



Vulnerability and impacts related to the rising sea level in the Metropolitan Center of Recife, Northeast Brazil

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Abstract. The Metropolitan Center of Recife figures as one of the most vulnerable regions to a rise in sea level along the Brazilian coast, due to its physical characteristics and to various problems related to flooding and coastal erosion. The analysis of potential flood zones and vulnerability assessments was based on an empirical approach, considering the estimates made by the IPCC on sea level rise and extreme scenarios of astronomical tide, storm surge and run up for the region. The results indicate that for a 0.5 m (optimistic scenario) rise in sea level, at least 39.32 km² of the area of the municipalities would become potential flood zones. In a scenario of critical sea level rise (1 m), this figure would increase to 53.69 km². Analysis of the entire coast indicates that 81.8% of urban constructions situated less than 30 m from the shoreline and located 5 m below ground level would be severely affected by changes in sea level. Currently 45.7% of the coast is considered a high vulnerability area. In view of the severe losses predicted by the simulated scenarios, response strategies identifying the most appropriate adaptation options must be developed.

Key words: coastal flooding risk, sea level rise, Northeast Brazil

Resumo: Vulnerabilidade e impactos relacionados a subida do nível do mar no centro metropolitano do Recife, nordeste do Brasil. O Centro Metropolitano do Recife figura como uma das cidades mais vulneráveis ao aumento do nível do mar do litoral brasileiro, devido às suas características físicas e aos diversos problemas referentes a inundações e erosão costeira. A análise das zonas potencialmente inundáveis e da vulnerabilidade costeira foi baseada numa abordagem empírica, considerando as estimativas realizadas pelo IPCC sobre a elevação do nível do mar e os cenários extremos de maré astronômica, ressaca e run up. Os resultados indicam que diante de um aumento do nível do mar da ordem de 0,5 m (cenário otimista), é esperado que, pelo menos 39,32 km² da área dos municípios analisados constituam zonas potencialmente inundadas. Num cenário crítico de elevação do nível do mar (1 m), este valor aumentaria para 53,69 km². A análise da costa como um todo indica que os 81,8% das construções urbanas, que estão a menos de 30 m da linha de costa e em terrenos abaixo de 5 m, deverão ser rapidamente atingidos pela mudança no nível do mar atual e que o litoral possui 45,7% de sua extensão sob zona de alta vulnerabilidade. Frente aos cenários simulados, aponta-se a necessidade de um planejamento público para mitigação dos futuros impactos.

Palavras-chave: risco a inundações costeiras, elevação do nível do mar, nordeste do Brasil

Introduction

The last report of the Intergovernmental Panel on Climate Change concluded that the planet climate is unmistakably experiencing rapid heating and this is partially due to human activities (IPCC, 2007). According to this and other recent studies (Neves & Muehe 1995, Thieler & Hammar-Klose

1999, Alfredini *et al.* 2008, Snoussi *et al.* 2008, Vargas *et al.* 2008), the rising sea level scenarios for near future are of great concern. The acceleration of the rate in which the sea level rises not only raises the possibility of intensified impacts – such as coastal erosion, habitat losses and saline intrusion in

coastal aquifers and rives – but could also result in complete suppression of sandy beaches and wetlands (Snoussi *et al.* 2007).

Such an impact, although felt globally, depends on local peculiarities; therefore, happens unevenly across countries, regions, communities and individuals as the result of different levels of exposure and vulnerability (Clark *et al.* 1998). Moreover, adapting coastal regions represent a larger challenge to developing countries than it does to developed ones, because of economic limitations. As an option for minimizing such effects, vulnerability and impact assessment provides a starting point for guidance in decision making for effective measures that envision impact reduction and reestablishment of initial conditions.

In Brazil, sea level trends for different places are sparing. For Recife, specifically, Harari *et al.* (2008) pointed a sea level rise of about 5.6 mm.year⁻¹. In spite of this gap, some studies have been dedicated to the coastal predictions in front of future sea level sceneries, as Alfredini *et al.* (2008), which describes islands and coastal urban areas as the most vulnerable to flooding in medium and long terms. Another study, made by Marengo *et al.* (2007) in national scale, pointed Pernambuco as one of the most affected states by the increasing on the sea level, at this moment and potentially. The same conclusion is showed by two another studies: Neves *et al.* (2007) and Naccarati (2008). According to these authors, both, natural and occupation characteristics contribute for the vulnerability of the area.

