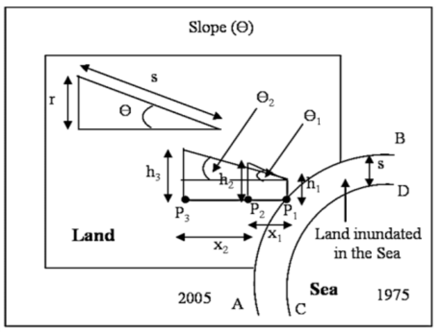
METHODOLOGY AND DATA USED

Geometrically rectified bands (4, 3, and 2) of NASA Landsat Multi Spectral Scanner (MSS) scenes with 60m spatial resolution, and Landsat Enhanced Thematic Mapper plus (ETM+) scenes with 30m spatial resolution are utilized to produce the land cover scenario of the Indian coastal region (Fig. 1) for the year 1975, and 2005 respectively. These datasets are obtained from Global Land Cover Facility (GLCF). The land cover scenarios of the region surrounded by the Indian coast was generated by using 86 Landsat scenes (185 km×185 km) for a particular year (figure not shown). The 90m SRTM scenes of U.S. Geological Survey (USGS) are utilized to compute the surface elevation over the region (Jarvis *et al.,* 2008). Annual mean sea level of Indian Ocean tide gauge data as obtained from Permanent Service for Mean Sea Level (PSMSL) are used to calculate the trends in sea level rise along Indian coast.

The onscreen visual interpretation technique is used to separate out the land areas of the region from the sea. It is based on the image characteristics over the region (*e.g.* Nayak and Behera, 2008). The islands or lands those are away from the coast are not considered in present study. The image resolution is kept 60meter for both the years 1975, and 2005. The total area of the land that surrounded by the Indian coast (as shown in Fig. 1) is estimated for both the years to calculate the land accretion during 1975-2005.

Table-1: Estimates the areas inundated into sea due to sea level rise along Indian coast during 1975-2005.

Name of the representative station/coastline	Sea level rise Trends (in mm/year)	Length of the coastline (in km) from Nayak *et al.* (2013)	Average slant height (in meter)	The areas inundated into sea (in sq km)
Mumbai	0.49	4187.59	0.771	3.227
Kochi	2.01	1148.77	2.161	2.483
Chennai	1.01	1277.63	1.754	2.242
Vishakhapatnam	2.15	1361.22	3.859	5.253



$$\theta_1 = \tan^{-1}\left(\frac{h_2 - h_1}{x_1}\right) \qquad \theta = \frac{\theta_1 + \theta_2}{2}$$

$$\theta_2 = \tan^{-1}\left(\frac{h_3 - h_1}{x_1 + x_2}\right) \qquad s = \frac{r}{\sin(\theta)}$$

Where, Θ is the slope at the Point;
h_i is the terrain height at the Point P_i;
x_i is the Euclidean distance from P_i to P_{i+1};
r is the sea level rise during 1975-2005;
s is the Slant height of the Land under sea for a unit area

Total area gone into sea from A to B = (arc length of AB) * s

Fig. 2: Showing the method for estimating the area inundated into the sea during 1975-2005 from point A to point B.

