Evaluating the Regional Coastal Impact Potential to Erosion and Inundation Caused by Extreme Weather Events and Tsunamis

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ABSTRACT

Hurricanes as the main drivers of coastal erosion and inundation are frequent in the Caribbean region even under consideration of projected continuation of global warming. A GIS-based model for the island Martinique was developed that evaluates the sensitivity of the coastal areas to erosion, flooding and inundation. This includes the analysis of the potential impact area extension. The results are illustrated in sensitivity and risk area maps for the Martinique coast. They revealed a high impact potential along low lying coastal parts but also along those coastal stripes with erosive rocks. The maps serve as base for further vulnerability studies. The overall aim was to develop an appropriate methodology that is easily applicable and transferable to other coasts.

INTRODUCTION

On average, every two to five years storms greater than Category 3 are passing close to any given island in the Caribbean. Meteo-France (1) 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 2005, Martinique was hit by 53 storms 19 of them categorized as hurricanes with wind speeds of more than 118 km/h. These storms have nearly at anytime caused extensive damage to the human coastal resources. Wave heights of over nine meters are common with erosion and inundation as its consequences. Considering Global Warming projections for the Caribbean region (2; 3) additionally expect an increasing frequency and intensity of hurricanes and tropical storms that coinciding with coastal flooding and high erosion rates at the shores (4).

Earthquakes within the Caribbean region are not rare due to the situation of the subduction zone of the Atlantic under the Caribbean plate. Tsunamis are therefore an omnipresent risk in the region. According to Lander et al. (5), who drew up a Caribbean database of tsunami events, Martinique has been hit by at least five verified waves during the last 250 years.

The coastal zone of Martinique is a very diverse space, partly occupied by settlements, used as famous tourist destination, or covered with valuable ecosystems. Most of the island's settlements are situated along the coast and beach tourism is the main income source. Therefore it is so much more remarkable that no satisfactory local emergency system exists and that the responsible public authorities have only published broad risk maps yet (6). The target of this case study was to evaluate the coastal sensitivity to flooding and erosion and its potential risk areas caused by extreme storm events. One scenario is also going to evaluate the potential impact area during tsunami events.

Recent and historical coastline changes on Martinique

Coastal erosion is a major problem along the northwestern shore of Martinique (7). Within 40 years, on average 25 to 35 m coastline recession has been observed here (8). At Bellevue even more than 70 m of the coast eroded during that time (7) and at Grand-Rivière community marine erosion removed 60 m of land within 50 years (9). The reasons are natural as well as anthropogenic: The coast mostly consists of fragile materials like unconsolidated volcanic rocks or alluvial sediments that are very sensitive to erosion. Even though the rivers transport enough sediment into the sea, the material that arrives on the coast gets directly canalized 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 totaling 200 000 to 350 000 t (7) 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 transport high sediment loads into the sea. From 1955 until 1994 the seaward progression at Marin and Galion Bay amounted to 30 m on average with a range between 15 and 70 m (10; 11). 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. But the sediments originating from land are often polluted with high concentrations of fertilizers 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 (10; 12).

MATERIALS AND METHODS

Through spatial analysis and scenario modeling the coastal sensitivity to flooding and erosion and the potential extension of the impact area caused by extreme storm events and tsunamis are evaluated. Extreme storm events mean in this case tropical storms and hurricanes. The methodology integrates two assessments: first, the sensitivity evaluation of the physical environmental factors of the coast, and second the determination of the risk area. Figure 1 gives an overview of the methodological structure of the GIS-Model.

Sensitivity assessment of the Martinique coast to erosion and inundation

In the following the GIS-based model that has been developed for this study will be described in more detail. First of all a geo-database was created combining the most important factors illustrating the nature of the coast as well as the coastal function. Afterwards the database was translated into a GIS to localize the coastal attributes with a spatial resolution of 10 * 10 m. These data build the base of the empiric GIS-based rating model that localizes those coastal stripes that are especially affected by erosion and inundation during hurricanes. Five parameters were chosen that influence the coastal risk of flooding and erosion during extreme storm events referring to intensive literature studies (see also 13; 14; 15; 16). Below, these five parameters are described in more detail:

Relative elevation. The coastward elevation of the land is important for inundation studies. The low lying coastal parts that are assumed sensitive to flooding are determined through its morphology and topography (17; 18; 19) as Table 1 explains.

