Journal of the Indian Society of Remote Sensing (June 2023) 51(6):1309–1327
https://doi.org/10.1007/s12524-023-01698-w

RESEARCH ARTICLE

Geospatial Assessment of Long-Term Changes (1937–2019) in Mangrove Vegetation and Shoreline Dynamics of Godavari Estuary, East Coast of India

Snigdha Dev Roy[1] · Shivam Trivedi[2]

Received: 3 July 2022 / Accepted: 31 March 2023 / Published online: 14 May 2023

Abstract

Godavari mangroves are the second largest mangrove ecoregion of India located on its eastern coast. Mangroves perform major ecological functions including shoreline stabilization and coastal protection. They have undergone serious alterations, largely induced by human activities resulting in increased vulnerability to coastal flooding. A reliable database on mangroves distribution and temporal changes is essential for their effective management and conservation. Present study analyzes the long-term changes in mangroves, as well as the geomorphological changes along the coast of Godavari Estuary over a span of 82 years (1937–2019), using topographical maps, remotely sensed multi-temporal satellite imageries for five time periods. Results indicated that the rate of land uses conversions of agricultural fields, degraded areas, mudflats and mangrove vegetation into aquaculture significantly increased during the late 1990s. About 40 percent of it was constructed on mangrove areas between 1980 and 2019. The area under aquaculture was estimated to be 6,388.62 ha in 2000, almost doubling-up to 11,924.67 ha in 2019. Mangrove cover in this region increased by 15.95 percent between 2000 and 2019 (including 11.9 percent in Coringa Wildlife Sanctuary) due to increased protection, consequent regeneration and accretion. Shift in Hope Island spit was observed in north and northwest directions, gradually growing nearly 3.84 km. High-resolution declassified satellite data were found very helpful for long-term mangrove mapping and analyzing geomorphological changes; enabling a better understanding of these regions to help decision makers/planners to find better solutions to existing coastal issues. The paper concludes with some recommendations to restore and conserve the existing mangrove cover in the study area.

Keywords Mangroves · Godavari · Aquaculture · Declassified imagery · Image segmentation · Object-based image analysis

Introduction

Delta ecosystems, which are regarded as the cradles of civilization in India, have a great economic significance in terms of agriculture, water resources, wetlands, wildlife habitats, fish production and tourism (Day et al., 1995; Rao et al., 2010). The Godavari delta, which is also called the rice bowl of Andhra Pradesh, is a major prograding delta located along the eastern coast of India, fringing the Bay of Bengal (Fig. 1). It is a densely populated zone of intense economic activity which houses 729 persons/km^2 (Dandekar & Thakkar, 2014), about twice the Indian average (382 persons/km^2). The vast delta is a complex of marine and coastal ecosystems including a riverine estuary, a large bay, mangrove forests, large parts of which are protected in Coringa Wildlife Sanctuary (CWLS), and multiple distributaries of the river crisscrossing these mangrove forests (Malla, 2020). The East Godavari River Estuarine Ecosystem (EGREE) enclosing Godavari mangroves is the second largest contiguous mangrove region along the eastern coast of India, after the famous Sunderbans in West Bengal (Nandy & Kushwaha, 2011; Shankar, 2021). Thus, the delta has a rich biodiversity and is home to numerous

✉ Snigdha Dev Roy
sdroy0408@gmail.com; snigdha770bp18@spa.ac.in

1 Department of Physical Planning, School of Planning and Architecture, 4 Block-B, Indraprastha Estate, New Delhi 110002, India

2 Regional Remote Sensing Centre-South, National Remote Sensing Centre, Indian Space Research Organisation, ISITE Campus, Karthik Nagar, Bengaluru 560037, Karnataka, India

Fig. 1 Thick mangrove forests of CWLS (top), Shrimp farm ponds established at the expense of mangrove forests in the Godavari Region (bottom)

rare species, making it an important region for conservation in India (Malla, 2020).

These coastal and marine ecosystems play a vital role in supporting human welfare by virtue of its immense biological and mineral resources as well as the life-supporting systems they provide (GMR Group, 2020; UNDP, 2011). Economic installations and production operations along the coast, such as aqua farms, agriculture, marine fishing, gas and oil exploration, harbors and ports, and tourism, have been largely contributing to the regional economy. The economic value of various resources provided by a hectare of mangroves is between 2,00,000 to 9,00,000 USD approximately (Nguyen Dang Vu, 2006). According to a research, this service is worth 2,700 USD per hectare in the Godavari Delta, which extrapolates to almost 90,000 USD annually for the entire region (CORDIS, 2003; UNDP, 2011). Besides contributing to the economy for the East Godavari region, the mangrove landscape also plays a crucial role in livelihood development (GMR Group, 2020). It offers innumerable ecosystem services to a population of more than 79,400 people who reside in the 44 mangrove-abutting settlements. These villagers are directly dependent on the mangroves for their livelihoods as well as for firewood, timber, and fodder (Malla, 2020). About 40 percent of the population is actively involved in fishing (UNDP, 2011). The wetlands support the livelihoods of over 3,85,392 fishermen (3,03,000 marine and 82,392 inland) from almost 99 coastal fishermen villages in the area, out of which 76,777 are active fishermen (Fisheries Department, 2021). The number of fishermen families (44,476) in this district was the highest in Andhra Pradesh, in contrast to other districts (Maheswarudu et al., 2014). The five fish landing centers in and around CWLS alone recorded about 4,480 tonnes of fish catch during 2001–2002 (UNDP, 2011). In 2019, the East Godavari District recorded a catch of 84,080 tonnes of marine fish and 32,175 of inland fish with a total Gross Value Added (GVA) of INR 828 Crores (APEDB, 2019). For the purpose of manufacturing lime, about 3,600 tonnes of molluscs are annually removed from Coringa mudflats and Kakinada Bay. Bivalve species *(Anadara granosa, Placuna placenta, Meretrix sp, Macoma sp)* and gastropods *(Cerithidea cingulata, Telescopium telescopium)* are regularly handpicked (Department of Ocean Development, 2001). The bark of *Ceriops decandra* is used for dying the fishing nets and the *Porteresia coarctata* grass is used as fodder (Ravishankar et al., 2004).

But being low-lying and fragile ecosystems, these densely populated zones are, of late, subjected to extensive land-use changes and unprecedented environmental degradation mainly driven by the expansion of the aquaculture industry and industrial development that are borne out of conflicting interests of various stakeholders inhabiting the deltas as well as the river catchments, leading to severe coastal erosion, habitat loss and a high risk of flooding, which would be exacerbated in lower areas if there is a rise in the global sea level (Sarma et al., 2001). Available literature (Rao, 2009a) suggest that the mangrove ecosystem on the eastern coast of India is among the most susceptible regional habitats to be exposed to sea-level rise.

Recently, the region has also lost several acres of mangrove vegetation in the proximity of fishing villages near Kakinada town, where the state government authorities have levelled a part of the land for a specific housing scheme (Reddy, 2020). According to the new CRZ notification 2019 (https://ncscm.res.in/pdf_docs/crz-2019.pdf), exemplary power has been given to the state authorities to make infrastructure interventions, also permitting exploratory drilling of oil and natural gas and all associated activities in CRZ-I zone (Ecologically Sensitive Areas). Nearly 100 acres of mangrove land have been levelled so far for this housing scheme, with mangroves being chopped down and salt creeks covered up in mud largely affecting the livelihoods of the fisherfolk (Puzhakkal, 2020; Reddy, 2020).

A study had estimated that more than 8.7 million people and 28,000 km^2 of deltaic area across 33 deltas studied (including Godavari) could suffer from enhanced inundation and increased coastal erosion by 2050, if no mitigation measures are undertaken for the conservation of these ecosystems (Ericson et al., 2006). In this background, it is essential to understand the magnitude of, and the factors responsible for, the degradation of this important coastal ecosystem in the country and its environmental implications on such areas. The present study is such an attempt in this direction which also analyses the potential of using high-resolution declassified CORONA and KeyHole (KH-9) satellite imagery for long-term changes in mangrove vegetation and shoreline change dynamics in combination.

CORONA had been a satellite reconnaissance program providing satellite imageries, originally used by the United States of America during 1959–1972 for surveillance purposes, mainly of the Soviet Union (USSR) and Chinese nuclear and strategic missile programs (Day et al., 1998; Richelson, 2003). KeyHole (KH-9) was the program that followed CORONA and it ended in the 1980s, which was designed to support mapping requirements and exact positioning of geographical points for the military (USGS, 2008). Since this data ranges back to the year 1960s to 1980s, they are often resembling the sole known existing photographs of human footprints and settlements of that time (especially CORONA). This was before digital technology was invented that is currently used in all the polar orbiting remote sensing satellites (Rao, 2009b). Furthermore, since many formerly natural areas have overgrown by urbanization, this data offer unique insights into places that may be vulnerable to natural disasters, especially areas where settlements have now grown into former riverbeds (Fekete, 2020). Coastal dynamics and spatial change in the mangrove cover of a region can be investigated using such satellite imagery. The need to delineate the mangrove cover and shoreline positions and assess its variation through space and time is particularly crucial, given the long history of human settlements and human-induced activities within or near the coastal zones (Burningham & Fernandez-Nunez, 2020). Thus, the study focuses on a multi-temporal approach where shoreline change dynamics and mangrove changes along the coastal areas of the Godavari Estuary has been assessed using different remote sensing datasets of over a span of 82 years. Factors influencing the shoreline equilibrium and its impacts on coastal urban areas have also been investigated.

Materials and Methods

Study Area

The Godavari mangroves are located between latitudes 16°30′ and 17° N and longitudes 82°10′ and 82°25′ E in the East Godavari District of Andhra Pradesh, India. The Godavari River emerges in the eastern slopes of the Western Ghats (close to the west coast of India) and flows eastward across the Indian peninsula for 1,465 km, before being decanted into the Bay of Bengal on the eastern coast of India (Praveenkumar & Jothiprakash, 2021). The second largest river basin (about 3,12,812 km^2) in peninsular India after Ganga accounts for about one-tenth of the country's total geographical area, out of which the delta takes up nearly 5,100 km^2 (GRMB, 2016). In the pre-dam scenario, the Godavari River ranked ninth among the largest sediment transporting rivers in the world (Malini & Rao, 2004).

