SPATIAL ANALYSIS AS TOOL FOR SENSITIVITY ASSESSMENT OF SEA LEVEL RISE IMPACTS ON MARTINIQUE

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Abstract

Sea level in the Caribbean region is expected to rise approximately10-20 cm by 2025. In some areas of Martinique coastal erosion and saltwater intrusion are already a severe problem. Because the island has a mountainous character, the majority of its settlements are situated along the coast almost at sea level. Considerations and strategies for dealing with potential sea level rise and its consequences for Martinique do not exist. This part of a detailed case study concentrates on the evaluation of sea level rise impacts on Martinique. It is going to test the suitability of spatial data for impact scenarios at a regional scale. Also, it conceptualises the possible effects of sea level rise on the island for future regional planning purposes.
An elevation model is created that visualises the low-lying coastal areas and a second model evaluates the sensitivity of each coastal segment to erosion, flooding and inundation. The resulting map distinguishes between coastal parts at high, medium, or low risk to sea level rise impacts. Results show that nearly three quarters of the Martinique coast are highly sensitive to flooding and erosion.

ADDITIONAL INDEX WORDS

Caribbean, Lesser Antilles, Regional Planning, GIS, Climate Change, Coastal Change, Erosion, Inundation

Introduction

During the last 100 years, the relative sea level in the Caribbean has risen of about 20 cm (MAUL, 1993a), and it is estimated to rise actually on average 2.8 to 5 mm/year (HANSON and MAUL, 1993).

Because of scarce data availability within the Caribbean and high spatial variability among the islands it is difficult to make concrete relative sea level rise estimates for each single island region. Regional projections state a rise in sea level of 20 to 50 cm by 2025, respectively approximately 65 cm by 2100 (IPCC, 2001; MAUL, 1993a), whereas the UNEP (2000) considers an increase of about 10 cm by 2025 in the Caribbean as realistic.

Projections for the Caribbean region (UNEP, 2000) additionally expect an increasing frequency and intensity of hurricanes and tropical storms that coinciding with coastal flooding and high erosion rates at the shores, also as a cause of rising sea level.

The Caribbean Environmental Program (CEP) describes the potential effects of sea level rise (SLR) in the Caribbean as follows (UNEP, 2000):

- more severe and frequent storm damage and 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
- increased salinity of rivers, bays, and aquifers
- reduction in biological diversity and possible wildlife extinctions
- loss of beaches, low islands, and spits
- loss of coastal structures, both natural and man-made
- greater populations at risk from natural disasters in low lying areas and island nations

In a region where most of the settlements are situated along the coast and beach tourism is the main income source, a change in coastline might have enormous effects on the island's economy, not to forget ecological consequences such as wetland loss, etc.

Nonetheless, site-specific values for Martinique are missing. Coastal erosion with increasing offshore loss of sediment is locally already a severe problem. Therefore this study is a first contribution to denominate the potential impacts sea level rise would cause at the island.

Background

Geographical overview of Martinique

Martinique is a French island of the Lesser Antilles in the Caribbean region. Figure 1 gives an overview of the Caribbean region.

Its humid tropical climate is moderated by trade winds, and the rainy season lasts from July to December. During that season floods often occur which are mainly caused by hurricanes. The geology of Martinique is dominated by volcanoes of different age. The island evolved over the last 20 million years because of eruptions of volcanoes that were displaced northwards due to tectonic movements. The youngest volcano is still active. It is the Mt. Pelée (1.396 m NN) situated in the north of the island. Superficially the island has mountainous character with numerous but small rivers.

Martinique is a French Department and EU „ultra-peripheral region". The economy is largely based on the export of agricultural goods (bananas, sugarcane, pineapples) and tourism as major income sources. Nearly one million visitors annually arrive on the island which is inhabited by approximately 390.000 people (MARQUES, 2002; CHARRIER, 2003).

Because the topography of the island is characterised by steep mountains, the majority of the settlements and about 87% of the population are situated along the coast below the 20 m contour line.

Migration fluxes from the inland island to the littoral are observed (HOCREITÈRE, 1999; WILLIAM, 2000). Today, most of the Martinique population is concentrated in the extending urbanized zone of the cities Fort-de-France and Schoelcher, where houses are built on a deep bay almost at the level of the sea.

The coastal zone of Martinique

Martinique's coastline is approximately 433 km long. The coast has only a small tidal range of at most 0.5m and the average swell reaches 1.2 to 2.5m (DELBOND ET AL., 2003).

The tectonic and geological relations, i.e. the contrast between the younger North and the older South, are also reflected by coastal shape: In the North the coastline is steep and smooth, whereas in the South it is flatter and disturbed by numerous bays, islands and peninsulas. The North coast from Macouba to St. Marie is bordered by steep cliffs with limited access to the sea. Between St. Marie and Trinité the distortions of the coastline are less pronounced. The peninsula of Caravelle marks one main change in the morphology: From the point of Caravelle on to the extreme South of the island a line of ragged reefs – remnants of a palaeo-littoral- move together more and more to the coastline until they fuse. To the South of Fort-de-France the coast alternates between spreading into the sea and deep bays. The largest bay is the Fort-de-France Bay. From Fort-de-France to the North to Trinité the coast is smoother and steeper with heights up to 200m.

On Martinique one can distinguish four main coastal types: Sandy bays, muddy bays, rocky shore and steep coast.

Today one fourth of the coastal zone (on Martinique defined as area of 81.2 m width on the landward side of the high tide level) is occupied by constructions, the rest is natural space with 10-12% agriculture. The majority of the Martinique communities are situated totally or partially within this zone very close to the shoreline. It has become necessary for the regional council to work out defence strategies against erosion in order to protect these settlements. Such defence strategies include offshore breakwaters, groins, seawalls, and bulkheads, etc. But to manage and protect the coast permanently from the sea, these protection measures are not suitable. Moreover, no considerations and strategies for a potential rise of the sea level and its consequences do yet exist. In the following the sensitivity of the Martinique coast to flooding and erosion caused by Climate Change and sea level rise is evaluated.

Historical coastline changes on Martinique

The coastal system is highly dynamic: While the ordinary swell generally promotes the regeneration of the sandy beaches, the swell during hurricanes erodes them.

In addition currents mobilise substantial amounts of sediments. Especially at the Northern coast (Community of Grand-Riviére) the diagonal leeway mobilises 30.000 to 90.000 m³ of sediments every year. This drift also depends on the wind direction. Currents converge in the direction the wind blows (usually from East to West) and either push the sediment against the coast inducing sedimentation, or discharge it leading to the erosion of soft shores by an increasing offshore loss of sediment. This kind of erosion is a major problem along the North-Western shore of Martinique (SAFFACHE, 1998) especially between the river Carbet and Cap Saint-Martin. Within 40 years, 25 to 35 m coastline recession has been observed here, that is 0.6 to 0.9 m of coastal area per year (SAFFACHE and DESSE, 1999). At Bellevue even more than 70 m of the coast eroded during the last 40 years (SAFFACHE, 1999b) and at Grand-Rivière community marine erosion removed 60 m of land within 50 years (ASSAUPAMAR, 2002). The reasons are natural as well as anthropogenic: The coast mostly consists of fragile material that is very sensitive to erosion, and even though the rivers transport enough sediment into the sea, the material that arrives on the coast gets directly canalised and discharged quickly because of the steep shore. No coral reef protects the Northern part of the island from the swell. This is also one reason why the swell is particularly erosive along that coast. In addition, quarries along rivers in the Northwest of Martinique extract large volumes of sand and gravel totalling 200.000 to 350.000 t (SAFFACHE, 1998) and therefore accentuate the erosion along the coast by hindering the supply of natural sediments to the beaches.

