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COASTAL DUNES FOR PROTECTION AND SAND RESOURCES

Contract Report

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COASTAL DUNES FOR PROTECTION AND SAND RESOURCES

by

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Executive Summary

Massive sand extraction of north coast dunes has reduced their natural capability for protection. This report aims to provide the scientific basis and engineering data for managing the dunes to protect the coast from high waves and long-term erosion, and to provide a source of sand for extraction. Additionally, the probable impact of submarine sand extraction on beach drawdown, interception of nearshore sand transport, and storm wave modifications is assessed. Of the three submarine deposits, extraction of the Cabo Rojo west deposit has a lower risk of impact on beaches than other sites.

The size, height and stability of residual dunes at Isabela, Hatillo and Carolina is inadequate in many places for long-term protection of life and property. As a result of high northern swells, October 11-13, 1982, dune ridges collapsed at Hatillo, Camuy and Carolina and the resulting washover deposits offer little protection. Since the dunes were breached at 23 points, many heights and widths are insufficient to protect the coast from wave runup of a one in 20-year hurricane. The data from hurricane wave predictions, dune dimensions and erosion rates are utilized to predict the dune height and width required for protection from hurricanes of different recurrence interval ranging from one in 5-year to one in 500 years. Critical erosion zones produced by sand extraction and natural processes are evaluated and recommendations offered to restore and enhance dune protection mainly by modifying natural processes and establishing a setback zone to allow natural processes to operate and to direct future extraction, vehicular traffic and development. The setback or dune management zone is determined by the existing dune dimensions, migration trends and historical erosion rates. These management approaches should reduce the risk of storm damage to property and human life and lessen the expenditure of funds on costly protective structures.

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1. Introduction.

Along the north coast of Puerto Rico, sand dunes once provided protection against storm surges, waves and flooding. They not only offered natural protection for human life and property but served as a source of sand to buffer beach erosion. Today, after several decades of massive sand extraction, few natural dunes remain. By removing back-up dunes and lowering foredune crests, storm waves now overtop and breach the remaining ridge and flood lowlying areas landward. Where dunes have been completely destroyed, ocean front property, settlements and mangrove habitats are exposed to the full force of ocean storm waves. The threat of cause and effect seems clear.

Given the deteriorating status of the dunes in response to man-induced and natural processes, the task now is to maintain the dunes in their best achievable condition. This report provides the scientific basis and engineering data for managing the dunes to minimize further damage and to ensure their stability. It provides direction for future sand extraction which allows some degree of protection for lowlying coastal areas and for a reserve capacity of sand to nourish adjacent beaches. If the dunes are to serve both as a sand and recreational resource as well as a barrier for storm protection, they must be understood so that present and impending problems can be thoughtfully managed.

2. Objectives.

The broad objective of this investigation is to develop guidelines to avoid excess removal of sand dunes that protect the coast from storm surge and high waves. The specific working objectives are:

- To determine the present condition of the dunes with respect to their height, width and stability. What protection do the dunes provide now?
- To predict the height of hurricane waves of a given frequency of occurrence including the worst that can happen.
- To determine what size and height dunes is required to protect the coast over a given time span.
- To identify critical erosion zones and recommend ways to alleviate erosion trends.
- To assess the probable impact of submarine sand extraction on nearshore sediment transport and beach dynamics.

3. Scope and Approach.

The investigation is conducted on three test sites selected by Department of Natural Resources scientists: (1) Playa de las Tres Palmitas, Carolina, (2) Carrizales Mangrove near Hatillo, (3) Punta Sardina and Jacinto, Isabela, Figure 3-1. The Carolina site is of special interest because of massive sand extraction in the 1950's for airport construction and the intense erosion reported during 1960-1980. Hatillo is a site of intense extraction that proceeded during the 1960's and 1970's. Carolina and Hatillo therefore, exhibit a range of extraction sites that vary with age and erosion impact. The sand dunes of Isabela have a history of intense extraction that proceeded during the 1970's with potential impacts. Additionally,many permit applications are pending for additional extraction.

The rationale for the approach to this study recognizes that the protective attributes of the dunes are determined by natural processes, their stability, size and height that act to prevent overtopping, overwash and erosion. The cause of erosion is the global rising sea level, magnitude of

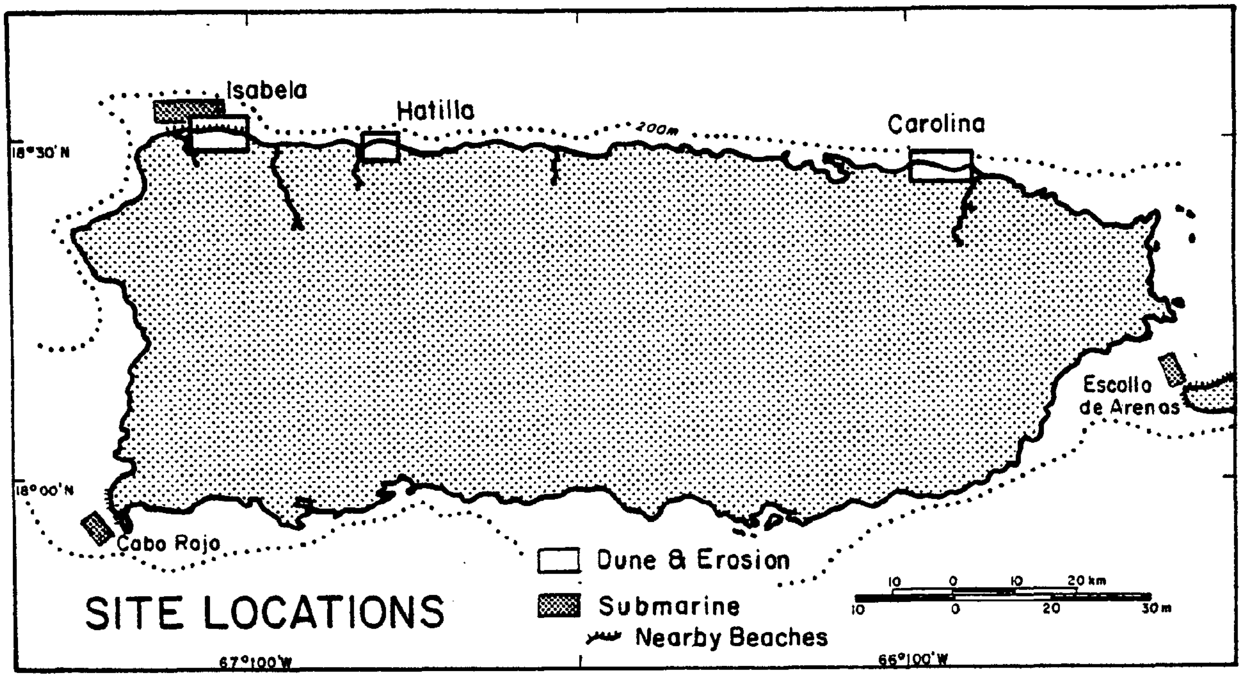

Figure 3-1. Location of investigation sites on the north coast of Puerto Rico and offshore coastal zones.

storms with a given frequency and decreasing sediment supply. In most cases these causes cannot be controlled. Where the value of property or facilities is relatively great, the cost of protective engineering structures can be justified as a short term solution. Structures are not considered justified however, as a substitute for sand dunes along long stretches of open coastline. An alternative approach to engineering structures is to manage the dunes in a way that is compatible with the forces and constraints of the natural system. By reducing the interference with natural processes, dunes can be maintained and their formation can be promoted.

The approach to managing the dunes takes into account the following ideas:

- The dune/beach system is dynamic. Dune sand is continually exchanged between the beach or nearshore zones.

- Dune height provides protection of property and life from the elevation of storm water and wave runup.

- Dunes constitute a reservoir of sand. When the dune face is eroded during storms, the sand released nourishes beaches and reduces erosion.

- Dune width combined with height provides a volume and mass of sand that reduces the landward extent of overtopping, overwash and flooding of zones behind the dunes.

- Over the long-term the dune/beach system can migrate landward in response to storms, erosion, rising sea level and a negative sediment budget.

- The life expectancy of protection depends on the lateral erosion rate and the dune height in relation to the heights and frequency that storm surge and runup attain.

The systematic plan of this investigation which combines numerical computations with field surveys, aerial photographic analysis and a background of knowledge and experience, follows four stages: First, the storm surge and runup regime generated by hurricanes is calculated to predict the height that waves of a given frequency of occurrence can reach. Secondly, the present condition and characteristics of the dunes is surveyed by elevation profiling and field observations focusing on the protection that the dunes now provide and the impacts produced by sand extraction. Thirdly, the trends of beach and dune erosion are determined using aerial photography for long-term trends and field observations as well as ground surveys for short-term trends created by storm waves of October 11-13, 1982. Fourthly, the new information on the wave regime, erosion trends and dune characteristics is synthesized to prescribe a degree of protection and to manage future sand extraction activities. Additionally, the probable impact of submarine sand extraction on nearshore sediment transport and beach deposits is assessed. Figure 3-2 summarizes graphically the overall plan of investigation.

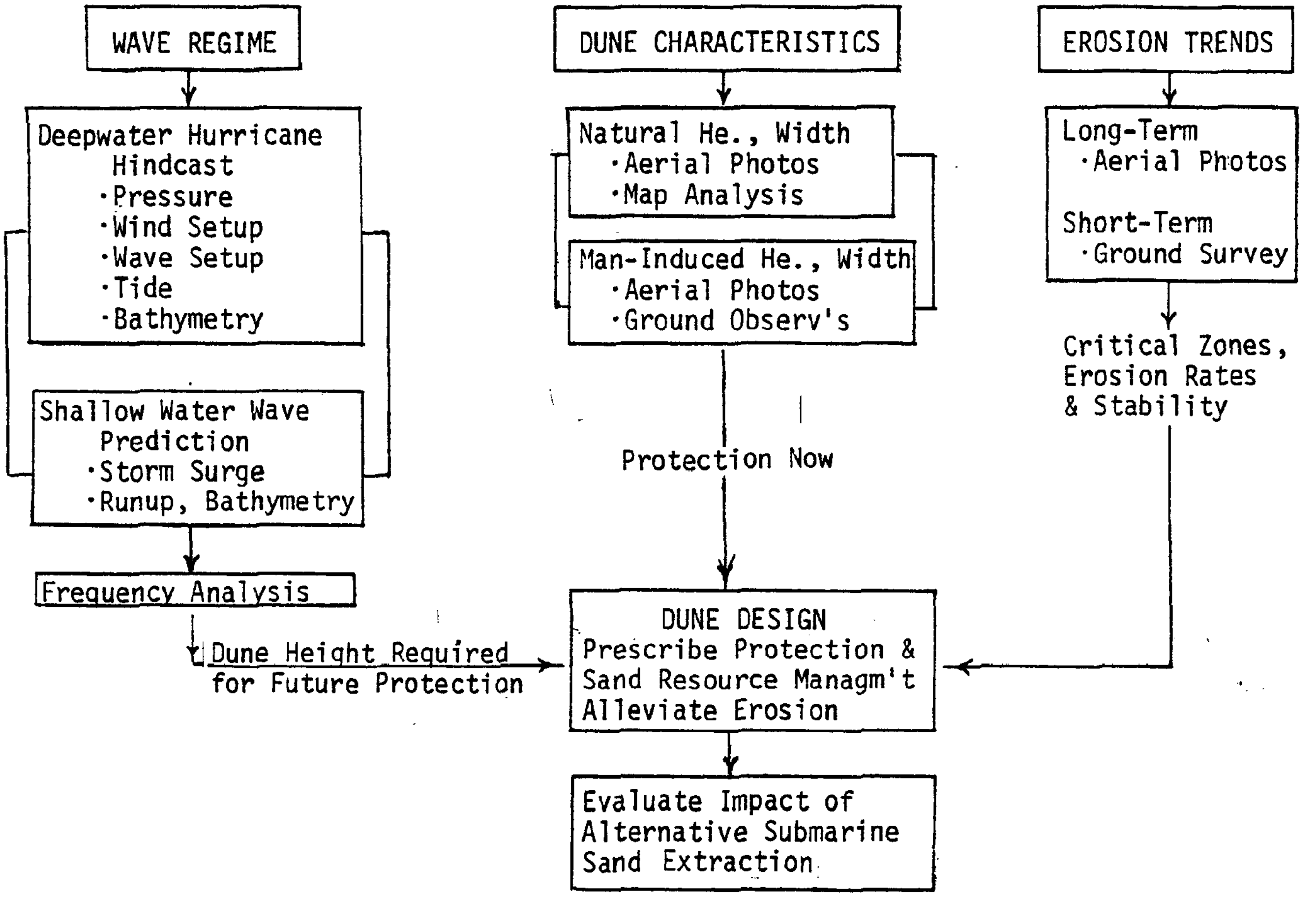

Figure 3-2. Schematic diagram showing elements of the investigation and overall plan of approach.

