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Another Look at the Impact of Hurricane Hugo on the Shelf and Coastal Resources of Puerto Rico, U.S.A.

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ABSTRACT

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Hurricane Hugo struck Puerto Rico on 18 September 1989. Coastal zone resources as diverse as offshore sand deposits, recreational beaches, and coral reefs were affected. Initial observations made during the week of the storm and subsequent observations are part of an ongoing shelf and coastal resources monitoring project.

Cores and aerial photographs reveal that at least 100,000 m^3 of sand was removed from the Escollo de Arenas, a large offshore sand deposit (90×10^6 m^3).

The berms of the beaches along the eastern and northern coast of the island were severely eroded. Wave impact and coastal flooding were augmented by a 0.6 m high tide and a 0.7 m storm surge in San Juan. Overwash fans containing about 5×10^4 m^3 of sand were deposited behind the frontal dune line in Piñones (east of San Juan). Approximately 90% of this material is considered to be unrecoverable, deposited in mangrove swamp or removed as part of street clearing efforts. At other sites, material lost from the berm was moved offshore and deposited in the nearshore zone.

Follow-up profiling shows that Hugo provided only a minor perturbation in the seasonal cycle of beach changes at most sites. In areas where a large volume of sand was deposited inland or below the seasonal wave base, the recovery has been slow.

Reconnaissance surveys in eastern Culebra show almost total destruction of the shallow coral, *Acropora palmata* whereas only partial destruction occurred to the corals off western Culebra and in Vieques Passage. Tens of square kilometers of highly productive seagrass meadows were destroyed by the formation of large sediment "blowouts."

ADDITIONAL INDEX WORDS: *Puerto Rico, berms, shoreline erosion, beach profile, coastal flooding.*

INTRODUCTION

Hurricane Hugo struck the Commonwealth of Puerto Rico on September 18, 1989, with winds greater than 240 km/hr (150 mph). The previous hurricane to make landfall on the island was Santa Clara in 1956. Unfortunately, no data is available on coastal and shelf response to major hurricanes before Hugo, so comparisons to previous storms are not possible. Natural coastal zone resources as diverse as offshore sand deposits, recreational beaches, and coral reefs were degraded by the storm. On an island where more than 85% of the population lives within 7 km of the sea and is dependant on the tourism that its beaches and coral reefs attract, it is necessary that a high-quality scientific data base be made available to help formulate public policy regarding residential and commercial rebuilding along the coast, beach replenishment, and future utilization of marine resources. Information concerning offshore mineral resources, specifically sand and gravel for construction and beach replenishment, is of major importance because suitable onshore sources have been depleted (COMMITTEE ON PUERTO RICO AND THE SEA, 1974, pp. 88–89).

Previous studies have discussed the impact of Hugo on Puerto Rico. RODRIGUEZ and WEBB (1990) discussed the immediate impact of the storm on the coastal resources. Aerial observations right after the storm suggested that a major portion of the Escollo de Arenas had been dispersed over the surrounding sea grass beds and that beach erosion occurred along several sections of the northeast coast. BUSH (1991) noted how the steep, rocky nature of the coastal zone, combined with low maximum storm surges, helped keep property damage at a minimum. However, crowding of

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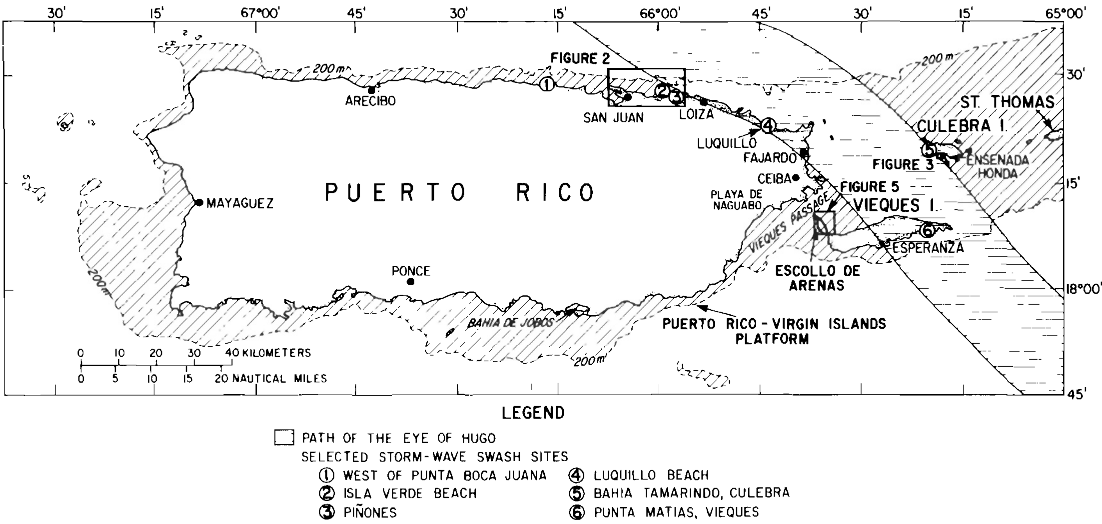

Figure 1. Index map of Puerto Rico showing the path of the eye of Hurricane Hugo and site localities discussed in the text. Numbers in circles are locations of storm wave swash measurements given in Figure 7. Boxed areas are locations of subsequent figures.

buildings into coastal lowlands and poor construction quality worked to increase damage in places.

A cooperative U.S. Geological Survey (USGS)-Department of Natural Resources (DNR) of Puerto Rico project has been monitoring important beach and shelf resources for about 20 years. This report examines the impact of Hurricane Hugo on resources of greatest interest to that project, namely, the Escollo de Arenas, the largest known submerged sand deposit in eastern Puerto Rico, and on the beaches in the vicinity of San Juan. As a direct consequence of Hugo, the coastal