The Metropolitan Center of Recife combines low topography, intense urbanization, high demographic density, and elevated ecological, tourist and economic values (Araújo *et al.* 2009). Furthermore, it presents several conflicts in coastal land and shoreline usage, which is one of the reasons it became one of the first regions in Brazil to be the subject of integrated studies on the problems of coastal erosion, with the collaboration of several spheres of public power (FINEP/UFPE, 2008).

Within this context, the goal of this paper is to present possible scenarios for Metropolitan Center of Recife, prompted by the rise in the average sea level trend forecasted by the IPCC emission scenarios. The aim is to foresee scenarios that will raise awareness in the decision makers, as well as to point out possible strategies for minimization of potential impacts of the rise in sea level in this region.

Methodology

Description of study area

The Metropolitan Center of Recife, which covers the cities of Paulista, Olinda, Recife and Jaboatão dos Guararapes, is located on the coast of the state of Pernambuco (Fig. 1) and extends over a sedimentary plain, with an average altitude of 4 m. The region presents Tropical Atlantic climate with an average annual temperature of 27°C and annual pluviosity of around 2000 mm unequally distributed between dry and rainy periods. The wind regime is governed by the general atmospheric pressure distribution pattern of the South Atlantic Ocean, with predominance of SE winds.

The tides registered in the region are all semi-diurnal and classified as mesotidal in terms of amplitude. The largest and smallest swells occur in the months of September and January, respectively, with significant wave periods between 5.1 and 6.8 seconds. The significant wave height varies between each location, with values of 0.29/0.27 for Paulista; 0.6/0.61 for Olinda; 0.97/0.66 for Recife and 0.61/0.44 for Jaboatão dos Guararapes (FINEP/UFPE, 2008).

The main ecosystems in this region are mangroves, fragments of Atlantic Forest, coral reefs, and restinga. The hydrographic system is well drained, with several rivers, streams and lakes. The Capibaribe River is the main watercourse.

Establishing Potential Flood Zones

The methodological steps proposed by Hoozemans *et al.* (1993), Snoussi *et al.* (2007) and Vargas *et al.* (2008) were followed, with determination of the resulting flood levels by the sum of the factors involved in the sea level rise. Therefore, the contributions of the following extreme water level-induced phenomena were simulated: maximum high water line in the last 20 years; sea level rise due to storm surge (meteorological tide plus wave run up) (FINEP/UFPE, 2008); projected sea level rise for the



Figure 1. Location of the studied coastal area in the Metropolitan Center of Recife, Northeast Brazil.

next century (IPCC, 2007), which can be optimistic (+0.5 m by 2100, or about 5 mm·year⁻¹) or critical (+1.0 m by 2100, about 10 mm·year⁻¹). These scenarios were adapted from the IPCC Emission Scenarios (B1 and A2), considering that the sea level rise for the next century may be up to roughly twice the maximum projection found in this report (Rohling *et al.* 2008). Equations (I) and (II) express the empirical approach used to determine the flood levels in coastal and estuary areas, respectively.

$$NI = PM + MM + SLR \quad (\text{Eq. I})$$

$$NI = PM + SLR \quad (\text{Eq. II})$$

where NI – Flood Level; PM – maximum high tide water level; MM – Meteorological Tide (including wave run up); SLR – Sea Level Rise.

For delimitation of potential flood zones, a Geographic Information System (GIS) was used. Rectified aerial photography in a 1:2000 scale (Pernambuco, 1974) was processed in order to digitalize the flood level lines. The entire territorial portion below such levels, therefore, would potentially be flooded in similar conditions to the ones in the above modeled scenarios.

The rectified aerial photography employs the average sea level in Imbituba, South Brazil, established by the Brazilian Institute of Geography and Statistics (IBGE). According to Neves & Muehe (1995), it is located 1.106 m above the datum used by the Hydrography and Navigation Board (DHN). The values considered and the resulting levels are in Table I.

Attribution of Degrees of Vulnerability to the Shoreline

Bearing in mind that sandy beaches serve as a buffer, reducing the energy that the oceans impose to the shore, one can say that the closer the first

man-made structures are to the shoreline, the higher their degree of vulnerability to the impacts of erosion and floods (Lathrop Jr. & Love, 2007). Accordingly, the degree of vulnerability was assigned based on the current capacity of the beaches of the Metropolitan Center of Recife to protect inland resources, be they economic, ecological or of cultural values.

