Coastal Ecological Sensitivity and Risk Assessment: A Case Study of Sea Level Change in Apodi River (Atlantic Ocean), Northeast Brazil

Mukesh Singh Boori[1], Venerando Eustáquio Amaro[2], Helenice Vital[3]

Abstract**—**The present study has been carried out with a view to calculate the coastal vulnerability index (CVI) to know the high and low sensitive areas and area of inundation due to future SLR. Both conventional and remotely sensed data were used and analyzed through the modelling technique. Out of the total study area, 8.26% is very high risk, 14.21% high, 9.36% medium, 22.46% low and 7.35% in the very low vulnerable category, due to costal components. Results of the inundation analysis indicate that 225.2 km² and 397 km² of the land area will be submerged by flooding at 1m and 10m inundation levels. The most severely affected sectors are expected to be the residential, industrial and recreational areas. As this coast is planned for future coastal developmental activities, measures such as industrializations, building regulation, urban growth planning and agriculture, development of an integrated coastal zone management, strict enforcement of the Coastal Regulation Zone (CRZ) Act, monitoring of impacts and further research in this regard are recommended for the study area.

Keywords**—**Coastal planning, Land use, Satellite data, Vulnerability.

I. INTRODUCTION

A nation should have adequate information on its natural resources as well as many interrelated aspects of its activities for decision making. Coastal landforms and wetlands are a few of such resources which have acquired importance as they influence various developmental activities along the coastal regions. Coastal region is an important resource as they are avenues for agricultural practice, ground water exploitation, coastal townships, recreational zones, silica sand and heavy mineral exploration, etc.

The coastal environment is undeniably one of the most affected by the agents of topography and landscape modeling. This is mainly its geographical location. Which is change due to wind, wave, tidal, marine currents, etc., besides these natural factors; there are many human factors, which is responsible for changes in the natural course of coastal dynamics. The set of these factors, natural and man-made, provide mixed results. The most obvious outcome of sea level rise (SLR) due to storms, tsunami or even global sea level change is the permanent inundation of coastal areas and it will have a serious impact upon the natural environment and socio-economic conditions in the coastal zone. Over time, inundation changes the position of the coastline and drowns natural habitat and coastal structures. Inundation can also exacerbate coastal erosion by transporting submerged sediments offshore, and extending the effects of coastal flooding by allowing storm waves to act further. Wave heights also increase when concentrated on head lands or when travelling into bays having wide entrances that become progressively narrower. Geographic features of near shore and coastal land of an area can alter the inundation pattern of tsunami waves. During the tsunami, the maximum vertical height to which water is observed with reference to sea level (spring tide or mean sea level) is referred to as run-up. The maximum horizontal distance that is reached by a tsunami is referred to as inundation. SLR would directly result in a corresponding higher shift to the zone of wave action on the beach. This would be reflected in a shoreline recession which will be larger on milder slopes.

Although there is great diversity in the textural composition of the beaches and, consequently, the lines back - these are generally made by mud, sand gravel and blocks of rock - for the most vulnerable to coastal dynamics are generally the sandy of natural unprotected beaches [1]. Where in These beaches the sediments are more easily reworked and depositional and retrains prorated to other sites, since it does not present great resistance to the erosions processes. The Coast of Apodi River is composed by sandy beaches, sometime which is protection of natural beach rocks.

In countries like Brazil, where the coastline is very long, mapping of these natural resources of coastal region by conventional techniques is a difficult task mainly due to their large extent in some areas and widespread habit. Satellite remote sensing is one of the most effective tools that can be used for mapping the natural resources in a rapid and accurate

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manner. This is made possible because of the repetitive and synoptic nature of orbital remote sensing. Coastal sensitivity assessment has been carried out using remote sensing (RS) and geographical information system (GIS) by [2]. It is strongly linked to the eco-environment and socioeconomic value assigned to coastal components. Possible changes to these values will assist in the selection and interpretation of possible responses to the changing boundary conditions such as SLR, human interference and other climatic changes [3]. The results of the sensitivity assessment will be very useful in integrated coastal zone management plan [4]. A coastal vulnerability index (CVI) was used to map the relative sensitivity of the coast to future SLR within the study area. [5] have completed risk assessment of coastal sensitivity along various coasts based on the work of [6]. They have incorporated six physical coastal variables: geomorphology, shoreline change rate, coastal slope, mean tide range, mean significant wave height and SLR. The main objectives of the present study were to develop a CVI for coastal erosion and then use it to assess the impact along the Apodi coast, with a view to identify and quantify the vulnerable low lying coastal areas of Apodi, due to SLR and land loss due to coastal erosion. RS and GIS tools can be used to prepare the land use and land cover map and shoreline change detection maps [7].

II. DISCRIPTION OF THE STUDY AREA

The study area is located on the northwestern portion of Rio Grande do Norte State, along the Apodi River. The Apodi River originates nearby Apodi city in the semiarid region on the Northeast Brazil, and flows NE through Mossoro, Areia Branca and Grossos districts of Rio Grande do Norte State, and discharges directly into the Atlantic Ocean (Figure 01). The geographic coordinates are limited by latitude 04°55'46".77 to 05°13'39".41 south and longitude 37°01'30".79 to 37°22'42".42 East.