However, anthropogenic activities also lead to sedimentation along the coast: On the Southern part of the island, rivers migrate forward into the sea because of high sedimentation rates. From 1955 until 1994 the seaward progression at Marin and Galion Bay amounted to 30m on average with a range between 15 and 70 m (SAFFACHE et al., 1999; SAFFACHE, 2000). This progression is caused by the denudation and the erosion of the soil from agriculturally used watershed areas because of the intensification of banana cultivation in combination with higher soil erosion rates. Accumulation of sediments along the coast is generally facilitated in shallow waters.

The sediments originating from land are often polluted with high concentrations of fertiliser and other chemicals brought onto the fields and threaten most relevant habitats along the coast and inside the bays, such as mangroves, coral reefs, and seagrass beds. There are plans to reduce, respectively to scotch this hyper-sedimentation in the bays by improved land use practices (SAFFACHE et al., 1999; PUJOS et al., 2000).

Methodology

Sensitivity evaluation of the Martinique coast to the consequences of sea level rise

The GIS model used in this assessment uses spatial coastal data combined with common SLR projections.

Based on the geomorphology and land use the Martinique coast is divided into 660 segments equivalent to its coastal type. Further attributes of these segments illustrating the nature of the coast as well as the coastal function are added into a database.

To evaluate the probability of flooding and coastal erosion, four categories (coastal elevation and coastal morphology, erodibility, aspect of site, natural protection) that influence its vulnerability are chosen. Relative local subsidence and elevation movements are added to these four categories. REVERT (1949) assumes subsidence for the Northern part of Martinique and a tendency to elevation for the Southern part of the island. Beach Rock at the East coast is indicative of an elevation of the Atlantic coast, whereas the Caribbean side is chaperoned of subsidence (PUJOS et al., 2000). Unfortunately no data are available. The Western coastal zone is characterised by earthquake herds, therefore subsidence or elevation might happen very abrupt. The influence of tectonics on relative sea level rise at Martinique still remains unclear. In general, the vulnerability to erosion and inundation may be more accentuated in the Northern and Western coastal parts of Martinique because of the tectonic influence.

Three sensitivity variables are added to the attributes of the categories ranging in value from 1 to 3 depending on the extent to which they are influencing coastal erosion and flooding. The categories and its risk assignments are listed in table 1.

Based on the category values, the following scheme is used to determine the coastal sensitivity index (CSI) (see also GORNITZ et al., 1997):

$$CSI = (X_1^2+X_2^2+X_3^2+X_4^2+Xn^2) / n \qquad X_1 \text{ to } X_n = \text{categories.}$$

The CSI (minimum CSI value 1, maximum 9) represents the relative sensitivity towards flooding and erosion of one given coastal segment:

If the CSI is between 1 and 3 the risk is low, a CSI of 4 to 6 denotes medium sensitivity and a CSI of 7 to 9 means the risk to inundation and erosion is very high.

Evaluation of coastal areas at risk to flooding and erosion

The IPCC (2001) declares that one of the most important climate change effects on coastal resources is sea level rise.

Shallow land in the Caribbean is especially sensitive to flooding and erosion during hurricanes or tropical storms. A rise in sea level would additionally cause erosion and inundation (UNEP, 2000). It would also move the zones at risk of flooding upward and landward (NICHOLLS et al., 1999). According to BEHNEN (2000), areas below 10 m level are most vulnerable to sea level rise. 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. Wetlands and other 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.

The elevation model used in this assessment is based on these assumptions, using three topographic maps at scale 1:25.000 with the lowest contour line at 5 m altitude above sea level (IGN 1996). Based on historical storm surge heights elevations below 2m, 5m, and 10m show the greatest risk to get flooded during storms with different intensity. If the sea level rises, the flooding risk will also shift to higher elevations.

Results

The impact potential of the Martinique coast to coastal erosion and inundation

In the following, the four categories of the sensitivity evaluation, namely elevation and morphology, erodibility, coastal exposition to the wind regime, and natural shelter of the coast, are described in more detail:

Relative elevation and coastal morphology. These two parameters are combined in one category. The relative coastal elevation is indirectly derived from the Martinique geomorphic map with a scale of 1:150.000 (HINNEWINKEL and PETIT, 1975) as well as directly from the elevation map. It shows the coastal sensitivity to inundation. Also, the geomorphology might reveal some information about the erodibility. But that aspect has its own category below.

For example, all low lying coastal types are sensitive to flooding, but sandy beaches are more sensitive to erosion than rocky shores. Also the steep coast is at risk to erosion with the extent depending on its geology (soft rocks vs. hard rocks).

Figure 2 shows the total length of the coastal types of Martinique. The low lying coastal areas dominate with about ¾ of the total coastal expansion (~ 326 km) of which the rocky shores derive by far the longest total coastal extent with nearly 180 km (42%), followed by 79 km (18%) of mangrove forests. The mangroves can be found in the Ford-de-France Bay and on the Southern and Eastern coast. Whereas sandy beaches (13%) and rocky shores are distributed over the whole coast, active cliffs (5%) are only found at the Northern and Western coast of Martinique.

Erodibility. The erodibility attribute is based on the geology variable of the database. It is derived from the geologic map of Martinique (WEYL, 1966; GRUNEWALD, 1961). Each coastal segment receives the geologic variable with the greatest total length of its respective segment.

Quantitative comparable data about coastal erodibilities for the Martinique rocks don't exist. For that reason, only relative statements about the resistance of each rock type to physical and chemical weathering are made, based on the relative hardness of the minerals comprising the rock.

In reality, a wider range of erodibilities exists for each single rock type depending on mineral content, cementation, grain size, and presence of planar elements (e.g. fractures) within the rock.

The coastal rocks of Martinique consist mainly of young unconsolidated volcanic material. The Martinique volcanoes are of mixed character, which means that the core consists of breccia that is mixed with laval thorns, while outer parts of the volcanoes are built up of loose masses. The Northern coastal geology is influenced by Mt. Pelée: At the border to the sea at the North-Eastern coast the main building rock is pumice, while in the North it is breccia and in the North-Western coastal part up to St. Pierre heat-tuff occurs with a small band of Alluvium. Heat-tuff originates from deposits of Mt. Pelée's heatcloud-eruptions and consists of great blocks embedded in finer material (WEYL, 1966). This fine unconsolidated material is highly erosive: heat-tuffs of the 1902 eruption have already been washed out completely. Along the West coast, between St. Pierre and Schoelcher, breccia and tuffs alternate with river sediments. The Bay of Fort-de-France is dominated by alluvium together with satellites of weathered volcanites. The underground of the capital Fort-de-France also consists of alluvial sediments, as the whole plain of Lamentin is made up of this material. Additionally, the plain is bordered by lava flows. Along the South-West coast lava flows and tuffs dominate the coastal geology, while in the South it is again changing: Here breccia and weathered volcanites are the main rocks to be found along the coast.