Erodibility. Quantitative comparable data about coastal erodibilities for the Martinique rocks don't exist. To evaluate the sensitivity of the coast to erosion the erodibility attribute is therefore based on the geology variable of the database. It is derived from the geologic map of Martinique (20) and based on knowledge about the comprising rock resistance (21; 22). 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 (23). Table 1 lists the erodibility ratings for the Martinique coastal geology that is described in short here. For more information see Grunewald (24). The coastal rocks of Martinique consist mainly of young unconsolidated volcanic material. The Volcano Mt. Pelée influences the northern coastal geology: At the border to the sea at the northeastern coast the main building rock is pumice interrupted by breccias and heat-tuff with a small band of alluvium. This fine unconsolidated material is highly erosive: The heat-tuffs of the 1902 eruption have already been washed out completely (25). Alluvial sediments dominate the bay of Fort-de-France. Along the south-west coast lava flows and tuffs dominate the geology, while in the south and along the east coast breccias and weathered vulcanite are the main rocks to be found along the coast with extensive fluvial sedimentation at river mouths, tuffs, and isolated tertiary volcanic cones in change. Small amounts of tertiary limestone occur only in the outer southeast island.

Mangrove forests foster the accumulation of alluvial and other unconsolidated sediments (26; 27). To prevent an overestimation of the erosion risk at mangrove stands the subcategory “mangrove vegetation” is added to this category “erodibility” as supplementation. If mangrove forest stands can be found on any underground, the erosion risk attribute is reduced by one sensitivity-rating category (for example, from high to medium erodibility). This decision is based on the vegetation map of Portecop (28), satellite data (19), as well as topographical maps (18).

Natural shelter of the coastal segments (Natprotect). 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. Coral reefs have the function of natural breakwaters along the coastline (13; 14). Where coral reefs serve as shelters the marine erosion is therefore less severe, but only under the condition of healthy reefs. The most extensive reef structures can be found along the eastern coast of Martinique, south of St. Marie. Many smaller islands are situated in front of the eastern main island coast as well. Smaller reefs form also a barrier towards the sea at the southern coast with the most extensive reef formations at St. Luce. In the shelter of the cays lay extensive seagrass-beds, and mangrove forests are found on the shore. Some isolated reef structures also occur in the bay of Fort-de-France. But most of the coral formations inside Fort-de-France bay are highly degraded and in a critical state due to pollution (29; 30). The remaining west and north coast are free of reef structures and protecting islands.

Coastal exposition to the wind regimes (Aspect). Cliff retreat rates are generally higher on windward coasts where wind and wave action is more intense (16; 31; 32). The windward parts of the Martinique coast are therefore more sensitive to erosion and inundation. Data on storm tracks of the last 155 years are used from the Caribbean Hurricane Network (33) to evaluate the main storm direction. On Martinique the cyclones track generally runs from east to west or from southeast to northwest. 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 meters and the sea level rises one to four meters (34).

Accumulation (Acc). One may not forget that besides erosion processes also accretion occurs along the Martinique coasts. The coastal system is highly dynamic: While the ordinary swell generally promotes the regeneration of the sandy beaches, the swell during hurricanes erodes them. On Martinique data on beach recovery are lacking, but studies from other Caribbean islands show beach recovery rates of 74 to 99 % in only four to seven months after a hurricane (35). Accumulation is therefore an important factor influencing the coastal shape.

Currents mobilize substantial amounts of sediments. This drift also depends on the wind direction (36). 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. On Martinique the swell as sediment supplier is only of minor importance for the coast. Often offshore loss of sediment takes place especially along the coasts with only small shelf areas. Saffache (37) determined the origin of the main coastal sediments from inland area, transported to the littoral by rivers. Cambers (35) also suggested the shelf width an important factor for beach recovery rates. We added the parameter "accumulation" to the risk evaluation, because the sensitivity of the coast to erosion and inundation gets clearly accentuated through sedimentation processes. For example: if the sedimentation rate is higher than the erosion rate, the sensitivity of the coast is minored by the model. "Accumulation" as a weighted spatial submodel takes the size of the shelf area and currents as well as sediment supply of rivers into consideration. Figure 2 gives an overview of this assessment. As result this category gives information about the relative sediment supply and discharge of each single coastal part.

After defining the parameters three variables were added to each ranging in weighting from 3 ("High"), through 2 ("medium"), to 1 ("Low"). This so called Coastal Sensitivity Index (CSI) was evaluated of the weighted extent to which the attributes are influencing coastal erosion and inundation. Table 1 exemplary lists the risk assignments and its index base for the categories "elevation" and "erodibility" (see also 15; 38; 39). This weighted risk assignment builds the base of the spatial model assessment. Table 3 and 4 give an overview of the spatial rating schemes of the sensitivity model considering erosion and flooding separately. The results are illustrated in a sensitivity map for the coastal zone of Martinique (see Figure 3).