Specific definitions for the aerial photo analysis, ground surveys and for designating dune management in relation to storm surge and wave runup are illustrated in Figure 3-3. Of note, dune height, H, is the difference between the highest point on the profile and the maximum beach elevation. It is the minimum crest elevation required to provide protection against storm surge and runup. This elevation is taken as the dune height plus the backbeach height above mean low tide level. The dune width, W, is the distance from the seaward dune face, at the break in profile slope between the backbeach and the dune face, to the landward base of the dune at the break in the profile slope between the dune backslope and the excavation floor, trough, washover or the upland. The latter zone of relatively low slope, is designated, L, Figure 3-3. The beach width, BW, is the distance from the break in profile slope between the backbeach and the dune face to mean low tide level.

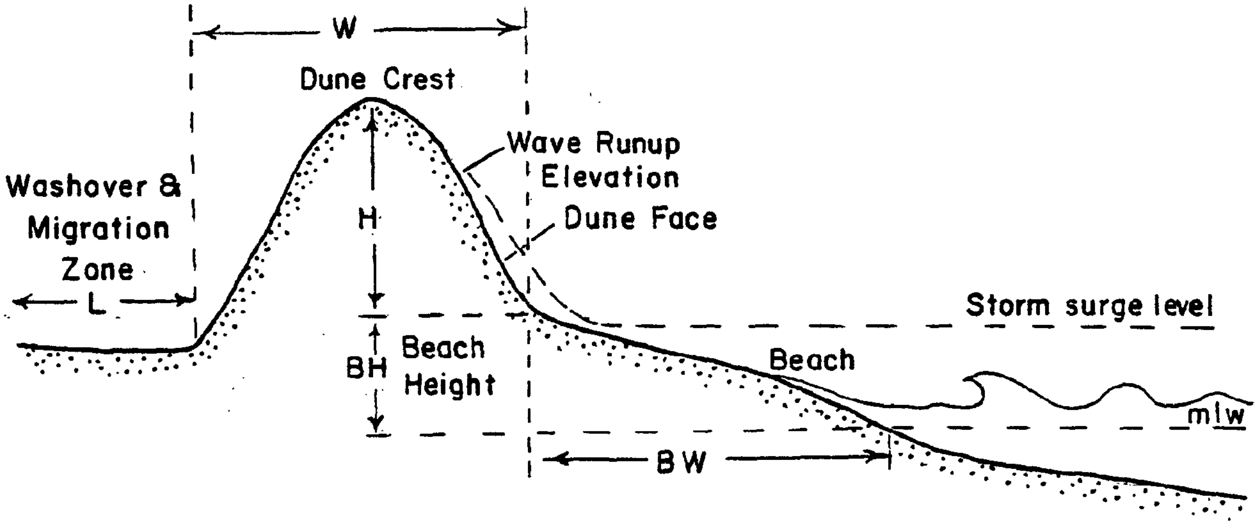

Figure 3-3. Beach and dune terminology and components of wave predictions.

4. Previous Investigations.

Although prior studies from other areas provide a background of knowledge upon which to build the present investigation, there are only a few studies dealing specifically with the sites and the problem investigated. The problem of dune protection and sand extraction is documented by NOAA (1978) while the hazard of coastal flooding is documented by PRDNR (1980). Preliminary guidelines for sand extraction are provided by Hernandez-Avila (1973) as based mainly on qualitative observations. This report gives insights into sedimentary processes active in the dunes but the guidelines are not intended "as a line of action". The magnitude of sand extraction and estimates of the total sand resource are provided by Castillo and Quinones (1980). Beach erosion at sites on the north coast other than those of this investigation, are reported by Olivieri (1956), Briggs (1961) and Morelock (1980). The marked effects of storm waves on beach erosion and alteration of dune height and width at Playa de las Tres Palmitas, Carolina before and after sand extraction, are recorded by Cintron and Pool (1976). Other sources of relevant background information include: (1) the study of Fields and Jordan (1972) that reports the height and frequency of wave swash marks along the north coast that are associated with Atlantic cyclonic storms called "northeners", (2) the reports of NOAA (1973), Ho (1975) and P.R. DNR (1980) define hurricane climatology and resulting storm tide statistics for the north coast, (3) the papers of Kaye (1959) and Morelock (1978) covering geologic features and sedimentary characteristics of beaches on the north coast, (4) the papers of Armon (1980), Cullen (1980) and Gares et. al. (1980) dealing with management of sand dunes, and (5) the papers of Grove and Trumbull (1978), Shidler (1980) and Schneidermann et. al. (1976) that describe sediment characteristics and bathymetry of potential submarine sand resources on the insular shelf.

5. Storm Surge and Wave Runup Predicitons

Since wave height is a key element that determines the dune height required to prevent overtopping, it is essential to predict the height of waves generated by hurricanes of a given occurrence frequency. The height waves reach on a dune during storms is a complex problem involving the interaction between wind, water and geometry of the dune or nearshore bottom. The problem resolves into two phases: (1) prediction of storm surge and associated set-up components; (2) prediction of runup on the nearshore bed and dune face. Because of the difficulty of selecting a single "worst case" hurricane, i.e. "the worst that has happened", the problem is approached by considering a "population" of all past hurricanes. By assuming that past, present and future storms fit a specific probability distribution, synthetic or model hurricanes can be derived that have a certain frequency of occurrence, e.g. once in one-hundred years. This viewpoint shows "the worst that can happen" at a particular coastal site during some definite period of years. Prediction of hindcast wave heights are necessary because observed wave heights during hurricanes are lacking. It has been general practice in coastal engineering to use synthetic or design storms, to estimate storm-induced surge (CERC, 1977).

Storm Surge. Whenever a hurricane or intense tropical depression approaches or crosses Puerto Rico, sea level rises above the normal tide level. The name given to the rise of water level above normal levels is called "storm surge". Lacking a sufficiently long record of observed water levels from the NOAA San Juan tide gauge, it is necessary to calculate what surge heights can be induced by a combination of factors that generate storm surge. For example, the direct stress of hurricane winds not only creates large surface waves but piles up water against the coast when it blows onshore. Low atmospheric pressure associated with hurricanes raises the ocean surface by the inverted barometer effect. Additionally, waves breaking near the shore create a wave setup or super-elevation of water that contributes to the storm surge. The bottom topography near the shore has a significant effect on storm surge heights. A gently sloping offshore bottom supports the generation of higher storm surges than a steep offshore bottom. It remains to determine the relative importance of these factors for a range of hurricanes with a certain frequency of occurrence.

Hurricane Climatology and Statistics. To hindcast storm surge with a certain frequency of occurrence at each site, the key parameters required for computation are: central pressure, radius of maximum wind, the speed of forward motion and the direction of motion, or hurricane track, relative to the coast. Additionally, the frequency with which hurricanes strike or pass the coast, either alongshore parallel to the coast or exiting across the island, is required. The probability of the central pressure (Pcpi), forward speed (Pv) and path (Pp) are independent and thus a storm can be assigned a set of characteristics (Ps) as follows:

$$Ps = Pcpi \cdot Pv$$

The frequency of a given storm (Fs) is:

$$Fs = Ft \cdot Pp \cdot Ps$$

Where Ft is the frequency of a storm track.

Data describing the climatological characteristics of the key parameters, central pressure, radius of maximum winds and forward motion are derived mainly from U. S. Navy hurricane reconnaissance flights for the period 1945-1972 in the Puerto Rico Zone 15-20° N latitude and 65-70° W longitude. The cumulative probability distributions of each parameter documented by NOAA (1973) for the federal flood insurance program, are used to represent the hurricane statistics on the north coast. Each probability distribution is divided into class intervals and values read off the mid-point. Altogether this method, called the joint probability method (Meyers, 1975), treats 128 hurricanes that taken as a whole represent the climatological possibilities on the north coast. These include four central pressures, 2 forward speeds and 16 tracks.

The central pressure distribution is based on the same statistical population of storms as the track frequency count including 29 hurricanes and tropical storms through the zone during 28 years. The probability distribution of central pressure is further divided in four class intervals in the range of 10 to 50 percent probability, to gain definition around the most intense and less frequent events (Table 5-1).

Table 5-1. Classification of central pressure data (CPI) and corresponding radius of maximum wind (R).

Class	Probability	CPI (mb)	R (km)
1	10%	924	9.25
2	10%	944	20.35
3	30%	967	27.75
4	50%	996	37.00

Wind strength increases radially outward from the center of a hurricane to a zone of maximum strength and then decreases more gradually toward the hurricane edge. The average distance from the storm center to the circular zone of maximum wind speed is defined as the radius of maximum wind (R). It is an index of the size and lateral extent of the hurricane which in turn determines the storm surge profile along the coast. Most R values are realtively low ranging 7 to 37 km. Less than 20 percent of 17 storms have R values greater than 27 km. The radius of maximum wind generally increases with increasing central pressure reflecting intensity of the hurricanes, Figure 5-1. For numerical computations, it is assumed that the radius of maximum wind is a deterministic function of central pressure:

$$R = f\ (CPI)$$

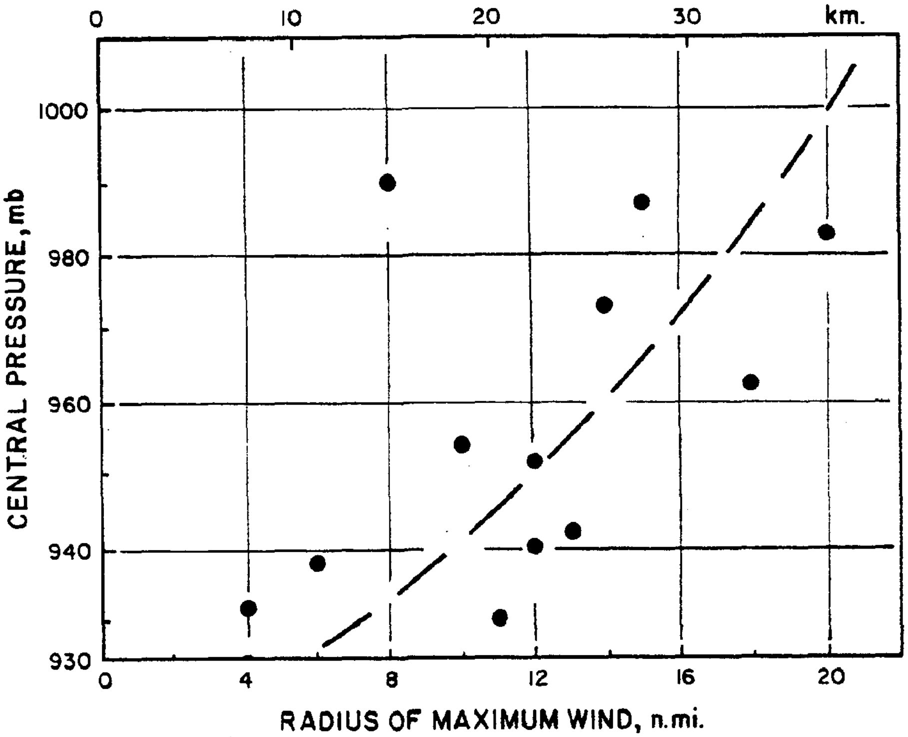

Figure 5-1. Radius of maximum wind as a function of central pressure; data from NOAA, (1975).