Climate of the area is semiarid tropical type [8], with mean annual *temperature* about 27.5°C. November is the best hot season with maximum temperatures exceeding 40°C. The daily temperature range is usually in between 8 and 10°C and annual fluctuations around 5°C.

The average *rainfall* is 700-900 mm/y and mostly concentrated during February-April and can fall at high intensities [9], but is accompanied by very high potential *evaporation* (in excess of 2,000 mm/y). These climate changes can be explained by the movement of the inter-tropical convergence zone (ITCZ), where the periods of drought are related to his removal from the coast, causing the lack of rainfall and the area of strong winds, while the rainy periods are linked to their shifting to the south, relating to more lenient wind. The normal relative *humidity* in a year is 68.7% and may fluctuate during the year a range of 20% [10, 11]. This is lower in September with 59.9% and higher in April to 78.1%.

Northeast Brazil is characterized by high incidence of *solar energy*, with uniform thermal regime characterized by high temperature and small variations during the year. This is due to geographical factors of the region, such as low latitude, near the sea and the gently wavy relief plan. The sunshine in the Apodi region is the highest in Brazil, reaching on average 2,900 hours per year, equivalent to 7.9 hours of daily sunlight. The average monthly variation over the year was a minimum of 6.3 hours/days to a maximum of 9.5 hours/day, measured on the Macao Meteorological Station-RN.

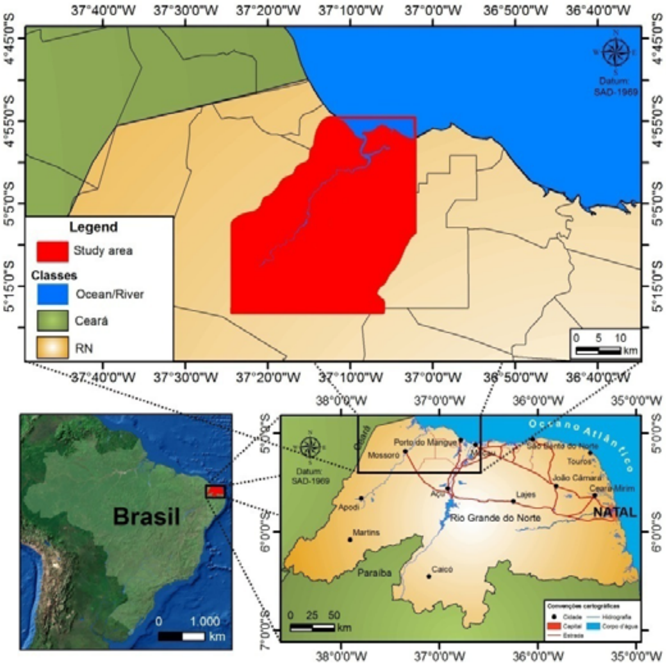

Fig. 1 Study area location on Rio Grande do Norte State, Northeast Brazil.

The speed and direction of *winds* influenced directly to the coastal processes and is the generation of waves. It's an important agent in the sediment dynamics on the beaches. The average winds speed masseur in the study area is 5 m/s in April and 9 m/s in between August to October, but can reach up to 18 m/s during the month of August [12].

The main *economic activities* of the area are shrimp, fisheries, agriculture, tourism and industrialization and hence there is an increase in urbanization along the coast. In addition to these, this coast is well known for the coastal ecosystem such as mangroves, coastal forest, salt ponds, shrimp farms and long sandy beaches. All these activities will be increasing the sensitivity of the Apodi coast to future SLR.

III. DATA PRODUCTS

A study related to coastal processes involves the analysis of both conventional and remotely sensed data. Conventional data are more accurate and site specific, but data collection is time consuming, expensive, requires more manpower and it may not be possible to extrapolate to a larger area. Remotely sensed data on the other hand have got advantages due to repetitive and synoptic coverage of the large, inaccessible areas quickly and economically. In the present study, to take the dual advantages, both conventional and remotely sensed data were used.

The main remote sensing products used in this research work were: orbital images of Landsat TM, ETM+, Spot 4-HRVIR, IKONOS, CBERS 2B and SRTM data. Topographic sheet were used in this research work were SB-24-XB-IV, SB-24-XDI, XDI-SB-24-1-2 MI-897-2. Digital image processing was performed using the ER Mapper 7.1 software, involving the geocoding in UTM cartographic projection Zone 24S - Datum SAD-69 and the Root Mean Square (RMS) were less than 1.0, standardizing the data and increasing the reliability of products obtained. Maps of geo-environmental units (geology, geomorphology, soils and vegetation) were prepared on scale of 1:150.000, from the interpretation of satellite imagery using Arc GIS 9.3 software and field applications. All secondary data collected from [10, 13] IDEMA, IBGE and metrological department of RN, Brazil.

