Coastal-Zone Hazard Maps and Recommendations: Eastern Puerto Rico

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ABSTRACT

A series of coastal zone hazard maps cover the area impacted by Hurricane Hugo (1989) in eastern Puerto Rico. The mapping strategy was to develop a tool for quick visualization of multiple hazards for use by coastal planners, managers, property owners, and potential property owners. The Puerto Rico shoreline is heavily developed in places and also highly compartmentalized in terms of shoreline types, geology, and adjacent shelf conditions. Hazards such as coastal erosion, storm surge, riverine flooding, landsliding, and seismic impact also may be compartmentalized. From a management perspective, resources therefore can be allocated on a compartment-by-compartment basis.

Six types of hazards were considered in this investigation: (1) shoreline-setting hazards (long-term coastal problems), (2) marine hazards (short-term impacts of coastal storms), (3) earthquake and slope hazards (ground shaking, landslides, and liquefaction), (4) riverine hazards (historical floods), (5) development hazards (high-density development at risk or low-density development in extreme-hazard settings), and (6) engineering hazards (special cases in which shoreline engineering projects such as breakwaters or sand mining have significant detrimental effects on portions of the shoreline). Shoreline segments were ranked as being at extreme, high, moderate, or low risk, depending on the number of hazards present within that segment. These rankings are likely to change, gradually over decades with natural coastal evolution, more rapidly as human development infringes on the coastal zone, or in an instant during a severe storm. The hazard maps provide a basis for hazard mitigation and management recommendations.

Key Words: coastal hazards, hazard maps, hurricanes, Puerto Rico, sea level changes

INTRODUCTION

Puerto Rico is highly developed. With a surface area of only 8896 km^2 (3435 square miles) and a population of over 3.6 million, the population density is $\sim$400 people per km^2. The island's mountainous terrain constrains private and commercial development to sites in or near level coastal areas, on flood plains, in areas of artificial fill, or on unstable hilly terrain. The high population density along with the intense development since the 1950s in the coastal zone has placed both population and property at risk. Development of industrial, commercial, public, and private property took place without knowledge or regard for the geologic hazards that affect the coastal zone. The predictable results are recurring disasters with increasing total property damage losses. Such a disaster occurred with the arrival of Hurricane Hugo in September 1989 and recurred with the passage of Hurricane Georges in October 1998.

Major hurricanes are reminders of their long history of impact on coastal areas and the growing density of property and population at risk within the coastal zone. After Hurricane Hugo, the United States Geological Survey (USGS) began a program to assess the impact of storms on coastal resources and environments and to provide baseline to compare the impact of future storm events (Schwab and Rodríguez, 1992; Delorey et al., 1993; Thieler and Danforth, 1993, 1994a, 1994b; Schwab et al., 1996a, 1996b;). The coastal-zone hazard mapping project presented here was part of that overall USGS effort (Bush et al., 1996a). The goal was to develop a tool to aid in visualizing the multiple hazards found along the shoreline in the hope that future development could avoid areas with the most hazards or that appropriate mitigation plans could be made.

Shoreline erosion, both long term due to sea-level rise and short term due to storms, is only one of many hazards affecting coastal areas. Other hazards include tsunamis, river flooding, earthquake- and rain-induced slope failure, and seismic ground shaking and liquefaction. An integrated assessment of all potential coastal zone hazards is necessary for a complete understanding of the shoreline response to geologic events. This study focuses on the multiplicity of coastal geologic hazards and their identification. Coastal-Zone Hazard Maps were prepared for eastern Puerto Rico depicting coastal geology and geomorphology, beach characteristics, immediate offshore (inner shelf) characteristics, and hazard potential from such events as flooding, marine overwash, erosion, earthquake damage, and landslides. In addition, special con-

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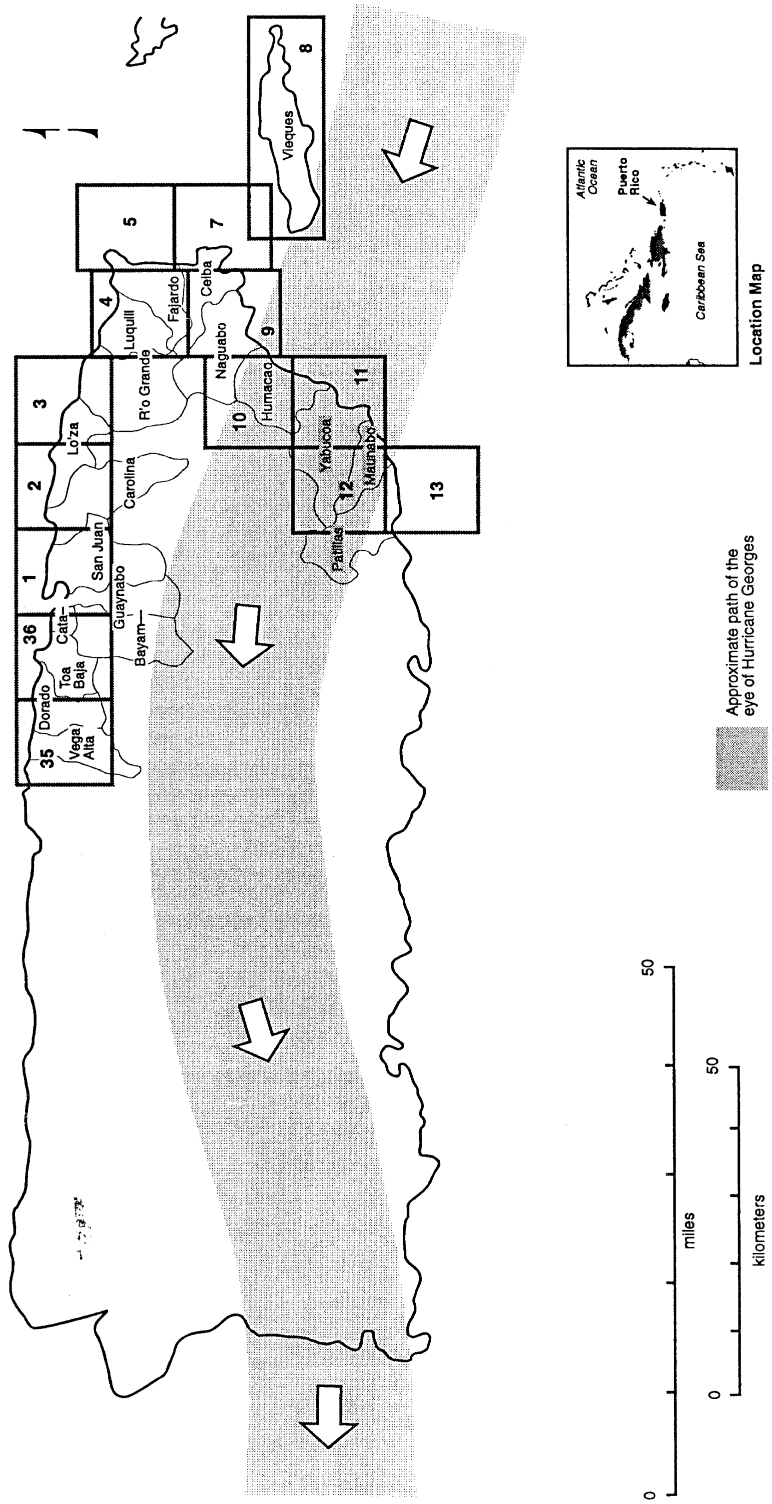


FIGURE 1: Location of USGS Topographic Quadrangle Maps used as bases for Coastal-Zone Hazard Maps. See Table 1 for list of hazard maps and corresponding USGS Topographic Quadrangles.

sideration was given to areas where shoreline engineering or dense development significantly increases the overall vulnerability (potential for property damage) along a given length of the shoreline. A detailed description of Puerto Rico's shoreline with information on the coastal hazards found along each area of the coast, and including an extensive bibliography, can be found in Bush et al. (1995).

METHODS ●

Coastal-Zone Hazard Maps were prepared for the eastern portion of Puerto Rico impacted by Hurricane Hugo using USGS 7.5-min topographic maps as a base. An area of the eastern coast of Puerto Rico encompassing 15 USGS topographic quadrangles was influenced by Hugo (Figure 1). The island of Culebra was not mapped. Owing to the land area covered by some of the quadrangles and the orientation of the shoreline, 12 separate hazard maps were compiled (Table 1). Plates 1–12 are the hazard maps (see also Table 2).

Within each quadrangle, the shoreline was divided into natural geomorphic units which are numbered sequentially (Table 2). These numbered segments represent natural units such as a shoreline downdrift of a particular river-mouth sediment source or pocket beaches between adjacent rocky headlands (coastal cells or coastal compartments). Each Coastal-Zone Hazard Map contains detailed information regarding individual shoreline segments including a schematic representation of the shoreline type. In addition, dominant hazards for each segment are identified in boxes parallel to the shoreline and an overall risk assessment for each segment is assigned as follows:

- E, Extreme, more than four identifiable hazards;
- H, High, three to four identifiable hazards
- M, Moderate, at least two hazards; and
- L, Low, one or no hazard.

Low risk does not imply absolute site safety because a single, potentially devastating, event is always possible. For example, the Puerta de Tierra section of San Juan, built on rock and at a high elevation, is at a relatively low risk from hurricane flooding, erosion, and landsliding. However, hurricane-related wind damage, storm-wave damage from exceptional storms, or a tsunami would be potentially devastating.

Few "safe" sites exist on shorelines, but the likelihood of property loss is expected to be lower in low-risk areas than in high-risk areas. The maps are intended to be as close to site specific as possible. Shoreline characteristics, however, vary over such short distances that the generalized maps can not always show site-specific risk. Individual sites should always be evaluated in the field. Isolated dangerous sites can occur in low-risk zones and vice versa.

Hazard Categories Considered in Risk Classification

The Hazard Maps focus on coastal hazards and relate only generally with in-land hazards. The specific hazards are listed in the boxes parallel to the shoreline being categorized. Specific hazards are outlined below. Hazards S, M, and E (below) are restricted entirely to the coastline. Hazards Q, R, and D pertain to terrestrial hazards, although they may occur very near the coast. The following hazard categories are presented on the Hazard Maps:

- S, Shoreline-Setting Hazards: Shorelines with chronic or severe erosion history, or low elevation. Considers only the natural setting regardless of the type of coastal development (see D). Beach type is included on each map, and mangrove coasts are noted.
- M, Marine Hazards: Coasts exposed to short-term impacts including wave runup and marine overwash, storm surge, and storm-surge ebb from hurricanes and other coastal storms, plus potential tsunami impact.
- Q, Earthquake and Slope Hazards: Areas have active faults, have steep slopes that are prone to slope failure and landslides during earthquakes and heavy rains, or are underlain by unconsolidated material or artificial fill prone to liquefaction during earthquakes.
- R, Riverine Hazards: Coastal floodplains have had historical severe floods or flood potential is high because of upstream dams with potential failure.
- D, Development Hazards: Density varies from high-density development where a great deal of property is at risk to low-density development in high-risk areas because of siting at low elevation or extremely close to the shoreline. Differs from Shoreline-Setting Hazards because it considers alteration of the natural setting of the shoreline by development in such a way as to place people or property at risk.
- E, Engineering Hazards: Shoreline engineering projects often have significant detrimental effects to portions of the shoreline. Examples are the breakwater at Boca de Cangrejos where downdrift beach loss has occurred and the causeway to Isla de Cabras which has altered sediment transport west of San Juan Bay. Removal of natural protection such as dunes and beaches through sand mining is included. Specific coastal engineering structures are shown on the maps.

