Regional spatial planning assessments for adaptation to accelerated sea level rise - an application to Martinique's coastal zone

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Abstract

Accelerated sea level rise and hurricanes are increasingly influencing human coastal activities. With respect to the projected continuation of accelerated sea level rise and global warming one must count with additional expenses for adaptation strategies along the coasts. On the mountainous island Martinique the majority of settlements are situated along the coast almost at sea level. But potential rises in sea level and its impacts are not addressed in coastal management, even if saltwater intrusion and coastal erosion with increasing offshore loss of sediment are locally already a severe problem. Following article deals with the evaluation of human vulnerability to accelerated sea level rise on the Martinique coast. In addition, it assesses the possible effects of sea level rise on the island for future regional planning purposes spatially. The actual situation and legislation measures for coastal zone management of the island are described and sea level rise response strategies are discussed. This paper sees itself as recommendation of action not only for Martinique.

KEYWORDS: GIS Modelling, Spatial Analysis, Caribbean, Climate Change, Coastal Zone Management

Introduction

Climate Change and Sea Level Rise in the Caribbean

During the last century a relative sea level rise of about 20 cm has been observed in the Caribbean (Maul 1993), and its speed is increasing rapidly. Relative sea level was estimated to rise on average 2.8 to 5 mm/year during the 1990s (Hanson and Maul 1993). Therefore, regional projections state a rise in sea level of 10 to 50 cm by 2025 as realistic (IPCC 2001; Maul 1993). Additionally, Climate Change scenarios project an increasing frequency and intensity of hurricanes and tropical storms for the Caribbean region (UNEP 2000), both causing coastal flooding and higher erosion rates at the shores. Accelerated sea level rise will not only have enormous consequences for the coastal structures as is going to be expressed through flooding, inundation, erosion, and recession of barrier beaches and shorelines, destruction and drowning of coral reefs and atolls, disappearance or redistribution of wetlands and lowlands, as well as increased salinity of rivers, bays, and aquifers, and loss of beaches and low islands. Also an extension of the coastal risk area is expected due to the combination of accelerated sea level rise with natural disasters (UNEP 2000). Besides the loss of natural coastal structures also man-made measures might get affected with greater populations at risk in low lying areas as could have already been observed in the region during the last few years.

Martinique and its coastal population

The economy of the Lesser Antilles' island Martinique is largely based on the export of agricultural goods (bananas, sugarcane, and pineapples) and tourism as major income sources. Nearly one million visitors annually arrive on the island that is inhabited by nearly 400.000 people (Marques 2002; Charrier 2003).

Because of its mountainous terrain, the majority of the settlements and about 90% of the population are situated along the coast below 20 metres. Neglecting security most of the houses were constructed very close to the shoreline. The urbanisation of Martinique was characterised by one migration flux from the inland island to the littoral and the concentration of population in one extending urbanisation zone. Fort-de-France is the biggest agglomeration area of the island and the pole of development. Here more than 43% of the total population live within 15% of the island's surface area (Génix and Lampin, 2003) almost at the level of the sea. Today, migration fluxes from the inland island to the littoral are still observed (Hocreitère 1999; William 2000). But due to rising standard of living as well as better infrastructure and mobilisation by car a suburbanisation to the inland island and mainly to southern districts also takes place. Riviére Salée, for example, showed a growth of more than 40% (Delbond et al. 2003). The northern island on the contrary is characterised by demographic and economic decline. The four communities in the extreme north, Grand Riviére, Prêcheur, Sainte-Pierre, Macouba counted the most severe shrinking between 1990 and 1999 of -10.34% (Delbond et al. 2003; see also Génix and Lampin 2003). This region suffers from insufficient infrastructure and rough terrain. The main economic activities here are export agriculture and fisheries (William 2000). The growing population of Martinique - in 2003 the annual population growth rate amounted to 1.4 ‰ (IFRECOR 2003) – additionally extents the coastal urbanisation.

Policy instruments for the coastal zone on Martinique

To make statements about adaptation strategies for the coastal zone it is of importance to learn the essentials of the local coastal zone management plans and the referring policy instruments. These contain regional and national but also EU-wide regulations because the Caribbean Lesser Antilles' island Martinique is a French Department (DOM - Departement d'Outre Mer) and therefore EU „ultra-peripheral region“. This chapter gives an overview of the most important legislation instruments for the coastal zone of Martinique.

« La loi des 50 pas géometriques » and its colonization. On Martinique the littoral is characterized by a zone called "les 50 pas du Roi" or "cinquante pas géometrique", that means a zone of 81.2 m from mean high water tide level landwards (Houdart 2004). After the "loi littoral" this stripe is today part of the public domain of the state. On Martinique the "50 pas" represent 3513 ha of which 35% are under intensive human use (public institutions, tourism, agriculture, fisheries, artisans, industries). The cause of the high population density within the 50 pas lies in Martinique's coastal zone management history: From 1922 until 1955 the privatisation of the 50 pas was enforced. From 1955 onwards the zone was again integrated into the public domain of the state. However, parcels of coastal land still have been sold – only half-legal - and until today the littoral is still seen as privileged space for houses. Additionally, the illegal occupation of the littoral without landholding for the economic reasons has been practised, when the sugar crisis and following concentration in urban tertiary activities took place. The development of agglomerations and diffuse habitats along the coast caused many problems. Therefore, the objectives have been formulated to organise and limit the urbanisation, the tourism and industry for a protection of the remaining natural zones. In 1962 the coastal zone has been placed to 65% under the control of the ONF (Office national des forêts) and finally in 1986 the "loi littoral" merged the 50 pas into the "public domain maritime". That includes that urban areas within this zone are reserved for

necessary installations of the public service, for economic activities, or for general utilisations of the sea. Urbanised areas within the “50 pas” are protected from constructions if they are used as beach, forest, garden, or park.