The whole Indian coastline is subdivided into four different parts *viz.* Mumbai, Kochi, Chennai, and Vishakhapatnam. Here the coastline refers to the land-water boundary *i.e.* where sea meets the land. The subdivisions of coastline are based on the work conducted by Nayak *et al.* (2013) and the arc lengths for each of the coastlines along the Indian coast are taken from their study (shown in Table-1). It shows that coastline lengths along Mumbai station, Kochi station, Chennai station, and Vishakhapatnam station are 4187.59km, 1148.77km, 1277.63km, and 1361.22km respectively. The linear trends in sea level rise during 1975-2005 are calculated at above four representative stations from PSMSL dataset. The heights at different coastal points (randomly selected, shown in Fig. 1) are obtained from the digital elevation values of SRTM image. It may be noted that there are no-data voids in SRTM images, so the locations with no-data voids are not considered during the collection of heights. The slant heights are calculated at each sampled points of the region that went under the sea during 1975-2005 using the method (shown in Fig. 2), as described in Nayak *et al.* (2013). In Fig. 2, C and D are two points assumed present in the year 1975. After 30 years, ‘r’ unit of sea level rise shifts both the points *i.e.* C and D in the year 1975 to A and B points respectively in the year 2005. The slope ‘Θ’ (average of Θ_1 & Θ_2) is calculated at each selected 615 coastal points along the coastline (Fig. 1) using three different points (P_1, P_2, P_3 as shown in Fig. 2) perpendicular to the coastline. The slant height ‘s’ is then calculated at each of the above 615 points using sine formula $r/\sin(\Theta)$. As mentioned earlier, the whole coastline is subdivided into four parts, the average slant heights are calculated along Mumbai using 142 coastal points, along Kochi using 165 coastal points, along Chennai using 183 coastal points, and along Vishakhapatnam using 125 coastal points. Finally, the coastal areas inundated into the sea during 1975-2005 along each of the four sub-parts are calculated by multiplying ‘s’ with the arc length of AB (as shown in Fig. 2).

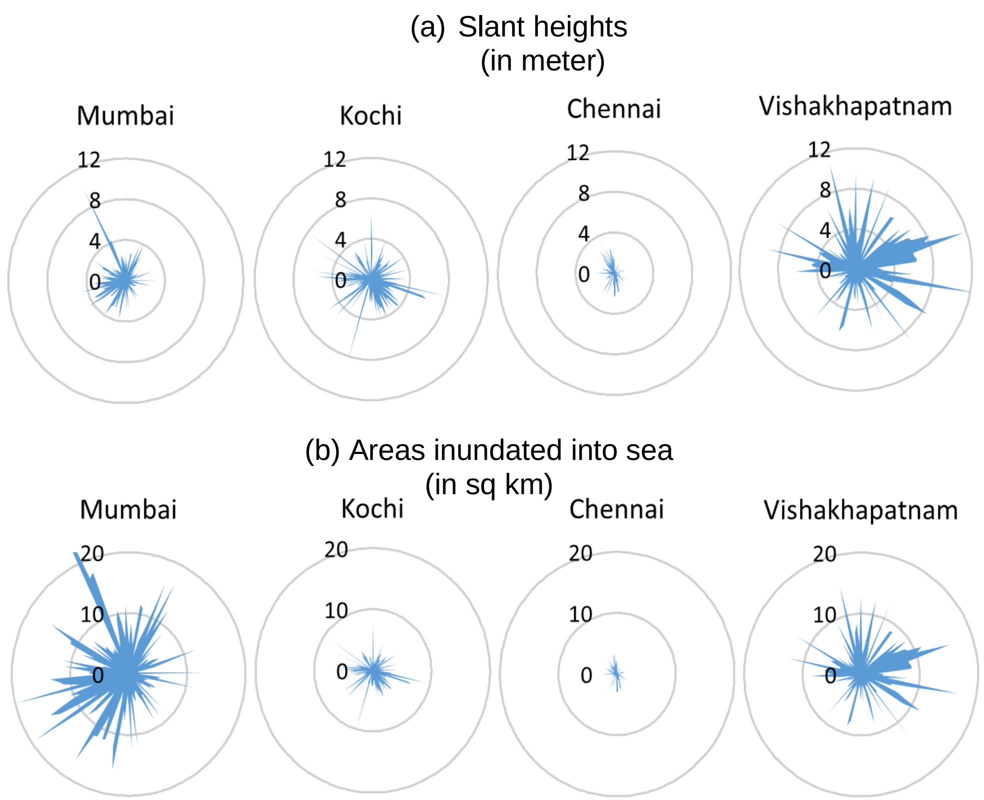


Fig. 3: Showing the slant heights (m) and areas inundated into sea at each points (shown in Fig. 1) along Mumbai, Kochi, Chennai and Vishakhapatnam.