Tertiary limestones occur only in the outer South-East island and only in small amounts. The St. Anne peninsula shows an interesting mix of volcanic flows, alluvium and weathered volcanites. Marine tuffs can only be found in the area of Le Vauclin in the South-East. The rest of the Eastern coast is dominated by deeply weathered tertiary volcanites (andesitic-bandaitic volcanism) with extensive fluvial sedimentation at river mouths, tuffs, and isolated tertiary volcanic cones in change. For more information see GRUNEWALD (1965). Figure 3 lists the total coastal length of the different geologic types of Martinique: Alluvial material is most common (163 km), followed by deeply weathered volcanites (119 km) and tuffs (65 km). 82.3% of the coastline has been rated as highly erosive.

On Martinique one can find recent volcanic soils, skeletal soils, calcite soils, fenny soils, as well as alluvial soils that are modified by different microclimates and the relief. For the evaluation of the coastal erodibility the soil parameter has not been taken into account. Soils are unconsolidated material and therefore equally erosive depending only on vegetation. Vegetation binds not only the soil but also alluvial sediments. Good examples are the mangrove forests. If forest stands can be found on alluvial underground, the erosion risk attribute is reduced for the coastal segment by 1/2. This decision is based on the vegetation map of PORTECOP (1971).

Coastal exposition to the wind regimes. The Martinique climate is influenced by North-Easterly and South-Easterly trade winds. During the rainy season the wind regime is very unstable. It varies between E, NE and S and even W. Especially during rainy season hurricanes and tropical storms occur that might have a great impact on coastal erosion and inundation. The windward parts of the Martinique coast are particularly endangered. Cliff retreat rates are generally higher on windward coasts where wind and wave action is more intense.

On the island the cyclones track generally runs from East to West or from South-East to North-West. On average, every two to five years storms greater than Category 3 are passing close to any given island in the Caribbean. METEO-FRANCE (2000) declares that a cyclonic phenomenon (hurricane or tropical storm) occurs every 3.6 years on Martinique, one serious hurricane on average every 13 years. From 1886 to 1997, Martinique was hit by 23 storms which have caused extensive damage (SAFFACHE et al., 2002).

The mean wave heights are higher along the Eastern coast than on the leeward parts. During hurricanes the swell at the Atlantic coast, which is on average between 1.2 to 2.5 m, reaches up to five to eight m and the sea level rises one to four m (DELBOND et al., 2003). A case study by METEO-FRANCE (PERRET et al., 1996) determines the risk of flooding along the coast during hurricanes: The most endangered sites lie in the Eastern part of the island between Trinité and Vauclin and in the Fort-de-France Bay around Ducos.

At the North-Western coast at l'anse Belleville the erosion rates during hurricanes have been extremely high in the past. SAFFACHE (1998) computed retreats from 2.5 to 7 m per cyclone event (for example for Hugo in 1989 or Klaus in 1990).

One may not forget that erosion and accretion processes both occur along the Martinique coasts. But the swell as sediment supplier is only of minor importance for the Martinique coast. Often offshore loss of sediment takes place. SAFFACHE (1999a) determined the origin of the main coastal sediments from inland area, transported to the littoral by rivers. The influence of sedimentation on coastal squeeze processes on Martinique is further examined in more detail below. The sensitivity of the coast to erosion and inundation does not change much because of such processes, and therefore sedimentation is not directly taken into account at this point of the study.

Natural shelter of the coastal segments. Coral reefs have the function of natural breakwaters along the coastline. The most extensive reef structures can be found along the Eastern coast of Martinique, South of St. Marie. Many smaller islands also lie in front of the Eastern main island coast. Smaller reefs form a barrier towards the sea at the Southern coast with the most extensive reef formations at St. Luce. Extensive seagrass beds lie in the shelter of these cays, and mangrove forests on the shore.

Some isolated reef structures also occur in the bay of Fort-de-France. Most of the local reefs inside this bay have been devastated by pollution. Today, the coral formations in Fort-de-France Bay are highly degraded and in a critical state as are many coral communities throughout Martinique and the Caribbean (PAULIN, 2002; SMITH et al., 1999).

The remaining West and North coast are free of reef structures and protecting islands.

The natural protection of the coastal segments, if sheltered by an island, reef or inside a bay, is taken into consideration in the analysis of this study, because the protected position might preserve the coast from high waves and erosive swells. 34 % of the Martinique coastline is protected naturally, 10% is only partly sheltered, whereas the majority of 56% of the total shoreline has been attributed as “open coastal”.

The category “natural protection” reduces the relevance of the wind aspect.

It is suggested that the maximum vertical accretion rates of healthy coral reef flats are going to be sufficient to accommodate the expected rate of sea level rise (VAN DAM et al., 2001). But the adaptive capabilities of reefs which are already degraded and under continuous stress from human activities, such as many Martinique reefs, are uncertain. Therefore the future status of natural protection under sea level rise is unclear.

The sensitivity of the coastal types to the effects of sea level rise and coastal erosion through the CSI is visualised in Figures 4 to 6.

The map reveals high sensitivity to flooding and erosion where historical and actual erosion have been observed. Furthermore, the coastal areas that might be endangered in the future if the sea level rises substantially are shown.

It is striking that only in the South-Western part of Martinique small coastal areas (in total approximately 6.5 km long) have a low CSI of 3 and below, while the majority of the remaining coastline is rated as highly sensitive to flooding and erosion (in total 315 km have a CSI of 7-9); 112 km are categorized as medium sensitive with CSI of 5-7 (Fig. 6). The coastline least at risk is marked with “lifted rocky shore” consisting of hard rock lava flows in leeward exposition. The most sensitive rock types are the pumice formations in the Northern part of the island that are highly erosive. In addition, nearly all sandy beaches of the island (>98%) are classified as “highly sensitive”, as are coastal segments with Northern and North-Western exposition (see Figure 5). That the coastline is protected through islands or reefs does not automatically mean that it is not at risk. As Figure 5d shows, 70% of the protected parts of the coastline have a CSI of 7; one reason might be that especially in the shelter of reefs and barrier islands the most sensitive coastal areas like mangrove forests or beaches are found. While this part of the analysis focused directly on the coastline, the subsequent assessment is going to determine the consequences for areas adjacent to the coast as well.