The “loi littoral” on Martinique. The most important law concerning the coastal zone on Martinique is the so called “loi littoral” (France Gouv 1986). It was elaborated in 1986 by the «Direction du transport maritime, des ports et du littoral», and by the « Direction générale de l’urbanisme et de l’habitat et de la construction », under collaboration of numerous French ministerial departements. It has been transmitted to Parliament in 1999. The regional objectives for the coastal zone described in the “loi littoral” are (Alduy and Gélard 2004):

- research and innovation of particularities and resources
- protection of biological and ecological equilibrium, erosion mitigation, preservation of sites and landscapes
- extension of urbanisation only within those sectors that are today occupied by diffuse urbanisation.
- prohibition of constructions and utilization of slopes adjacent to the littoral, if they blur the landscape character
- preservation and development of economic activities in relation to the sea, like fisheries, aquacultures, ports activities, ship construction and reparation and marine transport. For example, construction of new ports of pleasure is curbed, therefore existent ports shall be extended
- maintenance and development of agricultural activities or forestry, of industries, crafts, or tourism within the coastal zone

SMVM (schémas de mise en valeur de la mer) and SAR (schémas d’amenagement régionaux). Regional Management schemes (SAR) additionally regulate the utilization of the coastal zone for tourism, constructions and commercial use. In

France the state is traditionally responsible for coastal protection, but since the law of decentralisation (1984) the decisions for coastal management are in the hands of the regional councils. Its implementations are presented in the «Schéma de Mise en Valeur de la Mer (SMVM) ». The SMVM gives a high priority to protective measures: protection policies for the coastal strip concern natural coastal areas, areas of outstanding interest designated for protection (Etang des Salines, Morne Jaqueline, Caravelle, and the Lamentin mangrove swamp) and urban development buffer zones. In the DOM-TOM the SMVM are replaced by regional management schemes, the SAR. The SAR (Schémas d'Amenagement Régionaux) are elaborated and adopted by the Départements d'Outre-Mer and have to be accepted by the National assembly. On Martinique the SAR exists since 1998 (Hocreitère 1999). Planning policies on Martinique focus mainly on the regulation of urbanisation and town planning as well as on provisions to improvements of urban wastewater and rainwater run-off treatments. The SAR are jurisdictionally situated between the "loi littoral" and other documents of urbanism (Schémas de coherence Territoriale, plans Locaux d'ùrbanisme). They are seen as an orientation document and tool for integrated coastal management, for administration and durable development of activities.

As a French department, Martinique is a European territory in which most European Union agreements, directives and founding laws are applicable, as well as those rules that are more specifically designed for outlying EU regions such as the DOM-TOMs. For further information it is referred to the European Commission (2007).

Evaluating vulnerability and adaptation to sea level rise

"Vulnerability is the extent to which a natural or social system is susceptible to sustaining damage from Climate Change" (IPCC 2001). A study by the World Bank (Deeb 2002) criticises the lack of adequate data to conduct vulnerability assessments in the Caribbean. However, accelerated sea level rise already affects the Caribbean coasts and there is a need to formulate risk and vulnerability assessment methodologies compatible with the data available. The IPCC (2001) even declares that one of the most important climate change effects on coastal resources will be sea level rise. Volonte and Nicholls (1999) give a first overview of how to conduct vulnerability assessments in the region. Lewsey et al. (2004) therefore ask for increasing use of GIS and remote sensing to obtain useful results. Thumerer et al. (2000) conducted such a successful GIS assessment for the English east coast, for example. This study, however, aims to develop a methodology to assess the sensitivity of the coastal zone to sea level rise and address its impacts. A GIS-based assessment model has been developed, that allows spatial explicit assessments of coastal vulnerabilities. The application should ensure easy transformation to other coastal zones by utilisation of parameters that can be derived through GIS and always considering the individual characteristics of different coastal areas. The coastal zone of Martinique is a very diverse space, partly occupied by human constructions, used as famous tourist destination, or grown by valuable ecosystems. It is surprising that on Martinique present rises in sea level are not addressed in coastal management even if saltwater intrusion and coastal erosion is locally already a severe problem. On Martinique where most of the settlements are situated along the coast and beach tourism is the main income source, a change in coastline and an extension or intensification of the risk area might have enormous effects on the island's economy, not to forget ecological consequences such as wetland loss, etc. Therefore it was not only of importance to model the spatial impacts of sea level rise but also to evaluate its possible consequences and discuss potential and existing mitigation and adaptation strategies. Martinique has been chosen as case study site for there has been no vulnerability assessment available. There was a need to describe the actual situation and legislation measures for coastal zone management of the island. This article finally sees itself as recommendation of action not only for Martinique.

Methodology to conduct spatial planning assessments

The methodology is divided into three parts, the first evaluates the vulnerability of the coastal resources to sea level rise, the second investigates existing and potential coastal zone management strategies for formulation of policy targets, and the third part describes the spatial translation of suitable adaptation strategies via GIS. Figure 1 gives an overview of the applied methodological structure.