RESULTS

The rate of sea level rise at each of representative stations (Fig.:1) is calculated during 1975-2005 and given in Table 1. The rate of sea level rise at the Mumbai is found to be 0.49 mm per year, while it is 2.01 mm per year at the Kochi. The Chennai coast has experienced an increased rate of sea level as 1.01 mm per year, while the Vishakhapatnam coast has experienced it as 2.15 mm per year. However, the average rate of sea level along all four coasts is found to be 1.415 mm per year during 1975-2005. The slant heights of the inundated areas at earlier mentioned 615 coastal points along the Indian coast (Fig.1) are calculated using the method as described in the previous section. The averages of slant heights of the inundated areas along each representative station are calculated. The estimation shows that the slant heights of the inundated areas are 0.771m, 2.161m, 1.754m, and 3.859m along the coastlines for the representative stations Mumbai, Kochi, Chennai, and Vishakhapatnam respectively (Table-1), with an average of 2.136m during 1975-2005. The uncertainties of the slant heights along each representative coast are shown in Fig. 3a. The slant heights along Chennai coast have less uncertainties (below 3m) while those along Vishakhapatnam have higher uncertainties (up to 12m). Using the slant heights and the coastline lengths, the areas inundated into the sea along Mumbai station, Kochi station, Chennai station, and Vishakhapatnam station during 1975-2005 are calculated (Table-1). The areas inundated by sea due to sea level rise along Mumbai, Kochi, Chennai, and Vishakhapatnam are found as 3.227 sq km, 2.483 sq km, 2.242 sq km, and 5.253 sq km respectively. The inundated areas into sea at each point and their uncertainties are depicted in Fig. 3b. It shows that the estimation of inundated areas into sea have high uncertainty along Mumbai coast (higher than 20 sq km) and less uncertainty along Chennai coast (less than 5 sq km). The overall calculation (on average) shows that 13.205 sq km of areas of Indian coastal region are inundated into sea due to sea level rise during 1975-2005 AD. The total area of Indian coastal areas i.e. the area surrounded by Indian coast (as marked in Fig. 1) for the years 1975 and 2005 are calculated. We find that the total area in 1975 and 2005 are 1593954.808 sq km and 1594045.002 sq km respectively. This shows an accretion of 90.194 sq km area along Indian coast during 1975-2005. It is worth mentioning that the regions having high tidal range could produce some disparity in the above results (because the boundary between sea and land moves up and down due to tides). Thus, this can be estimated more accurately by using a tidal correction method. However, in our study the spline interpolation technique (Mitášová and Mitáš, 1993) using GIS is used to determine the best-estimated points in land-water boundary in both years. Many previous studies (*e.g.,* Yamano *et al.,* 2006; Chen and Chang, 2009; Turner *et al.,* 2013) have also used the spline interpolation (deterministic) techniques to determine the land-water boundary in their studies.