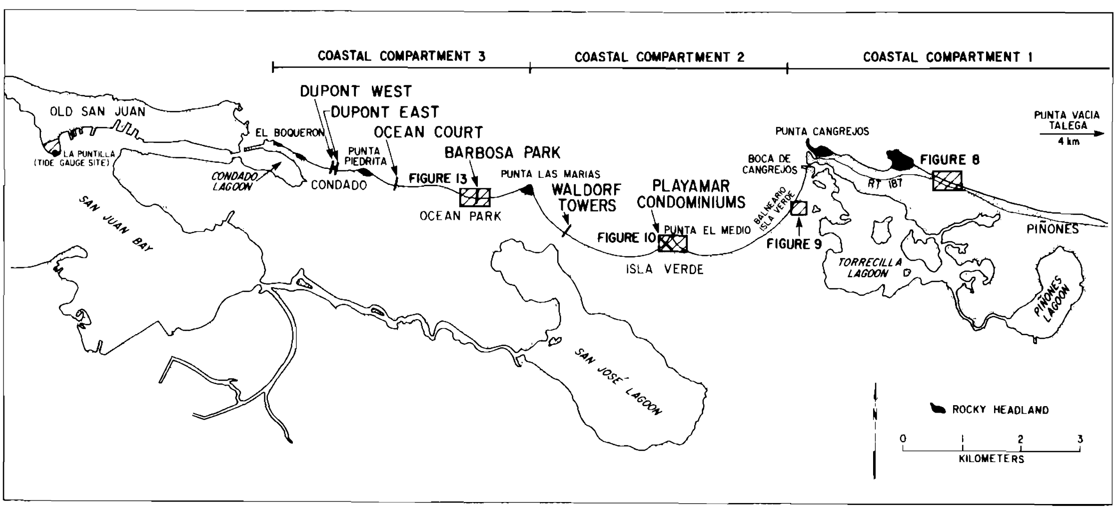

Figure 2. San Juan metropolitan area and coastal compartments. Also shown are locations of aerial and other photographs (Figures 8, 9, 10, and 13). Heavy lines perpendicular to shore are locations of beach profile sites discussed in text.

Figure 3. Aerial photograph of Ensenada Honda, Culebra, Puerto Rico taken on October, 1989. Strong winds combined with the storm surge jammed four sailboats under the bridge. Approximately 100 vessels out of 300 that took shelter in the "hurricane proof" harbor were sunk.

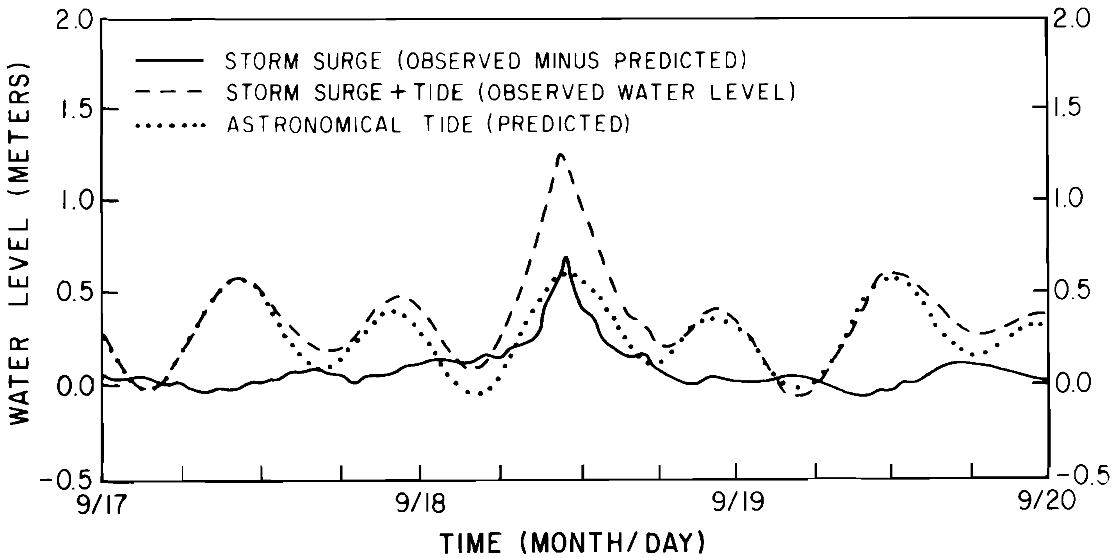

Figure 4. Hourly water levels at La Puntilla in San Juan Bay over a three day window (NOAA, 1989).

shelf monitoring project has been expanded to include assessments of coral reefs and seagrass beds.

THE STORM

Hurricane Hugo approached the U.S. Virgin Islands on 17 September 1989 as a Category Four hurricane with maximum sustained winds of 225 km/hr (140 mph) and a minimum sea level pressure of 934 mb (NOAA, 1990). The eye of Hurricane Hugo passed directly over St. Croix in the U.S. Virgin Islands and continued travelling in a WNW direction. During the morning of September 18, Hugo passed over the islands of Vieques and Culebra, and over the eastern and northeastern tip of Puerto Rico (Figure 1). Radar observations and satellite images revealed that the west side of the eyewall moved over land while the eastern side of the eye remained over water. Maximum winds at the San Juan metropolitan airport (Figure 2) were measured around 1030 hr. By noon, barely six hours after hitting Vieques, Hugo was approximately 30 km north of San Juan with maximum sustained surface winds down to 123 km/hr (77 mph) with gusts to 147 km/hr (92 mph) and minimum sea level pressure of 957 mb (NOAA, 1990). The lowest surface pressure recorded on Puerto Rico during Hugo was 946 mb at Ceiba (NOAA, 1990).

Hurricane Hugo caused tremendous damage to the development and infrastructure of eastern Puerto Rico. Over 80 percent of wooden structures were destroyed in Culebra and Vieques (FEMA, 1989). Thirty-thousand people were left homeless and property damage exceeded $1 billion. Thousands of boats were destroyed. Boat owners as far away as San Juan and St. Thomas took their vessels to Ensenada Honda, a legendry "hurricane-proof" bay at Culebra (Figure 1). Sustained southerly winds of 193 km/hr (121 mph) with gusts to 240 km/hr (150 mph) (GOLDEN, 1990) created a wave setup in Ensenada Honda estimated at greater than 4 m. Vessels 20 m and longer in length were carried up and over the coastal road with several sailboats ending up wedged under a bridge (Figure 3).

Results from computer simulations developed by NOAA called SLOSH models (for Sea, Lake and Overland Surges from Hurricanes) predicted a 2–3 m rise in sea level for Vieques Passage (MERCADO, *personal communication*, 1989). Observations of storm-swash debris lines indicate that these levels were attained. At about 10:30 a.m. local time, the hurricane was reaching its maximum intensity in San Juan. At La Puntilla in San Juan Bay (Figure 2), a 0.73 m storm surge developed coincident with the predicted astronomical high tide of 0.61 m (Figure 4) resulting in a water level of 1.34 m above Mean Low Water (MLW). The previous historical high of 0.73 m above MLW