To calculate the average distance between the maximum high water line and the closest infrastructure, a spatial analysis module available in a GIS environment was used. The line of first man-made structures was taken from UNIBASE (2002) – a cartographic base on a 1:1.000 scale – and the shoreline was obtained in situ using geodesic GPS equipment. The marker used was the High Water Line, or HWL.

Once the distances were calculated, limit values were established for each degree of vulnerability (Table II). In order to fulfill the safety conditions, beaches should not only present a backshore, but this sector should also be at least 30 m wide (FINEP/UFPE, 2008). This value was established through an estimation of the results obtained by Pajak & Leatherman (2002) and Costa *et al.* (2008) on the variation of the HWL position through time.

Analysis of the Coastal Resources at Risk

In a GIS environment, a layer containing the potential flood zones was superimposed to the layer containing occupation information. The resources at risk were divided into the following categories: wetland (mangrove and flooded areas), unoccupied land, beaches, buildings with over three floors, buildings with less than three floors and historical/cultural patrimony.

Table I. Values considered for the estimation of the levels in risk of flooding.

Scenario	Maximum high tide water level (m)	Storm surge effect	SLR (m)	Flood level (m)
Optimistic	2.7 (– 1.106)	1.0	0.5	3.1
Critical	2.7 (– 1.106)	1.0	1.0	3.6

Table II. Criteria used in the determination of the Degree of Vulnerability.

Backshore width (m)	Degree of vulnerability	Maintenance priority
Null*	Conditional	Constant maintenance
>30	Low	Moderate
<30	High	Maximum

* The high water line coincides with the first man-made structures, since there is no backshore and the shoreline was artificialized and immobilized.

Results

Establishing Potential Flood Zones

Jaboatão dos Guararapes presents the largest area among the studied cities, with 256 km². The area considered in this analysis was 15.45 km². The potential flood zone is shown in the following figure as polygons for the benign and critical scenarios (Fig. 2). The most important changes in both scenarios are seen in the areas surrounding the Pirapama-Jaboatão Estuarine Complex and also on the coastal strip positioned further south, on the Barra de Jangadas beach. Attention is drawn to Paiva Beach (Praia do Paiva), a sandy spit extremely vulnerable to the possibility of a rise in sea level. Of the 0.97 km² that form the extremity of the sandy spit, 0.30 km² would be left above water in a scenario with a 0.5 m sea level rise. In a critical scenario – 1m rise in the sea level – only about 0.15 km² of the initial area would be left.

It is worth while to observe that throughout practically the entire coast – except the portion in front of the Candeias beach, protected by a breakwater, and a small section of the Barra de Jangadas beach – the beach system is no longer an efficient means of coastal protection since one or more sectors have been suppressed. Nonetheless, there is still an estimated sandy beach loss of at least 13.71 m² as a result of coastal erosion

Recife is the city with lowest altitude among the ones studied here, with an average of only 4 m above sea level. As a result, in a scenario of a 0.5 m

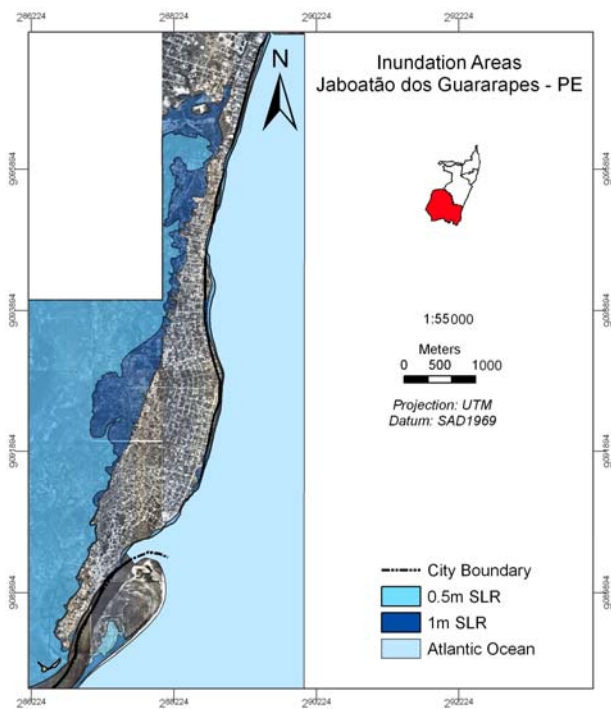


Figure 2. Potential flood zones in Jaboatão dos Guararapes.