Trimble hand held GPS of accuracy 10m was used to map the shoreline and to collect the coordinates of important land use/cover features in the study area during the pre and post classification field visits while preparing the land use/cover map. Finally Shuttle Radar Topography Mission (SRTM) data of approximately 90m resolution were downloaded from the website and used to prepare the digital elevation map (DEM) and then the inundation map of the study area. All these data sets were utilized to study the impact of SLR on land loss, land use/cover, and coastal erosion (Table 1).

IV. METHODOLOGY

Mainly we were focused on 20 sample sites (A) along the coast and (B) all around the Apodi River. Around the river locations are vegetation, industrial and urban area and along the coast locations are considered as one of the more deserted beaches with only small buildings (summer homes) without major electrical installations and less frequented by tourists, only a few fishermen. It is a very open beach, without natural or artificial obstacles, which makes it unprotected against the effect of tides, causing a likely retreat to the shoreline. Beach dunes are being constantly fed by the frontal dunes, which are at the beginning of the post-beach, which are formed mainly by sediment coming from estuary. The slope of estuary average does not exceed 2. Even in the estuary is the formation of beach cusps with a length of about 24m, only in April, May and June (winter). We can find a considerable amount of polluting materials such as glass, plastic, organic waste and from others. The vegetation is heterogeneous with low intensity, being common to salsa, coconut trees and the beach grass.

The CVI allows the six variables to be related in a quantifiable manner that expresses the relative vulnerability of the coast to physical changes due to future sea level rise. This method yields numerical data that cannot be equated directly with particular physical effects. It does, however, highlight areas where the various effects of sea level rise may be the greatest and it is the same as that used by [6, 5]. Land/beach loss due to coastal erosion and coastal inundation are the two types of physical impacts considered in the present study. The six variables are classified into two groups:

1. Ecological variables,
2. Geo-physical variables.

The eco-geophysical variables include (a) historic shoreline change, (b) geomorphology, (c) coastal slope, (d) mean tidal range, (e) mean significant wave height and (f) global SLR. Once each section of the coastline is assigned a vulnerability value for each specific data variable, the CVI was calculated as the square root of the product of the ranked variables divided by the total number of variables.

$$\mathrm{CVI} = \sqrt{\frac{a \times b \times c \times d \times e \times f}{6}} \tag{1}$$

where, a geomorphology, b shoreline change rate (m/yr), c coastal slope (%), d mean tidal range (m), e mean significant wave height (m), f global SLR (mm/yr).

The ecological variables consist of geomorphology, historic shoreline change rate, and coastal slope; they account for a shoreline’s relative resistance to erosion, long-term erosion/accretion trend, and its susceptibility to flooding, respectively. The geo-physical process variables include significant tidal range, wave height, and global SLR, all of which contribute to inundation hazards of a particular section of the coastline over time scales from hours to centuries. These six variables include both qualitative and quantitative information. Actual variable values are assigned a vulnerability ranking based on value ranges, whereas the non-numerical geomorphology variable is ranked qualitatively according to the relative resistance of a given landform to erosion.

In the present study, ranking was assigned for these variables along twenty stations in the study area and thus CVI was calculated for these stations. The stations were selected based on sensitivity and the magnitude of the changes in shoreline from 1986 to 2009. The CVI can be used by scientists and engineers to evaluate the likelihood that physical change may occur along a shoreline as the sea level rises and to take necessary actions. The CVI may also be used to judge suitable sites of industrialization, development of ports and harbours, urbanization or tourism. The values and ranking assigned for each variable are described in the following paragraphs.

TABLE I

RANGES OF VULNERABILITY RANKING FOR THE STUDY AREA

Sl. no.	Variable	Ranking of coastal vulnerability				
		Very low	Low	Mediam	High	Very high
		1	2	3	4	5
1	Geomorphology	Rocky cliffed coasts	Medium cliffs, Indented coasts	Low cliffs, lateritic plain	River deposits, alluvial plain	Coastal plain, beach, mud flats
2	Shoreline erosion/accretion (m/yr)	>+15	+5 to +15	-5 to +5	-15 to -5	<-15
3	Coastal slope (%)	>0.6	0.5–0.6	0.4–0.5	0.3–0.4	<0.3
4	Mean tide range (m)	>4.0	3.0–4.0	2.0–3.0	1.0–2.0	<1.0
5	Mean significant wave height (m)	<0.7	0.7–1.4	1.4–2.1	2.1–2.8	>2.8
6	Mean sea level rise (mm/yr)	<1.8	1.8–2.5	2.5–3.0	3.0–3.4	>3.4

A. Geomorphology

The local morphology is the result of semi-arid climate, predominantly activated in the most of northeastern Brazil. The study area show a significant influence of river-sea quaternary plains, where the direct action of coastal processes (tides, wind, waves, and currents) and anthropogenic modeling is an important agent. The geomorphology variable expresses the relative erodibility of different landform types (Figure 2A). The ranking is on a linear scale from 1 to 5 in order of increasing vulnerability due to SLR [6]. The value of 1 represents the lowest risk (rocky cliffed coast) and 5 represents the highest risk (coastal plain, beach, mud flats) as far as coastal erosion is considered. In the present study, a detailed geomorphology map has been prepared by using toposheets of 1: 50,000 scale (Table 1).

