INTERNATIONAL JOURNAL OF PLANT, ANIMAL AND ENVIRONMENTAL SCIENCES

Volume: 1: Issue-1: March-May -2011 **www.ijpaes.com**

A REMOTE SENSING AND GIS BASED APPROACH FOR CLIMATE CHANGE AND ADAPTATION DUE TO SEA-LEVEL RISE AND HAZARDS IN APODI-MOSSORO ESTUARY, NORTHEAST BRAZIL

Mukesh Singh Boori, Venerando Eustáquio Amaro
Geo-processing Laboratory, Dept. of Geology (Geodynamic & Geophysics division), Center of Exact Sciences and Earth, Federal University of Rio Grande do Norte, Natal –RN, Brazil.
msboori@gmail.com, amaro@geologia.ufrn.br

ABSTRACT: The Northeast Brazil is physically and socio-economically vulnerable to accelerated sea-level rise, due to its low topography and its high ecological and touristic value. The main threats in Apodi-Mossoro estuary that could be connected with sea-level rise and climate change are the flooding of coastal areas, erosion of sandy beaches and the destruction of harbor constructions and natural coastal hazards. Assessment of the potential land loss by inundation has been based on empirical approaches using a minimum inundation level of 1m and a maximum inundation level of 10m. The socio-economic impacts have been based on two possible alternative futures: first a worst situation measured by the economic condition in the maximum inundation level; and second a best situation measured by combining the sustainability on first scenario with the minimum inundation level. Inundation analysis, based on GIS and a modelling approach to erosion, has identified on 22 locations and the socioeconomic sectors that are most at risk to accelerated sea-level rise, climate change and hazards. Results indicate that 15.74% (216.10km^2) and 26.43% (362.81km^2) of the area will be lost by flooding at minimum and maximum inundation levels, respectively. The most severely impacted sectors are expected to be the residential and recreational areas, agricultural land and the natural ecosystem. Shoreline erosion is -5.38m/yr since 2003 to 2010 and it`s affect 21.48% the total area in the Apodi-Mossoro estuary which is very high vulnerable area. Potential strategies to ameliorate the impact of global climate change through sea level rise and natural coastal hazards include: wetland preservation; beach nourishment at tourist resorts; and the afforestation of dunes. As this coast is planned to become one of the most developed tourist resorts in RN state by 2012, measures such as building regulation, urban growth planning and development of an Integrated Coastal Zone Management Plan, are recommended for the region.
Keywords: Climate change, sea level rise, hazards, adaptation, RS & GIS.

INTRODUCTION

The Northeast Brazilian coast faces the Atlantic Ocean from the equatorial to the southern temperate regions. Nowadays, it is recognized that climate change and sea level rise will impact seriously upon the natural environment and human society in the coastal zone. This zone of variable width reaches an extension of approximately 8,000 km and shows a considerable diversity of coastal morphology, exposures and ecosystems. At present, 63% of Brazilian states share the coastal area where almost a quarter of the country's total population is concentrated. This zone forms one of the main socioeconomic areas of the country with more than 50% of the population inhabiting the coastal cities, as well as incorporating 90% of the industry. Furthermore, beaches and coastal resorts constitute a large percentage of the gross domestic product (GDP). However, due to diverse human pressures, many coastal areas are already experiencing acute environmental problems, such as coastal erosion, pollution, degradation of dunes, and saline intrusion of coastal aquifers and rivers. Accelerated sea level rise will intensify the stress on these areas, causing flooding of coastal lowlands, erosion of sandy beaches, and destruction of coastal wetlands. Therefore, sea-level rise has to be one of the main impacts of climate change on Northeast Brazil.

The sea-level rise due to the thermal expansion and melting of glaciers, ice caps and ice sheets is a topical issue on a global as well as on a regional scale (Zerbini et al., 1996; Nicholls and Mimura, 1998; Peltier, 1999; Mimura, 1999). Sea-level rise and natural disasters are both key problems that should be taken into consideration in climate change impact assessments for Northeast Brazil (Fig. 1). In particular, low-lying areas, which are strongly affected by flooding or by active processes of shoreline erosion and sedimentation, pose the most serious consequences for local communities and tourists and the destruction of harbour constructions. Functions and values of the coastal system have been degraded and public safety and economy have been impacted. These problems could be accentuated due to rapidly increasing population pressures, which often lead to inconsiderate or poorly planned development in natural hazard-prone areas and potential scenarios of climate change/relative sea level rise.

The description of many coastal areas as highly hazards prone zones by scientists has led to an increasing attention of the coastal risks and attempts to understand and mitigate them on the side of government and administrations. The concept of Integrated Coastal Zone Management (ICZM) is considered a good approach for this purpose, because it can combine the control of socio-economic development patterns, natural hazards prevention, and natural resource conservation at the same time. According to Kay and Alder (1999), most of the wide range of administrative, social and technical instruments used in an ICZM program could be analyzed through a simplified organizational framework.