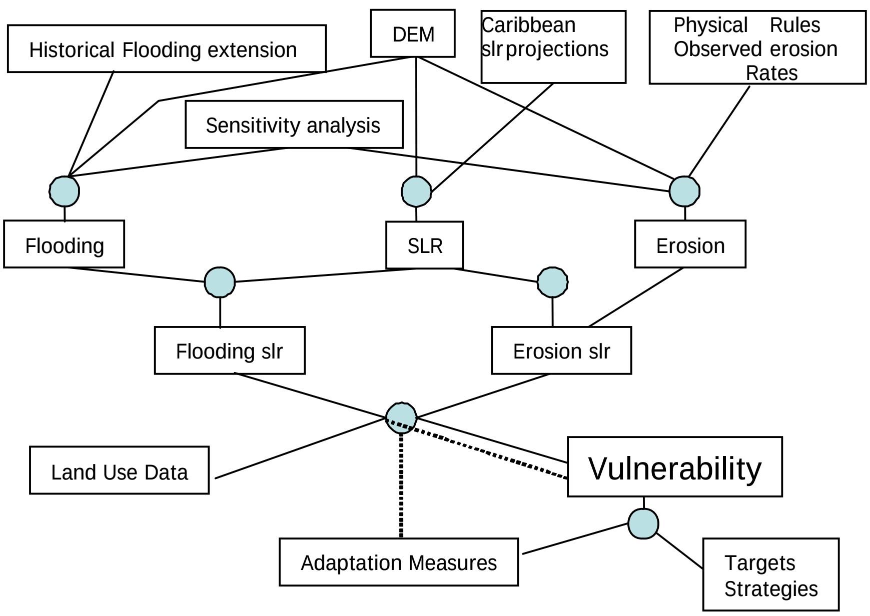

Figure 1. Structural overview of the Methodology

Vulnerability evaluation to sea level rise impacts

The aim of the first part of this study is to illustrate the human consequences of accelerated sea level rise to Martinique. Therefore, a GIS-based model has been developed that borders the potential coastal areas at risk with help of sea level rise scenarios.

The main threats to the coastal zone are flooding and erosion. Shallow land in the Caribbean is especially sensitive to flooding and erosion during hurricanes or tropical storms. Schleupner (2007) evaluated the present coastal risk areas on Martinique to erosion and inundation during hurricanes through a spatial model. This model has now been used as the base for the sea level rise impact study. If the sea level rises, the flooding risk will shift to higher elevations and would additionally cause erosion and inundation (UNEP 2000; NICHOLLS et al. 1999).

Two sea level rise scenarios have been chosen out of the IPCC scenarios and regional sea level rise projections (IPCC 2001, Maul 1993) and applied for Martinique. These scenarios state a rise in sea level to 2100 of 50 or 100 cm. The sea level rise scenarios are added to the flooding and erosion scenarios of the GIS model. Of importance is a SRTM3 (Version 2) digital elevation model of Martinique interpolated with digital topographical data of the coastal zone (IGN 1996).

The erosion and flooding scenario model additionally refers to following rules and remarks: According to Behnen (2000), areas below 10 m level are most vulnerable to sea level rise. Hereby, lower slopes experience a greater increase in flood risk due to sea level rise than steeper slopes (Nicholls et al., 1999). Bruun (1962) showed that, as the sea level rises, the upper part of the beach is eroded and the material is deposited offshore in a fashion that restores the shape of the beach profile with respect to sea level. The hence derived "Bruun Rule" implies that a rise of one meter would generally cause shores to erode 50 to 200 meters along sandy beaches. Coastal wetlands or muddy coasts would become even more vulnerable to erosion: unlike sand, muddy sediments can be carried great distances before dropping out of suspension. On this basis the UNEP (1989) projects a shoreline retreat for each centimetre of sea level rise up to several meters horizontally. Data on observed erosion rates and historical flooding extensions[1] are also used as "experience" values of the model and serve for validation purposes. As result we obtain a spatial assessment of the sensitivity of the coastal zone to sea level rise, flooding and erosion risk as well as its impact area.

The results of the flooding impact area evaluation through Coastal Sensitivity analysis are now translated into five graded rating classes from extremely high sensitivity to no sensitivity expressed through the F- index. Whereas the F-index gives information about the impacted area through flooding at sea level rise, the erosion risk is also of importance. Therefore, an index value for the erosion risk has been added (E). Not only the low lying coastal parts might be affected by sea level rise impacts but also those areas lying relatively high but which rocks are increasingly at risk to coastal erosion if sea level continues to rise. Through the consideration of flooding and erosion risk both effects can be taken into account separately or combined.

To get information about the human vulnerability land cover and socio-economic geo-data are included into the model. These are obtained from interpretation of satellite images (Landsat), topographical maps (IGN 1996)[2], and statistical data[3]. We used the distribution of beach hotels, coastal tourist destinations including beaches, human settlements, houses and population densities, as well as harbours, coastal industries and other infrastructures as parameters that were intersected separately into the risk area. This presented study initially explains the parameter "population density and infrastructure" in more detail. First of all a map of the population densities within the risk area as well as data on infrastructure have been created by intersection. To obtain statements about the vulnerability of the population and infrastructure the data were translated into a 5-levelled assessment scheme. Table 1 shows the description of the parameters and their scaling for the example of population density and infrastructure (D-index).

Table 1. scaling and description of the index parameters.

