PANAMJAS
Pan-American Journal of Aquatic Sciences

Potential vulnerability of the Brazilian coastal zone in its environmental, social, and technological aspects

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Abstract. Climate change caused by human action can be considered a major challenge facing human kind in the 21st century. Its potential to cause economic and social impacts is considerable, as it directly affects standards of living of coastal populations. This challenge can only be overcome through integrated actions taken by various sectors of society and supported by a deep knowledge of current and expected scenarios. This paper is a contribution to this knowledge, as it defines the vulnerability level of the Brazilian coastal zone based on a combination of environmental, social, and technological standards set forth in *Macrodiagnóstico da Zona Costeira e Marinha* (Macrodiagnosis of the Coastal and Marine Zone) by the Ministry of the Environment in 2008. Low-lying, densely populated, socially underprivileged regions with intricate technological networks are the most vulnerable and require a prioritized integrated action from policymakers. Throughout the entire country, several areas were rated as vulnerable or highly vulnerable, particularly the metropolitan regions of Belém, capitals of the Northeast, Rio de Janeiro, and Santos. Its potential to cause economic and social impacts is considerable, as it directly affects standards of living of coastal populations. This challenge can only be overcome through integrated actions taken by various sectors of society and supported by a deep knowledge of current and expected scenarios.

Key words: climate changes, natural risk, social risk, technological risk

Resumo. Vulnerabilidade potencial das zonas costeiras brasileiras em seus aspectos ambientais, sociais e tecnológicos. Considerado um dos grandes desafios a serem enfrentados pela humanidade no Século XXI, a resposta das sociedades aos efeitos de alterações nos padrões climáticos é fundamental no planejamento territorial, principalmente no que diz respeito às zonas costeiras. Mesmo alterações de pequena intensidade possuem potencial para causar impactos econômicos e sociais consideráveis, com efeito direto na qualidade de vida das populações costeiras. Este desafio somente poderá ser enfrentado a partir de ações integradas entre os diversos setores da sociedade e fundamentado no conhecimento profundo dos cenários atuais e previstos. O presente artigo apresenta uma contribuição a este conhecimento, definindo o grau de vulnerabilidade da zona costeira brasileira (em escala da União), com base em uma combinação de critérios ambientais, sociais e tecnológicos, definidos quando da publicação do Macrodiagnóstico da Zona Costeira e Marinha por parte do Ministério do Meio Ambiente em 2008. Regiões de baixa altitude, densamente povoadas, socialmente carentes e com intrincadas redes tecnológicas são as mais vulneráveis e que demandam prioridade de ação integrada por parte dos tomadores de decisão. Ao longo de todo o país diversas áreas foram classificadas com grau alto ou muito alto de vulnerabilidade, com destaque para as regiões metropolitanas de Belém, capitais dos estados da região nordeste, Rio de Janeiro e Santos.

Palavras chave: mudanças climáticas, risco natural, risco social, risco tecnológico

Introduction

Coastal zones, in their seemingly simple landscapes and usual dynamics, require at least the same - or possibly a more complex - level of consideration as inland spaces, for they involve issues related to changing sea level, paleoclimate, and vegetation history. In other words, the coast, like many other areas with ecological landscapes, may always be considered a heritage from earlier processes, redesigned by the now-prevailing coastal dynamics. Therefore, one can say coastal areas are three-way contact zones: land, sea, and climate, in addition to the remarkable showcases of individual ecosystems found in the land/sea mosaic comprising the total coastal space (Ab'Saber 2000).

The Brazilian coast, 8,698 kilometers long, and covering some 514,000 square kilometers, is a perennial challenge to management, due to the multiplicity of situations existing in such territory[1]. There are approximately 300 coastal municipalities facing the ocean, with privileged beaches for the development of tourist activities including leisure, fishing and many others. This dynamic landscape of fast physical and socio-economic changes is home to approximately 18% of the country's population, inasmuch as 16 out of 28 metropolitan regions lie along the coast. These densely populated areas coexist alongside large, sparsely populated areas. These are the areas of small-scale commercial or subsistence fishing communities, descended from *quilombolas* [dwellers of communities of descendants of fugitive African slaves], indigenous tribes, and other groups living in their traditional lifestyles. Considering the high level of preservation of their ecosystems, these areas will be the most relevant for preventive environmental planning.

In addition to the familiar environmental issues affecting this part of Brazil's territory, particularly with regard to causes and effects, there arises a new potential development in the shape of climate change. The need to adapt to this new development and mitigate the problems it has caused should figure prominently on the agenda of legislators and decision makers.

Within this context, it is important to understand the interactions between oceans and coastal zones and the climate change-related variables. Moreover, it is essential to build a strategic vision of this part of the territory, so that steps may be taken in response to new scenarios of global warming, rising sea levels and coastal erosion.

UNESCO, through its Intergovernmental Oceanographic Commission (IOC) has been concentrating efforts to establish methodologies to help Member States in the difficult task of identifying hazards brought about by climate change in coastal zones and making adaptations and acting to mitigate its undesirable effects.

That has been a priority among IOC's initiatives, after the disaster of December 2004, when a tsunami hit several countries along the Indian Ocean. Together with the World Meteorological Organization (WMO), IOC is starting to develop an initial multi-hazard warning system to guide governments in their decisions, especially with regard to integrated coastal management (IOC 2009).

In Brazil, efforts to build a technical and institutional structure able to withstand the effects of climate change are just getting underway. A recent study by TCU (the Federal Audit Office, similar to the GAO in the USA) titled *Auditorias de natureza operacional sobre políticas públicas e mudanças climáticas* (Operating audits on public policy and climate change) has concluded that the country lacks a national-scale study on the vulnerability of its coastline to climate change impacts (TCU 2009).

TCU emphasizes that, among the few existing Brazilian coastal vulnerability studies, a highlight is *Macrodiagnóstico da Zona Costeira e Marinha* (MDZCM), an instrument set forth by Law 7661/88, which established the National Coastal Management Plan.

The MDZCM diagnosed the main aspects on the Coastal and Marine Zone, mostly the changes in the energy policy, which led to a considerable increase in oil drilling, development, and extraction in this part of the territory, particularly after the state monopoly was broken up. The current and potential dimensions of the urban-manufacturing facilities and their interaction with other activities also went into this diagnosis, which included information on infrastructure, household and industrial wastewater, and toxic elements present in coastal municipalities, among others. The sources are identified by geographic type of receiving bodies (estuaries, bays, beaches, etc).

By combining a broad array of information, environmental hazard figures were generated which, in turn, measure threats to the living standards of Coastal and Marine Zone populations. Locations with a flooding potential, social risk potential, and technological risk potential could thus be identified (Nicolodi & Zamboni 2008).

This paper attempts to identify, based on data generated by MDZCM, the regions in the Brazilian coastal zone most vulnerable to the effects of climate change, and thereby provide support for a thorough assessment of the country's vulnerability, and help fill the gaps identified by the Federal Audit Office.

[1] An extension value which takes into account the irregular coastline forming bays and recesses, among other landforms. Of its 514,000 km^2 area, some 450,000 km^2 cover 17 coastal states, and 395 municipalities, including inner water surfaces – while the rest consists of Brazil's Territorial Sea (MDZCM 2008).

Vulnerability Analysis and the Environmental Risk Concept

The concept of risk is usually associated with an event which may or may not happen. However, the actual risk only occurs when assets are valuable, whether materially or not, since there is no risk if the perception of losing something does not exist. Therefore, one cannot envision risk if there is no danger of losing something. In this case, society faces a risk.

The notion of “possible loss”, which is intrinsic to risk, can be broken down into several components. When we examine spatial location, or even spatial distribution of hazards, the connection with cities – or more precisely, urban centers – becomes more evident. This is because they are the specific site of production and reproduction of manufacturing processes and a lifestyle which favors population concentration, encourages manufacturing output, business relationships, and service provision (Castro *et al.* 2005).

In this sense, risk assessment is based on the relationship between reliability and criticality of complex systems, where the dynamic behavior of numerous variables must be captured in a select set of indicators capable of monitoring the interactions that actually occur along different time scales, i.e., in the near, medium, and long term (Egler 2005).

Environmental risk analysis must be seen as a dynamic indicator of relationships between natural systems, the productive structure, and the social conditions of human reproduction at a given place and time. It is therefore important to consider the assessment of environmental hazards as the consequence of three basic categories:

a) Natural Risk: related to processes and events of a natural origin, or resulting from human activities. The nature of these processes is quite diverse on time and spatial scales, so the natural risk may present differing levels of loss, as a result of intensity (magnitude), spatial extent, and time of activity of the processes under consideration.

b) Technological Risk: The technological risk is inherent in productive processes and manufacturing activities. The idea of technological danger derives chiefly from manufacturing technology, as a result of inherent flaws, as opposed to natural dangers, perceived as an external threat (Castro *et al.* 2005). Technological risk may be defined as a potential event that can be life-threatening in the near, medium, and long term, as a result of investment decisions in the manufacturing structure.

c) Social Risk: This category can be analyzed and developed from different standpoints. It is often considered as the damage society (or part of it) can bring about. Another approach stresses the relationship between deprivation and vulnerability to natural disasters. For the purposes of this study, we have adopted the bias proposed by Egler (1996), where Social Risk is seen as the result of deprivation of social requirements for full human development, a fact that contributes to deterioration in standards of living. Its most obvious consequences are the lack of adequate living conditions, expressed in terms of access to basic services such as treated water, wastewater, and trash collection services. In the long term, however, these can affect employability, income, and technical development of the local population, as key elements to a full, sustainable, human development.

Taking these three basic dimensions as a starting point for a broader concept of environmental risk, a methodology for its evaluation must build on three basic criteria (Egler *op. cit.)*:

a) Vulnerability of natural systems, seen as the level between the stability of biophysical processes and unstable situations where there are substantial losses of primary productivity;

b) Density and potential expansion of the productive structure, which attempts to express fixed and flowing economic aspects in a certain area of the country in a dynamic concept;

c) Criticality of housing conditions, in terms of the gap between current standards of living and the minimum required for full human development.

These definitions are in agreement with UNESCO’s IOC, which defines coastal vulnerability as the state of coastal communities (including their social structure, physical assets, economy, and environmental support) that determine which are affected to a greater or lesser extent by extreme events (IOC 2009).

The same Commission further establishes that vulnerability analyses be conducted according to different – macro to micro – scales, depending on the approach to be given by the national integrated coastal management programs.

In this study, the macroscale will be used to define Brazilian coastal vulnerability by region, thus providing inputs for planning responses for their mitigation and adaptation.

Methodology

According to IOC’s proposed methodology, five stages are necessary to make national and regional climate change adaptation plans: 1) Identifying and quantifying the hazards; 2) Measuring vulnerability; 3) Assessing the risk; 4) Enhancing awareness and preparedness; 5) Mitigating the risk. This study addresses stages

1 and 2, which are the basis of the necessary knowledge to define the other stages.

Information generated by MDZCM (Nicolodi & Zamboni 2008) was used to prepare the overview map on the vulnerability of the Brazilian coastal zone with relation to natural risk, social risk, and technological risk. To the crossing of such results were added spatial information on population dynamics, geomorphology, use and occupation of the Exclusive Economic Zone (EEZ) and biodiversity[2]. In all cases, specific geoprocessing routines were resorted to, along with IDRISI and ARCGIS9[3] software.

The analysis scale of the issues addressed in MDZCM and the vulnerability analyses of the coastal zone proposed by this paper is 1:1,000,000. This scale corresponds to the scope of the area of study and enables practically all existing map bases to be included in the analysis context.

Natural risk charts are a direct product of a combination of altimetry aspects[4] with population data, added to assessment of vulnerability levels to inundation caused by extreme weather events, heavy rains, and prospects of a higher sea level.

The altimetry information was modeled into geographic information systems[5], and became a digital model of the Coastal Zone, to which data on the local population were added by subdistricts, provided by IBGE, the Brazilian Institute of Geography and Statistics, according to the census update provided by IBGE in 2006.

Upon refining the five levels of potential natural risk,[6] coastal process information was considered, through the use of statistical techniques (weighted averages). Eroded coastal areas added value by showing the regions more prone to flooding, since erosion tends to destroy natural barriers such as *restingas* (beach ridges with scrubby vegetation), dunes, sea cliffs, mangroves, etc. On the other hand, coastal areas with a sediment accretion and, consequently, shoreline progradation, subtracted value when determining risk ranges (Muehe 2006).

When weighting the factors, the combination of land elevations below 10 m above sea level and marine erosion was considered the most critical indicator of coastal environment vulnerability to floods. The risk potential could then be assessed by cross-referencing this information against the population data by subdistrict. An example of a natural risk map can be seen in figure 1.

Regarding social risk definition, the level of income of that part of the population earning up to three (3) times the minimum wage was used as background data, based on IBGE 2000 census results by district. Area ranking according to social risk potential[7] was obtained by crossing income data with the number of homes lacking garbage collection and wastewater services. The ranking system thus considered dwellings where wastes are disposed of in rudimentary cesspools, ditches, rivers, lakes, or into the ocean to be “lacking basic sanitation”. Regarding the destination of solid waste, the ranking system considered those dwellings where garbage is burned or buried, thrown into backyards or streams, the ocean, or ponds as “homes lacking garbage collection”. An example of a social risk map can be seen in figure 2.