Coastal areas at risk to flooding and inundation

Figure 7 shows the areas identified by the elevation model that are likely to be affected by flooding and inundation depending on their relative heights to present sea level. These areas are highlighted in black and grey on the map. However, this map only represents elevations and not likely future shorelines. Elevations above 100 m are not explicitly shown, because they are insignificant for this analysis. The slope between the contour lines is bound to be constant due to the coarse resolution of the elevation data. Therefore, the relief uncertainty limits the scale. Sea defence measures are not taken into consideration. Existing sea defence structures just reduce the erosion partially because they were not adequately set for aesthetic reasons. To manage and protect the coast permanently, the protection measures are not suitable (UNEP, 1989), because the use of structural solutions interferes with sediment transport along the coastline and, with that, the shoreline stability of adjacent properties (UNFCCC, 2000). Analyses show that 58 km² lie below an elevation of 2m, 113 km² below 5m, and 160 km² lie below the 10m contour line. Consequently, 14% of the total Martinique land area (<10m) is at risk of flooding and inundation. With a rise in sea level, the impacted area may increase to 221 km² or 19% of the land area.

The greatest expansion of the shallow coastal areas can be found in the Fort-de-France Bay and at the bays of the South-Western island. In contrast, the northern part of the island is dominated by the volcano Mt. Pelée. Here merely small areas show sensitivity to flooding and inundation. But the small land adjacent to the beach is often the most valuable for the local communities, because it is the only flat land available.

Discussion

Concluding, through spatial analysis it is possible to determine which coastal areas of Martinique are highly sensitive to the consequences of sea level rise. Moreover, the analysis shows that nearly three quarters of the Martinique coast are at risk of flooding and erosion. The represented elevation map shown gives an overview of the extension of the flood hazard zone. It forms the boundary for further vulnerability studies that take into account more specified erosion and accretion information as well as more detailed information on the human dimension regarding future shore protection efforts.

The low lying coastal parts identified by the elevation model are also the areas which are particularly sensitive to river and tsunami flooding. Interactions of river flooding and sea level rise could produce substantial increases in flood risk (NICHOLLS et al., 1999; ARNELL, 1999). Figure 8 shows the local communities with reported flooding and inundation problems (after ASSAUPAMAR, 2002): Besides some Northern communes that lie within the Mt. Pelée drainage basin, the majority of communes in the Southern part of the island suffer from temporal inundation and flooding.

Because of the tectonic activity tsunamis are also quite frequent in the Caribbean (ZAHIBO et al., 2001; see also LANDER et al., 2002). During tsunami events wave heights are higher than during hurricanes, and the endangered area for flooding often extends further inland. Sea level rise may accentuate the impacts of such extreme events by increasing the risk area further inland.

However, data on this subject are very scarce. Martinique has no observation network to monitor the health of wetlands, coral reefs and other marine ecosystems. In addition, the time frame for the expression of these responses is also unclear. Therefore, spatial analysis is yet quite restricted and this analysis should only be seen as starting point for more detailed studies.

Conclusion

The evaluation of sea level rise impacts at Martinique shows that the island is highly vulnerable to the consequences of sea level rise.

Spatial coastal data combined with common SLR projections are used in this assessment. Based on the geomorphology and land use the Martinique coast is divided into 660 segments that are attributed by four categories, namely coastal elevation and coastal morphology, erodibility, coastal exposition to the wind regime, and natural shelter of the coast, that influence its sensitivity to coastal erosion and inundation. Three sensitivity variables are added to the attributes of the categories ranging in value from 1 to 3 depending on the extent to which they are influencing coastal erosion and flooding. Based on the category values, the coastal sensitivity index (CSI) is determined that represents the relative sensitivity towards flooding and erosion of one given coastal segment.

The low lying coastal areas that are endangered by flooding and inundation dominate with about ¾ of the total coastal expansion.

Also in respect to its geologic types 82.3% of the coastline has been rated as highly erosive. Additionally the windward parts of the Martinique coast are particularly sensitive to erosion and flooding. During hurricanes the swell at the Atlantic coast reaches up to eight meters and the sea level rises up to four meters. Coral reefs have the function of natural breakwaters along the coastline. Therefore, the category “natural protection” reduces the relevance of the wind aspect. The protected position behind these natural shelters might preserve the coast from high waves and erosive swells. However, the majority of 56% of the total shoreline has been attributed as “open coastal”. In addition, the adaptive capabilities of reefs being already degraded and under continuous stress from human activities, such as many Martinique reefs, are uncertain. Therefore the future status of natural protection under sea level rise is unclear. Results of the CSI evaluation reveal that only in the South-Western part of Martinique small coastal areas (1.5%) have a low CSI, while the majority of the remaining coastline, nearly three quarters of the Martinique coast, is rated as highly sensitive to flooding and erosion; 26% are categorized as medium sensitive. The coastline least at risk is marked with "lifted rocky shore" consisting of hard rock lava flows in leeward exposition. The most sensitive rock types are the pumice formations in the Northern part of the island that are highly erosive. In addition, nearly all sandy beaches of the island (>98%) are classified as "highly sensitive", as are coastal segments with Northern and North-Western exposition.

Further analyses of the extension of the low lying areas show that 14% of the total Martinique land area is at risk of flooding and inundation. With a rise in sea level, the impacted area may increase up to 221 km^2 or 19% of the land area.

Concluding, the use of spatial analysis makes impact studies in areas with scarce data availability possible. Information derived from spatial analyses is useful for everybody interested in determining the present and future vulnerabilities of coastal zones to erosion and sea level rise if data from hands-on measurements are scarce or not readily available.

In future studies the impact evaluation will also include the socio-economic consequences of sea level rise. Areas and effects on population, constructions, tourism, and infrastructure are going to be calculated and visualised. 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.

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Zusammenfassung

Annahmen zufolge wird der Meeresspiegel in der Karibik etwa um 10 bis 20 cm bis zum Jahr 2025 weiter ansteigen. In einigen Gebieten Martiniques sind Küstenerosion und Salzwasserintrusionen schon heute ein ernsthaftes Problem für die Bevölkerung.
Da die Insel sehr gebirgig ist, befinden sich die Mehrzahl der Siedlungen entlang der Küste auf Meeresniveau. Dennoch existieren für Martinique bislang weder Bemühungen noch Pläne, die sich mit einem potentiellen Meeresspiegelanstieg und dessen Konsequenzen beschäftigen. Dieser Teil einer detaillierten Fallstudie konzentriert sich daher zunächst auf die Evaluation der möglichen Folgen eines Meeresspiegelanstieges für zukünftige Regionalplanungen auf Martinique.
Anhand eines erstellten Höhenmodells können die Ausmaße der niedrig gelegenen Küstengebiete genau erfasst werden. Zudem wurde ein GIS Modell entwickelt, das die Sensitivität eines jeden Küstenabschnittes auf Erosion und Überschwemmungen überprüft. Die daraus resultierende Karte unterscheidet zwischen Küstensegmenten mit hohem, mittlerem oder niedrigem Risiko der Folgen eines Meeresspiegelanstieges. Ergebnisse zeigen, dass fast zwei Drittel der Küsten Martiniques sehr sensitiv für Überflutung und Erosion sind.

Tables

Table 1: Categories and risk assignments in the sensitivity analysis to inundation and erosion.