For shoreline segments where a given hazard applies to only a portion of the shoreline segment or for which there is some special consideration, the hazard is enclosed in parentheses and is counted as one-half a hazard for the Risk Classification.

The hazard maps also show areas protected within the federal Coastal Barrier Resources System and within vari-

TABLE 1. List of coastal hazard maps and USGS Topographic Quadrangle maps comprising them. Culebra was not mapped. Refer to Figure 1 to see how quadrangles were combined into maps listed below.

Hazard Map	Topographic Quadrangle Names
1	San Juan
2	Carolina
3	Río Grande
4/5-W	Fajardo/Cayo Icacos (west; north-facing shoreline)
4/5-E	Fajardo/Cayo Icacos (east; east-facing shoreline)
6	Culebra (not mapped)
7/9	Punta Puerca/Naguabo
8	Vieques
10	Humacao
11	Punta Guayanés
12/13	Punta Tuna/Yabucoa
35	Vega Alta
36	Bayamón

TABLE 2. Shoreline reach hazards and risk ratings, numbered by risk map (see Table 1) and shoreline reach within each risk map.

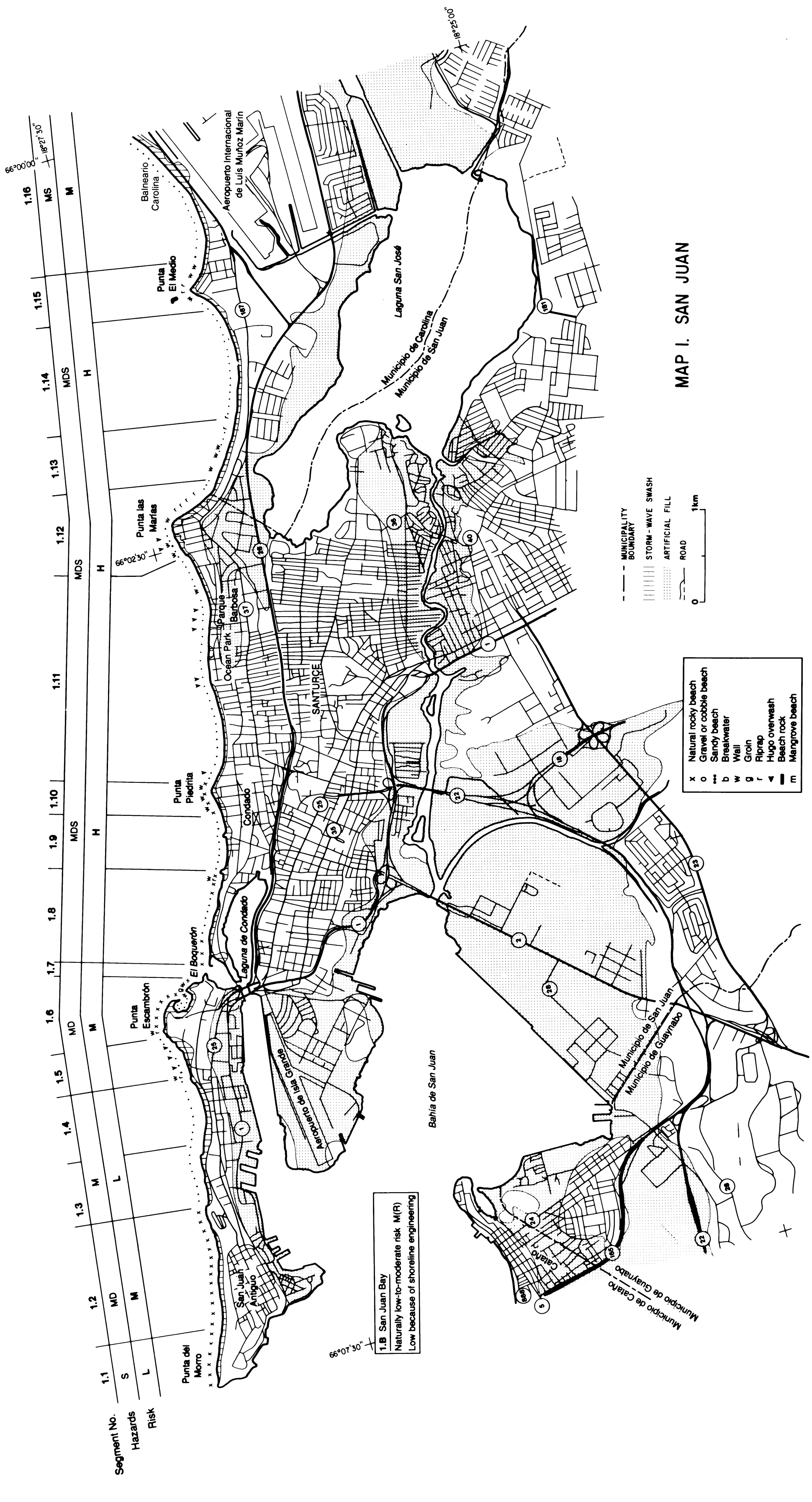
Segment	Hazards[a]	Risk
1.1	S	L
1.2	MD	M
1.3	M	L
1.4	M	L
1.5	MD	M
1.6	MD	M
1.7	MD	M
1.8	MDS	H
1.9	MDS	H
1.10	MDS	H
1.11	MDS	H
1.12	MDS	H
1.13	MDS	H
1.14	MDS	H
1.15	MDS	H
1.16	MS	M
2.1	(S)(M)	L
2.2	(S)(M)(D)E	M
2.3	(S)(M)DE(R)	H
2.4	M(S)(D)	M
2.5	MSD	H
2.6	M(S)(D)	M
2.7	MS(D)E(R)	H
2.8	M(S)(R)	M
2.9	MS(F)D	H
2.10	MS(R)D	H
2.11	(M)(S)	L
2.12	MS(R)	M
2.13	MSR	H
3.1	MSR	H
3.2	MSR	H
3.3	MSD	H
3.4	MSD	H
3.5	MS(D)(R)	H
3.6	MSR	H
3.7	MS(R)(D)(E)	H
3.8	MSR	H
3.9	MSR	H
3.10	MSR	H
3.11	MSR	H
3.12	MSRD	H
3.13	MSRD	H
3.14	MSR	H
4.1	SMD	M
4.2	(S)(M)	L
4.3	SMD	M
4.5	(S)(M)D	M
4.6	(M)(S)	L
4.7	MS(RS)D	H
4.8	RSM	H
4.9	(M)	L
4.10	RSM	H
4.11	(M)	L
4.12	(M)(S)(D)(E)	M
7.1	SM	M
7.2	SMD	H
7.3	SM	M
7.4	SM(D)(R)	H
7.5	SM	M
7.6	SM(D)(R)	H
7.7	SM	M
7.8	SMR	H

Continued

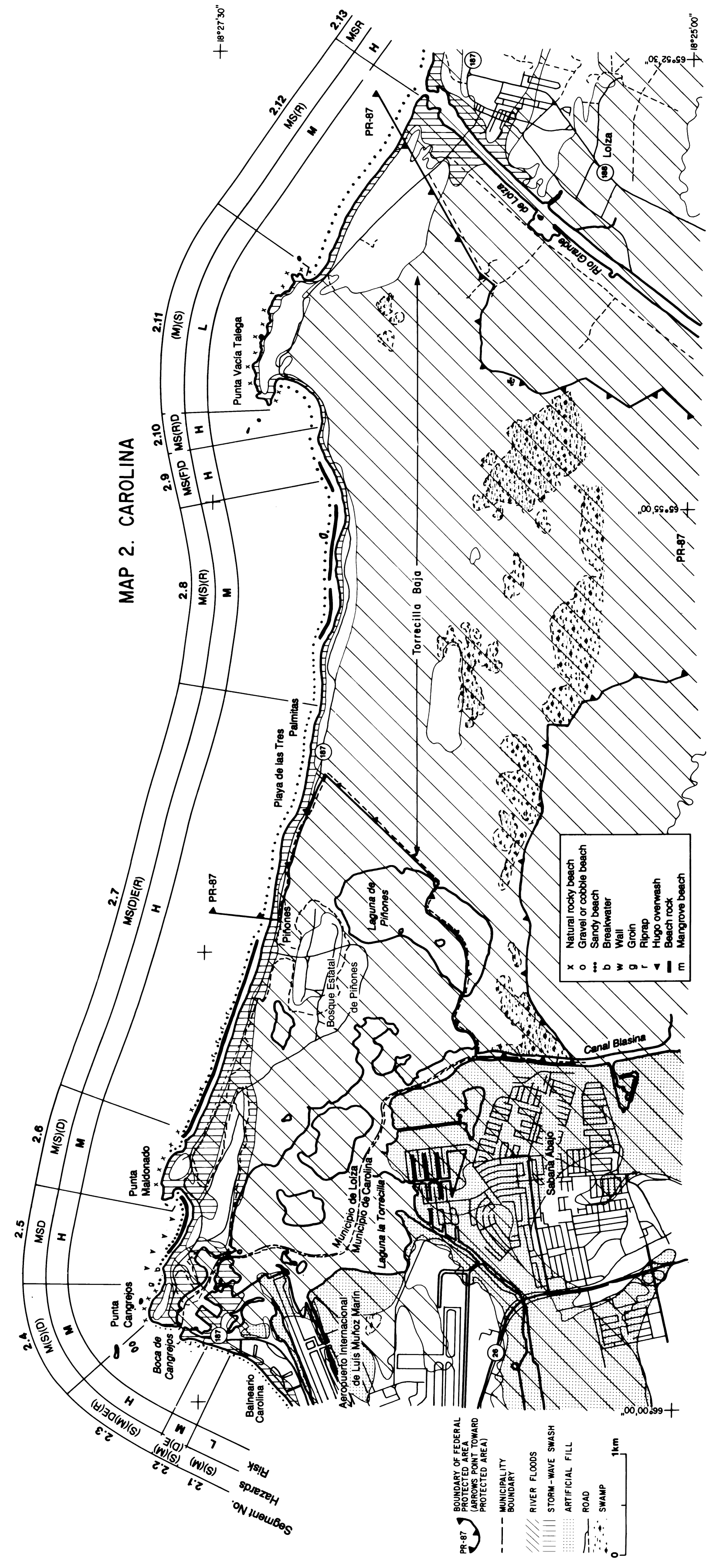
TABLE 2. Continued.

