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Coastal Zone Hazards Maps of Puerto Rico: Hurricane Hugo Impacted Portion of the Shoreline, Cibuco (Punta Garaza) to Punta Viento

by

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INTRODUCTION

Puerto Rico is one of the most highly developed lands in Latin America. With a surface area of only 8,896 square kilometers (3,435 square miles) and a population of over 3.6 million, the population density is about 400 people per square kilometer. Puerto Rico is an extremely mountainous island, thus constraining both private and commercial development in or near level coastal areas, on flood plains, areas of artificial fill and in dangerous hilly terrain. The high population density along with the intense development of industrial, commercial, public and private property in the coastal zone over the past 40 years has placed both population and property at risk. Most development took place without knowledge or regard for the geologic hazards which affect the coastal zone, and the predictable results will be recurring disasters. Such a disaster occurred with the arrival of Hurricane Hugo on September 18, 1989.

Hurricane Hugo resulted in 1 death and over $1 billion worth of damage and property loss. The storm was a reminder of both the long history of coastal hazard impact and the growing density of property and population at risk in the coastal zone. The positive outfall from Hugo was a concerted effort by the United States Geological Survey (USGS) and other institutions to assess the impact on coastal resources and environments caused by this storm, and to provide baseline data against which to measure the impact of future storm events (Schwab and others, 1996a, b; Thieler and Danforth, 1993; Thieler and Danforth, 1994a, b; Delorey and others, 1993). The coastal zone hazard maps of this study are one contribution to the overall USGS study (Schwab and Rodríguez, 1992).

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 tsunami, river flooding, earthquake- and rain-induced slope failure, and landslides. An integrated assessment of all potential coastal zone hazards is necessary for a complete understanding of 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 Puerto Rico depicting coastal geology and geomorphology, beach characteristics, offshore (inner shelf) characteristics, and hazard potential from such events as flooding, overwash, erosion, earthquake damage, and landslides. In addition, special consideration was given to areas where shoreline engineering or dense development significantly increases the overall vulnerability of a coastal stretch. A detailed description of Puerto Rico's shoreline with information on the coastal hazards of each shoreline reach, and including an extensive bibliography, can be found in Bush and others (1995).

METHODS

Coastal Zone Hazard Maps were prepared for the 13 quadrangles representing the portion of the Puerto Rico main-island shoreline impacted by Hurricane Hugo using USGS topographic maps as a base (Fig. 1). Within each quadrangle, the shoreline is divided into natural geomorphic units which are numbered sequentially. These numbered segments represent "reaches" or "stretches" that constitute natural units such as shores 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 4 identifiable hazards
H	High	3 to 4 identifiable hazards
M	Moderate	at least 2 hazards
L	Low	1 or no hazard

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

Few truly "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, however shoreline characteristics 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

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

S Shoreline-Setting Hazards — Long-term problems such as severe erosion history or low elevation. Differs from Development hazards because this category considers only with the natural setting regardless of the type of coastal development. Beach type is included on each map, and mangrove coasts are noted.

M Marine Hazards — Short-term impacts of wave runup and overwash, storm surge, and storm-surge ebb from hurricanes and other coastal storms, plus potential tsunami impact.

Q Earthquake and Slope Hazards — Areas with active faults, steep slopes that are prone to slope failure and landslides during earthquakes and heavy rains, or areas of unconsolidated material or artificial fill prone to liquefaction during earthquakes.

R Riverine Hazards — Areas on floodplains with historic severe floods or where flood potential is high because of dams upstream.

D Development Hazards — 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 development (where the natural setting of the shoreline has been altered for development in such a way as to place people or property at risk).

E Engineering Hazards — Special cases where shoreline engineering projects have significant detrimental effects to portions of the shoreline. Examples are the breakwater at Boca de Cangrejos and the causeway to Isla de Cabras. Also includes areas where natural protection has been removed through sand mining of the dunes and beaches. Specific coastal engineering structures are shown on the maps.