The results discussed above indicate that the average rate of sea level rise along Indian coast is 1.415 mm per year in late 20th century and the average slant height of 2.136m of inundation area that went under sea during the said period. Our estimations of average rate of sea level rise are slightly different from those reported in Unnikrishnan and Shankar (2007). The overall estimation with consideration of accretion and inundation during 1975-2005 indicates that the Indian coastal areas are increased by 103.399 sq km. This is the addition of coastal areas accreted (90.194 sq km) and the coastal areas inundated (13.205 sq km) during 1975-2005. However, it is difficult to unambiguously identify the causes of such land accretion, we compared few sample regions along the Indian coast in 1975 with those in 2005 (shown in figure 4). These samples are taken from satellite images with 60m resolution where the land accretion is clearly discernable. The geographical locations of these sample regions are mentioned in the Fig. 1. Fig. 4a shows that some regions (marked as yellow colored circle) which was covered by the sea in 1975 are filled with land in 2005. Similarly, Fig. 4b shows that the regions (marked as magenta colored circle) which were covered by the sea in 1975 are transformed into land by 2005. It is also observed that some visible land in 1975 have gone under the sea or have been disappeared in 2005 as shown in Fig. 4c (yellow colored region). The cyan colored region of Fig 4c shows just opposite *i.e.,* some lands accreted in 2005 which were under the sea in 1975. Similarly, Fig. 4d shows that some regions which were under the sea in 1975 are covered by lands in 2005 (cyan colored region), whereas the magenta colored regions of Fig. 4d shows that some lands have gone under the sea or have been disappeared in 2005. Fig. 4e & 5f also indicate that some areas which were under sea in 1975 are converted to land in 2005. Here the question of tidal effect at each sample region may arise, but this can be neglected in conceptual analysis. Each sample region is taken from one scene of satellite imagery in same day except Fig. 4e which was taken from the mosaicked satellite imagery. Closer investigation into each region clearly indicates some accretion and erosion depending on regions. For example, Fig. 4d clearly shows some accretion in 2005 (marked as cyan circle) and some erosion in 2005 (marked as magenta circle). This implies the negligence of tidal effect, which is somehow disappeared after using of spline interpolator. Otherwise in both marked region of Fig. 4d, either land erosion or land accretion was observed at the same time.

