Vulnerability to sea level rise of an estuarine island in southern Brazil

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ABSTRACT

This article presents a sea level rise vulnerability map built for Marinheiros Island, South Brazil, through specific routines for support decision in a Geographical Information System. A previous environmental diagnosis allowed the recognition of 5 vulnerability factors including physical, biotic and socio-economic variables. Each one was standardized to a continuous scale of values using the fuzzy approach, and later, analyzed together by multi-criterion evaluation module of the software to produce the final map. The most vulnerable areas are located at the northeast margins of the island as a result of the coincidence of several of the considered factors. In the remaining areas the vulnerability values decrease progressively from the margins to the center. Although the final result tends to be subjective because it is the decision maker what determines the criteria, the factors, the individual weighting and the decision rules, exercises of projection as performed in this work are very useful to explore certain alternatives and to insert sea level variable in the urban planning.

Keywords: Coastal vulnerability; Sea level rise; Geographical Information System

RESUMO

Este trabalho apresenta um mapa de vulnerabilidade à elevação do nível do mar para a Ilha dos Marinheiros-RS, Brasil, elaborado por meio de rotinas de apoio à decisão em um Sistema de Informações Geográficas. Um diagnóstico ambiental prévio permitiu o reconhecimento de cinco fatores principais de vulnerabilidade, incluindo variáveis dos meios físico, biótico e socioeconômico. Cada um dos fatores foi padronizado para uma escala contínua de valores usando a lógica *fuzzy* e depois, analisado conjuntamente pelo módulo de avaliação multicritério do software para produzir o mapa final. As áreas mais vulneráveis estão localizadas na margem nordeste da ilha como resultado da coincidência de vários dos fatores considerados. Nas demais regiões, os valores de vulnerabilidade decrescem progressivamente das margens para o centro da ilha. Embora o resultado final tenda a ser subjetivo, uma vez que é o tomador de decisão que determina os critérios, os fatores, os pesos relativos e as regras de decisão, exercícios de projeção como o realizado nesse trabalho são úteis para explorar certas alternativas e inserir a variável "nível do mar" no planejamento municipal.

Palavras-chave: Vulnerabilidade costeira; Elevação do nível do mar; Sistema de Informações Geográficas

1. Introduction

The sea level rise effects over the coastal zone have been a frequent focus of concern by every coastal government around the world. Since small islands are one of the most vulnerable regions to these effects , several studies have been made and generates, for these areas, to evaluate the future impacts and adapted strategies for this phenomenon (Mimura 1999).

The vulnerability, according to the concept adopted in the Third International Panel for Climate Change Report (IPCC 2001), is defined as an extension in which a natural or social system is susceptible to bear the effects of the climatic changes; it is a function of the *sensitivity* (rate of response to the phenomena), the *adaptive capacity* (rate of adjustment or regulation) and the *rate of exposition* of the system facing the climatic hazard. In this perspective, the islands are included as one of the most vulnerable systems since the degree of exposure makes them very sensitive to small climatic changes and the adaptive options are in most of the cases very restricted.

In the last years, there has been a substantial increase in the development of vulnerability indexes for specific coastal areas related to multiple uses or coastal processes such as sea level rise, human occupation impact, coastal erosion and oil spills. However, a revision of these indexes (Cooper & McLaughlin 1998, McLaughlin *et al*. 2002) shows that there is a strong need to include socio-economic variables in the classification procedures. According to Gornitz *et al*. (1993), the economic cost of losing houses and infrastructure is going to affect the efforts to protect a region under risk, and therefore determining its vulnerability.

In Brazil, the Ministry of Environment's concerns in determining the impact of the climatic global changes over the Brazilian ecosystems allowed the analysis of a case study of Marinheiros Island, Southern Brazil, to assess the potential impacts related to the sea level rise. Marinheiros Island belongs to the 2nd district of Rio Grande city and is located in the central portion of a large embayment of the Patos Lagoon estuary which is part of the wide and long Rio Grande do Sul coastal plain. The estuary encompasses the area between the Patos Lagoon inlet and a virtual line connecting the spits of Ponta da Feitoria and Lençóis (70 km of extension). This area is the final compartment or cell of the Patos Lagoon, a transitional depositional site for the hydro-sedimentary mass of continental source which drains to the Atlantic Ocean (figure 1).