The speed of forward motion in a hurricane can increase storm surge heights particularly in landfalling fast moving storms. Along the north coast of Puerto Rico however, which is affected by exiting and alongshore hurricanes, the forward motion is relatively slow, mainly less than 30 km per hour. Therefore, the affect of forward speed on is relatively small. From the percentage of 17 storms which are representative of a 100-year period, two forward speed classes are derived as shown in Table 5-3.

Table 5-3. Classification of forward speed.

Class	Probability	Vf(m/s)
1	0.5	5.3
2	0.5	9.3

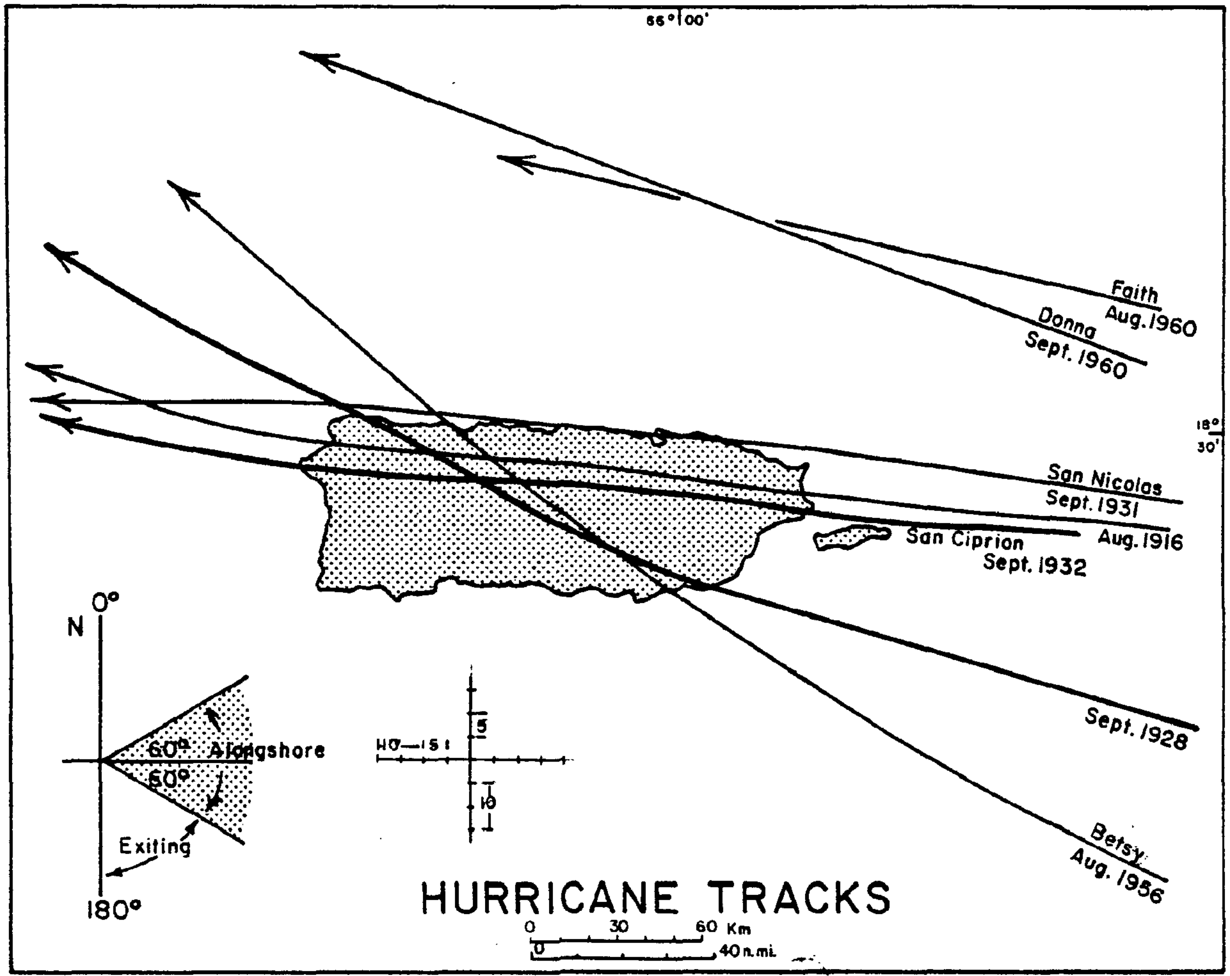

Figure 5-2. Predominant hurricane tracks for several hurricanes passing near Puerto Rico.

Most hurricanes approach Puerto Rico from either (1) the east and pass alongshore the north coast, or (2) the southeast and exit across the north coast, Figure 5-2. Alongshore storms have tracks directed between 60 and 120 degrees and a probability of 0.5, whereas exiting storms are directed between 120 and 180° and have a probability of 0.5 (Figure 5-2). The track frequency is defined as the number of storm tracks per unit time that cross a line from any direction per unit length 1, normal to the storm track. Given a point on the north coast, consider two 9.2 km (5n.mi.) segments on either side of the point (Figure 5-2) and two 18.5 (10n.mi.) segments adjacent to these for a total of 16 tracks. Then the storm frequency in the 9.2 km segments is 0.016 per year and in the 18.5 km segments is 0.032 per year (Ho, 1975). That is, for the Puerto Rico zone there are 3.2 storms per 18.5 km per 100 years.

Surge Prediction. To predict the total rise of water level resulting from storm surge, computational procedures initially follow the bathystrophic storm tide model (CERC, 1977). Results are then compared with the output of a modified hydrodynamic model called SPLASH used by NOAA for the National Flood Insurance Program (NOAA, 1973). Both models aim to convert the hurricane climatology of theoretical hurricanes into hurricane surge climatology.

In the bathystrophic model (CERC, 1977), the surge height generated from a synthetic hurricane, which is propagated shoreward along a line perpendicular to the coast, is calculated by the steady state integration of wind stress at discrete points along the locus of the radius of maximum winds. In this one dimensional model, the storm path is fixed by the method. The maximum surge is obtained by moving the hurricane along the north coast at a distance of 5.5 km (3 n mi) offshore with maximum winds impinging on the coast.

The total rise of water (S_T) is treated as the combined height of the components: atmospheric pressure or inverted barometer setup ($S\Delta p$), the astronomic tide (S_A), the wave setup (S_W), wind setup in the x component (S_x) and y component (S_y), and an initial setup or forerunner (S_e). While the CERC procedures assume a 0.6 m (2 feet) forerunner, no evidence could be found that this is a significant term in tropical hurricanes and therefore is neglected. Summarizing:

$$S_T = S\Delta p + S_A + S_W + S_x + S_y$$

The model assumes the buildup of water induced by a hurricane is superimposed on mean high water, i.e. it arrives in phase with the high tide which amounts to 0.3 m (1.1 feet) at San Juan.

The basic procedures used for test runs on 10-year and 100-year storms consist of:

1. Construct smoothed bathymetric profiles across the shelf from the 310 m water depth to the shore for each of the three sites.
2. Write the bathystrophic equations in finite difference form to facilitate manual computations utilizing derivatives.

3. Determine the recurrence interval for each storm parameter from NOAA hurricane climatology, e.g. CPI and R.

4. Compute the atmospheric pressure setup using equation 3-71 (CERC, 1977) assuming the storm passes 5.5 km (3 n.mi.) offshore; start computation when storm is one radius to the east (37 km or 20 n.mi.).

5. Compute the maximum gradient wind speed using equation 3-35 (CERC, 1977) and the maximum sustained wind speed using equation 3-34 (CERC, 1977); obtain the maximum deepwater significant wave height at the point of maximum wind from equation 3-31 (CERC, 1977) corrected for storm path and coastal orientation using diagram 3-34 (CERC, 1977).

6. Compute the maximum breaker height using diagram 2-65 and 2-66 (CERC, 1977) to find the breaker index with beach slopes of 0.012 (Carolina), 0.034 (Hatillo) and 0.021 (Isabela) and depth of water at breaking.

7. Compute the wave setup and setdown at the breaker point using equations 3-47 and 3-48 (CERC, 1977).

8. Sum the barometric setup, wind and wave setup and add the mean height of the astronomic tide.

Results of the detailed computations for a one in 10-year hurricane and a one in 100-year hurricane are contained in an assemblage of tables and equations provided separately. The smoothed bathymetric profiles are illustrated in Figure 5-3. Table 5-3 gives the computed breaker height as well as water depth at which breaking is initiated and the corresponding distance offshore. Table 5-4 gives values for the storm surge components and total surge at each site as estimated by CERC (1977) procedures.