Evaluating the impact area to erosion and inundation

After defining the coastal sensitivity this second part of the study deals with the determination of the risk area (see Figure 1 for an overview). The GIS model used in this assessment uses spatial coastal data combined with historical hurricane impact evaluations. The impact zone of coastal areas to flooding is determined through topographical data at scale of 1:25.000 (18) as spatial base. Out of these an elevation model has been created by using TIN interpolation. This elevation map was subsequently combined with historical data of flooding extension (1; 6; 40; 33). In the same way the topographical data were intersected with data on observed erosion rates (9; 10) to obtain the impact area of coastal erosion processes (41; 42). Results of the coastal sensitivity evaluation model were integrated into both analyses to prevent an overestimation of the impact areas. Concerning the potential sensitivity to flooding varying maximum heights of range have been assigned to the scenarios.

One flooding scenario was developed that deals with the potential impact area assessment of tsunami events. In this case the results of the sensitivity study that consider hurricane impacts play no role because of unpredictable driving force directions. Because of tectonic activity tsunamis are quite frequent in the Caribbean (5; 43). Information about historical tsunami damage in the Caribbean are used to evaluate the extension zone (5; 43). During tsunami events wave heights are higher than during hurricanes, and the endangered area for flooding often extends further inland (5; 43; 44).

RESULTS

Coastal areas at risk to flooding and inundation

The geographical analysis of the rating categories revealed that the coast of Martinique consists of four main coastal types that are defined as sandy bays, muddy bays, rocky shores, and steep coasts. In the north of the island the coastline is steep and smooth, whereas in the southern part it is flatter and disturbed by numerous bays, islands and peninsulas. 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. Respecting only the geology 82.3 % of the coastline has been rated as highly erosive. On Martinique alluvial material is most common (163 km), followed by deeply weathered vulcanite (119 km) and unconsolidated tuffs (65 km). The category "natural protection" on the other hand shows that 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 sensitivity study revealed that only 11 % of the total coastline of 432 km is rated low sensitive to erosion, while the majority is either medium sensitive (48 %) or has a high sensitivity (41 %). In this case the northern coastline between Fort-de-France and the Caravelle peninsular is particularly endangered. This section is signalized through loose, unconsolidated materials. Therefore it is not astonishing that the most sensitive rock types to erosion during hurricanes are the pumice formations in the northern part of the island. But also along the eastern coast occur sections with high erosion risk. These are mainly the coastal parts of peninsulas towering into the sea. The bays in between them present on the other hand only medium erosion risks. The few coastal sections with very low erosion risk are found first in the south-western island close to Les Anses d'Arlet but also along the Atlantic coast, for example at the southern Caravelle peninsular. The accruing rock formations here are marked with low erodibility.

The analysis of flooding sensitivity revealed that more than one fourth (27 %) of the total coastline has a low sensitivity to hurricane flooding. These are, as anticipated, the coastal parts that are characterized by steep coasts with heights over the expected flooding mark.

Nevertheless, nearly as many coastal parts, namely in total 28 % of them, have still a high risk to get flooded during storms. These risk areas can again be found at the northern island between Fort-de-France and La Trinitè as well as along the coasts of the greater peninsulas Caravelle, Les Anses d'Arlet, or Sainte Anne. But especially along the northern coast only very narrow coastal stripes are involved, with arising mountainsides in the hinterland. Altogether, 45 % of the coastline has medium risk of flooding and inundation. Many bays along the southern island and also the Fort-de-France bay have been rated with medium sensitivity. Coral reefs are mostly located in front of the bays, that are reducing the wave pressure or islands and peninsulas protect the coast from the main storm direction. The coastal segments with rated medium sensitivity to flooding own still a small probability to get inundated during hurricanes, but moreover fall into the impact area of more extreme events like tsunamis, for example. This is going to be discussed in more detail in the vulnerability chapter below.

Coupling the sensitivity to erosion and the flooding risk within the GIS-based model we gain following results: 13 % of the total coast of Martinique own low sensitivity, 43 % have medium sensitivity, and 44 % show a high risk of coastal flooding and erosion. The relative distribution of sensitivity in relation to erosion and flooding is represented through the two-digit CSI, while the first number figures the erosion risk from low (1) to high (3) and the second number of the CSI the flooding risk in the same way. The CSI that cover at least one „3" is rated with „high total sensitivity", and those CSI that contain at least one „1" (and no „3") is rated with „low total sensitivity". "Medium sensitive" are those coastal parts with CSI of "22". For example, a CSI of "23" means medium erosion risk (2) but high flooding risk (3) of the selected coastal area. It has been rated as "high" total sensitivity. Analysis shows that the CSI of „22" occupies by far the greatest length followed by CSI of "33". Figure 3 finally illustrates the results of potential erosion and flooding risk in a map.