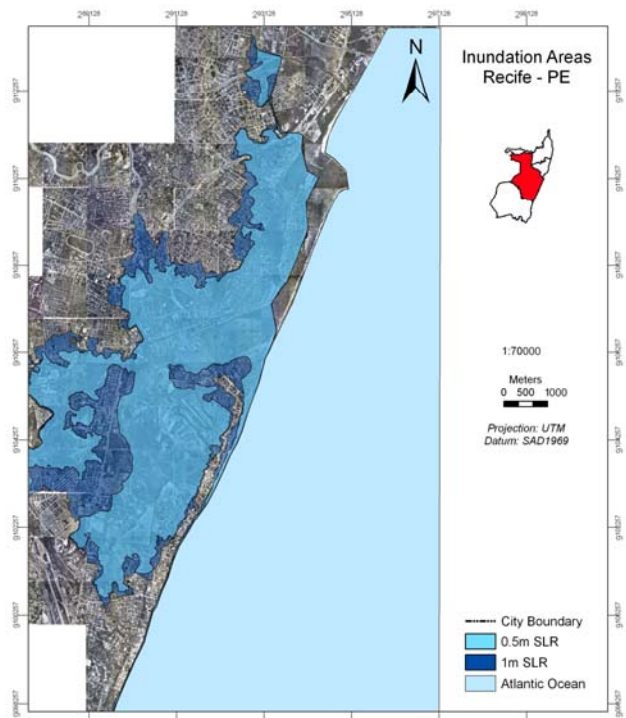


Figure 3. Potential Flood Zones in Recife.

sea level rise, it is estimated that the flooded area would amount to about 25.38 km²; while in the critical scenario, with a 1 m rise in sea level, it would be approximately 33.71 km² (Fig. 3).

The city of Olinda is located on the highest average altitude among the cities studied, at roughly 16 m above sea level. Consequently, the forecast is that the most affected areas would be those situated near the city boundary with Recife, in the lowlands, bathed by the Pina Basin (Fig. 4).

According to the flood levels isolines analysis of the Del Chifre beach, better known as the Olinda isthmus, and considering a progressive flood of the spit, due to a rise in the level of flooding, there is a possibility that this sandy spit may develop insular characteristics, with an estimated area between 0.076 km² (optimistic scenario) and 0.069 km² (critical scenario). In light of the predictions for the other cities of the Metropolitan Center of Recife, this coastal strip does not present itself as an area highly prone to flooding. However, the coast of Olinda presents a severe and historical erosive process, with a noteworthy part of its extension (around 59%) impermeabilized by coast defense projects, which hinder the limited capacity of its beaches to act as protection zones for resources located inland.

The city of Paulista presents the most extensive coast among the cities in this study. It is limited to the North and to the South by the Timbó and Paratibe River estuaries, respectively. With a

total area of 94 km², approximately 26.53 km² were analyzed (coastal and estuarine areas). The potential flood zones in the city are shown in figure 5.

Vulnerability Analysis

Generally speaking, the beaches of the Metropolitan Center of Recife would be severely affected in case of a sea level rise. An analysis of the entire coast indicates that 81.8% of urban constructions are less than 30 m from the shoreline. Comparatively, only small portions of the coast present a beach system little affected by adjacent development. Jaboatão dos Guararapes stands out in this sense, presenting 36% of its coastline with low variability. Olinda presents the most critical scenario, where 59% of the coast no longer has recreational beaches and the integrity of the urban development depends exclusively on coastal protection projects (Fig. 6).

damage to historical and cultural patrimony such as an important culture and leisure center (SESC) and the Nossa Senhora da Piedade Church, both located on the Piedade Beach. This patrimony is vulnerable in both scenarios, optimistic and critical.