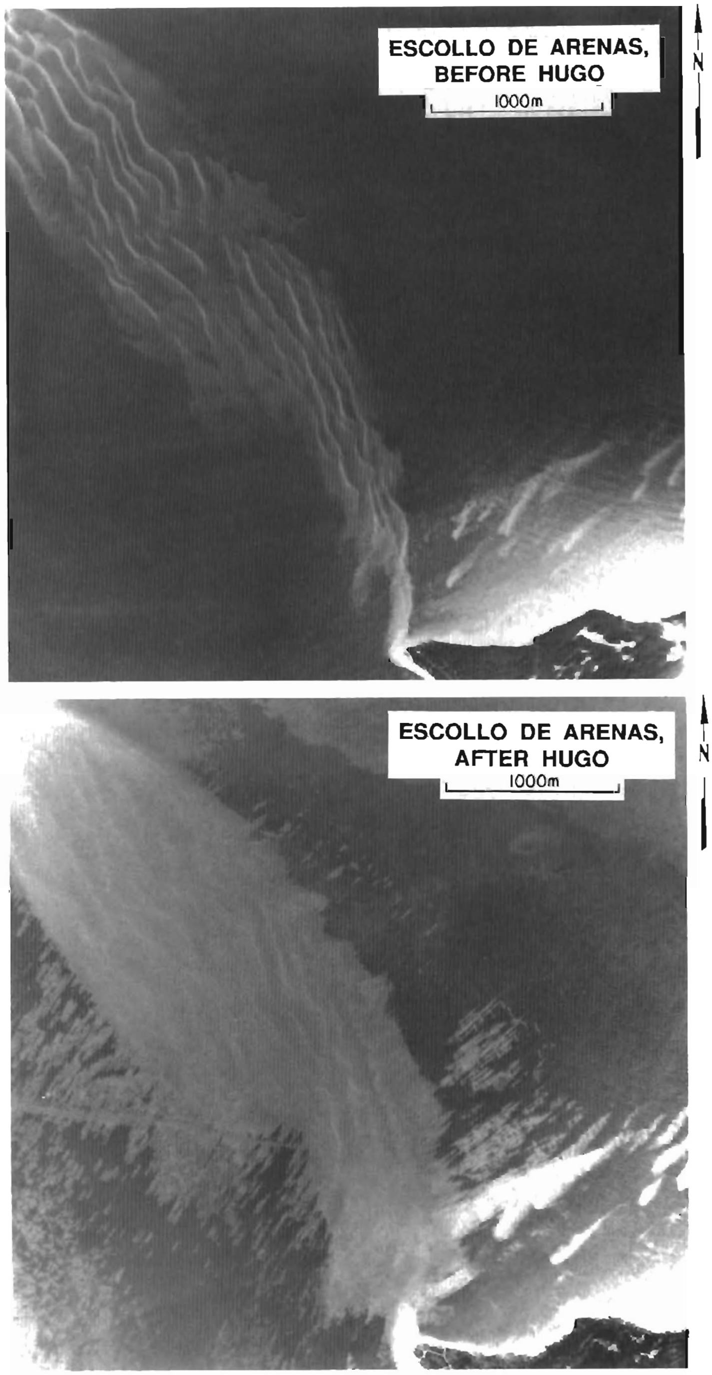

Figure 5. Aerial view of the Escollo de Arenas before and after Hugo. (Upper) Before Hugo. Note the well-developed bedforms on the surface of the sand deposit. The area of the deposit is approximately 3 km^2. (Lower) After Hugo. Hugo smoothed the characteristic bedforms of the surface of the deposit, dispersing sand over the adjacent sea floor. Seagrass beds to the east and west of the Escollo were buried. The resulting sand apron and large "blowout" areas of grass removal increased the area of exposed sand by 60%.

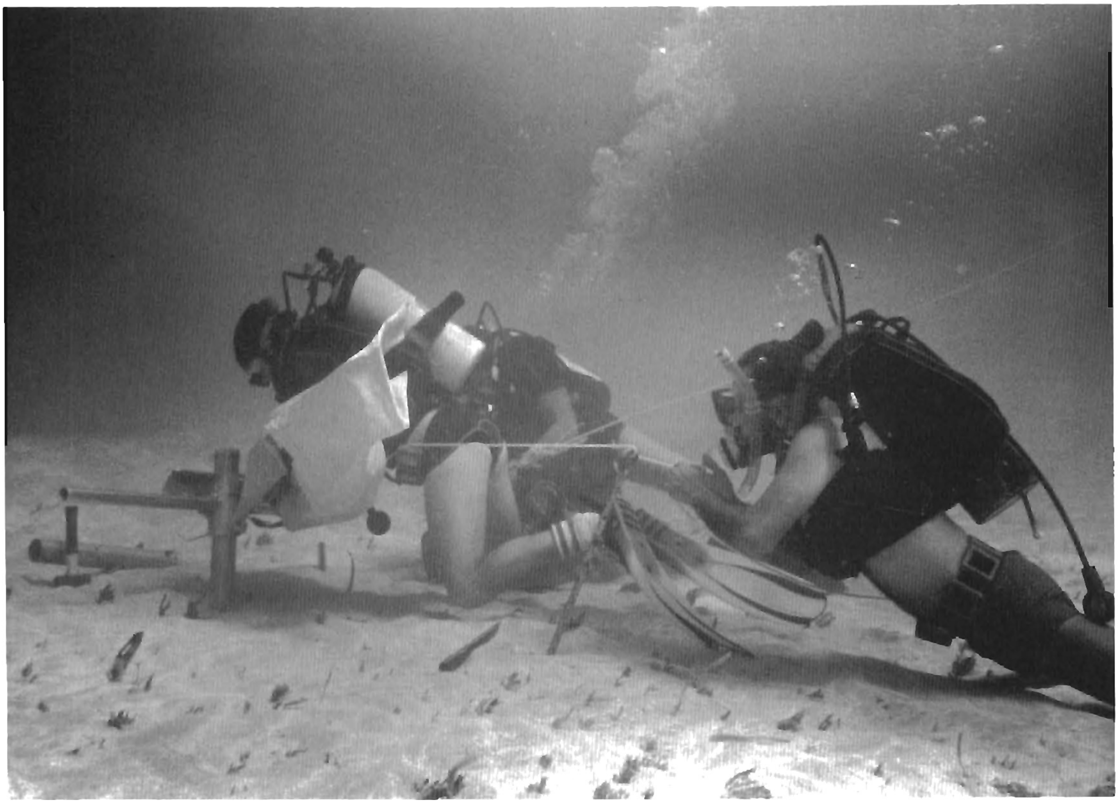

Figure 6. Underwater photograph showing sand covering seagrass beds on the fringes of the Escollo de Arenas.

occurred in November of 1982 (NOAA, 1989). The SLOSH model hindcast a water level between 1.0 and 1.4 m above MLW for northern San Juan Bay.

An interesting aside is that heavy rainfall was of limited extent, and Hugo passed over the island very quickly; therefore, it was considered a "dry hurricane". Minimal flooding occurred away from the coastal zone because torrential rains fell only in limited areas over the northeast part of the island. Rain gauges in Puerto Rico and the U.S. Virgin Islands averaged between 12 and 23 cm (5–9 in) of rainfall with a maximum of 34.41 cm (13.55 in) in the mountains of northeastern Puerto Rico (NOAA, 1990).