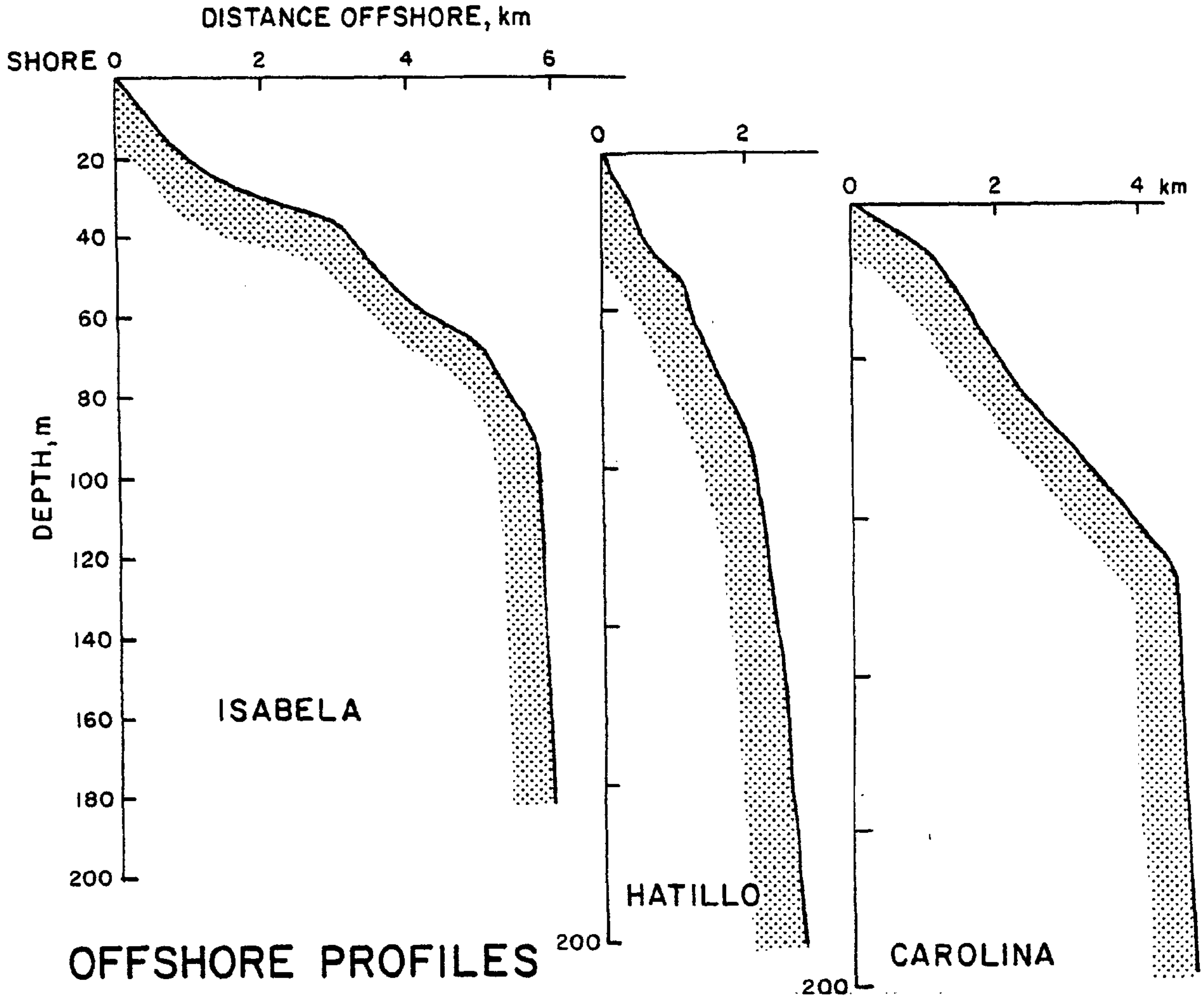

Figure 5-3. Smooth bathymetric profiles for the shelf and adjacent slope at each study site.

Table 5-3. Breaker height, water depth and distance offshore at which wave breaking is initiated for different hurricanes.

Storm/ Site	Breaker Height, m	Water Depth, m	Distance Offshore, m
1-10 yr	H_b	d_b	
Carolina	6.1	7.6	635
Hatillo	9.8	12.2	359
Isabela	7.9	9.8	464
1-100 yr			
Carolina	5.2	6.4	534
Hatillo	8.2	10.4	305
Isabela	6.7	8.2	392

Table 5-4. Values for setup components of storm surge and total rise of water at different sites on the north coast above mean low water.

Storm	Carolina m.	Hatillo m.	Isabela m.
10-yr			
Atmos. Press.	0.09	0.09	0.09
Wave Setup	0.88	1.28	1.07
Wind Setup	-	-	-
Astron. Tide (San Juan)	0.31	0.31	0.31
Total Setup, m	1.28	1.68	1.47
Total Setup, ft	4.2	5.5	4.8
100-yr			
Atmos. Press	0.58	0.58	0.58
Wave Setup	0.73	1.10	0.88
Wind Setup	0.15	0.06	0.12
Astron. Tide (San Juan)	0.31	0.31	0.31
Total Setup, m	1.77	2.05	1.89
Total Setup, ft	5.8	6.7	6.2

The range of total setup values from site to site is relatively small (Table 5-4), e.g. between 1.77 and 2.05 m, for the 100-year storm. The difference of setup values at a single site between 10-year and 100-year storms varies within relatively narrow limits. The 10-year values are only slightly smaller than the 100 year values. Of note, the wave setup values for the 10-year storm are larger than corresponding values for the 100 year storm. Moreover, the 10-year breaker heights are also greater than the 100-year heights at all sites except Hatillo (Table 5-3). This anomalous data arises because the CERC method fixes the storm path, and the induced wave setup is sensitive to distance offshore. For example, a 10-year storm can have a greater extent and wider radius of maximum wind than a 100-year storm on the same path. Thus, it can have a greater fetch and larger waves than the 100-year storm. Consequently, it is necessary to take into account the combination of all storm paths that procuce the total surge with a given recurrence interval. This is accomplished by the NOAA hydrodynamic surge model SPLASH (NOAA, 1973). Despite constraints of utilizing this model on a steep coast and for relatively small hurricanes affecting Puerto Rico, the model produces an output in terms of joint probability of each event whereby the pressure, forward speed, direction of entry and astronomical tide are independent of coastal placement. The resulting surge curve, Figure 5-4 is the best predictive curve available. It represents the still-water level that may be expected on the open coast such as on a tide guage protected from wave action. The validity of the data is partly confirmed, by an observed peak tidal height, 0.73 (2.40 ft) above mean low water (or 0.88 m, 2.9 ft. above mean sea level) recorded on the NOAA San Juan tide guage during an 18-year period, 1960-1978.

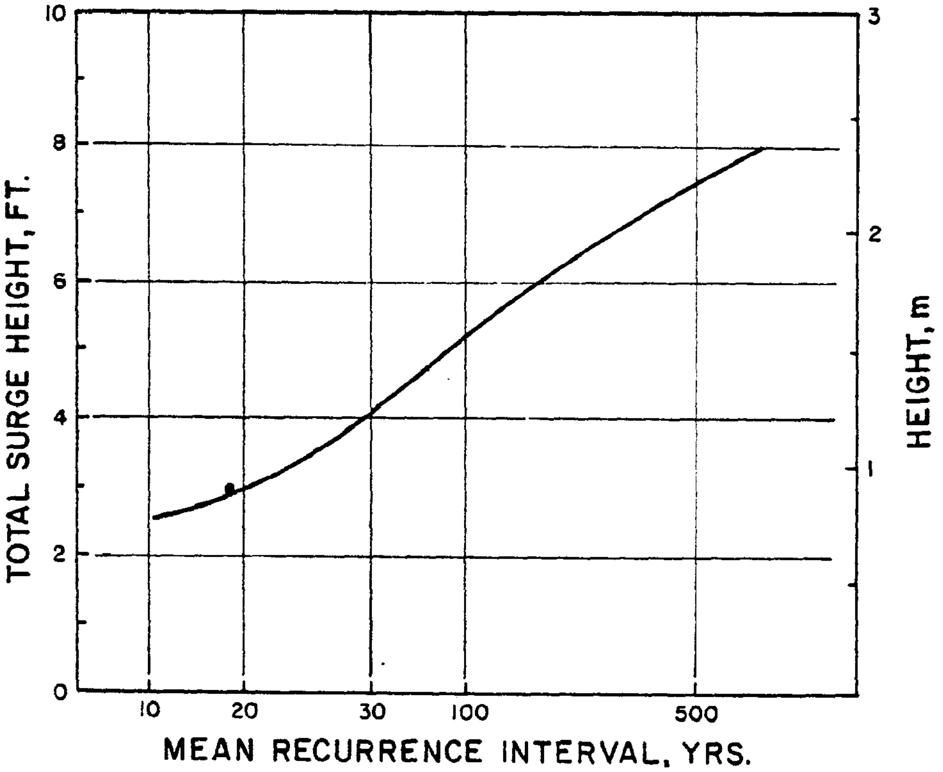

Figure 5-4. Total storm surge frequency curve for San Juan, from NOAA (1975); heights based on mean sea level. Dot represents highest tide reached on the NOAA San Juan tide guage during the 18-year period 1960-1978.

Hindcast of Hurricane Waves in Deep Waters.

To predict the heights of ocean waves induced by hurricane winds, the numerical techniques and formulas of the Shore Protection Manual (U. S. Army, CERC, 1977) are used. The significant wave height, i.e. the average height of the one-third highest waves of a given group, at the point of maximum wind is derived from the formula:

$$H_o = 16.5\, e^{\frac{R\Delta p}{100}} \left[1 + \frac{0.208\, \alpha V_F}{\sqrt{U_R}} \right],$$

and the wave period is derived from:

$$T_s = 8.6\, e^{\frac{R\Delta p}{200}} \left[1 + \frac{0.104\, \alpha V_F}{\sqrt{U_R}} \right],$$

where

H_o = deepwater significant wave height in feet

T_S = the corresponding significant wave period in seconds

R = radius of maximum wind in nautical miles

Δp = $P_n - P_o$, where P_n is the normal pressure of 29.92 inches of mercury, and P_o is the central pressure of the hurricane

V_F = The forward speed of the hurricane in knots

U_R = The maximum sustained wind speed in knots, calculated for 30 feet above the mean sea surface at radius R where

$$U_R = 0.865\, U_{max} + 0.5\, V_F \quad \text{(For moving hurricane)}$$

U_{max} = Maximum gradient wind speed in knots 30 feet above the water surface

$$U_{max} = 0.868\, [73\, (P_n - P_o)^{\frac{1}{2}} - R(0.575f)]$$

f = Coriolis parameter = $2\omega \sin\phi$, where ω = angular velocity of earth = $2\pi/24$ radians per hour

Latitude (ϕ)	25°	30°	35°	40°
f (rad/hr)	0.221	0.262	0.300	0.337

α = a coefficient depending on the forward speed of the hurricane and the increase in effective fetch length, because the hurricane is moving. For slowly moving hurricane $\alpha = 1.0$.

Once H_0 is determined for the point of maximum wind from the initial equation it is possible to obtain the approximate deepwater significant wave height H_0 for other areas of the hurricane by use of Figure 3-34, in CERC (1977).

The corresponding approximate wave period may be obtained from

$$T = 2.13 \sqrt{H_0} \text{ (secs.)}$$

where H_0 is in feet derived from empirical data showing that the wave steepness H/T^2 will be about 0.22.

By using the functional relationship between CPI and R. (Table 5-1, Fig. 5-1), graphs of CPI~16.e $\frac{R\Delta p}{100}$ and CPI~U_{max} (e.g. Figure 5-5) and CPI~8.6e $\frac{R\Delta p}{100}$ have been prepared. Then for any specified CPI V_f only the terms in brackets need be computed. For eight hurricanes with CPI's ranging 924 to 996mb and two forward speeds, 18.9 km per hr (10.5 kt) and 33 km per hr (18.5 kt), the maximum deepwater significant wave height after modification for storm path and speed, ranges 7.0 m to 8.9 m, the cumulative probability distribution is given in Figure 5-6.