For shoreline segments where a given hazard applies to only a portion of the shoreline 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 maps also show areas protected within the federal Coastal Barrier Resources System (CBRS Units) and within various Commonwealth Protected Units. 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" should be 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 which includes shoreline orientation, 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 either a revetment, seawall, groin or breakwater. Wetlands are broken down 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, potential for flooding, and, in the case of engineering structures, provide evidence of past property loss, and serve as predictors of future property loss.
2) Beach information for shorelines that are predominantly beaches include beach type (sand, gravel, mud, pocket), composition (mostly carbonate, siliciclastic, or mixed), the presence of beachrock or abundant heavy-mineral concentrations, beach width, and critical erosion areas. Beaches provide a natural buffer against wave erosion and storm surge. The parameters evaluated here serve as indicators of where erosion and storm-wave impact are hazards.
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 (FIRM's) available from the Federal Emergency Management Agency are also considered. These are derived from model studies, but these quantitative predictions are only as good as the models upon which they are based. Such predictions 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) based on the newly-developed air-photo interpretation technique of Thieler and Danforth (1994a, b) 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., the sea-level rise may accelerate erosion, or a neighboring seawall or groin field 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 which 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, 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 with all the world's coastal nations, Puerto Rico's shoreline is feeling the effects of severe and persistent erosion. All information (e.g., studies of air photos, beach surveys, comparisons of old and new charts and maps) point to this conclusion. Local variations in beach type, beach configuration and composition influence the amount of erosion, and even cause accretion, the building out of the beach, in some spots. But overall, the beaches are moving landward and the shoreline is retreating. Erosion is far more critical along unconsolidated shorelines than on rocky stretches. There are several causes for the erosion.

Shoreline erosion results from the effects of large events such as hurricanes and large ocean swell from north Atlantic winter storms. Sandy shorelines respond to changes in the nearshore current and wave regime. Changes or variations in the supply of sediment to the beaches can also lead to local erosion. Potential accelerated sea-level rise as a result of global warming would also contribute to coastal erosion. This long-term coastal erosion driven by sea-level rise results in beach narrowing in front of seawalls and buildings. Ground subsidence on either a regional scale (e.g., tectonic influence) or a local scale (e.g., ground water withdrawal) may also contribute to erosion.

Poorly designed engineering structures that interfere with the natural movement of beach sand are probably responsible for much of the sand loss. Other human-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 proposed Coastal Management Program for the Commonwealth of Puerto Rico (NOAA/DNR, 1978) includes a good summary of the coastal erosion problems on the island (e.g., how the Mayagüez urbanization of San José is losing homes to the advancing sea; how erosion has destroyed a school near Jobos Bay). 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, and others (1985), Morelock, and Taggart (1988), Thieler and Danforth (1993), Thieler and Danforth (1994a, b). General shoreline information can be found in Bush and others (1995)

Hurricanes and Other Storms

Hurricane Hugo provided an example of multiple natural hazards associated with a single climatic event. Hugo was a category III to IV 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 about 70 mph at Luis Muñoz Marín Airport in Isla Verde. Hugo was a relatively dry hurricane by tropical standards, causing no serious flooding although more than 400 landslides were triggered by associated rainfall and runoff (Larsen and Torres Sanchez, 1992). Hugo also was a relatively fast-moving hurricane and its maximum winds impacted Puerto Rico for less than one hour. 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 from the beach for tens of meters inland 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 and others, 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 1 highlights the historic frequency of hurricanes and wave- producing tropical storms passing in the vicinity of Puerto Rico. Without periodic reminders, people grow complacent in 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. The populace and officials should not grow complacent again, allowing themselves to think they have "survived the big one." A direct hit from a major storm (such as Camille, 1969 or Gilbert, 1988) would be disastrous, especially if shoreline development continues unchecked or uncontrolled. For more details of the impact of Hurricane Hugo, the reader is referred to NOAA (1990); Bush (1991); and Rodríguez and others (1994).

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. Storm surge may result in flooding and overwash.

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 slope angle, and the strength of the soil. Some idea of earthquake hazards for Puerto Rico are given by McCann (1984, 1985) and Molinelli (1984, 1985). Buildings 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 (see areas of artificial fill delineated on maps). The same goes for highways or interchanges and other services (e.g., utility lines) built on artificial fill. This hazard applies to much of the development in the San Juan metropolitan area. Development in steep mountainous areas, especially where constructed on unconsolidated material, is highly susceptible to damage and destruction. Major seismic events may also cause tsunamis, affecting the coastal areas. Table 2 lists the major historic earthquakes which have occurred around Puerto Rico.

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 quake 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, a recently discovered scar of a giant insular slope scar suggests the possibility that giant submarine landslides may also be triggering mechanisms important in generating tsunamis (Schwab and others, 1991), although a submarine slide itself could also be triggered by an earthquake. Table 3 lists important tsunamis affecting the island (from Lander and Lockridge, 1989).

Coastal and Riverine Flooding

Coastal sea level may be 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, 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. In the 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, 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. Fortunately, Hugo was a relatively dry hurricane and coastal flooding was less than expected for a storm of this size. 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.