The spatial model reveals high sensitivity to flooding and erosion where historical and actual erosion have been observed. The map (Figure 3) shows that the coastal parts with low sensitivity rating are well distributed over the whole island but only in small coastal areas. The coastal segments least at risk are attributed with “lifted rocky shore” consisting of hard rock lava flows in leeward exposition along the southwest coast at Anses d’Arlet. Coastal parts with medium sensitivity are only found along the southern island coasts mainly inside the bays and cays whereas the towering coastlines in between have been rated as highly sensitive as are also most of the coastal parts along the northern island.

Analysis of the risk area

For the evaluation of the impact area several scenarios have been developed considering historical data on hurricane and tsunami impacts. Based on historical storm surge heights on Martinique spatial analysis revealed that elevations below 2 m, 5 m, and 10 m show the greatest risk to get flooded depending on the intensity of the storms. Additionally, at the northwestern coast at l’Anse Belleville the erosion rates during hurricanes have been extremely high in the past. Saffache (7) computed retreats from 2.5 to 7 m per cyclone event. Spatial analysis identifies the areas that are likely to be affected by flooding. Figure 4 shows the results in a map. The high impact areas are highlighted in black and dark grey on the map. Elevations above 100 m are not explicitly shown, because they are insignificant for this analysis. Analyses 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. The greatest expansion of the coastal impact areas can be found in the Fort-de-France bay and at the bays of the southwestern island. In contrast, in the northern part of the island that is dominated by the volcano Mt. Pelée merely small, narrow areas show sensitivity to flooding. But this small land adjacent to the beach is often the most valuable for the local communities.

DISCUSSION AND CONCLUSION

The analysis shows that nearly half of the Martinique coast is at risk to flooding and erosion. The most sensitive coastlines are those along the northern coast and also the southern coasts that tower into the sea. The coastlines most at risk to flooding during hurricanes are situated along the northern Island between Fort-de-France and La Trinitè as well as along the coasts of the greater peninsulas Caravelle, Les Anses d'Arlet, or Sainte Anne. The represented risk area map shown gives an overview of the extension of the flood hazard zone. The impact area evaluation considers several flooding scenarios based on historical data. The results are now able to form the boundary for further vulnerability studies that take into account more detailed information on the human dimension.

Concluding, through spatial analysis it was possible to determine which coastal areas of Martinique are highly sensitive to the consequences of extreme storm events and tsunamis. The methodology is easy applicable and can be projected to other islands/coastlines. In addition the information gained from the spatial analyses are useful as base for the regional planners of the Martinique coastal zone for the conduction of more detailed local studies. Information derived from spatial analyses is also useful for everybody interested in determining the present and future vulnerabilities of coastal zones to erosion and inundation if data from hands-on measurements are scarce or not readily available. This includes the evaluation of damage costs caused by hurricane or tsunami flooding. The results obtained from the GIS-based model fill the gap of missing data sources. The interactions of detailed spatial evaluations and economic models promise more accuracy of results and are the main challenge for both sciences.