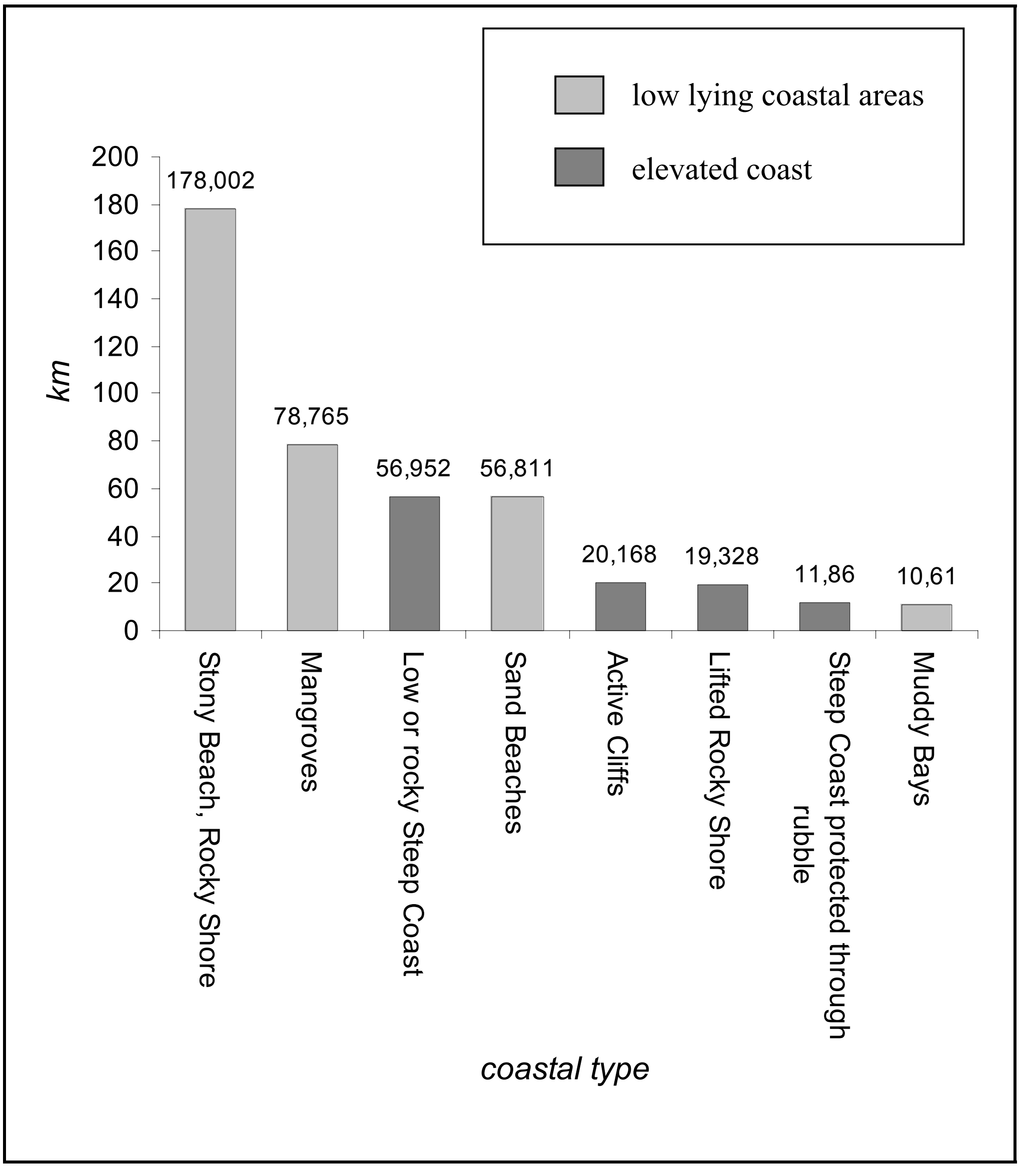
Based on Bacon (1994);Gornitz et al.(1997); CPACC (1999), altered

Figure Captions

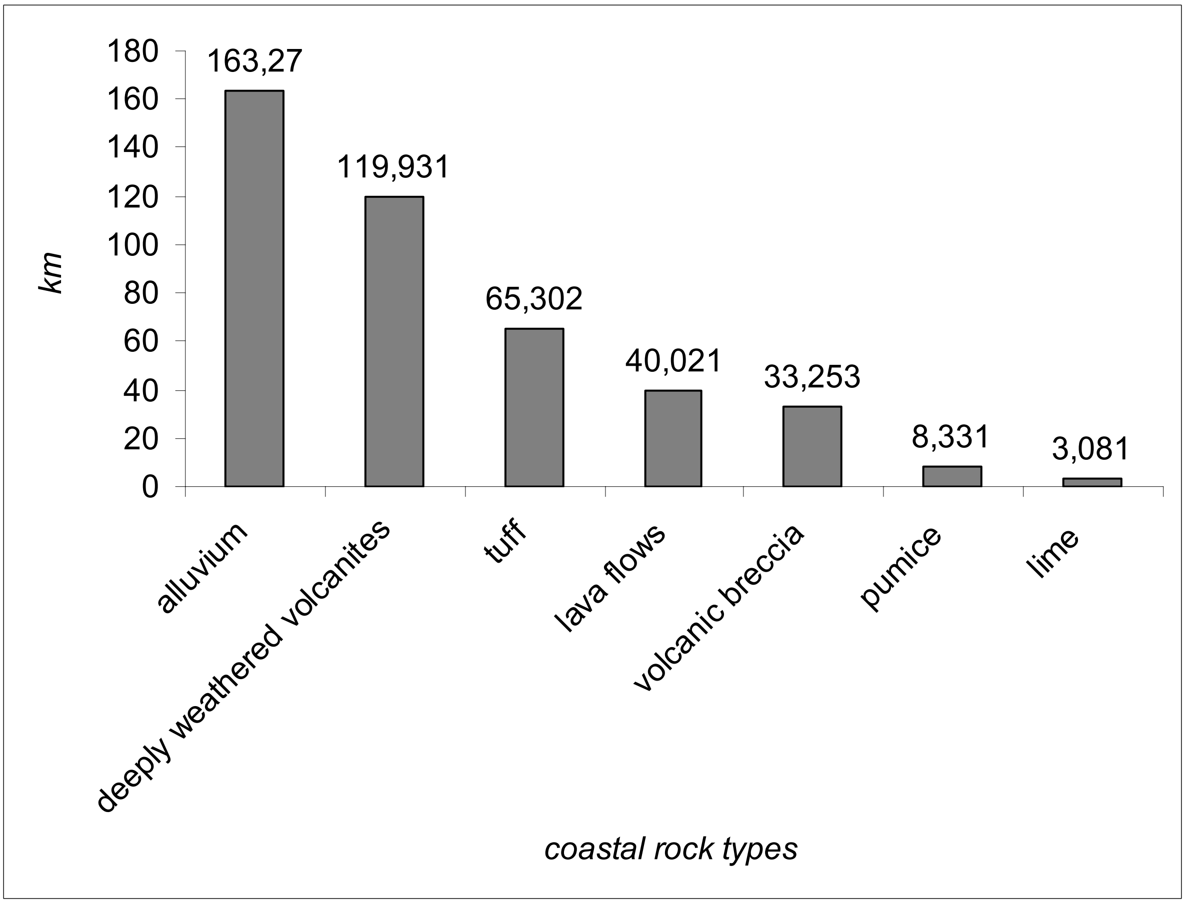
Figure 1: The Caribbean. Source: ESRI Database “The World”
Figure 2: The total length of the Martinique coastal types
Figure 3: The total length of coastal rock types on Martinique
Figure 4: Sensitivity of the Martinique coast to flooding and inundation
Figure 5: Sensitivity of selected categories to flooding and erosion
Figure 6: Total length of each sensitivity index at the Martinique coast
Figure 7: Sensitivity of low areas to flooding and inundation