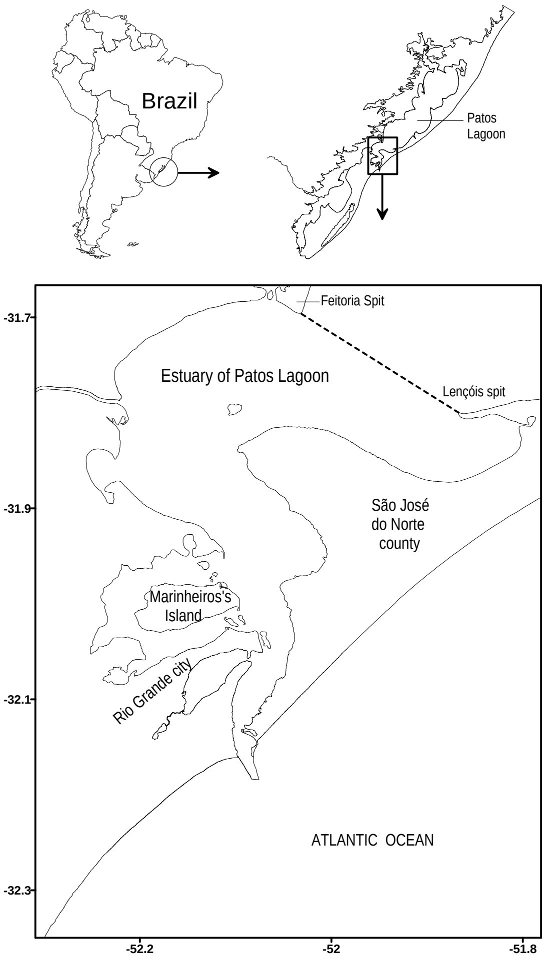

Figure 1: Localization of study area

Although there are a variety of very important ecosystems in the estuarine area, the island has several characteristics that in the overall make it special in the regional context. Its representative area (40 km^2), cultural and scientific significance, traditional population (fishermen and agriculturists), diversity of environment (dunes, forest, terraces, marshes and lagoons) and its great potential for tourism stand out. These characteristics make the island a representative case study which can serve as a model for the evaluation of all estuarine region.

This work presents a sea level rise vulnerability map for Marinheiros Island which integrates the main variables of vulnerability including physical, biotic and socio-economic factors. The map was generated by using specific routines for support decision available in the Geographical Information System (GIS) Idrisi Andes.

2. Development of a vulnerability map: selection of criteria and factors

Characteristically, a process of decision making leads to a choice between a set of alternatives. Geographical decision-making allows the analysis and interpretation of geographical information that is related to the alternatives in question.

According to Eastmann (2006) a criterion is some basis for a decision that can be measured and evaluated; a factor is a criterion that enhances or detracts the suitability of a specific alternative for the activity under consideration. It is, therefore, most commonly measured on a continuous scale.

The first task was to find comprehensive criteria to be used in order to reach the objective to elaborate the vulnerability map of the island to sea level rise. The environmental diagnosis of the island performed by Tagliani *et al*. (2006a) allowed the recognition of 3 vulnerability criteria: elevation, proximity to the margins and erosion tendency. These criteria were separated in 5 vulnerability factors that were materialized in 5 raster layers:

2.1. Lowland areas around the margins

This raster layer was generated from the digital terrain elevation model (DTM) of Marinheiros Island (figure 2). The DTM was created in a Geographic Information System using precision control points collected by a Differential Global Position System (DGPS). The horizontal and vertical data of the official geodetic point existing at Rio Grande Naval Station were transferred to the island in order to set two new geodetic points located at extreme positions in the island (east and west), which were the basis for the altimetric mapping of the whole study area. The precision parameters used in this project were 0,02 m + 1 ppm (pixel per meter) for horizontal data and 0,04 m + 2 ppm for the vertical data (Tagliani *et al.* 2006b)

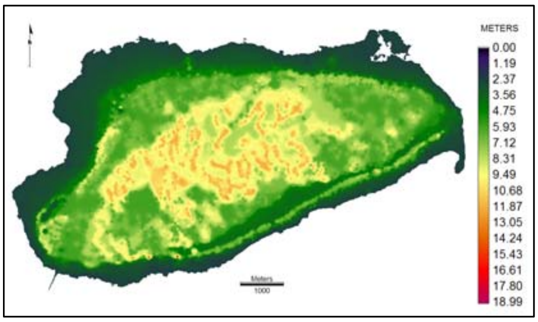

Figure 2: Digital Terrain Model of Marinheiros Island - orthogonal view

2.2. Sensitive ecosystems in lowland areas (original forest, marshes)

The second layer was obtained from reclassification of the vegetation and land use map of Marinheiros Island. In order to be utilized in the vulnerability map, the vegetation classes denominated “original forest” and “marshes” were grouped in a single layer after being submitted to a digital filter (median 7 x 7) in order to eliminate non representative pixels (figure 3).