References and Notes

1. METEO-France 2000. Histoire des Cyclones de la Martinique. http://www.meteo.fr/temps/domtom/antilles/pack-public/cyclone/tout_cyclone/sommaire.htm [last visited 20.4.2007].
2. IPCC (ed.) 2001. *Climate Change 2001. The scientific Basis.* Contribution of Working Group III to the Third Assessment Report of the Intergovernmental Panel on Climate Change (Cambridge, UK: Cambridge University Press).
3. UNEP (ed.) 2000. *Coastal Zone Management.* Caribbean Environmental Programme. http://www.cep.unep.org/issues/czm.html. [last visited 30.8.2006]
4. Maul, G. A., 1993. Implications of the Future Climate on the Ecosystems and Socio-Economic Structure in the Marine and Coastal Regions of the Intra-Americas Sea, in: G. A. Maul (ed.), *Climate Change in the Intra-Americas Sea* (London, Great Britain: Edward Arnold).
5. Lander, J. F., Lowell, S. W. & Lockridge, P. A. 2002. A brief history of tsunamis in the Caribbean Sea,*Science of Tsunami Hazards*, 20 (2), 57-94.
6. Perret, G., Feuillatre, L. & Frayssinet, P. 1996. *Estimations du risque lié aux marées de tempête en Martinique.* Etudes et Développement 1 (Fort-de-France, France: METEO-France, Direction Interrégionale Antilles-Guyane).
7. Saffache, P. 1998. *Le littoral martiniquais: milieux, dynamiques et gestion des risques.* (Schoelcher, Martinique, France: Ph.D. thesis, UAG Geode-Caraibe (EA 929)).
8. Saffache, P. & Desse, M. 1999. L'evolution contrastée du littoral de l'ile de la Martinique. *Mappemonde*, 55 (3), 24-27.
9. Assaupamar, 2002. *État écologique de la Martinique par district*. http://www.assaupamar.mq/dossiers/etatecolo.html. (last visited 20.11.2006).
10. Saffache, P., Blanchart, E., Hartmann, C. & Albrecht, A. 1999. The progression of the outline of the Marin Bay coastline (Martinique): consequences of anthropogenic activity on surrounding watersheds, *Earth and Planetary Sciences*, 328, 739-744.
11. Saffache, P. 2000. Érosion des basins-versants et engraissement côtier: le cas de la baie du Galion (Martinique), *Earth and Planetary Sciences*, 330, 423-428.
12. Pujos, M., Pons, J-C. & Parra, M. 2000. Évolution des métaux lourds dans la sédimentation récente de la baie de Fort-de-France (Martinique). *Oceanologica Acta*, 23 (6), 701-715.
13. Dominguez, L., Antuso, G. & Gracia, F. J. 2005. Vulnerability assessment of a retreating coast in SW Spain, *Environmental Geology*, 47 (8), 1037–1044.
14. Frihy, O. E., El Ganaini, M. A., El Sayed, W. R. & Iskander M. M. 2004. The role of the fringing coral reef in beach protection of Hurghada, Gulf of Suez, Red Sea of Egypt, *Ecological Engineering*, 22 (1), pp. 17-25.
15. Gornitz, V. M., Beaty T. W. & Daniels, R. C. 1997. A Coastal Hazards Data Base For The U.S. West Coast. Oak Ridge, Tennessee: *National Technical Information Service, Environmental Sciences Division Publication No. 4590, Report ORNL/CDIAC-81, NDP-043C*.
16. Stone, G. W. & Oxford, J. D. 2004. Storms and their significance in coastal morpho-sedimentary dynamics, *Marine Geology*, 210, 15.

17. Hinnewinkel, J-C. & Petit, M. 1975. *Géomorphologie*. Planche 5. scale 1:150,000, 1 sheet, in: Lasserre, G. (ed.) *Atlas des Départements Francais d'Outre-Mer. 2. La Martinique*. (Paris: IGN France).

18. IGN (ed.) 1996. *4501 MT, TOP 25: Fort-de-France. Montagne Pelée. Île de la Martinique.* (Paris, France: Institut Geographique National), scale 1:25,000, 1 sheet. *4502 MT, TOP 25: Le Lamentin. Presqu'Île de la Martinique. Île de la Martinique.* (Paris, France: Institut Geographique National) scale 1:25,000, 1 sheet. *4503 MT, TOP 25: Le Marin. Presqu'Île des Trois Îlets. Île de la Martinique.* Paris, France: Institut Geographique National, scale 1:25,000, 1 sheet.

19. Landsat Data

20. Grunewald, H. 1961. *Carte géologique de la Martinique. Notice Explicative*. Paris, France: IGN scale 1 :50,000, 2 sheets.

21. Hooke, R. L. & Rohrer, W. L. 1977. Relative Erodibility of Source-area Rock Types, as determined from second-order variations in alluvial fan size, *Geol. Soc. Am. Bull.* 88, 1177-1182.

22. Annadale, G. W. & Kirsten, H. A. D. 1994. On the Erodibility of Rock and other Earth Materials, *Proc. Hydraulic Engeering ASCE*, Buffalo, New York, 68-72.

23. Annadale, G. W. 1995. Erodibility, *Journal of Hydraulic Research*, 33 (4), 471-494.

24. Grunewald, H. 1965. *Géologie de la Martinique*. (Paris, France).

25. Weyl, R. 1966. *Geologie der Antillen. Beiträge zur Regionalen Geologie der Erde*, (Berlin, Germany: Gebrüder Borntraeger).

26. Augustinus, PGEF 1995. *Geomorphology and sedimentology of mangroves*. In: G. M. E. Perillo (ed.) Geomorphology and sedimentology of Estuaries. Developments in Sedimentology, 53 (Amsterdam Elsv. Science BV).

27. Woodroffe, C. 1992. Mangrove sediments and geomorphology, in: A. Robertson & Alongi, D. M. (eds) *Tropical Mangrove Ecosystems. Coastal and Estuarine studies* 41. (American Geophysical Union, Wash. DC), 7-41.

28. Portecop, J. 1971. Végétation. Planche 9. scale 1:150,000, 1 sheet, in: Lasserre, G. (ed.) *Atlas des Départements Francais d'Outre-Mer. 2. La Martinique* (Paris: IGN France).