Index	Flooding Risk (F)	Population/Infrastructure Density (D)	Erosion Risk (E)
1	Very high flooding risk (flooding at every storm event under present conditions)	Very high densely settled areas (>750 Inhabitants/km²), also harbours, ports, industries	Very high erosion risk (under present and future conditions even without storm event)
2	High (flooding at storm events from category 2 onwards under present conditions or at any storm event under slr scenarios)	High densely settled area (250 – 749 I/km²), important infrastructure	High (under present and future conditions at any storm event)
3	Medium (flooding at storm events from category 3 onwards under present conditions or from category 1 or two storms under slr scenarios, no flooding during tropical storms)	Medium settlement (100-249 I/km²) and infrastructure density	Medium (erosion only under slr scenarios and any storm events)
4	Low (flooding only at extreme events like tsunamis, or under hurricanes with intensities of 4 or 5 at all scenarios)	Sparely settled (20-99 I/km²), agricultural use, few infrastructure	Low (rock resistance against erosion high, erosion only under slr scenarios and during extreme storm events)
5	No flooding risk (at any scenario)	Negligible human utilization (0-19 I/km²)	No erosion risk (at any scenario)

The three parameters build the basis for the vulnerability evaluation that is expressed through the five-levelled vulnerability index (VB) with “1” meaning highest vulnerability of erosion and inundation considering sea level rise. The assessment relies on logical constraints that are shown in following equations:

$$VB1 = \left(F_1 \vee E_1\right) \cap \left(D_1 \vee D_2\right)$$
$$VB2 = \left(F_2 \vee E_2\right) \cap \left(D_1 \vee D_2\right)$$
$$VB3 = \left[\left(F_3 \vee E_3\right) \cap \left(D_1 \vee D_2\right)\right] or \left[\left(F_1 \vee F_2\right) \cap D_3\right] or \left[\left(E_1 \vee E_2\right) \cap D_3\right]$$
$$VB4 = \left[\left(F_4 \vee E_4\right) \cap \left(D_1 \vee D_2 \vee D_3 \vee D_4\right)\right] or \left[\left(F_1 \vee F_2 \vee F_1\right) \cap D_4\right] or \left[\left(E_1 \vee E_2 \vee E_3\right) \cap D_4\right]$$
$$VB5 = \left(F_5 \vee E_5\right) or \left[\left(F_1 \vee F_2 \vee F_3 \vee F_4\right) \cap D_5\right] or \left[\left(E_1 \vee E_2 \vee E_3 \vee E_4\right) \cap D_5\right]$$

$\vee$ – logical"or"
$\cap$ – intersection

The level “VB1” consists in this case of those areas that show very high erosion- or flooding risk and very high to high settlement density (for scaling see Table 1). On the other hand is the vulnerability level “5” characterized by negligible erosion or flooding risk or alternatively, by very high to low erosion or flooding risk and no human utilization. VB3 is reached either through medium erosion- or flooding risk and very high to medium settlement density or through very high to high erosion- or flooding risk and medium settlement density. As result vulnerability maps for each human coastal resource illustrate the corresponding vulnerability to the effects of sea level rise. The results also allow further analysis in combination with adaptation strategy evaluations.

At this state all artificial measures of the coast are excluded from the model. In the following a methodology is described to apply these measures and potential additional adaptation measures to sea level rise to the model to obtain more realistic statements about the vulnerability to sea level rise impacts.

Formulation of CZM strategies and targets

After the evaluation of vulnerability of the human coastal resources there is a need to define targets for coastal zone management practices concerning sea level rise effects. The objective of this part of the methodology is to discuss coastal zone management strategies by describing the actions and measures undertaken concerning accelerated sea level rise on Martinique. The investigations of Climate Change/Sea Level Rise response strategies are based on intensive literature review (Bray et al. 1997; Cambers 1992; CPACC 1999, CPACC 2000; CgCED; Nurse 1997; Phillips and Jones 2006; Volonte and Nicholls 1999). The evaluation of the coastal zone management strategies in combination with intensive literature review and the results of the sensitivity and vulnerability assessments described above build now the base for formulation of policy options and targets for the entire coastal zone of Martinique. Any of these targets might be realized by several defined adaptation strategies.

Development of Adaptation Potentials

In the last step the most suitable adaptation measures per coastal segment are evaluated through the targets and the vulnerability evaluation. For translation of the targets into a GIS we assume that the adaptation strategy also determines the adaptation measure. Depending on its vulnerability, geomorphology and land cover the above-formulated targets can be determined for each coastal segment. That means, for example, that only those coastal parts are considered for protection strategies that demand those measures by high vulnerability. The evaluation of adaptation strategies is carried out for each vulnerability parameter separately. As result adaptation maps are obtained concerning the vulnerability of different coastal resources. Dynamic interaction occurs in that way that the natural system impacts on the socio-economic system and planned adaptation by the socio-economic system influences the natural system (Nicholls 2003). Concluding, adaptation might reduce the impacts of sea level rise and climate change (Burton et al. 1998).