The coastal zone of the RN state, Northeast Brazil represents such a system affected by natural hazards and risks, especially by flooding and erosion, in a context of climate change/sea level rise scenarios, which can lead to loss of land, severe property damage and alteration of its ecological characteristics. Therefore, this work aims to describe natural hazards impacts, in order to identify, assess of risk of the coastal zone based on remote sensing and GIS technology. The main objectives of this contribution are: (1) to determine areas at risk from flooding and erosion; (2) to assess the most vulnerable sectors at risk; (3) to estimate the influence of global climate warming on sea-level rise and coastal landscapes; (4) to determine areas at risk and rates of potential damage; and (5) to identify the most reasonable options available to mitigate these risks to the coast.

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 (Fig. 1). 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 (KÖPPEN, W. 1948), 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 (RADAMBRASIL, 1981), 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% (IDEMA 1999, MAFRA, L. C. A. 2002). This is lower in September with 59.9% and higher in April to 78.1%.

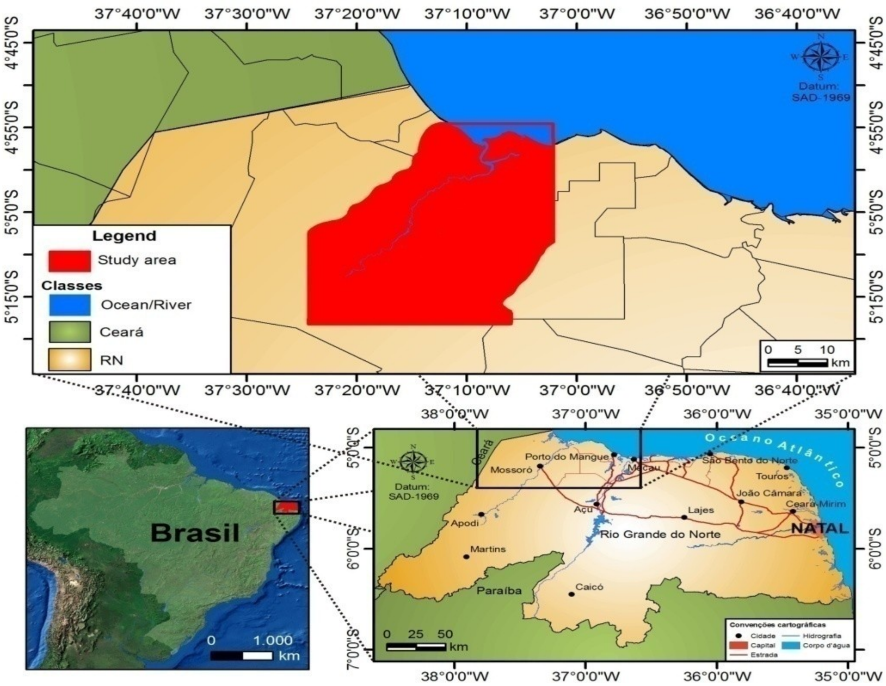

Fig.1 Study area location on Rio Grande do Norte State, Northeast Brazil.

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-Mossoro estuary 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.

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 (Chaves M.S. & Vital H. 2001).

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.

METHODOLOGY

The shoreline response to sea level rise is often estimated using the Bruun Rule, which states that a typical concave-upward beach profile erodes sand from the beachfront and deposits it offshore, so as to maintain constant water depth. Shoreline retreat depends on the average slope of the shore profile. Detailed measurements according to the Bruun Rule (Bruun, 1962; Hands, 1983) were made using large-scale (1:25,000) topographic and geomorphic maps and calculations along the coastline at 22 sample site. The Bruun Rule equation is quite simple in its form:

$$\mathbf{R = SGL / (b + h)}$$

where R is the retreat due to sea-level rise, S is above present sea level, G is the proportion of eroded material which remains in the active profile, defined as the inverse of an over fill ratio, L is the active profile width, b is the typical land height, often controlled by the dunes, and h is the depth of closure which defines the sea ward limit of the profile.

To estimate shoreline erosion we used landsat TM and ETM+ data since 2003 to 2010 and define all year's coastal line variations, the calculated shoreline erosion was -5.38m/yr. In sea level scenario we used IPCC data for 2050 and 2100, according to the table 1. The active profile width is 205m (Geo-processing Lab., UFRN). For elevation height we used SRTM data and depths of closure were related to a datum was 2.35m above low water (Brazilian Navy - ADCP). Calculations were performed on 22 coastline segments that were defined mainly by the width of the active profile which varied slightly along the coast of the study area. Minimum and maximum values of land loss were presented in m^3 and as a percentage of the total sand area.

Based on the measurements, calculations, and field observations, new coastline positions were drawn on the topographic maps. Field observations were used to compare possible coastline changes obtained by the Bruun Rule or by map measurements with the current state, and to make corrections where necessary. Two different coastline positions were drawn, depending on either normal weather conditions or potential storm surges. Both zones were subjected to inventories of land loss and temporary damages.