B. Shoreline Change Rate

The results obtained in the analysis of the profiles are fully related climatic variations between summer and winter. Approximately 70% of the world’s sandy beaches have been identified as eroding [14]. Though beaches along the Apodi coast are maintaining dynamic equilibrium, there will be temporary sea erosion during the monsoon, due to high wave activity [15]. In the winter months was the formation of the front dune, which increased in volume over the months, ex. they approached the month of July (end of winter), the volume gradually increased in the sediment profile. In the summer months, the winds were very strong up to reach approximately 31.3 km/h, so that these dunes were remobilized front line of the profile, reflecting the migration may be the same for SW, and/or to the power cords of the large mobile dunes that are behind the profile. Training and remobilization front dunes can be explained as follows: For the winter months, with the increase of rain, the dunes are partly saturated in water and consequently more compressed, and difficult to mobility by the action of the winds. Already during the summer months, with the decrease of rains, the dunes become dry and therefore more mobile, and with help from strong winds, tend to migrate.

To calculate the shoreline erosion/accretion rate along the Apodi coast, TM, ETM+, Spot 4-HRVIR, IKONOS, CBERS 2B and SRTM data of 1986 to 2009 were analyzed using the ERDAS Imagine software. The vector layers of 1986 and 2009 were overlaid using Arc GIS software [16] and the final map was obtained (Figure 2B). During this period of RS data analysis, some of the sites showed significant erosion and the river mouths showed a tendency of shifting towards the southeast. The minimum width of beach was 3m under accretion and erosion, whereas the maximum beach width was 100m under accretion and 96m for erosion. The ranking of the shoreline change rate is based on the range of change in beach width values. By superimposing the RS data on the base map, the area of accretion and erosion was calculated and then the maximum erosion and maximum accretion rate were estimated as -17.00 m/yr and +17.67 m/yr respectively. Shorelines with erosion/accretion rates between -5 m/yr and +5 m/yr are ranked medium. With ± 5 increments, increasingly higher erosion or accretion rates are ranked as correspondingly higher or lower vulnerability. Along the Apodi coast waves approach the coast with their crest parallel to the coast and hence there will be an offshore–onshore movement of the sediments. During the monsoon season, due to severe wave activity, a large quantity of sediment will be moved to the offshore region; once the wave activity is reduced during the non-monsoon period, almost the same quantity of sediment will be brought back to the coast, by the waves, and hence, the beach is in dynamic equilibrium. However some stretches of the beach are subjected to severe wave attack and hence erosion at these places will be more and they are identified as critical erosion areas (CEAs) [15]. Because of this reason the net erosion is more than the net deposition, which forms the basis for the present analysis.

C. Coastal Slope

Determination of the regional coastal slope identifies the relative vulnerability of inundation and the potential rapidity of shoreline retreat because low-sloping coastal regions are thought to retreat faster than steeper regions [17]. The regional coastal slope was calculated for a distance of 360m perpendicular to the shoreline (-1m to 67.5m on the sea side and 67.5m to 360m towards the land side). The bathymetry details were obtained from naval hydrographic charts and contours using toposheets. Fig. 2C represents the coastal slope of the study area at different stations. A slope greater than 0.6% is assigned low vulnerability and less than 0.3% is assigned high vulnerability. These values are also fixed based on the physiography, contour details from SRTM data and generated DEM.

D. Mean Tidal Range

The general situation in this area is high-energy conditions of tides, causing the continuous mobility sediments along the bottom to the near of coast. The presence of small deltas of tide over the island barrier systems and mouth of river, as well as the formation of spits perpendicular to the coast, shows the strong influence of tides.

Tides along the Apodi coast are of the mixed type with semi diurnal components dominating. Semi diurnal tides would mean two high waters and two low waters in a day. The tidal variation - RTR observed is among 2 <RTR <15 (Vital, in press), thus being classified in the group of back mixed, dominated by waves and tides. Tidal range is ranked such that micro tidal coasts are at high risk and macro tidal coasts are at low risk. The reasoning is based primarily on the potential influence of storms on coastal evolution, and their impact relative to the tide range. For example, on a tidal coastline, there is only 50% chance of a storm occurring at high tide. Thus, for a region with a 4m tide range, a storm having a 3m surge height is still up to 1m below the elevation of high tide for half a tidal cycle. A micro tidal coastline, on the other hand, is essentially always ''near'' high tide and therefore always at the greatest risk of inundation from storms.

E. Mean Significant Wave Height

The mean significant wave height used for the calculation of CVI is a proxy for wave energy which drives the coastal sediment budget; wave energy is directly related to the square of wave height:

$$E = (1/8)\rho g h^2 \tag{2}$$

Where, E energy density (N/m^2), h wave height (m), ρ water density (N/m^3), g acceleration due to gravity (m/s^2).