The lower Godavari River bifurcates into two distributaries – Gautami and Vasishta. Vainateyam, the third distributary branches out of the Vasishta farther downstream, while Gautami's terminal branching forms the fourth distributary, Nilarevu. Both these distributaries enter the sea through two mouths, one at Bhairavapalem in the north and the other near Kottapalem at the southern limit of the mangrove-bay complex (Fig. 2). The older tributaries of Gautami have been retained as Corangi and Gaderu canals that are about 11 and 21 km long, respectively (Rao, 2009a). In July 1978, the state government declared a portion of the Godavari mangroves as CWLS under Sect. 18 of the Wildlife Protection Act, 1972, extending in an area of about 235.7 km^2 in order to rehabilitate saltwater crocodiles that were on the verge of extinction, to protect other endangered species such as Olive Ridley turtles and Indian Otters, and to conserve the mangrove vegetation of

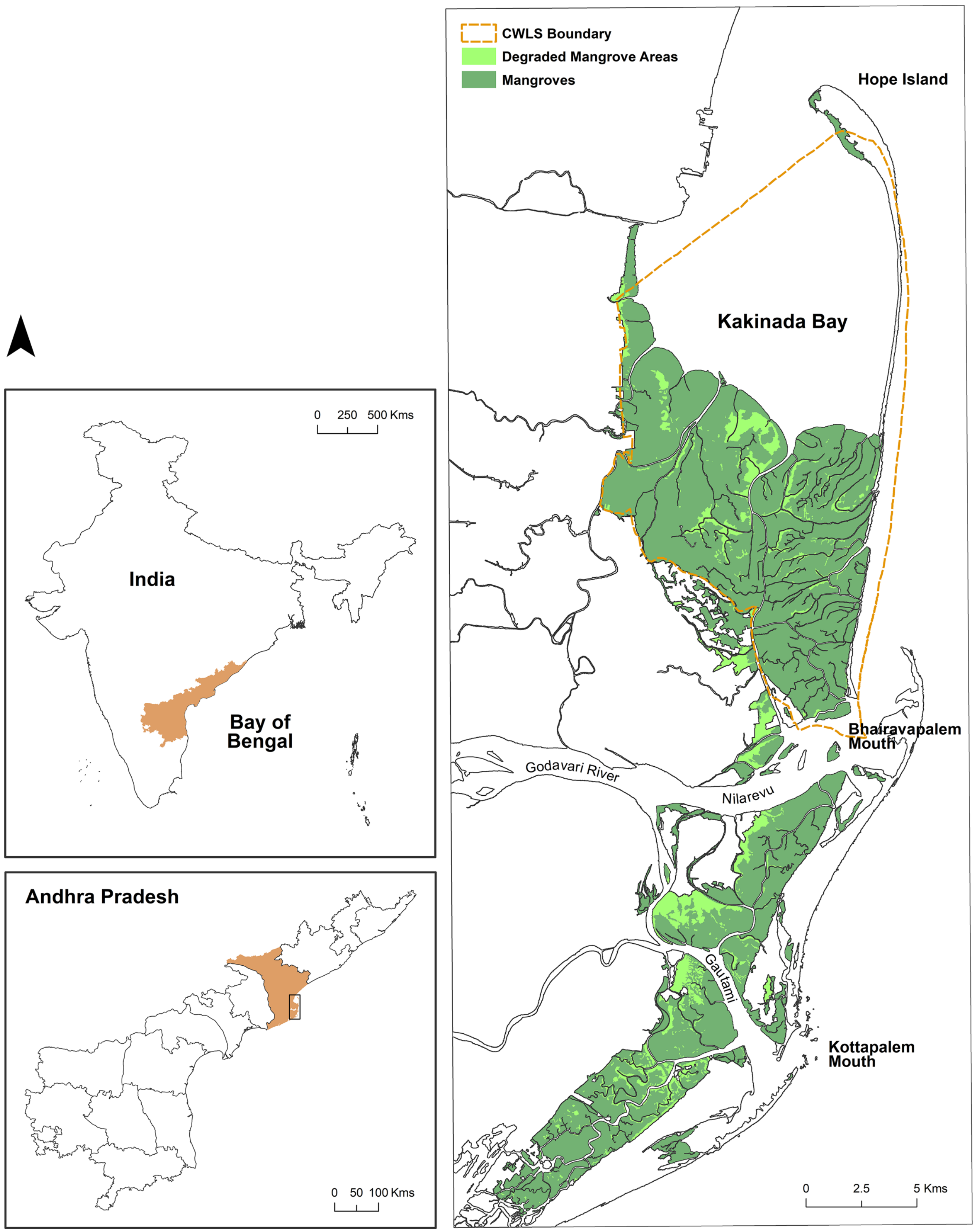


Fig. 2 Location map of the study area – Godavari Estuary (Mangrove Wetland)

the estuary (National Wildlife Database, 2020; UNDP, 2011).

The region has a semi-arid climate, with temperatures ranging from 22 °C in January to more than 35 °C in April and receives an average rainfall of about 1100 mm annually (Selvam, 2003). The region is also prone to severe cyclonic activities accompanied by stronger waves and occasional storm surges which often reach several kilometers inland in this extremely low-lying region sloping seaward at an average gradient of just about 0.011 percent (Rao et al., 2010). Tidal data from Kakinada at the north-eastern part of the Godavari delta indicate that the annual mean tidal range is $\sim$ 1.0 m and that the mean annual high tide is 1.38 m and the low is 0.36 m with the highest average monthly tides occurring in October and November and the lowest in February and March (Rao et al., 2013).

Remote Sensing Datasets

The present study was carried out using several sets of remotely-sensed, multi-temporal satellite images and topographic maps, spread over the past eight decades. Topographical map (1:250,000 scale) prepared by U.S. Army Map Service from 1937 (T_1), high-resolution declassified CORONA and KeyHole-9 images from 1965 (T_2) and 1980 (T_3), respectively, Landsat 7 TM images from 2000 (T_4) and Resourcesat-2A LISS IV MX images from 2019 (T_5) covering the intended region were digitally processed. Statistics for T_1 data should be deemed only as rough approximations due to its arguable mapping accuracy. Image to image rectifications for the 1980 data was carried out using Landsat 2 MSS from 1977 because of cloud cover, with an overlap error less than 1 pixel. The geometric projection for both images was set to UTM (Standard LANDSAT projection for the Indian region). The details of the data used in the present study have been shown in Table 1.

The topographical map and the satellite images for T_2, T_3, and T_4 were downloaded from the University of Texas site (http://www.lib.utexas.edu/maps/ams/india/#) and the United States Geological Survey (https://earthexplorer.usgs.gov/), respectively. Satellite data for T_5 were procured from NRSC Data Centre (NDC), National Remote Sensing Centre (NRSC), Hyderabad. The CWLS boundary was extracted from the shape file of protected areas of India available from the Wildlife Institute of India (WII), Dehradun.

Data Processing and Base Preparation

Three CORONA strips with dimensions 3 $\times$ 30 inches each ($\sim$ 3 m resolution) were provided in four split components (a, b, c, and d), whereas one strip of Keyhole image ($\sim$ 4 m resolution) with dimensions 9 $\times$ 18 inches was provided in two image components (a and b). They all were processed in Image Composite Editor to stitch the components of each image together, which faced errors related to projection type as ends of the strip were more skewed due to the panoramic effect. Thus, over-warped edges in the overlap area were also trimmed before georeferencing to achieve good matching. For this study, the first two components were stitched for each CORONA strip.

Following the completion of this process for all the images, KeyHole (1980) and CORONA (1965) images were georeferenced with Geographic Coordinate System World Geodetic System (GCS WGS) 1984 datum in QGIS 10.0, where Bing Map was effectively utilized as the reference image to provide more than 200 accurate Ground Control Points (GCP). Since the study present study employed only one strip of KeyHole imagery, no mosaicking was required. However, in order to obtain a uniform spectral intensity within and across all the CORONA strips, a number of color correction techniques were used iteratively in Erdas Imagine Software 2014. The detailed methodology for the registration of declassified imageries is given in Fig. 3.

Landsat 5 TM data for 2000 and Resourcesat-2A LISS IV MX data with 70 km swath for 2019 were in their original 30 m and 5 m resolution, respectively. Landsat 5 TM images were pan-sharpened where a high-resolution panchromatic band (B4) was merged with the lower resolution multispectral bands to create a single high-resolution (15 m) color image for better visual interpretation. These datasets were then subjected to a series of pre-processing techniques to create a seamless mosaic using the Erdas Imagine 2014 image processing software. Both the images were displayed in False Color Composite (FCC) using the band combination of 4, 3, and 2.

Classification and Shoreline Analysis

A multi-temporal image comparison was conducted by manual visual image interpretation through which a ten-class suitable, site-specific classification scheme was developed (Table 2), which has been adopted from the coastal feature classification proposed by Nayak et al. (1991).

Satellite images of all the years were subjected to multi-resolution segmentation using eCognition Developer software. It is a method which allows an image to be segmented into a network of homogeneous image regions at any required resolution (Tiwari et al., 2009). These image objects are abstract representations of image information that serve as building blocks for ensuing classification. It was tested out using various combinations of compactness

Table 1 Details of data used for different time periods in this study

Time Period	Map/Sensor Type	Year Issued/Date of Acquisition	Reference ID	Spatial Resolution (m)	Spectral Resolution
T_1	Topographical Map	1937	U502 Series: NE 44–15	1:250,000 Scale	
T_2	CORONA	1965/10/07	DS1025-1023DF083 DS1025-1023DF084 DS1025-1023DF085	~ 3	Panchromatic
T_3	KeyHole (KH-9)	1980/10/05	DZB1216-500481L004001	~ 4	Panchromatic
	Landsat 2 MSS *(For Reference)*	1977/09/17	LM02152048197709172019 0907	60	Green Red NIR
T_4	Landsat 7 TM	2000/12/08 2000/10/28	LE07141048200012082017 0208 LE07141049200012082017 0208 LE07142049200010282017 0209	15	Green Red NIR
T_5	Resourcesat-2A LISS IV MX 70 × 70 km swath	2019/10	–	5	Green Red NIR

and shape parameters at different resolutions. To obtain the image objects for all the time periods, multilevel resolution segmentation was carried out at different scales for each image since they had varying resolutions, with a constant compactness of 0.3 and shape factor of 0.7. All the features were obtained in separate image objects, which could then be further refined and classified in the ArcGIS environment.