In Recife, the large area with buildings with less than three levels is highly vulnerable to a sea

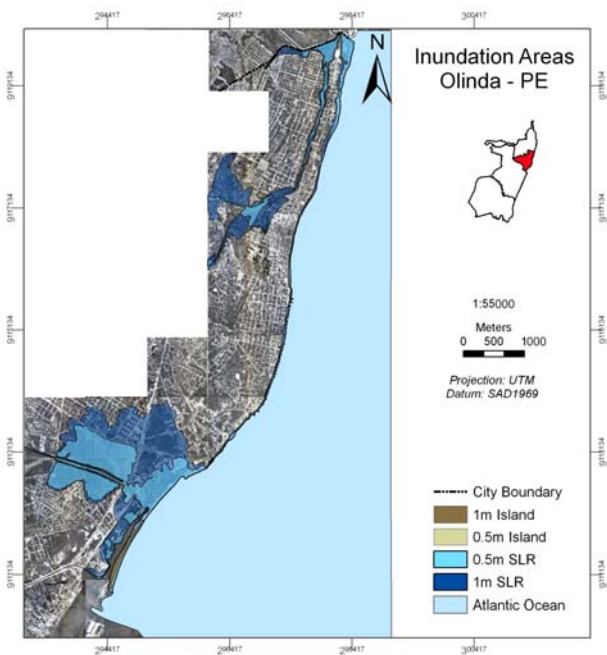


Figure 4. Potential flood zones in Olinda.

Analysis of Resources at Risk

Types of land use and the area (in m²) of the affected resources in the cities studied are represented in figure 7.

For the city of Jaboatão dos Guararapes, in an optimistic scenario, the relatively pristine areas – unoccupied and beach areas – would suffer the greatest impact. On the other hand, in a critical scenario, the areas with buildings of cultural and historical interest would amount to 57% of the affected resources, exceeding the sum of vulnerable beach and unoccupied areas.

In the case of an overwash, there could be

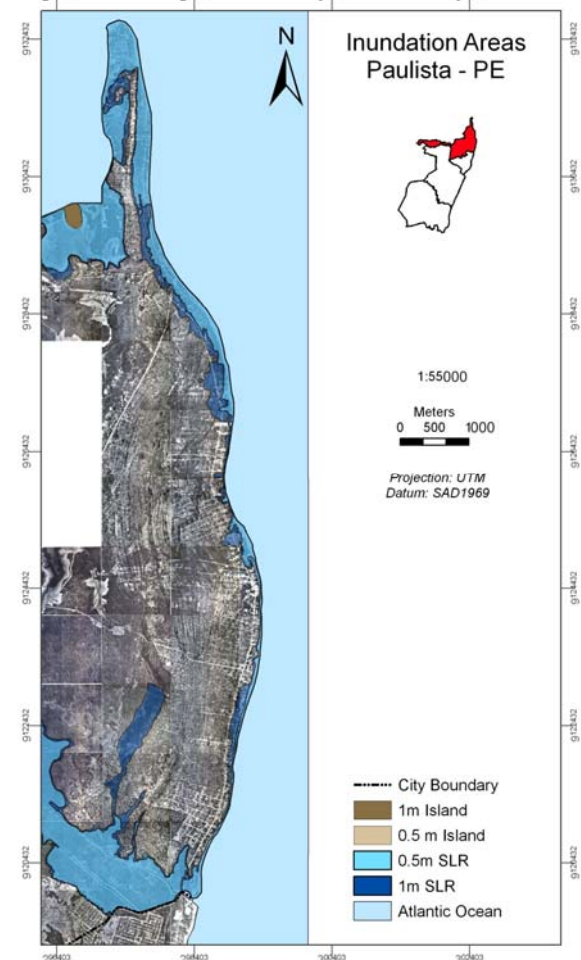


Figure 5. Potential flood zones in Paulista.

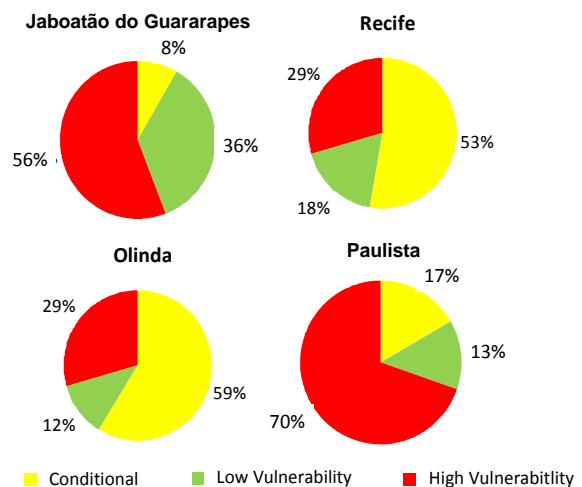


Figure 6. Areas with high, low and conditional vulnerability percentages.

level increase. From a historical-cultural perspective, we highlight the potential flooding of part of a green area of 33,000 m² set apart for leisure and a cultural center in the Boa Viagem neighborhood (Dona Lindu Park). In the optimistic and critical scenarios, the impacted areas would be of approximately 3,100 m² and 13,200 m² in area, respectively.

