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Funding was provided by the Andrew W. Mellon Foundation to the Coastal Research Center of the Woods Hole Oceanographic Institution (WHOI) and the NOAA National Sea Grant College Program Office, Department of Commerce, under Grant No. NA86-AA-D-90.

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Technical Report

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Approved for Distribution:

David G. Aubrey, Director
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HURRICANE IMPACTS ON THE CARIBBEAN COASTAL/MARINE ENVIRONMENT: USING SCIENTIFIC ASSESSMENT TO PLAN FOR THE FUTURE

by

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Abstract

The passage of Hurricane Hugo through the eastern Caribbean provided a unique opportunity for multidisciplinary study of (1) the effects of severe storms on tropical coastal and marine ecosystems, and (2) the physical and biological responses of those ecosystems to intense storm-induced changes. In addition to its direct value as basic science, this study can be used to facilitate development of improved coastal and marine resource management capabilities.

1.0 Executive Summary

Hurricane Hugo wreaked havoc on coastal and marine ecosystems in the Caribbean; some of the damage will persist for years to come. Although hurricanes and tropical storms are natural episodic events, impacts from recent hurricanes may have been exacerbated by poorly planned development, previously stressed coastal ecosystems, and careless recovery efforts. Since some global climate models project future increases in both the frequency and severity of tropical storms and hurricanes, it is time that we learn from our past experiences to brace for the future.

Cross-comparison with data from other major hurricanes (including Gilbert and Allen) will allow us to generate a larger and more meaningful data set. We wish to test two hypotheses: 1) that marine ecosystem structure is shaped by severe episodic events, 2) that the impact from these events is accentuated when ecosystem stress causes pre-existing degradation of the coastal environment. The information garnered from this research will allow us to develop models which forecast large-scale ecosystem effects from tropical storms. The testing of the hypotheses and data analyses/model generation will require careful ecological and physical measurements of impact and recovery across many scales of ecosystem structure. A multi-disciplinary effort is required to

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achieve such a comprehensive assessment. The ultimate objective is to determine the relationship between episodic events and the structure of marine ecosystems in order to provide guidance for use and management of marine resources.

1.1 Research Scope

Marine and terrestrial ecosystems respond to environmental conditions on a variety of temporal and spatial scales. Tropical ecosystems generally evolve gradually and under conditions that include episodic disturbances. Occasionally, however, severe episodic events impact these systems and cause massive structural damage and impaired ecosystem functioning. A fine line exists between what can be considered normal episodic disturbance and atypical, prolonged disturbance and stress. The latter may be occurring more frequently as tropical storms increase in their intensity and make landfall on overdeveloped, acutely stressed coastal environments.

Due to the recent (1989) passage of Hurricane Hugo in the Lesser Antilles, and the earlier (1988) passage of Hurricane Gilbert in the western and central Caribbean, we have the opportunity to compare the impacts of severe storms on similar but geographically isolated habitats. More importantly, we have had the opportunity to examine impact, response, and recovery in areas that have been degraded by man's activities and compare those to more pristine and undisturbed areas. All of these opportunities increase the utility of this research for designing and implementing wise coastal management.

The scientific work focuses on the abiotic components of the environment and the physical processes that maintain the ecosystem, the biotic components that contribute to the trophic structure and biodiversity in different habitats, and the linkages between the physical and biological components of coastal systems. Important habitats in the tropical coastal landscape, including coral reefs, seagrass beds, sandy lagoons, mangrove systems, coastal ponds, and shorelines, have all acted as focal points for the assessment. Assessments include an inventory of physical damage to the terrestrial and marine portions of the coastal zone, an analysis of the extent to which physical biological processes have been altered by storm impact, and the generation of information allowing quantitative and qualitative modelling of storm surge, wave impact and uprush, wind impact, and population dynamics. The synthesis of information from affected areas has been facilitated by our own rapid response work and the large quantities of data generated by local scientists.

A major portion of our work has focused on translating scientific results into information useful to the regulatory sector. Effective risk assessment and management of tropical ecosystems is often hampered by poor scientific understanding. Even where good scientific information exists, it is often not made available to policy-makers and thus cannot be used as a basis for formulating effective management.

2.0 Hurricane Hugo

Hurricane Hugo, in 1989 was the strongest storm to strike the Caribbean since Hurricane Gilbert in 1988, and both caused much damage. The total property loss was more than $10 billion dollars with more than $7 billion of that in the continental United States and the remainder in the northeastern Caribbean. The total loss of life was 28 in the Caribbean and 21 in the continental United States, remarkably low considering the widespread destruction.

The total number of deaths associated with Hugo in the Caribbean is estimated as follows:

Antigua and Barbuda	1
Guadeloupe	11
Montserrat	10
St. Kitts and Nevis	1
Puerto Rico	2
U.S. Virgin Islands	3

On September 15th Hurricane Hugo was a category 5 hurricane, the strongest category, with a Mean Sea Level Pressure (MSLP) of 918 mb and an estimated maximum sustained surface wind speed of 160 miles h^{-1} (72 m/s) prior to entering the Caribbean. Fortunately, the hurricane weakened to a category-4 hurricane before entering the Caribbean.

A hurricane watch was first issued for the northeastern Caribbean islands from St. Lucia through St. Martin and the British Virgin Islands on the evening of September 15. Later that day, hurricane warnings were issued, and on the following day were extended to include Puerto Rico and the U.S. Virgin Islands. This meant that well over 24 hours of warning were provided prior to the center moving into the eastern Caribbean in the late evening and early morning hours of September 17 and 18. Response in the region was excellent based upon the relatively low loss of life from this category-4 hurricane which produced between $2-3 billion in damage in the region. This effective warning and response system was not something that just happened when Hugo appeared. It was the result of years of cooperative work by governments in the region.