Thus, the ability to mobilize and transport coastal sediments is a function of the wave height squared. For, statistical analysis wave records containing at least 100 waves are required. For every 100 waves, the waves of E and NE, as the main state of sea in this region, which show significant heights from 10 to 80 cm and varying period 4 to 8 seconds. Lower values of wave periods (4 to 4.5 seconds) are observed in the May-August months. The best wave periods (7.5 to 8 seconds) are observed predominantly in the January to April months. The greatest heights are recorded predominantly in November and the lowest in the May to June months. The waves more high during periods of tide floods, With respect to the other periods, it was observed that the ENE and NE waves have highest values of 11 seconds. The waves from east and ESE period are around 5 seconds. Therefore as per the data available for the study area, these waves are considered medium vulnerable.

F. Mean Sea Leave Rise

A sea level rise would directly result in a corresponding higher shift to the zone of wave action on the beach. This would be reflected in a shoreline recession which will be larger on milder slopes. [18] has presented a theory which estimates the shoreline recession for a given rise in sea level. According to this estimate, every millimeter rise of sea level on the coast must result in a shoreline retreat of about 1m. The North Brazilian Current flowing approximately parallel to the fall of the platform, reaching speeds is about 30-40 cm/s, overlapped by waves and tides components [19]. Drifting coastal currents flowing from east to west in the northern coast of Rio Grande do Norte. Waves (20-105 cm/s) are the forces dominant in net sediment transport along the coast of Rio Grande do Norte due to the obliquity of the intense winds. Coastal currents directed by winds and increase the rate of sediment transport, while the tides have a lower transport capacity due to relatively lower intensities of currents in the tide (5-60 cm/s). This can be well observed in the region by the presence of extensive spits (spurs) parallel to the coast [20], as well as small spits perpendicular to shore [21]. There are also reports from earlier studies that there is a relative sea level fall then a sea level rise along the coast, Apodi coast towards the south and on the down slope of MPL, is susceptible to SLR. By considering a global sea level rise of 1.8–2.0 mm/yr (IPCC) and also reports from earlier studies, a sea level rise is considered as low vulnerability for the study area [22]. Finally the ranges of vulnerability rankings assigned for all the six variables are furnished in Table 1. In addition to the estimation of the above parameters, the land use/land cover map for the river mouth areas and DEM for the complete study area have been prepared, for the inundation analysis and to know the submergence of different land use/cover features due to future SLR.

G. Land Use/Cover Map

The Apodi River is the second river in extension of Rio Grande do Norte State, with mouth in the Atlantic Ocean between the municipalities of Grossos and Areia Branca (Fig. 2D). The length of the sand spit at some places is more than 3km, and they are highly vulnerable to sea erosion and these

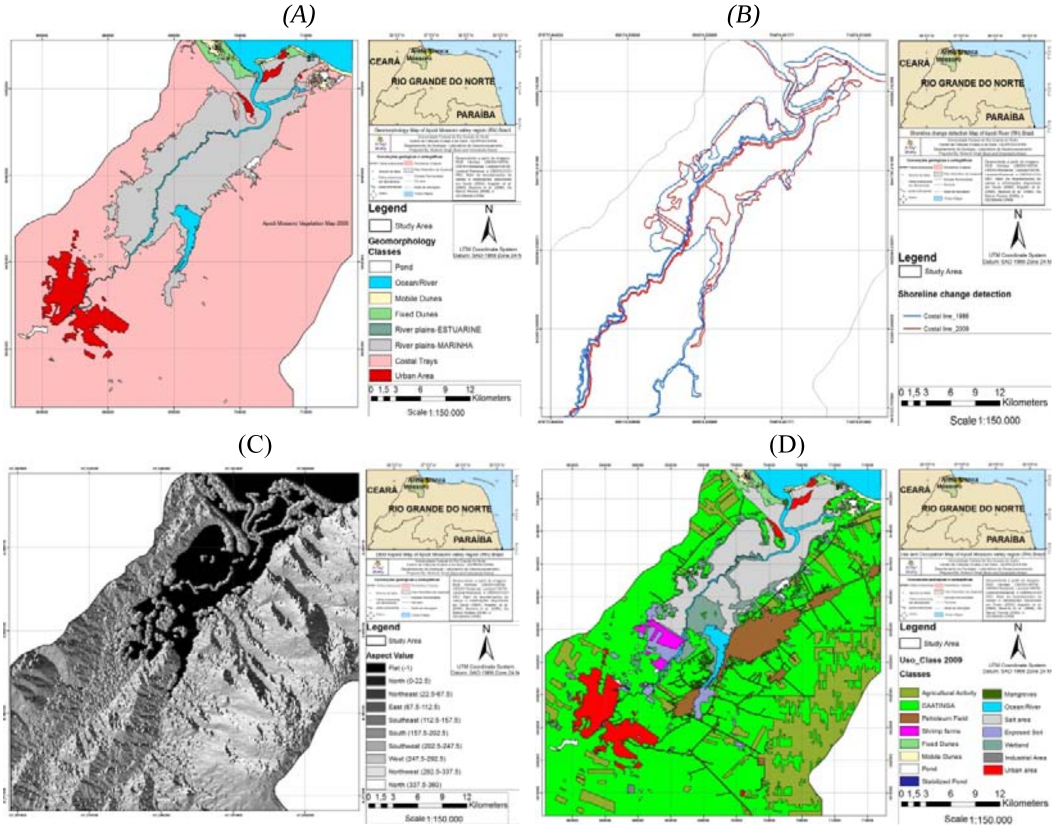

Fig. 2 Eco-geophysical maps. (A)Simplified Geomorphology map; (B) Shoreline change detection map, 1986 and 2009; (C) Simplified Slope map; (D) Land use Map in the year 2009, based on CBERS 2B/ CCD + HRC image.

areas are also highly populated in addition to several salt industry, shrimp and fish processing industries. Because of this reason river mouths in the study area were selected for the land use/cover map preparation. TM, ETM+, Spot 4- the land use/cover map. The classified output Apodi river mouth is shown in Fig. 2D, which is required for the inundation analysis.