Segment	Hazards[a]	Risk
7.9	SM	M
7.10	SME	H
7.11	SM	M
7.12	SMF(R)	H
7.13	SM	M
7.14	S	L
7.15	SM	M
7.16	S	L
9.1	MSR	H
9.2	(M)(S)	L
9.3	(M)(S)	L
9.4	MSR(D)	H
9.5	MSRD	H
10.1	(M)(S)(D)R	M
10.2	MSR	H
11.1	MSR	H
11.2		L
11.3	MS	M
11.4	MSR	H
11.5	(S)(M)D(E)	M
11.6		L
11.7	(M)(S)D	M
11.8	F(S)(D)	M
11.9		L
11.10	SD	M
11.11		L
11.12	(S)M(D)	M
11.13		L
11.14	(S)M(D)	M
13.1	MS	M
13.2	S	L
13.3	M(S)(R)	M
13.4	MR	M
13.5	S	L
13.6	SMD(E)	H
13.7	SM(R)	H
13.8	SM(D)	H
35.1	(R)MS	H
35.2	SMD	H
35.3	M	L
35.4	SMD	H
35.5	SMD	H
35.6	MS(D)(R)	H
35.7	(M)(R)	L
35.8	MSR	H
36.1	M(D)S	M
36.2	M(D)S	M
36.3	M	L
36.4	MS	M
36.5	M	L
36.6	EM	M
36.7	EMSDR	E
36.8	EMSDR	E
36.9	EMSDR	E
36.10	EMSDR	E
36.11	M	L
San Juan Bay	(D)(E)M	M

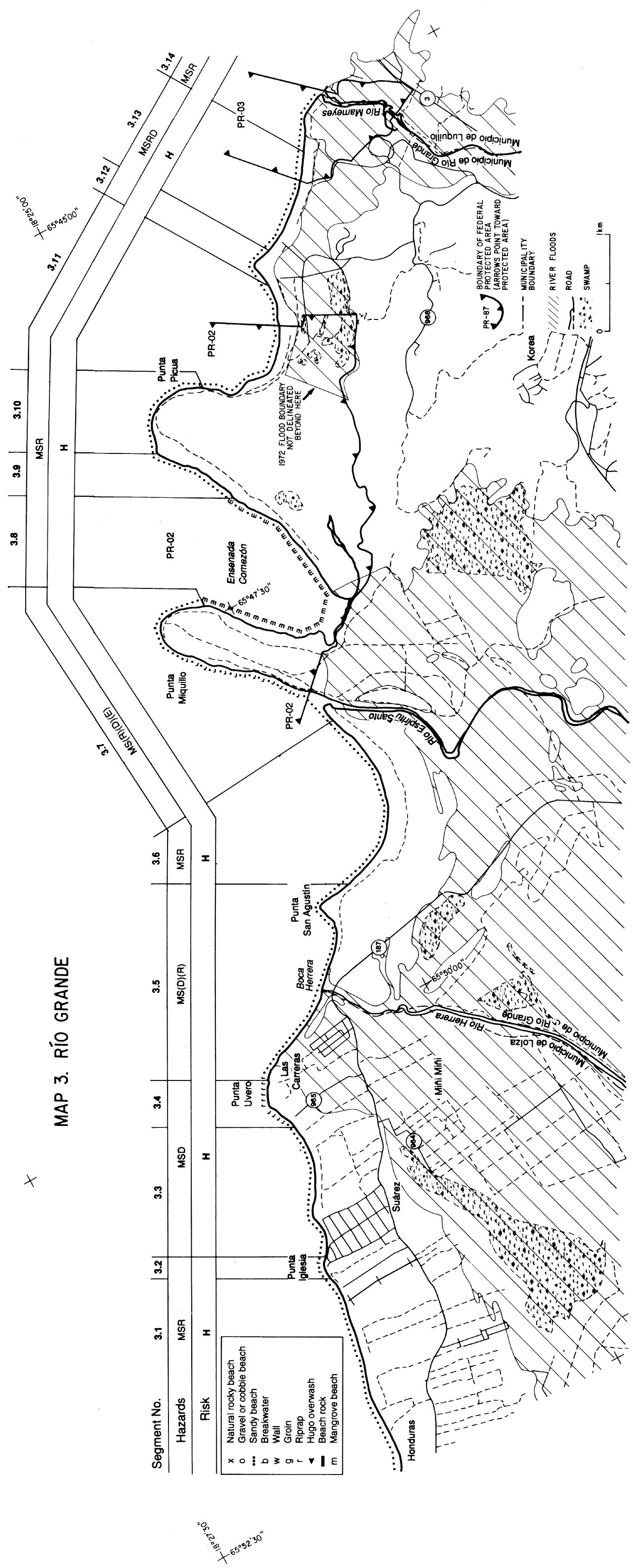
[a]The hazards are abbreviated as follows in the table (see text for discussion of each hazard): S, shoreline-setting hazards; M, marine hazards; Q, earthquake and slope hazards; R, riverine hazards; D, development hazards; and E, engineering hazards.



Map 1. San Juan.



Map 2. Carolina.

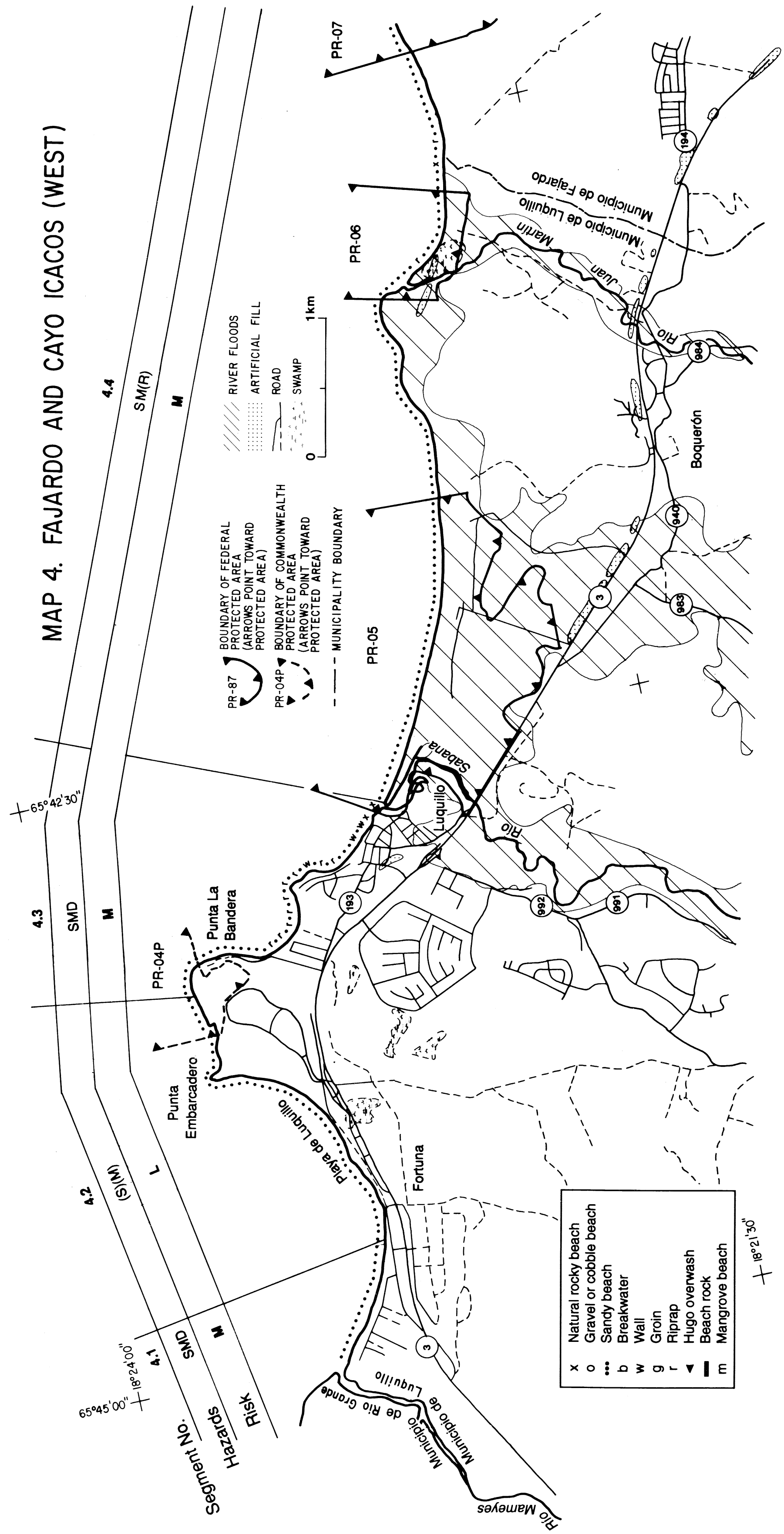


Map 3. Río Grande.

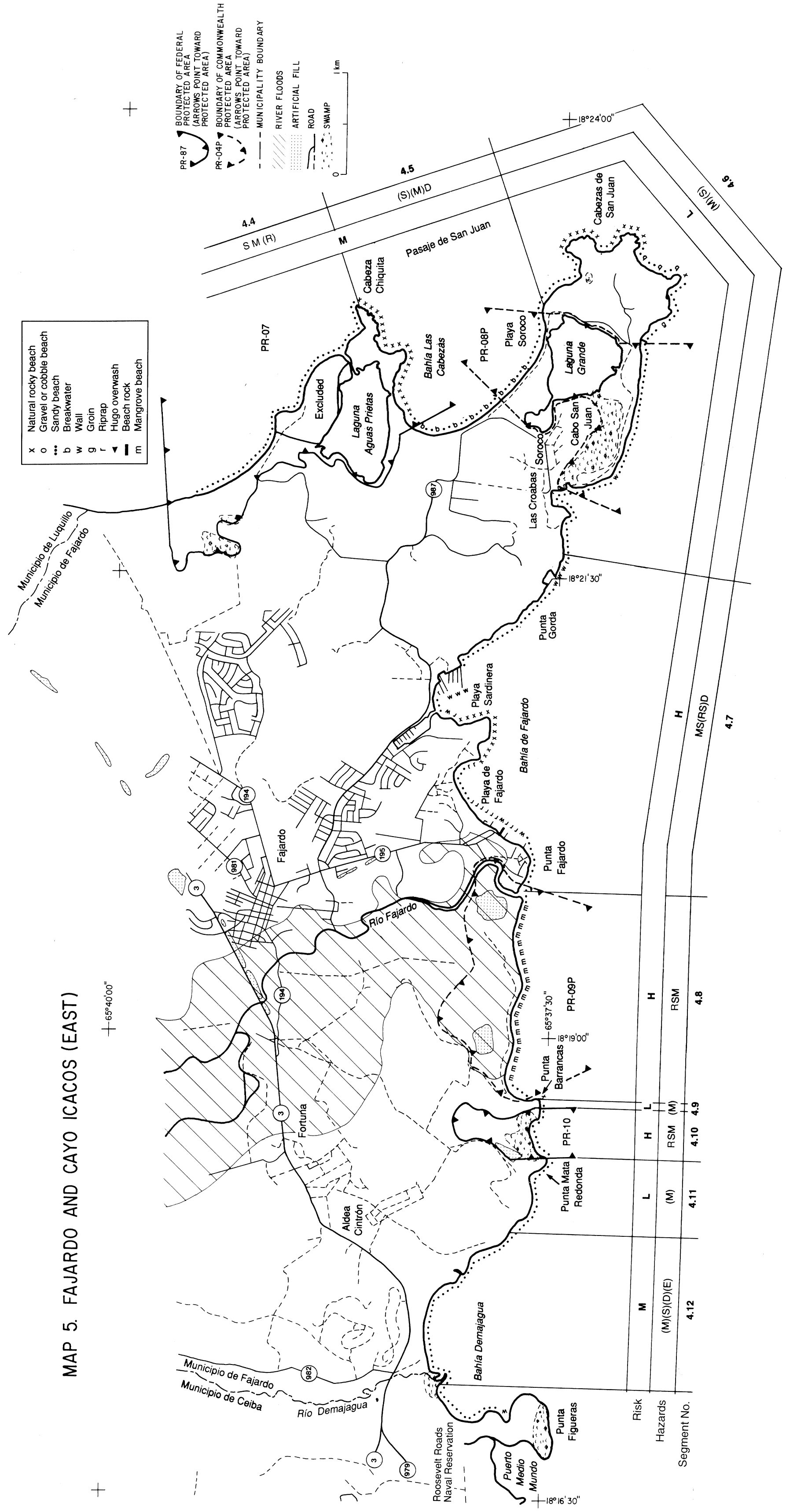
ous Commonwealth Protected Units as delineated in U.S. Department of the Interior (1988). Units are outlined on the maps and labeled with the prefix “PR-” and a corresponding unit number. Commonwealth Protected Units additionally contain the letter “P” after their identifying unit number. Marshes are indicated, but mangrove areas are not shown on the maps. Both areas represent protected environments, and extensive mangrove areas are included in the designated Coastal Barrier Resources System management units. Shoreline types also are indicated on the maps, and “mangrove beaches” are considered to be high-risk zones.