The 1989 season was characterized as a Cape Verde (African) hurricane year in which seven of the tropical cyclones were named near those islands and then tracked westward across the Atlantic. The season had 11 named storms, seven of which acquired hurricane intensity. This compares to the past 50-year average of 9.5 tropical storms, of which 5.5 became hurricanes. Africa contributed 100% to the total number of storms during 1989, indicating the highly tropical characteristics of the 1989 hurricane season. This equals the value for 1979 when the Cape Verdetype hurricanes David and Frederic occurred. Typically, Africa is the main source of storms for the Atlantic basin.

The Hurricane Destruction Potential (HDP) is a measure of a hurricane's potential for wind and storm surge destruction. It is defined as the sum of the square of each hurricane's maximum winds for each six-hour period of its existence. The average HDP during African years of the 1967-89 period was larger than the average HDP of the non-African years. This continues to lend credence to the idea that usually the most intense hurricanes are spawned by African waves, thus underlining the importance of monitoring such waves.

2.1 Hugo's Meteorological Statistics

A reconnaissance aircraft reaching Hurricane Hugo, while it was in the Atlantic east of the Antilles, reported a central pressure of 918 mb, a wind speed of 85 m s^{-1} at an altitude of 500 m and a surface wind speed of 72 m s^{-1}. This turned out to be Hugo's maximum intensity and designated the cyclone as a category five hurricane.

On September 17th, just before Hugo's eye passed over Guadeloupe, an aircraft reported a wind speed of 70 m s^{-1} at 700 mb. A surface pressure of 941.4 millibars has since been reported from Guadeloupe (Table 1). It is estimated that the hurricane's maximum 1-min surface wind had decreased to 62 m s^{-1} at this time. The maximum surface wind was again estimated at 62 m s^{-1} when the eye passed over St. Croix at 0600 GMT on the 18th. Few direct tide gauge measurements of the storm surge water levels have been received, however.

Table 1. Hurricane Hugo-selected surface observations, September 1989.

	Minimum sea-level pressure		Maximum surface wind speed ($m\ s^{-1}$)			Storm surge (tide height above normal)	Rain (storm total)
	Pressure (mb)	Date/time (UTC)	1-minute average	Peak gust	Date/time (UTC)*	(m)	(mm)
Guadeloupe	941.1						
St. Maarten							
Juliana Airport			21	35	18/0200		
Puerto Rico							
Gurabo							234
Isla de Culebra				76			
Isla Verde	970.3	13/1415					
Luquillo	956	18/1300					
Roosevelt Roads	946.1	18/1250	46	54	18/1158		
San Juan	970.3	18/1444	35	41	18/1350		76

3.0 Trip Reports:

3.10 Hurricane Hugo-Related Impacts on the Marine Ecosystems of the Antilles (M. T. Agardy)

3.11 Summary

This report summarizes a preliminary survey of Hurricane Hugo-induced impacts on the marine and coastal ecosystems of several Caribbean islands. The damaged sites were visited during 15-25 November, 1989, roughly two months after the hurricane ravaged the islands. Wherever possible, surveying included photography (aerial and conventional), snorkeling and SCUBA diving observation, and sampling.

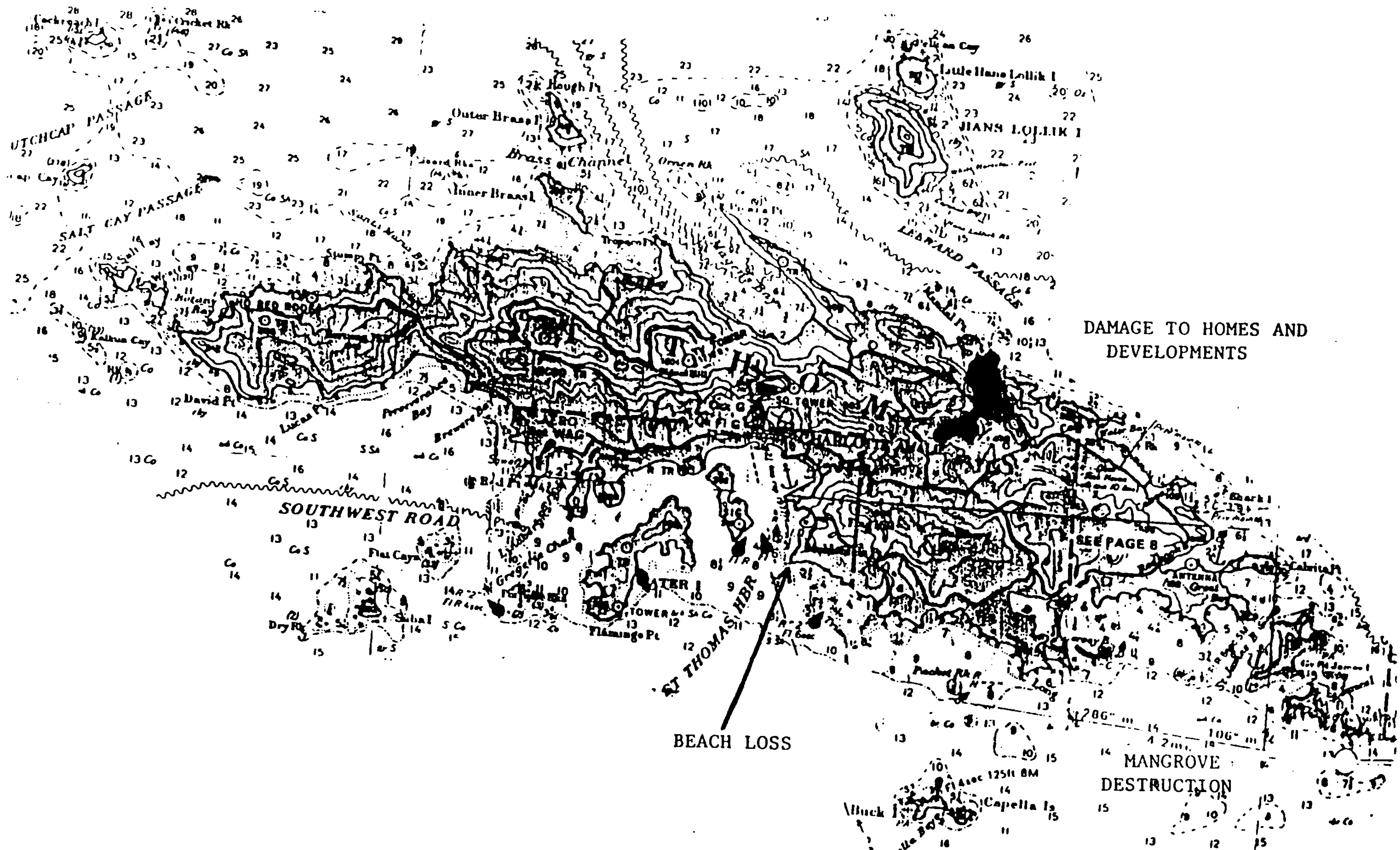
The most prominent impacts on the coastal ecosystem observed were breakage of corals (especially Acropora species), abrasion of stony corals by sand-laden currents, siltation and sedimentation of reefs and seagrass beds, widespread and catastrophic destruction of seagrass beds through the creation of new blow-outs, "uprooting" of macroalgae, gorgonians, and sponges, mangrove deforestation, and physical damage to all coastal habitats from debris. Secondary effects included oil spill damage (St. Croix), sewage-related nutrient loading (St. Croix) and environmental damage from reconstruction/recovery efforts (throughout the impacted area). Government ministers and local scientists are aware of the primary and secondary impacts, but appear to be completely overloaded in post-hurricane work and unable to initiate scientific studies or monitoring programs. Furthermore, no regional efforts to study hurricane impacts have been undertaken.