As to technological risk, the data came from sources referred as technological, such as, for example, power generating units or manufacturing facilities. Their construction methodology resulted from the number of industry employees per city in relation to the industry’s polluting potential. The definition of polluting potential followed the methodology proposed by RAIS, the Annual List of Social Information issued by the Labor Ministry (2002)[8].

The data resulting from the crossing of this information were grouped into four categories representing technological risk potential levels (low, medium, high, and very high). Moreover, the maps include the location of thermal plants according to the fuel used, natural gas and oil production and extraction activities, and oil industry-related

[2] The inclusion of these variables did not necessarily occur during the analyses of Geographic Information Systems, but rather, during the descriptive analysis of the results.

[3] Such routines include Boolean operations with maps, attribute analysis of georeferenced databases, and multi-standard evaluations.

[4] The altimetry data came from SRTM-NASA, available on the U.S. Geological Service.

[5] Such modeling took place at the Geography Department of the Federal University of Rio de Janeiro (UFRJ) when the data base’s MDZCM was prepared.

[6] These are: very high, high, moderate, low, and very low.

[7] These can be: very low, low, medium, high, and very high.

[8] Types of industry according to polluting potential: (a) very high: Rubber, Tobacco, Leather, Chemicals, Mining, Non-Metal Ores; (b) high: Metallurgy, Textiles, Foodstuffs and Beverages, Paper and Printing; (c) medium: Mechanics, Rolling Stock, Footwear, Wood and Furniture; (d) low: Electronics and Communications, Civil Construction, Public Utilities. It should be pointed out that IBAMA measures the polluting potential of manufacturing activities, especially with regard to the *Cadastro Técnico Federal* (a mandatory registration list of companies in polluting, or potentially polluting, industries) (http://www.ibama.gov.br/cadastro).

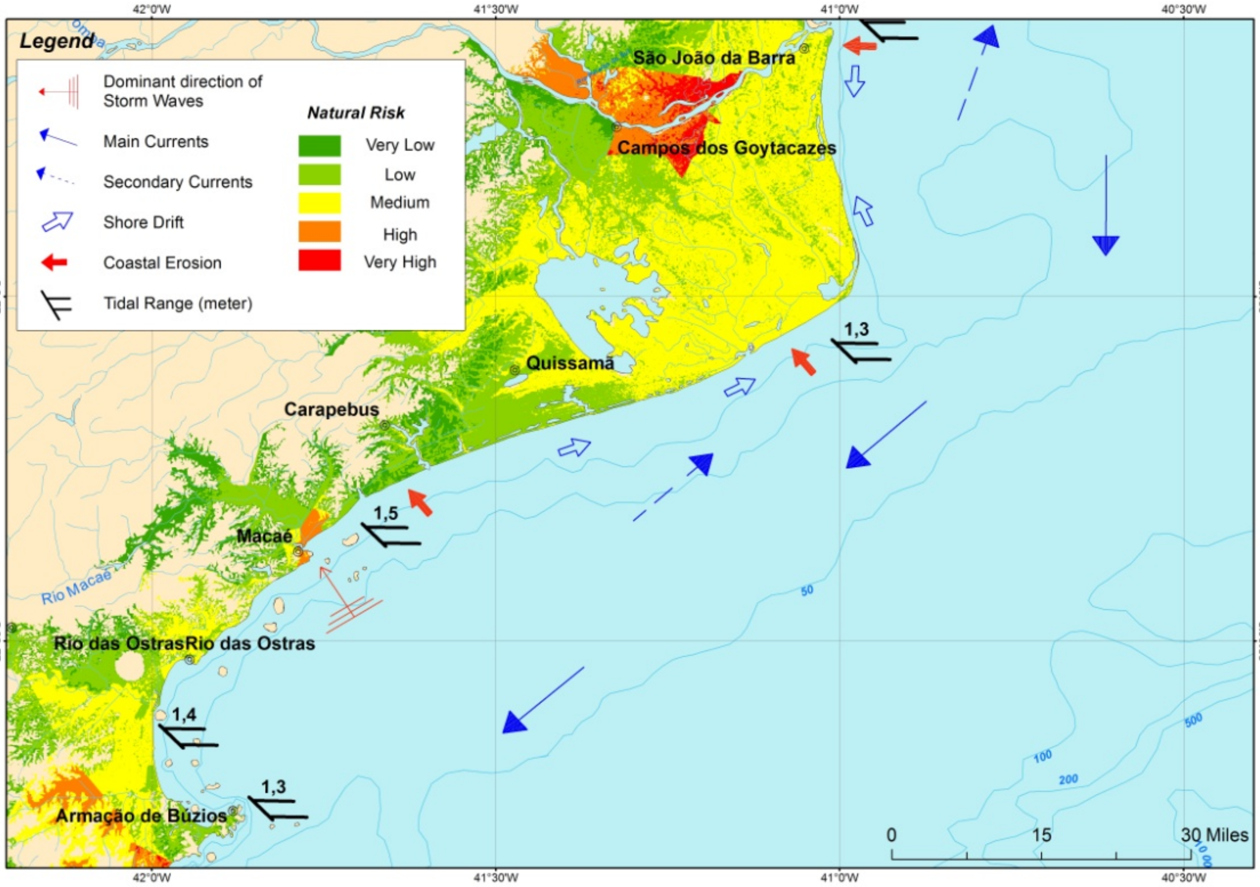

Figure 1. Example of a Natural Risk Map.

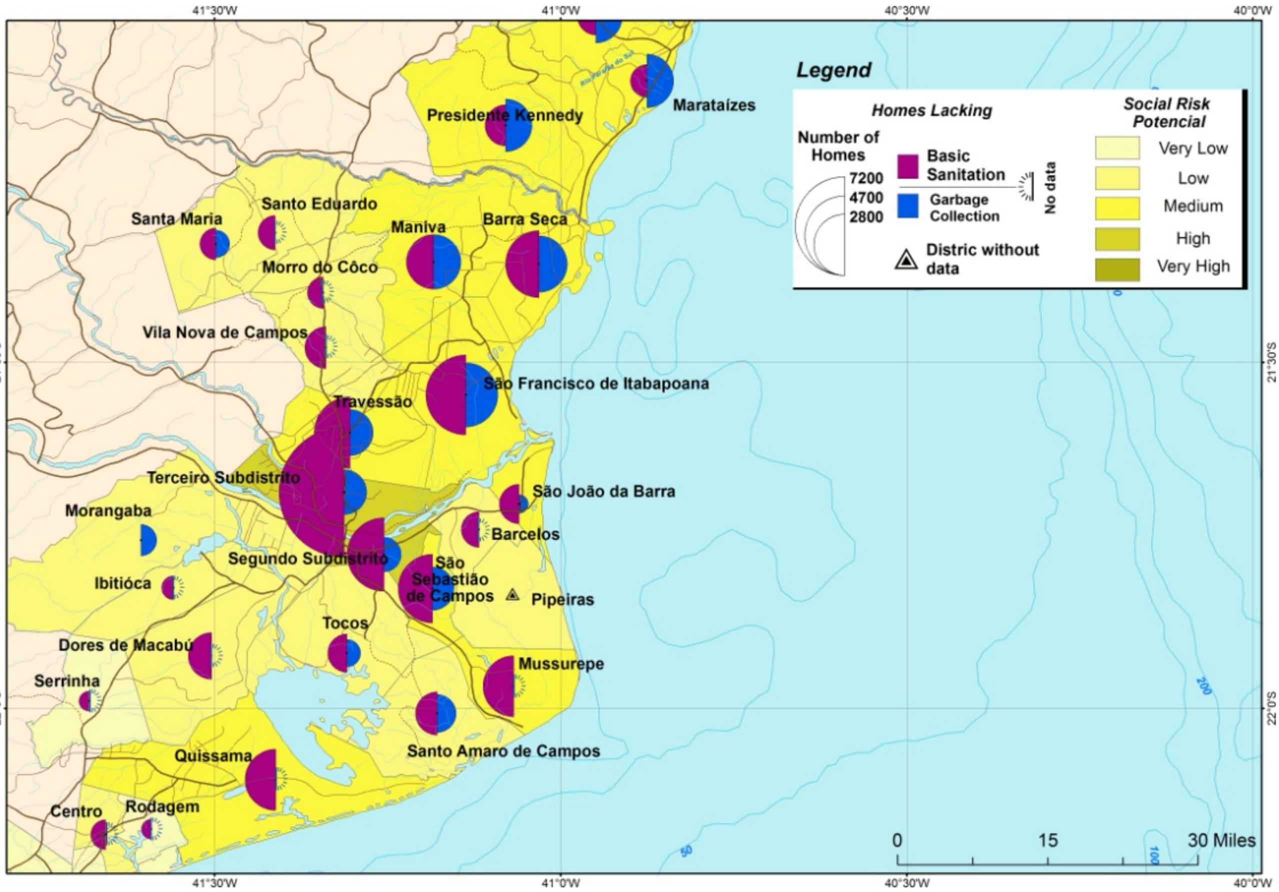

Figure 2. Example of a Social Risk Map. The risk potential is shown in yellow at subdistrict level.

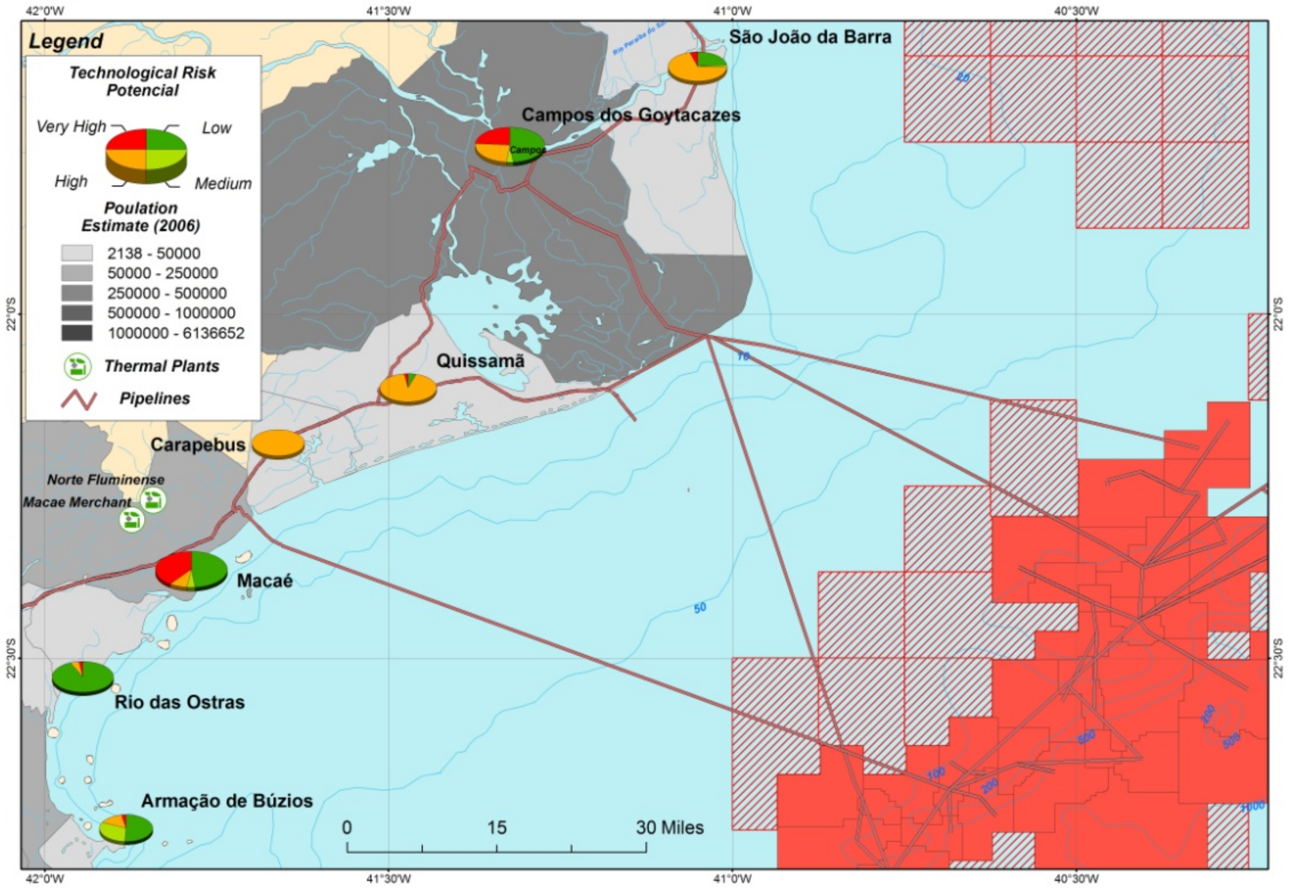

Figure 3. Example of a Technological Risk Map. The pie chart indicates the risk potential at each municipality. The town population appears as a gray background.

facilities (pipelines, refineries, etc). This mapping activity is based on population estimates by municipality, made in 2006, which give an idea of the number of people potentially affected by an accident involving technological risk. This is related to the various stages of the productive activity, from the extraction of raw materials to the marketing of goods. An example of a technological risk map can be seen in figure 3.