Results

Sensitivity and Vulnerability evaluation to sea level rise impacts

The evaluation revealed that the coastal sensitivity to flooding and erosion increased with rising sea level in comparison to present conditions whereas the spatial distribution of sensitive coastal segments generally remained the same. Schleupner (2007) showed that under present conditions 13 % of total coastline of 432 km is rated with low sensitivity, 43 % have medium sensitivity, and 44 % show a high risk of coastal flooding and erosion. For the evaluation of vulnerability the knowledge of the risk area is of importance. The extension of the impact area serves as base for the vulnerability evaluation of anthropogenic resources. The coast is especially attractive for residential, economic and for tourist activities. The spatial analysis showed that tourism infrastructure, road networks and major settlements are usually all located along the coast giving locals and visitors an easy access to the coastal and marine natural resources. Analyses of the present impact state to flooding show that 58 km² have a very high flooding risk, 55 km² lie in the range of high impact risk, and 57 km² reveal to medium risk, that also means within potential flooding impact. Altogether, this amounts an area of 170 km² or about 16 % of the islands surface. More than 62 % of the infrastructure and half of the Martinique population (53%) are situated within this zone. The spatial evaluation of the impact extent concerning accelerated sea level rise identifies the areas that are likely to be affected by flooding and erosion depending on the scenarios and their relative heights to sea level. In total a coastline of 106 km would be affected by erosion if sea level continues to rise up to 50 cm, mainly along the north-western island's coast. This is about one fourth of the coast including an assumed 500 m landward impact zone (Cambers 1997). Additionally the flooding impact area has been determined. Under consideration of a sea level rise of 50 cm the model evaluated an enlargement of the flooding impact area to 221 km² or 20.5 % of the total islands area. Now, 68 % of the infrastructure and 65 % of the total population would be affected. This is a total population number of about 260 000. More than 36 % of the impact zone is attributed with the category "expansion area" of settlements. An evaluation of infrastructure and constructions situated within this zone reveals that settlements along the southern coast are seldom found below an elevation of 5m whereas at the northern coast they reach further down to sea level. But also tourist hotels can be found very close to the sea and below the 5 m level. However, the majority of coastal constructions are built on average at heights between 5 and 10 m above the present sea level and therefore within the risk zone to flooding and erosion. Figure 2 illustrates the vulnerability of affected human coastal population. The greatest expansion of the coastal impact areas can be found in the Fort-de-France Bay and at the bays of the south-western island. These areas are also those parts of the island where high population numbers and settlements are concentrated. Vulnerability of the population and also of houses is therefore high. But also in the northern half of the island the anthropogenic developments are situated right between the sea and the steep slopes of Mt. Pelée. These small, narrow areas show highest sensitivity to flooding and erosion at any scenario. Here, the small land adjacent to the beach is often the most densely settled area, because it is the only flat land available.

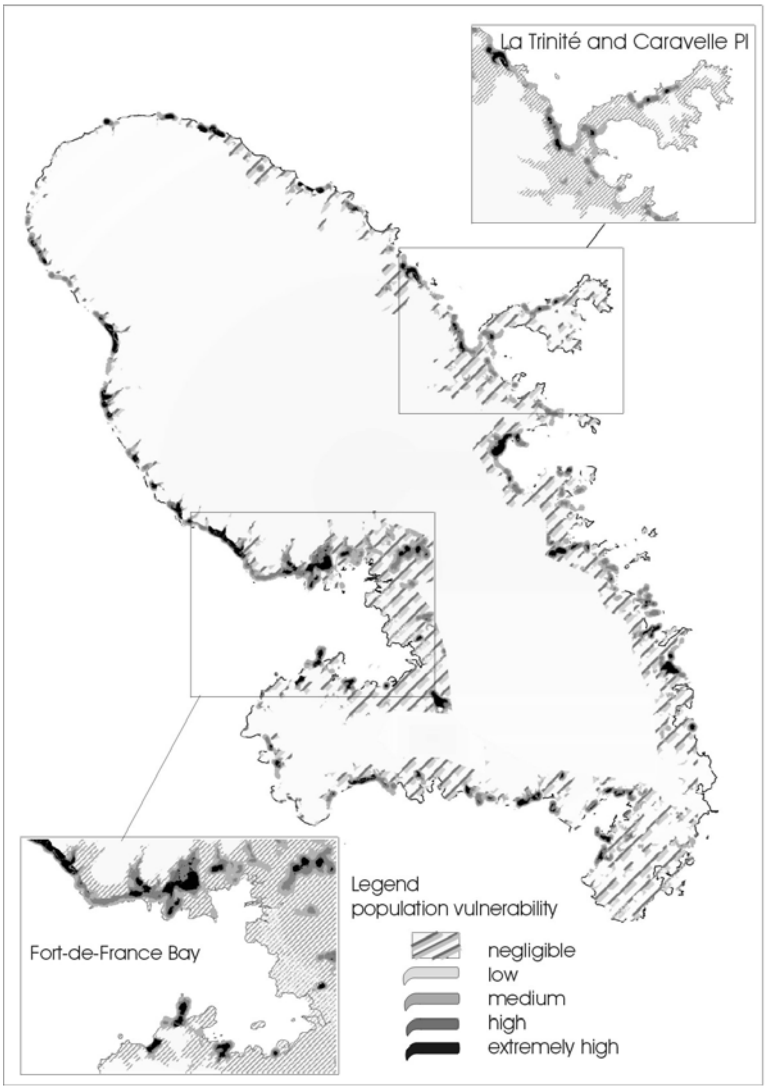

Figure 2. Vulnerability to sea level rise and its impacts concerning population density.

Table 2 illustrates that the space of settlement is limited by topography. The distribution of population in relation to its relative height to present sea level shows that elevations below 100 m are highly dense settled and that the majority of population lives at slope angles below 10%.