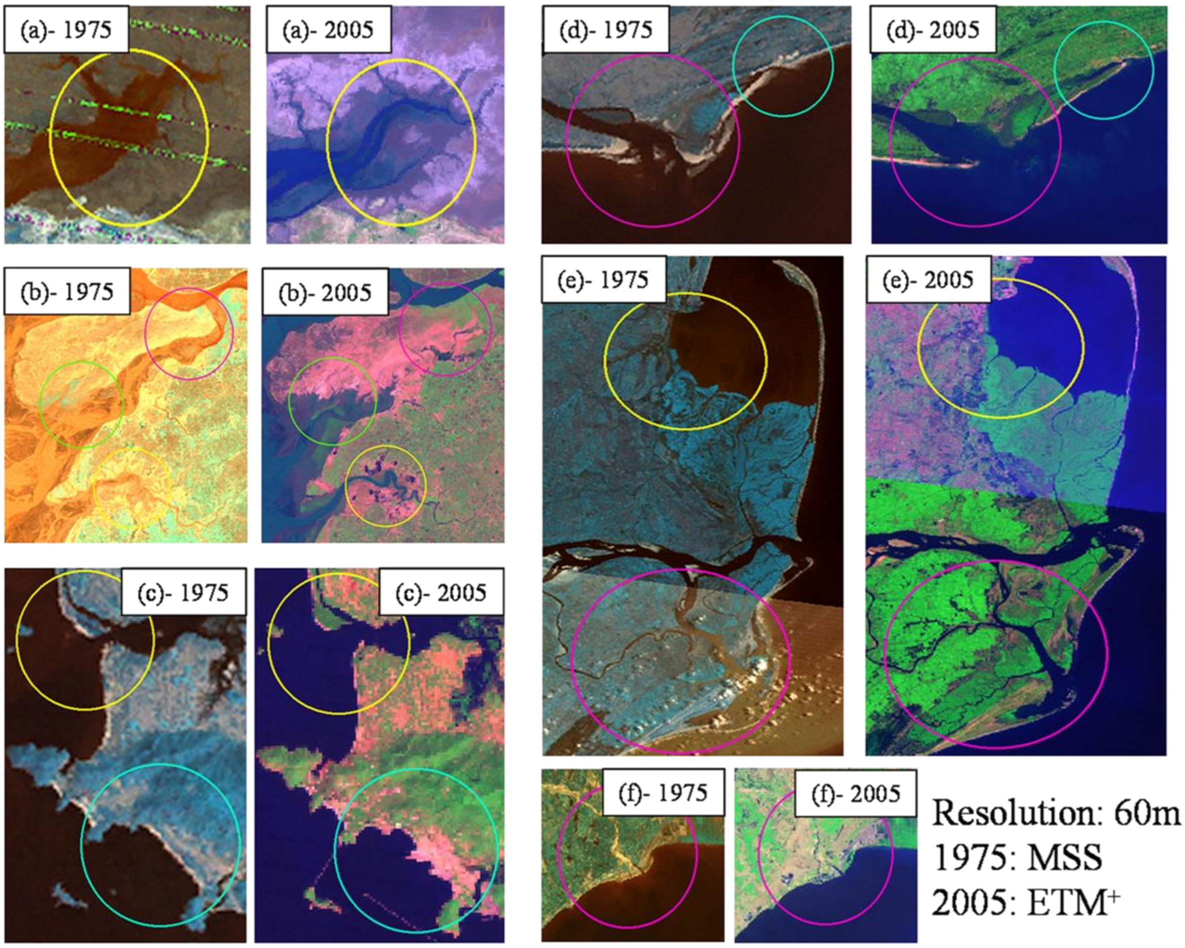


Fig. 4: Few sample coastal regions taken from satellite images where the land expansion or contraction is visible. The location of each images are shown in Fig. 1.

DISCUSSIONS AND CONCLUSIONS

This study presents the coastal changes along entire Indian coast in recent decades due to sea level rise during 1975-2005. Our results indicate that the Indian coastal area is accreting and it is estimated as 103.399 sq km during the period 1975-2005AD. Out of which, 13.205 sq km areas have gone under the sea along Indian coast due to sea level rise during this period. The satellite images (shown in Fig. 4) also justifies this and clearly indicate that some areas along Indian coast are accreted and some areas are eroded. However, the quantitative analysis of accretions or erosions at each region is not discussed in this study. Only the total area cover by the Indian coast is estimated from the Landsat datasets, which shows an accretion. Coastal areas with accretion are also highlighted in various studies across the globe *e.g.,* along the coast Gulf of Mexico (Callaway *et al.,* 1997); Louisiana coast (Cahoon, 1994); Puerto Rico coast (Ryan *et al.,* 2008); low lying pacific Islands (Wbb and Kench, 2010). The cause of the accretion may be ascribed to waves of the extreme events such as storm surges, tsunami etc. crash straight over the top of the reefs such as atoll, platform reef, fringing reef, barrier reef etc. and transport the debris and sediments to the coast (Ryan *et al.,* 2008; Mukhopadhyay and Karisiddaiah, 2014). Soil erosion and transport by the rivers to the coast may be another cause. The soil evolution due to weathering and subsequent transport of materials to the land-ocean interface by the wind, longshore currents and tides (*e.g.,* Cohen *et al.,* 2015) could also be reason for coastal accretion. The anthropogenic activities such as urbanization along coastal regions, building industries and waste disposals etc. may be another cause of coastal accretion (*e.g.,* Lee *et al.,* 2006). On the other hand, the inundation of coastal area that exacerbate coastal erosion in many places may be ascribed to human activities such as removing beach sands, shrimp farming, weakening coral reefs, land reclamation etc. as well as natural processes such as storm surges, extreme events, cyclones etc. The results also indicate an average rate of sea level rise of 1.415 mm per year during 1975-2005 AD along Indian coast and an average slant height of 2.136 m of inundation area that went under sea during this period.

All the above estimates are based on the increase of sea level along Indian coast, the slopes as obtained from 90m SRTM Image, and the preparation of land-water boundary along the Indian coast without tidal corrections. Thus the estimates are associated with the errors that already present in the SRTM datasets and also associated with the errors that occurred during the area estimation of Indian land. The above estimates can be improved by providing more reliable slopes and appropriate boundary points using further higher resolution images along the coastline after tidal correction. Though our results show an accretion along Indian coast, but still the causes of such accretion remained unclear and needs more research with more accurate datasets.