The factors considered in the complete hazard description or assessment of each shoreline segment are:

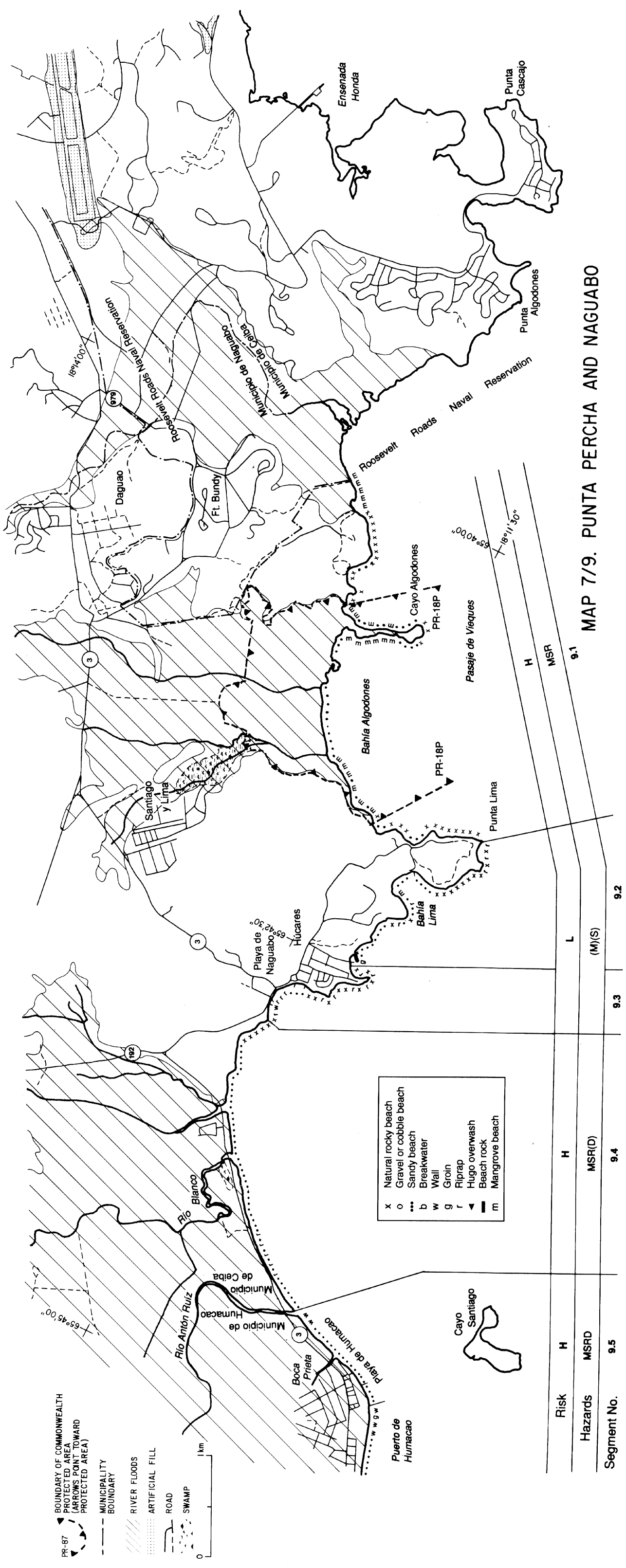
1. General shoreline information that includes shoreline orientation and shoreline type such as consolidated rocks (eolianite, Tertiary limestone, metamorphic rocks, and igneous rocks) or unconsolidated sediments (alluvial fans, eolian dunes, and beach). If the shoreline is armored, the type of engineering structure is identified as a revetment, seawall, groin, or breakwater. Wetlands are divided into mangrove swamps, freshwater swamps, brackish lagoons, and freshwater lagoons. Rivers, streams, and other inlets are identified as well as discharge information, if known, and the presence or absence of barrier spits. These characteristics determine shoreline resistance to erosion, rate of erosion, and potential for flooding and, in the case of some engineering structures, provide evidence of past erosion events and serve as predictors of potential future property loss.
2. Beaches provide a natural buffer against wave erosion and storm surge. Beach information includes beach texture (sand, gravel), composition (mostly carbonate, siliciclastic, or mixed), whether the beach is a pocket beach, the presence of beachrock or abundant heavy-mineral concentrations, beach width, natural rocky beaches, seawalls and other engineered rocky beaches, and critical erosion areas.
3. Offshore areas focus on the sediment grain size, sediment composition, shelf slope, shelf width, and the presence of offshore barriers and reefs. These characteristics are indicative of the potential wave energy reaching the coast or how storm surge will behave (e.g., narrow shelf allows greater wave energy, whereas wide shelf may dissipate wave energy but increases magnitude of storm surge). Offshore barriers and reefs tend to reduce the impact of these hazards.
4. In areas prone to coastal flooding where previous information is available, the storm-wave swash penetration area is shown on the maps (limited to north-facing coastline only). Predictions of flood-zone water levels and inland penetration from Flood Insurance Rate Maps available from the Federal Emergency Management Agency are also considered. These Flood Insurance Rate Maps are derived from model studies; therefore, these quantitative predictions are only as good as the models upon which they are based. Such predic-



Map 4. Fajardo and Cayo Icacos (west).



Map 5. Fajardo and Cayo Icacos (east).



Map 7/9. Punta Puerca and Naguabo.

tions usually are for specified expected conditions (e.g., a 100-year storm event). Locations of significant overwash sand due to storm surge and storm waves attributed to Hurricane Hugo are shown on the maps.

5. Shoreline erosion history is from the average erosion rate data of Thieler and Danforth (1993) derived from the air-photo interpretation techniques developed by Thieler and Danforth (1994a, 1994b), and is used to determine historical shoreline change. Calculated erosion rates are a good indicator of the erosion hazard. However, such rates change with time and conditions (e.g., sea-level rise may accelerate erosion, or a neighboring seawall or groin may cut off the sediment supply to a beach causing the erosion rate to accelerate).
6. General quadrangle descriptions include the coastal plain width, range of elevations, landslides that have been mapped on geologic maps or observed, and areas of artificial fill. These characteristics are particularly important in identifying flood potential, areas of likely slope failure, or where soil liquefaction hazards are likely.