3.12 St. Thomas

St. Thomas was spared much of the destruction befalling her neighboring islands. Roofs were damaged in some areas; resorts near the water had structural damage (Table 2). Interestingly, most of the terrestrial damage occurred in the lee of the island on the north side. The boating community was hardest hit, with wrecked yachts and pleasure boats lining the shore along virtually the entire south and east coasts. Sand erosion occurred at Frenchman's Reef at the entrance to Charlotte Amalie Harbour, and at Bolongo and Cowpet Bays. Mangroves were impacted at the Mangrove Lagoon. Coral reefs show some signs of siltation, especially in the northeast portion of the main island and some of the offshore cays. Soft corals and sponges were uprooted and have washed ashore at nearly all the beaches; some seagrass beds have also been damaged. The V.I. Division of Fish and Wildlife (DFW) is particularly interested in quantifying the impact of seagrass destruction on fisheries and conch fisheries (Map 1).

TABLE 2: SUMMARY OF PRELIMINARY ASSESSMENT OF HURRICANE-INDUCED IMPACTS ON THE COASTAL ECOSYSTEMS OF THE ANTILLES (NOVEMBER, 1989)

ISLAND	OVERVIEW OF PRIMARY DAMAGE	INDIRECT IMPACTS OBSERVED	STUDY SITES (MOST DAMAGED AREAS)	FOLLOW-UP POTENTIAL
ST. THOMAS (U.S.)	SOME HOTEL DAMAGE; LOSS OF PRIVATE HOMES, EVEN ON LEE SIDE; WIDESPREAD YACHT DESTRUCTION; SOME MARINA & PIER DAMAGE; LARGE-SCALE SAND TRANSPORT AND INUNDATION OF REEFS AND SEAGRASS BEDS	WATER-BOURNE DEBRIS BREAKING CORAL; LOWERED WATER QUALITY FROM REHABILITATION PROJECTS	OUTER PORTION OF CHARLOTTE AMALIE HARBOR; MANGROVE LAGOON; COWPET BAY; OFFSHORE CAYS	REHABILITATION WORK; MANGROVE STUDIES
ST. JOHN (U.S.)	HOTEL DAMAGE (MOSTLY LANDSCAPING); HIGH TURBIDITY WITH UNQUANTIFIED EFFECTS AT ALL NORTH SHORE REEFS; SOME DEFOLIATION OF MANGROVES IN CORAL BAY; LIMITED REEF DAMAGE (AT EAST END)	NONE OBSERVED	CORAL BAY; EAST END	CORAL REEF IMPACTS (GOOD BASELINE DATA EXIST)
ST. CROIX (U.S.)	MASSIVE DESTRUCTION AT WEST END; LONG REEF CORALS DESTROYED; SEAGRASS AND SOFT CORAL DESTRUCTION AT WEST END; MAJOR DAMAGE AT BUCK ISLAND NATIONAL PARK; SAND LOSS AT SANDY POINT AND SOUTH SHORE BEACHES; MANGROVE DESTRUCTION AT SALT POND; DEBRIS, OIL AND SEWAGE POLLUTING VIRTUALLY ALL COASTAL SYSTEMS	HESS OIL SPILL, RAPIDLY CONTAINED, BUT SOME RELEASED INTO SO. SHORE WATERS; WAPA HEATING OIL SPILL STILL NOT CLEANED UP, PROBABLE POISONING OF ORGANISMS IN CHRISTIANSTED HARBOR; RAW SEWAGE PUMPED INTO COASTAL WATERS DUE TO TREATMENT PLANT FAILURE	WEST END; SANDY POINT; LONG REEF; BUCK ISLAND NATIONAL PARK	YOU NAME IT: LONG AND SHORT TERM IMPACTS ON REEFS, FISHERIES, SEAGRASS BEDS, MANGROVES, SALT PONDS, LAGOONS, ETC.
PUERTO RICO (U.S.)	WIDESPREAD DESTRUCTION OF NATURAL HABITATS AND TOWNS ALONG EASTERN SHORE (ESP. SOUTHEAST); SEVERE DAMAGE TO WETLANDS IN RIO GRANDE AREA; MASSIVE DEFORESTATION IN ELYUNQUE NATIONAL FOREST WITH MAJOR E.S. IMPACTS; POSSIBLE IMPACT ON MANATEE POPULATION IN ALGODONES AREA; UNQUANTIFIED BUT PROBABLY SEVERE DAMAGE TO BIRD ROOKERIES IN ROSY RDS. NAVAL STATION	DEBRIS REMOVAL AND RECONSTRUCTION IMPACTING SENSITIVE AREAS; LONG TERM SEDIMENTATION OF COASTAL AREAS	RIO GRANDE MANGROVES; ENSENADA HONDA (ROSY ROADS NAVAL STATION); PALMAS DEL MAR BEACHES; BAHIA ALGODONES; EL YUNQUE	SEDIMENT LOADING AND IMPACTS ON REEFS & LAGOONS; BEACH RENOURISMENT; ARMY CORPS ENDORSED REHABILITATION
CULEBRA (U.S)	NEAR TOTAL DESTRUCTION OF WATERFRONT DEVELOPMENTS AT CULEBRA (TOWN); UNKNOWN BUT POSSIBLE SEVERE DAMAGE TO US NAVY RESERVE; SAND REMOVAL AT TWO LARGEST BEACHES (SEA TURTLE CRITICAL HABITATS); WIDESPREAD SEAGRASS BED DESTRUCTION; LIKELY FISHERIES IMPACTS; REEF DAMAGE	CONTINUED SOIL AND SAND EROSION AND HIGH TURBIDITY IN COASTAL WATERS	NORTHERN TURTLE-NESTING BEACHES; CAYO DE LUIS PENA REEFS; SEAGRASS BEADS IN S/E AREA; ISLA CULEBRITA REEFS	COOPERATIVE WORK WITH FISH AND WILDLIFE SERVICES AT REFUGE; SEAGRASS MORTALITY AND IMPACTS ON FISHERIES AND HERBIVOROUS SEA TURLTLES