Flood plains are easily identified and mapped as hazard zones, and development on any floodplain is at risk (doubly so in the coastal zone). Table 4 is a list of major historic floods in Puerto Rico, keyed to the USGS Hydrologic Investigations Series showing floods around the island (Table 5). 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 her people are forced to live on and among the slopes of the Central Cordillera. Likewise, roads must be built through this rugged terrain. 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 dumps large volumes of water in short periods of time. The biggest problems occur when limestone beds rest on 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. These occur mostly in areas of deeply weathered volcanic and intrusive rocks. Such rocks weather easily and quickly 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 Sanchez, 1992).

The landslide problem of 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. 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 through May 7, 1985, 24 inches of rain fell onto the 30 degree slopes of the southern side of the island. A mudslide started near the top of the slope and grew in size and fury 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 geologic boundaries. That is, the coastal lowlands have generally lower susceptibilities to landsliding while 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 formerly infiltrated the ground now are 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, causing increased scour and erosion (e.g., Thieler and others, 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, or the quality of construction declines (for example, poor design or materials, 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 upland property. Typical structures include various types of seawalls, breakwaters, and groin fields. Unfortunately, these structures 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; 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 obvious clue to past erosion problems.

RECOMMENDATIONS

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 implications of erosion include:

(a) the threat to shorefront buildings;

(b) the threat to infrastructure such as highways, power, water, and sewer lines;
(c) beaches in front of walls and revetments narrow increasing the danger to shorefront buildings from storm waves;
(d) the perceived need for more hard stabilization structures (e.g., seawalls) which will result in additional loss of beach recreational quality and ease of beach access; and
(e) 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 the level of the sea; a rise which is expected to accelerate in coming decades. The erosion problem will accelerate with the sea-level rise, therefore, the sea-level rise must be a factor in Puerto Rico's shoreline management planning and practices.

A long-term study of shoreline erosion in Puerto Rico is needed. The study should assess the island-wide and community-by-community erosion situation, start a continuous beach-profiling program, make island-wide and community-wide recommendations as to shoreline-management alternatives and begin planning for the sea-level rise. The first aspect of this study, island-wide determination of historical shoreline change analysis to determine erosion rates, recently was completed (Thieler and Danforth, 1993; Thieler and Danforth, 1994a, b).

Marine Hazards and Recommendations

Though remote, the probability exists for future losses of life and property in the event that seismic sea waves (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. There are similarities between planning for tsunami impact and hurricanes, with respect to coastal flooding and wave impact. In that regard, some of the same 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 must live in the hazardous, hilly terrain of the Central Cordillera, several steps can be taken to lessen the chance of property damage from earthquakes, landslides, and other slope stability hazards. Reports of meetings held in 1984 and 1985 to address the various natural hazards active in Puerto Rico are available from the USGS as Open File Reports. The first (Gori and Hays, 1984) includes chapters on planning against geologic hazards, evaluating geologic hazards, earthquake and ground-failure hazards, responding to hazards, and formulating plans to deal with geologic hazards in Puerto Rico. The second (Hays and Gori, 1985) includes sections on assessing earthquake hazards and mitigating their effects, a review of societal and technical lessons learned from past earthquakes that are applicable to Puerto Rico, activities in Puerto Rico to reduce potential losses from earthquake hazards, and four appendices. These reports provide valuable recommendations.

River Flood Hazards and Recommendations

The rainy seasons of Puerto Rico, when many inches of rain can be dumped seemingly instantaneously, create an annual threat of intense 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 (DNR, 1987) is an attempt to reduce flood losses. The initial project of the Plan was flood mitigation for the Río Grande de Lo°za Valley where the floodway was cleared, protective dikes were restored or added, drainage improved, and about 1300 families relocated out of harm's way; all at a cost of $51 million.

An island-wide flash flood warning system has been installed. Other flood mitigation studies and plans have been made by the Puerto Rico Department of Natural and Environmental Resources in San Juan. These mitigation plans never will be completely effective, and programs to increase and maintain public awareness of the flood hazard, particularly what to do during and after a flood event, should be continued.

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. With no buildings close to the shoreline, there is no erosion problem!

Puerto Rico must improve and enforce existing setback requirements and improve building codes to address 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, soft solutions need to be incorporated in long-term planning (e.g., relocation programs, 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 which would ultimately end up on the beaches adjacent to river mouths.