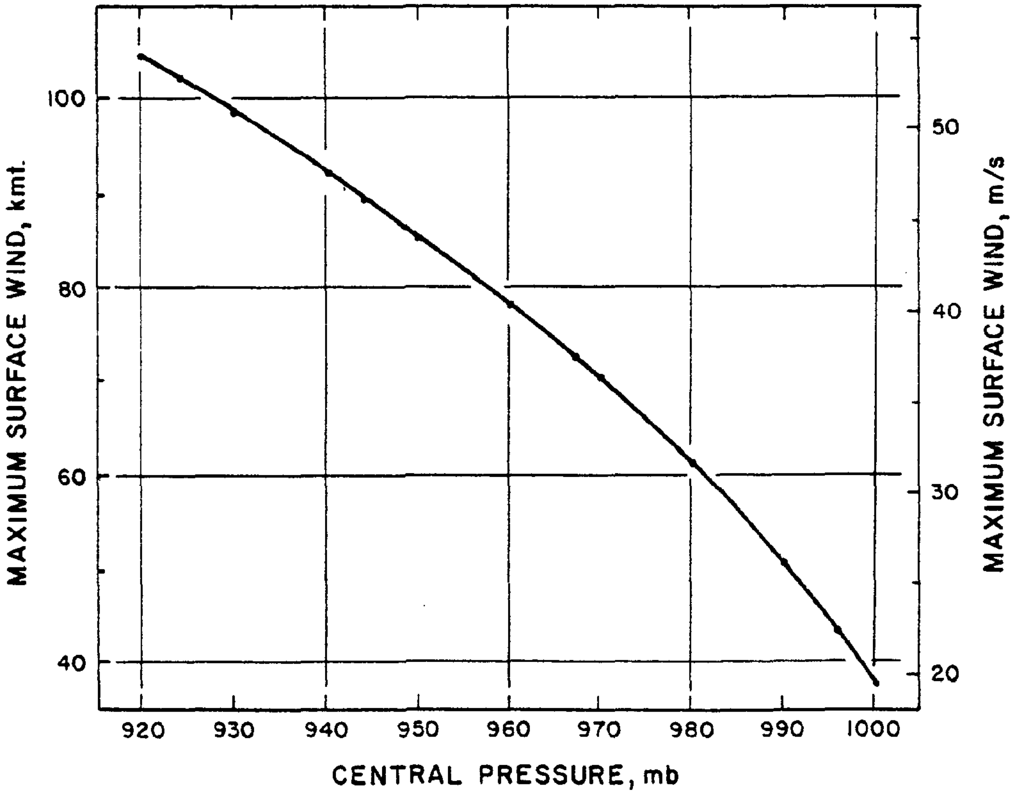

Figure 5-5. Graph of central pressure index (CPI) versus maximum sustained surface wind speed (Umax).

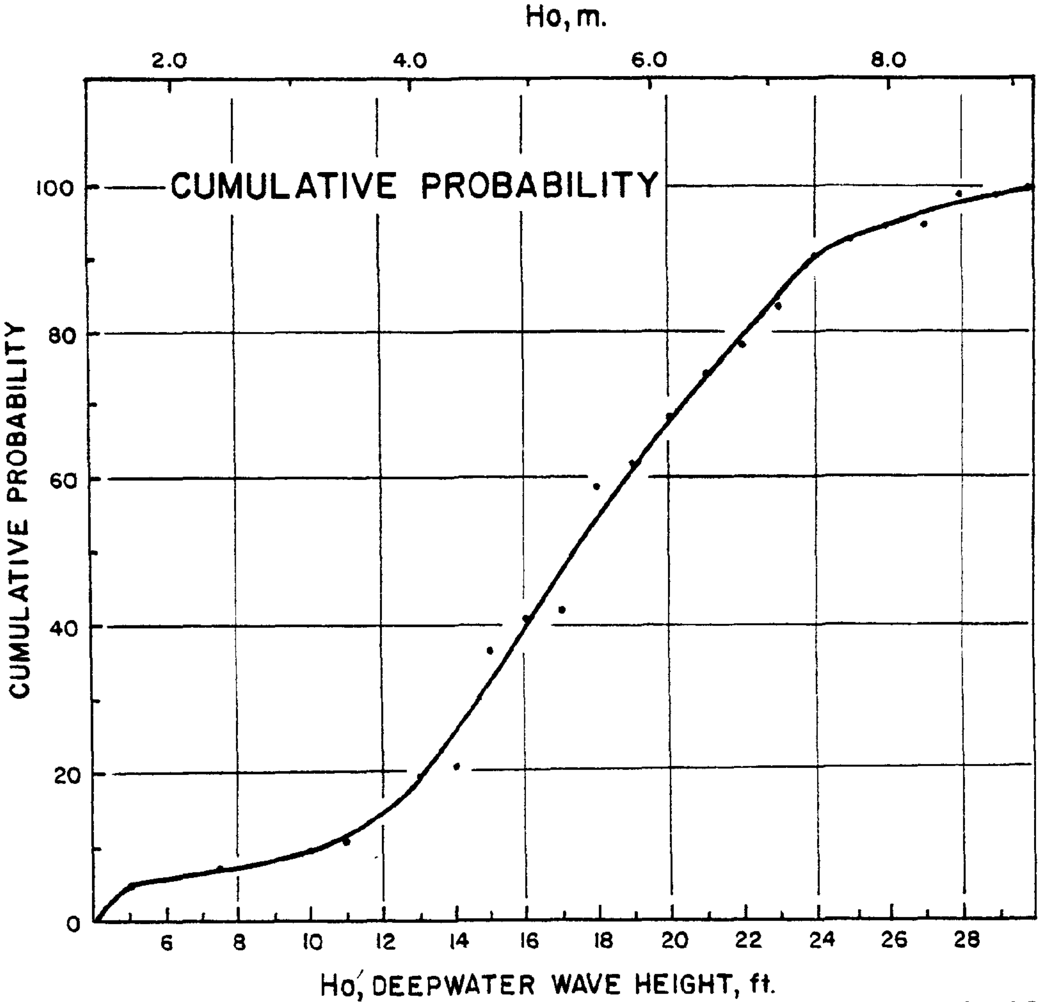

Figure 5-6. Cumulative probability curve for maximum deep water significant wave height (H_0') on the north coast after modifications for storm speed and disection.

A recurrence graph for deepwater significant height for the north coast sites is developed in two stages. First, the maximum deepwater significant wave height (H_0) at the point of maximum wind is corrected for storm size and path to obtain the deepwater significant wave height at the coastal sites. The corrected wave height, $H_0' = \alpha H_0$ where α accounts for storm path and coastal orientation following Figure 3-34 of the Shore Protection Manual (CERC, 1977). Second, to convert the probability of wave height in terms of recurrence interval, the wave height probability is multiplied by the frequency of hurricanes in each of the 16 selected approach paths. As previously defined the frequency associated with each path is:

$$F_s = F_t P_p P_s$$

Since two principal paths are considered, alongshore or exiting, $P_p = 0.5$ for all cases, and $F_s = 0.5\ F_t\ P_s$. The computations are accomplished for the 128 hurricanes with 16 paths, 4 central pressure conditions and two forward speeds, relatively slow and fast. Then, the deepwater significant wave heights on the north coast and associated annual frequencies are separated into a series of class intervals and a histogram of wave heights is constructed. This is used to derive a cumulative probability graph of the significant deepwater wave height (H_o') which has been adjusted for storm path and coastal orientation. The end-product is a graph of deepwater significant wave height as a function of recurrence interval, or return interval, Figure 5-7. For example, a recurrence interval of 100 means that there will be one hurricane in 100 years during which the deepwater significant wave height just seaward of the breaker zone, is likely to reach a height of 8.1 m (26.6 ft). Table 5-5 provides the graphical information in tabular form.

Runup. Superimposed on the build-up of water produced by storm surge, wave energy is dissipated after breaking by runup on the beach slope and dune face. Runup is calculated as the vertical height above stillwater level that the rush of water reaches (CERC, 1977). Runup depends on the incoming wave characteristics, the shape and slope of the beach and dune as well as on the nearshore bottom slope and water depth.

To calculate the height of runup on a beach/dune face, basic procedures of CERC (1977) are used in which the beach/dune face is treated like a "flexible" seawall or breakwater. The beach/dune profiles acquired in this study between July-September 1982 are assumed to be in equilibrium with energy forces although sand extraction may have created an imbalance. Recognizing the variations in shore configuration and nearshore topography, runup is computed initially for each profile where both the beach/dune elevations and nearshore water depths

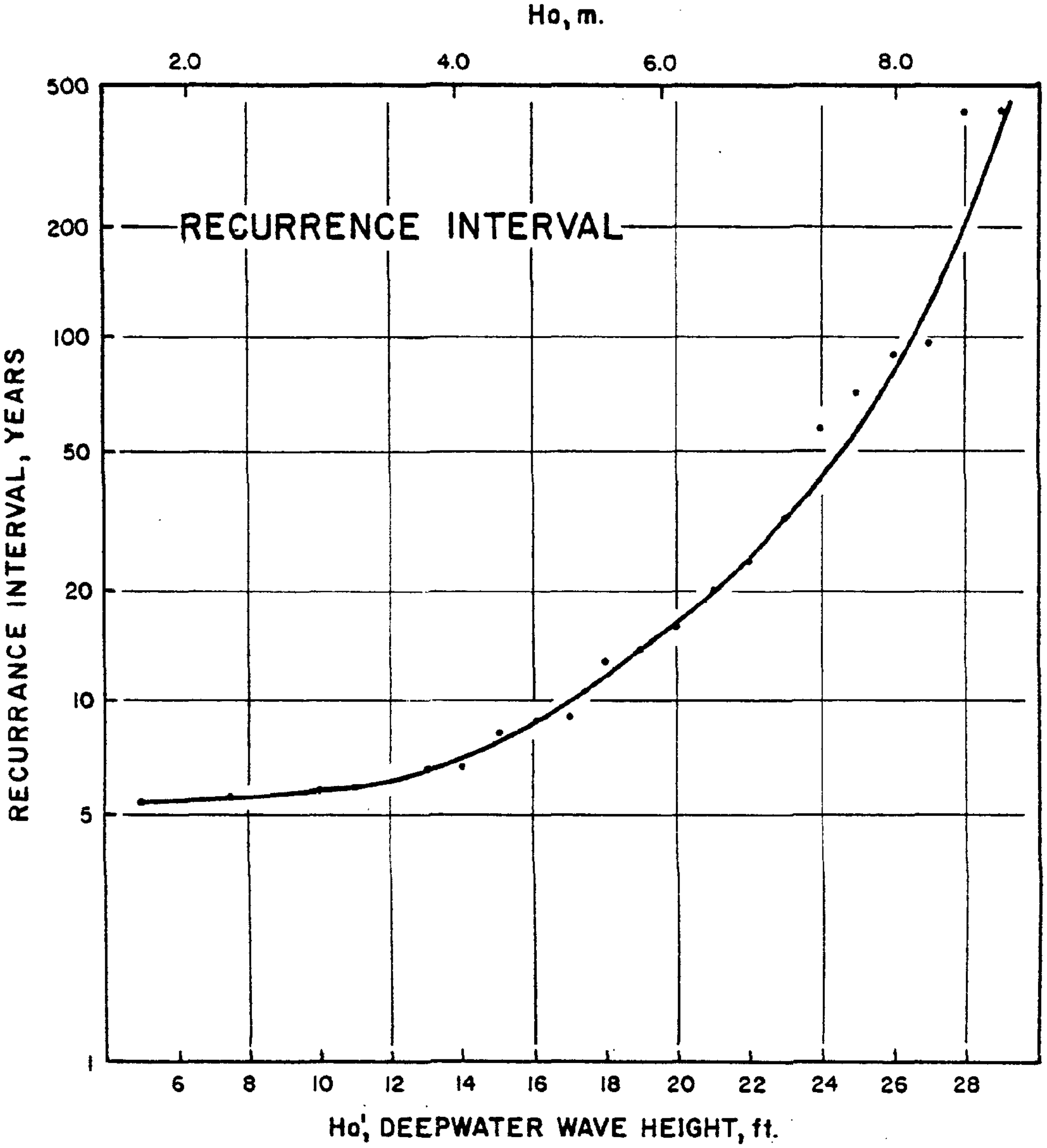

Figure 5-7. Recurrence interval curves for maximum deep water significant wave height (H_o') on the north coast after modification for storm speed and direction.