MAP 2. MOST SEVERELY AFFECTED AREAS OF ST. THOMAS, U.S. VIRGIN ISLANDS

3.13 St. John

Despite rumors to the contrary, many of the coral reefs within the boundary of the St. John National Park were not adversely affected by Hugo. Turbidity continues to be high from sediment loading. Mangroves were affected in the Coral Bay area, but impact does not seem to be long term. Water-borne debris continues to persist and may cause substantial post-hurricane damage to corals.

3.14 St. Croix

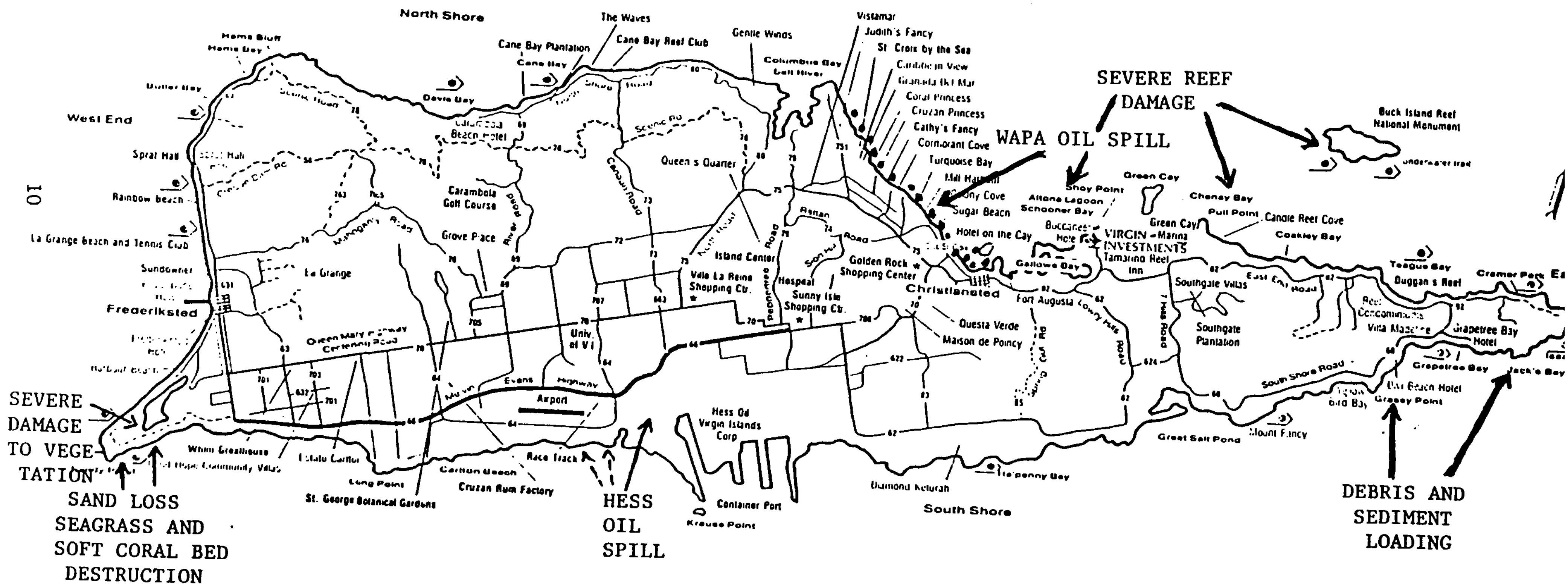
St. Croix was devastated by the hurricane, and has barely recovered in the time since. Virtually every habitat was affected, some severely. Primary damage included reef breakage and siltation at Long Reef, Buck Island Reef, and Green Cay; mangrove and other tree deforestation on the west end; damage to the Sandy Point Salt Pond; sand erosion on south shore beaches; and massive seagrass bed destruction. Secondary impacts include oil spill damage from the Hess Oil and WAPA spills; eutrophication from the dumping of untreated sewage; and debris damage. Wind-borne sand deposits in inland areas measure up to a meter in depth. Evidence of seagrass bed and soft coral destruction exists in the stormline at Sandy Point; dead sponges, sea fans, and gorgonians exceed 30 individuals per meter of tideline.