In terms of coastal resources endangered by flooding in Olinda, in an optimistic scenario of sea level increase, it was mostly the smaller constructions that were found to be at risk. In a critical scenario, though, taller buildings (>3 stories) are included in the vulnerable area.

Among the vulnerable areas of Paulista, Maria Farinha Headland demands attention since it is an area of great ecological and economic importance. From a historical and cultural perspective, Pau Amarelo Fort and a water park relevant for the tourism industry near the Maria Farinha Beach represent potentially impacted patrimonies.

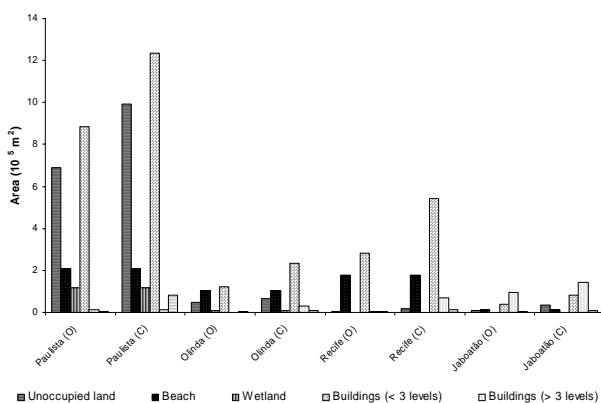


Figure 7. Resources at risk in each city for both scenarios: optimistic and critical.

Discussion

The present analysis was restricted to coastal and estuarine areas, which are the most affected by an increase in the sea level. For this reason it should be made clear that the numbers and debate here presented are underestimated and that the potential flood zones in the studied area are even greater, bearing in mind the low altitude of the terrain and vast drainage network that bathes the region and branches out to other estuarine areas.

In terms of environmental impact, we emphasize that important ecological losses may occur not only along the estuary – a rich and important ecosystem – but also to the south portion, beyond the area studied, to the Paiva Beach. This site, as previously mentioned, is a restinga rich in flowers and with typical morphological aspects, with ecological potential that justifies better protection of this ecosystem (Sacramento *et al.* 2007).

On the coast of Jaboatão dos Guararapes, the loss of beaches and damage to constructions by the shoreline, due to its exposure to the energy of the ocean, are common. For this reason, there are currently ten coastal defense construction sites along the shore, among them seawalls, groins, revetments and breakwaters (FINEP/UFPE, 2008). As mentioned previously, the shoreline of the city presents a high degree of verticalization, which increases the magnitude of the impact caused by coastal flooding.

For Recife, among the areas prone to flooding in both scenarios, attention is drawn to Recife Antigo (Old Recife). It represents an important economic and administrative center of the city with great historical and cultural value since it is the origin of the city of Recife. It is currently of great significance for cultural and artistic activities.

Attention should also be given to the fact that the largest estuarine complex in the studied area is located in the city and includes the Pina Basin, the Capibaribe and Beberibe Rivers. The Port of Recife is also located in the city. This Port, along with the Port of Suape, handles all cargo movements in the State of Pernambuco. The region has suffered flooding since the beginning of its occupation, but the intensification of the phenomenon makes an increase in the silting rate a possibility throughout the port area. This would increase the demand for dredging and would potentially be detrimental to port operations.

Although the potential flood area is narrow in the coastal strip, the intensification of the erosive process is notable, considering that there are buildings located very close to the beach, leaving little room for morphodynamic processes. As in Jaboatão dos Guararapes, the Recife shoreline presents a high degree of verticalization, to such an extent that the small area of land lost, or endangered by erosion, would imply in large economic losses and social disorganization. Additional disturbance could be implied by the fact that countless inhabitants use water extracted from the water table using wells, which could become unfeasible because of saline intrusion.