IMPACT OF HURRICANE HUGO ON THE ESCOLLO DE ARENAS

The Escollo de Arenas is an offshore sand and gravel deposit located off the northwest tip of Vieques Island (Figure 1). About 90 × 10^6 m^3 of sand and gravel form a 6 km by 0.1–1.0 km shoal (RODRIGUEZ and TRIAS, 1989) regarded as an important potential economic resource. Water depths over the shoal generally range from 4 to 8 m, except near Vieques Island where the water shoals to 2 m. The bathymetry of Vieques Passage in the area surrounding the shoal is irregular. Isolated high areas are present and water depths generally range from 10 to 18 m.

Tidal currents with velocities that commonly exceed 140 cm/s maintain a wide variety of bedforms on the surface of the shoal (RODRÍGUEZ, 1979). Sandwaves having wavelengths on the order of 100 m and amplitudes of 2 to 3 m are the most common bedform. Hurricane Hugo smoothed these bedforms and dispersed the sediment over the adjacent sea floor (Figure 5) increasing the areal extent of the shoal by 60%. Most of the redistribution occurred along the eastern margin

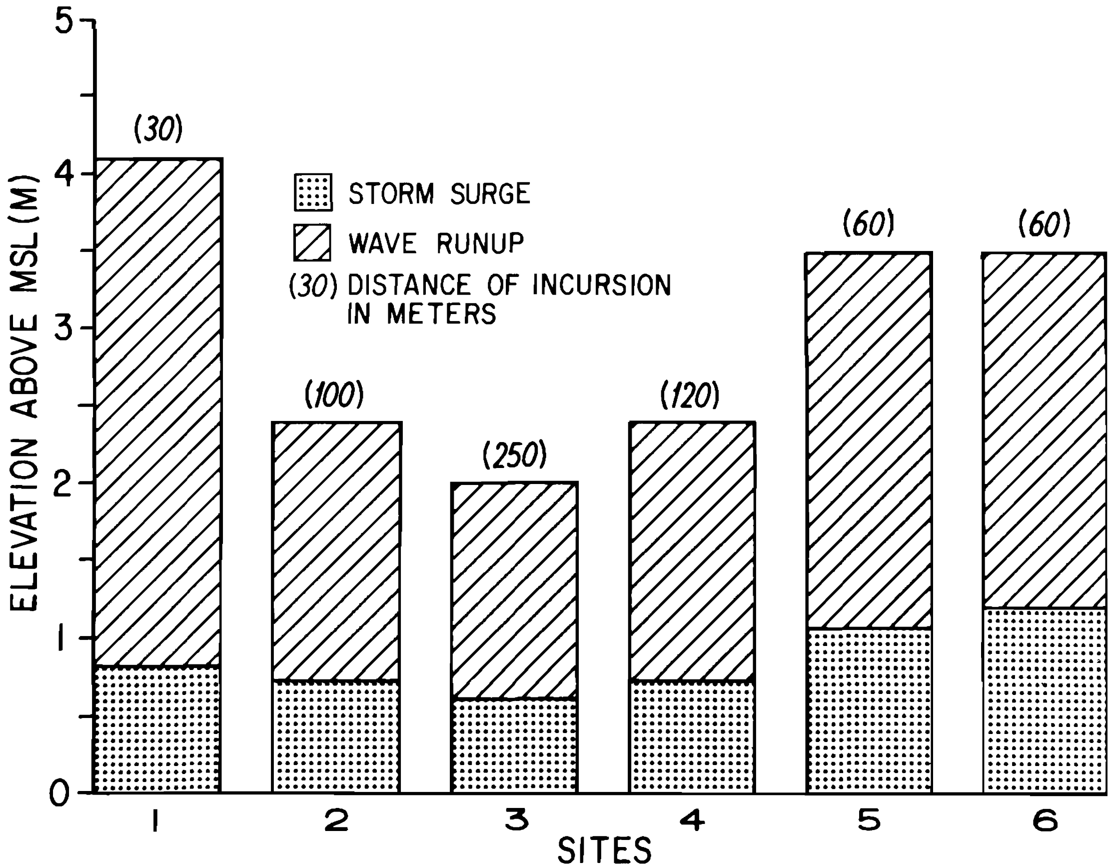

Figure 7. Storm-wave swash for six sites in Puerto Rico. Site location numbers are shown on Figure 1. Storm-wave swash is a combination of storm surge and wave runup. Storm surge was similar for the six sites, but wave runup varied as a function of coastal profile. Landward incursion of storm water is given by the values in parentheses at the top of each column. Coastal flooding was severe in low lying areas (sites 2, 3, 4). Although storm wave swash was greater in steeper profile areas (sites 1, 5, 6), overall incursion was less.

of the Escollo, burying over 1 km^2 of seagrass beds. The algal plains along the western margin were also severely affected by the formation of large northeast trending "blowouts" or areas of deep scouring of the seagrass meadows. Vibracores taken three months after Hugo showed 5 to 10 cm of sand deposited on the seagrass beds (Figure 6). These results coupled with aerial photo-interpretation suggest an unrecoverable loss of between 10 and 20 $\times$ 10^5 m^3 cubic meters of sand from the Escollo (worth more than \$2,000,000 at current market prices). The loss is considered unrecoverable from a commercial standpoint because the sand was deposited as a thin layer on top of a muddy substrate typical of seagrass bed communities. Mining of that sand could cause resuspension of muds which could undoubtedly have detrimental effects to coral reefs in the vicinity.

HUGO'S IMPACT ON SAN JUAN'S BEACHES

The beaches and coastal development along the northern and eastern coasts were damaged by direct wave impact, sand overwash, undermining of structures, and local flooding. The degree of impact depended on the shoreline composition (rocky versus sandy stretches) and morphology, the degree of exposure to open sea, and the elevation of the backshore area. Wave run-up heights and incursion distances were measured using standard

Figure 8. Aerial view of heavily overwashed section of Piñones. See Figure 1 for location. (Upper) Before Hugo. The artificial dune discussed in the text was located in the right half of the photograph. (Lower) After Hugo (October 1989). More than 40,000 m^3 of sand overwashed across the road effectively removing the material from the active beach system. Whereas vegetation worked to restrict the extent of the overwash, roads perpendicular to shore acted as conduits, allowing the overwash to penetrate several hundred meters inland in places.

Figure 9. Balneario Isla Verde (see Figure 2 for location). (Upper) January 1988 photograph of Balneario parking lot. Scarp has been maintained by frequent storms. Arrow points to light pole that was toppled by Hurricane Hugo. (Lower) September 1989 photograph showing Hugo erosional scarp and toppled light pole.