The definition of Brazilian coast vulnerability was made in five hierarchical levels, following the same categories as for Social Risk, Technological Risk, and Inundation Risk. For data-crossing operations the following values were established per category: Very Low ≤ 1, Low >1 and ≤ 2, Medium >2 and ≤ 3, High >3 and ≤ 4, Very High >4 and ≤ 5.

The first stage consisted in establishing a sole Technological Risk rating for the municipalities. This was calculated by the weighted average between risk potential categories. A process example may be seen in Table I.

The results were ranked in five intervals using the *Geometrical Interval* algorithm, available as an ArcGIS function. In this system, the class intervals are based on a geometrical series. The geometric coefficient in this classifier can change once (to its inverse) to optimize the intervals. The algorithm creates these geometrical intervals by minimizing the square sum of elements per class.

The reclassified technological risk potential can then be spatially crossed with the social risk and the natural risk data. To this end, phrases and sentences similar to those used in mathematics were used to describe Boolean operations. The model used to describe the GIS sentences, involved the logical combination of the vector maps through conditional operators which supported the assumption to which the analysis was directed. The Vulnerability Index obtained from this crossing was developed through the simple average between the three types of risk involved (Fig. 4).

Results and Discussion

From the onset of European colonization, the establishment of populations and socio-economic utilization of coastal areas have been increasingly intense. This territory occupation by about one quarter of the Brazilian population, has begun with the appropriation of common spaces in the Coastal

Table I. Example of weighted average calculation for the new categories of Technological Risk.

Municipality	V. High Risk	High Risk	Medium Risk	Low Risk	Final Risk (Weighted Average)
Araruama	3605	1536	4608	2614	3087.2
Armação de Búzios	60	192	576	310	244
Arraial do Cabo	3565	220	660	266	1515.5
Cabo Frio	4615	3324	9972	3234	5196.7
Casimiro de Abreu	230	828	2484	1744	1100.1
Iguaba Grande	90	4	12	156	58.1
Macaé	63535	13608	40824	32586	39982.2
Maricá	1335	1040	3120	934	1575.9
Rio das Ostras	275	452	1356	3432	1008.2
Saquarema	565	440	1320	296	652.6

Final Risk = [(V.High Risk*5)+(High Risk*4)+(Medium Risk*3)+Low Risk*2)]/(5+4+3+2)

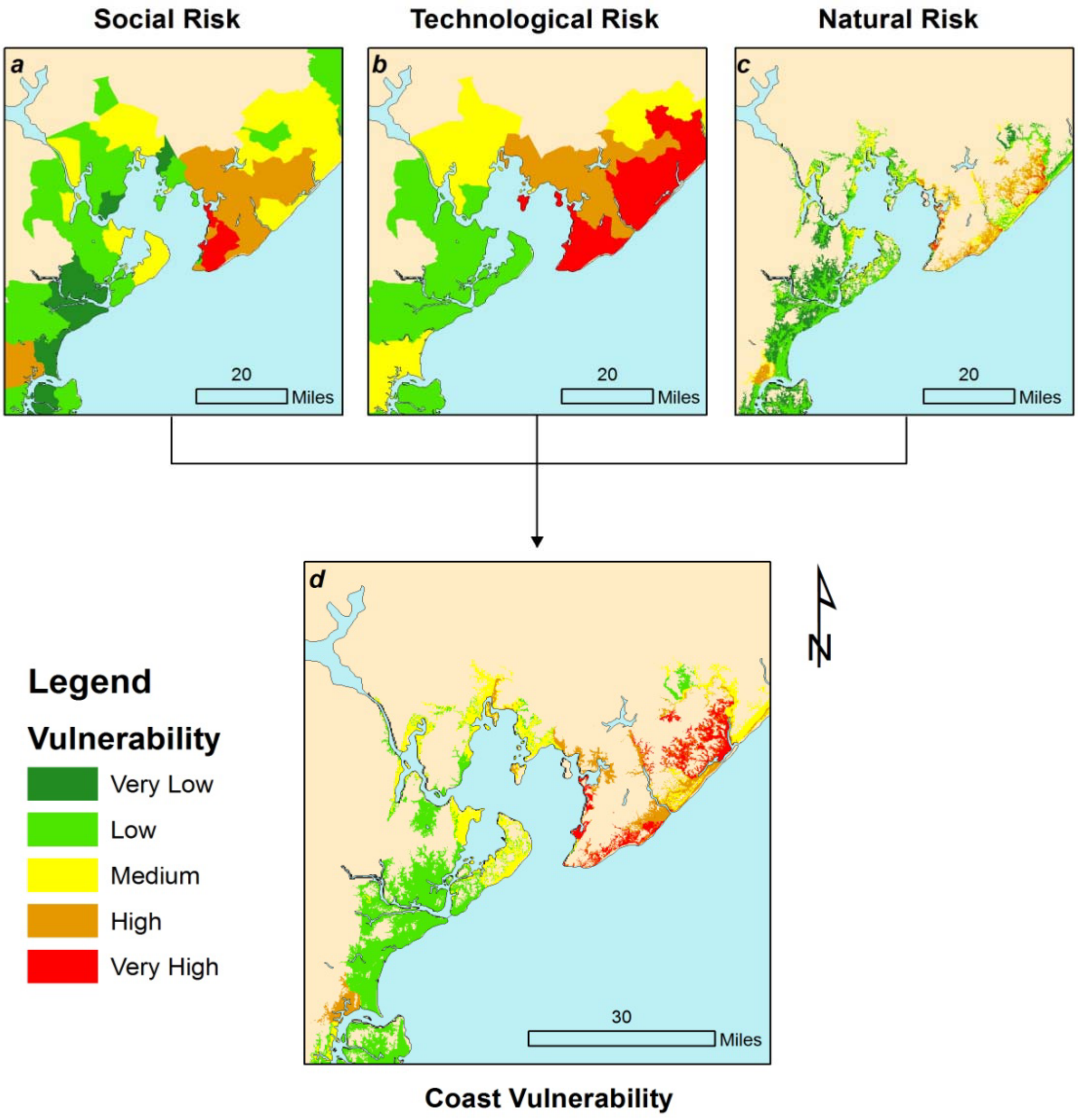

Figure 4. The spatial crossing made between the three risk types: (a) Natural Risk; (b) Social Risk; and (c) Technological Risk. The result is shown by (d) Coast vulnerability, obtained by simple average.

Zone, through its typical activities and uses, and its main inducing vectors relate to port, manufacturing, oil, and tourist activities.

Intrinsically linked to human occupation due to its cause and effect relationship, the coast's geomorphological characteristics, associated with climate and ocean processes, impart a unique relevance to flooding-related issues. Therefore, the resulting loss of physical space to the development of economic and social activities that are inherent to it stand out from an a priori analysis of the risks of natural disasters to which these continental and marine transition areas would be exposed (Tessler 2008).

The analysis of the Brazilian coastal vulnerability to the effects of climate change studied herein will be presented in a regionalized form to organize the results of this work.

North Region

The Brazilian North Region generally displays a low vulnerability level, with exceptions in the vicinity of its three large capital cities: Macapá, Belém, and São Luís. In these cases, vulnerability was rated high or very high (Fig. 5).

This ranking is explained by a combination of factors, mainly physical (coastal dynamics and geomorphology), socioeconomic (average population income, lack of basic services) and technological (types of industry, types of pollution, and their representativeness of the number of workers).

In geomorphological terms, the coast and continental shelf of the North Region are dominated by mud sediment from the Amazon, with significant coastal stretches under accelerated erosion while others – due to the buildup of sediment from the local river network – have prograded.

The emerged coastal region is formed by a low-lying Holocene plain, its width varying between 10 and 100 km, while the inner portion is dominated by older plain deposits and rocks of the Pre-Cambrian Guyana shield, with an altitude below 500 m, forming the source areas of part of the coastal river network. Tidal influence is quite strong. For example, on Maracá Island, macrotides, predominantly semidiurnal, exceed 9.8 m, while to the north, at Oiapoque Bay, this amplitude is lower (about 2.7 m).

In its southern portion, the coast shows a finger-like muddy progradation, which emphasizes the irregular coastline. Its appearance is of a sea-drowned coastline, typically a succession of small

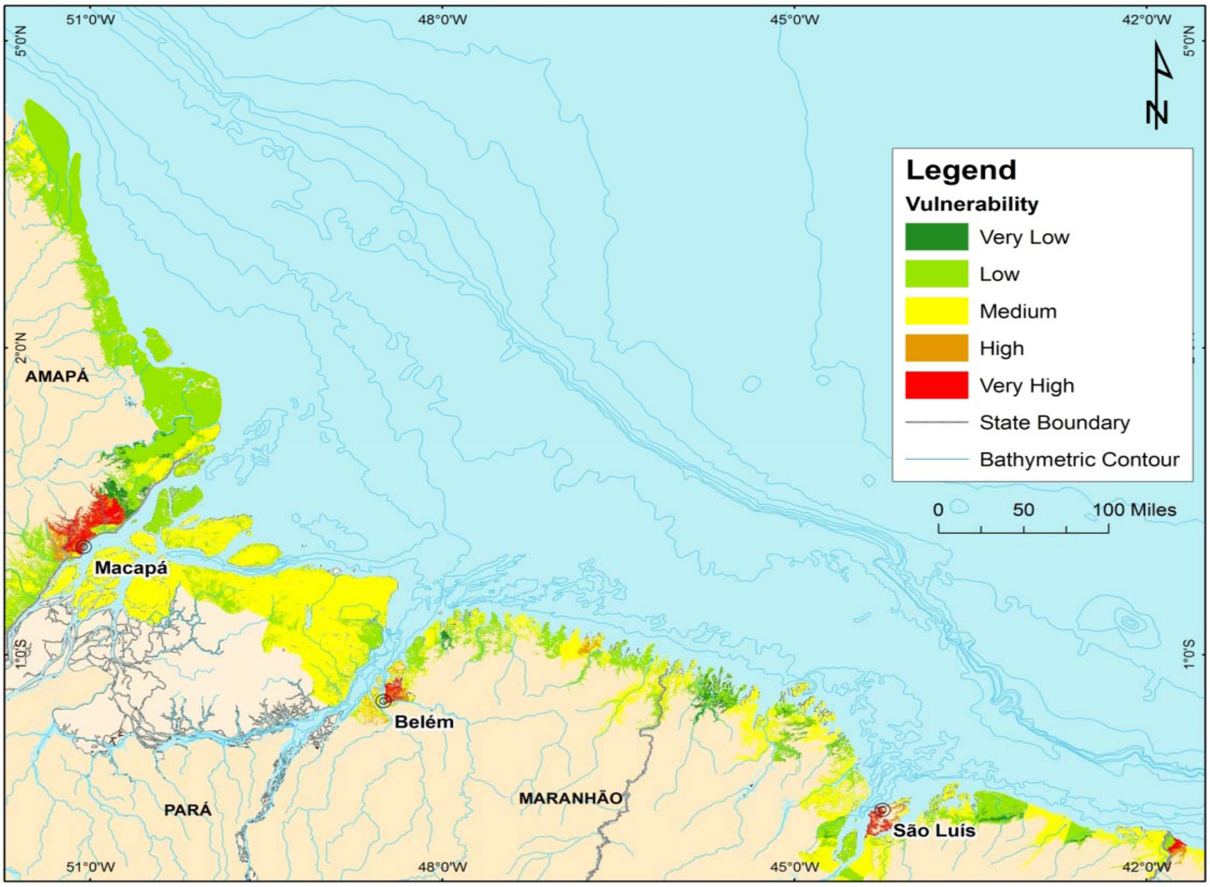

Figure 5. Vulnerability of the Brazilian North Coast. Low vulnerability level, except in the vicinity of three large capitals: Macapá, Belém, and São Luís.

estuaries and sediment accretions which jointly look like *rias* (drowned river valleys), and the reason why they are called *re-entrâncias* (recesses) in Maranhão state. Many of them resulted from prograded muddy deposits, forming long landforms more or less perpendicular to the coast. The North coast, here shown from Oiapoque (in Amapá state) to the south of Maranhão, is a high energy segment, with a strong sediment mobility, very much influenced by the intense water and sediment discharge from the Amazon River and the hydrodynamic factors of the ocean, particularly tides (Muehe & Nicolodi 2008).

Such characteristics provide low vulnerability levels to this area, which change when analyzing the existing metropolitan regions. The North coast of Brazil is characterized by scanty human presence, consisting mainly of traditional extractive and foraging communities, large empty areas, dozens of municipalities with a small population density, but with important regional complexes such as Macapá and metropolitan concentrations in Belém and São Luís (Strohaecker 2008).