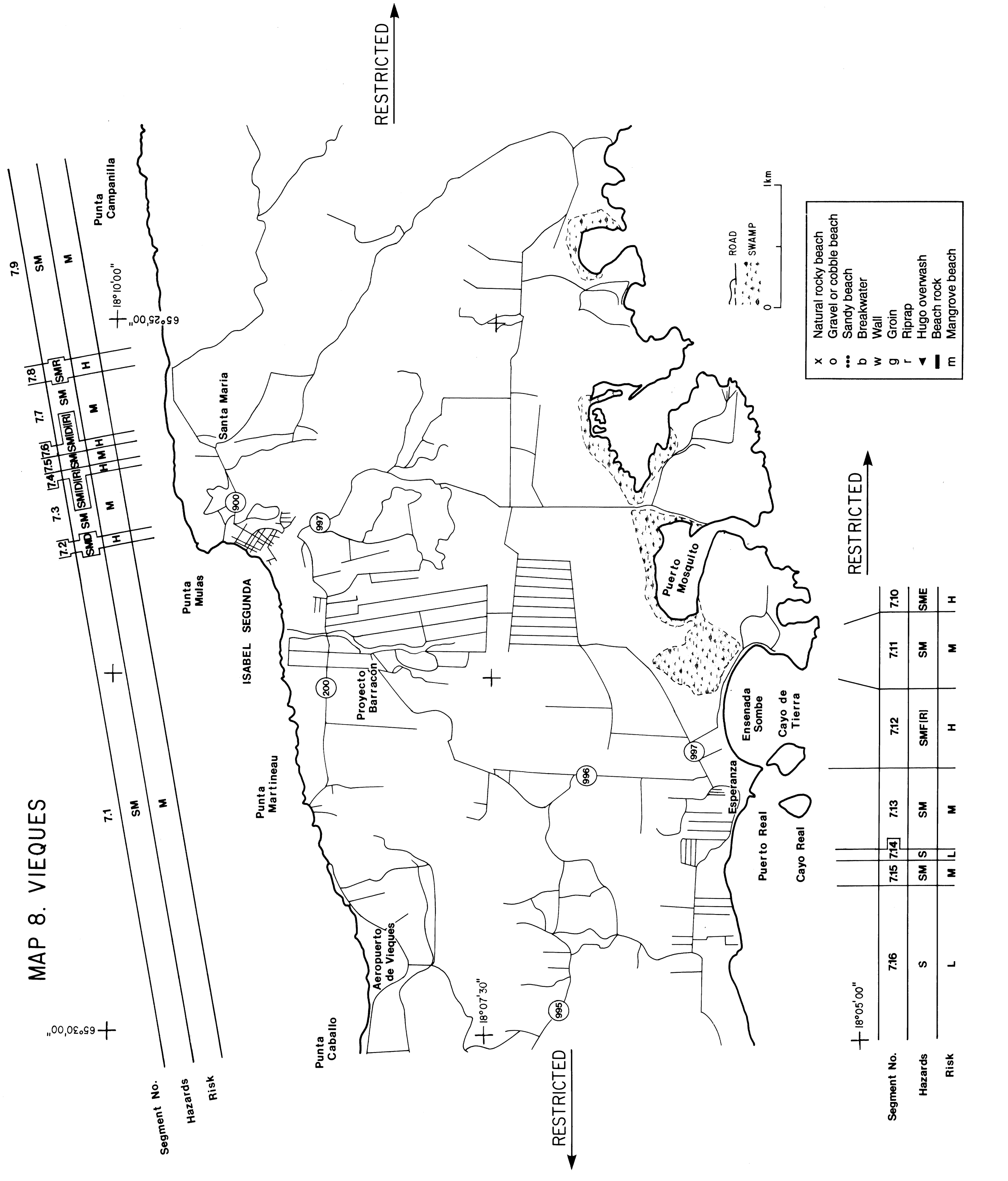
MULTIPLE COASTAL HAZARDS

Although risk assessment is based on recognition of specific natural processes and the resultant hazards, such processes do not always operate independently. Furthermore, any given hazard may be induced by more than one process. For example, hurricanes or tropical storms are accompanied by several processes that are classified as natural hazards. Among them are wind, waves, rising water (storm surge), and rain. These processes may have secondary effects. Excessive rainfall may cause landslides or river flooding or lead to dam failure all results of the hurricane's rainfall and all serious natural hazards. Landslides can be rainfall induced, but they can also be induced by earthquakes (Seed, 1968). Human activities may alter natural processes, magnifying or creating new hazards (e.g., dam failure may cause flooding, or the dam may block sediment flow to the coast increasing the rate of local beach erosion). Each of the several natural hazards evaluated on these maps are briefly discussed below.

Shoreline Erosion

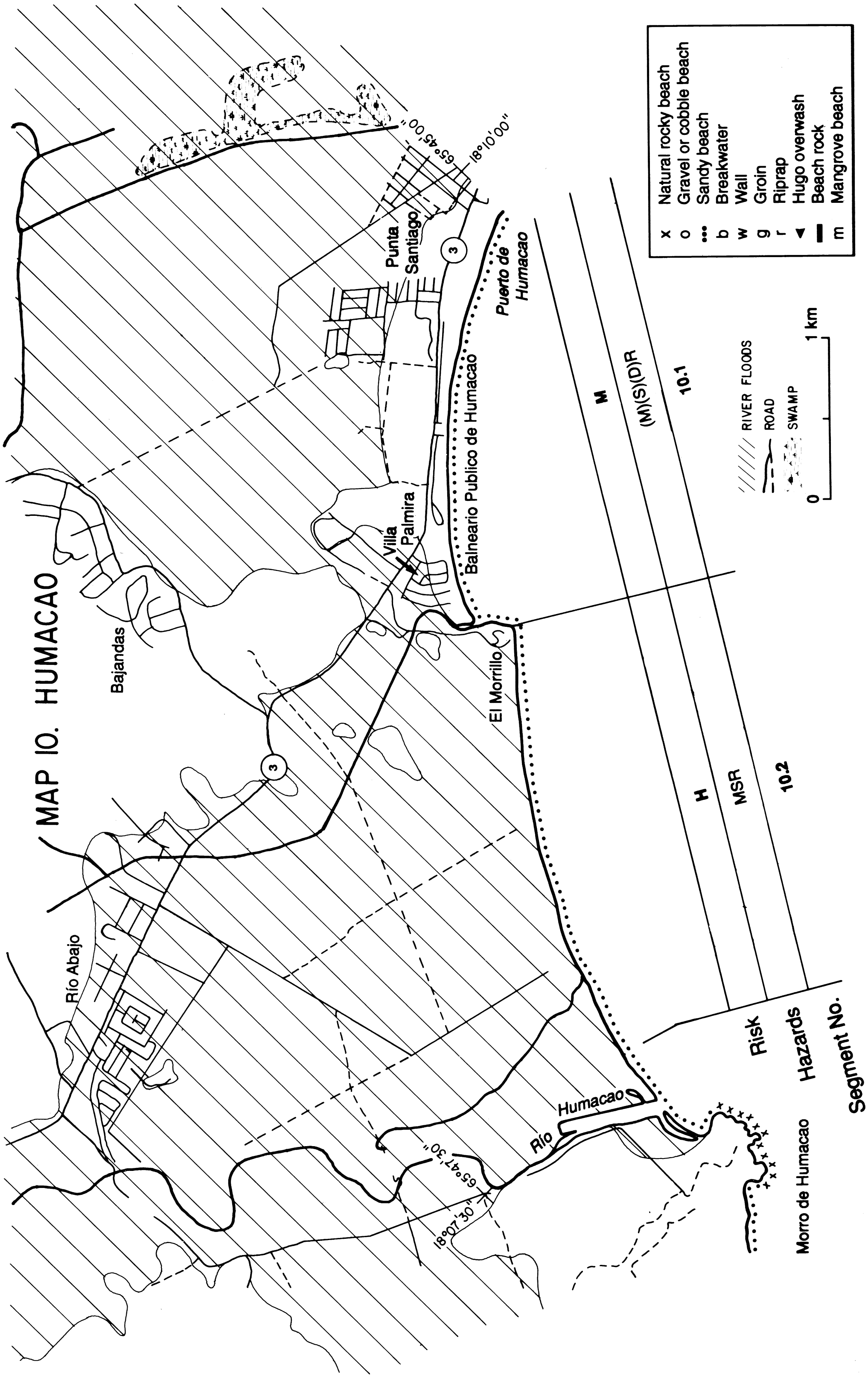
As along much of the world's coasts, Puerto Rico's shoreline is feeling the effects of severe and persistent erosion. All available information (e.g., studies of air photos, beach surveys, and comparisons of old and new charts and maps) points to this conclusion. Local variations in beach type, configuration, and composition influence the amount of erosion. Erosion is far more critical along unconsolidated shorelines than on rocky stretches. Not all coasts are eroding, beach accretion does occur locally, but overall, the beaches are moving landward and the shoreline is retreating.

There are several causes for the erosion: (1) Impacts from extreme events such as hurricanes and large ocean swell from north Atlantic winter storms. Sandy shorelines respond to increases in the nearshore current and wave regime by transferring sediment from the subaerial beach to the



Map 8. Vieques

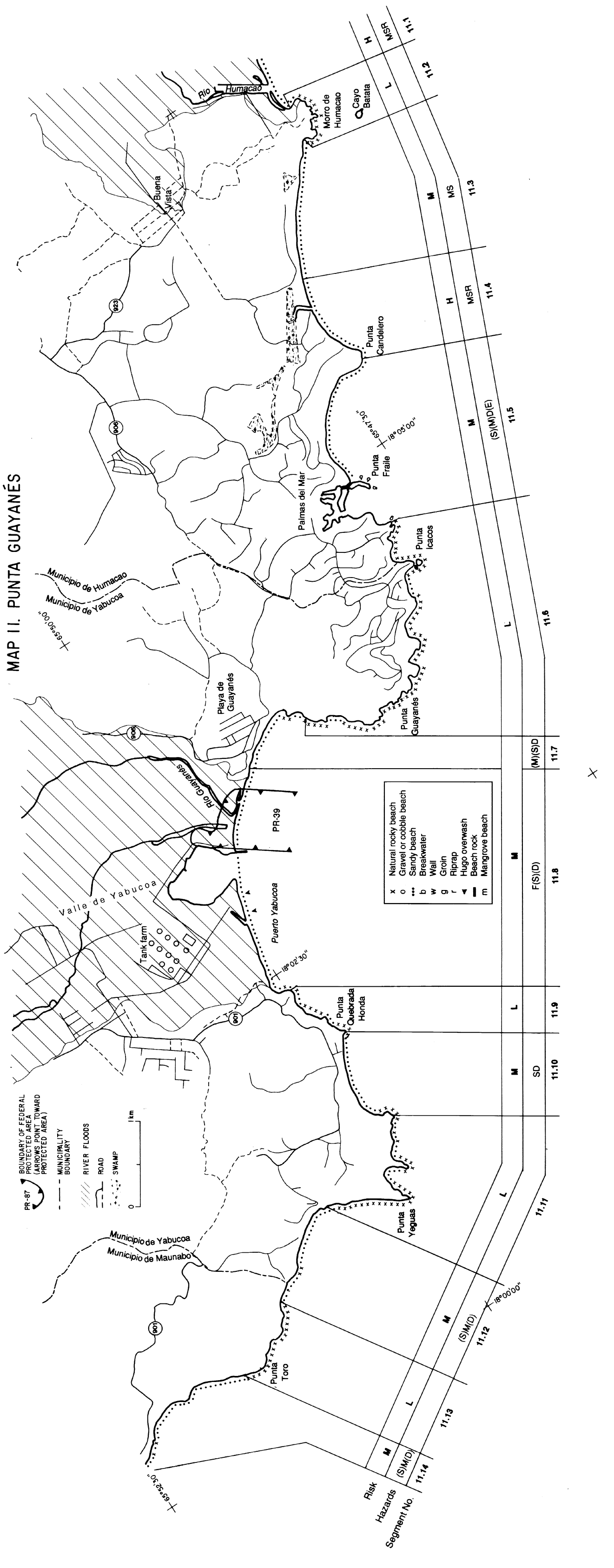
nearshore in an effort to dissipate wave energy. (2) Changes or variations in the supply of sediment to the beach. Long-term erosion is often the result of reduced sediment supply. (3) Sea-level rise contributes to coastal erosion and results in beach narrowing in front of seawalls and buildings. Sea-level rise may be part of a global trend (Intergovernmental Panel on Climate Change, 1996) or more local in occurrence. Ground subsidence on either a regional scale (e.g., tectonic influence) or a local scale (e.g., ground water withdrawal). (4) Poorly designed engineering structures that interfere with the natural movement of beach sand are probably responsible for much of the sand loss. Other human-



Map 10. Humacao.

induced factors include mining of sand from beach and dune areas and the changes to the nearshore hydraulic regime through activities such as dredging, harbor construction, jetties, and breakwaters.

The Draft Environmental Impact Statement for the Coastal Management Program for the Commonwealth of Puerto Rico (National Oceanic and Atmospheric Administration/Puerto Rico Department of Natural Resources, 1978) includes a



Map 11. Punta Guayanés.