In the sandy coastal regions, it is now well-established that sea-level rise leads, in average, to erosion and consequent recession of the shoreline (Snoussi & Niazi 2007). Sea-level rise is the main cause of shoreline retreat in coastal areas under dynamic equilibrium, i.e., where the natural sand supply allows the potential and the effective littoral drift to be equal. However, on sandy shores, where this supply has been strongly reduced (as already discussed), the main cause of shoreline retreat is

sediment deficiency, Ferreira *et al.* (2008). In this case, which is similar to the study area, this deficiency plays a larger role in erosion than the accelerated sea-level rise and coastal morphology and size will be mainly dependent on the direct result of human actions.

In Olinda, the flood problems are a historical inconvenience for the population. Floods are annual events in some of the main neighborhoods of the city, and are among the most distinguished environmental impacts, causing loss and disarray to the population. Some areas in this location are flooded from time to time, which damages road structures, makes the circulation of vehicles and people impractical, jeopardizes commerce and causes public health issues (Melo 2003). Anthropogenic causes are added to the geographic features and contribute to the intensification of the problem, such as the illegitimate occupation of freshwater swamp forests, illegal landfills in mangroves, criminal disposal of solid waste and the nonexistence of an efficient draining network.

The city, due to its historical erosion and flood problems, has a large range of coastal defense structures in place, which may provide efficient protection from the sea level rise (Neves & Muehe 1995). Presently, these structures, in addition to countless sections with hydraulic landfills, put the coastal streets in flood zones above sea level, reducing the area vulnerable to flood effects. In Paulista we can highlight the potential flooding of an area relevant from an ecological and economical point of view, the Maria Farinha Headland. On this site there is a complex estuarine system of elevated scenic attributes that have contributed to recent development of the tourism industry with the installation of marinas, hotels, inns and water park.

Generally, and in what is referred to as vulnerability assessment, the studies developed by FINEP/UFPE (2008), considering only the current erosion rate and the rate at which construction presses closer to the beach, indicate that the width of the beach tends to decrease with the passage of time. This analysis demonstrates that in most of the coastline analyzed, a significant part of the vulnerability may be related to the accelerated occupation of areas immediately inland. With the predicted sea level rise, a higher demand for shoreline protection structures is expected throughout the metropolitan coast of Recife.

Regarding the methodology adopted, the use of GIS is justified by the fact that the spatial component of climate risk is critical for building knowledge on climate risk, potential management options and challenges in local level. A range of

methods is available for exploring climate risk across a landscape, however, as with any scientific assessment process, the appropriate methodology depends on the needs of stakeholders as well as potential constraints placed upon a project such as funding, time, data access and expertise (Preston *et al.* 2009).

Based on worldwide experience in policy creation, on data and recommendations of the MAI-PE Project (FINEP/UFPE 2008), and on the results given in this paper, the implementation of public policies for the protection of coastal and flood zones are suggested in two fronts: (I) expansion and consolidation of scientific knowledge of the phenomenon, since the effects of the change in the relative sea level will differ according to local characteristics; and (II) management and establishment of adaptive measures to minimize its impact. These fronts complement the suggestion of Jallow *et al.* (1996), which present the following means to deal with the problem of coastal vulnerability to the sea level rise: urban growth planning, public awareness, wetland preservation and mitigation, and coastal zone management.

Conclusion

The Metropolitan Center of Recife, due to its physical characteristics and its current erosion and flood problems, presents itself as a region highly vulnerable to an increase in sea level. Additionally, it has unfavorable social characteristics for responses to flooding, including high demographic density and intensified vertical growth on the coast, as well as occupation of riverside areas. The impact associated with the relative sea level rise may intensify if relief measures are not taken.

These results comprise first an approach to the impacts caused by the combined projected changes in coastal areas in the Metropolitan Center of Recife. Since the response prediction and scenario anticipation for these areas are highly complex tasks, it is essential to obtain more funding from research foundations, institutions responsible for development of human resources and from those in charge of public policies in order to perform further research on the matter. The bigger the knowledge base and the better the prediction of the impacts resulting from climatic change, the better the plans for economic, social and environmental risk prevention will be.

Acknowledgments

The authors wish to thank the agency Financiadora de Estudos e Projetos (FINEP/MCT) and the Recife, Jaboatão dos Guararapes, Olinda and

Paulista City Halls for funding the Integrated Environmental Monitoring Project – MAI-PE (Projeto Monitoramento Ambiental Integrado),

which enabled the acquisition and the detailed analysis of recent information on the coastal dynamics of these cities.

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Received December 2009

Accepted June 2010

Published online January 2011