H. Inundation Map

[18] has presented a theory which estimates the shoreline recession for a given sea level rise. According to this estimate, every millimeter rise of sea level on the coast must result in a shoreline retreat of about 1m. Factors such as near shore topography, location and orientation of the coastal segment, tidal range, morphology of the coast etc are responsible for the resistance of the coast to the rise in water level. The intensity and magnitude of the water level rise are also an important factor governing the magnitude of inundation of the area. By keeping the SLR and tsunami in mind, an inundation map was prepared for the study area using the virtual GIS module of ERDAS Imagine software for six run-up values i.e., 0m, 1m, 3m, 5m, 7m and 10m with reference to the mean sea level, by taking the digital elevation model (DEM) as a base map. This HRVIR, IKONOS, CBERS 2B data of 1986 to 2009 were analyzed up to the level-II classification by adopting the maximum likelihood algorithm of the supervised classification technique [23] for the preparation of DEM was prepared using Shuttle Radar Topography Mission (SRTM) data, which are available as 3 arc sec (approx. 90 m resolution) DEMs. The inundation module available in ERDAS Imagine was used to generate different scenarios of sea level rise. The six run-up values used to prepare the inundation maps are shown in Fig. 3. This map is useful in determining the extent of vulnerability of the area to SLR as well as storm and tsunami waves.

Once, the calculations of each parameter were completed, they were assigned a relative risk value based on the potential magnitude of its contribution to physical changes on the coast as the sea level rises, and CVI was computed using Eq. (1). Detailed discussion about land loss, erosion of beach due to SLR is provided in next Section.