The geomorphologic characteristics of the north coast of Pará form a physical barrier to an intensive process of population settlement on the coast. But a few parts of this segment have had a disorderly population growth. Population density in this area is approximately 27 inhabitants per km^2, in contrast to other sections with a density of 3.5 inhabitants per km^2. Significant values can be noticed just in the Belém area and its surroundings (of about 220 inhabitants/km^2).

São Luís is located in the Golfão Maranhense (Maranhão's Big Gulf) region. São Luís has the state's only significant population concentration (> 170 inhabitants per km^2) on this coastal lowland. Therefore, only the area around the Maranhão state capital is highly vulnerable.

In addition to this analysis of population dynamics, it should be noted that the coverage of waste collection services seen in the North Region is much lower than in other regions of Brazil, and it is also the one with the worst provision of this basic service: 6,790 tons/day.

This situation, further to the data on basic sanitation, leads to a coefficient ratio between the total population and the population exposed to social risk of 33.7% for the North Region, which, in absolute figures can be translated into 2.206,138 inhabitants, most of them residing in the capitals and their outskirts (Astolpho & Gusmão 2008). This data becomes even more relevant when considered a few results of global assessments made by IPCC, which confirm the fact that disadvantaged populations, who are less able to adapt, are the most vulnerable (Marengo 2006).

Adding to high levels of vulnerability of the metropolitan areas in the North, is the association between the metal-mechanical complexes and the paper and pulp industry on the coast of the Pará and Maranhão states, with massive investments in the production of metallic minerals such as iron and aluminum, and extensive planted land used to produce pulp. This is a determining factor that increases the technological risk and vulnerability of the Coastal Zone at critical points, as is the case of Barcarena, in Pará state, and São Luís, in Maranhão (Egler 2008).

Northeast Region

The Coastal Zone of the Northeast Region, marked here by the coast between the north of Piauí state and the south of Bahia state, features a great diversity of ecosystems, with distinct physical and geomorphologic characteristics affected by a broad range of pressure vectors, which ultimately define the region's vulnerability.

Unlike the North, where only metropolitan areas were found to be highly vulnerable, the Northeast alternates between the five vulnerability levels which do not necessarily have a direct relationship with population dynamics.

In geomorphological terms, the upper part of the region is dominated by sedimentary deposits of the Barreiras group, in front of which numerous dune fields have developed, fed by sediments coming from the inner continental shelf, as, for example, the Parnaíba River Delta and Jericoacoara, in Ceará.

In Rio Grande do Norte state one can see the Barreiras Group sea cliffs and a wide development of active dune fields along the entire coast. One can notice the natural barrier formed by the dunes on the river estuaries, which leads to insufficient drainage and forms swampy valleys, in addition to an increased number of estuaries and mangroves starting in Paraíba state, as a result of a higher precipitation volume.

To the east of this dune field, the Parnaíba River estuary displays a coastal stretch considered medium to highly vulnerable, particularly due to the strong erosion caused by the cyclic floods that hit the Parnaíba River downstream during the high-water season (Fig. 6).

The coast of Ceará, marked here and there by higher land, has a large number of eroded coastal sections linked to moving barchan dune fields, the Barreiras terrace deposits, and outcrops of the crystalline basement. In addition, the Ceará coast has a low population density, except near Fortaleza, where this density is higher, and the vulnerability level is also high. In the Aracati area, where vulnerability is medium to high, the factors affecting this ranking are related to the significant shortage of basic sanitation, the accelerated manufacturing development, and the increase of shrimp farming activities and tourism.

Another especially vulnerable area is the vicinity of Mossoró, in the innermost portions of the coastal region. This situation occurs due to a number of factors, including the existing low-lying areas that tend to flood owing to the drainage of Apodi and Mossoró rivers, an acute shortage in the provision of basic services, and an intricate logistic oil and gas network, which extends all the way to the area near Macau, where the Guamaré Natural Gas Plant is located. In this section, the highlight is the coastal erosion, which is so strong, that it is already affecting oil industry equipment installed in the area (Muehe 2006).

When analyzing this region's social risk, one can see that the situation is critical in large centers, particularly in Natal, João Pessoa, and Fortaleza.

The lack of sanitation in these areas is significantly greater than the lack of garbage collection services. In Fortaleza, the data on the shortage of garbage collection services show a tendency toward solving the problem, while the sewerage situation is of extreme concern in almost all municipalities and districts. This same situation, although less severe, can be noticed in Maceió, Aracaju, and nearby areas (Astolpho & Gusmão 2008).

In the Northeast, the population exposed to social risk is 25.71% of the total population, which, in absolute numbers, may be translated into 12.286,455 inhabitants potentially more vulnerable to the effects of climate changes.

In the central part of the Northeast, the main areas of higher vulnerability include the metropolitan areas of Natal, João Pessoa, and Recife (Fig. 7). According to Neves *et al.* (2006) about 42% the coast of Paraíba is exposed to the effects of erosion. Similar geomorphologic characteristics extend to the coast of Pernambuco, which has a higher population density, compared with the coast of Paraíba and Alagoas. Along this entire segment, low to medium natural risks predominate, with the exception of the areas with the highest urban concentration (João Pessoa and Recife) and deeply eroded segments (Paulista, Itapojuca, Suape, Cabo de Santo Agostinho, and Recife).

Another factor that adds to the region's high vulnerability is the displacement of the chemicals complex to the Northeast coast along Salvador, Aracaju, and Maceió, due to the expansion of the energy boundary on the coast. This fact has brought a massive concentration of pipelines, terminals, and plants. The surroundings of the Recôncavo Baiano area and the cities of Aracaju (SE), Maceió (AL) Recife-Cabo (PE), and Macau-Guamaré (RN) are highlights in this process, where the energy production equipment increases the exposure to environmental hazards (Egler 2008).

In the southern portion of the Northeast Region, the most outstanding morphological feature is the São Francisco River delta, site of the country's worst coastal erosion. Bittencourt *et al.* (2006) indicate as likely causes the embankment interventions to contain the river flow upstream from its mouth, mainly those related to the construction of hydroelectric plants, which implies great potential inundation of inner drainage areas, which rates this section as of high risk.

From the São Francisco River to the Caravelas River plain, there is a general tendency for the coastline to prograde and stretches with sea cliffs of the Barreiras Group to erode. Dune fields appear near the mouth of the São Francisco and on the northern coast of Bahia. Near Salvador, the Barreiras River is replaced by outcrops of Pre-Cambrian and Cretaceous crystalline basement.

Higher-than-average coastal sections, coupled with a low density population, have a medium to low vulnerability. At some places, this level is high only where population density is higher and basic sanitation is deficient, i.e., at Valença, Ilhéus, and Porto Seguro - urban centers combined with river mouths (Fig. 8).

In the Salvador metropolitan area, the high vulnerability levels are not only related to these factors, but also to high technological risk posed by the Camaçari manufacturing complex, namely the oil industry, and particularly the Landulpho Alves Refinery, the Candeias Natural Gas Production Unit, and the Termobahia, Rômulo Almeida, and Camaçari thermal plants (Fig. 9).

Southeast Region

The coast of Espírito Santo state and the north coast of Rio de Janeiro state are geomorphological boundaries of the Northeast coast. This stretch is dominated by Tertiary terraces and the sea cliffs (Barreiras), Pre-Cambrian crystalline promontories and Quaternary plains of river and sea origin. Between the mouths of São Mateus and Itabapoana rivers, the Barreiras terraces and sea cliffs extend along the entire coast, displaying live and dead

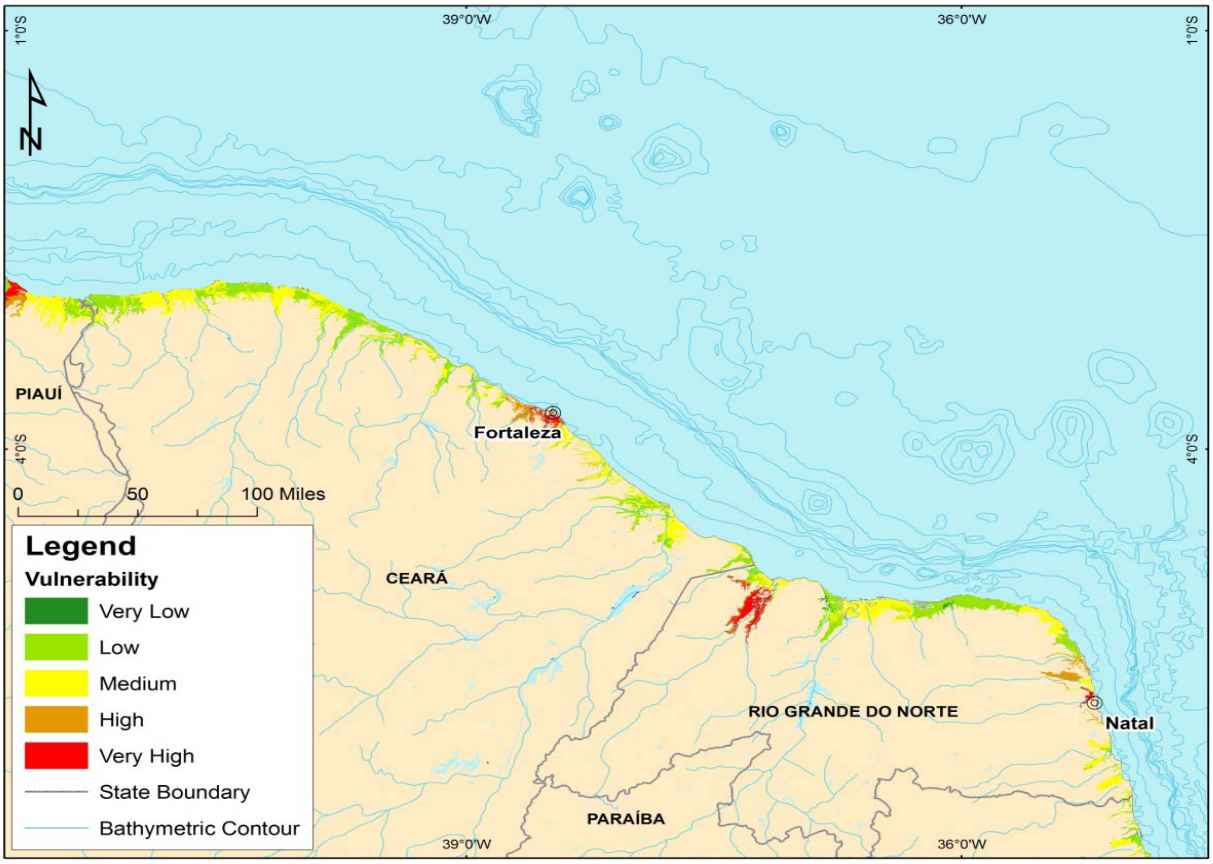

Figure 6. Vulnerability Map of the North Region, showing the states of Piauí, Ceará, and Rio Grande do Norte.

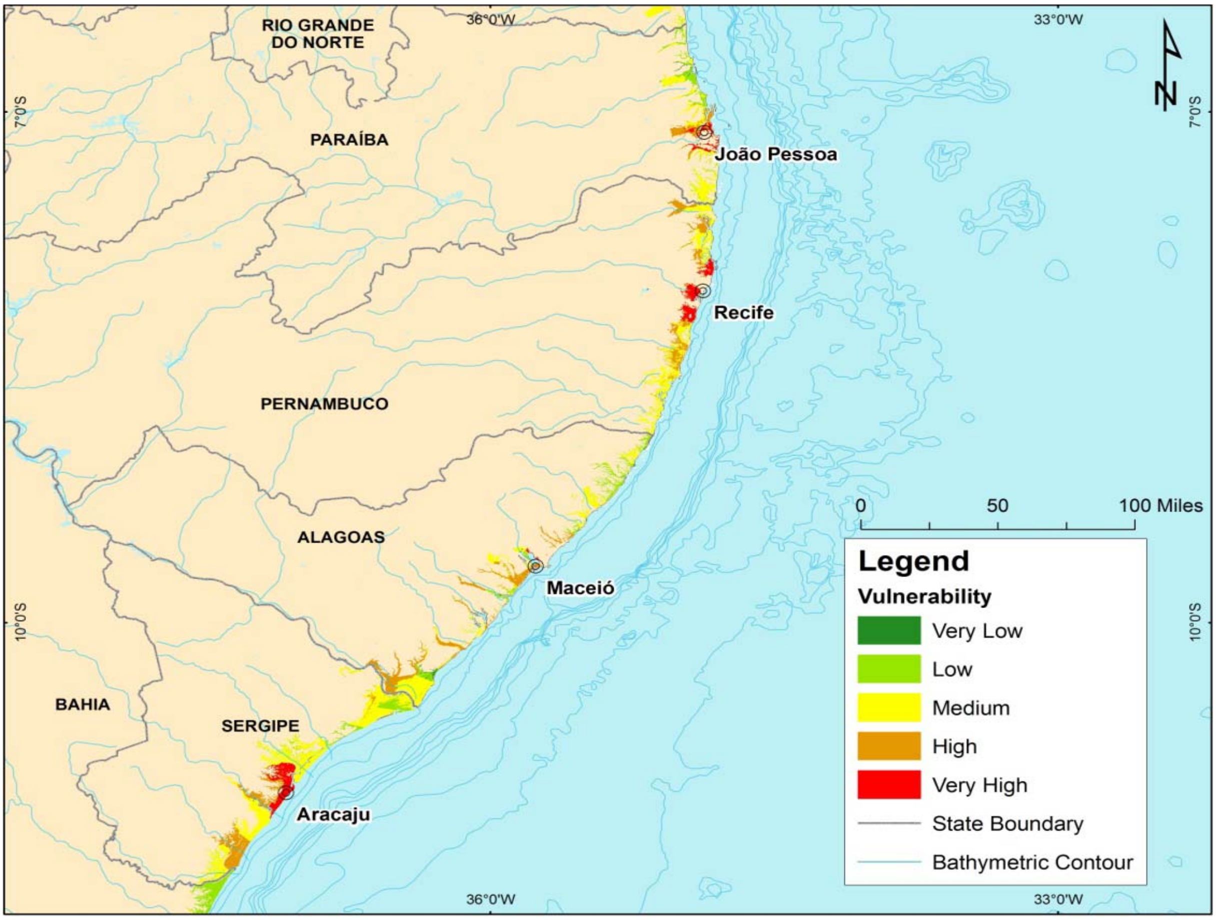

Figure 7. Coastal vulnerability of Paraíba, Pernambuco, Alagoas, and Sergipe states.

cliffs, and marine abrasion terraces. The sedimentary coastal plains are little developed, and the plain at the Doce River mouth is the most relevant.