Figure 8: Communes with reported flooding problems. Data adapted from ASSAUPAMAR (2002)

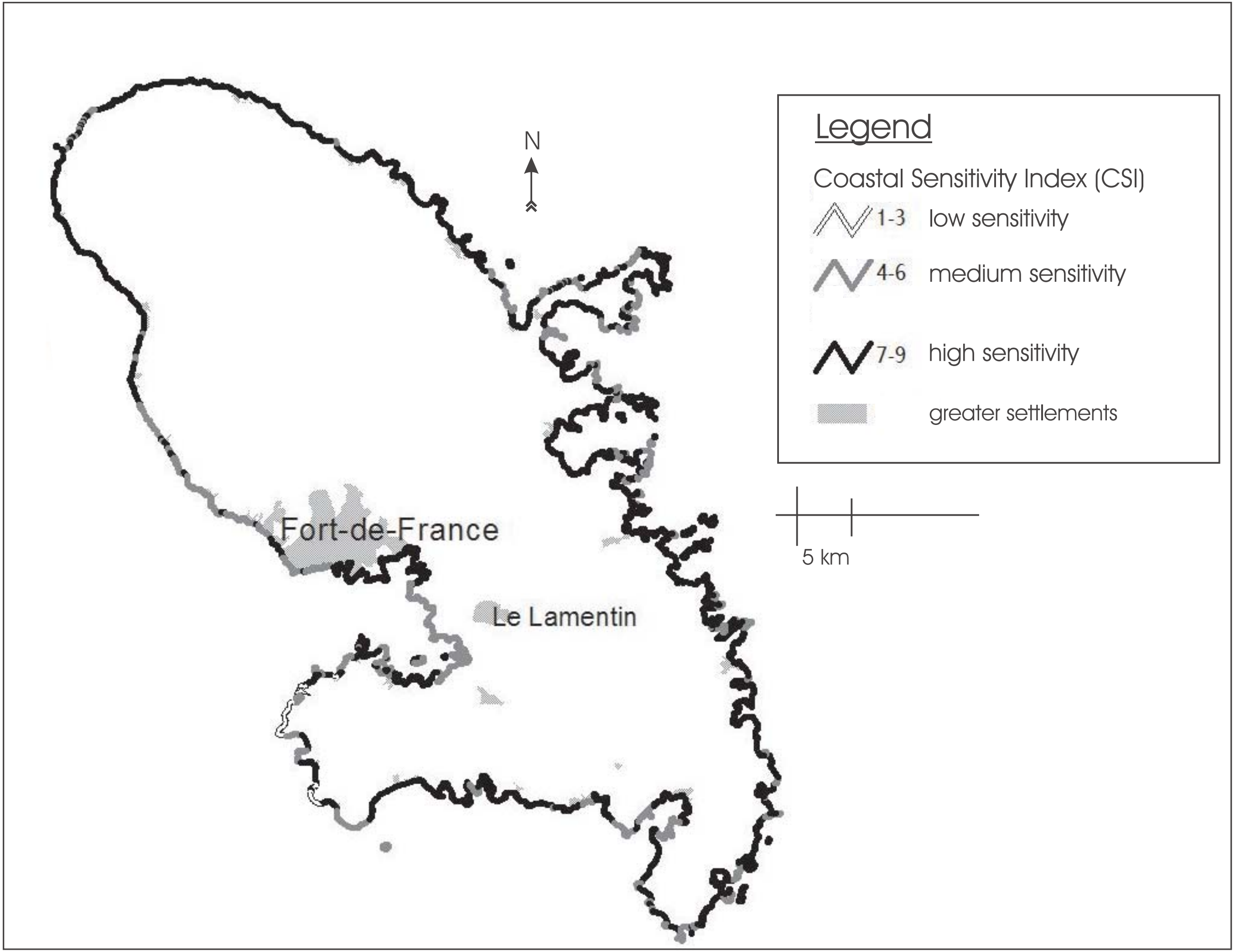

N
United States
Cuba
Dominican Republic
Atlantic Ocean
Haiti
Jamaica
Puerto Rico
Guadeloupe
Caribbean Sea
Honduras
Martinique
Nicaragua
Trinidad
and Tobago
Costa Rica
Colombia
Venezuela
Panama



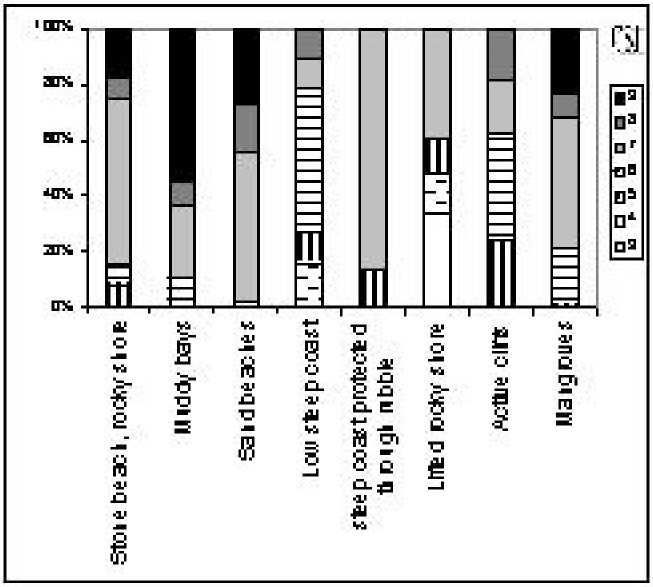
low lying coastal areas
elevated coast
km
200
180
160
140
120
100
80
60
40
20
0
178,002
78,765
56,952
56,811
20,168
19,328
11,86
10,61
Stony Beach, Rocky Shore
Mangroves
Low or rocky Steep Coast
Sand Beaches
Active Cliffs
Lifted Rocky Shore
Steep Coast protected through rubble
Muddy Bays
coastal type