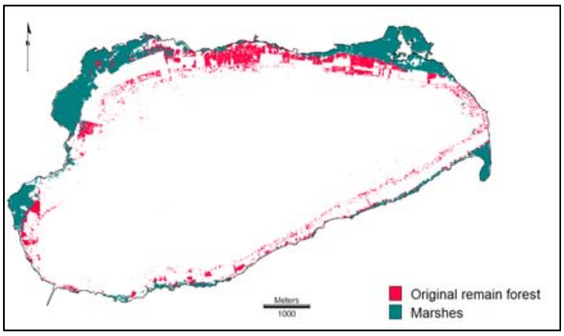

Figure 3: Original vegetation in lowland areas

2.3. Intensive land use in floodable lagoonal terraces (crop cultures)

The “agriculture areas” class was also separated in a single layer from the same map according to figure 4.

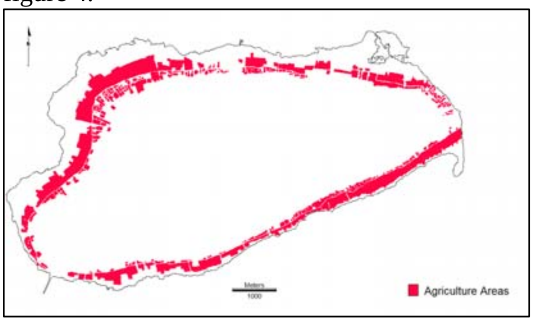

Figure 4: Agriculture areas in floodable terraces

2.4. Margins displaying erosion tendency

Shoreline changes were analyzed through the interpretation and comparison of a historical series of aerial photography mosaics at the 1:40,000 (1947) and 1:60,000 (1964, 1996) scales and an IKONOS satellite image (2004). The island margin position for each analyzed year was digitalized and the resulted vector files were converted to a raster format for the use in the cross correlation analysis. Erosion rates for all the island margins were calculated based on the differences between the mosaics of 1947 and 2004 (figure 5).

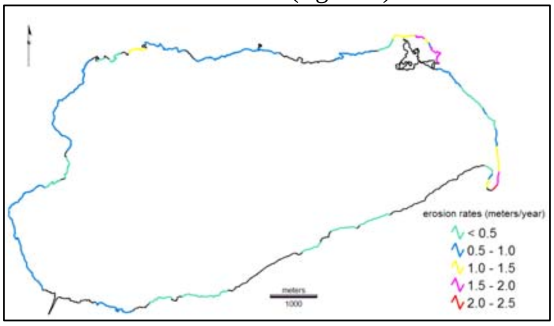

Figure 5: Erosion rates of margins

The procedure done in the SIG included the automatic determination of continuous distance between the margins of the two mosaics (1947 and 2004) and its further reclassification in five class intervals (<0.5 m/yr; 0.5-1.0; 1.0-1.5; 1.5-2.0; 2.0-2.5). The analysis of this raster file allowed the delimitation of different shoreline sectors according to their class interval producing five individual layers.

2.5. Location of residences and infra-structure installations close to to the margins.

The last layer was generated by grouping all the facilities and infra-structure nowadays existing in the island, such as residences, schools, clubs, bars, churches, harbors and fishing piers, all essential to the development of the economic, recreational, tourist and religious activities of the islanders, as well as, tourists and occasional visitors (figure 6). The location map for all of these facilities was built based on information collected *in situ*, geo-referred using Global Position System (GPS) receiver and placed over the IKONOS image satellite (Soares 2005).