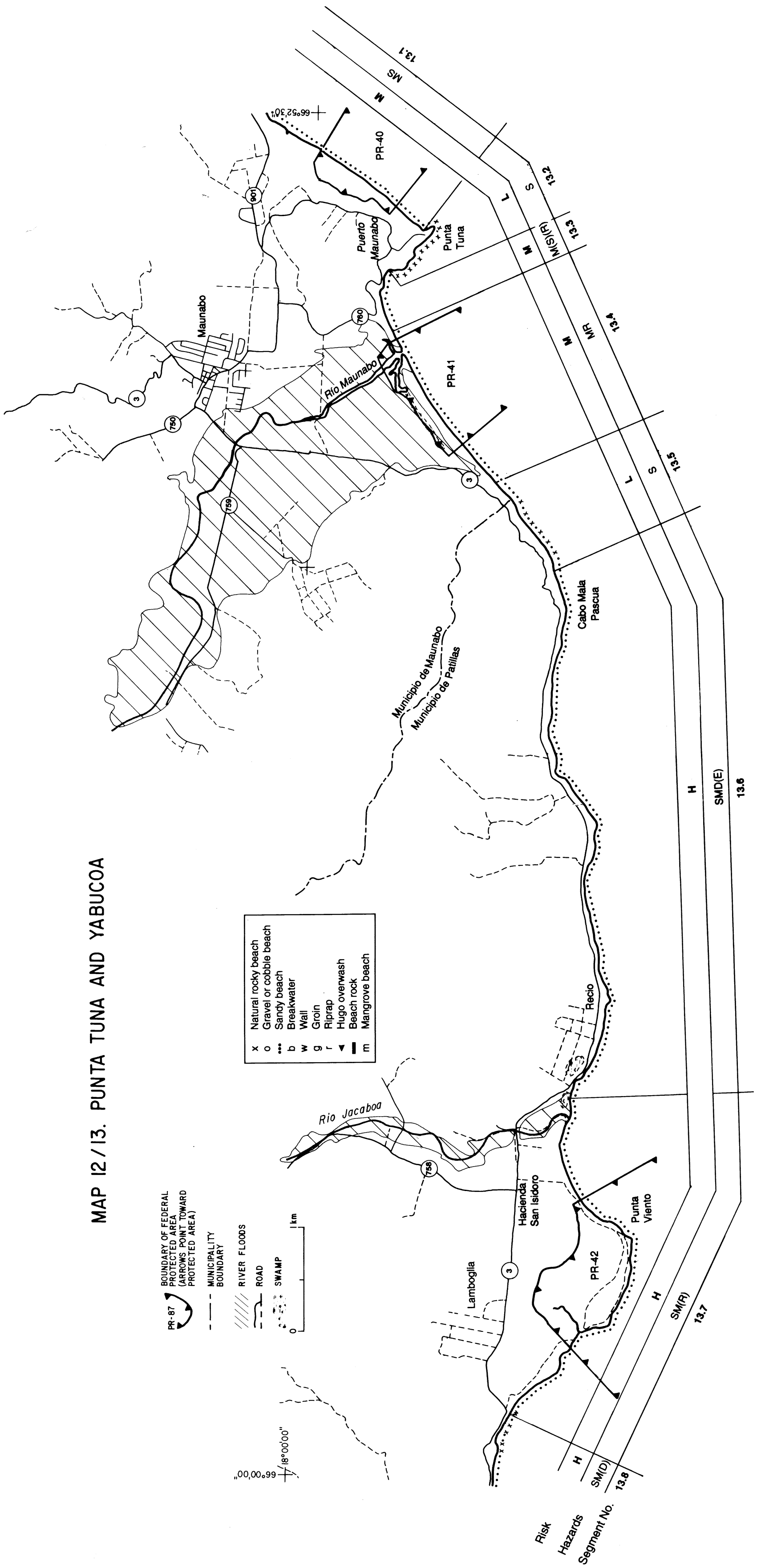
good summary of the coastal erosion problems on the island. The report notes that erosion is caused by both natural processes and human activities and admits that little can be done in the long run to offset the natural causes of erosion. Other studies of erosion include Morelock (1984), Morelock et al. (1985), Morelock, and Taggart (1988), Thieler and Danforth (1993), and Thieler and Danforth (1994b). General shoreline information can be found in Bush et al. (1995).

Hurricanes and Other Storms

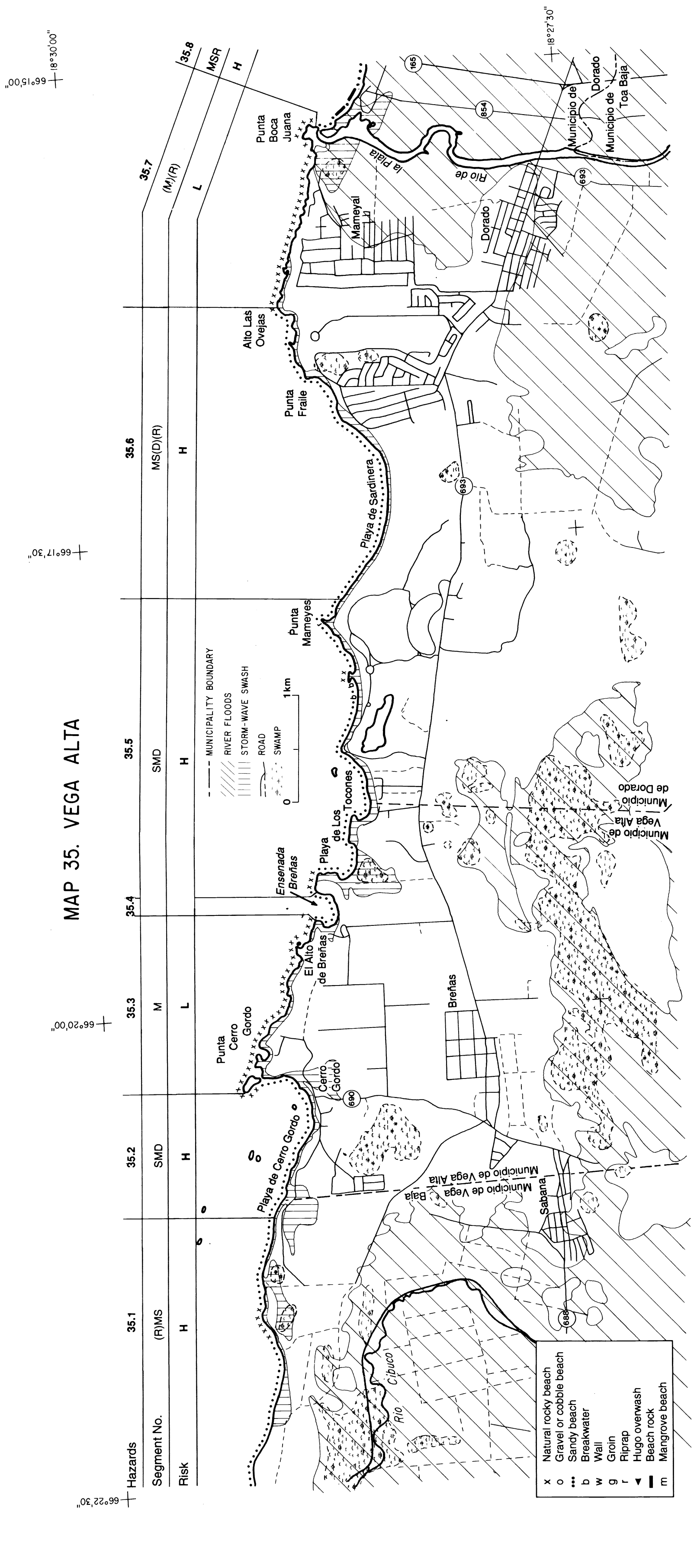
Hurricane Hugo provided an example of multiple natural hazards associated with a single climatic event. Hugo was a category 3–4 hurricane which skirted the northeast corner of the island. Maximum sustained winds were on the order of 140 mph or less at Roosevelt Roads Naval Station on the east coast and $\sim$70 mph at Luis Muñoz Marín Airport in Isla Verde on the eastern north coast near the capital city of San Juan. Hugo was a relatively dry hurricane by tropical standards, causing no serious flooding, although $>$400 landslides were triggered by associated rainfall and runoff (Larsen and Torres Sánchez, 1992). Hugo also was a relatively fast-moving hurricane and its maximum winds impacted Puerto Rico for $<$1 h. Nevertheless, Puerto Rico sustained over $1 billion in damages. Two-thirds of the island's municipalities were declared disaster areas, mostly because of wind damage. Sand was washed tens of meters inland from the beach along the Escambrón, Piñones, and Cabezas de San Juan areas. An estimated 500,000 m^3 of sand was lost from the beach system in the Piñones area alone (Rodríguez et al., 1994).

Hurricane Georges (1998) bisected Puerto Rico from east to west, and hurricane-force winds were felt over the entire island. The coastal impacts were not as severe as Hugo, but the wind, flooding, and landslide hazards were much more pervasive. For results of post-Hurricane Georges studies, visit the USGS internet web site (http://coastal.er.usgs.gov/hurricanes/georges/). For more details of the impact of Hurricane Hugo, the reader is referred to National Oceanic and Atmospheric Administration/National Ocean Service (1990), Bush (1991), Finkl and Pilkey (1991), and Rodríguez et al. (1994).

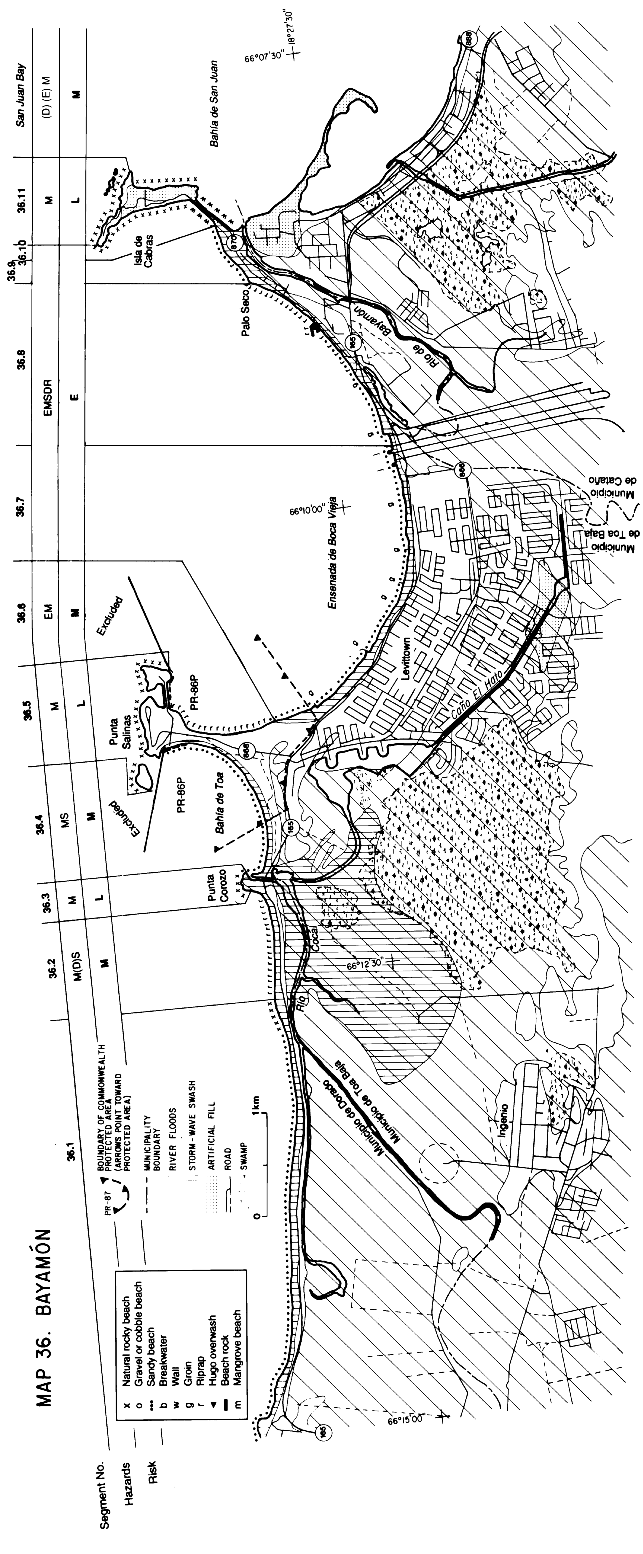
Until Hugo in 1989, a hurricane had not made a direct hit on Puerto Rico since Hurricane Betsy in 1956, a period of 33 years. Table 3 highlights the historic frequency of hurricanes and wave-producing tropical storms passing in the vicinity of Puerto Rico. Without periodic reminders, people tend to grow complacent with regard to coastal hazards such as hurricanes. The majority of the coastal construction in Puerto Rico has occurred since the 1956 storm. Hugo was only a glancing blow; Georges was a direct hit. With the passing of each successive hurricane, the populace and officials of Puerto Rico realize that storm impacts are growing more and more disastrous, especially if shoreline development continues unchecked or uncontrolled.