Sea level scenarios

The estimates for future sea-level rise used in this research (Table 1) were those presented by Warrick et al. (1996); they ranged from 200 to 860 mm for the IS92a green house gas emission scenario in 2100, with a best estimate of 490 mm. According to the IPCC, this scenario assumed: (1) a level of emissions that would contribute to a doubling of carbon dioxide concentration in the atmosphere by the end of the 21st century; (2) a world population of 11.3 billion people by 2100, from population projections by the World Bank; and (3) an annual growth rate in gross national product (GNP) of 2.3% by 2100. Data on land movements (subsidence/uplift) were not available for the study area. However, as the long-term geological data suggested in significant tectonic variations, the rise in global sea levels were considered a credible scenario.

Table 1- IPCC scenarios for sea-level rise (Warrick et al., 1996).

Scenarios	Sea-level rise (cm)	
	2050	2100
Low (no acceleration)	7	20
Best	20	49
High	39	86

Coastal topography and land use

An initial requirement for the analysis of flooding impacts was the development of spatial datasets. A 1m spatial resolution digital elevation model (DEM) with error within 224 mm (1σ) in elevation was constructed using Landsat TM, ETM+, Spot 4-HRVIR, CBERS 2B and IKONOS satellite multispectral dataset with 4m spatial resolution and stereo-pairs of aerial photographs taken in 2010. Our 2010 elevation Data were based on a static GPS survey, which had sub-centimeter positional accuracy in three dimensions. At the airfield, these data were consistent with the DEM data and a database of ground control points (GCPs) measured by a ground positioning system. This was undertaken using the Arc GIS software. The horizontal resolution of the DEM was 2m, which accurately represented narrow features such as roads and dunes; the vertical accuracy was 0.5m. The GIS environment was used to classify and map the typology of land threatened by inundation. The length of the sand spit at some places is more than 2km, and they are highly vulnerable to sea erosion and these areas are also highly populated in addition to several salt industry, shrimp and fish processing industries.

Satellite data from 1986 to 2009 were analyzed up to the level-II classification by adopting the maximum likelihood algorithm in the supervised classification technique (Lillesand Thomas M, Kiefer Ralph W, Chipman Jonathan W 2004) for the preparation of the land use/cover map and find fifteen major land-use classes. The classified output Apodi river mouth is shown in Fig. 2, which is required for the inundation analysis.

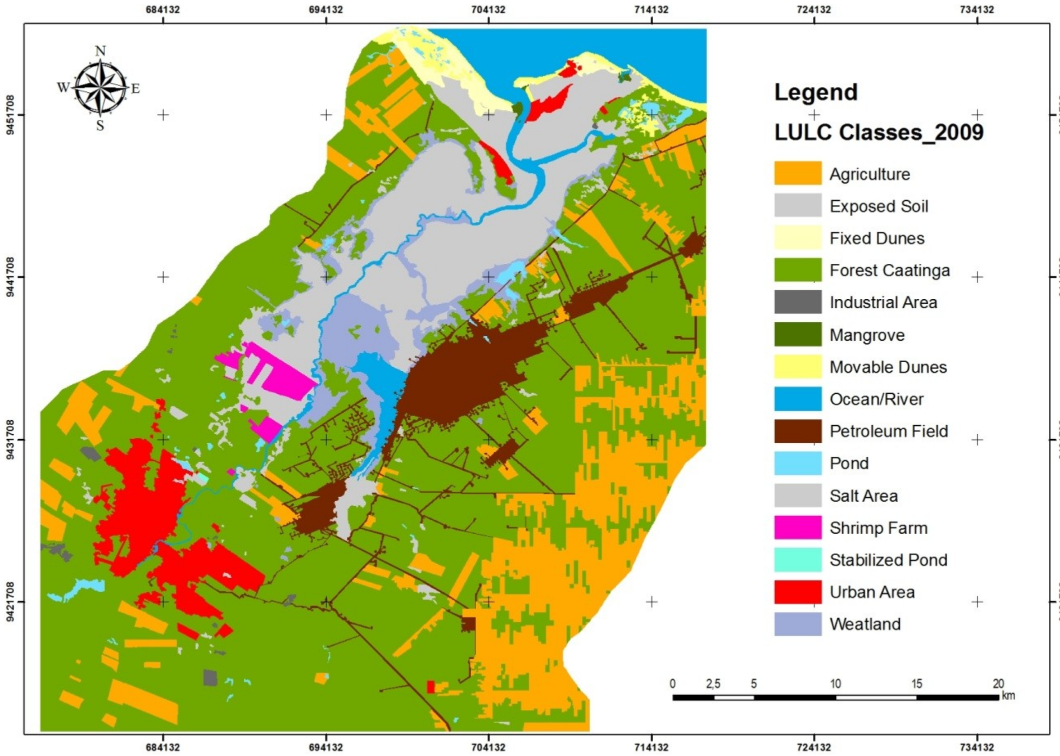

Fig. 2- Land use/ land cover map of the Apodi-Mossoro estuary 2009.