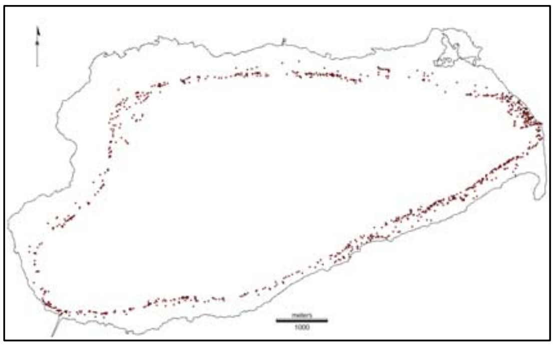

Figure 6: Location of infra-structure and residences

3. Standardizing the factors

In order to find areas that are common to each criterion of vulnerability, each factor was standardized to a continuous scale by using the fuzzy approach. With this procedure each factor was modeled as a continuous variable ranging from the most (255) to the least (0) suitable value. Since multiple criteria have varying importance, each criterion has to be further assigned to a specific weight which reflects its relative importance to the other criteria under consideration.

3.1. Elevation factor

This is the main factor to be considered in an impact analysis of sea level rise. Considering that the objective of the map is to represent the vulnerability of the island in face of sea level elevation scenarios, we can establish that the lower the elevation the higher its vulnerability. In order to scale this inverse relationship, a decreasing linear function was used (*fuzzy* approach), generating a map with values ranging from zero (less vulnerable) to 255 (more vulnerable).

3.2. Vegetation factor

The original vegetation is a very important component of the ecosystem that encloses and sustains several ecological processes. Despite of its importance, it has been submitted to degradation along the time which justifies the large amount of legal mechanisms of protection at federal, state and municipal level. Nowadays it is one of the environmental components that deserve priority for conservation. Thus, the presence of original vegetation in areas potentially subjected to sea level rise and consequently under risk of disappearing was considered an important vulnerability factor in this analysis.

The patches of original forest still existing in Marinheiros Island perform several ecological functions including, among others, the maintenance of the atmospheric environmental quality, solar energy fixation, biomass production, nutrients storage and habitat protection. Additionally, it deserves distinction for its relative rarity in the ecosystem in analysis and for being object of specific environmental protection legislation.

The intertidal marshes occupy the island borders and are essentially flooded by brackish water being occupied by annual and perennial tidal marsh and wetland plants (Costa & Davy 1992). According to Costa (1987) there are approximately 70 species in the lower estuarine marsh flora. This community plays an essential role in the stability of the substrate controlling erosion, serving as habitat for several organisms and constituting an important source of detritus for the estuarine food chain (Cordazzo & Seeliger 1988). An evaluation of the environmental vulnerability degree between different types of vegetation communities would be a very difficult task since it involves the consideration of a large amount of variables almost impossible to quantify. In this manner the option was to consider only the proximity of the margins as a vulnerability factor stating that the smaller the distance from the margin the higher the vulnerability.

The original vegetation layer was used to redefine the values (fuzzy routine) according to a decreasing linear function. After the redefinition, the values indicate that the cell which possesses the zero value has the lowest vulnerability (more distant from the margin) and the 255 value the highest (closer to the margin).

3.3. Erosion rate factor

The erosion rate is an important factor in the vulnerability analysis since the region with higher erosion rates will have the effects of the sea level rise accentuated. Each one of the five individual layers produced from the reclassification of the erosion map was submitted to a distance evaluation over which the continuous values were scaled to display a direct relationship, that is, the higher the proximity of the margins under erosion, the higher the vulnerability (increasing linear function, fuzzy routine of the decision support module). Each one of five resulting maps presents values varying from zero (less vulnerable) to 255 (more vulnerable).

3.4. Infra-structure factor

The location of the inhabitants' houses as well as schools, churches, historical buildings, public telephones, bars, bakeries, health center, clubs and other facilities of the island were considered as a very important social-economic vulnerability factors. These equipments and facilities not only provide the development of economic, recreational, and religious islanders' activities, but also offer tourists and occasional visitors a range of leisure options.

Forty six (46) infra-structure equipments and nine hundred and twelve (912) inhabitants' houses were grouped in a single raster image. From that, a continuous distance surface was generated with scaled values according to a linear decreasing function. The utilized criterion was also the margins proximity and then, after the scaling, the values indicate that the cell which had the zero value had the lowest vulnerability (more distant from the margin) and the one with the 255 value the highest (closer).

3.5. Agriculture factor

Agriculture is the oldest and most traditional economic island activity, dating from the foundation of Rio Grande city in the beginning of the last century. Despite the reduction of both the cultivated area and the traditional population, agriculture is still the most important activity especially if we take into account that the fishing activities have been abandoned as a result of a series of problems associated with the artisan fisheries in the Patos Lagoon estuary.