The land–water interface is where the shoreline change analysis was done, leaving aside creeks, stream mouths and its inner parts and rivers. The classified maps of each year were used for delineating the shoreline by merging the polygons of all features except water. The scale selected for the wetland categorization was 1:250,000 as suggested by Nayak et al. (1991) for a better understanding of the areas, their inter-comparison and change detection. The overall configuration of the delta-front shoreline in the respective time periods was compared using overlay analysis in ArcGIS from which the geomorphological changes between successive datasets have been interpreted. Furthermore, a field survey was also carried out and geotagged field photographs were collected for use in the classification procedure (Fig. 1).

Change Detection

After the images of the five time periods (T_1, T_2, T_3, T_4 and T_5) were classified independently, the post classification change detection method was applied in ArcGIS 10.8, where they were compared to assess the quantitative and qualitative aspects of the changes in the spatial extent of mangroves and other land cover types. From the change map, the change area matrix table was generated which provided "from-to" information.

Accuracy Assessment

The quality of the classified images was tested separately for T_2, T_3, T_4 and T_5 through a rigorous accuracy assessment technique carried out in ArcGIS 10.8. Ground verification of 110–115 points was done for the land use and land cover classes of each time period and Bing Map was used as a high-resolution reference image. After this, the confusion matrix approach was adopted to calculate the overall accuracy and kappa statistics.

Results and Discussion

The long-term changes in the mangrove vegetation in the study area can be attributed to various factors such as natural regeneration and restoration, accretion and erosion, extensive land use changes particularly shrimp farms and aquaculture, which has been discussed in the following sections in detail.

Mangrove Change due to Natural Regeneration and Restoration

The interpretation of the satellite images reveal that the mangrove vegetation is concentrated more on the northern side (CWLS) of the Godavari River than on the southern

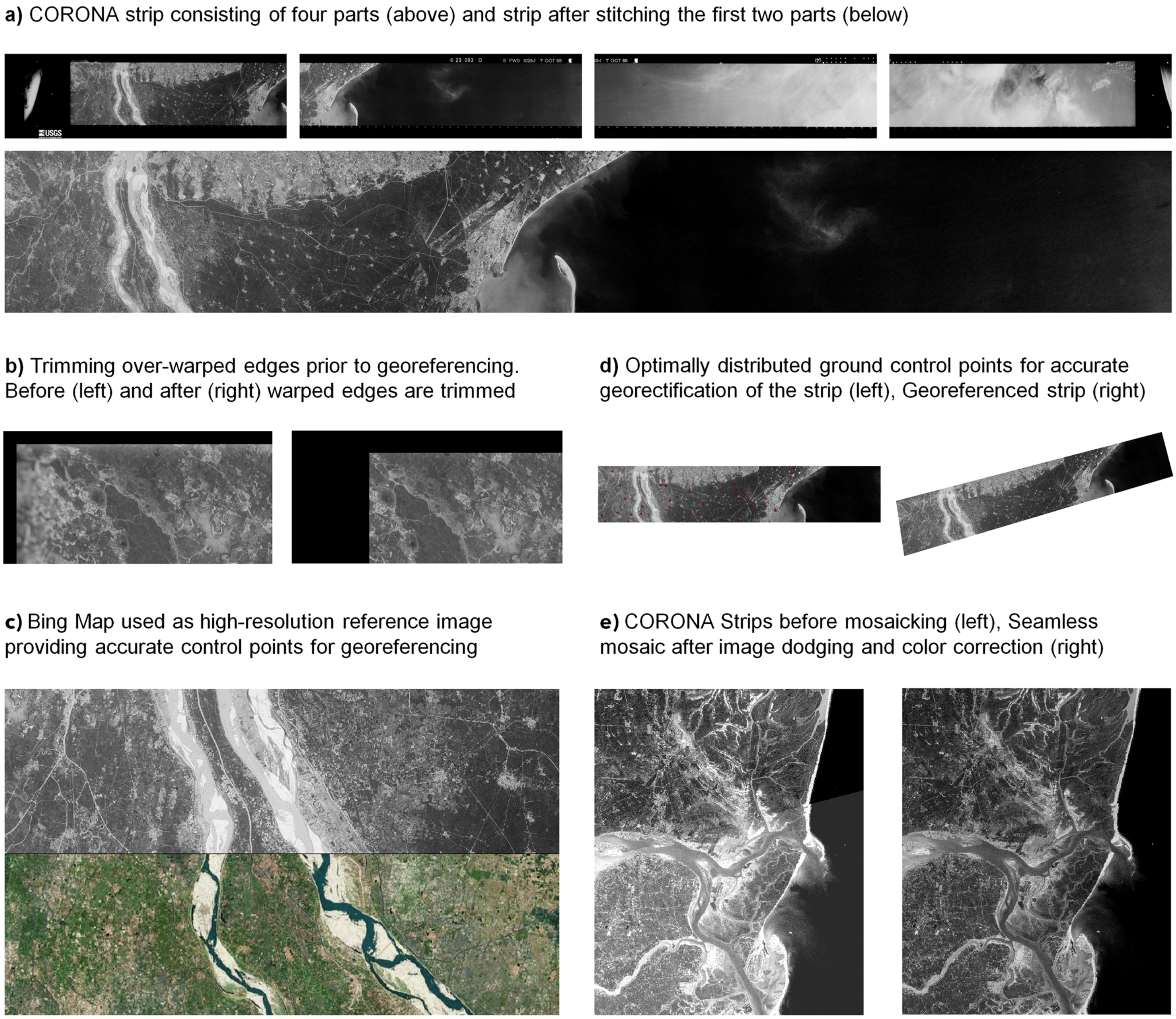
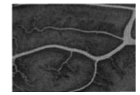
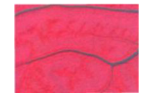
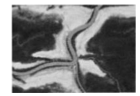
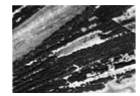
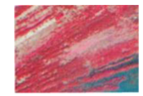
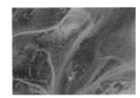
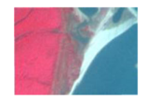
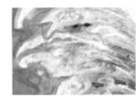
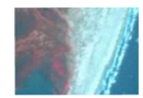
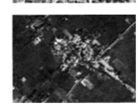
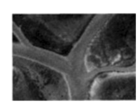
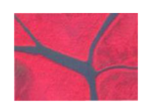


Fig. 3 Methodology used for the registration of CORONA and KeyHole images

side (Non-Sanctuary Area) as can be seen in Fig. 4. In 2019, the CWLS constituted almost 60 percent of the total mangrove cover present in the study area. This is because of the prolonged tidal flushing of mangroves in the sanctuary area which takes place through the creeks of Matlapalem *kalava* (canal), Corangi and Gaderu canals, bringing in dissolved nutrients like phosphates and nitrates to the mangroves (Ramasubramanian et al., 2006; Ravishankar et al., 2004). The canal system is highly intricate, and the flow nature is complex due to stratification that occurs throughout the year. Seawater enters from the north at Kakinada Bay and the south at Bhairavapalem. Long and widely branching mangrove creeks, where significant lateral water trapping occurs, provide an excellent habitat and nursery for a variety of fish *(Carangidae, Sciaenidae, Clupeidae and Leiognathidae)* and invertebrate species *(P. monodon, Metapenaeus affinis, Penaeus indicus and M. monoceros)* many of which are commercially important (Satyanarayana et al., 2002). The most dominant mangrove species found in the region are *Rhizophora mucronata, Rhizophora conjugata, Acanthus ilicifolius, Bruguera gymnorrhiza, Suaeda nudiflora, Lumnitzera racemosa, Excoecaria agallocha* and *Excoecaria marina* (Satapathy et al., 2007). This region is also protected from high energy water currents and velocity winds by the Hope Island sand spit which is an island located off the coast of Kakinada that acts as wave breakers (Bagaria et al., 2021a; Ramasubramanian et al., 2006). It is noted for its natural breakwater spread over 1,000 ha that has protected the coast during cyclones (Shankar, 2021).

During 1933 to the early 1970s, the Andhra Pradesh Forest Department (APFD) took over the management of

Table 2 Details of coastal features identified in the study

Features	Shape	Texture	Location	Association	Panchromatic		False Color Composite		Remarks
					Tone	Imagery	Tone	Imagery	
Wetland with Vegetation									
Mangroves	Irregular smooth	Smooth	Intertidal area	Low energy coasts or depositional area. Warm waters	Black/ Dark Grey		Bright Red		Grows on substrate mud/mud sand composition, where percentage of mud is more
Degraded Mangroves	Irregular smooth	Smooth	Intertidal area		White/ Light Grey		Pale Red		
Coastal Vegetation	Irregular	Rough	–	Clayey or silty	Black		Red		–
Wetland without Vegetation									
Mudflats	Irregular smooth	Smooth	Along lowest waterline	Low energy coasts	Light/ Dark Grey		Brown		Usually clayey and silty. Vegetation maybe present
Sand	Linear crescent	Smooth	Adjacent to coast, on land–water boundary	Open coast	Pure White		Pure White		Made up of fine sand particles, broken moluscan shell, etc
Aquaculture	Regular rectangular	Smooth	–	–	Light/ Dark Grey		Light/ Dark Blue		Place for cultivating fish/aquatic plants
Terrestrial Land									
Urban Area	Regular	Rough	–	–	Black/ White		Cyan/ White		–
Rural Settlements	Irregular	Rough	–	–	Black/ White		Red/ White		–
Agriculture/ Crop Land	Regular rectangular	Smooth	–	–	Black/ Grey		Grey/ Red		–
Other Features									
Creeks/ Water Body	Meandering	Smooth	Intertidal/Supratidal area	Mudflat	Light/ Dark Grey		Blue		Intricate network of narrow inlets of sea water in tidal flats