Figure 10. Empress Hotel boardwalk located at Punta El Medio. An extensive boardwalk, bar and pool built out over the ocean in the mid-1980's was destroyed by Hugo and has since been rebuilt.

surveying techniques. Coastal flooding around the island was augmented by hurricane-generated waves that reached maximum heights of about 4 m. The combination of storm surge and the wave runup caused severe coastal flooding in low-lying areas (Figure 7).

The coastline in the San Juan area is compartmentalized into short sandy sections divided by rocky headlands. This report concentrates on three coastal compartments (from east to west): Punta Vacía Talega to Punta Cangrejos, Punta Cangrejos to Punta Las Marias, and Punta Las Marias to El Boquerón (Figure 2).

Baseline beach profiles for these areas have been collected intermittently since 1984 (VELAZCO *et al.*, 1986). Prior to Hugo, two-dimensional profiles measured shape of beach and distance from a fixed benchmark established at the landward edge of the backbeach area at 23 sites. New equipment utilized since Hugo allows three-dimensional measurement of beach volume changes. The new data is preliminary, however, so all references to beach profiles in this paper are to two-dimensional profiles and beach widths. Beach widths were determined as the intersection of an arbitrary datum (average elevation of the lower limit of the swash zone) with the beach profile. From 1984 to 1985, beach widths in San Juan eroded or accreted as much as 20 to 30 m in response to seasonal changes in wave height and direction (WEBB and VELAZCO, 1991). However, the average rate of change in beach width over the 5 years studied ranged from 1–4 m/yr.

Storm waves generated during Hugo destroyed ten beach profile benchmarks by undermining the structures that supported them. Subsequently, five of the benchmarks were reestablished. Of 18 beach sites profiled before and after the hurricane, eight stations experienced an average width loss of 4 m, two stations remained the same width, while eight stations were wider by an average of 7 m. All beach profiles were flattened by the storm waves making the beaches more vulnerable to overwash and flooding after the storm.

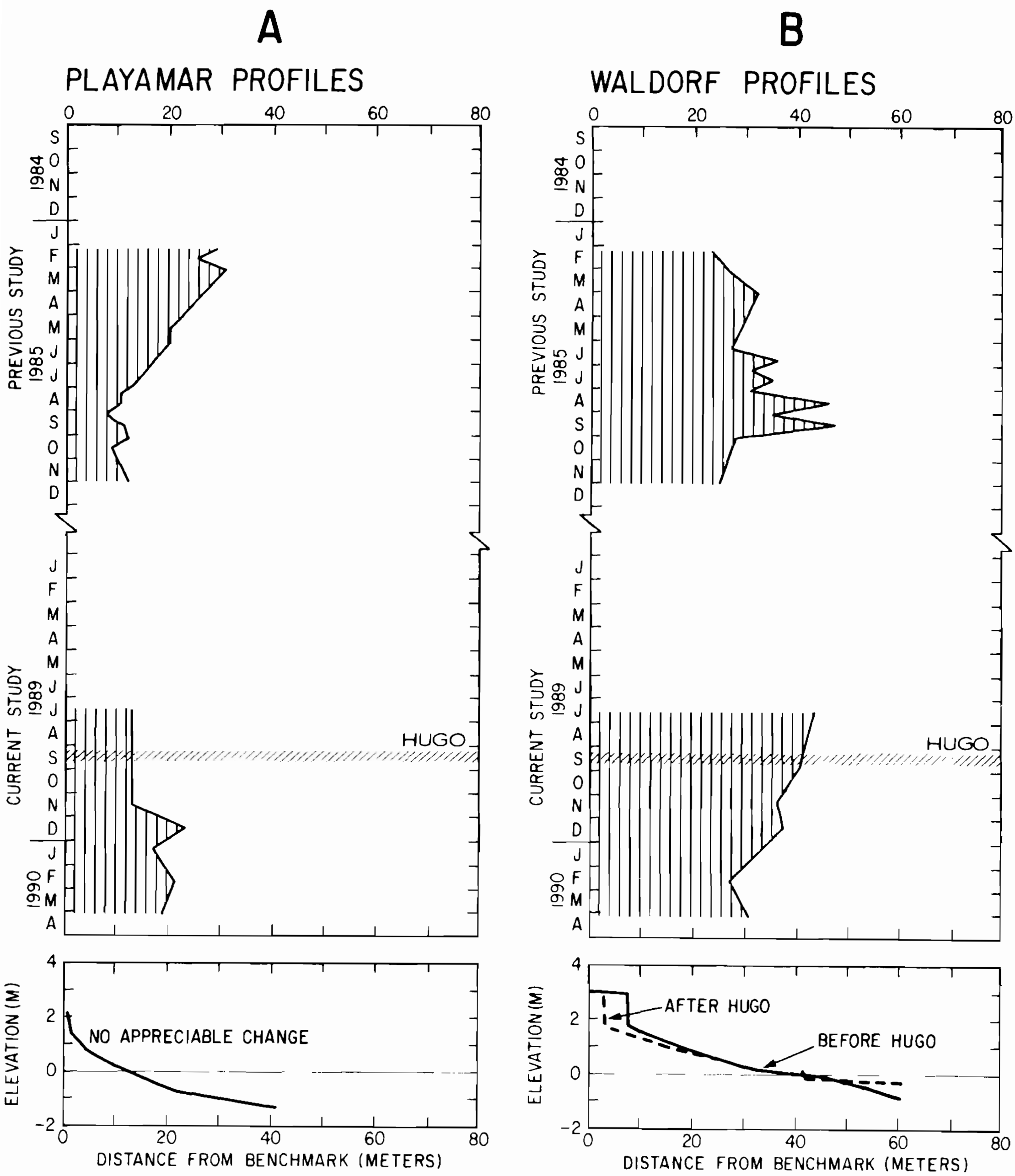

Figure 11. Distance from benchmark versus time as observed from October 1984 to November 1985 and again from July 1989 to April 1990. The profiles beneath the graphs show the change in the beach morphology caused by Hugo. (A) Playamar, (B) Waldorf Towers, (C) Barbosa Park, (D) Ocean Court, (E) Dupont East, and (F) Dupont West (see Figure 2 for locations).