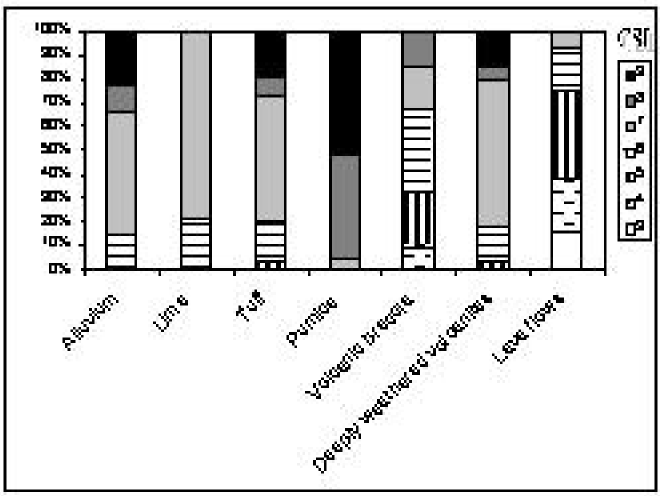
km
180
160
140
120
100
80
60
40
20
0
163,27
119,931
65,302
40,021
33,253
8,331
3,081
alluvium
deeply weathered volcanites
tuff
lava flows
volcanic breccia
pumice
lime
coastal rock types



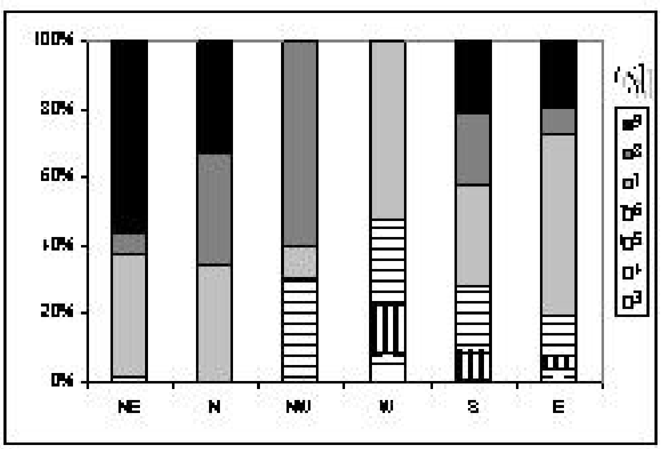
Legend
Coastal Sensitivity Index (CSI)
1-3 low sensitivity
4-6 medium sensitivity
7-9 high sensitivity
greater settlements
N
5 km
Fort-de-France
Le Lamentin



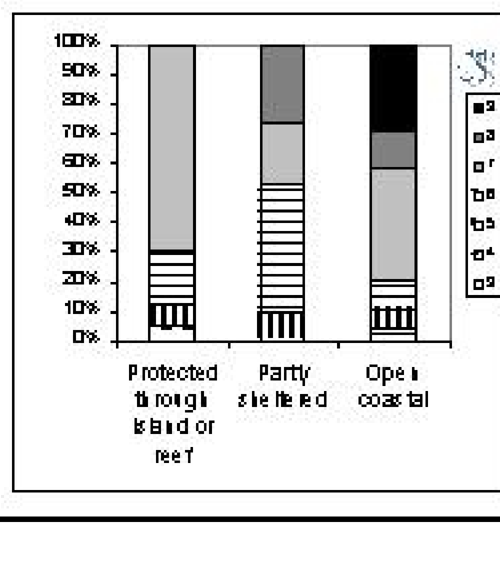
a. Sensitivity of morphologic types to flooding and erosion