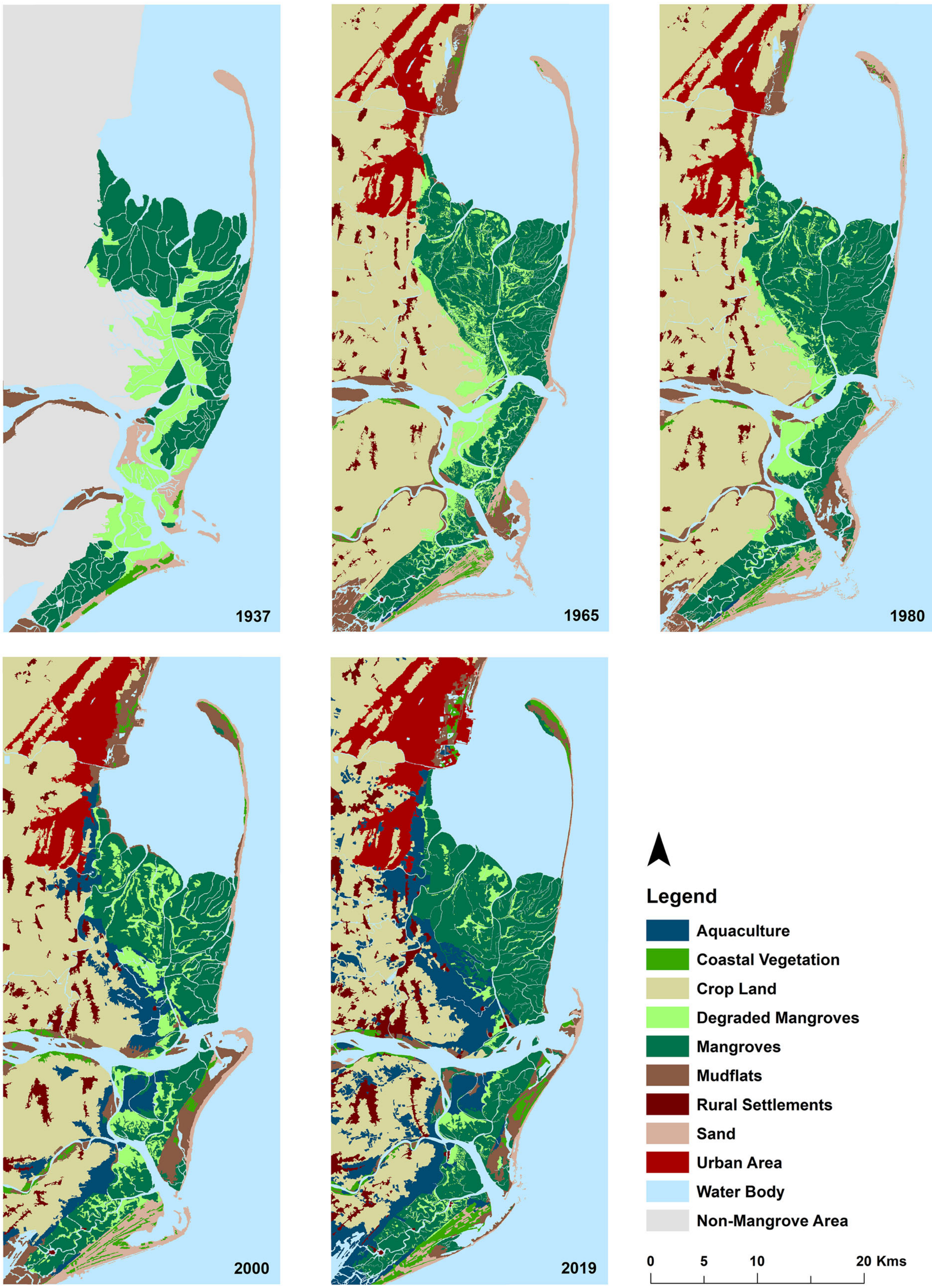


Fig. 4 Mangrove extent and cover between different time periods

Table 3 Magnitude of land use and land cover change in Coringa Wildlife Sanctuary (CWLS) between different time periods

Classes	Area (Ha.)				
	1937 (T_1)	1965 (T_2)	1980 (T_3)	2000 (T_4)	2019 (T_5)
Mangroves	10,639.25	9,862.06	10,603.75	9,404.86	10,527.89
Degraded Mangroves	1,741.50	1,519.91	1,048.86	1,975.45	899.47
Coastal Vegetation	0.00	2.18	15.50	86.05	97.66
Mudflats	0.00	30.53	105.14	393.50	306.21
Sand	262.24	907.79	741.89	561.39	107.14
Aquaculture	0.00	0.00	0.00	133.96	143.62
Rural Settlements	–	0.00	0.00	0.00	1.58
Agriculture/Crop Land	–	3.23	22.00	0.00	0.00
Creeks/Water Body	11,882.15	11,244.30	11,032.86	11,014.79	11,486.43

mangroves and systematically felled mangrove trees (Ravishankar et al., 2004). This unscientific management practice resulted in the development of hypersaline condition, which was one of the primary causes for the degradation of Godavari mangroves (Ravishankar et al., 2004; Selvam et al., 2004). Apart from this, other major causes included anthropogenic factors such as grazing by cattle, and collection of mangroves for firewood and fencing materials by nearby villages. Therefore, it can be examined from Table 3 that the mangrove cover was reduced from 10,639.25 ha to 9,862.06 ha in CWLS during 1937–1965.

In the 1980s, the degraded areas might have been left undisturbed and recovered/healed on its own due to local conditions as in the 1980 classified image, the restoration of mangrove vegetation in the degraded area is clearly noticed. Table 3 shows that the degraded area reduced from 1,519.91 ha in 1965 to 1,048.86 ha in 1980 in the sanctuary area after the CWLS was established with an overall reduction of 30.5 percent (1,356.60 ha) in the whole study area during that period. *Suaeda maritima* and *S. mudiflora* are commonly found in degraded and partially degraded areas (Ravishankar et al., 2004).

The change analysis of 2000 and 2019 indicates a significant reduction of degraded areas (1,075.98 ha), where the mangrove cover has also shown a positive increment of 1,123.03 ha in the CWLS. This shows the efficacy of various government interventions and restoration strategies in the area. Few studies (Bagaria et al., 2021b; Reddy & Roy, 2008) observed that the majority of positive changes in CWLS during this period was due to the active involvement of the government that has made efforts towards protecting the natural areas and undertaken various plantation and afforestation initiatives.

The APFD initiated various mangrove restoration programs in the Godavari Estuary in 1991 by digging canals in the degraded areas of CWLS (Ravishankar et al., 2004). The M. S. Swaminathan Research Foundation, a Chennai based non-government organization (NGO), had initiated reforestation projects in the area during 1997 to 2004 funded by the India-Canada Environment Facility (Rao, 2009a). Around 165 ha of degraded mangroves had been restored in five demonstration villages in the delta region during this period (Ravishankar et al., 2004). As part of the shelterbelt program, the state forest department also planted *Casuarina equisetifolia* along the coast (Ravishankar et al., 2004; Reddy & Roy, 2008), as a result, the area under coastal vegetation increased significantly from 763.41 ha in 1980 to 1,449.25 ha in 2000 (Table 4).

Mangrove Change due to Accretion and Erosion

Between 1980–2000, the results indicate pronounced erosion (1,812.98 ha), more than accretion (1,380.79 ha), along the delta front shoreline and estuarine banks of Godavari, putting the mangrove forests at higher risk. This is due to the fact that this area had been barricaded by several barrages and dam constructions which had picked up momentum during that time period in the Godavari River basin starting with the magnificent Sriramsagar in 1972, which was the first large-scale dam across the Godavari River followed by Jayakwadi in 1976, Balimela in 1977, Upper Indravati in 1994, Upper Wainganga in 1995 and many others built across the Godavari River and its multiple tributaries (Rao et al., 2010). Godavari delta has been classified as a delta that is receding faster than sea-level rise (Syvitski et al., 2009). According to Gupta et al. (2012), the drop in historic sediments of Godavari post damming was as high as 74 percent.

Though between 2000 and 2019, the mangrove forest increased by 15.95 percent (2,416.09 ha) as a result of increased protection, consequent regeneration and accretion. During this period, the extent of mangroves increased by 1,583.03 hectares owing to newly accreted areas (Table 5). The accretion was most likely caused by alluvium sedimentation from the Godavari River's flow

Table 4 Magnitude of land use and land cover change in the study area between different time periods

Classes	Area (Ha.)				
	1937 (T_1)	1965 (T_2)	1980 (T_3)	2000 (T_4)	2019 (T_5)
Mangroves	15,772.44	16,770.12	18,588.59	15,151.09	17,568.50
Degraded Mangroves	7,138.10	5,803.02	4,446.42	5,023.03	2,292.93
Coastal Vegetation	478.26	797.54	763.41	1,449.25	2,171.73
Mudflats	1,666.10	3,969.02	4,456.31	5,465.21	3,412.02
Sand	2,860.03	3,704.66	3,973.74	3,420.08	1,389.47
Aquaculture	0.00	58.43	68.01	6,388.62	11,924.67
Urban Area	–	5,248.15	5,415.70	6,451.62	7,948.48
Rural Settlements	–	1,824.42	2,145.39	3,012.44	4,508.87
Agriculture/Crop Land	–	34,299.92	33,758.62	28,455.84	22,531.50
Creeks/Water Body	54,784.38	56,032.73	54,892.05	53,691.06	54,760.86

Table 5 Changes in mangrove vegetation in the study area between different time periods

Changes	Area (Ha.)			
	1937–1965	1965–1980	1980–2000	2000–2019
Restoration/Natural regeneration in degraded areas	4,939.13	2,203.99	735.61	2,691.63
Natural regeneration in accreted areas	2,109.54	1,770.31	1,380.79	1,583.03
Total Gain	7,048.67	3,974.30	2,116.41	4,274.66
Degradation due to aquaculture	51.99	–	960.62	266.49
Degradation due to agriculture/built-up area	29.72	59.90	29.26	24.42
Degradation due to selective felling	1,677.69	1,064.00	2,751.05	538.12
Degradation due to erosion	4,291.59	1,031.93	1,812.98	1,028.21
Total Loss	6,050.99	2,155.84	5,553.91	1,857.25
Net Gain/Loss	997.68	1,818.47	− 3,437.50	2,417.41

through the Corangi and Gaderu canals. Until now, this is one of the very few Indian studies that has reported an increase in the extent of mangroves since 2000 (Singh et al., 2004). Erosion also reduced the mangroves by 1,028.21 ha during the same period. Floods during the southwest monsoons have been gradually eroding the mangrove vegetation along the southern bank of the Nilarevu River (Ramasubramanian et al., 2006). The small mangrove islands near the Bhairavapalem mouth seen in the 2000 image have also been eroded in the 2019 image. In 2000, the Hope Island sand spit had grown drastically and now, the northern part of it bears plantations and new mangrove formations.