Although good baseline data on coral reef and coastal habitats exist for many parts of the island, further work in St. Croix will be complicated by the general condition of the island. Map 2 shows areas of major impact.

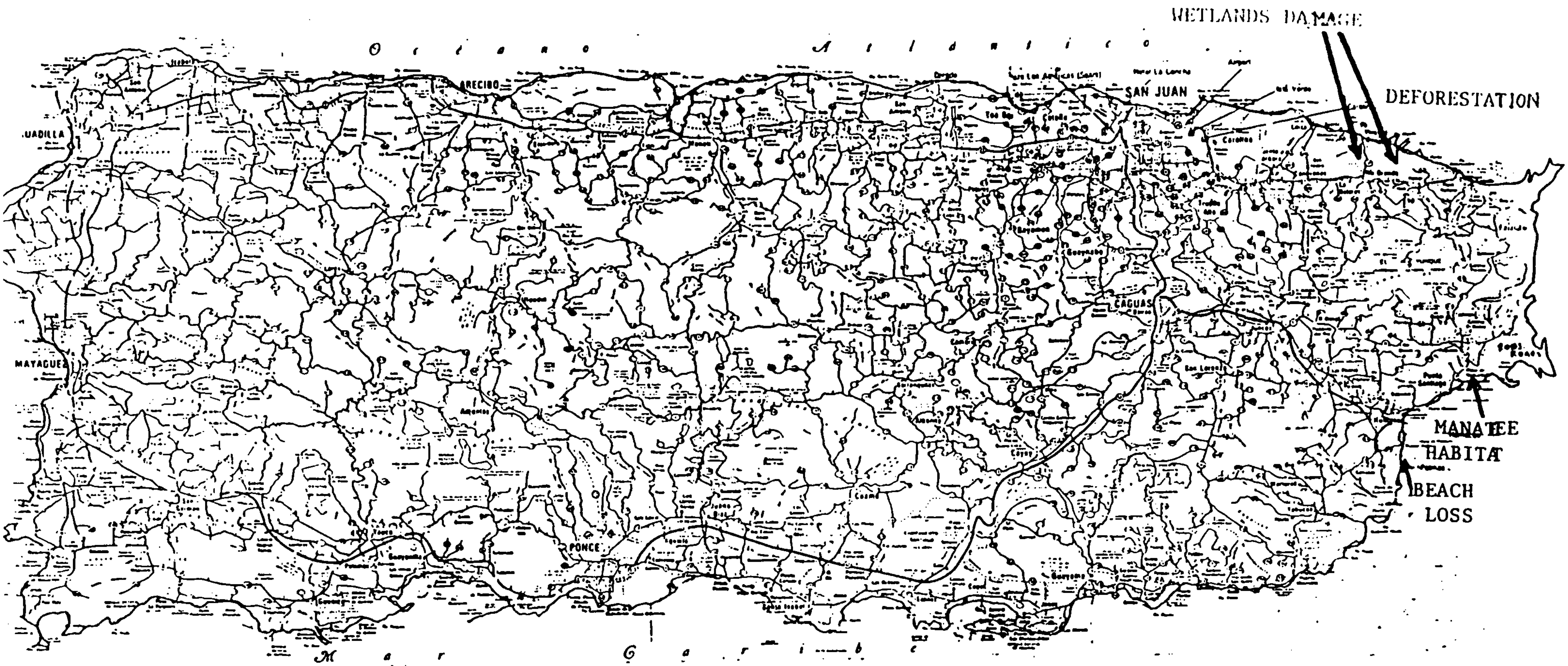
3.15 Puerto Rico

Puerto Rico can boast of having the most systematic surveys of damage to the coastal environment, although their efforts are directed primarily towards endangered species and not to coastal systems in general. On mainland Puerto Rico, Hugo caused most damage to the eastern and northeastern portions of the island. Extensive defoliation and deforestation of mangrove wetlands in the Rio Grande area is visible by air. Ground surveys along the eastern shore point to erosion of some of the major resort area beaches. Similar impacts are likely to have occurred in the Roosevelt Roads Naval Station (Rosy Roads), which is not open to the public but which got a much more direct hit by Hugo. The Rosy Roads area is critical habitat for many bird species, and Department of Natural Resources (DNR) scientists will be trying to assess damage to avifauna in the coming months. They will also investigate the impact of Hugo on critical habitats for the West Indian manatee, an endangered species found in coastal areas to the southeast. Utilities have been restored in the damaged areas, and rental cars and hotel rooms are easy to obtain. Map 3 shows sites of major damage.

MAP 3. MOST SEVERELY AFFECTED AREAS OF ST. CROIX, U.S. VIRGIN ISLANDS



MAP 3. MAJOR AREAS OF IMPACT IN PUERTO RICO



The two small islands to the east of Puerto Rico, Culebra and Vieques, received the brunt of the storm damage. Ninety percent of the homes on the island were severely damaged or destroyed. Seagrass beds around the island of Culebra were obliterated, complicating local efforts to promote the recovery of the green turtle (Chelonia mydas) there. Sea turtle nesting beaches were only slightly damaged, and new beaches were formed by some of the displaced sand. Ecosystem damage on these two islands is continuing and is exacerbated by unregulated reconstruction activities.

3.20 Effect of Hurricane Hugo and Subsequent Recovery of Coastal Landforms and Plant Communities on St. Croix, U. S. V. I. (David M. Burdick & Graham S. Giese)

3.21 Introduction

Barrier beaches serve an important protective function for shoreward ecosystems and societal infrastructure through dissipation of storm wave energy and as barriers to storm-elevated sea levels. Plant communities are intimately connected with both the development of barrier landforms and their effectiveness as storm buffers. The structures (types of plants, e. g., grasses, shrubs), composition (species abundances) and distribution of coastal plant communities are largely controlled by elevation and hydrology, substrata composition, and exposure to wind and salt. Because of their position and role in shoreline protection, these systems often bear the brunt of the storm's energy and exhibit dramatic storm impacts. However, despite the importance of these plant communities to the development and maintenance of coastal barrier systems, little is known about their post-storm recovery strategies.