Shoreline stabilization in Puerto Rico is uncontrolled. Most states have begun to more closely regulate hard shoreline stabilization (seawalls, revetments, groins) and two states prohibit it altogether. Often in Puerto Rico 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 are more commonly considering controlling hard stabilization. Closer monitoring of beach dynamics, including beach profiling and beach volume-change studies, are imperative and have begun in Puerto Rico (Richmond and others, 1992). Alternatives to hard stabilization that are being considered in other areas include development set-backs, relocation or demolition of low-cost shorefront buildings, and beach replenishment.

"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. To back this up, a program of beach "surveillance" is needed. 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, and could probably build a case for U.S. Army Corps of Engineers' financial participation.

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

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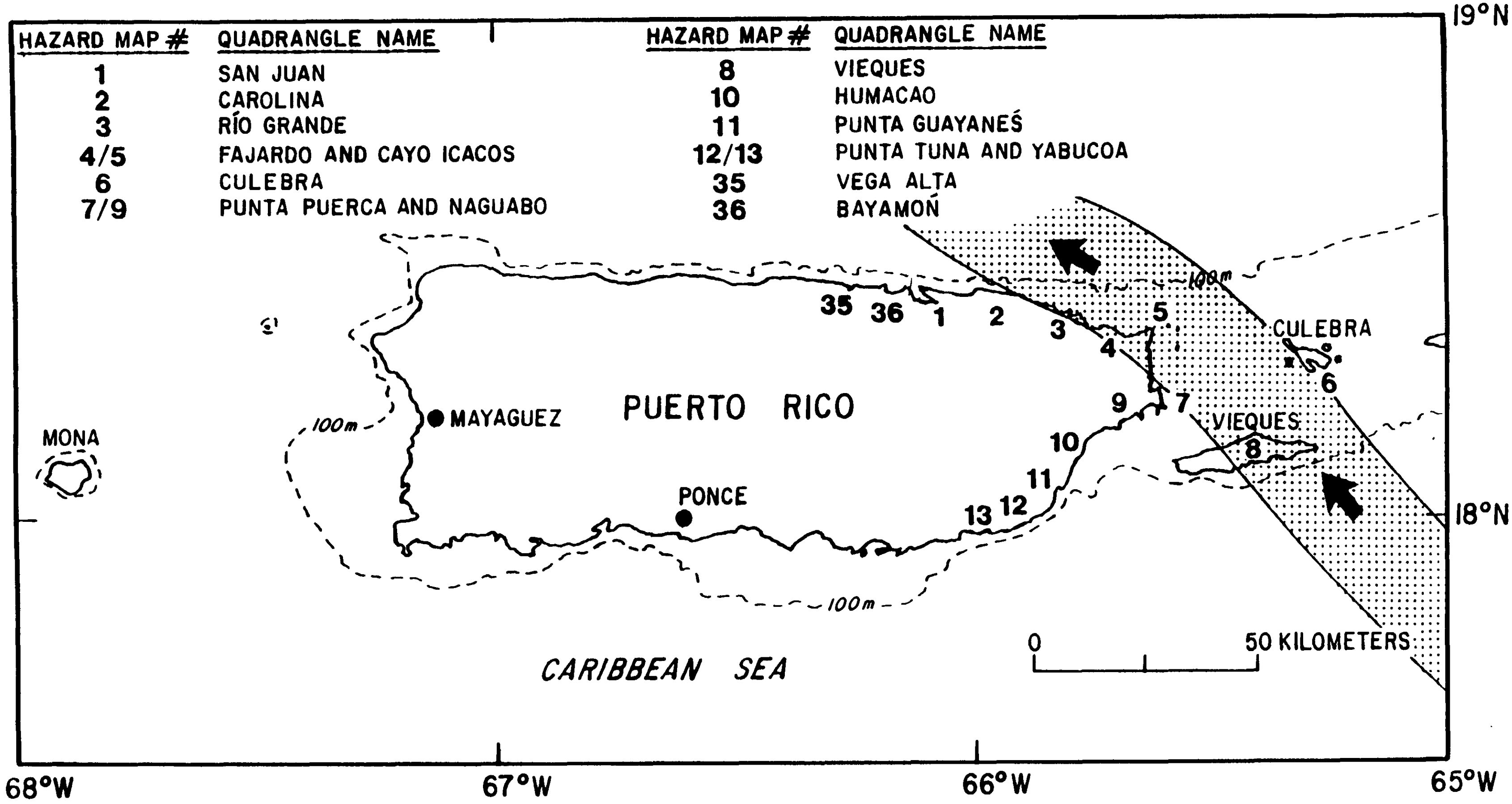