Mangrove Change due to Aquaculture Farms and other Land Uses

Aquaculture and shrimp farming are the second major activity spread in the area after agriculture. The classified data reveal that aquaculture in the region covered a very scarce area of 58.43 ha and 68.01 ha during 1965 and 1980s, respectively. The map of 2000 and 2019 indicates that the major changes have been taking place in the vicinity of the mangrove-abutting areas as a result of increased anthropogenic pressure. These shrimp farms are mostly located in the private lands of the rural settlements fringing the mangroves. It can be seen from the analysis, that the rate of land use conversions of agricultural fields, degraded areas, mudflats and mangrove vegetation into shrimp farms during the late 1990s has increased substantially. The overall area of aquaculture was 6,388.62 ha in 2000 that almost doubled to 11,924.67 ha in 2019 (Table 4).

Analysis of the satellite data of 2000 and 2019 also shows that a total area of 1,227.11 ha of mangrove vegetation has been converted into aquaculture farms in the last four decades. About 38 percent (4,519.44 ha) of the aquaculture farms have been built on mangrove areas in over a span of 40 years out of which 277.58 ha is in the sanctuary area. The mangrove vegetation underwent a negative change of 3,437.50 ha mainly due to this reason during the same period. Satapathy et al. (2007) suggested that this has contributed to the production of 12,000 tonnes of shrimps from converted mangrove wetlands annually. Now catfish, carp, and a few species of shrimps as well as finned fish are commonly cultured in the area. The tiger prawn spawner *(Penaeus monodon)* is the main species cultivated in the region (Muralidhar et al., 2013). According to a study, the mangroves in this area have the potential to support an estimated catch of around 50,000 tiger prawn spawners annually, with a net worth of 6 million USD (Rönnbäck et al., 2003).

It is also noticeable that the rural settlements and urban areas have increased significantly during the years from 1,824.42 ha and 5,248.15 ha in 1965 to 4,508.87 ha and 7,948.48 ha in 2019, respectively. Analysis shows that 24.4 ha of mangrove cover, 207.2 ha of mudflats and 93.6 ha of degraded areas have been encroached upon by agriculture and built-up area during 2000–2019. It is evident that the mangrove vegetation cover can vary greatly based on the area's dynamics, natural events, and development activities (Reddy & Roy, 2008).

Research confirmed that shrimp farming and aquaculture have been an appealing and profitable choice for many farmers that had been begun in 1988 in the eastern coast of India who had to regularly deal with crops being flooded, intrusion of salt into irrigation water, and Bay of Bengal cyclones (Jayanthi et al., 2010). Despite this, a recent study done in 2019 by Animal Equality indicated that fertile lands across the Godavari delta region that are being furiously converted into aquaculture for shrimp and fish farming have shown an increasing salination in the quality of groundwater. Their putrefaction outside the ponds has also caused turbidity of water, foul odors and siltation with detrimental effects on local flora and fauna. As a result, it has raised several adverse effects in the region both in the physical environment and socio-economic environment (Satapathy et al., 2007). Gupta et al. (2001) observed that conversion of agricultural land to aquaculture has long-term environmental impacts such as permanent loss of agricultural land, overall groundwater contamination, etc. Thus, local aquaculture farmers must be educated about the detrimental consequences of unregulated and unmonitored aqua-farming. The government should provide special grants/incentives to projects that focus on expanding and improving the way the fish is farmed sustainably.

Geomorphology and Shoreline Changes

The geomorphic process of erosion and sedimentation, flooding and sea-level changes continuously modify the shoreline. The accurate demarcation of shoreline is very important for planning conservation measures (Nayak et al., 1991). Rao et al. (2003) found CORONA photographs to be very accurate for mapping of geomorphological changes in the Godavari estuary region which could not have been interpreted through modern day remote sensing imageries as these coastal linear features representing the former shoreline positions have been mostly changed due to recent intensive land use conversions. Analysis suggests that the high erosion trend of the coast has transformed to less and stable condition by 2019 as shown in Fig. 5. This observation can be supported by a similar study conducted by Murali et al. (2020) in the same region. Significant changes are noticeable in the Godavari shoreline configuration due to deposition (D) at the sand spits on the southern side of the Bhairavapalem mouth and erosion (E) at the coastline along the Bay of Bengal on the northern side of the Nilarevu River, i.e., from the river mouth to the tip of Hope Island as well as at the barrier islands (Fig. 6). Deposition of sediments on the southern bank of the River Gautami has been recorded by a study (Ramkumar, 2003), which has resulted in a gradual shift of the Gautami estuary since past eight decades. This observation is backed up by the results of the present study where the Gautami estuary has moved to the west from 1965–2019 (Fig. 6). Enlargement and elongation of Hope Island in the north and northwest directions is also seen over the years. A recent study (Bagaria et al., 2017) found that there was a disconnection between the estuary lobe and

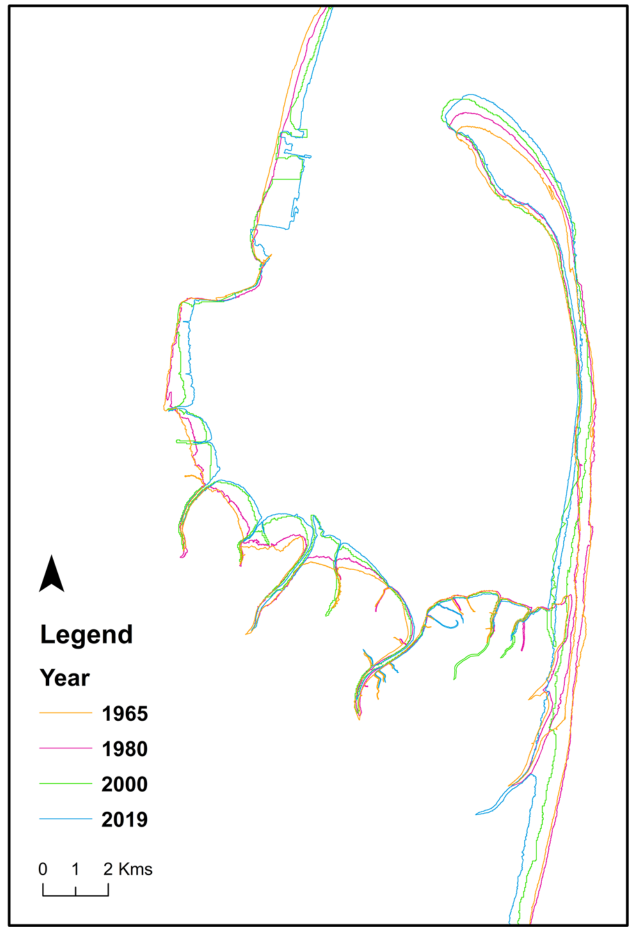


Fig. 5 Map showing shoreline changes in Kakinada Bay and Hope Island Spit

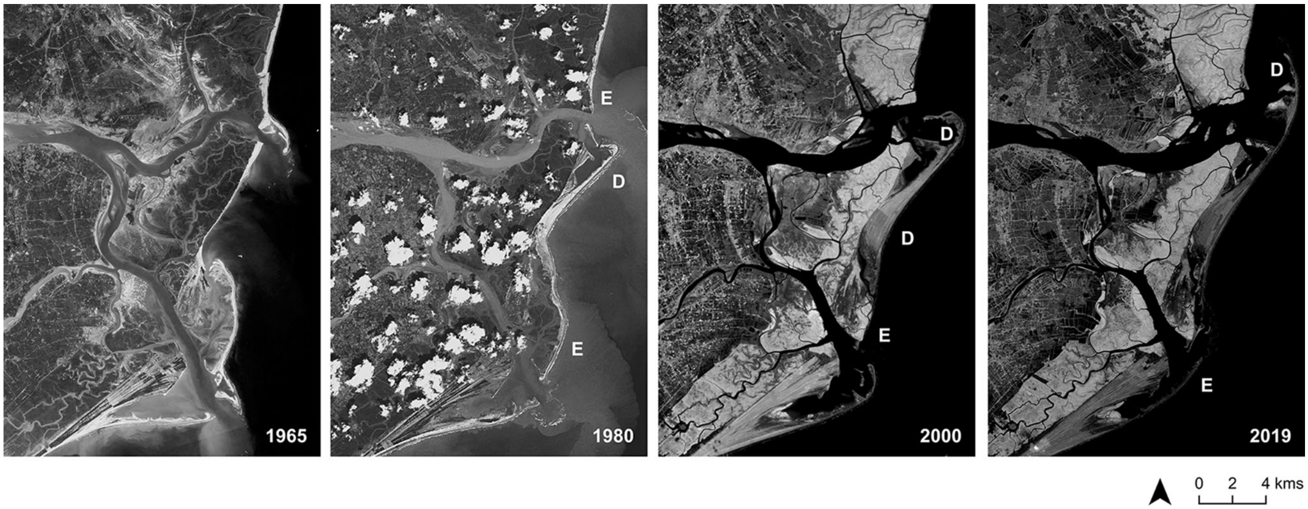


Fig. 6 Geomorphological changes in terms of Deposition (D) and Erosion (E) of the barrier islands between different time periods

Table 6 Increase in the length (in km) of Hope Island Spit and Bhairavapalem mouth between different time periods

Year	Hope Island Spit	River Span
1937 (T_1)	16.85	0.6
1965 (T_2)	18.38	1.27
1980 (T_3)	18.55	1.93
2000 (T_4)	19.64	2.45
2019 (T_5)	20.69	3.12

the sand spit that can also be seen in the 2019 map prepared in the present study. The length of the sand spit was 16.85 km during 1937 that has gradually increased to 20.69 km in 2019 (Table 6). According to Rajawat et al. (2015), due to dam construction this region saw significant coastal erosion brought on by changes in the equilibrium of sediment transport. The results from the shoreline analysis are a major contribution towards the proper understanding of shoreline dynamics across the Godavari Estuary.