1.3 Inundation level scenarios

The nearest tide gauge to the study area was at Macao Meteorological Station-RN (measured by the Brazilian navy - ADCP), which had measurements available for the current study area; data on sea-level variations included astronomical as well as meteorological elevations. Data on swells, waves and storm surges were obtained from DE AREIA BRANCA A GUAMARÉ (http://www.mar.mil.br/dhn/chm/cartas/download/cartasbsb/cartas_eletronicas_Internet.htm) and from the Environmental Impact Assessment (EIA) report on the implementation of the Chart nº 720 - DE AREIA BRANCA A GUAMARÉ (2009). 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 1.5 <RTR <13.5 (Vital, H. et al. 2010), 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; macro tidal coasts are at low risk and meso tidal in between. 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. The values used to estimate the potential land loss by inundation were used between 1m to 10m for minimum and maximum inundation levels, respectively.

Coastal erosion

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 (Bird Eric & C.F. Coasts 1984). Though beaches along the Apodi coast are maintaining dynamic equilibrium, there will be temporary sea erosion during the monsoon, due to high wave activity. 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 from 2003 to 2010 were overlaid using Arc GIS software (Burrough P.A. & Mc Donnel R.A. 1998) and the final map was obtained (Fig. 3). During this period of remote Sensing 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 2m under accretion and erosion, whereas the maximum beach width was 301.36m under accretion and 146.14m for erosion. The ranking of the shoreline change rate is based on the range of change in beach width values. By superimposing the remote sensing 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 -313.39 m/yr and +80.06 m/yr respectively. Shorelines with erosion/accretion rates between -5.38 m/yr and +5.38 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) (Dwarakish G.S. & Usha Natesan 2002). Because of this reason the net erosion is more than the net deposition, which forms the basis for the present analysis.

Socio-economic impacts

Having determined the land loss due to erosion and inundation, the impacts of this loss were evaluated for the major socio-economic sectors (urban and tourist areas, agricultural and forest land) and for the natural ecosystems at risk; this was undertaken by overlaying maps for both inundation scenarios and land use. However, these images did not represent the possible future for the region, because they were based on the current socio-economic status; the impacts of scenarios for predicted inundation should be linked with equivalent scenarios for socio-economic change. The latter were not easy to predict, as they depended on the nature of future development and the way the authorities might manage the coastal environment.

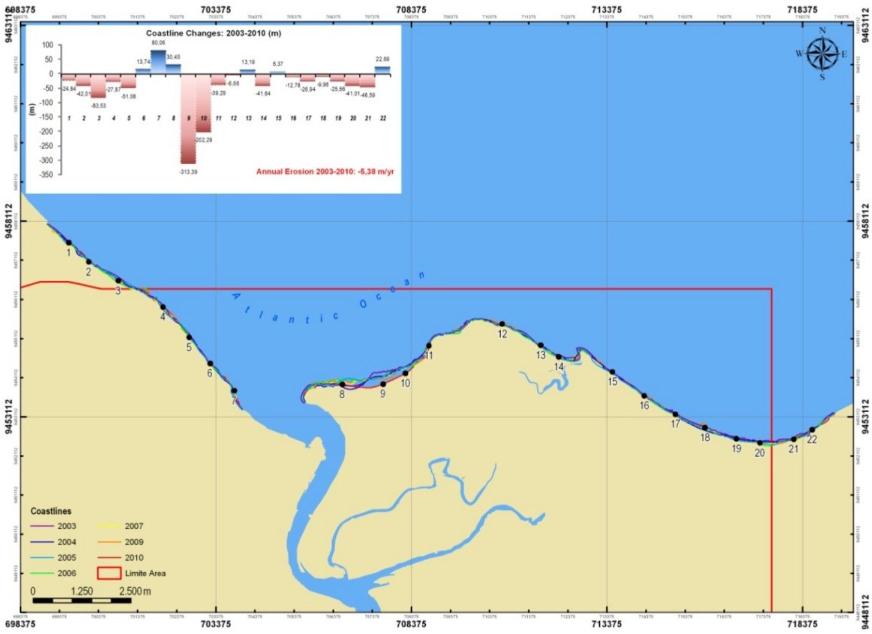

Fig. 3 – Coastline erosion and variation in Apodi coast from 2003 to 2010.

Due to the lack of information on socio-economic change in Apodi-Mossoro estuary, two plausible alternative futures were considered for this study:

- **Economic development:** coastal zone of the study area will continue to be the location and concentration of economic and tourist activity. Political efforts are consolidated through policy drive to exploit natural resources, develop infrastructure and practices driven by profit goals. This scenario imposes a high level of stress upon the environment and natural resources. Science and technology aim at improving efficiency and emphasizing profitability.
- **Sustainability:** demographic trends (population growth and urbanization rate) are favorable. There is multi-stakeholder participation, broad alliance between public and private sector, science/knowledge community, and a development of the capacity to implement policy. Pressures on the ecosystems, such as the wetland, are reduced through careful and appropriate land use planning. More land is protected by local and national regulatory and governance mechanisms.