Figure 1. Location of USGS Topographic Quadrangle Maps used as bases for Coastal Zone Hazard Maps. 35-Vega Alta, 36-Bayamón, 1- San Juan, 2-Carolina, 3-Río Grande, 4-Fajardo, 5-Cayo Icacos, 6- Culebra (not mapped), 7-Punta Puerca, 8-Vieques, 9- Naguabo, 10-Humacao, 11-Punta Guayanés, 12-Yabucoa, 13-Punta Tuna. Topographic Quadrangles combined into single Hazard Maps are: 4 & 5 (Fajardo & Cayo Icacos), 7 & 9 (Punta Puerca & Naguabo), and 12 & 13 (Yabucoa & Punta Tuna).

Table 1. Tropical storms and hurricanes affecting Puerto Rico.

Yr/Mo	Note[1]	Imp[2]	Type[3]	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
1979/8-9	*	A	H	E-W	David
1979/7	L	N	T	NE-NW	Frederic
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

1 L - landfalling storm
\# - storm passing over small portion of island
* - no landfall but passed near enough to impact island

2 Imp = portion of island impacted; letters are compass directions

3 T - tropical storm
H - hurricane

Table 2. Historic earthquakes affecting Puerto Rico (Díaz, 1990)

Year	Magnitude[1]
1787	8 to 8.2
1867	7.8
1917	7.0
1918	7.5
1943	7.8
1946	7.6 to 8.1
1946	7.0
1948	7.3

1 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).

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Table 3. Tsunamis affecting Puerto Rico

Date	Location	Wave Run-up[1] (m)	First[2] Motion	Comments
18Nov1867	Fajardo	obs	F	small wave
18Nov1867	Vieques	obs	F	high wave
18Nov1867	Yabucoa	obs	F	sea retreated 137m
17Mar1868	Arroyo	obs	F	small recession and flooding
17Mar1868	Naguabo	obs	F	small recession and flooding
11Oct1918	Aguadilla	3.4		
11Oct1918	Río Loíza	1.0	F	
11Oct1918	Arecibo	0.6		
11Oct1918	Boquerón	1.5		
11Oct1918	Guánica	0.5		
11Oct1918	Isabela	2.0		
11Oct1918	Isla Caja de Muertos	1.5		
11Oct1918	Mayagüez	1.5		
11Oct1918	Ponce	obs		
11Oct1918	Punta Agujereada	6.0		
11Oct1918	Punta Borinquen	4.5		
11Oct1918	Punta Higüero	5.2		
11Oct1918	Río Culebrinas	4.0		
4Aug1946	San Juan	obs		
8Aug1946	San Juan	obs		
8Aug1946	Aguadilla	obs	F	sea retreated 24m
8Aug1946	Mayagüez	obs	F	sea retreated 76m

1 obs - tsunami motion or its effects was observed but amplitude not reported

2 R - rise in water level
F - fall in water level

Table 4. Historic river floods in Puerto Rico shown on the Coastal-Zone Hazard Maps (excerpted from U.S.G.S. Division of Water Resources records).

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

Table 5. List of USGS Hydrologic Investigations Atlases for Puerto Rico.

HA-77	Bayamön and Cataño (Lopez, 1962)
HA-128	Toa Alta, Toa Baja, and Dorado (Lopez, 1964)
HA-261	Ponce (Hickenlooper, 1967)
HA-262	Barceloneta and Manatí (Hickenlooper, 1967)
HA-265	Humacao (Lopez, 1967)
HA-271	Arecibo (Hickenlooper, 1968)
HA-288	Mayagüez (Hickenlooper, 1968)
HA-289	Vega Alta and Vega Baja (Hickenlooper, 1968)
HA-375	Añasco, (Fields, 1971)
HA-382	Yabucoa (Fields, 1971)
HA-414	Guayanilla-Yauco (Fields, 1971)
HA-438	Caguas, Curabo, Juncos, and San Lorenzo (Fields, 1972)
HA-445	Patillas-Maunabo (Haire, 1971)
HA-446	Guayama area, (Haire, 1971)
HA-447	Salinas (Haire, 1971)
HA-448	Santa Isabel (Haire, 1971)
HA-456	Río Guanajibo Valley (Haire, 1972)
HA-457	Aguadilla-Aguada (Johnson, 1972)
HA-532	Eastern Lajas valley and the lower Río Loco basin (Johnson, 1974)
HA-533	Carolina-Río Grande (Haire, 1975)
HA-545	Fajardo-Luquillo (Haire, 1975)
HA-584	Naguabo (Haire, 1978)

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