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REFERENCES

Alesheikh, A. A., Ghorbanali, A. and Nouri, N. (2007) Coastline change detection using remote sensing. International Journal of Environmental Science & Technology, v. 4(1), pp. 61-66.

Angusamy, N., and Rajamanickam, G. V. (2006) Depositional environment of sediments along the southern coast of Tamil Nadu, India. Oceanologia, v. 48 (1), pp. 87-102.

Bindoff, N. L., Willebrand, J., Artale, V., Cazenave, A., Gregory, J., Gulev, S., Hanawa, Quere, C. Le, Levitus, S., Nojiri, Y., Shum, C. K., Talley, L. D. and Unnikrishnan, A. (2007) Observations: oceanic climate change and sea level. *In:* Climate Change 2007. The Physical Science Basis. Fourth Assessment Report of the Intergovernmental Panel on Climate, Cambridge University Press, Cambridge, UK, and New York, pp. 385-432.

Cahoon, D. R. (1994) Recent accretion in two managed marsh impoundments in coastal Louisiana. Ecological Applications, v. 4(1), pp. 166-176.

Callaway, J. C., DeLaune, R. D. and Patrick Jr, W. H. (1997) Sediment accretion rates from four coastal wetlands along the Gulf of Mexico. Journal of Coastal Research, v. 13, pp. 181-191.

Chandramohan, P., Jena, B. K. and Kumar, V. S. (2001) Littoral drift sources and sinks along the Indian coast. Current Science, v. 81(3), pp. 292-297.

Chen, W. W. and Chang, H. K. (2009) Estimation of shoreline position and change from satellite images considering tidal variation. Estuarine, Coastal and Shelf Science, v. 84(1), pp. 54-60.

Cohen, S., Willgoose, G., Svoray, T., Hancock, G. and Sela, S. (2015) The effects of sediment transport, weathering, and aeolian mechanisms on soil evolution. Journal of Geophysical Research: Earth Surface, v. 120(2), pp. 260-274.

Jarvis, A., Reuter, H.I., Nelson, A. and Guevara, E. (2008) Hole-filled SRTM for the globe Version 4, available from the CGIAR-CSI SRTM 90m Database.

Jayappa, K. S., Vijaya Kumar, G. T. and Subrahmanya, K. R. (2001) Influence of Coastal Structures on the Beaches of Southern Karnataka, India. Journal of Costal Research, v. 19(2), pp. 389-408.

Kunte, P. D. and Wagle, B. G. (2005) The beach ridges of India: A review. Journal of Coastal Research, v. 42, pp. 174-183.

Lee, S. Y., Dunn, R. J. K., Young, R. A., Connolly, R. M., Dale, P. E. R., Dehayr, R., Lemckert, C. J., Mckinnon, S., Power, B., Teasdale, P. R. and Welsh, D. T. (2006) Impact of urbanization on coastal wetland structure and function. Austral Ecology, v. 31(2), pp. 149-163.

Manjunatha, B. R. and Shankar, R. (1992) A note on the factors controlling the sedimentation rate along the western continental shelf of India. Marine Geology, v. 104, pp. 219-224.

Mergner, H. and Scheer, G. (1974) The physiographic zonation and the ecological conditions of some South Indian and Ceylon coral reefs. Proceedings of the Second International Coral Reef Symposium (Australia), v. 2, pp. 3-30.

Mettier, R., Schlunegger, F., Schneider, H., Rieke-Zapp, D. and Schwab, M. (2009) Relationships between landscape morphology, climate and surface erosion in northern Peru at 5º S latitude. International Journal of Earth Science, v. 98, pp. 2009-2022.

Mitášová, H. and Mitáš, L. (1993) Interpolation by regularized spline with tension: I. Theory and implementation. Mathematical Geology, v. 25(6), pp. 641-655.