These qualitative storylines are of course subjective and need to be further developed and quantified so as to provide the inputs to an integrated assessment (IA), as defined by the IPCC (2001). Indeed, the IA would be the best tool to produce policy-relevant guidance to the stakeholders (Shackley and Deanwood, 2003; Holman et al., 2005).

RESULTS

The DEM presented in Figure 4 shows that low-lying land is more extensive at the north and centre of the valley. The areas lower than 2m above mean sea level (MSL), which are at risk of inundation under the minimum inundation level, are dunes, forest, wetland, shrimp and salt industry and urban area basically whole Areia Branca and Grossos city.

Risk assessment

The main results of land loss due to inundation are presented in Figure 4. The most significant changes would occur on the mouth of the Apodi River, Areia Branca and Grossos city and over the north and northeastern part of the study area, where there is low-lying land and the natural coastal defenses, such as dunes, have been destroyed. At the minimum inundation level (1m in Fig. 4), 15.74% (216.10km^2) of the total area (Table 2) would be flooded including: urban areas; natural vegetation and agricultural land; industrial area and beaches and marshes.

The area of submergence for 3m rise in water level is up to 231.22km² (16.84%) and subsequently for 5m, and 7m rise in water level are 256.40km² (18.68%) and 295.70km² (21.54%) respectively (table 2). 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.
At the maximum inundation level (10m in Fig. 4 & 5), 26.43% (362.81km^2) of coastal land would be under direct risk of flooding including: the cities; the ports and the tourist resort; agricultural land; most of the coastal wetland; forest area, beaches and coastal dune, shrimp and salt industry. Such a loss of land implies that the population living presently in these areas would be displaced. Even if some parts of the ecosystem of the wetland are not destroyed, because those parts could adapt to sea-level rise and move landwards, the species richness is likely to decrease, due to unfavorable new conditions where several plant communities and rare species would disappear. The area least vulnerable to inundation would be the southern part of the study area. However, parts of city and port, as well as an important recreational beach and a natural forest, would be flooded.

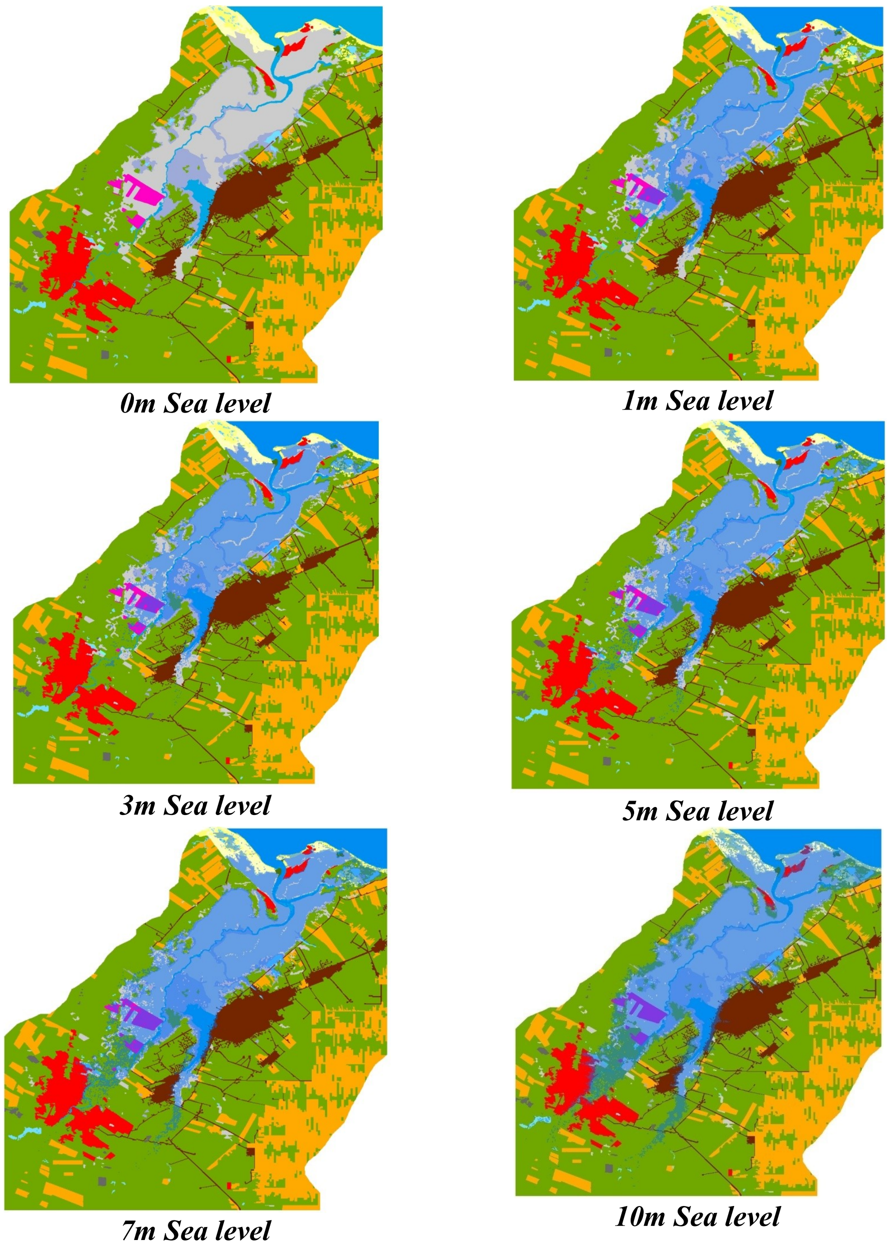

Fig.4 - Land area vulnerable to inundation in the Apodi-Mossoro estuary, Northeast Brazil.