Table 2. distribution of population in relation to its relative height to present sea level.

altitude (m)	**area (km²)**	**Pop. (inh)**	**Popdens (inh/km²)**	**area (km²) slope <10%**	**Pop. (inh.) slope < 10%**	**Pop. dens slope < 10%**
0-10	117	79 500	679	96	88 000	916
10-100	363	255 500	704	288	221 000	767
> 100	628	64 000	102	277	61 500	222
total	1 108	399 000	360	661	370 500	560

Martinique as a tourist destination is famous for its fine sandy beaches, clear water and pristine habitats. 13 % of the total coastal area consists of sandy beaches. But the fine sands beaches along the southern coast that serve as main tourist destinations are the most vulnerable to coastal erosion during hurricanes. On Martinique 62 % of all beaches and 66 % of tourist used beaches are potentially at risk to erosion. That means also that the erosion rate is higher than the rate of accumulation. In addition, especially the tourism industry often occupies areas very close to the sea, often even below 5 m on former mangrove forested areas. These constructions have a very high risk to get flooded during hurricanes. Not to mention the loss of mangroves forests whose are not only important for biodiversity conservation and fisheries but serve also as Erosion and flooding protectors of the hinterland. Altogether, 80 % of the coastal hotels and tourist resorts including Camping areas are at risk as well as 92 % of the main coastal tourist destinations without overnight stay possibilities like small islets, fishery settlements, lonely beaches, for example.

The distilleries and the sugar refineries are the main business besides tourism on the island. Only a few are found in the impact area of inundation, the great majority is situated in the hinterland. Nevertheless, the coast of Martinique is attractive for industrial developments as well. Especially the Fort-de-France bay with its extending docks providing space for diverse industries as chemical industry or construction industries but also in some other places were industries build close to the sea. An analysis of the locations of vulnerable industries of Martinique revealed that places at St. Pierre, Fort-de-France and at La Trinité are the most at risk to flooding during hurricanes.

The model shows that a rise in sea level would result in an increase of the impact areas and therefore in an accentuation of the human population at risk.

Coastal zone management on Martinique - legislation and response strategies to accelerated sea level rise

After the evaluation of human vulnerability Martinique’s coastal zone management strategies and its adaptation plans to accelerated sea level rise, intensified erosion and inundation shall now be described. The formulation of goals for future coastal zone management concerning sea level rise builds the main conclusion out of these descriptions.

In France all levels of government have their role in developing planned adaptation measures. The coastal zone management of the Départements d’Outre Mer (DOM) mentions several coastal response strategies. These are the protection measures (“défense rigide”), but also accommodation and planned retreat strategies (“défense souple”) (see also Deneux 2002). The following explanation of coastal zone management strategies on Martinique refers to the definition of the terms by Klein (2002). In practice, many response strategies are hybrid and combine approaches (Nicholls 2003).

Accomoation or planned retreat (“défense souple”). At (planned) retreat all natural system effects are allowed to occur and human impacts are minimised by pulling back from the coast. Whereas at accomodation the difference is that human impacts are minimised by adjusting human use of the coastal zone (Nicholls 2003). The accommodation or planned retreat concept accepts and integrates natural coastline evolution into conservation plans. Also accelerated sea level rise is tolerated here. On Martinique a Water Management Masterplan (SDAGE) has been completed in 1999. Here, coral reefs, seagrass beds and mangroves are taken into account as sensitive areas. Especially the Conservatoire du littoral favours the défense souple along parts of the Martinique coast, where protection measures shall be avoided. The Conservatoire du littoral (Conservatoire de l'espace littoral et des ravages lacustres) is a public organisation with the remit of ensuring the definitive protection of outstanding natural areas on the coast, banks of lakes and stretches of water of 1 000 ha or more (Boyer 2000). These are mainly the natural and especially the protected parts of the Martinique coastline and less the highly populated areas. Martinique has several protected land areas (Regional Nature Park, Caravelle Peninsular and Sainte Anne islets, the Montagne Pelée, the Rocher du Diamant) boardering to the sea. The Regional nature Park park comprises two separate areas that constitute 60% of the island's surface of Martinique. It includes the mountainous, volcanic part of the island, but also coastal cliffs, lagoons, and beaches. It excludes the cultivated lowlands. Other areas with nature protection include the Rocher du Diamant and Cap Salomon. The Coastal and Lakeshore Conservation Agency (CELRL) has purchased six areas totalling 1 135 ha on Martinqiue (Pointe Rouge/Trinite, Caravelle/Trinite, Grand Macabou/Marin-Vauclin, Morne Larcher/Anses d'Arlet-Diamant, Cap Salomon/Anses d'Arlet and Anse Couleuvre/Precheur). But not only nature protection sites but also other utilized areas might be managed through the accommodation concept. The Conservatoire states that it should not be necessary to intervene at present into utilized zones that might only be impacted in 50 years earliest. The French Senat on the other hand sees a need to assess at least the future potentials of these coastal zones according to their future cultivability.