This stretch consists of sections of medium to low coastal vulnerability. Only three sites were ranked as vulnerable (medium to very high levels): the Doce River, Vitória, and the inner drainage areas of the Paraíba do Sul River (Fig. 10).

In the case of the Doce River, one can see that the combination of the above-mentioned conditions, coupled with high levels of coastal erosion, make the region of São Mateus and Conceição da Barra more vulnerable.

What adds to this situation is the fact that the stretch of the Coastal Zone between Mucuri, on the southern coast of Bahia, to the center-north of Espírito Santo, especially near Linhares and Aracruz in Espírito Santo, is specializing in the production of pulp for the foreign market, as can be seen from the concentration of equipment used by the paper and pulp industry, particularly the continuous dimensions of the area involved (Egler 2008).

The Doce River drainage at the end of its flow at Linhares occurs on low ground showing marginally to its main flow a number of tributaries connected to ponds. Attributing higher risk levels relates to inundation potential for low land with a rate of human occupation slightly above the region's average. Vitória, Vila Velha, and Guarapari have the highest population densities in low coastal areas, with population densities above the Espírito Santo state coast average.

The drainage of the Paraíba do Sul River, in the Campos dos Goytacazes area, occurs at near sea level land, through densely populated areas bound by the Pre-Cambrian crystalline complex. This geomorphologic setting, associated with the population density of northern Rio de Janeiro state, are typical of the vectors leading to high vulnerability levels in the area. The town of Atafona, on the south bank of the Paraíba do Sul River mouth, has one of the most intense erosive phenomena of the entire Southeast coast of Brazil (Muehe *et al.* 2006).

The stretch between Cabo Frio and Guanabara Bay has a rim formed by narrow ridges separated by rocky headlands, with the development of lagoons behind the ridges. This section is also known as the Lake Region. The general direction of the coastline, which directly exposes this coastal stretch to the south (with waves from the south quadrant) and, from time to time, to the action of heavy storms, which explains the strong erosion.

The highest levels of vulnerability identified on the eastern coast of Rio de Janeiro state are in the areas of São João da Barra and Macaé, which, in the last two decades, have experienced a sharp urban development linked to oil prospecting activities on the contiguous continental shelf (Fig. 11). In Cabo Frio, the increase in population in the urban areas, in a land that displays higher landforms (promontories and hills) and low-lying coastal plains, lead to an increased potential hazard to which the area is exposed (Tessler 2008).

The Guanabara Bay region is one of the most emblematic cases in Brazil, with regard to vulnerability. Its low topography lies along a geological fault that extends toward the ocean from the crystalline complex. To this depression converge all drainage networks from Serra do Mar mountain range at the back of the bay, which were blocked at their low flows by high sea levels during the Holocene.

In contrast with the ocean beaches located at its outer edges, constantly exposed to storm cycles originating from south quadrants, the inner bay coastline is affected only occasionally by more powerful events. Its vicinity, however, concentrates one of the highest population densities in the country[9], sometimes along the lower river streams that flow into the system. In extreme tidal situations followed by heavy rain on the mountain range (associated with the passage of frontal systems which drown the drainages in their lower flows) the inner bay coastline, which is lower, is exposed to inundation events (which increases the volume of rivers).

In addition to this context, Rio de Janeiro has the highest ratio in Brazil, between the exposed population (78%) and its total population, equivalent to 11.194,150 people – some 5 million of which in the capital alone. Data on the social risk of this portion of the Brazilian territory are alarming, as shown in (Fig. 12).

In addition to these factors which lead to high vulnerability, the Rio de Janeiro metropolitan area holds a petrochemical complex, with an intricate network of refineries[10], natural gas plants[11], gas pipelines, and offshore oil fields.

The location of a coastal mountain range near the existing shoreline, west of Guanabara Bay, with its promontories marking small individual beaches and conspicuous inlets and sedimentary plains

[9] Rio de Janeiro is the state with the greatest total population residing in metropolitan areas (75.2%). Additionally, the state includes most coastal municipalities with population densities over 1,000 inhabitants/km^2, as is the case of Rio de Janeiro City and Niteroi, the towns of *Baixada Fluminense* (in the state's low-lying area) and the outskirts of the metropolitan area.
[10] Duque de Caxias and Manguinhos Refineries.
[11] REDUC I and II and Cabiunas I, II, and III.

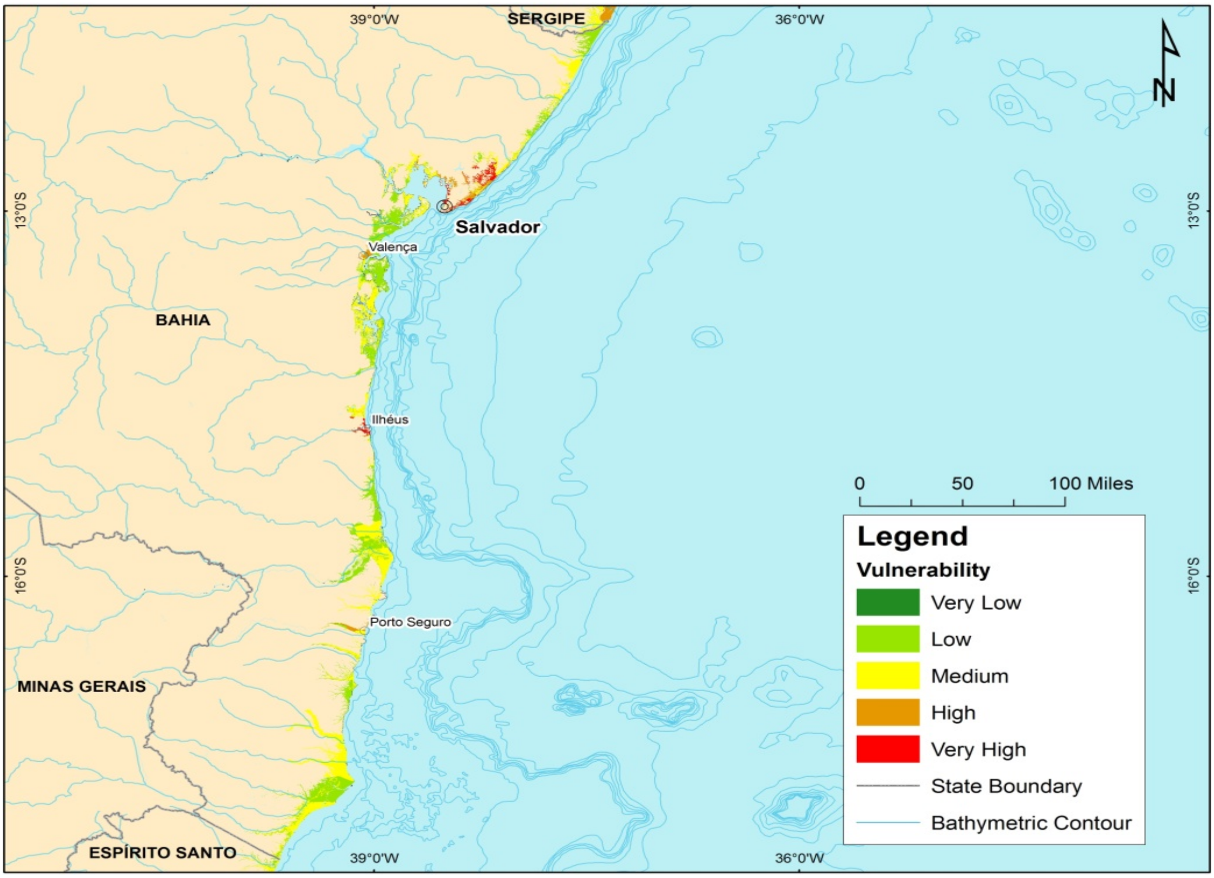

Figure 8. Urban centers in Bahia state, where vulnerability is high due to a high population density and an inadequate basic sanitation service.

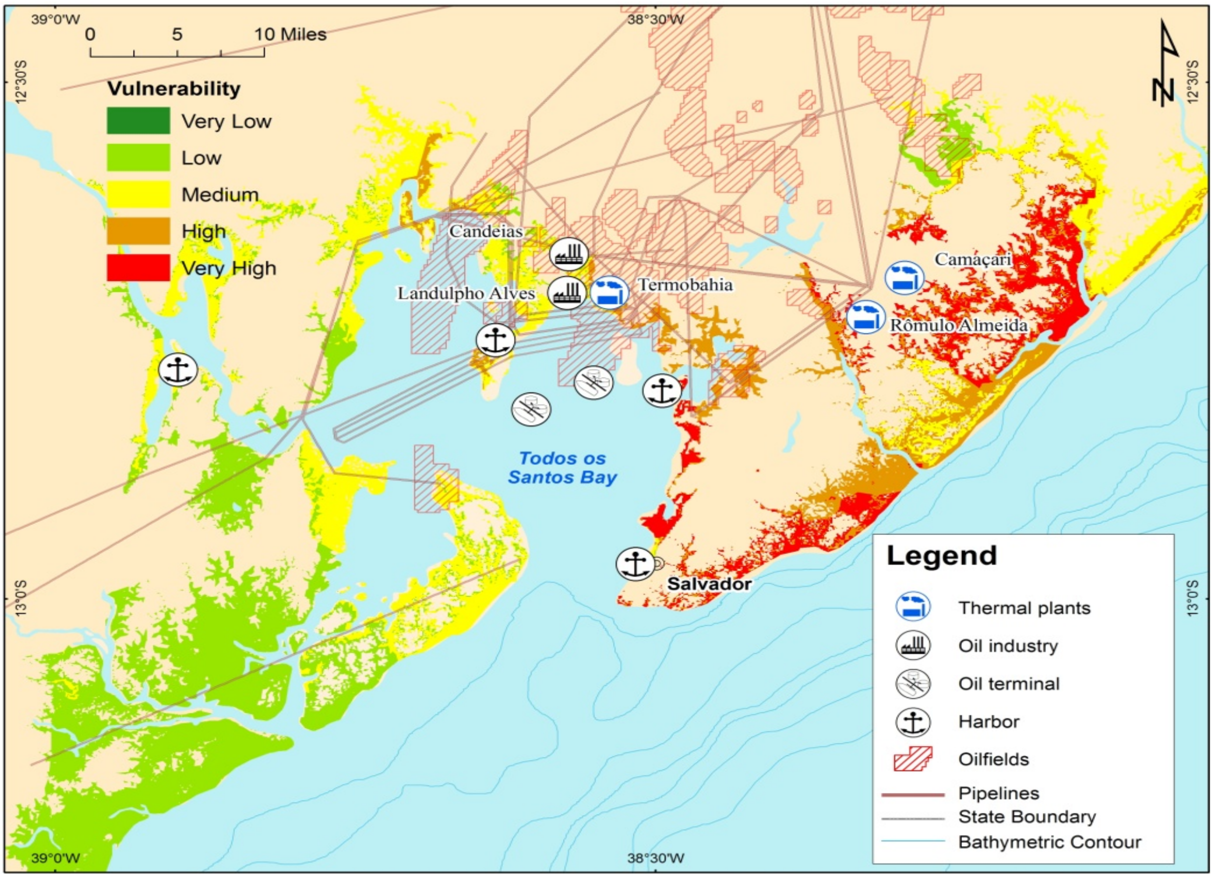

Figure 9. The metropolitan area of Salvador. High vulnerability levels linked to high technological risk.