Class Name	**0m Sea level**		**1m Sea level**		**3m Sea level**		**5m Sea level**		**7m Sea level**		**10m Sea level**	
	(km²)	***(%)***	**(km²)**	***(%)***	**(km²)**	***(%)***	**(km²)**	***(%)***	**(km²)**	***(%)***	**(km²)**	***(%)***
Agriculture	189.52	13.81	0.01	0.00	0.03	0.00	0.06	0.00	0.14	0.01	0.83	0.06
Wetland	48.23	3.51	24.05	1.75	25.89	1.89	29.95	2.18	35.99	2.62	43.57	3.17
Forest	724.29	52.76	3.85	0.28	8.06	0.59	15.20	1.11	30.52	2.22	61.72	4.50
Exposed soil	28.92	2.11	4.71	0.34	6.60	0.48	10.38	0.76	15.74	1.15	20.39	1.49
Fixed dunes	11.89	0.87	0.67	0.05	0.70	0.05	1.07	0.08	2.03	0.15	6.70	0.49
Industry	3.31	0.24	0.00	0.00	0.02	0.00	0.04	0.00	0.04	0.00	0.13	0.01
Pond	8.94	0.65	1.55	0.11	3.44	0.25	4.32	0.31	4.86	0.35	6.05	0.44
Mangroves	0.81	0.06	0.23	0.02	0.23	0.02	0.27	0.02	0.36	0.03	0.62	0.04
Mobile dunes	11.03	0.80	1.12	0.08	2.63	0.19	4.80	0.35	6.00	0.44	8.32	0.61
Ocean & river	66.98	4.88	50.80	3.70	51.22	3.73	52.40	3.82	54.05	3.94	56.11	4.09
Petroleum	77.86	5.67	0.70	0.05	0.92	0.07	1.41	0.10	2.75	0.20	5.79	0.42
Salt area	137.01	9.98	123.27	8.98	125.57	9.15	128.18	9.34	132.21	9.63	135.96	9.90
Shrimp farm	10.49	0.76	4.70	0.34	5.39	0.39	7.21	0.53	8.96	0.65	10.23	0.75
Stabilized pond	0.21	0.01	0.00	0.00	0.00	0.00	0.16	0.01	0.18	0.01	0.21	0.01
Urban area	53.30	3.88	0.45	0.03	0.52	0.04	0.94	0.07	1.87	0.14	6.18	0.45
Total	***1372.79***	***100.00***	***216.10***	***15.74***	***231.22***	***16.84***	***256.40***	***18.68***	***295.70***	***21.54***	***362.81***	***26.43***

Table 2 - Potential land loss of the main sectors for 1m, 3m, 5m, 7m and 10m inundation levels scenarios (in km^2 and in % of the total inundated areas)

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 risk 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.

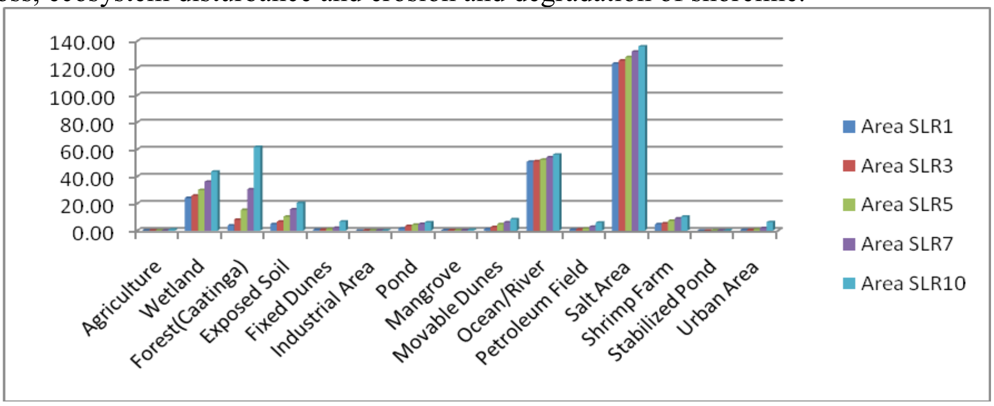

Fig.5 - Inundation graph of the Apodi-Mossoro estuary, Northeast Brazil.