Protection (“défense rigide”). Protection means that natural system effects are controlled by soft or hard engineering, reducing human impacts in the zone that would be impacted without protection (Bijlsma et al 1996; Klein et al 2001). The protection measures are the main response strategies against erosion and inundation in France (Deneux 2002). The legislation of France manages a total coastline of 6.959 km (5.500 km continental and 1459 km outre-mer). About 35% (1.925 km) of the French coast consists of beaches, and 21 % of these beaches are artificially protected by measures (Deneux 2002). The government gives subventions for measures of coastal protection. In addition it coordinates the politics about “protection and prevention of the coast” (“PPR littoraux”) under integration of the districts. On Martinique it has also become necessary for the regional council to develop defence strategies against erosion to protect the coast. But the operations to protect the inhabited places from the sea are complex and a single technical solution does not exist. Three types of buildings are common on Martinique: longitudinal (made of cement and concrete) and transversal (made of basalt rocks) constructions, as well as breakwaters. The communities of Lorrain, Marigot, Precheur, Diamant, and St. Anne use the first type, whereas the transversal buildings can only be found at Tartane. Breakwaters are mostly built in front of hotel complexes in the South. Moles, piers and other docks that absorb wave energy are also considered as protection measures. These measures might be effective, but they are cost intensive. Besides this the changed wave actions have negative influences on the environment. Naturally, the beach gets permanently sediments from rivers and from the sea to compensate for the wave forces. The use of structural solutions interferes with the sediment transport along the coastline and, consequently, the shoreline stability of adjacent properties (UNFCCC 2000). To manage and protect the coast permanently the protection buildings are therefore not suitable (UNEP 1989). An alternative or supplementation to the protection buildings is beach nourishment („artificiel rechargement“) on suitable locations (Phillips & Jones 2006). The revenue generated from beach tourism might be financially liable for this cost intensive measure. However, environmental impacts have not been well studied yet (Greene 2002).

Education, training, Public Awareness. Additionally to the above mentioned the information strategy is of great importance. Public awareness and the development of evacuation plans should be included in every adaptation strategy. Whereas in the Caribbean many island states formed alliances and partnerships to elaborate coastal zone management or hazard evacuation plans, respectively to formulate Climate Change mitigation strategies (for example, CPACC, OGCED), the French governed islands Martinique and Guadeloupe also are relatively isolated within the Caribbean region, even if today one goal is the strengthening of Inter-Caribbean cooperation. On Martinique formulation of targets concerning sea level rise and even the evaluation of the risk areas are missing as well as adequate public information.

After intensive study of the Martinique coastal zone management legislation (see Introduction) and comparisons with other studies (CgCED 2002; Klein 2002; Lewsey et al. 2004; Bray et al. 1997; Cambers 1992; CPACC 1999, CPACC 2000) policy options for the coastal zone of the island concerning accelerated sea level rise were able to be formulated. In the following the derived targets for Martinique are listed:

- protection of existing or rehabilitation of degraded mangrove forests that have the capacity to reduce the impacts of natural hazards
- accommodation to rising sea levels of natural areas
- creation and maintenance of buffer zones / set back areas between land and sea where safety is not guaranteed
- relocation or abandonment of settlement/infrastructure only if existing safety standard is not maintained, people directly affected agree, and the coastal defence administration is kept free of extra costs
- prohibition of new buildings, modern estates or hotels within the highest risk areas
- conditional development: existing living houses within high risk areas shall not be rebuild if once destroyed
- abandonment of private market forces: only industrial or commercial use permitted within highest risk areas
- protection of densely settled coastlines with hard and soft structures
- strengthen of risk awareness of coastal population
- development of illustrated public evacuation plans considering sea level rise
- protection of economically valuable beaches from erosion only by measures of low habitat impact

Illustration of Adaptation Potentials

The targets as well as the results of the vulnerability analysis serve as base for the development of a GIS-based model that is able to illustrate the potential distribution of adaptation measures. One map has been created for each vulnerability factor. Figure 3 shows the adaptation measures concerning the vulnerability of the population concerning its density. About 18 % of the total coastline therefore needs to be protected by hard measures, whereas another 15 % or about 78 km of the coast that shows vulnerability might adapt to rising sea levels by mangrove forest conservation and regeneration.