The land use map was reclassified to a Boolean raster file with only agricultural areas from which a continuous distance surface was generated. This file was scaled to indicate that the cell which has the zero value has the lowest vulnerability (more distant from the margin) and the one with the 255 value the highest (closer).

4. Weighting of the Factors

IDRISI features a weight routine to calculate weights, based on the pairwise comparison method (Saaty 1980 *apud* Eastmann 2006). In this methodology a matrix where each criterion is compared with each other relative to its importance, on a scale range from 1 to 9 is constructed. Then, a weight estimate is calculated and used to derive a consistency ratio (CR) of the pairwise comparisons. The consistency ratio indicates the probability that the matrix ratings were randomly generated. Saaty indicates that the matrices with CR greater than 0.10 should be re-evaluated, and the process is repeated until the desired value of CR < 0.10 is reached.

The Weighted Linear Combination method from the decision support module of the IDRISI GIS allows the retention of all the continuous data variability and it also gives the compensation possibility between the factors by a group of weight that indicates the relative importance of each one. The comparison Saaty´s scale (table 1) establishes the following qualitative relations.

Table 1: Saaty's comparators scale

1/9 extremely	1/7 very strongly	1/5 strongly	1/3 moderately
Less important			
1 equally			
1/3 moderately	1/5 strongly	1/7 very strongly	1/9 extremely
More important			

Each factor of the matrix (table 2) indicates how much the factor of the left column is more important than the corresponding factor in the upper line, considering the vulnerability to sea level rise. For example, the elevation factor was evaluated as being strongly more important (value = 5) than the agriculture one.

As expected, a quick look of the matrix shows that elevation is the main factor being always more important than the others. The socio-economic factors (infra-structure and agriculture) were evaluated as being more important when compared to the others (except for elevation) which in the end is going to reflect in a vulnerability map where the socio-economic factor was prioritized in relation to the physical-natural factors.

The calculations of the compensation factors (table 3) indicate the importance of any factor in relation to the others.

Table 2: Saaty's pairwise comparison matrix

FACTORS	Agriculture	Elevation	Infra-structure	Vegetation	Rate 1	Rate 2	Rate 3	Rate 4	Rate 5
Agriculture	1								
Elevation	5	1							
Infra-structure	1	1/9	1						
Vegetation	1/3	1/9	1/3	1					
Rate 1	1/3	1/7	1/3	1	1				
Rate 2	1/3	1/7	1/3	1	1	1			
Rate 3	1/3	1/7	1/3	1	3	3	1		
Rate 4	1/3	1/7	1/3	1	5	3	3	1	
Rate 5	1/3	1/7	1/3	1	5	5	5	3	1

Table 3: Calculated weight for each factor in the vulnerability analysis

Agriculture	0.1259
Elevation	0.4392
Infra-structure	0.1221
Vegetation	0.0439
Rate 1	0.0293
Rate 2	0.0302
Rate 3	0.0449
Rate 4	0.0651
Rate 5	0.0994

5. Generating the vulnerability map

Finally, the vulnerability map was generated by the multi-criteria evaluation module of the IDRISI (MCE) where a multiplication between the compensation weights and corresponding factor images followed by the sum of all factors occur. Since this sum is equal to 1, the map has a continuous range of values similar to the standardized image factors (figure 7).

The sea level elevation vulnerability map displays continuous values ranging from 0 (zero) to 255. The areas with higher vulnerability, with values in the 200-255 range are located mainly in the regions of Marambaia and Porto Rei (darker red). In these locations the vulnerability factors are elevated due to the coincidence of several considered factors, such as, large number of residences, margins under erosion, presence of original vegetation and a flat and plain lowland lagoonal terrace intensively used for agriculture. It is also noticeable a dark stripe with elevated vulnerability from Porto Rei to Marambaia, almost parallel to the southeast margin of the island.

The values indicate the location of Lagoa do Rei natural drainage channel by which the estuarine waters would enter the lagoon in a 1.5 m sea level elevation scenario.

Values between 150 and 200 in most cases occur for the other marginal regions of the islands also indicating a high vulnerability but the relative absence of infra-structure and houses in these locals set the values to lower levels.

In the rest of the island the values progressively decrease landward since the center of the island displays the higher elevations (dune fields), and absence of infra-structure, houses and agriculture activities.