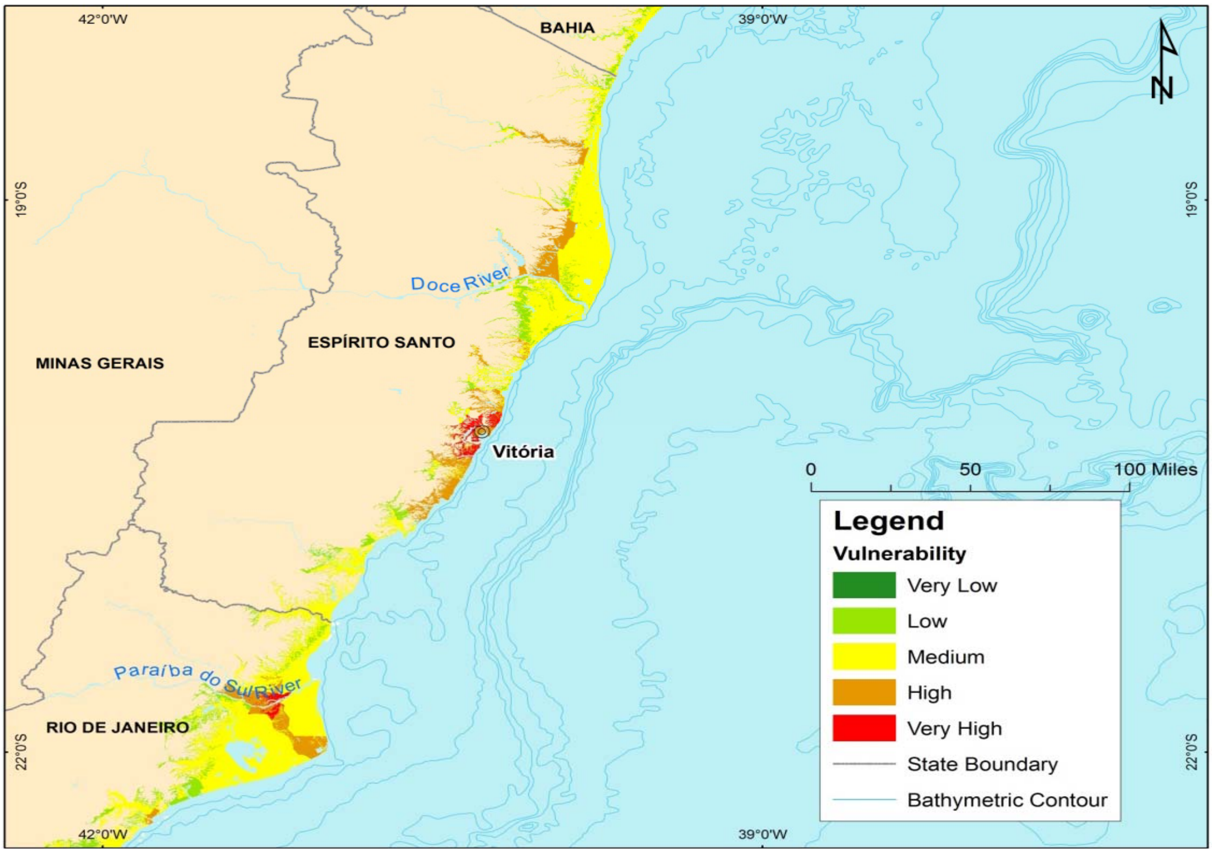

Figure 10. Medium to very high vulnerability level locations: the Doce River, Vitória and the inner drainage areas of the Paraíba do Sul River.

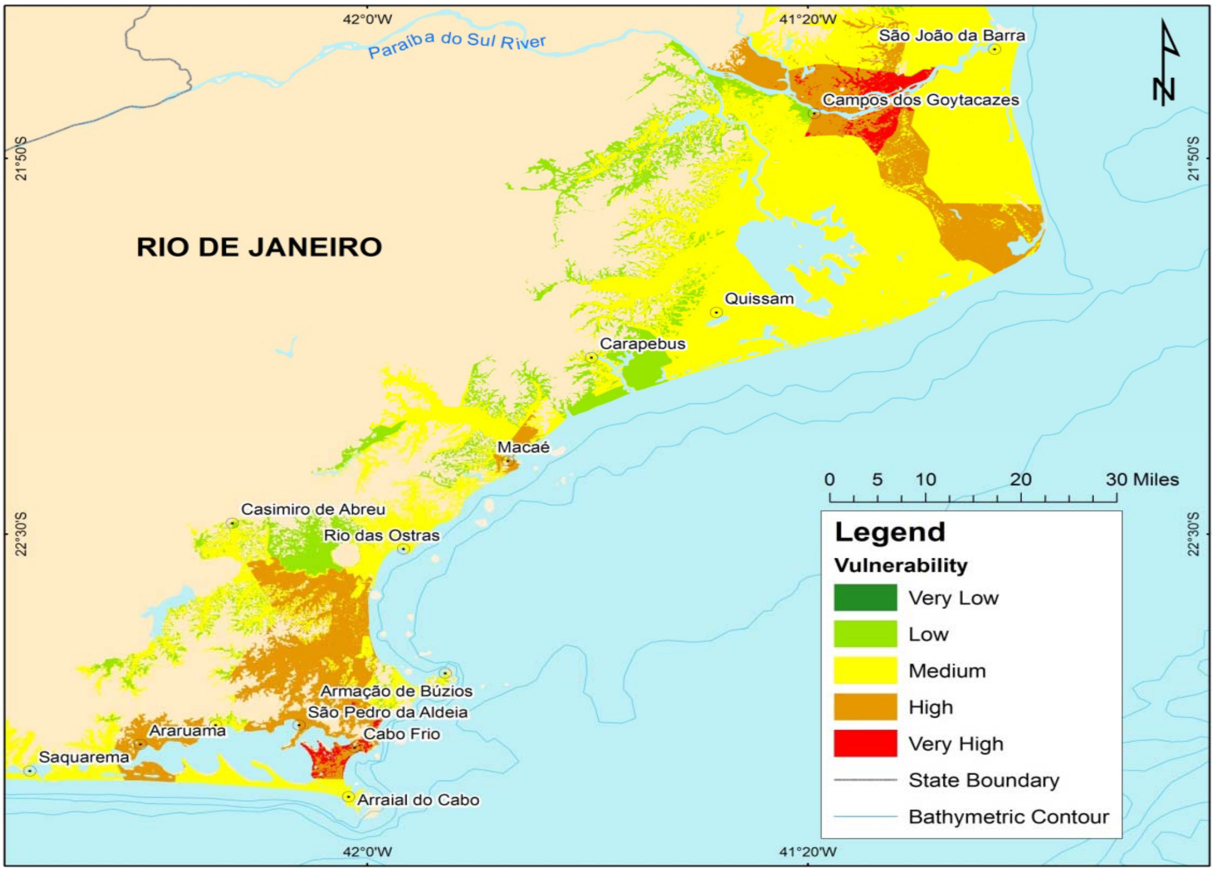

Figure 11. Higher vulnerability levels identified on the eastern Rio de Janeiro state coast associated with the São João da Barra and Macaé areas.

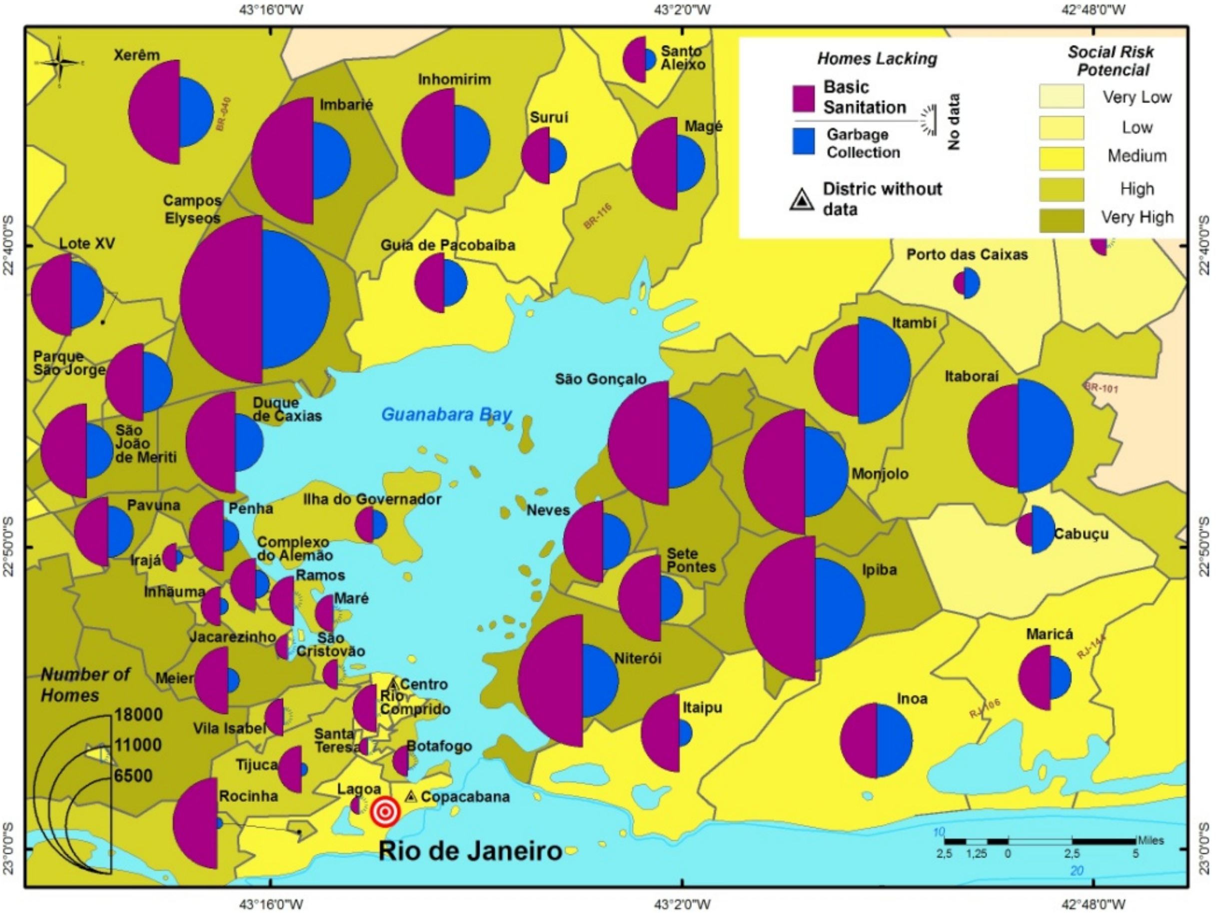

Figure 12. Social risk map of Guanabara Bay, in Rio de Janeiro. Graphic forms in purple represent the lack of sewers in subdistrict households. The shortage of garbage collection services is shown in blue. (Adapted from MDZCM, 2008).

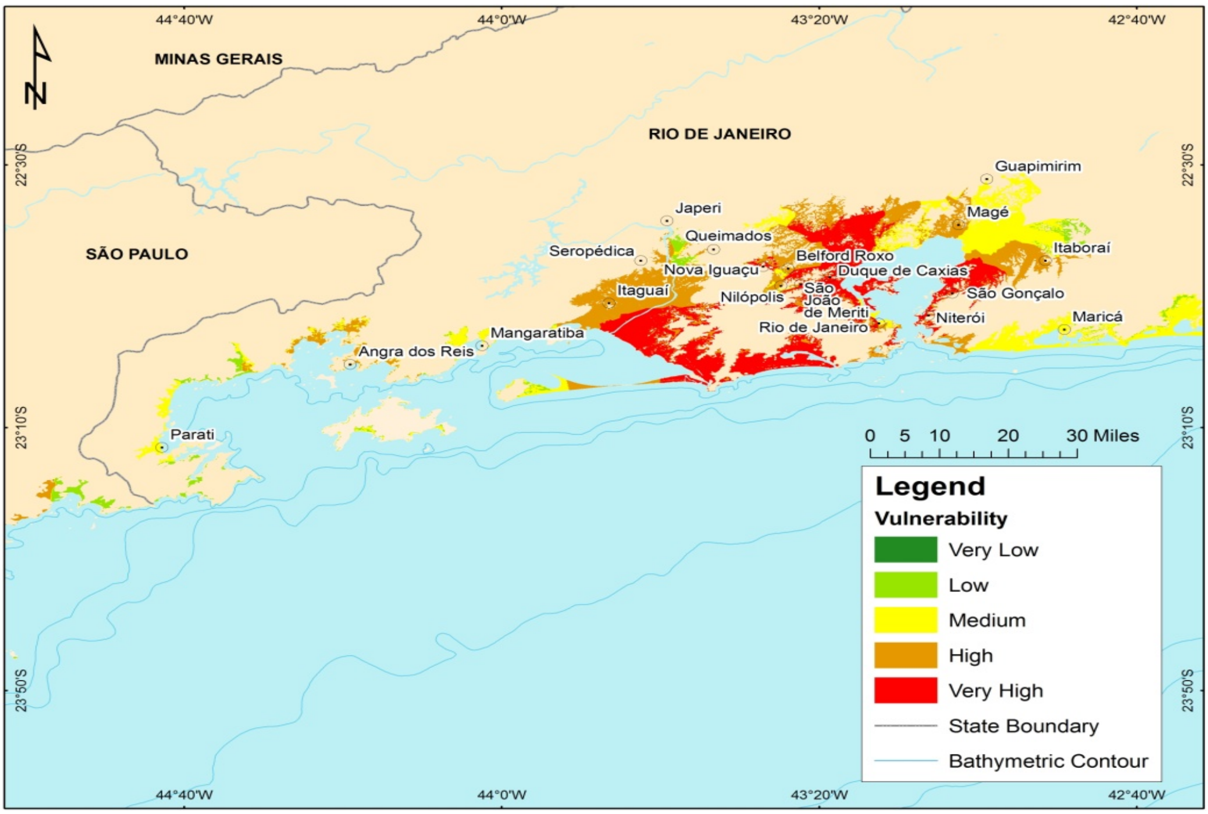

Figure 13. High vulnerability level in the metropolitan Rio de Janeiro area. The coastal area south of Guanabara Bay has a low vulnerability.

formed in the mountain range recesses, shape a geomorphologic region of many different ground levels occupied by permanent, low density populations.