29. Paulin, M-H. 2002. Un bilan préoccupant. Les récifs coralliens de la Martinique, *Antiane Èco*, 53, 24.

30. Smith, A. F., Rogers, C. S. & Bouchon, C. 1999. Status of Western Atlantic Coral Reefs in the Lesser Antilles, in: H. A. Lessios & Macintyre, I.G. (eds.) *Proceedings of the 8th International Coral Reef Symposium*, Vol. 1,(Smithsonian Tropical Research Institute, Balboa, Republic of Panama), pp. 351-356.

31. Ferreira, O. 2005. Storm groups versus extreme single storms: predicted erosion and management consequences, *Journal of Coastal Research*, 42, 221-227.

32. Morton, R. A. & Sallenger jr., A. H. 2003. Morphological impacts of extreme storms on sandy beaches and barriers, *Journal of Coastal Research* Vol 19 (3), pp.5560-573.

33. http://stormcarib.com [last visited 20.09.2006]

34. Delbond, V., Richer, Y. & Saffache, P. 2003. *Enjeux et aménagements des littoraux dans les DOM, l'exemple de la Martinique*. Site officiel des géographes de la Martinique. www.martinique-online.com/histgeo [last visited 12.12.2005].

35. Cambers, G. 1996. *Hurricane impact on beaches in the Eastern Caribbean Islands 1989-1995.* http://www.unesco.org/csi/act/cosalc/hur1.htm [last visited 15.01.2007].

36. Kinsman, B. 1965. *Wind waves- their generation and propagation on the ocean surface.* (Prentice-Hall).

37. Saffache, P. 1999. Cultures intensives et prélévements sableux dégradent le littoral martiniquais, *Combat Nature*, 124, 11.

38. Bacon, P. R. 1994. Template for evaluation of impacts of sea level rise on Caribbean coastal wetlands, *Ecological Engineering*, 3, 171-186.

39. CPACC (Caribbean Planning for adaptation to Climate Change) 1999. *Sustainable use of the coastal zone*, http://www.cpacc.org [last visited 12.08.2006].

40. Saffache, P., Marc, J. & Cospar, O. 2002. *Les cyclones en Martinique: Quatre siècles cataclysmiques* (Matoury, Guyane Française: Ibis Rouge).

41. Dietrich, G., Kalle, K., Krauss, W. & Siedler, G. 1975. *Allgemeine Meereskunde.* (Berlin).

42. Walkden, M. J. A. & Hall, J. W. 2005. A predictive model of the erosion and profile development of soft rock shores, *Coastal Engineering*, 52, 535-563.

43. Heck, N. H. 1947. List of seismic sea waves, *Bull. Seismological Soc. Am.*, 37 (34), 269.

43. Zahibo, N. & Pelinovsky, E. N. 2001. Evaluation of tsunami risk in the Lesser Antilles, *Natural Hazards and Earth System Sciences*, 1, 221-231.

44. Rubio, M. 1982. Occurrencia de tsunamis en el Caribe. *Investigationes Sismologicas en Cuba*, Academia de Ciencias de Cuba, Instituto de Geofisika y Astronomia, 2, 170-180.

45. This research was financed by the DINAS-Coast project (2001-2004) (http://www.dinas-coast.net) funded by the European Commission under the Fifth Framework Programme: “Thematic Priority Mitigation and Adaptation to Global Change”. The project’s aim was to model the national, regional and global Vulnerability of Coastal Zones to Climate Change and Sea Level Rise (www.dinas-coast.net). The ESRI-Absolventenprogramm sponsored the Software ArcGIS9.

Illustrations and Tables

Table 1. Risk assignments for the parameter elevation and erodibility

Sensitivity Index	1 (low)	2 (medium)	3 (high)
a. elevation	**high**	**intermediate**	**low lying**
after topography	> 20 m mountainous inland area	>10 to ≥ 20 m hilly inland area	0 - 10m flat land, lakes, wetlands
after morphology	steep coast lifted rocky shore	active cliffs low steep coast	sand and stone beaches rocky shore mangroves muddy bays
b. erodibility	**low**	**intermediate**	**high**
based on geology	volcano cones lava flows	lime unconsolidated volcanic breccia heat tuff	alluvium deeply weathered volcanites pumice tuff

Table 2. Spatial rating scheme for evaluation of the coastal erosion risk

categories	erodibility			protection			accumulation			exposition		
Sensitivity	High	Intermedium	Low	sheltered	partly sheltered	open coastal	high	medium	low	leeward	windward	other coast
High	x	–	–	○	○	○	–	x	◙	○	○	○
	–	x	–	–	–	x	–	–	x	–	x	–
Medium	–	x	–	–	–	x	x	◙	–	○	○	○
	–	x	–	–	x	–	–	–	x	○	○	○
	–	x	–	x	–	–	x	–	–	–	x	◙
	x	–	–	○	○	○	x	–	–	○	○	○
	–	x	–	–	x	–	x	◙	–	–	x	◙
	–	x	–	x	–	–	–	x	◙	○	○	○
	–	x	–	–	–	x	–	–	x	x	–	◙
Low	–	x	–	x	◙	–	x	◙	–	x	–	–
	–	–	x	○	○	○	○	○	○	○	○	○