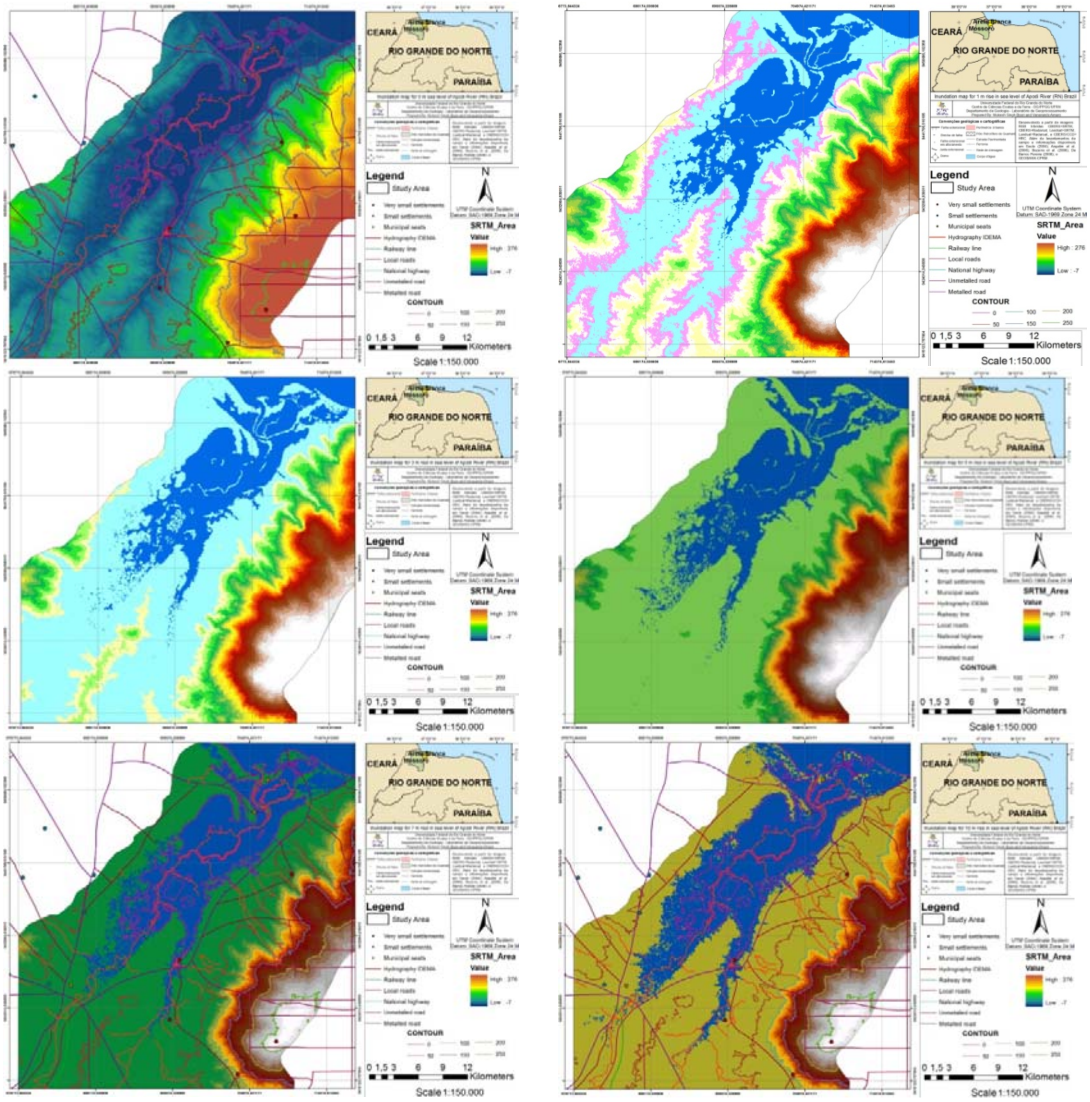

Fig. 3 Inundation map with contour line of the Apodi Region, Northeast Brazil.

V. RESULT AND DISCUSSTION

After assigning the risk value based on each specific data variable to each section of the coastline, the CVI has been calculated using Eq. (1). The calculated CVI value for the coastal stretch ranges from 0.0 to 3. The CVI scores are divided into Unrated (less than or equal to 0.99); Very low (from 1.0 to 1.39); Low (1.4 to 1.79);

Medium (from 1.8 to 2.29); High (from 2.3 to 2.59), and Very high (greater than or equal to 2.60) by means of the cluster principle and visual inspection of the data. Locations along the coastal stretch are under the very high vulnerability category. Places such as river plains, salt pond, and agriculture land fall under the high category whereas forest area has low vulnerability. Fig. 5B shows the percentage length of the coastal stretch that has very high, high, medium, low and very low vulnerability. The total area of the study is 1372 Km², out of which 8.26% of the mapped shoreline is classified as being at very high risk due to future SLR, mobile dunes and industrializations. The percentage of high and medium risk is 23.48%, and the 22.46% of the shoreline is under the low risk category. From this it is very clear that the Apodi coast is highly vulnerable for future SLR, and the different land use/cover features under the direct risk of flooding include coastal villages and city, agricultural land, wetland, salt pans, aquaculture ponds, link roads, beaches and coastal dunes.

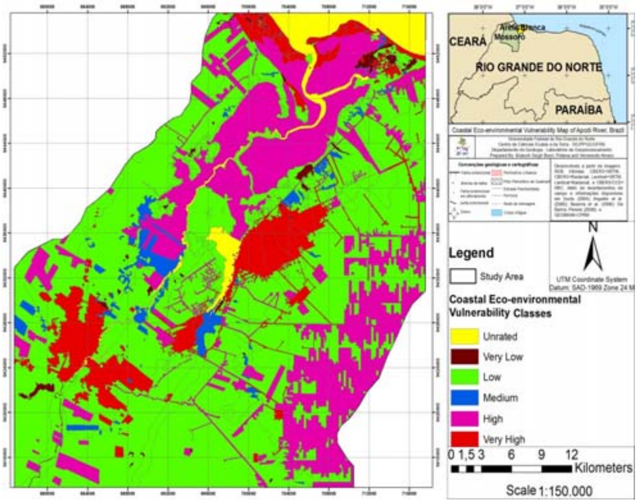

Fig. 4 Costal eco-environmental vulnerability map of Apodi Region, Northeast Brazil.

This implies that the population living presently in these areas would be displaced. Fig. 04 shows the vulnerable areas along the study area for the SLR determined using coastal vulnerability indices. The area of submergence for different sea level rises in the form of a bar chart is shown in Fig. 5A.

The area of submergence for 1m rise in water level is up to 225.2Km² and subsequently for 3m, 5m, 7m and 10m rise in water level are 235.9Km², 287Km², 318.4Km², and 397.4Km² respectively. The low lying areas of the study area are highly vulnerable for submergence in case of a tsunami or a rise in sea level. From the land use/cover map, it is clear that the maximum area is covered by Industrial, agriculture lands and other categories, which include aquaculture ponds in the low lying area, and they will get affected first by future SLR. The inundation maps can be overlaid on land use/land cover maps to find out the extent of submergence of different land use/cover areas. It is necessary to incorporate the elevation levels for new/expanded settlement areas under the town planning acts so that human life and property are saved from natural hazards/vulnerabilities. The run-up levels can be used as guidance to determine safe locations of settlements from the shoreline. Based on the vulnerability assessment study, it is clear that three issues are of great concern to the authorities and decision makers: coastal land loss, ecosystem disturbance and erosion and degradation of shoreline.