Table 5-5. Summary of hurricane wave statistics.

Recurrence Intervals, years	Deepwater Signif. Wave Height, H'_o m	ft.
500	9.0	29.5
100	8.1	26.6
50	7.5	24.6
20	6.4	21.1
10	5.2	17.0

have been measured. These computations assume the probability and recurrence interval of the runup corresponds to the frequency of the deepwater significant waves. Additionally, tests were run on near-maximum deepwater waves, i.e. the average of the highest one percent of all waves. However, since the highest one percent of all waves may break farther seaward than significant waves, the runup can be less than for significant waves. The design height used in engineering structures is usually the significant wave height (H_o), i.e. the average of the highest one-third of all waves present. This is a height where erosion and failure of the dune face probably can occur in addition to overtopping.

Since the frequency of the runup may differ from the frequency of the deepwater significant wave, with small more frequent waves producing a greater runup than large less frequent waves, the frequency recurrence of the runup itself is considered.

The procedures used consist of:

1. Construct combined nearshore bathymetric and beach/dune profiles for each transect surveyed in 1982, Appendix A.
2. Specify the deepwater wave height, both H_o' or H_1, and the corresponding frequency of occurrence, i.e. 10, 20, 50 and 100-year, from Figure 5-7 this section.
3. Determine the wave period and water depth for breaking, using CERC equations: $T = 2.13 \sqrt{H_o'}$ and H_o'/gT^2.
4. Determine the Breaker Height Index Hb/H_o' Figure 7-3, for H'_o/gT^2 from CERC (1977), using the curve for the given slope, m. Determine Hb.
5. Determine the ratio of depth at breaking, d_b, and breaker height, Hb, from Figure 7-2, CERC (1977).
6. On the constructed profile define the stillwater level (SWL) from the total surge height diagram, Figure 5-4 this study and draw it on each profile for each recurrence interval considered.
7. Determine the breaker location, i.e. distance of breaking offshore from the intersection of the breaker depth and the profile.
8. Estimate the runup, R, above stillwater level to get the first, hypothetical slope of the composite slope, and compute $\cot \theta = \Delta x/\Delta y$; determine db/H'_o.

9. Determine R/H'_o from Fig. 7-10 or Fig. 7-11 (CERC, 1977), with lines extended on right, and then determine R the runup height measured vertically from SWL.
10. Compute a new value for cot θ using the next slope and derive d_b/H_o, R/H'_o and R using CERC (1977) Figure 7-10 or 7-11 for successive slopes following Figure 7-22, CERC (1977).

The above procedures are carried out initially for each profile assuming a specified recurrence interval and correspondence of runup recurrence to deepwater wave recurrence. Then the frequency of runup itself is computed based on an average or "design", profile for each site in which profiles having similar depths are averaged. In this computation the probability curve of deepwater significant wave heights, H_o', is divided into ten percent class intervals and the runup computed for each class interval.

The distribution of predicted runup wave heights with a specified recurrence interval corresponding to the deepwater significant wave recurrence interval is given in Table 5-6. The range of values for a 100-year hurricane in eastern and central Tres Palmitas, Carolina is relatively small, 2.3 m to 3.1 m, whereas 3.9 m is predicted for transect 3 in the western section. This is expected because the western sector has deeper water offshore, i.e. 700 m to the 20 m depth curve, than the eastern sector with 1500 m to the 20 m depth curve, Figure 7-5. For the same size deepwater significant wave, e.g. 8.0 m for the 100-year storm, waves are predicted to break closer to shore (275 m) at transect 3 than other transects at Tres Palmitas. Surprisingly, the 10-year runup wave height, 2.7 m, is greater than the 20-year and 50-year heights, 2.2 and 2.3 m on transect 11, Table 5-6. This anomolous situation arises because smaller more frequent waves can break closer to shore and produce a greater runup than the 20-year and 50-year waves. At Isabela the highest 100-year runup wave height, 3.8 m, is predicted at transect XII in the western sector, whereas runup heights are relatively low at transects VIII and XXI, Table 5-6, Figure 6-2.

Runup wave heights for maximum deepwater significant waves, i.e. average of the highest one percent of all waves, are compared with corresponding heights of significant waves, in Tables 5-6, 5-7. As expected at one location the maximum wave heights are 10 to 59 percent greater than the significant waves. The predicted maximum runup heights are probably heights that can be recorded by the highest swash marks or by the upper limits of floating debris and instantaneous overtopping. On the other hand the runup heights of significant waves are believed to represent heights that can produce full scale overtopping and erosion of the dune face as well as flooding of low lying areas behind the dunes.

When profiles having similar offshore water depths at each site are averaged to construct a "design" profile and the corresponding recurrence interval of the runup itself is computed, the predicted heights at different sites for a 50-year storm range from 2.2 to 3.3 m and for a 100-year storm, from 2.8 to 4.1 m, Table 5-8. When these values are compared to elevations of swash marks and overtoppings of the October 11-13 storm, a 5 year to 8 year storm (Table 7-2), they are relatively low. This may be an artifact of the CERC (1977) procedures being conservative. They do not take into account the elevation storm surge forerunners, possibly 0.3 to 0.6 m, or runup "wind spray" on the dunes. Moreover, the procedures do not take into account the local irregularities in shore configuration that can cause refraction, and they do not account for long-term rise of sea level, possibly 0.2 to 0.4 m over 100 years. The relatively low run-up values may be caused by the fact that the fetch for tropical hurricanes is often short in contrast to northern swells and since hurricanes move relatively fast, the duration of wave-generating

Table 5-6. Distribution of total runup wave heights* predictions by transect for deepwater significant wave heights (H'_o) at various hurricane recurrence intervals.

Location	Runup Wave Height, m Recurrence Interval, years 10-yr	20-yr	50-yr	100-yr
Carolina				
10	1.3	1.4	1.9	2.3
11	2.7	2.2	2.3	2.7
12	1.9	2.0	2.6	3.1
3	2.7	2.8	3.3	3.9
Hatillo				
II	1.6	1.9	2.6	3.1
IV, VI, XXIV**	2.0	2.3	2.9	3.5
Isabella				
VIII	1.3	1.4	1.7	1.9
IX	1.3	1.6	2.2	2.4
XXI	1.2	1.5	1.8	1.9
XIX	2.1	2.3	2.8	3.3
XVII	1.9	2.1	2.8	3.5
XIV	1.3	1.5	2.0	2.5
XII	1.9	2.3	3.1	3.8

*Height includes runup height plus storm surge height.

**Based on average slope of three transects with simplified bathymetry from NOS chart only.

Table 5-7. Distribution of total runup wave heights* predictions for maximum deepwater significant wave heights at various hurricane recurrence intervals.

Location	Runup Wave Height; m Recurrence Interval, years 10-yr	 20-yr	 50-yr	 100-yr
Carolina				
10	1.5	1.6	2.1	2.6
11	1.6	1.8	2.3	2.7
3	2.8	3.1	3.7	4.3
Hatillo				
II	2.3	2.7	3.4	4.1
Isabella				
VIII	3.0	3.7	4.1	4.6
XII	2.9	3.5	4.0	4.8

*Height includes runup height plus storm surge height.

forces is relatively short. Because of these unknown factors, the computed runup heights (Table 5-8) are increased by 30 percent to provide design dune heights. Table 5-9 gives the final values of design dune height for selected recurrence intervals and Figure 8-1 gives the full distribution of values for each "design" site.

Table 5-8. Summary of total runup wave height predictions at different locations. Based on runup of deepwater significant waves.

Location	Runup Wave Height, m Recurrence Interval, Years 10-yr	 20-yr	 50-yr	 100-yr
Carolina				
Deepwater Offshore[1]	2.1	2.4	3.1	3.9
Shallow Water Offshore[2]	1.7	1.8	2.2	2.8
Hatillo[3]	1.6	2.0	2.7	3.6
Isabela				
Deepwater Offshore[4]	2.1	2.4	3.3	4.1
Shallow Water Offshore[5]	1.4	1.5	2.2	2.9

Table 5-9. Summary of total runup wave height predictions for design dune heights at different locations. Based on corrected runup of deepwater significant waves.

Location	Runup Wave Height, m Recurrence Interval, years 10-yr	 20-yr	 50-yr	 100-yr
Carolina				
Deepwater offshore[1]	2.7	3.1	4.0	5.1
Shallow water offshore[2]	2.2	2.3	2.9	3.6
Hatillo[3]	2.1	2.6	3.5	4.7
Isabella				
Deepwater offshore[4]	2.7	3.1	4.3	5.3
Shallow water offshore[5]	1.8	1.9	2.9	3.8

[1] Data from transects 3, 12

[2] Data from transects 10, 11

[3] Data from transect II

[4] Data from transects VIII, XII, XVII, XIX, XXI

[5] Data from transects IX, XIV, XV

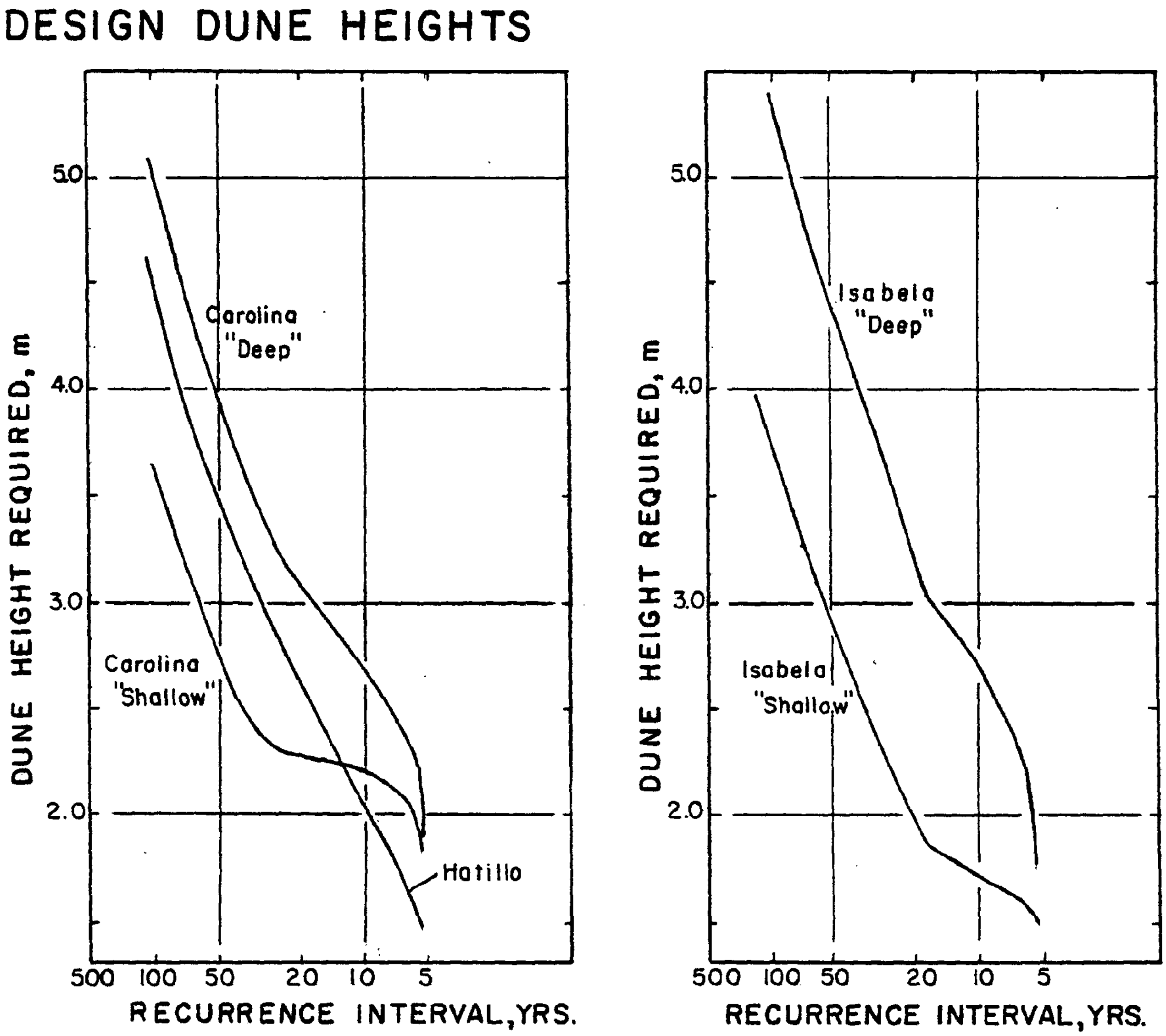

Figure 5-8. Runup prediction curves for selected "design" sites.