Legend:
- **x** condition that has to be fulfilled per category
- ◙ "or" = alternative to "x" in same category
- – "and not"
- ○ all included into rating

Table 3. Spatial rating scheme for evaluation of the coastal flooding risk

categories	elevation			protection			exposition		
Sensitivity	High	Intermedium	Low	sheltered	partly sheltered	open coastal	leeward	windward	other coast
High	−	−	X	−	−	X	○	○	○
	−	−	X	X	◙	−	−	X	◙
Medium	−	−	X	X	−	−	−	X	◙
	−	−	X	X	−	−	X	−	−
	−	−	X	−	X	◙	○	○	○
	−	−	X	−	X	−	○	○	○
Low	X	◙	−	○	○	○	○	○	○

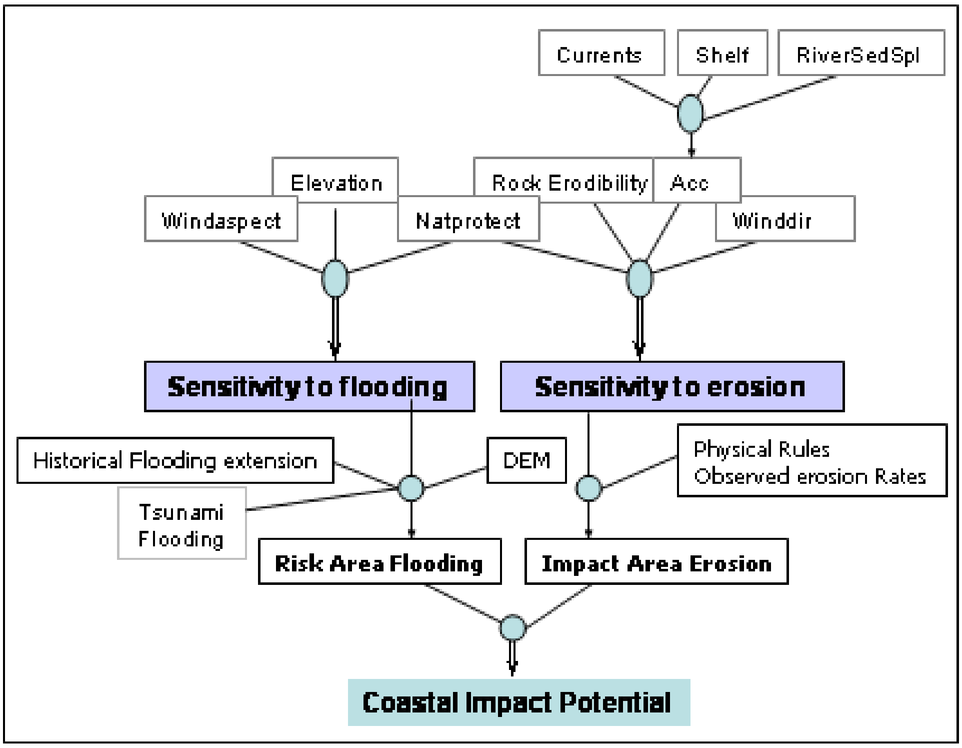

Figure 1. Overview of the methodological structure of the GIS-based Model.

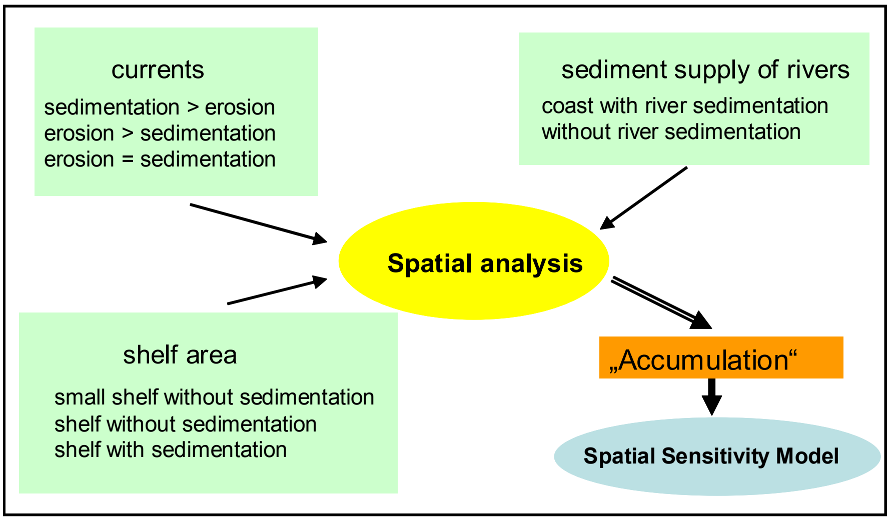

Figure 2. Overview of the "Accumulation"-model of sediment supply along the Martinique coast. The results are a parameter of the sensitivity analysis.