Coastal Regulation Zone (CRZ), as part of the Environmental Protection Act to protect the coast from eroding and to preserve its natural resources and would be adopted. Accordingly coastal stretches of seas, bays, estuaries, creeks, rivers and backwaters which are influenced by tidal action in the landward direction up to 500 m from the high tide line (HTL) were considered as coastal regulation zones [24]. The low lying nature of the Apodi coastal zone coupled with significant land reclamation investments and extensive industrial, commercial, and residential activity emphasizes that ecological and socio-economical systems are currently facing tremendous pressure due to rapid urbanization, industrialization, and economic development. SLR phenomena are going to accelerate degradation of the coastal and marine resources and could lead to serious displacement of people, commercial and industrial activities. Hence, strict enforcement of the CRZ Act is needed in order to protect the coastal ecosystem and to reduce degradation.

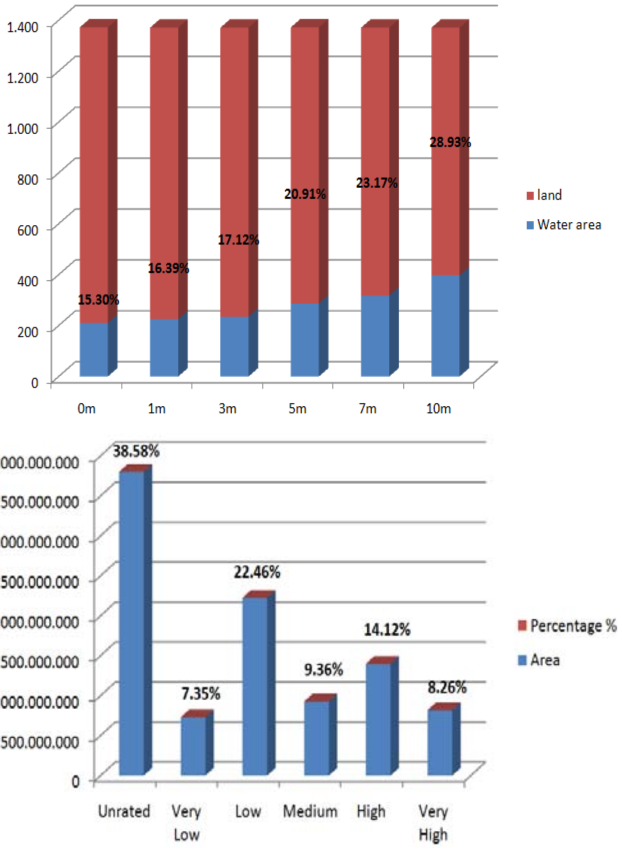

Fig. 5 (A) Representation of the inundation area and (B) Costal eco-environmental vulnerability.

The options available for the protection of the Apodi coast from future SLR could be dune afforestation, mangrove restoration and management, periodic beach nourishment and building seawalls and groins. The construction of seawalls is costly and hence it would be used only for some settlements at high risk of inundation. The performance of properly constructed and maintained seawalls along the coast is satisfactory [15]. The integrated coastal zone management plan, though active in Brazil, is still not fully functional. It must emphasize more on building regulation, urban growth planning, development of institutional capacity, involvement of local community, increasing public awareness and should be based on long-term sustainable developmental programmes.

The dunes of the coast are being put under pressure by way of human interference. Strict legislation should be put forward to restrict growth of housing complexes in the dune areas. Over exploitation of ground water in the dune areas should be avoided as this leads to sea water intrusion and subsequent conversion of the dunes into saline-rich bodies of soil. Since a few dunes nearer the coastline are of shifting nature, it is suggested that these are stabilized by practicing mixed and social forestry. Depending on their stability and soil texture, certain dunes can be flattened and the area used for agriculture including coconut groves. While agriculture is being practiced, care should be taken to avoid soil erosion.

Dunes in some regions may be the cause of the regular occurrence of floods in the inland areas. This is because these dunes act as barriers for the flood waters reaching the sea. Therefore, construction of channels across the dunes may help ease the frequent flood situations. In last more detailed mapping (on 1:50 000/25 000 scale) using temporal satellite data is suggested for more effective micro level landuse planning along the Apodi coast.

VI. CONCLUSION

The present study was carried out with a view to identify vulnerable areas due to future sea level rise (SLR) along the Apodi coast through the analysis of conventional and remotely sensed data, and the conclusions of the same are as follows. The coastal vulnerability index (CVI) provides insight into the relative potential of coastal damage due to future SLR. The maps presented here can be viewed in at least two ways: (i) to identify areas where physical changes are most likely to occur as sea level rises; and (ii) as a planning tool for managing and protecting resources in the study area. The rate of erosion was 0.5869km²/yr during 1986–2009; and 8.26% is at very high risk, 14.12% high, 9.36% medium 22.46% low and 7.35 in very low vulnerable category, due to future SLR. Based on the inundation study, it was found that 225.2 Km² and 397.4 Km² of the land area will be submerged by flooding at 1 m and 10 m inundation levels respectively. The most severely affected sectors are expected to be the residential and recreational areas, agricultural lands and the natural ecosystem. These are to be protected through strict enforcement of the Coastal Regulation Zone (CRZ) Act and any further coastal developmental activities and protection work along the Apodi coast should be based upon an integrated coastal zone management (ICZM) approach for long-term sustainable development.

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