During the course of 82 years, the river span of Nilarevu has also widened and that of Gautami has narrowed indicating a shift in the direction of river discharge. Rao et al. (2005) also observed such instances of increased erosion in the delta because of the widening of one of the draining channels. The river course has changed much near Bhairavapalem mouth, which was earlier towards the east in 1965, has eventually shifted towards the northeast in 2019. In 1965, the river span was about 0.6 km while in 2019 it has increased to 3.12 km owing to erosion (Table 6).

Classification Accuracy

The overall classification accuracies for T_2, T_3, T_4 and T_5 came out to be 93.91, 93.85, 92.85 and 95.49 percent, with kappa statistics of 0.93, 0.93, 0.92, and 0.94, respectively (Table 7). Accuracy assessments for each time period are shown in Table 8. The minimum level for accuracy assessment in the identification of wetland categories in remotely sensed data should be at least 85 percent (Nayak et al., 1991), indicating that the analysis produced very good results. The best results were of sand, followed by mangroves. While cropland and urban area showed relatively lower accuracies. Overall, the land cover classes could be distinguished well.

Conclusions and Recommendations

The present study attempts to understand the long-term changes in the mangrove vegetation and shoreline dynamics that have occurred along the eastern coast of the Godavari region and evaluating the cause of the same. Time series data for five time periods during a span of 82 years (1937–2019) reveal that the period from 1980 to 2000 was the most significant with reference to mangrove cover changes, as there was a drastic reduction in mangrove vegetation by 2000, which was estimated to be 3,437.50 ha. Overexploitation, conversion of mangrove into other land uses especially aquaculture and coastal erosion were found to be the three major threats in the region. Despite many causes of mangrove cover depletion, it has been found that there was an overall increase of 2,417.41 ha in the mangrove cover during the period 2000–2019 as compared to 1980–2000. The CWLS area had a positive increment of 1,123.03 ha in the mangrove

Table 7 Accuracy assessment of land use and cover classes in the study area between the time periods

Classes	1965 (T_2)		1980 (T_3)		2000 (T_4)		2019 (T_5)	
	UA	PA	UA	PA	UA	PA	UA	PA
Mangroves	1.00	1.00	1.00	1.00	1.00	0.76	1.00	1.00
Degraded/Mudflats	1.00	0.76	1.00	0.90	1.00	0.76	1.00	1.00
Coastal vegetation	1.00	0.90	1.00	0.90	0.80	1.00	1.00	0.90
Mudflats	0.90	1.00	0.90	1.00	1.00	1.00	1.00	1.00
Sand	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Aquaculture	1.00	1.00	1.00	1.00	0.70	1.00	1.00	0.90
Urban area	0.80	0.88	0.90	0.90	1.00	1.00	0.90	0.90
Rural settlements	1.00	0.90	0.90	0.90	1.00	0.90	0.70	1.00
Cropland	0.76	0.90	0.84	0.78	0.90	0.90	0.90	0.81
Water body	0.95	1.00	0.90	1.00	0.90	1.00	1.00	1.00
Overall accuracy (%)	93.91		93.85		92.85		95.49	
Kappa statistics	0.93		0.93		0.92		0.94	

UA: User's Accuracy, PA: Producer's Accuracy

vegetation during 2000–2019 which indicates the effectiveness of various government interventions for conservation in the area. Accretion and restoration have played a significant role in the formation and improvement of the mangrove cover in the area during the last eight decades. The study also revealed that the Godavari front shoreline has shifted significantly during the past eight decades.

CORONA and KeyHole photoreconnaissance satellite imagery has been found very useful for this study. There is a huge potential of using these easily available, high-resolution declassified data for long-term change-detection studies. This data can also help in delineating the various geomorphic changes in different time periods and also provide inputs to study the coastal erosion and accretion. Therefore, it is suggested that improved tools of remote sensing (high-resolution data) and GIS can enable a better understanding of coastal areas, so that a sound strategy can be devised for the conservation and management of such ecosystems.

The present research pertaining to the study of shoreline changes and mangrove mapping will help the decision makers and planning practitioners during the formulation of Coastal Regulation Management and Conservation Plans in identifying regions prone to mangrove degradation. This data is expected to also support the local authorities in adopting multi-disciplinary measurement strategies for the protection of eroding stretches of the mangrove shoreline as well as identifying the load of human activities on the sediment stability within the coastal zone.

To ensure proper maintenance of mangrove ecosystems, it is imperative to assess, sustain and further improve the extremely precious mangroves of the Godavari Region.

Joint Mangrove Management

It is recommended to engage various sectors and stakeholders involved in coastal areas through joint mangrove management and place development needs in a wider framework of planning and management. This will help address the underlying causes of the vulnerability of mangrove ecosystems, such as ensuring sustainable use of adjacent land, marine and river ecosystems to avoid impacts to soil surface, freshwater, nutrient and sediment supplies. Local fishermen communities can be stewards for mangrove management, and their support is likely to boost a project's chances of success. Such communities can volunteer in projects for restoration, regulate the use and access of mangroves, and directly benefit from sustainable management as well.

Local Awareness

Improving local awareness about the impacts of human activities in coastal areas is very important for the protection of mangrove ecosystems. The East Godavari River Estuarine Ecosystem (EGREE) Foundation in partnership with various Village Level Institutions (VLIs) and Non-Government Organizations (NGOs) have the authorization to execute such awareness among the stakeholders at various levels in the Godavari Region.

Alternative Sustainable Livelihood Models

Promoting sustainable livelihood models that do not rely on the consumption or pollution of mangrove resources could be another way to reduce the pressure on mangroves. Training and skill acquisition programmes on alternative

Table 8 Accuracy assessment of land use and cover classes in the study area for different time periods

Classes	Aquaculture	Coastal Vegetation	Cropland	Degraded Mangroves	Mangroves	Mudflats	Rural Settlements	Sand	Urban Area	Water Body	Total	UA	Kappa
1965													
Aquaculture	10.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.00	1.00	0.00
Coastal Vegetation	0.00	10.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.00	1.00	0.00
Cropland	0.00	0.00	10.00	1.00	0.00	0.00	1.00	0.00	1.00	0.00	13.00	0.77	0.00
Degraded Mangroves	0.00	0.00	0.00	10.00	0.00	0.00	0.00	0.00	0.00	0.00	10.00	1.00	0.00
Mangroves	0.00	0.00	0.00	0.00	10.00	0.00	0.00	0.00	0.00	0.00	10.00	1.00	0.00
Mudflats	0.00	1.00	0.00	0.00	0.00	9.00	0.00	0.00	0.00	0.00	10.00	0.90	0.00
Rural Settlements	0.00	0.00	0.00	0.00	0.00	0.00	10.00	0.00	0.00	0.00	10.00	1.00	0.00
Sand	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.00	0.00	0.00	10.00	1.00	0.00
Urban Area	0.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	8.00	0.00	10.00	0.80	0.00
Water Body	0.00	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	21.00	22.00	0.95	0.00
Total	10.00	11.00	11.00	13.00	10.00	9.00	11.00	10.00	9.00	21.00	115.00	0.00	0.00
PA	1.00	0.91	0.91	0.77	1.00	1.00	0.91	1.00	0.89	1.00	0.00	0.94	0.00
Kappa	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.93
1980													
Aquaculture	10.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.00	1.00	0.00
Coastal Vegetation	0.00	10.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.00	1.00	0.00
Cropland	0.00	0.00	11.00	0.00	0.00	0.00	1.00	0.00	1.00	0.00	13.00	0.85	0.00
Degraded Mangroves	0.00	0.00	0.00	10.00	0.00	0.00	0.00	0.00	0.00	0.00	10.00	1.00	0.00
Mangroves	0.00	0.00	0.00	0.00	10.00	0.00	0.00	0.00	0.00	0.00	10.00	1.00	0.00
Mudflats	0.00	1.00	0.00	0.00	0.00	9.00	0.00	0.00	0.00	0.00	10.00	0.90	0.00
Rural Settlements	0.00	0.00	1.00	0.00	0.00	0.00	9.00	0.00	0.00	0.00	10.00	0.90	0.00
Sand	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.00	0.00	0.00	10.00	1.00	0.00
Urban Area	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	9.00	0.00	10.00	0.90	0.00
Water Body	0.00	0.00	1.00	1.00	0.00	0.00	0.00	0.00	0.00	19.00	21.00	0.90	0.00
Total	10.00	11.00	14.00	11.00	10.00	9.00	10.00	10.00	10.00	19.00	114.00	0.00	0.00
PA	1.00	0.91	0.79	0.91	1.00	1.00	0.90	1.00	0.90	1.00	0.00	0.94	0.00
Kappa	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.93
2000													
Aquaculture	7.00	0.00	0.00	3.00	0.00	0.00	0.00	0.00	0.00	0.00	10.00	0.70	0.00
Coastal Vegetation	0.00	8.00	1.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	10.00	0.80	0.00
Cropland	0.00	0.00	10.00	0.00	0.00	0.00	1.00	0.00	0.00	0.00	11.00	0.91	0.00
Degraded Mangroves	0.00	0.00	0.00	10.00	0.00	0.00	0.00	0.00	0.00	0.00	10.00	1.00	0.00

Table 8 (continued)