6. Dune Characteristics, Past and Present

The type and extent of coastal dunes vary widely. The status of the dunes prior to extraction was analyzed from aerial photographs dated 1936 and 1950 and from old topographic maps dated 1922 and 1950. The present dune status which is mainly after extraction, was determined from aerial photos dated 1977 and field observations of this investigation.

Three types of dunes are recognized: (1) high massive dunes, greater than 10 m high and transgressive landward, (2) low massive dunes, less than 10 m high extending landward, (3) single dune ridge paralleling the beach. Figure 6-1 displays the distribution of dune types before extraction and mainly after extraction at the time of investigation.

In the Isabela area prior to extraction, 69 percent of the well-developed dunes were high massive dunes (type 1) with elevations greater than 10 m and extending landward from the dune face 180 to 300 m (Figure 6-1, Table 6-1). Single ridges were limited to areas protected by headlands, e.g. immediately west of Punta Jacinto and Punta Sardina. The natural dunes that parallel the coast were broken by numerous blowouts with advancing blowout noses directed landward toward the southwest. The largest dune deposit was located between Pena de los Pozos and Punta Sardina (Figure 6-1) where an estimated 2.6 million cubic meters was extracted (Castillo and Quinones, 1980). The second largest dune system extracted in the area was located west of Punta Jacinto, where an estimated 2.5 million cubic meters of sand was removed. The dunes east of Punta Sardina were generally lower and narrower than west of the point. Figure 6-2 displays this area showing a portion of a "residual" or natural dune with its surface broken by blowouts. The sand mainly consists of terrigenous quartz and feldspar with small amounts of calcium carbonate fragments derived from the sea.

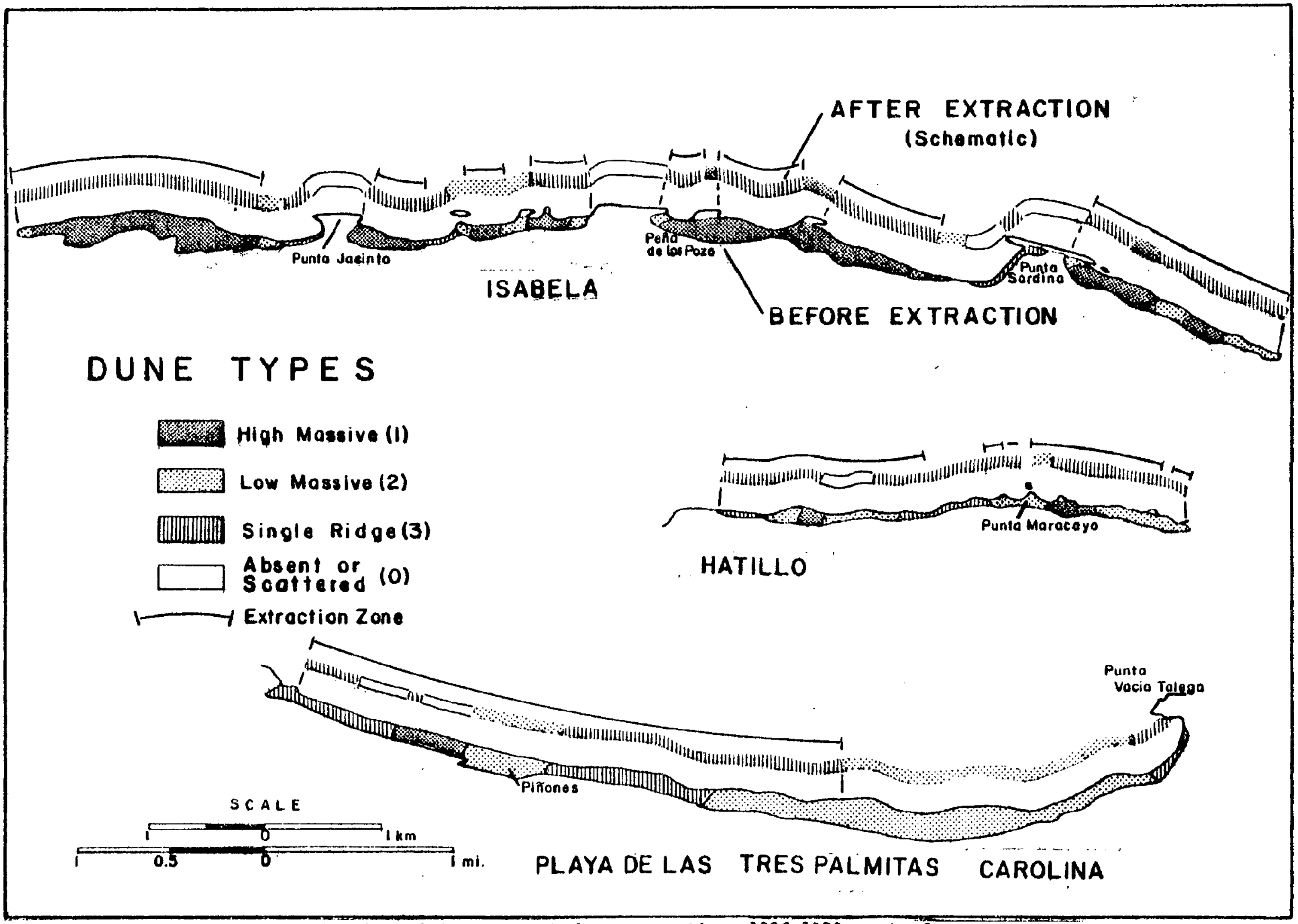

Figure 6-1. Distribution of dune types before extraction, 1936-1950, and after extraction (1977-1982) at Isabela, Hatillo and Playa de las Tres Palmitas.

After more than eight years of large scale extraction, the Isabela dunes consist of a narrow ridge scarped on its seaward face, broken by blowouts and breached by storm waves. The most marked change of dune type occurred in zones where the greatest amount of sand was extracted, i.e. west of Punta Jacinto and between Peña de los Pozos and Punta Sardina. For the coast as a whole, only 17 percent of the original volume of sand remains in the "residual" dune ridge (Castillo and Quinones, 1980).

Table 6-1. Status of dune systems before and after extraction (1982) according to percentage of different dune types present along the coast.

	Isabela		Hatillo		Carolina	
Dune Type	Before Extraction	After Extraction	Before Extraction	After Extraction	Before Extraction	After Extraction
Absent or Scattered (0)	0	0	0	13	0	12
Single Ridge (3)	13	82	30	83	41	45
Low Massive (2)	18	12	53	4	50	43
High Massive (1)	69	6	17	0	9	0

In the Hatillo area prior to extraction, 53 percent of the dunes were of the low massive type (2) with widths of 50 to 150 m (Figure 6-1, Table 6-1). A prominent single ridge stabilized by vegetation extended west of Pta. Maracayo 370 m to 1100 m. Locally, dunes reached heights greater than 10 m just east of Pta. Maracayo and one km east of Hatillo. The latter dune deposit was extensively disected by blowouts but most other dunes were stabilized by vegetation except the seaward face of the dune mass just east of Pta. Maracayo.

After more than 25 years of intermittent extraction the dunes are narrowed to a single ridge about 30 to 60 m wide (Figure 6-1). The most marked change took place near transect V east of Hatillo, where northern swells washed out the remaining foredune ridge for a distance of about 500 km along the shore (Figures 6-1; 7-6B). Consequently, the integrity of the dune system has been broken by excess extraction. Elsewhere, about 30 percent of the original volume of the sand dune remains as a "residual" dune ridge (Castillo and Quinones, 1980). Extraction operations led to substantial infilling and burial of mangroves lying behind the dunes.

Prior to extraction the sand dunes at Playa de las Tres Palmitas, Carolina constituted the longest dune system on the north coast. Most dunes (55 percent) were well-developed low massive dunes (type 2) with elevations between 3 and 8 m and widths of 80 to 280 m. A single dune ridge joined zones between the low massive dunes occupying 45 percent of the dune zone. Locally, the ridge reached more than 10 m elevation just west of Pinones and just west of Punta Vacia Talega, (zone 3, Figure 6-1). In the 1936 aerial photography the entire dune system was stabilized by coconut trees but former washovers are evident at Piñones, about 500 m east of Piñones and near Punta Vacia Talega. The sand mainly consists of terrigenous quartz and feldspar with small amounts of calcium carbonate particles derived from the sea.

Sand was extracted mainly during the 1950's from the area west of Piñones. The high massive ridge and low massive dunes were lowered and narrowed. Zones consisting of a prominent single ridge ranging to 12 m high west of Pinones were reduced to an extensive washover area (Figure 6-1) and rapid shoreline erosion set in. To protect this area from wave action an artificial breakwater consisting of scrap automobiles buried in sand was constructed but it failed to accrete and stabilize.

Blowouts and Stability. Blowouts develop where the vegetation cover of loose dune sand is destroyed or removed so that the sand is no longer held in position. They are often initiated by a lot of pedestrian and off-road vehicular traffic where footpaths or auto tracks are worn over the dunes. Some blowouts are started in dune gaps, breaches or on crests where the vegetation is lost by extraction followed by natural wind erosion. In places, eolianite or cemented sand, in the interior of the dunes acts as a base that protects the dune from further wind erosion. Most of the blowouts in the Isabela region are embedded in high dune topography where elevations are generally greater than 3 m. Wind speeds are usually greater across high topography than across low dune topography (Armon, 1980). Another observed trend is that most blowouts occur in zones where the shore faces the northeast (Figure 6-4) a direction from whence strong winds blow between December and March. Blowouts result in landward migration of sand into low lying or extracted areas behind the main dune ridge (Figure 6-3). This sand is largely trapped and removed from the active beach-dune transport system. Where dune gaps and breaches are lowered by blowouts, protection from storm surge and high waves is reduced. Therefore the occurrence of blowouts highlights the dangers involved with any loss of vegetation cover, especially on a slightly northeast facing shore.

