Spatio-Temporal Analysis of Coastal Dynamics along the Cuddalore Taluk Coast, Tamil Nadu, India

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Abstract
Urban coasts and estuaries undergo significant changes in erosion and accretion due to both natural and human factors. This study investigated the shoreline changes along the coast of Cuddalore Taluk, Cuddalore District, from 2003 to 2023. Shoreline changes were analysed seasonally for 20 years using multi-year remotely sensed data. All data were geo referenced with the UTM projection of WGS 1984 and digitised shorelines with the FCC Colour Image. Transect lines (155–231) were generated with a 100m space and 600m length along the shore using the DSAS tool. The tool generates EPR Statistic Reports for multi-year shorelines on each transect line. Shoreline changes were classified into five classes: High Erosion, Low Erosion, Stable, Low Accretion and High Accretion, based on the EPR Statistics Report. The overall result showed that 60% of the stable areas had coverage within a 4.7 km radius. Low erosion was 27% at 2.1 km and 0.5 km, with Low Accretion (6.4%) accumulated along the coast. However, 5.1% High Accretion was observed 0.4 km away, and High Erosion (1.3%) was observed 0.1 km away. The study has concluded that low-rate accretion occurs along the coast due to both natural and human interventions. Furthermore, scenario-based predictive models should be developed to predict long-term coastal development, including sea-level rise, changing storm frequency, and changing sediment supply. These models will support evidence-based coastal zone management, erosion mitigation planning and adaptation strategies at local and regional level.
Keywords: Coastal Dynamics, DSAS, EPR, Accretion, Erosion, Remote Sensing.

Introduction

The coastal ecosystems in India are facing a wide range of natural and anthropogenic stresses due to climate change and economic development. Therefore, proper management of these sensitive regions for holistic and sustainable development is the need of the hour (Gurugnanam. B et al., 2022).

As human civilisation expands rapidly along the Earth's coastlines, driven by the abundance of natural resources, the coastal environment faces mounting challenges. Climate change and infrastructure development exert immense pressure on coastal regions, thereby elevating the risks associated with various hazards, including coastal erosion, storms, rising sea levels, saltwater intrusion, and degradation of biological resources (Ramanujam et al., 2024). Tidal inundation, sea level rise, land subsidence, erosion, and sedimentation are among the physical processes (Chrisben Sam. S & Gurugnanam.B, 2022a) that greatly influence the dynamic nature of coastal areas, ultimately shaping the changes observed in both the shoreline and the overall coastal landscape (Pereira et al., 2022). Shorelines are important dynamic coastal features where land, air, and sea meet. In any open coast, when man-made structures such as harbours or breakwaters interfere with the littoral current, shoreline changes drastically. Chauhan et al. (1996) have opined that shoreline changes can be easily monitored using satellite data, an experience they have firsthand on the Indian coast. He stated that during low tide, the maximum land is exposed, and even the low-water line and land-water boundary are distinctly visible. He has also highlighted that this technology enables better mapping of the shoreline. These changes can affect ecosystems, communities, physical, climatic, and biological aspects, as well as the economy and social well-being (Raji et al., 2019; Sudhakar et al., 2020; Sudhakar & Gurugnanam, 2022). Shoreline migration has been identified using satellite images through various methods, including automatic (Mason and Davenport, 1996; Kuleli et al., 2011), semi-automatic, and manual approaches (Crowell et al., 1997; Moore et al., 1999; Priest, 1999). Thanikachalam et al. (2009) studied the changes in coastal morphology and seafloor changes, noting the changes along the coast of the Gulf of Mannar. Demir et al. (2004) discussed the impacts of sand dredging in the nearshore zone, including both direct and indirect effects on sediment transport. Monitoring changes in littoral profiles to develop erosion signatures is one approach used to quantify coastal erosion (Kana, 2013). Numerous researchers, viz., Selvavinayagam (2008); Chand and Acharya (2010); Kumaravel et al., (2013); Nateson and Subramaniam (1994); Natesan et al., (2013); Anitha and Natesan (2014), have monitored the shoreline changes along the Tamil Nadu coast using remote sensing and geospatial techniques. The shorelines are extracted from multi-temporal and multi-resolution satellite images of the Landsat series, downloaded from the United States Geological Survey (USGS) Earth Explorer archives (Chrisben Sam S &Gurugnanam, 2022b). The Digital Shoreline Analysis System (DSAS) is an ArcMap extension tool created by the U.S. Geological Survey (USGS) for shoreline analysis. The extension is downloaded from the link provided on the USGS website. The setup for the installation is used to run the tool. The Microsoft. NET framework and MATLAB component runtime utility were used to work with the tool (Madore, 2014). DSAS works by generating orthogonal transects at a user-defined separation and then calculates rates of change and associated statistics, which are reported in an attribute table. The DSAS tool requires user data to meet specific field requirements (Robert Thieler, 2005).The acquired data were transferred to the ArcGIS platform, and the shoreline changes were studied. In this study, the shoreline positions and changes over the last 20-year period, i.e., from 2002 to 2023, were examined using DSAS Techniques. The collected data were fed into the ArcGIS platform, which was used to analyse the changes in the coastline. The study examined the coastal conditions and changes over the last 20 years, from 2002 to 2023, by applying the DSAS method. Quantifying changes in the coastline in terms of erosion, accretion and stability is done by means of a digital shoreline analysis system (DSAS). The rate of change of the shoreline and statistical indicators such as net shoreline movement (NSM), end point rate (EPR), and shoreline change envelope (SCE) were estimated for spatial and temporal variability. Identify vulnerable coastal segments to erosion and accretion and assess their relationship to natural processes and anthropogenic intervention.