Map 12/13. Punta Tuna and Yabucoa.



Map 35. Vega Alta.



Map 36. Bayamón.

Hurricanes are not the only coastal hazards of concern to shoreline property owners. Swell from far distant winter storm centers is responsible for the large erosive waves impacting the north coast (Fields and Jordan, 1972). Storm surge may result in flooding and overwash.

TABLE 3. Tropical storms and hurricanes affecting Puerto Rico.

Yr/Month	Note[a]	Impact[b]	Type[c]	Path	Name
1876/9	L	A	T	E–W	
1891/8	L	E	H	SE–N	
1891/10	*	S	T	SE–SW	
1893/8	L	NE	H	E–SW	
1896/8–9	L	SW	H	S–W	
1898/9	#	NE	T	NE–N	
1899/9	L	SW	H	S–W	San Ciriaco
1901/7	L	SW	H	SW–W	
1901/10	#	NE	T	E–N	
1903/7	L	A	T	SE–NW	
1916/8	L	A	H	E–W	
1924/8	*	NE	T	NE–NE	
1926/7	L	SW	H	SW–SW	
1928/9	L	A	H	SE–NW	
1931/8	#	A	T	SE–NW	
1931/9	L	N	H	NE–NW	San Nicolas
1932/9	L	A	H	E–W	San Ciprian
1938/8	#	N	T	NE–NW	
1942/11	#	NE	T	E–N	
1950/8	#	SW	T	SW–SW	Baker
1956/8	L	A	H	SE–NE	Betsy
1975/9	*	N	T	E–W	Eloise
1979/7	L	N	T	NE–NW	Frederic
1979/8–9	*	A	H	E–W	David
1979/9	L	S	T	E–SW	Claudette
1981/9	L	E	T	SE–N	Gert
1984/11	*	E	T	E–E	Klaus
1989/9	L	NE	H	E–NE	Hugo
1995/9	*	NE	H	SE–NW	Marilyn
1996/7	*	NE	H	SE–NW	Bonnie
1996/9	L	SW	H	SE–NW	Hortense
1998/10	L	A	H	E–W	Georges
1999/11	*	S	H	SW–NE	Lenny

[a] L, landfalling storm; #, storm passing over small portion of island; and *, no landfall but passed near enough to impact island.
[b] Portion of island impacted; letters are compass directions.
[c] T, tropical storm; H, hurricane.

Earthquakes and Tsunamis

Puerto Rico lies in a relatively active tectonic zone. The entire island is susceptible to major damage from earthquakes, and the relative risk is essentially equal across the entire island. Differences in amounts of damage around the island will thus be a factor of development density, age, and type; the local slope; and the strength of the soil. Discussions of earthquake hazards for Puerto Rico are given by McCann (1984, 1985) and Molinelli (1984, 1985). Buildings, highways or interchanges, and other services (e.g., utility lines) built on artificial fill or some types of natural unconsolidated sediments (e.g., some coastal plain deposits) that are susceptible to liquefaction may suffer extreme damage (areas of artificial fill are delineated on the hazard maps). Much of the development in the San Juan metropolitan area is located on fill and unconsolidated sediment. Development in steep mountainous areas, especially where constructed on unconsolidated material, is highly susceptible to damage and destruction. Major seismic events may

TABLE 4. Historic earthquakes affecting Puerto Rico (Díaz, 1990)

Year	Magnitude[a]
1787	8–8.2
1867	7.8
1917	7.0
1918	7.5
1943	7.8
1946	7.6–8.1
1946	7.0
1948	7.3

[a] The magnitude given is the Richter magnitude scale, which measures the amplitude of seismic waves recorded by seismographs. The Richter scale was developed about 1900. The magnitude of earlier earthquakes is estimated (Díaz, 1990).

also cause tsunamis, affecting the coastal areas. Table 4 lists the major historic earthquakes that have occurred around Puerto Rico.

Several notable seismic events have occurred in Puerto Rico during historic times. The 1787 earthquake caused destruction everywhere in Puerto Rico except the southern coast. The 1867 earthquake created a destructive tsunami that impacted the southeastern coast. The 1615, 1751, 1776, and 1946 earthquakes were in the Dominican Republic but caused severe damage in western Puerto Rico. The 1918 earthquake almost leveled the city of Mayagüez on the western coast.

Tsunamis affecting Puerto Rico are discussed by Lander and Lockridge (1989). To date, all known tsunamis affecting the island were the result of earthquakes. However, the discovery of a giant insular slope scar suggests the possibility that giant submarine landslides may also be triggering mechanisms important in generating tsunamis (Schwab et al., 1991), although a submarine slide itself may also be triggered by an earthquake. Table 5 (Lander and Lockridge, 1989) lists important tsunamis affecting the island.

Coastal and Riverine Flooding

Coastal sea level may be temporarily raised by storm surge, wave runup, unusual high tides, or tsunamis, resulting in flooding of low coastal areas (e.g., mangrove coasts, floodplains at river mouths, lowlands around embayments, and the lower coastal plain). High rainfall and runoff associated with hurricanes and other tropical disturbances inundate river floodplains and ultimately affect the coastal zone at the rivers' mouths. Dam failure or channel blockage, especially in times when runoff is already high, add to the flood hazard. For example, during a January 1992 storm, tons of water hyacinth plants were washed down the Río de la Plata, clogging the river channel under the bridge at Dorado and causing additional upstream flooding as well as damaging the bridge.

Flooding in low-lying coastal areas is a chronic and potentially severe hazard. The rainy season (typically the summer months, although tropical storms may bring high associated rainfall into the autumn months) creates an annual threat of intense river flooding which is further increased during hurricanes that can release large volumes of water in a relatively short time span. With industrialization and increase in island population, more and more development has, by necessity, taken place in coastal flood-plain zones. As a result, the potential and occurrence of damage on the island resulting from flooding has increased.

TABLE 5. Tsunamis affecting Puerto Rico.

Date	Location	Wave Run-up (m)[a]	First Motion[b]	Comments
18 Nov 1867	Fajardo	obs	F	Small wave
18 Nov 1867	Vieques	obs	F	High wave
18 Nov 1867	Yabucoa	obs	F	Sea retreated 137 m
17 Mar 1868	Arroyo	obs	F	Small recession and flooding
17 Mar 1868	Naguabo	obs	F	Small recession and flooding
11 Oct 1918	Aguadilla	3.4		
11 Oct 1918	Río Loíza	1.0	F	
11 Oct 1918	Arecibo	0.6		
11 Oct 1918	Boquerón	1.5		
11 Oct 1918	Guánica	0.5		
11 Oct 1918	Isabela	2.0		
11 Oct 1918	Isla Caja de Muertos	1.5		
11 Oct 1918	Mayagüez	1.5		
11 Oct 1918	Ponce	obs		
11 Oct 1918	Punta Agujereada	6.0		
11 Oct 1918	Punta Borinquen	4.5		
11 Oct 1918	Punta Higüero	5.2		
11 Oct 1918	Río Culebrinas	4.0		
4 Aug 1946	San Juan	obs		
8 Aug 1946	San Juan	obs		
8 Aug 1946	Aguadilla	obs	F	Sea retreated 24m
8 Aug 1946	Mayagüez	obs	F	Sea retreated 76m

[a] obs, tsunami motion or its effects was observed but amplitude not reported.

Flood plains are easily identified and mapped, and development on any floodplain is at risk (doubly so in the coastal zone). Table 6 is a list of major historic floods in Puerto Rico, keyed to the USGS Hydrologic Investigations Series showing floods around the island (Table 7). The hazard maps show the limits of coastal flooding from several historic winter storms mapped by Fields and Jordan (1972).

Landslides

Because Puerto Rico is a small, densely populated island, many of its people live on and among the mountainous terrain of the Central Cordillera. Likewise, roads must be built through this rugged terrain, and excavation of the steep slopes for industrial and residential purposes has produced many potentially dangerous areas. The great amount of rainfall that is received by the island intensifies the problem, especially when a tropical storm or hurricane produces large amounts of rainfall in short periods of time. One of the biggest problems occurs where limestone beds are interbedded with clay layers that behave as slip planes when wet. Under such conditions, great masses of rock can slide unimpeded down the steep slopes. Mudflows and rockfalls also are major problems and occur mostly in areas of deeply weathered volcanic and intrusive rocks. Such rocks weather easily and quickly degrade to clay and mud in this warm, wet environment. The end result is rivers of mud or mixtures of rock and mud flowing down the mountain slopes (e.g., the landslides triggered by Hurricane Hugo discussed by Larsen and Torres Sánchez, 1992).

The landslide problem in Puerto Rico was addressed by Monroe (1979). In that work, the entire island was classified into areas of highest, high, moderate and low susceptibility to landsliding. Such studies are not absolute, however, and an area classified as having a moderate risk of landsliding became the site of one of the worst landslide disasters ever in Puerto Rico. From May 5–7, 1985, 24 in of rain fell onto the steep (30°) slopes of the southern side of the island. A mudslide started near the top of the slope and grew in size as it raced toward, and then through, the small town of Mameyes, Municipio of Ponce. The death toll may never be precisely known, but as many as 96 people died in the slide and associated flooding, one of Puerto Rico's worst natural disasters.

In general, landslide susceptibility boundaries mimic the topographic boundaries. That is, the coastal lowlands have generally lower susceptibilities to landsliding, whereas the steep, mountainous Central Cordillera has generally higher susceptibilities.

Development and Engineering

Construction of buildings, roads, utility and service lines, and related structures can contribute to hazard potential by altering the natural environment. Areas where water for-

TABLE 6. Historical river floods in Puerto Rico shown on the Coastal-Zone Hazard Maps (excerpted from USGS Division of Water Resources records).