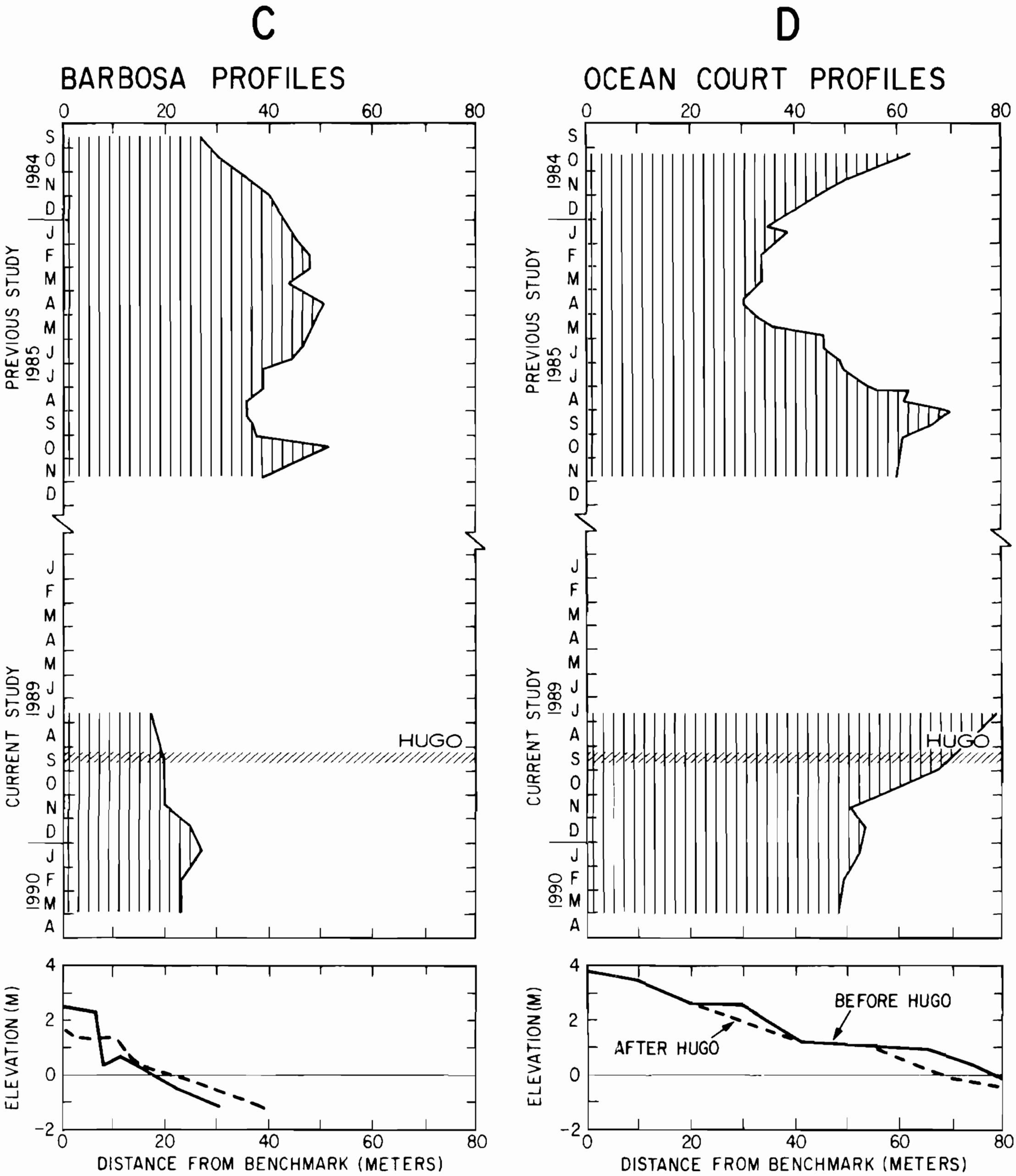

Figure 11CD.

The worst structural damage (qualitatively measured) occurred in areas that have been overwashed and flooded in the past by storm swells generated by extratropical storms. For example, the overwash pattern observed in the San Juan area after Hugo was almost identical to the storm wave swash from several winter storms as reported by FIELDS and JORDAN (1972). In most