Classes	Aquaculture	Coastal Vegetation	Cropland	Degraded Mangroves	Mangroves	Mudflats	Rural Settlements	Sand	Urban Area	Water Body	Total	UA	Kappa
Mangroves	0.00	0.00	0.00	0.00	10.00	0.00	0.00	0.00	0.00	0.00	10.00	1.00	0.00
Mudflats	0.00	0.00	0.00	0.00	0.00	10.00	0.00	0.00	0.00	0.00	10.00	1.00	0.00
Rural Settlements	0.00	0.00	0.00	0.00	0.00	0.00	10.00	0.00	0.00	0.00	10.00	1.00	0.00
Sand	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.00	0.00	0.00	10.00	1.00	0.00
Urban Area	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.00	0.00	10.00	1.00	0.00
Water Body	0.00	0.00	0.00	0.00	2.00	0.00	0.00	0.00	0.00	19.00	21.00	0.90	0.00
Total	7.00	8.00	11.00	13.00	13.00	10.00	11.00	10.00	10.00	19.00	112.00	0.00	0.00
PA	1.00	1.00	0.91	0.77	0.77	1.00	0.91	1.00	1.00	1.00	0.00	0.93	0.00
Kappa	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.92
2019													
Aquaculture	10.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.00	1.00	0.00
Coastal Vegetation	0.00	10.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.00	1.00	0.00
Cropland	0.00	0.00	9.00	0.00	0.00	0.00	0.00	0.00	1.00	0.00	10.00	0.90	0.00
Degraded Mangroves	0.00	0.00	0.00	10.00	0.00	0.00	0.00	0.00	0.00	0.00	10.00	1.00	0.00
Mangroves	0.00	0.00	0.00	0.00	10.00	0.00	0.00	0.00	0.00	0.00	10.00	1.00	0.00
Mudflats	0.00	0.00	0.00	0.00	0.00	10.00	0.00	0.00	0.00	0.00	10.00	1.00	0.00
Rural Settlements	1.00	1.00	1.00	0.00	0.00	0.00	7.00	0.00	0.00	0.00	10.00	0.70	0.00
Sand	0.00	0.00	0.00	0.00	0.00	0.00	0.00	10.00	0.00	0.00	10.00	1.00	0.00
Urban Area	0.00	0.00	1.00	0.00	0.00	0.00	0.00	0.00	9.00	0.00	10.00	0.90	0.00
Water Body	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	21.00	21.00	1.00	0.00
Total	11.00	11.00	11.00	10.00	10.00	10.00	7.00	10.00	10.00	21.00	111.00	0.00	0.00
PA	0.91	0.91	0.82	1.00	1.00	1.00	1.00	1.00	0.90	1.00	0.00	0.95	0.00
Kappa	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.95

income generating skills that are less or not dependent on mangrove resources such as tailoring, bid making, bee keeping, ecotourism, etc. should be encouraged.

Alternative Energy Sources

Encouraging the use of alternative energy sources to meet the growing demand without cutting mangroves for fuel or engaging in oil and gas exploration activities that damage mangrove ecosystems. The abundance of palm and casuarina trees in the region can be used as an alternative for mangrove wood for fuelwood and construction purposes.

Sustainable Aquaculture

Since, aquaculture is one of the main drivers of mangrove loss in the area, it needs to be developed in a more sustainable way. The local fishermen communities need to be sensitized about the negative impacts of unbridled, unmonitored aqua-farming. Standards for sustainable aquaculture take mangroves into account, prohibiting siting and encroachment in mangrove areas and requiring mangrove restoration and rehabilitation.

Integrating Mangrove Conservation in Sectoral Legal Frameworks

Provisions of sectoral laws such as forest management regimes, development permitting regulations and environment laws should be taken advantage of, in order to promote the conservation of mangrove ecosystems. It should be ensured that mangroves are included into emergency and natural disaster frameworks and that pollution rules such as Andhra Pradesh Pollution Control Norms take into account the particular impact of activities on mangroves.

Allocation of Financial Resources

Appropriate funds should be allocated to institutions that are involved in mangrove conservation and management for equipment, human resources and technical tools to undertake, inter alia, inventories, economic valuation, capacity building, public engagement, monitoring and management activities, recognizing the high value of mangrove ecosystems and the importance of their prioritization.

Acknowledgements We extend our sincere thanks to Dr. Ch. Sudhakar Reddy, Scientist-SG and Head of Department, Forest Biodiversity and Ecology Division, National Remote Sensing Centre (NRSC), Indian Space Research Organization (ISRO), Hyderabad and Dr. K Ganesha Raj, Former General Manager, Regional Remote Sensing Centre-South (RRSC-S), ISRO, Bengaluru for their technical guidance and encouragement. We thank the staff of RRSC-S for providing overall support during the course of our work. We also thank Kaladi Yaspal Varma, M. Tech (Remote Sensing), JNTUK Institute of Science and Technology, for supporting the geotagged field information collection for the study area.

Author Contributions Both the authors contributed to the conceptualization and design of the study. Material preparation, data collection and analysis were performed by SDR, with technical guidance from ST. The first draft of the manuscript was written by SDR and ST reviewed and commented on previous versions of the manuscript. Both the authors read and approved the final version of the manuscript.

Funding No funding was received for conducting this study.

Data Availability The datasets generated during the present study are available on reasonable request.

Declarations

Conflict of interest The authors declare no conflicts of interest.

Consent for publication Authors have read and agreed to the published version of the manuscript.

Consent to participate Not Applicable.

Ethics Approval Not Applicable.

References

APEDB. (2019). *East Godavari*. Economic Development Board Andhra Pradesh. Retrieved July 30, 2021, from https://apedb.gov.in/about-eastgodavari-district.html

Bagaria, P., Mitra, D., Nandy, S., & Sivakumar, K. (2021a). Shifting shoreline of the estuarine landscape in the East Godavari. *Environmental Earth Sciences*. https://doi.org/10.1007/s12665-021-09790-5

Bagaria, P., Nandy, S., Mitra, D., & Kuppusamy, S. (2017). Application of different satellite image classification techniques for mapping land use and land Cover of East Godavari River Estuarine Landscape, Andhra Pradesh, India. *International Journal of Advancement in Remote Sensing, GIS and Geography, 5*(1), 37–52.

Bagaria, P., Nandy, S., Mitra, D., & Sivakumar, K. (2021b). Monitoring and predicting regional land use and land cover changes in an estuarine landscape of India. *Environmental*

Monitoring and Assessment. https://doi.org/10.1007/s10661-021-08915-4

Burningham, H., & Fernandez-Nunez, M. (2020). Shoreline change analysis. In D. W. Jackson & A. D. Short (Eds.), *Sandy Beach Morphodynamics* (pp. 439–460). Amsterdam, Netherlands: Elsevier.

CORDIS. (2003). Assessment of mangrove degradation and resilience in the Indian subcontinent: the cases of Godavari Estuary and South-west Sri Lanka. Brussels: European Commission.

Dandekar, P., & Thakkar, H. (2014). *Shrinking and Sinking Deltas: Major role of dams in delta subsidence and effective sea level rise*. India: South Asia Network on Dams Rivers and People. Retrieved July 20, 2021, from https://sandrp.files.wordpress.com/2018/03/shrinking_and_sinking_delta_major_role_of_dams_may_2014.pdf

Day, D., Logsdon, J., & Latell, B. (1998). *Eye in the Sky: The Story of the CORONA Spy Satellites*. Washington DC, USA: Smithsonian Institution.

Day, J. W., Pont, D., Hensel, P. F., & Ibañez, C. (1995). Impacts of sealevel rise on deltas of the Gulf of Mexico and the Mediterranean: The importance of pulsing events to sustainability. *Estuaries, 18*(4), 636–647. https://doi.org/10.2307/1352382

Department of Ocean Development. (2001). *Critical habitat information system for coringa mangroves, Andhra Pradesh, India.* Chennai: ICMAM Project Directorate. Retrieved July 20, 2021, from https://www.nccr.gov.in/sites/default/files/Coringa.PDF

Fisheries Department. (2021, July 29). East Godavari District, Government of Andhra Pradesh. Retrieved July 31, 2021, from https://eastgodavari.ap.gov.in/fisheries-department/

Ericson, J., Vörösmarty, C., Dingman, S., Ward, L., & Meybeck, M. (2006). Effective sea-level rise and deltas: causes of change and human dimension implications. *Global and Planetary Change, 50*(1), 63–82. https://doi.org/10.1016/j.gloplacha.2005.07.004

Fekete, A. (2020). CORONA high-resolution satellite and aerial imagery for change detection assessment of natural hazard risk and urban growth in El Alto/La Paz in Bolivia Santiago de Chile Yungay in Peru Qazvin in Iran and Mount St Helens in the USA. *Remote Sensing MPDI, 12*(19), 3246.

GMR Group. (2020). *Mitigative Measures Against Activities (Proposed) in Ecosensitive Zone Area by GMR Enterprizes Private Limited, New Delhi.* Delhi: Kakinad Wildlife Range of Wildlife Management Division. Retrieved July 20, 2021, from http://forestsclearance.nic.in/writereaddata/17022017J59DPFK8Mitigationplangmr.pdf

GRMB. (2016). *About Godavari Basin*. Godavari River Management Board. Retrieved July 31, 2021, from https://grmb.gov.in/grmb/basin

Gupta, H., Kao, S.-J., & Dai, M. (2012). The role of mega dams in reducing sediment fluxes: a case study of large Asian rivers. *Journal of Hydrology, 464*, 447–458. https://doi.org/10.1016/j.jhydrol.2012.07.038

Gupta, M., Krishnarajan, V., & Nayak, S. (2001). Brackish water aquaculture site selection in coastal track of Cannanore (Kerala) Using remote sensing and GIS techniques. *Journal of the Indian Society of Remote Sensing, 29*(1–2), 79–83.