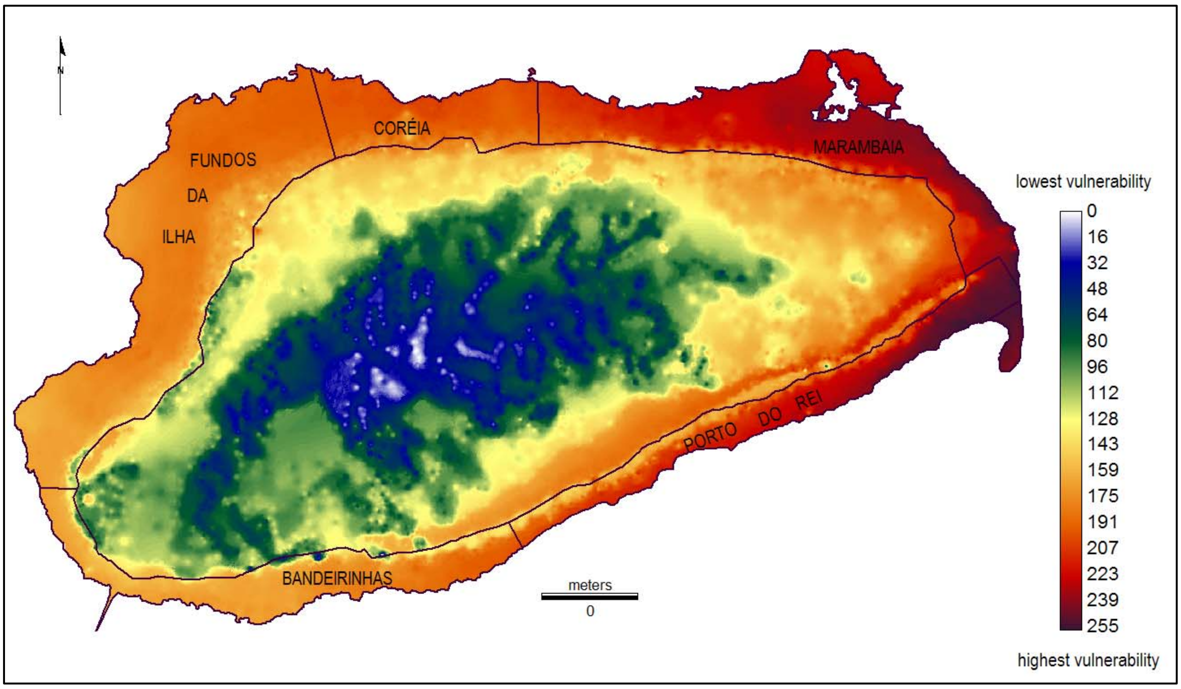

Figure 7: Sea level rise vulnerability map

6. Final Considerations

The evidences of sea level rise around the world, independently of its causes, unequivocally demonstrate that evaluation of the vulnerability of coastal ecosystems is a required, strategic and urgent task.

In the small and medium size coastal counties of Brazil, there is absence of human and technical resources, inexistence of institutional integration and complete lack of awareness about the threats posed by these problems. Due to this situation, it is illusory to think that local government is going to allocate resources to prevent future impacts of sea level rise or even to make any effort in this sense. This task will only be done by means of a cooperation effort between state and private entities in which the universities and the research centers play a fundamental role.

Marinheiros Island vulnerability map shows the spatial vulnerability according to the criteria used, demonstrating what would be the most critical areas in a sea level rise scenery. This map has a practical planning application being very useful for decision makers. It may be used in environmental and urban planning, as well as a guideline to orientate the best alternatives to minimize the already detected erosion effects. The inclusion of real sea level rise rates, if available, would not change the results here found, in fact, it would merely add a temporal dimension to the analysis.

An important factor to be considered in an analysis of impacts of sea level rise on the coast of Rio Grande do Sul state is the variation in the sea level and the Patos Lagoon during certain periods of the year, caused by influence of storm surges associated with cold fronts (Calliari *et al*. 1996). Such events associated with periods of higher water level in the lagoon during the flood seasons, cause severe erosion along all the lagoonal and island margins, implying in severe land loss to the ecosystems also affecting the socio-economic activities.

Anyway, exercises of projection as performed in this work are a useful tool in helping the decision-makers to explore certain alternatives. It also helps to orientate discussions if the planners want to insert sea level rise in the urban planning.

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