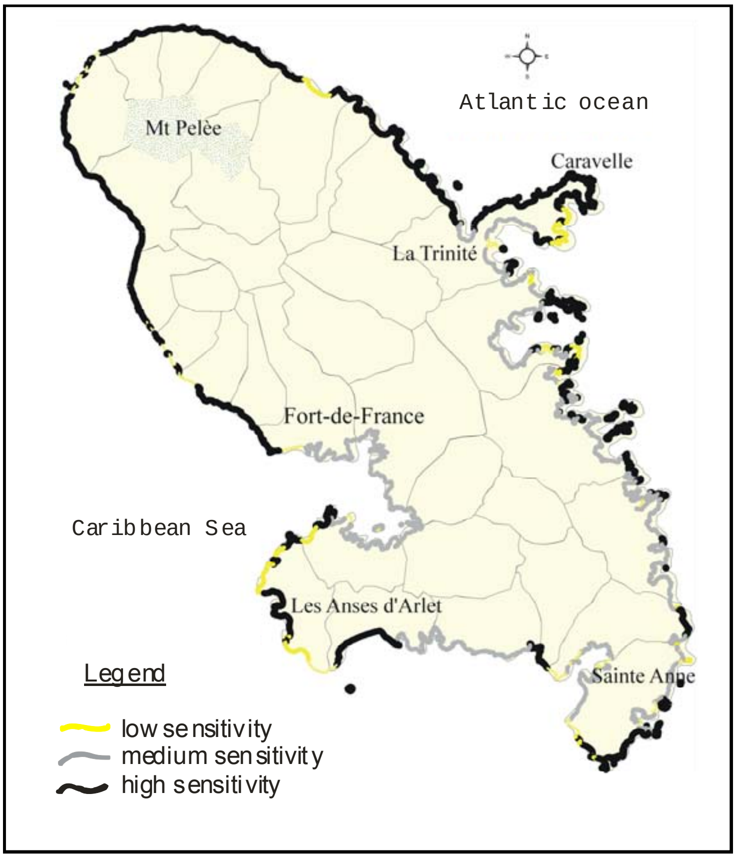

Figure 3. Map of the coastal sensitivity to erosion and flooding on Martinique.

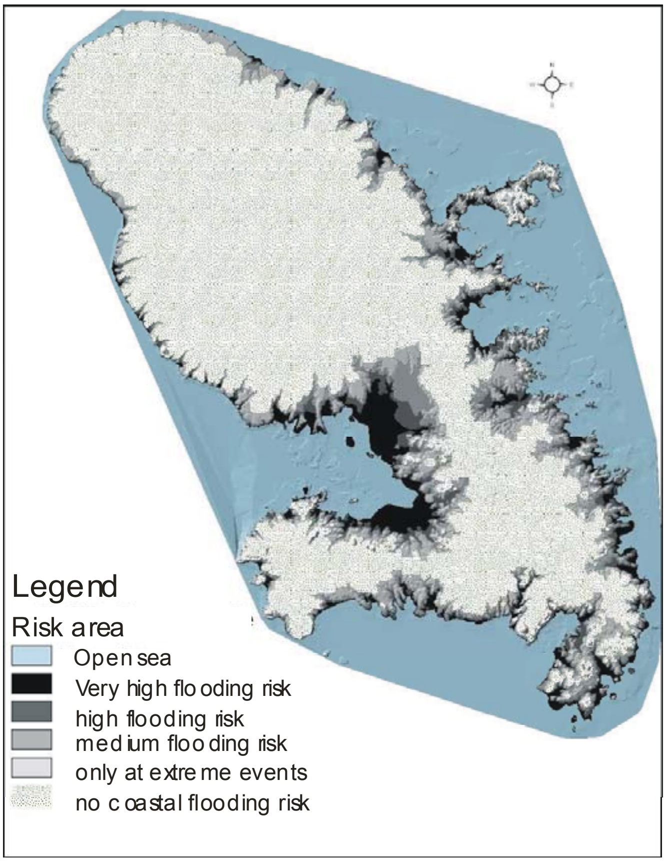

Figure 4. Map of the risk areas to flooding during hurricanes or other extreme coastal flooding events like tsunamis.