Jayanthi, M., Ravichandran, P., & Ponniah, A. (2010). *Status of mangroves in relation to Brackishwater aquaculture development in Tamil Nadu, India.* Chennai: Central Institute of Brackishwater Aquaculture. http://www.ciba.res.in/Books/ciba0499_.pdf

Maheswarudu, G., Ghosh, S., & Rao, M. V. (2014). Marine Fisheries Census 2005 and 2010 of Andhra Pradesh: A comparison. *Marine Fisheries Information Service, Technical and Extension Series, 221*, 16–20. http://eprints.cmfri.org.in/10373/1/13-MFIS-221.pdf

Malini, B. H., & Rao, N. K. (2004). Coastal erosion and habitat loss along the Godavari delta front - a fallout of dam construction(?). *Current Science, 87*(9), 1232–1236. http://re.indiaenvironmentportal.org.in/files/file/Godavari%20Delta%20dam%20construction.pdf

Malla, G. (2020). *Fishing cats of the Godavari mangroves, Andhra Pradesh*. WCS-India. Retrieved July 20, 2021, from https://india.wcs.org/Newsroom/Blog/ID/14990/Fishing-cats-of-the-Godavari-mangroves-Andhra-Pradesh

Murali, M., Reshma, K., Kumar, S., Balaji, A., Raju, K. M., & Ramakrishnan, R. (2020). Spatio-temporal coastal morphological changes of Godavari delta region in the east coast of India. *Journal of Coastal Research, 95*(1), 626. https://doi.org/10.2112/SI95-122.1

Muralidhar, M., Mariappan, K., & Dayal, J. (2013). Climate change and coastal aquaculture in West Godavari District, Andhra Pradesh: Impacts, vulnerability, adaptations and mitigations for resilience. *Journal of Agrometeorology, 15*(2), 116–122.

Nandy, S., & Kushwaha, S. P. (2011). Study on the utility of IRS 1D LISS-III data and the classifcation techniques for mapping of Sunderban mangroves. *Journal of Coastal Conservation, 15*(1), 123–137. https://doi.org/10.1007/s11852-010-0126-z

National Wildlife Database. (2020). *Wildlife Sanctuaries*. ENVIS Centre on Wildlife & Protected Areas, Wildlife Institute of India. Retrieved August 1, 2021, from http://wiienvis.nic.in/Database/wls_8230.aspx

Nayak, S. et al. (1991). *Manual for mapping of coastal wetlands/landforms and shoreline changes using satellite data.* Ahmedabad: Space Applications Centre. IRSUP/SAC/MCE/TN/32/91. 63 p. 1991

Nguyen Dang Vu, L. (2006, July 18). *Climate change threatens important mangroves*. SciDevNet. Retrieved July 20, 2021, from https://www.scidev.net/global/news/climate-change-threatens-important-mangroves/

Praveenkumar, C. H., & Jothiprakash, V. (2021). Spatio-Temporal Trend Analysis of Long-Term IMD-Gridded Precipitation in Godavari River Basin, India. In R. Jha, V. Singh, V. Singh, L. Roy, & R. Thendiyath (Eds.), *Climate Change Impacts on Water Resources: Hydraulics, Water Resources and Coastal Engineering* (pp. 59–66). Cham, Switzerland: Springer.

Puzhakkal, D. (2020, May 18). *Satellite images reveal 100 acres of mangroves felled for housing project in Kakinada*. Earth Journalism Network. Retrieved July 20, 2021, from https://earthjournalism.net/stories/satellite-images-reveal-100-acres-of-mangroves-felled-for-housing-project-in-kakinada

Rajawat, A. S., Chauhan, H. B., Ramakrishnan, R., Rode, S., Bhanderi, R. J., Kumar, M., & Keshri, K. N. (2015). Assessment of coastal erosion along the Indian coast on 1:25,000 scale using satellite data of 1989–1991 and 2004–2006 time frames. *Current Science, 109*(2), 347–353.

Ramasubramanian, R., Gnanappazham, L., Ravishankar, T., & Navamuniyammal, M. (2006). Mangroves of Godavari – Analysis Through Remote Sensing Approach. *Wetlands Ecology and Management, 14*(1), 29–37. https://doi.org/10.1007/s11273-005-2175-x

Ramkumar, M. (2003). Progradation of the Godavari Delta: A fact or empirical artifce? Insights from coastal landforms. *Journal of the Geological Society of India, 62*(3), 290–304.

Rao, N. K. (2009b). CORONA Satellite Photographs – A New (Old) Tool for Earth Scientists. *Geological Society of India, 73*(3), 425–429. https://doi.org/10.1007/s12594-009-0022-z

Rao, N. K., Sadakata, N., Malini, B., Sarma, V., Takayasu, K., & Kawase, M. (2003). Reconstruction of the Late Holocene progradation of the Godavari Delta, India: A preliminary study. *The Japanese Geomorphological Union, 24*(3), 295–309.

Rao, N. K., Sadakata, N., Malini, B., & Takayasu, K. (2005). Sedimentation Processes and Asymmetric Development of the Godavari Delta, India. In L. Giosan (Ed.), *River Deltas-Concepts, Models, and Examples* (pp. 433–449). Tulsa, Oklahoma: The Society for Sedimentary Geology.

Rao, N. K., Saito, Y. K., Kumar, K. C., Gajji, D., Rajawat, A., & Kubo, S. Z. (2013). Holocene Evolution of a Wave-dominated fan-delta: Godavari delta, India. *Palaeogeography, Palaeoclimatology, Palaeoecology, 440*(2015), 213–233. https://doi.org/10.1016/j.palaeo.2015.09.006

Rao, N. K., Subraelu, P., Kumar, K., Demudu, G., Malini, B., Rajawat, A., & Ajai. (2010). Impacts of sediment retention by dams on delta shoreline recession: Evidences from the Krishna and Godavari deltas. *India. Earth Surface Processes and Landforms, 35*(7), 817–827. https://doi.org/10.1002/esp.1977

Rao, R. (2009a). Climate change mitigation through reforestation in Godavari mangroves in India. *International Journal of Climate Change Strategies and Management, 1*(4), 340–355. https://doi.org/10.1108/17568690911002870

Ravishankar, T., Gnanappazham, L., Ramasubramanian, R., Sridhar, D., Navamuniyammal, M., & Selvam, V. (2004). *Atlas of Mangroves Wetlands of India.* Chennai, India: M. S. Swaminathan Research Foundation. Retrieved July 20, 2021, from https://www.indiawaterportal.org/sites/default/files/iwp2/Mangrove_wetlands_of_Andhra_Pradesh_Atlas_MSSRF_2002.pdf

Reddy, J. (2020, May 17). *The dire impact of removing mangroves in Andhra for a govt housing scheme*. The News Minute. Retrieved July 20, 2021, from https://www.thenewsminute.com/article/dire-impact-removing-mangroves-andhra-govt-housing-scheme-124722

Reddy, S., & Roy, A. (2008). Assessment of three-decade vegetation dynamics in Mangroves of Godavari Delta, India using multi-temporal satellite data and GIS. *Research Journal of Environmental Sciences, 2*(2), 108–115.

Richelson, J. (2003, June 1). *A "rifle" in space*. Air Force Magazine. Retrieved July 20, 2021, from https://www.airforcemag.com/article/0603kh7/

Rönnbäck, P., Troell, M., Zetterström, T., & Babu, D. E. (2003). Mangrove dependence and socio-economic concerns in shrimp hatcheries of Andhra Pradesh. *India. Environmental Conservation, 30*(4), 344–352. https://doi.org/10.1017/s0376892903000365

Sarma, V., Gurram, M. K., Malini, B., & Rao, N. K. (2001). Land use/land cover change detection through remote sensing and its climatic implications in the Godavari delta region. *Journal of the Indian Society of Remote Sensing, 29*(1), 85–91. https://doi.org/10.1007/BF02989918

Satapathy, D. R., Krupadam, R. J., Kumar, L. P., & Wate, S. R. (2007). The application of satellite data for the quantification of mangrove loss and coastal management in the Godavari estuary, East Coast of India. *Environmental Monitoring and Assessment, 134*(1–3), 453–469. https://doi.org/10.1007/s10661-007-9636-z

Satyanarayana, B., Raman, A. V., Dehairs, F., Chaganti, K., & Chandramohan, P. (2002). Mangrove floristic and zonation patterns of Coringa, Kakinada Bay, East Coast of India. *Wetlands Ecology and Management, 10*(1), 25–37. https://doi.org/10.1023/A:1014345403103

Selvam, V., Eganathan, P., Karunagaran, V. M., Ravishankar, T., & Ramasubramanian, R. (2004). *Mangrove plants of Tamil Nadu.* Chennai: M. S. Swaminathan Research Foundation. Retrieved July 20, 2021, from https://www.forests.tn.gov.in/tnforest/app/webroot/img/document/MSSRF-MANGROVES-IN-TAMILNADU.pdf

Selvam, V. (2003). Environmental classification of mangrove wetlands of India. *Current Science, 84*(6), 757–765. http://59.160.153.188/library/sites/default/files/Environmental%20classification%20of%20mangrove%20wetlands%20of%20India.pdf

Shankar, A. (2021, January). *Bringing mangroves back to life in East Godavari*. UNDP-India. Retrieved July 20, 2021, from https://www.in.undp.org/content/india/en/home/climate-and-disaster-resilience/successstories/mangrove-conservation-in-the-egree.html

Singh, I. J., Singh, S. K., Kushwaha, S. P., Ashutosh, S., & Singh, R. K. (2004). Assessment and monitoring of estuarine mangrove forests of Goa using satellite remote sensing. *Journal of the Indian Society of Remote Sensing, 32*(2), 167–174. https://doi.org/10.1007/bf03030873

Syvitski, J. P., Kettner, A. J., Overeem, I., Hutton, E. W., Hannon, M. T., Brakenridge, R., & Nicholls, R. J. (2009). Sinking Deltas due to Human Activities. *Nature Geoscience, 2*(10), 681–686.

Tiwari, P. S., Pande, H., & Pandey, A. K. (2009). Automatic urban road extraction using airborne laser scanning/altimetry and high resolution satellite data. *Journal of the Indian Society of Remote Sensing, 37*(2), 223–231. https://doi.org/10.1007/s12524-009-0023-9

UNDP. (2011). *Mainstreaming Coastal and Marine Biodiversity into Production Sectors in the Godavari River.* Andhra Pradesh, India: United Nations Development Program. Retrieved July 20, 2021, from https://info.undp.org/docs/pdc/Documents/IND/00060659_Project%20Document%20-%2076477.pdf

USGS. (2008) *USGS EROS Archive - Declassified Data - Declassified Satellite Imagery - 2*. United States Geologial Survey. Retrieved July 20, 2021, from https://www.usgs.gov/centers/eros/science/usgs-eros-archive-declassified-data-declassified-satellite-imagery-2?qt-science_center_objects=0#qt-science_center_objects