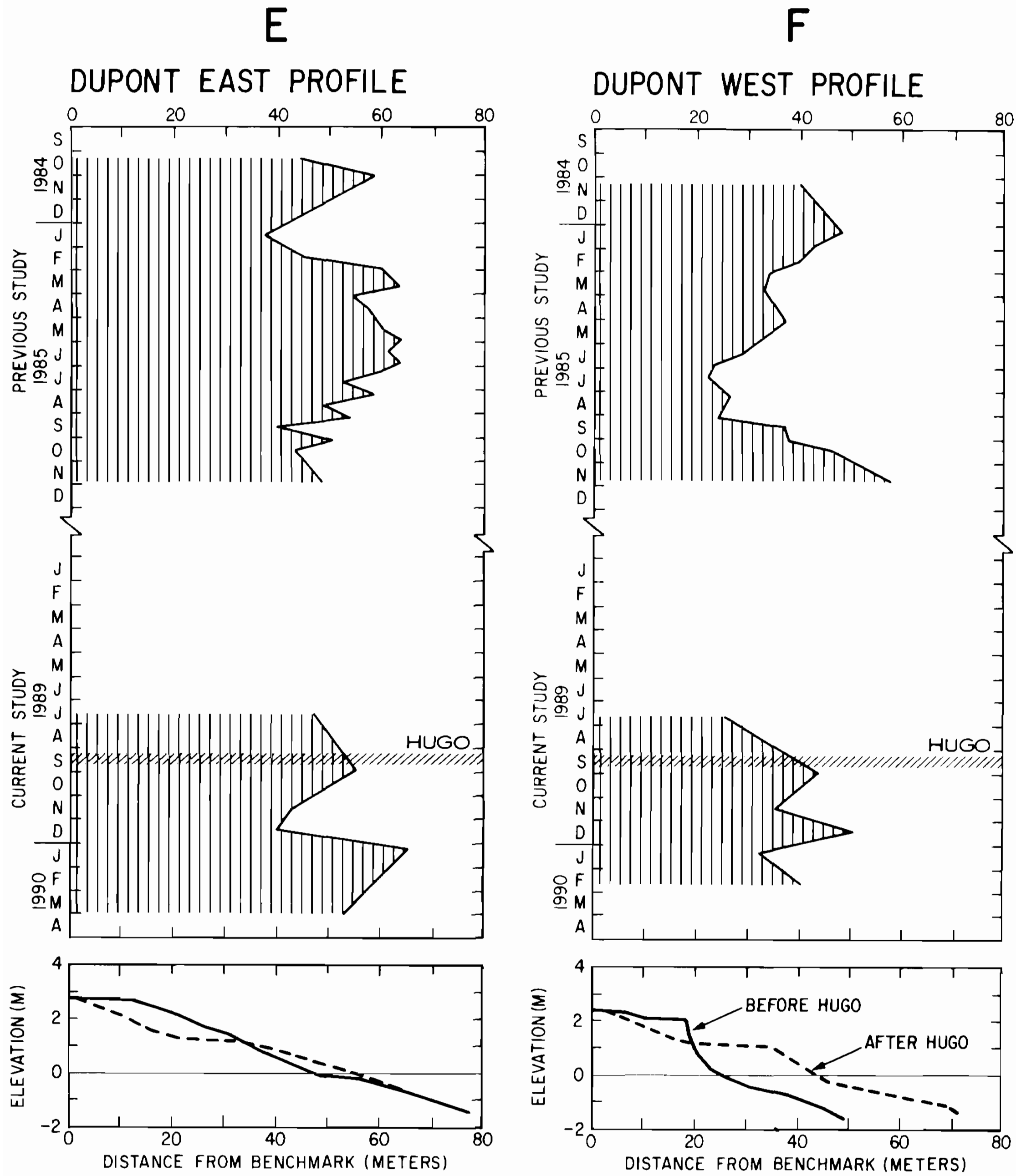

Figure 11EF.

cases, the overwash and undermining has been exacerbated by conflicts between natural processes and man-made structures.

Follow-up profiling studies show that the impact of Hugo on beaches where the sand remained in the active beach system (documented here for 6 of 24 monitoring sites) produced only a temporary perturbation in the seasonal cycles. Longer

Figure 12. Photograph of Waldorf Tower Condominium ocean front showing effects of Hurricane Hugo.

term impacts are being felt on beach systems that were overwashed or on those that suffered major erosion of vegetated back-beach scarps. Where present, the scarps effectively become the shoreline during periods of heavy swell. As the scarps are further eroded, the development behind them becomes more vulnerable to coastal flooding. In general, overwash did not occur where the backshore elevations exceeded 3 m.

Following is a detailed description of specific profile locations within the three coastal compartments in the study area (Figure 2):

Punta Vacia Talega to Punta Cangrejos

Long-time residents of the Piñones sector state that overwash has been common in the area following removal of a massive dune system bordering the north side of highway 187 for fill in the 1950's. Without the protection of the dunes, even moderate energy waves have the potential to overwash the road and deposit the sand in the mangroves of Torrecilla Lagoon. In 1986, the U.S. Army Corps of Engineers constructed a 56,000 m^3 artificial dune along a 300 m section of the road in order to mitigate the problem. The project cost approximately $300,000. In 1987, an extratropical storm generated swells that impacted the Piñones area, eroding a large portion of the artificial dune. Hugo completed its total destruction, carrying the remaining material landward. A total of over 500,000 m^3 of sand was overwashed along the entire 1 km stretch of shoreline of coastal compartment 1 (Bush, 1991). The thickness of the deposit exceeded 1 meter along several kilometers of Highway 187. In the aftermath of Hugo, the Puerto Rico Department of Natural Resources used heavy equipment to return 46,000 m^3 of the overwashed sand back to the active beach system. Whereas vegetation worked to restrict the landward extent of the overwash penetration, roads

Figure 13. Aerial view of Barbosa Park (see Figure 2 for location). (Upper) Before Hugo (August 1989). Significant quantities of sand are regularly deposited on the shore parallel street by minor overwashes and eolian transport. (Lower) After Hugo (October 1989). Overwash extended across the street into the track area.

perpendicular to shore acted as conduits, allowing the overwash to penetrate several hundred meters inland in places (Figure 8).

Punta Cangrejos to Punta Las Marias

Balneario Isla Verde

The rapidly eroding shoreline is evidenced by a stranded boat ramp some 50 m from shore. When storm events are relatively frequent, a 1 m scarp is maintained along the northern section of beach where a paved parking lot is eroding (Bush, 1991). Hugo further undercut the parking lot causing 10 m of retreat, leaving behind a fresh scarp (Figure 9). Farther south along the open beach most used for recreation, Hugo flattened the natural berm, undercutting several lifeguard stands and shower facilities located within 15 m of the shoreline. The storm waves lowered the beach face several feet, exposing fresh beachrock. In the days following Hugo, the beach material was redistributed into large cusps with a 20 m spacing. Two years after Hugo, the scarp and the beach had returned to

Figure 14. Barbosa Park after Hugo (September 1989). Hurricane Hugo destroyed the sidewalk and undermined the street.

the previous position and a beach profile close to equilibrium had been established.

Punta El Medio to Punta Las Marias

Both the Empress Hotel, built on Punta El Medio, and the infrastructure in front of the Playamar Condominium were heavily impacted by Hugo (Figure 10). Although the beach on the western flank of the point changed little (Playamar profile, Figure 11A), the sidewalk was undermined and the adjacent streets flooded.

East of Punta Las Marias, the shoreline has retreated more than 50 meters since the 1930's. Hugo damaged the seawalls and gabions but did not cause extensive flooding or alter beach width or the profile significantly. Farther east, Hugo cut heavily into the berm behind Waldorf Towers (Figure 11B) destroying the sidewalk (Figure 12).

In contrast, between the Playamar profile and the Waldorf Tower sites, a broad depositional beach withstood the storm waves with minimal amount of backbeach flooding and no noticeable change in beach width and profile.

Punta Las Marias to El Boquerón

Barbosa Park

Battered seawalls extend from Punta Las Marias to Barbosa Park preventing sand from overwashing but also from forming natural dunes. At Barbosa Park significant quantities of sand are regularly deposited on the shore-parallel street north of the park by minor overwash events and eolian transport. Hurricane Hugo caused a major overwash and significantly altered the profile of the beach (Figures 11C and 13). To maintain the street clear of sand, the municipality regularly collects and transports the sand offsite. Removal of that sand has prevented the natural rebuilding of sand dunes that existed there before the road was built. Hugo destroyed the sidewalk and undermined the streets (Figure 14).