As is common during summer on most of the Brazilian coast, beaches that are far from big cities get a large inflow of temporary population. Therefore, most of this coast does not present a high vulnerability level (Fig. 13).The group of cities near Santos known as *Baixada Santista*, which includes the Santos bay and estuary, as well as the surrounding urban areas, contain Brazil's largest sea port and manufacturing complexes on the small estuary and coastal plains, which have developed around channels, on the foothills of Serra do Mar. The region's high population density, its typical socio-economic features, and its geomorphologic configuration of a pronounced retreat in the crystalline complex, determined, for almost the entire area, a high vulnerability level (Fig. 14).

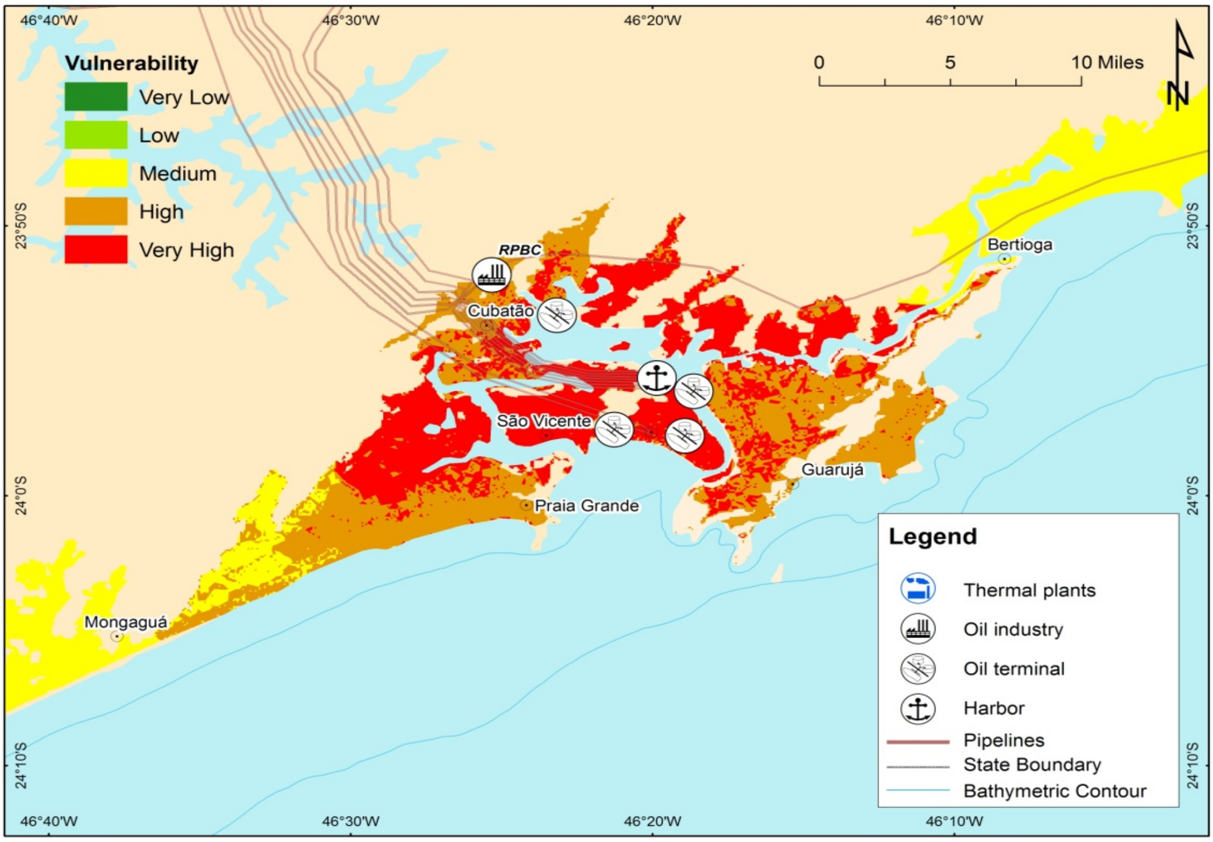

Figure 14. Baixada Santista and the Santos estuary. A combination of socio-economic, technological and geomorphologic features resulted in high vulnerability.

Another factor that makes the entire region more vulnerable is a visible concentration of manufacturing facilities between Santos and Macaé where there are oil and gas extraction fields, terminals, and pipelines, thermal and nuclear power plants, and a host of chemicals, metal and mechanical complexes. Furthermore, energy boundaries are being expanded toward the South coast, with an increase in oil prospection in the Santos Basin, plus the construction of pipelines, and an expanded chemical industry in Paranaguá.

South Region

A scenery of broad amphitheaters is the predominant geomorphologic feature in the Paranaguá Bay region, which includes the coastal area south of *Baixada Santista* to Itajaí, on the coast of Santa Catarina state. This segment contains three major seaports (Paranaguá, São Francisco do Sul, and Itajaí). These municipalities and/or their surroundings have significantly higher population densities than the average population per km^2 of the Southeast coast of Brazil. This mixture of topographic and population factors, the socio-economic importance of these urban centers, plus the instability factors affecting the shoreline, produce medium to high vulnerability levels (Fig. 15).

On the coast of Santa Catarina, the Joinville area, the Itajaí Valley, and Greater Florianópolis have very high vulnerability levels, because of their high urban concentrations in areas below 10 meters above sea level. Floods as those that occurred in 1983, 1984, and recently in the November 2008 disaster, in which 135 people perished and over 1.5

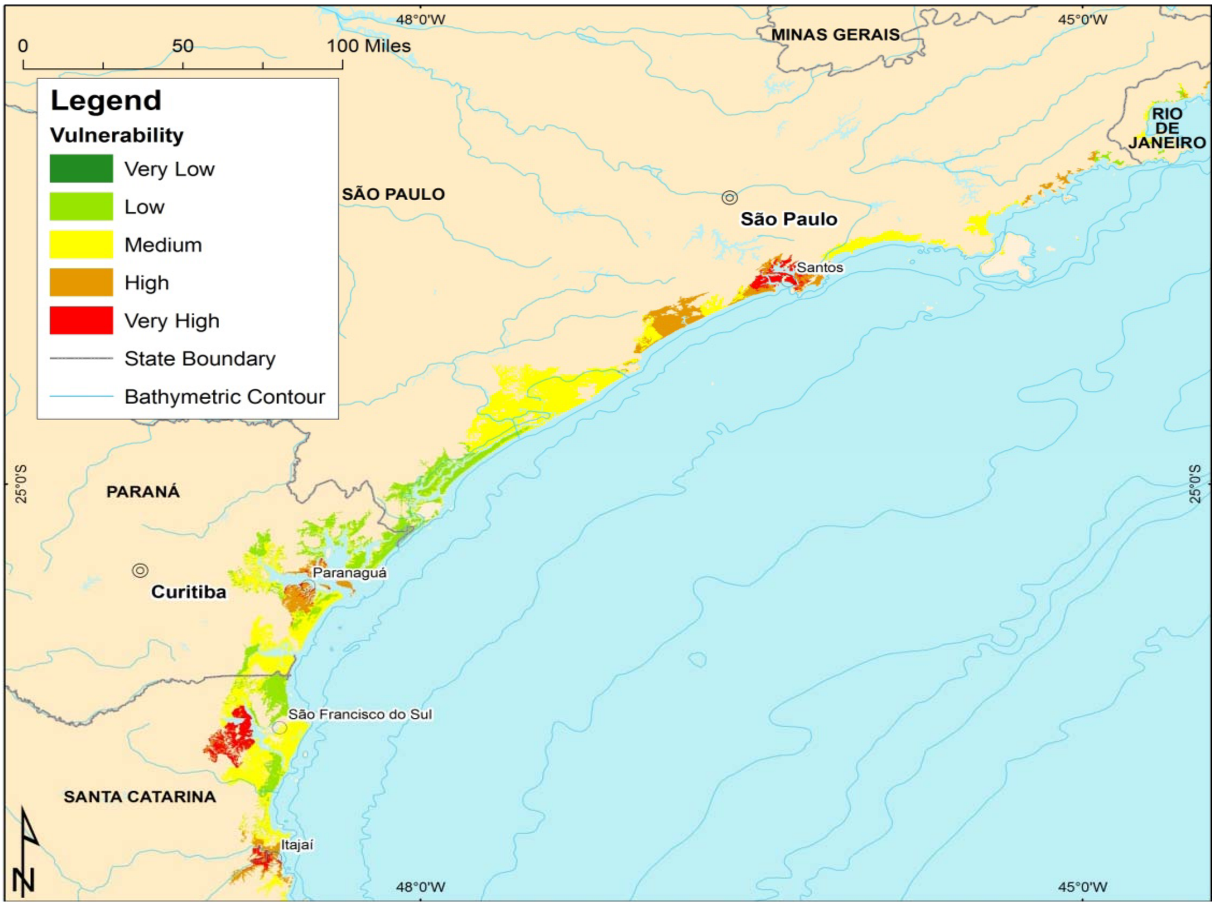

Figure 15. Vulnerability of the northern part of the South Region. The topography, population density, and socio-economic factors of urban centers generate medium to high vulnerability levels.

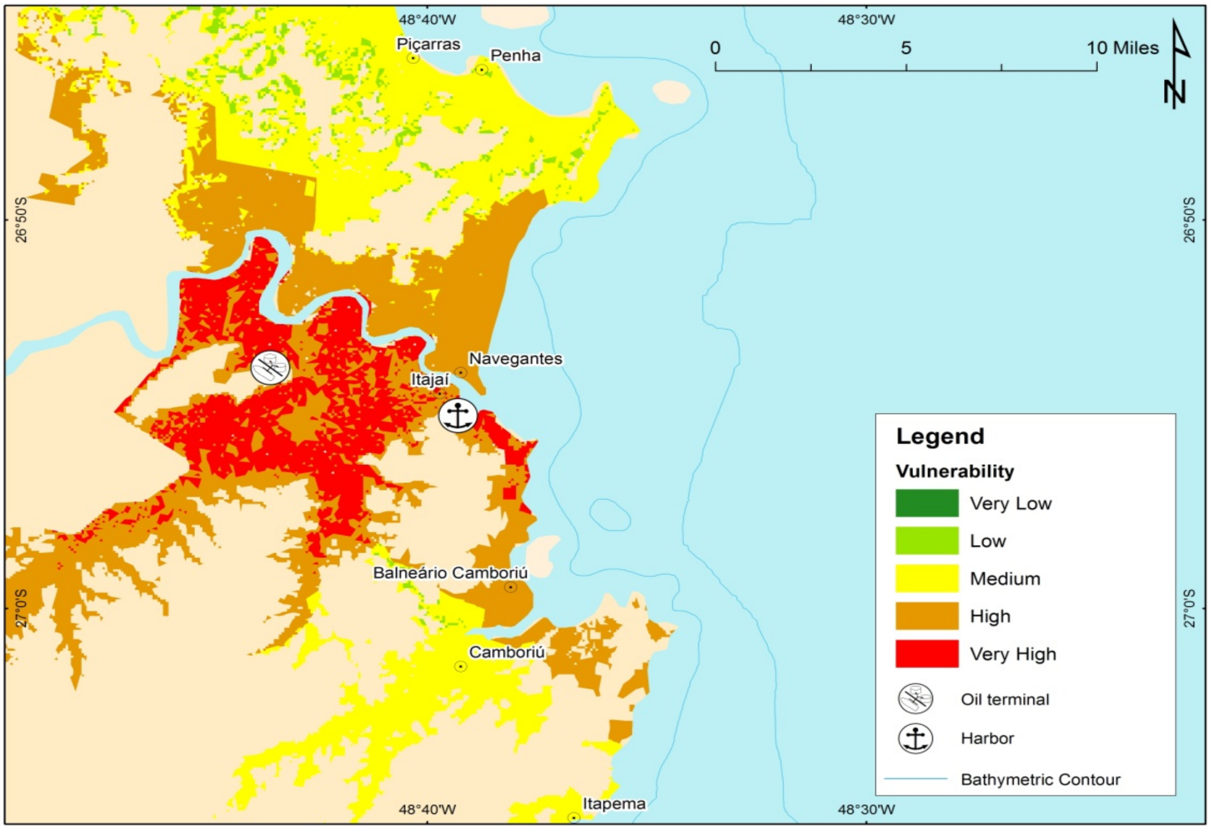

Figure 16. The high and very high vulnerability region corresponds to the distal portion of the Itajaí-Açu River basin, which has undergone frequent inundation in recent years, particularly during recent events in 1983, 1984, and 2008.

million people were injured, fully confirmed this vulnerability (Fig. 16).