We have completed two post-storm surveys that examined the response to Hurricane Hugo of barrier beaches and their plant communities on St. Croix, U. S. Virgin Islands. Most of our effort was devoted to the detailed description of two barrier beach systems, Shoy's Beach on the north coast and Halfpenny Bay beach on the south coast of the island. Our objectives were: (1) to quantify the impacts of Hurricane Hugo on the landforms and vegetative communities of these barrier beaches, and (2) to conduct a preliminary assessment of the recovery rates and processes of the landforms and vegetation, and the relationships between landforms and plant communities during the recovery process.

3.22 Field Study and Data Analysis Methods

Our work took place during the periods January 7-20 and November 9-15, 1990. In addition to our detailed study of the two barrier beach systems, Shoy's and Halfpenny Bay, we conducted a generalized island-wide survey of hurricane impacts on the beaches and shore vegetation of St. Croix, covering approximately 80 percent of the island's coastline. In January, we made a very limited one-day survey of impacts on selected beaches on St. Thomas. In November, we consulted with the Island Resources Foundation on St. Thomas, and provided this group with various data of hurricane impact on St. Croix sites from January and November, 1990.

To provide a frame of reference for observations at the Shoy's Beach and Halfpenny Bay sites, we made three transects at each location. The barrier beach systems were typically composed of three parts: beach, dune and swamp. Quantitative measurements of barrier beach profiles and plant communities were made using standard survey and plant quadrat methods (1 m^2 quadrats, stratified randomized design with communities as blocks). Sand deposited during and following the storm was warmer in hue (pinkish or brownish) than older sand deposits (white to grey). The depth of new sand deposits were determined at all vegetation quadrats. Trees that had fallen prior to the storm were recognized by their advanced state of decomposition if they had died, and by the reorientation of their branches if they had remained alive. Differences between communities, sites and dates were tested using analysis of variance (ANOVA) and t-tests.

Pre- and post-storm aerial surveys of our detailed study sites were used to estimate shoreline erosion. Aerial photographs were taken at a scale of 1:9600 in March, 1988 and again in September, 1989, five days after the storm. Changes in position of the vegetation line (dune scarp) normal to the shore were measured from transparencies. In addition, an independent estimate of shoreline erosion was obtained in January by measuring the distance from the new dune scarp seaward to the edge of where intact plant roots were protruding from the new beach sand.

3.23 Results and Discussion:

3.231 North Shore: Shoy's Beach

Dune retreat amounted to approximately 20 feet, as estimated from field observations as well as from aerial photography (Table 3). Low areas of the dune line were overwashed by the storm surge, resulting in new sand deposits that increased the surface elevation of the dunes by up to 1.4 feet. Overwash fans extended more than 100 feet from the dune scarp into the back-barrier mangrove swamp (Figure 1).

Table 3. Estimates of beach retreat rates (mean distance in feet +/- standard error) at Shoy's Beach and Halfpenny Bay beach based on aerial photography (n=20) and direct measurement from the seaward edge of the protruding roots (old dune scarp) to the new dune scarp (n=3).

METHOD	SHOY'S BEACH	HALFPENNY BAY
Aerial photography	21.0 +/- 2.0	33.8 +/- 3.6
Root line to dune scarp	19.7 +/- 1.7	32.3 +/- 0.3