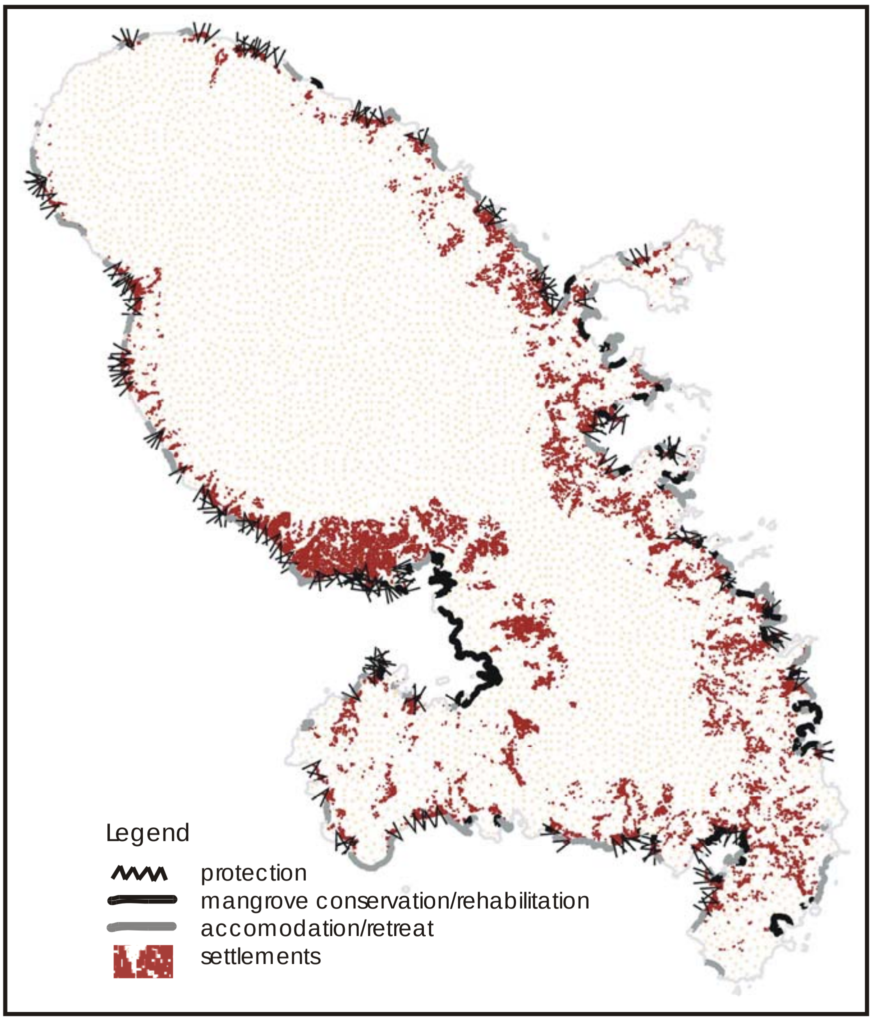

Figure 3. potential adaptation measures with respect to vulnerable population to sea level rise impacts.

The remaining coastline might serve well with accommodation even if along 93 km in total scattered houses or small settlements are found along the coast and within the impacted area. It is notable that the results of the model differ with each vulnerability factor. An example should make this clear: The optimal adaptation measure of vulnerable population in the Fort-de-France Bay might be the protection of mangrove forests. Concerning the vulnerable infrastructure along this coastal stripe the optimal adaptation measure would now partly be protection. The reason is that no humans live within this mangrove area, but the airport of Martinique as an important economic factor is situated here. Therefore it gets clear that the adaptation measures always rely on the viewpoint of priorities. A combination of all of these single maps into one is not recommendable without knowledge of the regional priorities. Furthermore, these measures always rely on cost-benefit analysis. Therefore, the maps can be seen as preliminary overview for further local studies.

Discussion and conclusions

The evaluation of the erosion and inundation risk with rising sea level on Martinique showed a high coastal impact potential. More than 60 % of the human coastal resources are at risk at present conditions and this number will increase if sea level continues to rise. The evaluation of settlements at risk and tourist beaches and accommodations proved very high risk to the majority of buildings and beaches. The main income factor on Martinique is the beach tourism (see also Para *et al*., 2002). Hotels are built close to sea level to facilitate the access to the beach. If sediment loss further continues, Martinique is endangered to loose not only the majority of its famous beaches and its valuable mangrove habitats but also its prestige as beach tourist destination. The projected loss of beaches as a consequence of erosion and inundation can cause severe economic impacts on the tourism industry as have Uyarra et al. (2005) shown, for example. In the mountainous parts of Martinique the small areas adjacent to the beach are often the only flat land available and are therefore compactly colonised. A retreat back to the hinterland as adaptation to sea level rise is often very complicated for various reasons. One may be the safe distance to the active volcano Mt. Pelée.

The expected accelerated sea level rise will accentuate the impact and broaden the risk area. The narrow land adjacent to the beaches is often the only flat land available and densely settled. A retreat back into the hinterland is complicated because of competing land uses, as are nature conservation areas of unique flora and fauna, land areas for export agriculture, but also other risk areas where settlements are prohibited, for example at the upper slopes of the volcano Mt. Pelée or along river flooding areas. The development of a Coastal Zone Management Plan considering sea level rise and its impact area as well as elaboration of public information and evacuation plans is therefore of utmost importance. The best response to sea-level rise and climate change in the coastal zone is therefore an appropriate mixture of mitigation and adaptation (Nicholls 2003). The decision of the optimal adaptation strategy depends on the priorities and financial limitations of the responsible authorities. But whatever the final adaptation strategy might be: public participation in decision-making and resource management shall be integrated into the planning process.

A study by the World Bank (Deeb 2002) concluded that it is widely impossible to conduct vulnerability assessments in the Caribbean because of the lack of adequate data. Also on Martinique no vulnerability assessment has been undertaken, and extreme events like hurricanes are not integrated into the coastal management plan. Besides this the data sources are poor. This study showed that spatial analysis allows the evaluation of potential coastal risk areas by using an empirical assessment model. The utilization and interpretation of satellite images and other spatial data can compensate missing base data partly. But nevertheless, more background data would improve the accuracy of the vulnerability assessment. Further socio-economic aspects can be easily integrated into the model to illustrate human vulnerability. Through GIS-maps the results are visualised and can be used for public illustration. In this connection the results of this empirical assessment might also serve as base data for more specific economic impact models.

Besides this, the methodology is easily applicable and allows individual transformation to other coasts. As long as adequate data are missing, spatial modelling is a feasible methodology to obtain statements about coastal impacts due to erosion, inundation or sea level rise. It is of importance by localising the risk areas and spatial illustration of human impacts. This GIS Analysis gives a spatial explicit assessment of risks that might be further investigated in individual cases.

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Notes

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[2] Landsat Data used from www.geocomm.com
SRTM3 (Version2) Data from EastViewCartographic: www.cartographic.com
Other spatial data: www.geoportail.fr

[3] Statistical data are obtained from www.martinique.pref.gouv.fr, as well as from Charrier 2003; Conseil Regional; INSEE; Marques 2002, Statistique-publique