The southern part of Santa Catarina state up to the border of Uruguay, is characterized by sandy barriers highly exposed to a strong wave and storm regimen with a tidal range of less than 1 m. Numerous lagoons developed behind the barriers with only few outlets.

Although the geomorphological context alone cannot explain the high vulnerability levels, it is important to emphasize that this region is critical for the occurrence of uncommon, extreme events of great magnitude, as was the case of Catarina Hurricane, which struck in 2004 and all but wiped out the bordering area between the two southernmost states of Brazil.

The only place defined as highly vulnerable in Rio Grande do Sul state is the Rio Grande area near the Patos Lagoon outlet, which is kept open through two 4.5 km long jetties (Rio Grande bar piers). This scenario includes the main urban center in the inner estuary, with a population of around 200.000 inhabitants living on low, flat ground and over areas expanded by the water surface landfill. The land occupied by housing coexists with spaces dominated by the activities of one of the country's most important ports, combined with an expanding manufacturing and petrochemicals complex of great relevance to the state (Fig. 17).

The role of the port of Rio Grande in this part of the area of high vulnerability, should be considered in conjunction with the Metropolitan Area

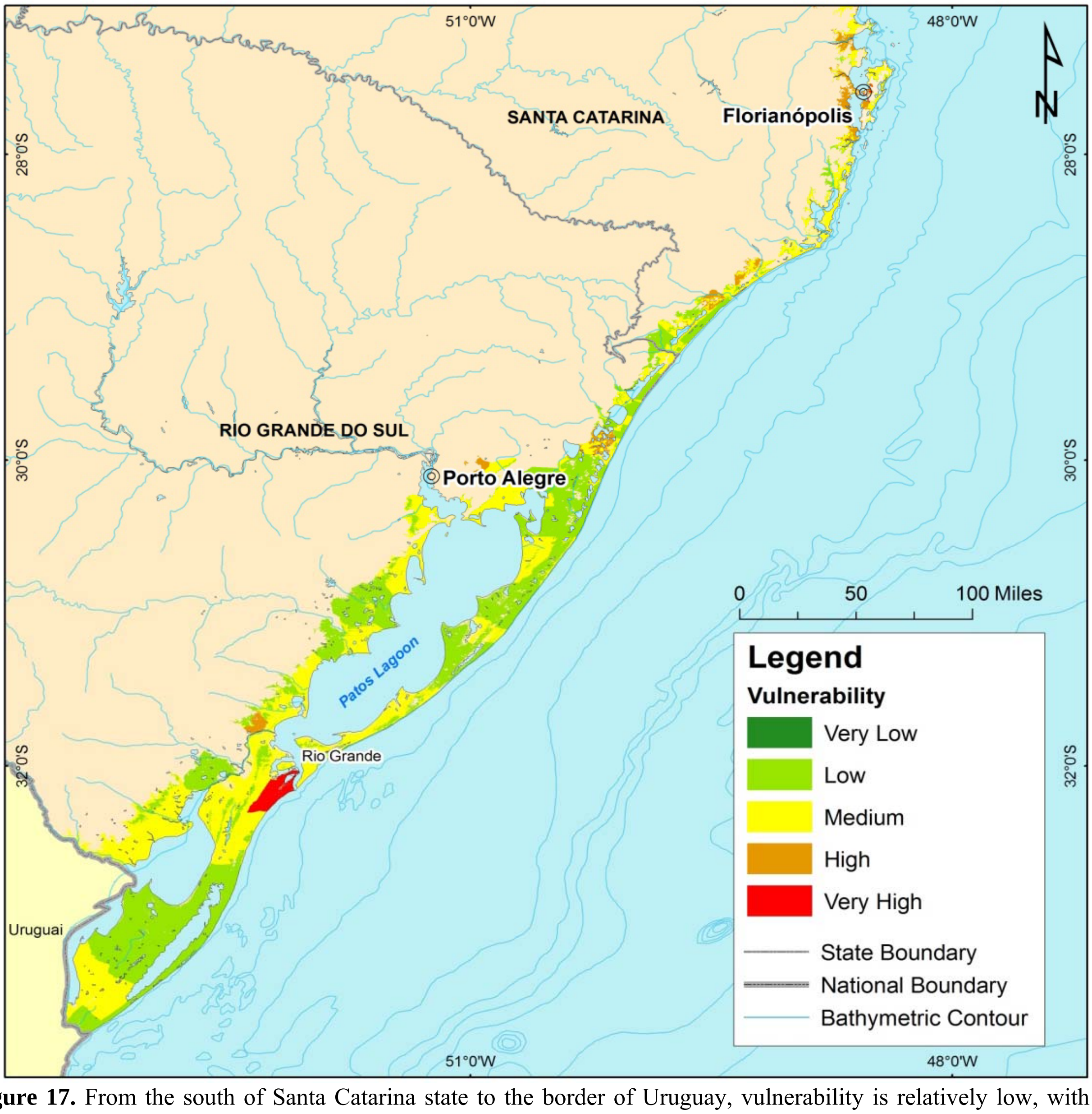

Figure 17. From the south of Santa Catarina state to the border of Uruguay, vulnerability is relatively low, with the exception of the urban area of Rio Grande. This region is subject to weather events of great magnitude, such as Hurricane Catarina in 2004.

of Porto Alegre, as regards the lagoon area where they are located. The likelihood of an increased trading of energy, goods and services and the implementation of new plants in the area due to its Mercosur standing, are specific elements that will probably increase the threat of technological hazards on the South coast in the coming decades (Egler 2008).

Conclusions

The Coastal Zone is the most dynamic geographical area in the country, since the time when the country was a colony of Portugal, and connections from structural centers directed internal flows directly to seaports, next to which the first urban centers were established (Moraes 1999).

The analysis of the combination between a likely unchanging tendency of this scenario in the near future and the context of global climate changes, points inevitably to the importance of undertaking a realistic coastal management, with priority actions, and human and financial resources.

Knowing about the mesoregions more or less vulnerable to the impacts of the direct effects of climate change is essential for the public authorities to make their decisions. These effects are directly linked to three major types of causes, defined in this paper as natural risk, social risk, and technological risk. The combination of these concepts, when applied to the national territory have enabled the definition of the five levels of vulnerability used, illustrating the scene presented as a challenge to be faced by integrated coastal management in Brazil, especially in the current context of climate change.

From this standpoint, the Intergovernmental Oceanographic Commission (IOC) has defined the climate change-related risks as shown in Table II. With the exception of tsunamis, Brazil is exposed to varying levels of the other risks defined by IOC.

In addition to the risks to which the Brazilian coast is directly exposed, other factors are expected to indirectly influence the dynamics of this part of the territory. According to Marengo (2006), modeling carried out by IPCC indicate possible significant changes to the outflow of the largest Brazilian rivers: an increased volume in the Plata and Paraná River basins and a decrease in the Ama-zon and the Pantanal basins. The variation in those water volumes will lead to a

Table II. Definition of climate change-related risks to Coastal Zones, according to the Intergovernmental Oceanographic Commission (IOC, 2009). and the relations with the observed in Brazil.

Risk	Definition		Vulnerable areas
Rapid onset hazards	Tsunami	A series of ocean waves generated by displacement of the ocean floor from an earthquakes, volcanic events, or large asteroid impacts.	Because the Brazilian coast is a "passive" coast, such events aren't expected, although they can't be discarded.
	Storm surge	Temporary rise in sea level caused by intense storm associated with low pressure and strong onshore winds.	The entire coast, especially the southeast and south, due to greater energy involved in the dynamics of this coastal region.
	Extreme wind-forced waves	Extreme instances of waves generated by winds somewhere in the ocean, be it locally or thousands of kilometers away.	The entire coast, especially the states of Santa Catarina and Rio Grande do Sul.
Cumulative or progressive hazards	Long-term sea level rise	Global sea level rise due to a thermal expansion of oceans and increased melting of land-based ice.	There's no availability long data series in the country, with the exception of Rio de Janeiro and Sao Paulo. In these cases, there is evidence of elevation about 3 mm/year.
	Coastal erosion	Loss of coastal land caused by waves, tides currents or drainage that can be enhanced by each of other hazards.	There is evidence of coastal erosion in several areas of the Brazilian coast. The phenomenon is more complex when it comes to urban coasts.

new sediment transport regime and its consequences on the shoreline.

These effects were identified by Neves & Muehe (2008). They include: a) coastal erosion and progradation; b) damaged coastal protection works; c) structural or operating losses at ports and terminals; d) damaged urban construction work in coastal cities; e) damaged structural or operating sanitation work; f) exposure of underground pipelines or structural damage to exposed pipelines; g) saline intrusion in estuaries; h) saline intrusion in aquifers; i) mangrove evolution; j) damaged coral reefs.

The scene has been set and there is no doubt the challenge of adapting and mitigating the consequences of such events is enormous, and cannot be faced without a detailed technical reference study consisting of micro- and macroscale vulnerability assessments.

The results obtained are included in this reference study based on a georeferenced data base, and can potentially assist in dealing with two of the various issues raised by the Federal Audit Office during its audit of public policies and climate change (TCU 2009):

1 – Brazil has no vulnerability study of its coast against the impacts of changing climate on a national scale.

2 – The country's available data are insufficient to build climate change impact scenarios in coastal areas.

The main sectors likely to be affected in a climate change scenario include ports and tourism. Brazil has a port sector that moves an annual 700 million tons of various goods and accounts for over 90% of all exports. One example was the destruction of the Itajaí seaport by heavy rains that hit Santa Catarina state in November 2008. Port reconstruction work will require over R$ 320 million, in addition to downtime losses estimated at US$ 35 million per day.

In the case of tourism, it is worth noting that the largest investments have been made in infrastructure work in coastal zones. For example, of the 14 tourist centers covered by the PRODETUR / NE-II program, with a US$ 400 M funding, 12 are located in the Coastal Zone[12].

These are examples of situations which the Brazilian society should be prepared to handle. The analysis of coastal zone vulnerability should guide the priority given to government actions. The areas defined as of high or very high vulnerability should be on the top priority list when decisions and plans are made.

In terms of institutional planning, Nicolodi & Zamboni (2008) analyzed the main actions undertaken by the Federal Government in the coastal zone and found that, although the management tools developed between 1996 and 2006 have brought some advance[13], integrated strategic planning is still incipient.

An integrated strategic planning must include the variables related to climate change vulnerability, especially when analyzing geographic action priorities.

Neves & Muehe (2008) reported the following actions that should make up the mentioned integrated strategic planning:

- permanent (long term) environmental monitoring;
- proposing effective municipal legislation governing urban occupation;
- effective state policies on coastal management;
- directing federal action efforts: legislation and education;
- action monitoring and coordination;
- identification sources of funds, their application, and forms of control;
- planning and prioritization of studies to undertake traditional actions (retreat, accommodation, and protection).

Key initiatives to address the "climate change in coastal areas" theme, such as the Global Ocean Observation System (GOOS)[14], linked to the Intergovernmental Oceanographic Commission (IOC), or the surveys on coastal erosion made by the Marine Geology and Geophysics Program (PGGM)[15] must be encouraged as a way of maintaining a structural base for decision-making by institutions responsible for the country's coastal and marine management.

[12]Source: http://migre.me/3H24g access on 11/27/2008.

[13]The authors identified as main instruments: *Projeto Orla* (Rim Project) Agenda 21, *Planos Diretores Municipais* (Municipal Master Plans), *Conselhos Municipais de Meio Ambiente – CMMA* (Municipal Environmental Councils), *Zoneamento Ecológico Econômico Costeiro – ZEEC* (Coastal Ecological and Economic Zoning), *Áreas de Exclusão Temporária de Óleo e Gás* (Areas of Temporary Oil and Gas Exclusion), *Sistema Nacional de Unidades de Conservação* (National System of Conservation Units), *Mapeamento da Sensibilidade do Litoral ao Óleo* (Mapping of the Coastal Sensitivity to Oil).

[14]The Brazilian component of this program may be accessed from: www.goosbrasil.org

[15]The results are organized in the book *Erosão e Progradação do Litoral Brasileiro* (Muehe 2006).

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Received January 2010
Accepted May 2010
Published online January 2011