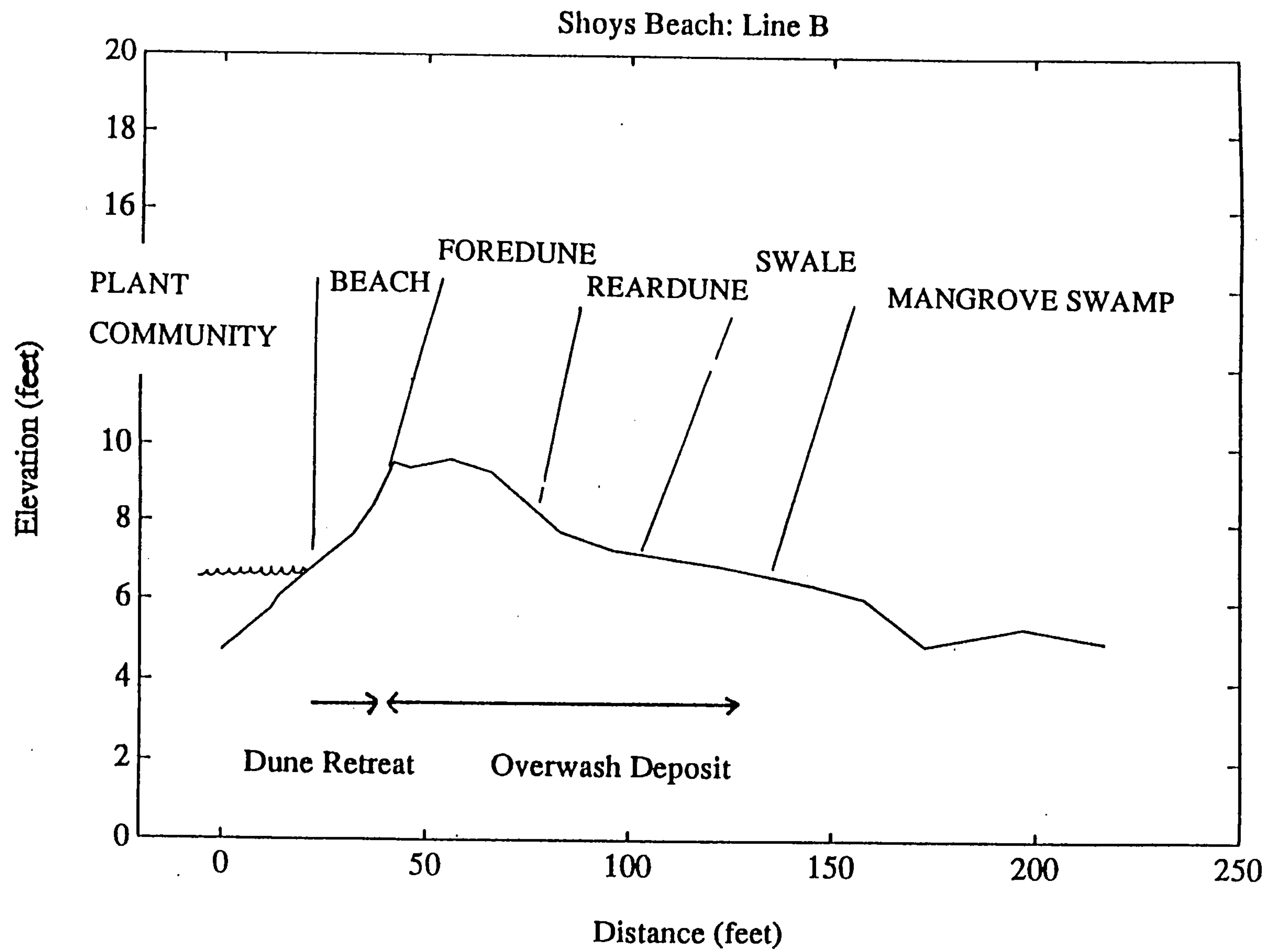


Figure 1. Elevation profile of a representative transect at Shoy's Beach, showing the plant communities and the zones of dune retreat and overwash deposits.

Plant communities included a pioneer community on the back shore consisting of grasses and vines; foredune and backdune communities dominated by grasses, shrubs and trees; a swale community of grasses and sedges; and a mangrove swamp community (Figure 1).

Although sheltered from the brunt of the storm by the dune, 12% of the mangroves were toppled and 26% appeared to have died, as of our January sampling. The November survey was similar with respect to toppling, with 14 % of the trees fallen, but mortality was 43%, exhibiting a 26% increase (significant at alpha=0.025) since January. Results from the resurvey in November were expected to show that some of the trees that appeared dead in January would have resprouted, reducing the overall mortality rate from the storm. However, these results indicate that mangrove mortality following the storm continued to increase, and suggest that some of the trees we saw resprouting in January could not recover and died sometime before November.

The recovery process at Shoy's Beach appeared to be slower than that of Halfpenny Bay Beach, and more complex. The elevation profiles of the transects showed little or no replenishment of the beach sand (Figure 2). Some of the sand that had returned to the beach by January, 1990, eroded away from the foreshore and backshore by November, even to the point of removing pioneer vegetation that was mapped in January, and killing other vegetation that had subsequently colonized the beach. This post-Hugo erosion appeared to be greater where the beach had detached from the beach rock (Transect C). In these areas, a pool of water was always present between the rock terrace and the beach to landward.

Vegetation recovery continued, albeit more slowly than that of the south barrier beach (Figure 3). Neither understory nor overstory cover showed a significant increase in November when compared to January (see Table 4). In the dune, where large overwash fans were colonized by grasses, vines and seedlings, understory cover increased, but not significantly (Figure 3). Although the severely-damaged trees on the dune continued to releaf through November, overstory cover was very variable, resulting in no significant increases. No changes in understory or overstory were found for the mangrove swamp community. Although the young plants initiated following the storm were growing vigorously, some of the damaged shrubs that had releafed by January appeared to have died subsequently, increasing the overall mortality from the storm.