Mukhopadhyay R. and Karisiddaiah S.M. (2014) The Indian coastline: Processes and landforms. *In:* V. Kale (ed.) Landscapes and landforms of India. World Geomorphological Landscapes. Springer, Dordrecht, pp. 91-101.

Narayana, D. V. V. and Ram, Babu (1983) Estimation of soil erosion in India. Journal of Irrigation and Drainage Engineering, v. 109, pp. 419-434.

Nayak, S., Mandal, M., Adhikari, A. and Bhatla, R. (2013) Estimation of Indian coastal areas inundated into the sea due to sea-level rise during the 20th century. Current Science, v. 104(5), pp. 583-585.

Nayak, S. and Behera, M. D. (2008). Land Use/Land Cover classification and mapping of Pilibhit district, Uttar Pradesh, India. The Indian Geographical Journal, v. 83, pp. 1-10.

Rajawat, A. S., Chauhan, H. B., Ratheesh, R., Rhode, S., Bhanderi, R. J., Mahapatra, M., Kumar, M., Yadav, R., Abraham, S. P., Singh, S. S., Keshri, K. N. and Ajai (2014) Assessment of coastal erosion along Indian coast on 1: 25, 000 scale using satellite data. ISPRS-International Archives of the Photogrammetry, Remote Sensing and Spatial Information Sciences, v. 1, pp. 119-125.

Ramakrishnan, R. and Rajawat, A. S. (2012) Simulation of suspended sediment transport initialized with satellite derived suspended sediment concentrations. Journal of Earth System Science, v. 121 (5), pp. 1201-1213.

Ryan, K. E., Walsh, J. P., Corbett, D. R. and Winter, A. (2008) A record of recent change in terrestrial sedimentation in a coral-reef environment, La Parguera, Puerto Rico: A response to coastal development? Marine Pollution Bulletin, v. 56(6), pp. 1177-1183.

Singh, P. D. and Kambekar, A. R. (2016) Assessing impact of sea level rise along the coastline of Mumbai city using Geographic Information System. Springer Transactions in Civil and Environmental Engineering, Understanding Built Environment, Chapter 9, pp. 87-96.

Thanh, T. D., Saito, Y., Huy, D. V., Nguyen, V. L., Oanh Ta, T. K. and Tateishi, M. (2004) Regimes of human and climate impacts on coastal changes in Vietnam. Regional Environmental Change, v. 4, pp. 49-62.

Turner, J. F., Iliffe, J. C., Ziebart, M. K. and Jones, C. (2013) Global ocean tide models: Assessment and use within a surface model of lowest astronomical tide. Marine Geodesy, v. 36(2), pp. 123-137.

Unnikrishnan, A. S. and Shankar, D. (2007) Are sea-level-rise trends along the coasts of the north Indian Ocean consistent with global estimates? Global Plant. Change, v. 57(3-4), pp. 301-307.

Webb, A. P., and Kench, P. S. (2010) Vulnerability of atoll islands to sea level rise: multi-decadal analysis of island change in the central Pacific. Global and Planetary Change, v. 72, pp. 234-246.

Williams, J. S., Cahoon, D. R., Gutierrez, B. T., Anderson, K. E., Thieler, E. R. and Gesch, D. B. (2009) Sea-level rise and Its effects on the coast. Coastal sensitivity to sea-level rise: A focus on the Mid-Atlantic Region, U.S. Climate Change Science Program (USCCSP), Chapter 1, pp. 11.

Yamano, H., Shimazaki, H., Matsunaga, T., Ishoda, A., McClennen, C., Yokoki, H., Fujita, K., Osawa, Y. and Kayanne, H. (2006) Evaluation of various satellite sensors for waterline extraction in a coral reef environment: Majuro Atoll, Marshall Islands. Geomorphology, v. 82(3), pp. 398-411.

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