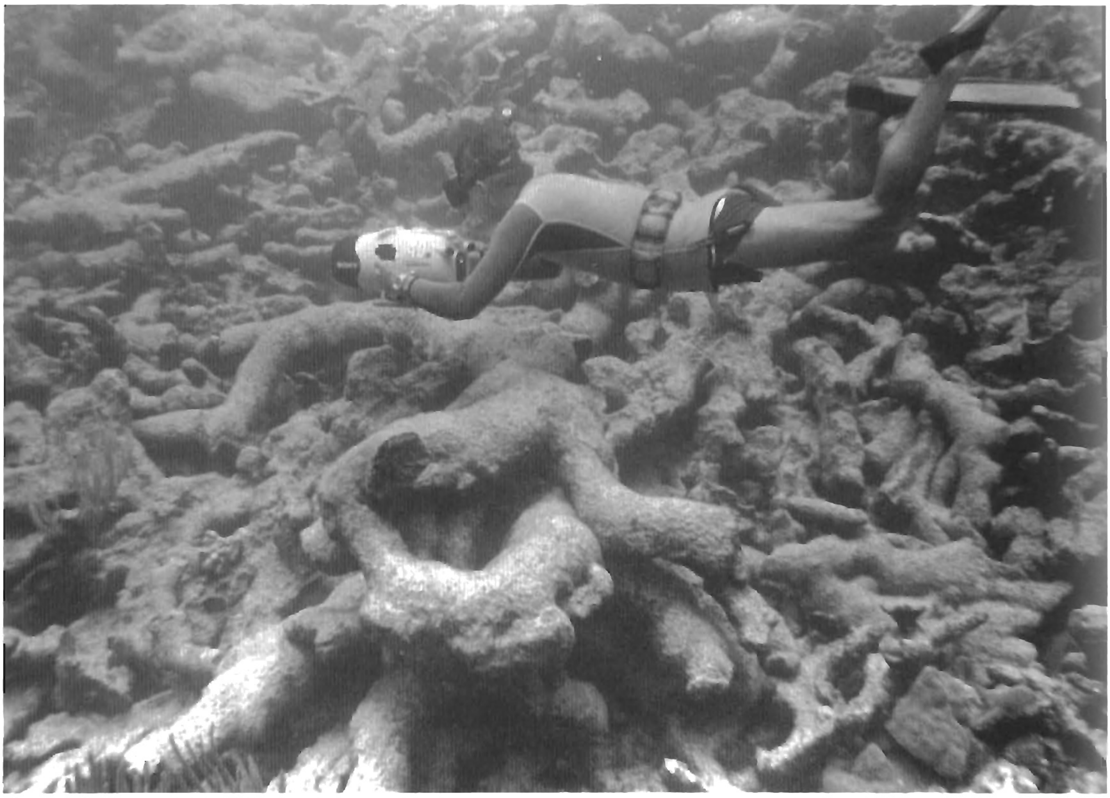

Figure 15. Underwater photograph of coral rubble in eastern Culebra (July 1991). E. Shinn photograph.

Ocean Court

The Ocean Court beach has typical seasonal cycles, wider in the summer and narrower in the winter (Figure 11D top). Hugo flattened the beach (Figure 11D bottom). The backshore elevation is approximately 4 m and flooding did not occur.

Dupont Plaza

A groin west of Punta Piedrita (behind the Dupont Plaza Hotel) traps sand travelling to the west during the summer when winds and associated wave trains are from an easterly direction. An opposite pattern is commonly observed during the winter season with the arrival of storm waves from western North Atlantic extratropical depressions. Wave erosion diminishes the beach to the east of the groin during the winter as the longshore transport to the west slows and even reverses (Figure 11E and 11F, top). Hugo-generated waves arrived from a more northerly direction and thus reversed the sand transport direction to the east. During Hugo, the beach on the west side of the groin increased much more than that on the east side (Figure 11E and 11F, bottom).

IMPACT ON CORAL COMMUNITIES

Coral reefs are important to the local fishing industry as sites of high biological productivity and are visited by thousands of tourists every year. The effect of Hugo on corals was patchy and diverse. Damage was minimal on the south coast of Vieques and in Vieques Passage but extensive to the coral reefs on the east side of Culebra. Approximately 10% of the live colonies of *Acropora palmata*, the principal builder of reefs in the Caribbean, inspected in Vieques Passage showed damage attributable to the hurricane. However, nearly total destruction of this species occurred in eastern Culebra (Shinn, *personal communi-*

Figure 16. Mat of seagrass debris deposited by Hugo onto the beach at Esperanza, Vieques.

cation, 1991). The finger coral, *Porites porites*, and staghorn coral, *Acropora cervicornis*, were also greatly affected. Large quantities of these delicate branching corals had been reduced to gravel-size rubble forming steep (20° to 30°) debris slopes (Figure 15) that buried boulder corals such as *Montastraea annularis*. In spite of the devastation, the reefs on the eastern side of Culebra are showing signs of healthy regrowth (SHINN, *personal communication*, 1991). Monitoring of coral community response will continue as part of the USGS-DNR project.

IMPACT ON SEAGRASS BEDS

Seagrass beds serve as the habitat for a diverse population of flora and fauna. In the Caribbean, they are important for their function as a nursery for the spiny lobsters and other crustaceans and juvenile fishes. Bottom currents generated by Hugo were sufficiently strong to scour out the sediments from around the roots of the seagrass. The storm waves tore up extensive areas of seagrass and deposited the debris on beaches on the south coast of Vieques Island and along the south and southeast coast of the main island. The mat of seagrass debris on the beach at Esperanza, formed a large spit (approximately 2,000 m^2) over a meter thick (Figure 16). More than a square kilometer of seagrass beds were uprooted around the Escollo de Arenas, and another 1 to 2 km^2 were covered with sand. Significant deposits were found as far west as Jobos Bay where a mixture of calcareous sand and seagrass debris formed a 0.5 m thick overwash deposit in the adjacent mangroves. Likewise, the main ocean street in Playa de Naguabo was covered by 0.5 m of seagrass debris in places. Monitoring of seagrass bed recovery and dynamics will continue as part of the USGS-DNR project.

SUMMARY AND CONCLUSIONS

Hugo was the most intense Hurricane to impact Puerto Rico since 1956, and the first since regular coastal and shelf monitoring began in the 1970's.

Hugo caused sea level to rise to record levels, resulting in severe coastal flooding, and impacted the coast with 4+ meter waves. Considering the intensity of Hurricane Hugo, the impact on the shelf and coastal resources of the island was limited. The impact of these storm forces on the beach and coastal resources of Puerto Rico are:

(1) Over 100,000 m^3 of sand from the Escollo de Arenas was spread out over adjacent seagrass beds.

(2) Hugo caused severe to moderate erosion of the beaches in the San Juan area.

(a) Hugo created new backshore scarps, temporarily increasing the vulnerability of the coast to future high-energy (greater than 3 m swell) storms.

(b) With the exception of major overwash deposits, it appears that most of the eroded material remained within the active beach system.

(c) Most of the beaches have now returned to their normal, seasonally-fluctuating behavior.

(d) New berms have formed with dimensions similar to those observed before the storm; the degree of protection to backbeach areas from moderate-energy (1 to 3 m swell) events is much the same as it was before Hugo.

(3) Hugo devastated the coral communities of Culebra while inflicting minor damage to the corals of Vieques Passage.

(4) More than a square kilometer of productive seagrass beds surrounding the Escollo de Arenas was uprooted and another 1 to 2 km^2 were covered by sand. Other seagrass beds off the eastern and southeastern coasts were also affected.

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