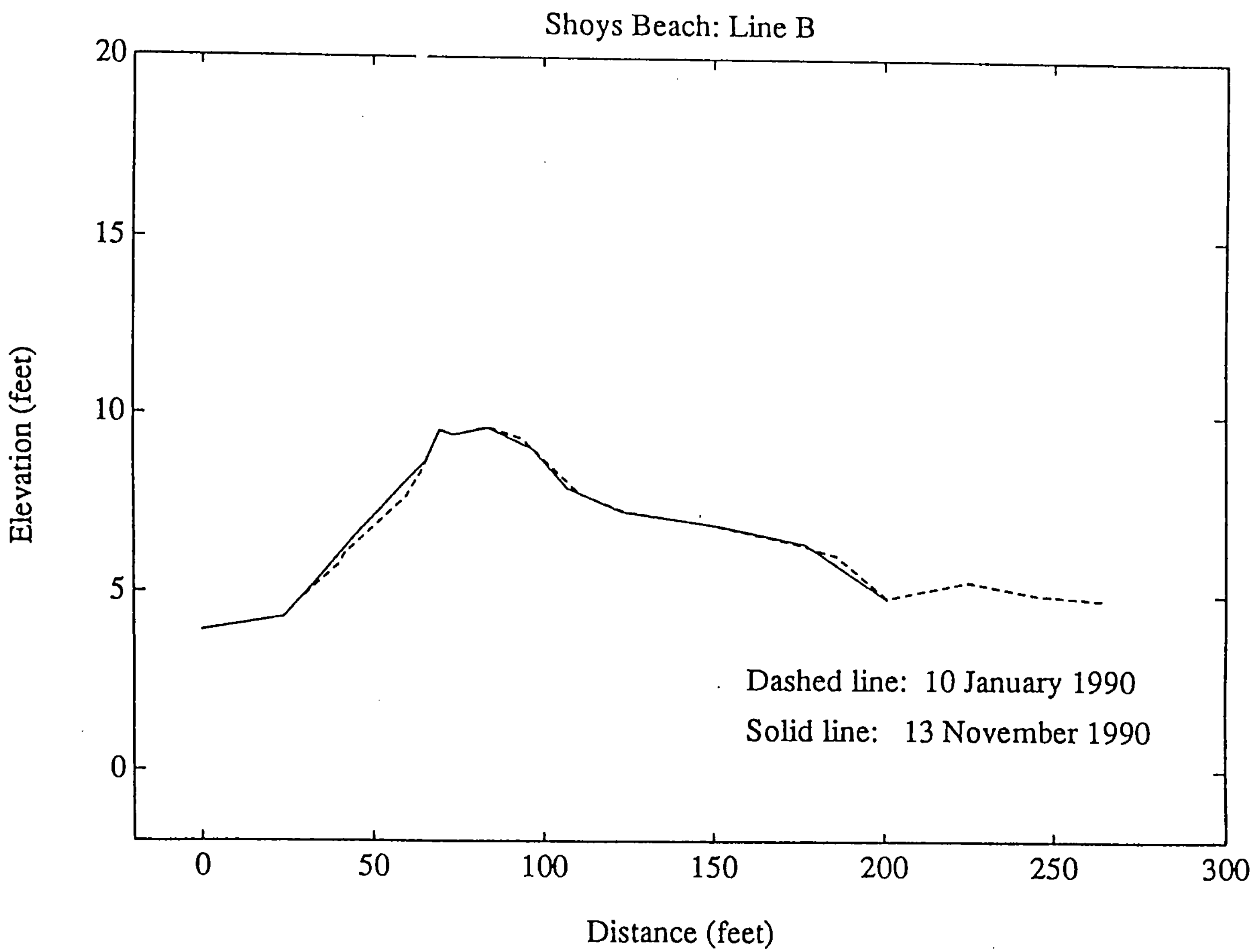


Figure 2. A comparison of elevation profiles at Shoy's Beach from a representative transect surveyed in January and November, 1990.

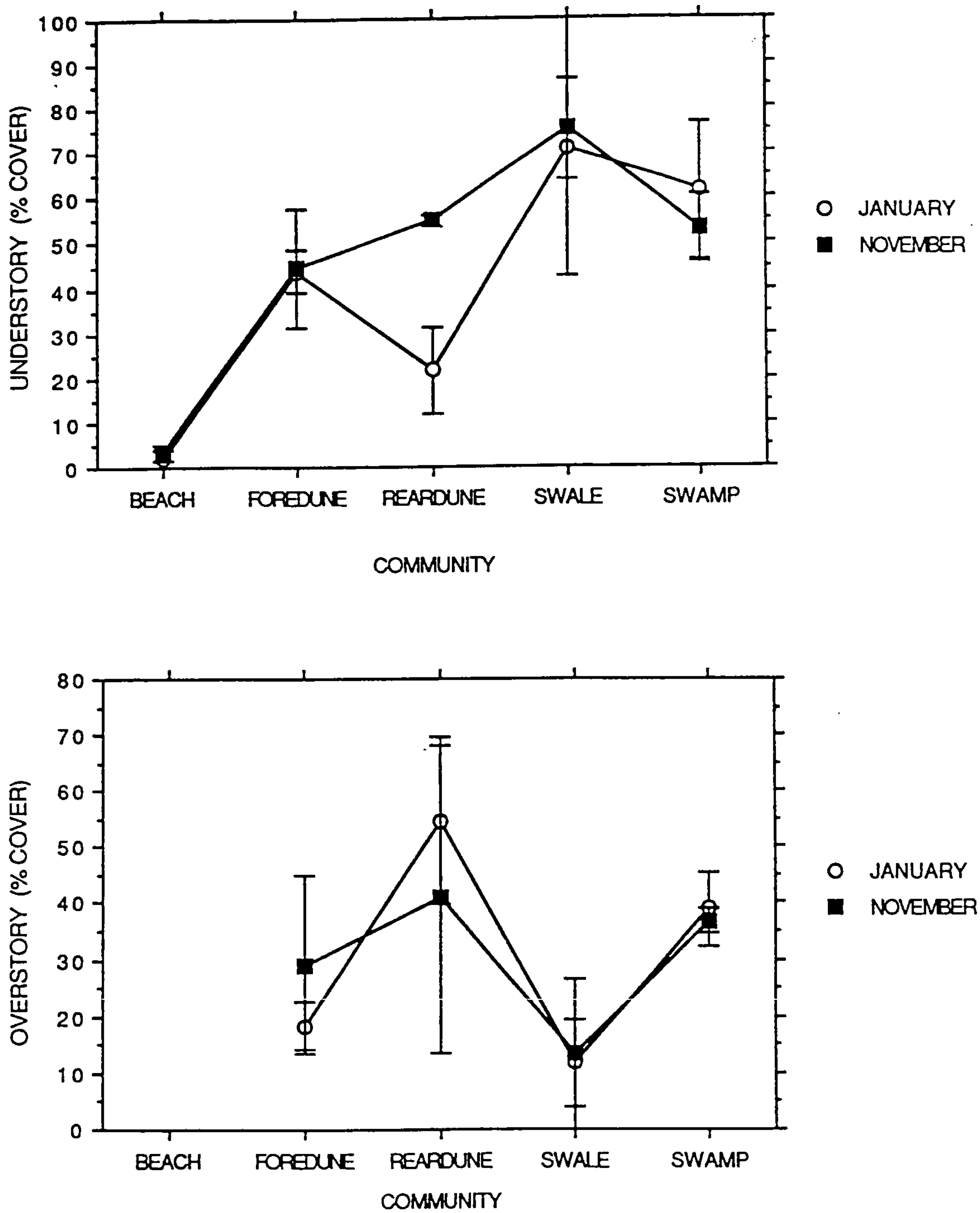


Figure 3. Plant cover means and their standard errors of three transects at Shoy's Beach. a. Understory cover. b. Overstory cover. Only communities exhibited significant differences (P value < 0.10).