Socio-economic impacts

In *economic development aspects*, continuing development will increase the flood risk and the impacts from inundation. Salt marshes, shrimp farms and beaches will decline or be lost, because they are unable to maintain elevation relative to sea-level rise, or to migrate landwards. Combining this socio-economic scenario with the maximum inundation level generates a future which is likely to be the worst-case situation.

Under *sustainability scenario*, integrated coastal zone management (ICZM) and appropriate planning, including avoiding development in the flood plain around the wetland and on the dunes, will minimize the flood risk. Managed realignment will lead to a large expansion in salt marshes, shrimp farms and related intertidal habitats, which has additional benefits for flood-control (Dwarakish G.S. & Usha Natesan 2002). In combination with the minimum inundation level, these scenarios correspond to the best-case situation for the region.

Response strategies and adaptation

To prevent coastal land loss, some options which could be applied in Apodi-Mossoro estuary are the construction of seawalls and beach nourishment. These are well known techniques and have been extensively discussed in the context of sea-level rise (Nicholls et al., 1995). It is obvious that the cities at risk, such as Areia Branca and Grossos would need to be protected by seawalls and dikes. Most of the harbours need upgrading. To ensure effective protection, the seawalls must be much longer than the protected coastline length. Despite the high cost, seawall construction is one option to prevent socio-economic damage in the cities, including relocation of the population. The most useful option to preserve unique and valuable natural ecosystems would be the hardening of headlands to avoid coastline straightening. This method can be applied in the areas where we have nothing to lose on the shores of bays behind the headlands. Hardening of headlands will result in much stronger erosion of bays. In the areas where this option is not applicable losses of unique ecosystems seem to be inevitable.

In view of the severe losses due to sea-level rise, together with the extensive expansion in the development of the region, response strategies identifying the most appropriate adaptation options must be developed. Regarding the coastal wetland, even if important autonomous adaptations could occur, mainly under the sustainability scenario, the response to sea-level rise will also require planned adaptation (Klein and Nicholls, 1998). The most useful option to preserve this valuable ecosystem is to continue the efforts of rehabilitation and management initiated in the framework of the new coastal wetland projects, and to declare this wetland as a protected area. Indeed, if the wetland evolves under natural conditions, without any concrete structures, its potential for migration on to adjacent low-lying uplands, allows it to grow with the sea. GIS information bases represent the first phase of a planned adaptation process.

On the short-term scale, the best option available for the adaptation of the city coast to rising sea level could be periodic beach nourishment, associated with breakwaters and dune afforestation, which would protect tourist resorts at risk from erosion and inundation. Building of seawalls is a high cost option; it would be used only for some settlements at direct risk of inundation. It is well known that such hard structures have adverse environmental impacts.

In the medium term, an ICZM plan must be adopted to include building regulation, urban growth planning, development of institutional capacity, and increasing public awareness (Snoussi and Tabet Aoul, 2000). This plan should actively involve the local communities and the stake-holders. As such, engagement with climate change and implementation of policy response will be more effective (Shackley and Deanwood, 2003). The ICZM plan should also deal with impacts from both climatic and non-climatic change, ensuring that coastal development will not increase the vulnerability of the region.

Finally, the sandy beaches of Apodi-Mossoro estuary need to be protected by beach nourishment, as the coastal area in Northeast Brazil are usually located at a distance from the shoreline today; there are only a few areas where retreat would be the most reasonable adaptation option.

CONCLUSION

As a result of the present analysis, it can be concluded that a sea-level rise of 1m would result in considerable changes in coastal ecosystems and would lead to significant economic hazards. In particular, different regions of Northeast Brazil would suffer from different reasons.

Increasing erosion and changes in the sedimentation would cause serious disturbance for sandy beaches and dunes, particularly in north and central part of Apodi-Mossoro estuary. In addition, vanishing sandy beaches will have a negative impact on recreation. Even, the direct destruction of the coast will not be so strong. Although seashore plant and animal communities would migrate in land, the interaction of changing water level and land use would result in the decrease of species richness.

The economic hazards will be the highest in the urban areas, particularly in Mossoro, Areia Branca and Grossos city, where roads, houses and other constructions are often very close to the present shoreline. These results draw attention towards the importance of upgrading awareness of decision-makers and planners to the potential future impacts of sea-level rise on this region. However, to be more complete, this study should include other assessments. In particular, it is recommended that:

1. The impact of sea-level rise on freshwater resources, including the saltwater intrusion and water logging problems should be considered;
2. Vulnerability assessments should include detailed socioeconomic impacts, together with evaluation of the costs of these impacts and those of the adaptation measures; and
3. Response strategies should be based upon an ICZM approach for long-term sustainable development.

REFERENCES

Bird Eric CF. Coasts: an introduction to coastal geomorphology. UK: Basil Blackwell Publisher Limited; 1984.

Bruun, P., 1962. Sea-level rise as a cause of shore erosion. Journal of Waterways and Harbors Division, ASCE, New York 88, 117e130.

Burrough PA, Mc Donnel RA. Principles of geographical information systems. New York: Oxford University Press; 1998.