Date	Event/Area Affected
8 Aug 1899	Arecibo
13 Sep 1928	Arecibo, Barceloneta, Manatí, Añasco, Guayanilla, Yauco, Guayama, Salinas, Santa Isabel, Lajas Valley, Naguabo
Sep 1932	Arecibo, Guayanilla, Yauco
3 Mar 1933	Mayagüez
Aug 1935	Patillas, Maunabo
4 Aug 1945	Bayamón, Cataño
Sep 1954	Patillas, Maunabo
13 Oct 1954	Arecibo, Ponce, Guayanilla, Yauco
12 Aug 1956	Añasco, Naguabo
June 1957	Guayama, Salinas
May 6, 1958	Ponce
6 Sep 1960	Río de la Plata, Humacao, Yabucoa, Caguas, Carolina, Río Grande, Fajardo, Luquillo, Naguabo
27 Aug 1961	Bayamón, Cataño, Humacao, Patillas, Maunabo, Guayama, Salinas
30 July 1963	Mayagüez, Río Guanajibo
3 Aug 1963	Lajas Valley
11 Dec 1965	Barceloneta, Manatí, Vega Alta, Vega Baja
27 Nov 1968	Aguadilla, Aguada
26 Jan 1969	Fajardo, Luquillo
6 May 1969	Fajardo, Luquillo
21 May 1969	Fajardo, Luquillo
5–10 Oct 1970	Patillas, Maunabo, Guayama, Salinas, Santa Isabel, Carolina, Río Grande, Fajardo, Luquillo, Naguabo
21 Oct 1972	Fajardo, Luquillo

TABLE 7. List of USGS Hydrologic Investigations Atlases for Puerto Rico.[a]

Hydrologic Atlas Numbers	Area Affected
HA-77	Bayamön and Cataño
HA-128	Toa Alta, Toa Baja, and Dorado
HA-261	Ponce
HA-262	Barceloneta and Manatí
HA-265	Humacao
HA-271	Arecibo
HA-288	Mayagüez
HA-289	Vega Alta and Vega Baja
HA-375	Añasco
HA-382	Yabucoa
HA-414	Guayanilla-Yauco
HA-438	Caguas, Curabo, Juncos, and San Lorenzo
HA-445	Patillas-Maunabo
HA-446	Guayama area
HA-447	Salinas
HA-448	Santa Isabel
HA-456	Río Guanajibo Valley
HA-457	Aguadilla-Aguada
HA-532	Eastern Lajas valley and the lower Río Loco basin
HA-533	Carolina-Río Grande
HA-545	Fajardo-Luquill
HA-584	Naguabo

[a]Available from the U.S. Geological Survey Division local office or from USGS publications office: U.S. Geological Survey, Water Resources Division, Ft. Buchanan Bldg. 652, Ft. Buchanan, Puerto Rico 00936-4424; U.S. Geological Survey, Map Distribution, Federal Center, Box 25286, Denver, CO 80255.

merly infiltrated the ground may now be impervious and increased runoff results, thus increasing the flood potential. Return flow of storm-surge flood waters (storm-surge ebb) may be funneled by streets and constrictions between buildings, increasing flow velocity and causing increased scour and erosion (e.g., Thieler et al., 1989; Gayes, 1991; Lennon, 1991; Priddy, 1991; Thieler and Bush, 1991). Buildings themselves may break up in the storm surge or flood or detach from their foundations and become battering rams that destroy adjacent structures. In other words, as the density of development increases, the quality of construction declines (for example, poor design or materials, and aging), or poor siting of buildings, roads, and services occurs, the risk for property damage and loss increases.

On the shoreline, shore-hardening engineering structures are often emplaced to stabilize the shoreline position and protect inland property. Typical structures include various types of seawalls, breakwaters, and groin fields. Unfortunately, these structures may cause a redistribution of wave energy and obstruct sediment supply to adjacent beaches, resulting in beach loss or shifts in the erosion pattern. Such structures may have detrimental effects on their landward side as well (e.g., increased storm-surge ebb scour or flooding behind walls).

The Coastal-Zone Hazard Maps include a development hazard component as well as showing the location and type of shore engineering structures. Such structures are usually an indication of past erosion problems.

RECOMMENDATIONS

Based on the review of multiple hazards of the eastern Puerto Rico coastal zone as afforded by the compilation of Coastal-Zone Hazard Maps, several recommendations can be made. Many of the recommendations made here are echoed in the report *Puerto Rico and the Sea—1999* (Beller et al., 1999), which lays out strategies for all aspects of coastal and marine planning and development.

Shoreline Setting Hazards and Recommendations

The beaches of Puerto Rico are very dynamic features that respond to both seasonal variations in wave climate as well as large storm events. Most of Puerto Rico's shoreline is eroding. Rates, however, are generally slow to the extent that total actual area of land loss is not important in most areas. Erosion is generally a more serious problem on unconsolidated shorelines than on rocky stretches. Serious impacts of erosion include:

- Land loss and the threat to shorefront buildings and infrastructure such as highways, power, water, and sewer lines;
- The narrowing of beaches in front of walls and revetments, increasing the danger to shorefront buildings from storm waves;
- The perceived need for more hard stabilization structures (e.g., seawalls) that will result in additional loss of recreational beach quality and ease of beach access; and
- The economic impact to all levels of government of preparing for and responding to natural hazards.

Underlying all of the world's shoreline erosion problems is a rise in sea level, a rise that is expected to accelerate in coming decades. The erosion problem will increase with the sea-level rise; therefore, the sea-level rise must be a factor in Puerto Rico's shoreline management planning and practices (Bush et al., 1995, 1996b).

Although historical shoreline change analysis has determined island-wide erosion rates (Thieler and Danforth, 1993, 1994a, 1994b), a long-term study of the impact of shoreline erosion on Puerto Rico is needed. The study should assess the overall and community-by-community erosion situation relative to existing development; start a continuous beach-profiling program to monitor changes in shoreline position, beach characteristics, and sand supply; make overall and community-wide recommendations as to shoreline-management alternatives (for example, controlled development, relocation, and need for beach nourishment); and begin planning for future sea-level rise.

Marine Hazards and Recommendations

Although rare, the probability exists for future loss of life and property in the event that tsunamis strike the coast of Puerto Rico. Even if a large tsunami occurred only once in a hundred or thousand years, plans should be made for detection, warning, evacuation, and sheltering for susceptible communities. The tsunami impact zone is approximately the same as for hurricanes; thus there are similarities between planning for tsunami impact and hurricanes with respect to coastal flooding and wave impact. In that regard, most of the recommendations made for shoreline setting hazards (above) pertain to marine hazards as well.

Earthquake and Slope Stability Hazards and Recommendations

Although a significant portion of the population of Puerto Rico live in the hazardous, hilly terrain of the Central Cordillera, steps can be taken to lessen the chance of property damage from earthquakes, landslides, and other slope stability hazards. Recommendations from meetings held in 1984 and 1985 addressing the multiple hazards active in Puerto Rico are not reiterated here. Gori and Hays (1984) made recommendations for planning against geologic hazards, evaluating geologic hazards, earthquake and ground-failure hazards, responding to hazards, and formulating plans to deal with geologic hazards. Hays and Gori (1985) outlined methods for assessing earthquake hazards and mitigating their effects, reviewed societal and technical lessons learned from past earthquakes that are applicable to Puerto Rico, and noted activities in Puerto Rico to reduce potential losses from earthquake hazards.

Riverine Flood Hazards and Recommendations

In addition to hurricanes, the rainy seasons create an annual threat of river flooding and landslides. Increased assets in flood zones mean more losses with each flood, but mitigating flood impact is also costly. The Puerto Rico Flood Hazard Mitigation Plan (Puerto Rico Department of Natural Resources, 1987) moved to reduce flood losses. The initial planned project was flood mitigation for the Río Grande de Loíza Valley where the floodway was cleared, protective dikes were restored or added, drainage improved, and ~1300 families relocated out of harm's way, all at a cost of $51 million.

Subsequent flood mitigation studies and plans by the Puerto Rico Department of Natural and Environmental Resources, including installation of an island-wide flash flood warning system, have reduced losses but are not completely effective. Programs to increase and maintain public awareness of the flood hazard, particularly what to do during and after a flood event, should be continued. Programs for relocation out of the flood zones, although costly, should continue and be expanded.

Development Hazards and Recommendations

Perhaps, the major "cause" of shoreline erosion is emplacement of buildings too close to the shoreline. Some beachfront communities have avoided this by staying well back from the beach. Examples are Villa Palmira near Playa de Humacao on the east coast and Suarez on the north coast.

Puerto Rico must improve and enforce existing setback requirements and improve building codes to minimize the impact from the natural forces to be experienced by buildings due to wind and potential flooding. Inspection and enforcement are keys to successful mitigation of development hazards. For developments already in harm's way, alternatives to hard engineering structures need to be incorporated in long-term planning (e.g., relocation programs or nourishment of recreational protective beaches).

Engineering Hazards and Recommendations

Two major causes of erosion along the Puerto Rico shoreline are shoreline engineering structures and mining of sand from beaches, dunes, and rivers which are the sources of beach sand. Puerto Rico should require coastal sand conservation and enforce a ban on coastal sand extraction. Sand mining on Puerto Rico beaches should be halted immediately. This includes halting removal of sand from rivers that would ultimately end up on the beaches adjacent to river mouths.

Shoreline stabilization in Puerto Rico is uncontrolled, and often the cost of saving erosion-threatened buildings is much more than the buildings are worth (e.g., Urbanization Las Carreras in Loíza on the north coast). Recently, shoreline management policies have considered controlling hard stabilization structures. Closer monitoring of beach dynamics, including beach profiling and beach volume-change studies, are imperative (Richmond et al., 1992). Alternatives to hard stabilization include development set-backs, relocation or demolition of low-cost shorefront buildings, and beach nourishment. Hard shoreline stabilization (seawalls, revetments, and groins) should be closely regulated or prohibited altogether.

"Neighborhood inconsistencies" in the type and degree of hard stabilization leads to differential accelerated erosion (e.g., Mar Azul urbanization in Hatillo). Hard stabilization must be controlled, perhaps through a stricter permitting process, and a program of beach monitoring is needed to assess beach changes. Alternatives to hard stabilization as noted above must be evaluated and considered. At least two communities, Luquillo and San Juan (Isla Verde to the Condado) could benefit immediately from beach replenishment.

Historically, the building of seawalls and revetments is usually done on a crisis basis, allowing no time for deliberation concerning other alternatives. Many miles of Puerto Rico's recreational beaches have been seriously degraded and even destroyed through attempts to halt shoreline erosion to protect buildings. A concerted effort is needed to halt beach degradation in Puerto Rico. Beaches are a valuable recreational and economic resource, a natural buffer that protects coastal land during extreme events, and a culturally important landform to the people of Puerto Rico.

Preservation of recreational beaches should be given high priority, in many cases higher priority than preservation of shorefront buildings.

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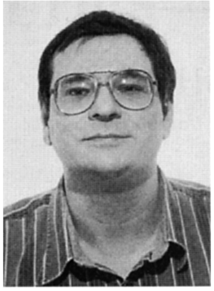

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