b. Sensitivity of coastal geologic types to flooding and erosion

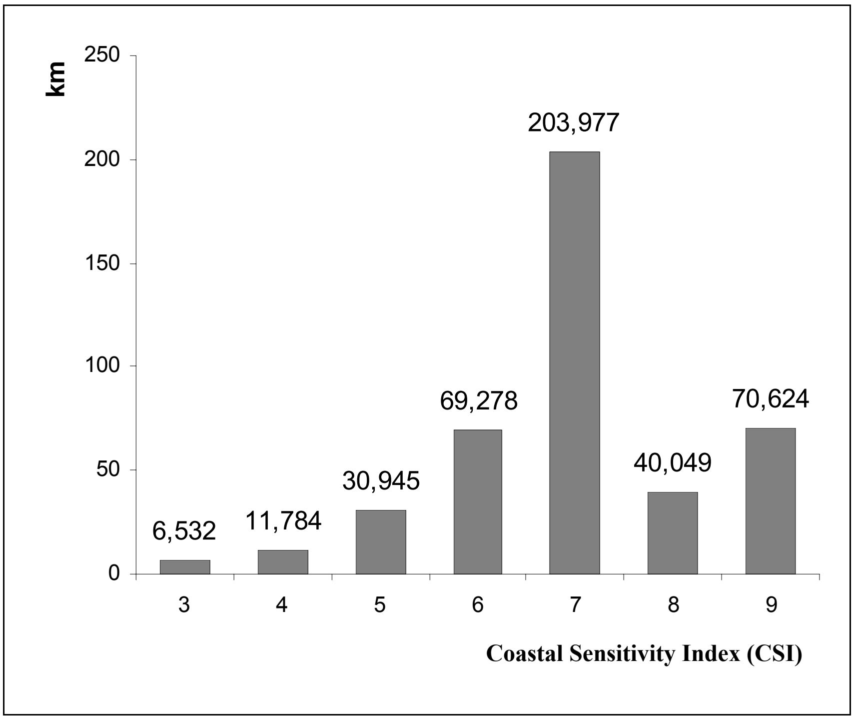


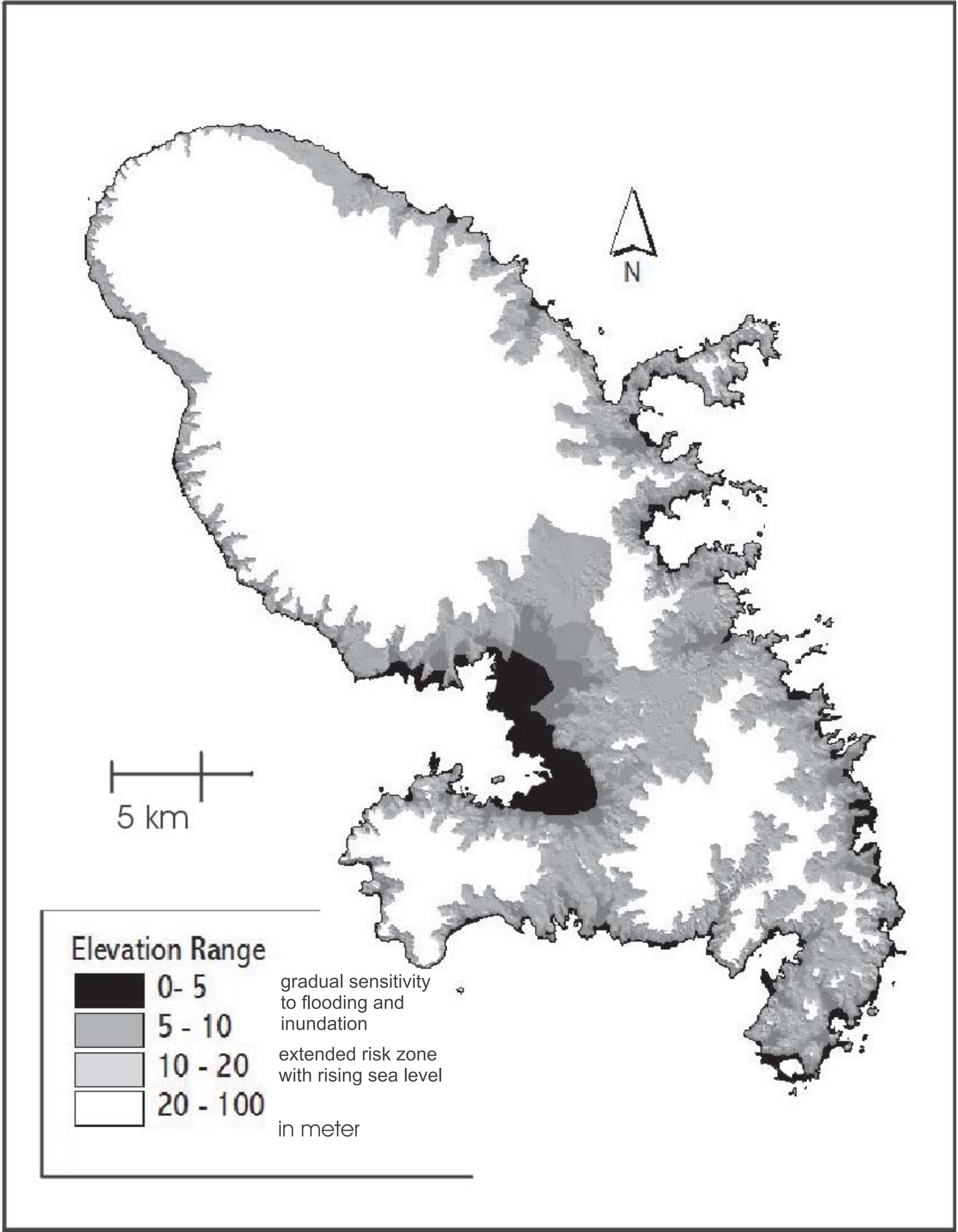
c. Sensitivity of coastal exposition to the wind regime to flooding and erosion

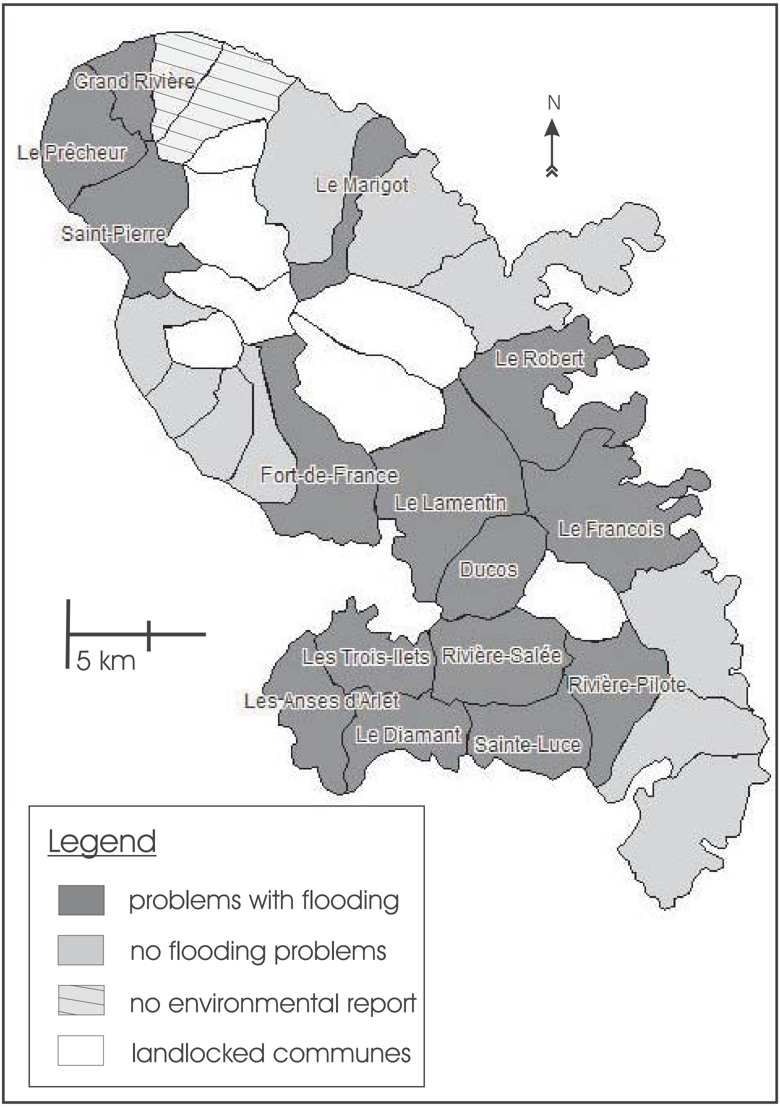


d. Sensitivity of natural protection to flooding and erosion

CSI = Coastal Sensitivity Index


km
250
200
150
100
50
0
203,977
69,278
70,624
40,049
30,945
11,784
6,532
3
4
5
6
7
8
9
Coastal Sensitivity Index (CSI)


N
5 km
Elevation Range
0- 5
5 - 10
10 - 20
20 - 100
gradual sensitivity to flooding and inundation
extended risk zone with rising sea level
in meter



Grand Rivière
Le Prêcheur
Saint-Pierre
Le Marigot
N
Le Robert
Fort-de-France
Le Lamentin
Le Francois
Ducos
5 km
Les Trois-Ilets
Rivière-Salée
Rivière-Pilote
Les Anses d'Arlet
Le Diamant
Sainte-Luce
Legend
problems with flooding
no flooding problems
no environmental report
landlocked communes

Sensitivity to Inundation and Erosion	*1*	*2*	*3*
	Low	**Intermediate**	**High**
1. **Morphology and Elevations**			
a. Relative elevation	High (>20 m, mountainous inland area)	Intermediate (>10 to ≤ 20 m, hilly inland area)	Low (0 to 10m, flat land, lake, wetlands)
b. Coastal morphology	steep coast protected through rubble	active cliffs	sand beaches
	lifted steep coast (>100m)	low steep coast	muddy bays
	lifted rocky shore	stone beach, rocky shore	
		mangroves	
c. $a^2 + b^2 / 2$	1 to 3	4 to 6	7 to 9
2. Erodibility (based on geology)	**Low**	**Intermediate**	**High**
	volcano cones	lime	alluvium
	lava flows	unconsolidated volcanic breccia	deeply weathered volcanites
		heat tuff	pumice
			tuff
3. Exposition to wind regime	leeward	other coast	windward
4. Natural protection	sheltered by bay/island/reef	partly sheltered	open coastal area
5. Sedimentation	**High**	**Intermediate**	**Low**
	shelf area with sedimentation	shelf without sedimentation	shelf without sedimentation