Chaves M.S. & Vital H. 2001. Impactos ambientais na zona costeira do Campo PetrolíferoMacau-5, Macau-RN. In: Congresso Brasileiro de P&D em Petróleo e Gás, 1, UFRN –SBQ Regional RN, Natal, Anais, p. 222

Dwarakish GS. Usha Natesan. Coastal Structures Vs Shoreline Configuration. NITK Research Bulletin 2002;11(3):25–33.

Hands, E.B., 1983. The Great Lakes as a test model for profile responses to sea level changes. In: Komar, P.D. (Ed.), Handbook of Coastal Processes and Erosion. CRC Press, Boca Raton, FL, pp. 167–189.

Holman, I.P., Rounsevell, M.D.A., Shackley, S., Harrison, P.A., Nicholls, R.J., Berry, P.M., Audsley, E., 2005. A regional, multisectoral and integrated assessment of the impacts of climate and socio- economic change in the UK. Part I. Methodology. Climate Change 71, 9e41.

IDEMA, 1999. Informativo Municipal: Areia Branca. Secretaria de Planejamento e Finanças,Instituto de Desenvolvimento Econômico e Meio Ambiente-IDEMA,p.1-16.

IPCC. 2007. Fourth Assessment Report. Intergovernmental Panel on Climate Change Secretariat. Geneva, Switzerland. http://www.ipcc.ch/

Kay, R. and Alder, J., 1999. Coastal Planning and Management. E & FN Spon, London: 375 p.

Klein, R.J.T., Nicholls, R.J., 1998. Coastal zones. In: Feenstra, J.F., Burton, I., Smith, J.B., Tol, R.S.J. (Eds.), Handbook on Methods for Climate Change Impact Assessment and Adaptation Strategies. UNEP/Institute for Environmental Studies, Nairobi/Amsterdam, 35 pp.

KÖPPEN, W. 1948. Climatologia: Um Estúdio de los Climasde la Tierra. Versión de Pedro R. Henrichs. México, Fondo de Cultura Econômica, 478

Lillesand Thomas M, Kiefer Ralph W, Chipman Jonathan W. Remote sensing and image interpretation. New York: John Wiley and Sons Publications; 2004.

MAFRA, L. C. A. 2002. Caracterização Geológica e Geomorfológica do Município de Porto do Mangue / RN, com Vista à Elaboração do Mapa de Sensibilidade Ambiental ao Derramamento do Óleo. Natal - UFRN/DG – Relatório de Graduação.

Mimura, N., 1999. Vulnerability of island countries in the South Pacific to sea level rise and climate change. Climatic Research 21, 137– 143.

Nicholls, R.J., Mimura, N., 1998. Regional issues raised by sealevel rise and their policy implications. Climatic Research 11, 5 –18.

Nicholls, R.J., Leatherman, S.P., Dennis, K.C., Volonte, C.R., 1995. Impacts and responses to sea-level rise: qualitative and quantitative assessments. In: Nicholls, R.J., Leatherman, S.P. (Eds.), Journal of Coastal Research, Special Issue, vol. 14. The Coastal Education and Research Foundation (CERF), Fort Lauderdale, FL, pp. 26– 43.

Peltier, W.R., 1999. Global sea level rise and glacial isostatic adjustment. Global and Planetary Change 20, 93– 123.

RADAMBRASIL, 1981. Levantamento de Recursos Naturais Geologia/Geomorfologia/ Pedologia/Vegetação/Uso Potencial da Terra. Rio de Janeiro/RJ: Ministério das Minas e Energia, v. 23 – Folhas SB. 24/25 – Jaguaribe/Natal, 740p.

Shackley, S., Deanwood, R., 2003. Constructing social futures for climatechange impacts and response studies: building qualitative and quantitative scenarios with participation of stakeholders. Climate Research 24, 71e90.

Snoussi, M., Tabet Aoul, E.H., 2000. Integrated coastal zone management programme, northwest African region case. Ocean & Coastal Management 43, 1033e1045.

Vital H., Samia F. and Moab P. G. 2010. Response of the Apodi-Mossoro estuary-incised valley system (NE Brazil) to sea-level fluctuations. Brazilian journal of Oceanography, 58 (special issue PGGM): 13-24, 2010.

Warrick, R.A., Le Provost, C., Meier, M.F., Oerlemans, J., Woodworth, P.L., 1996. Changes in sea level. In: Houghton, J.T., Meira Filho, L.G., Callander, B.A., Harris, N., Kattenberg, A., Maskell, K. (Eds.), Climate Change 1995. The Science of Climate Change. Cambridge University Press, Cambridge, UK, pp. 365e405.

Zerbini, S., Plag, H.-P., Baker, T., Becker, M., Billiris, H., Bu¨rki, B., Kahle, H.-G., Marson, I., Pezzoli, L., Richter, B., Romagnoli, C., Sztobryn, M., Tomasi, P., Tsimplis, M., Veis, G., Veronne, G., 1996. Sea level in the Mediterranean: a first step towards separating crustal movements and absolute sea-level variations. Global and Planetary Change 14, 1 – 48.