Study Area

The present study area, which forms part of the Cuddalore Coast in Cuddalore district, lies between 11° 44' and 11° 42' N latitude and 79°

45' and 79° 47' E longitude. The length of the seashore line is approximately 7.7 km, lying between Gunduuppalavadi and Pachchyankuppam (Fig. 1). The geology of the study area consists of sedimentary rocks of Cenozoic to recent age, mostly sandstone, covered by the Cuddalore Formation, known as Cuddalore sandstone. Sandy beaches are mostly covered along the coasts. The Cuddalore coast is bounded by two major rivers, the Gadillam and Ponnaiya rrivers in the north and the Velar and Coleroon rivers in the south, which control minor streams along the coast.

Figure 1 Study Area

Materials and Methods

In this study, seashore lines were extracted from Landsat satellite data (Table 1). The images were pre-processed through geometric correction and calibrated using radiometric correction (Arulbalaji & Gurugnanam, 2014a; Arulbalaji & Gurugnanam, 2014b; Arulbalaji, 2016). The images were reprojected to align with a single coordinate system for further processing. The seashore lines were digitised using FCC satellite data on the ArcGIS platform. GIS is an efficient tool for mapping and analysing spatial data sets (Nijagunappa et al., 2007;Gurugnanam et al., 2008; Bagyaraj, 2014; Kom et al., 2022, Kom et al., 2023). The shoreline was digitised, and the shorelines were imported into the DSAS Tool in ArcGIS. The baseline was created parallel to the shoreline and served as the baseline for the DSAS analyses, facilitating the generation of Transect Lines. The transect lines were generated along the perpendicular to the shorelines, and the DSAS statistical reports of End Point Rate (EPR) for multi-year shorelines were finally analysed using DSAS Techniques. The Statistical results are classified into five categories, viz., High Erosion (> -4 m/yr). Low erosion (-4 to -1 m/yr.), Stable (-1 to 1 m/yr.), Low accretion (1 to 4 m/yr.) and High Accretion (>4 m/yr.) for EPR (Sudhakar et al., 2019; Sudhakar et al., 2020)

Result and Discussion

The change in coastal landforms is primarily due to natural and marine forces, which in turn give rise to various land form features. Anthropogenic activity that takes place along the coastal regulation zone is also a reason for the erosion and deposition of sediments along the coast. The stress produced by these factors leads to instability in coastal environments. A comprehensive study was conducted to identify the shoreline changes that occurred in the study area. A systematic approach to the prompting parameters provides an outline of the various landforms formed by erosion and accretion. This process is time-consuming, and if the region is large, it will be challenging to survey, resulting in incomplete data if outdated methods are used. To overcome this difficulty, satellite data interpretation techniques are used to detect shoreline changes using remote sensing and GIS, which is also employed in mapping them. It is highly beneficial to discover the changes that have occurred in an area. The spectral properties were used to delineate land form features along the coast. Remote sensing data from IRS P6 LISS IV MX, Landsat TM, and ETM are used to demarcate the shoreline and track its changes. The Landsat images, multi-dated IRS–LISS III, and Landsat ETM imageries with different resolutions are used to study variations along the coast. The DSAS software is used to assess shoreline changes over 20 years, from 2003 to 2023.

Table 1 Shoreline Change Analysis in the Cuddalore Coast

Shoreline Change Analysis	End Point Rate of Shoreline Changes			
	Max (m)	Min (m)	Avg (m)	Length (km)
High Erosion	-4.1	-4.1	-4.1	0.1
Low Erosion	-1.0	-3.9	-2.2	2.1
Stable	0.9	-1.0	-0.3	4.7

Low Accretion	3.3	1.1	1.7	0.5
High Accretion	5.5	5.0	5.3	0.4

The results of the shoreline change studies on the Cuddalore coast reveal that a stable coast has been dominant due to the construction of Seawalls, Groynes, and Jetties along the coast (Fig. 4). This results in around 60% shelter on a 4.7 km stretch of the Cuddalore Coast (Fig. 3). However, a high-to-low rate of accretion was also observed. The high accretion has expressed at the rate of 5.3m/y noticed (5%) at 0.4 km and 0.5km of shoreline is low accretion (6.4%) with the rate of 1.7m/y (Table - 1), due to construction of jetties on both side of Kodilamestury (Fig.2). Southern side of the jetties sediments has been accumulated along the shore by drift current (Fig.4) as a result low to high accretion. However, a high-to-low rate of erosion was observed in the middle of the coast. Low erosion is observed at -2.2m/y along a 2.1 km length of the coast, which is 26% of the coastal length (Fig. 3). However, high erosion was less than low erosion. It covers only 0.1 km of the length of the coast (1.3%) with a rate of -4.1m/y (Table 1), owing to the construction of jetties on the Pennai and Kolidamestuaries (Fig.2). The then-Pennai was located on the northern side of the coast. Kolidamis located on the southern coast. The southern side of Kolidam jetties features an accretionary shoreline (Fig. 2) resulting from sediment accumulation. Between then and the Pennai and Kolidam coastal regions, stable to high to low erosion was experienced due to the jetties constructed on both estuaries. The stable areas are observed near the estuaries and in the middle of the coast, where high to low erosion is noticed due to littoral current deflection caused by the construction of jetties (Fig. 4).

Policy and Management Implications

The presence of stable and low erosion areas highlights the need to strengthen integrated coastal zone management frameworks by integrating scientific coastal monitoring with land use planning, port operations, and urban sprawl control. Coastal stretches which are subject to significant erosion require immediate, site-specific intervention. Soft engineering measures, such as beach nourishment, dune restoration, and enhancement of mangroves or coastal vegetation, should be prioritised, as they preserve the natural dynamics of sediment. Hard engineering structures should be avoided unless supported by a detailed impact assessment, as they have the potential to disturb sediment transport over long distances. Areas subject to low erosion should be managed using preventive and adaptive strategies, including regular monitoring of the coastline using high-resolution satellite data and analysis based on the DSAS. Early detection of coastal instability will allow early mitigation to be implemented before erosion becomes more severe Dominance…

Coastal infrastructure development, coastal modification, and mining activities should be strictly regulated by the effective enforcement of coastal regulation zones to minimise human-caused instability. In order to maintain natural accretion processes, integrated sediment management strategies should take into account river discharge, sediment inputs and dynamics of estuaries, in particular in estuary and coastal areas. Information on coastal change should be integrated into coastal climate change adaptation and disaster risk reduction policies, taking into account projected sea level rise, increased storm and extreme wave events, to increase long-term coastal resilience.

Future studies should focus on the integration of multi-source datasets, combining shoreline mapping by remote sensing, field observations (beach profiles, sediment characteristics), and numerical models of hydrodynamic and sediment transport. Developing predictive models of coastal change under different climate and development scenarios will provide coastal planners and managers with robust decision-support tools to enable proactive and sustainable management of coastal areas.

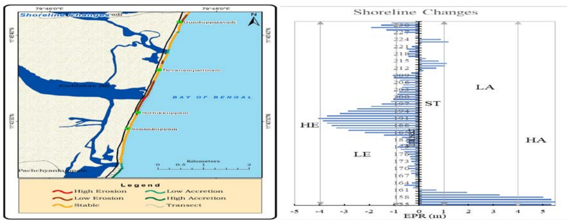

Figure 2 A) Cuddalore End Point Rate of Shoreline Change Map and B) Graphical Representation ST- Stable Coast, LA – Low Accretion, HA- High Accretion, LE- Low Erosion, HE- High Accretion

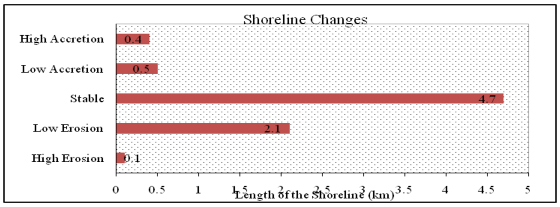

Figure 3 Shoreline Change Classification and its Length of Changes

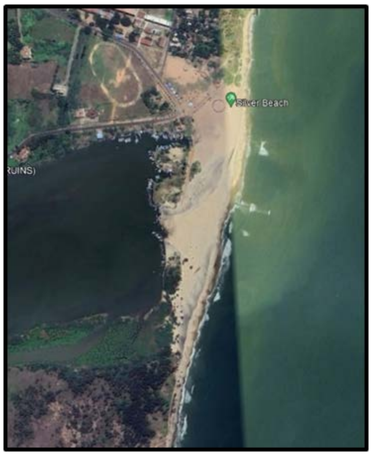

Figure 4 Sediment Accumulated near the Estuary and Seawalls, Groynes and Jetties are Constructed along the Coast

Conclusion

This study assessed the shoreline changes along the coast of Cuddalore, Cuddalore District, Tamil Nadu, India. This study concludes that the Maniple area of the Cuddalore coast has been dominated by a stable coast, characterised by absorption in Sonankuppam and Devanampattinam, owing to the construction of seawalls and groins along the shore. A low-to-high rate of erosion occurred at Sothikkuppam. It is the mouth of Pennai and Kolidam estuary due to wave and tidal actions,

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