Stability of the dunes is assessed in terms of: (1) extent and density of vegetation cover, (2) occurrence of blowouts, and (3) extent of landward migration manifest in washover lobes and blowout noses. Data to assess these features were obtained from aerial photography dated 1977 and from field surveys of this study (1982). Results are compiled into a chartlet showing the distribution of "stable" and "unstable" dunes, Figure 6-4. Unstable dunes are mapped where there is evidence for active gain or loss of sand from the surface and landward part of the dunes. These are largely

Figure 6-2. View east along dune ridge east of Punta Sardina, Isabela showing extraction zones (e) in relation to natural dune zone (n) with blowouts on crest. Note narrow beach and high water line at dune face (f); photo during storm of October 11-13, 1982.

Figure 6-3. Blowout zone near transect XIII, Isabela, showing active erosion in dune gaps (g) and deposition landward behind dunes (d). September 1982.

unvegetated zones. Stable dunes by contrast lack evidence for migration and are covered by vegetation. A few areas exhibit "recovery", that is, they display more vegetative cover in 1977-1982 than formerly, i.e. in prior aerial photography, 1936-1950, and thus have become more stable. The term recovery does not take into account portions of the dunes stabilized by residential developments, parking lots and road beds.

In the Isabela area, blowouts are very active in a zone 0.5 to 1.5 km west of Punta Jacinto, a coast with a slight northeast exposure and moderate elevation (Figure 6-4). Vegetation has been lost by natural erosion combined with dune buggy traffic. East of Punta Jacinto, dunes bordering small lunate embayments vary from stable to unstable (Figure 6-4). Generally the western or central sides of the embayments with greater exposure, are often unstable whereas eastern sides of the embayments with some degree of protection from headlands and islands are stable. Of note, dunes along the west side of the embayment west of Punta Sardina are unstable (Figure 6-4) inasmuch as they exhibit blowout, washovers and loss of vegetation by traffic and sand extraction. East of Punta Sardina dunes vary from stable to unstable depending on the degree of local blowouts, extraction and washovers.

In the Hatillo area, dunes are largely stable west and east of Punta Maracayo but locally vegetation cover is discontinuous and they are unstable (Figure 6- 4). In an unstable zone more than 0.5 km long near transect V west of Punta Maracayo, the residual dune ridge left by extraction is transformed into an extensive washover fan (Figure 6-4). Dunes backing Playa de las Tres Palmitas, Carolina are very unstable in the western sector as evidenced by extensive washovers in a zone 1.0 km long (Figure 6- 4). This is a contrast to dunes in the eastern sector that are extensively stabilized by coconut palms. East of Piñones, dunes are more extensively covered by

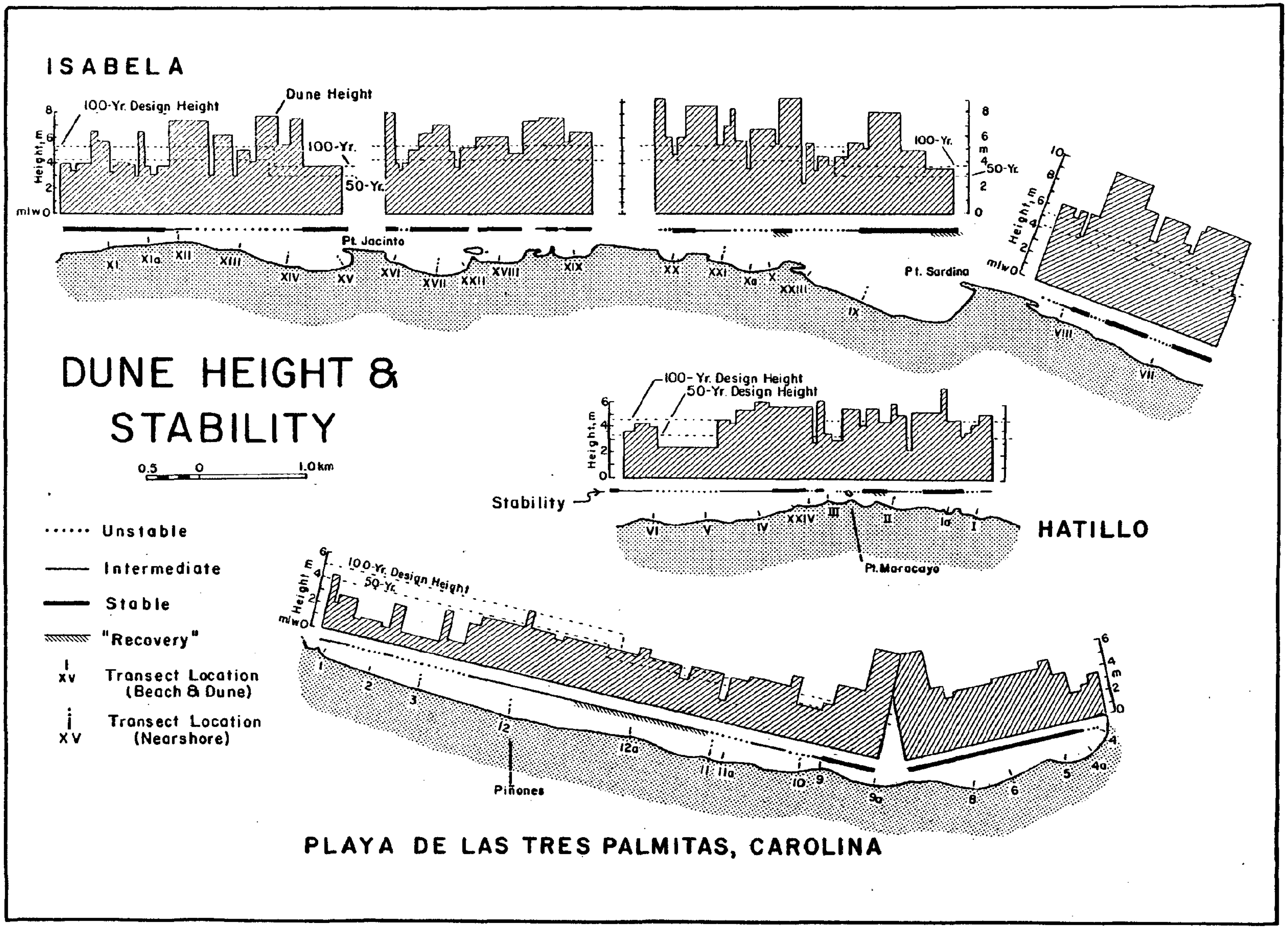

Figure 6-4. Transect locations for 1982 ground survey; distribution of dune height (H + BH) above mean low water based on aerial photos 1977, and ground observations, 1982, in relation to 50-year and 100-year design heights required for protection, cf. Table 5-9, Figure 5-8. Distribution dune stability by class; for details see text.

vegetation than in the 1960's, a zone which is generally recovering from former extraction. Recovery however, has been slowed or arrested by traffic of off-the-road vehicles.

The assessment demonstrates that the dune system is dynamic to some degree and certain zones are migrating landward in response to natural processes and prior sand extraction. Any management plan must take these trends into account. It must be designed to allow the dynamic processes to operate and allow migration to proceed without interference, though at a slower rate than at present.

Dune Height. Since dune height is a key element that determines the degree of protection from storm surge, runup and overtopping, elevations were surveyed along 25 transects transverse to the dune ridge. They were run July 28-30, September 14-17, 1982 and resurveyed after storm conditions, October 21-24, 1982. Transects were located at intervals of about 0.5 km along the coast (Figure 6-4). The transects are tied down to picture points on 1977 aerial photos and marked on their landward end in the field with a steel rod or existing structure so that they may continue to be used for future dune or beach studies. Appendix A gives the specific locations of transects with respect to the reference markers. Transect elevations were also tied on their seaward end to predicted mean low water. The level rod was set in the surf at an estimated elevation believed to represent the still water surface and then corrected to predicted mean low water at the time of survey using NOS tidal height tables for San Juan. Resurveys of the same lines indicate most transects are tied to mean low water with an accuracy less than ± 10 cm height. Field techniques follow convential survey leveling procedures using a tape, rod and self-leveling level. Elevations were taken along the beach and dune profile at intervals, or at break points, mainly less than 20 m apart. The elevations include side points consisting of gaps, crests, breaches and overtopping zones. The survey data were reduced to mean low water, plotted on graph paper and the dune height and width characteristics computed. Additional elevations and widths between the transects were determined from 1977 aerial photos using a photogrammetric stero plotter with an overall working accuracy of ± 0.45 m. Using the photo dimensions and transect elevations, basic height and width catagories were identified and shoreline segments with similar heights and similar widths charted (Figure 6-4). Elevations from 11 transects run by Ramon Martinez of DNR at Playa de las Tres Palmitas, Carolina in 1980, and resurveyed on three transects after the October 11-13, 1982 storm (November 1982), are included in this evaluation.

The distribution of dune height (H + BH) along the coast is presented in Figure 6-4. The greatest height, over 10 m, occurs 0.9 km east of Punta Sardina where an isolated segment of a natural dune is left intact (Figure 6-2). When the dune height distribution is considered in relation to heights of predicted hurricane storm surge and wave runup, horizontal dashed lines on Figure 6-4, it is evident that few zones offer complete height protection from wave heights attained by a hurricane that occurs once in 100 years. Only the zones east of Punta Sardina, west of Punta Maracayo (transects XXIV-IV) and eastern Tres Palmitas (transects 5-9) offer protection from 100-year hurricanes. On the other hand the lowest height, less than 1.3 m, occurs in unstable washover zones of western Tres Palmitas (Figure 6-4), and east of Hatillo (transects V and VI). In these zones, heights are inadequate to protect the coast from predicted wave heights attained by a hurricane with a five year recurrence interval. Another zone of relatively low dune heights associated with sand extraction is located west of Punta Jacinto (transects XI and XIa) which provides only "20-year hurricane protection". Locally, there are numerous gaps and breaches that allow overtopping of predicted "20-year high" hurricane waves, notably: (1) west of Punta Jacinto (transect XIII); (2) west of Punta Sardina (transects XXIII, Xa) and (3) east of Punta Jacinto (transect XVI). In most cases the reduced heights and "loss" of protection is caused by excess sand extraction at foredune gaps followed by wave overtopping and erosion.

Figure 6-5 gives design profiles used for runup computations which represent averages of two to five profiles from selected segments except Hatillo which is based on one profile. The graph shows the predicted runup in relation to the average height for the entire segment . As a result of different design profiles for different segments, runup varies with location. For example, for Carolina "Deepwater Offshore", a hurricane with a 20 year recurrence interval produces a runup of 3.1 m, whereas a hurricane of 25 year recurrence interval overtops the average dune height. Additionally, the dune height required to prevent overtopping in a storm with a certain recurrence interval may be predicted from Figure 6-5.

Dune Width. The width of dunes plus height defines the volume of sand, and in turn the mass of sand available to buffer overtopping waves and to nourish beaches when the dune face is eroded. Dune width (w) data is derived from the same ground surveys previously described for dune height. Table 7-1 shows that the distribution of dune width varies from less than 4 m to more than 160 m. The small widths are usually produced by extraction whereas the large widths ususally represent natural undisturbed dunes. In the Isabela area dunes are relatively narrow, less than 25 m on the west end at transects XI and XIa; east of Punta Jacinto, transect XVI; and west of Punta Sardina, transects XXI, Xa, IX. These are mostly the same zones where dune height has been lowered by sand extraction. In the Hatillo area, dunes are relatively

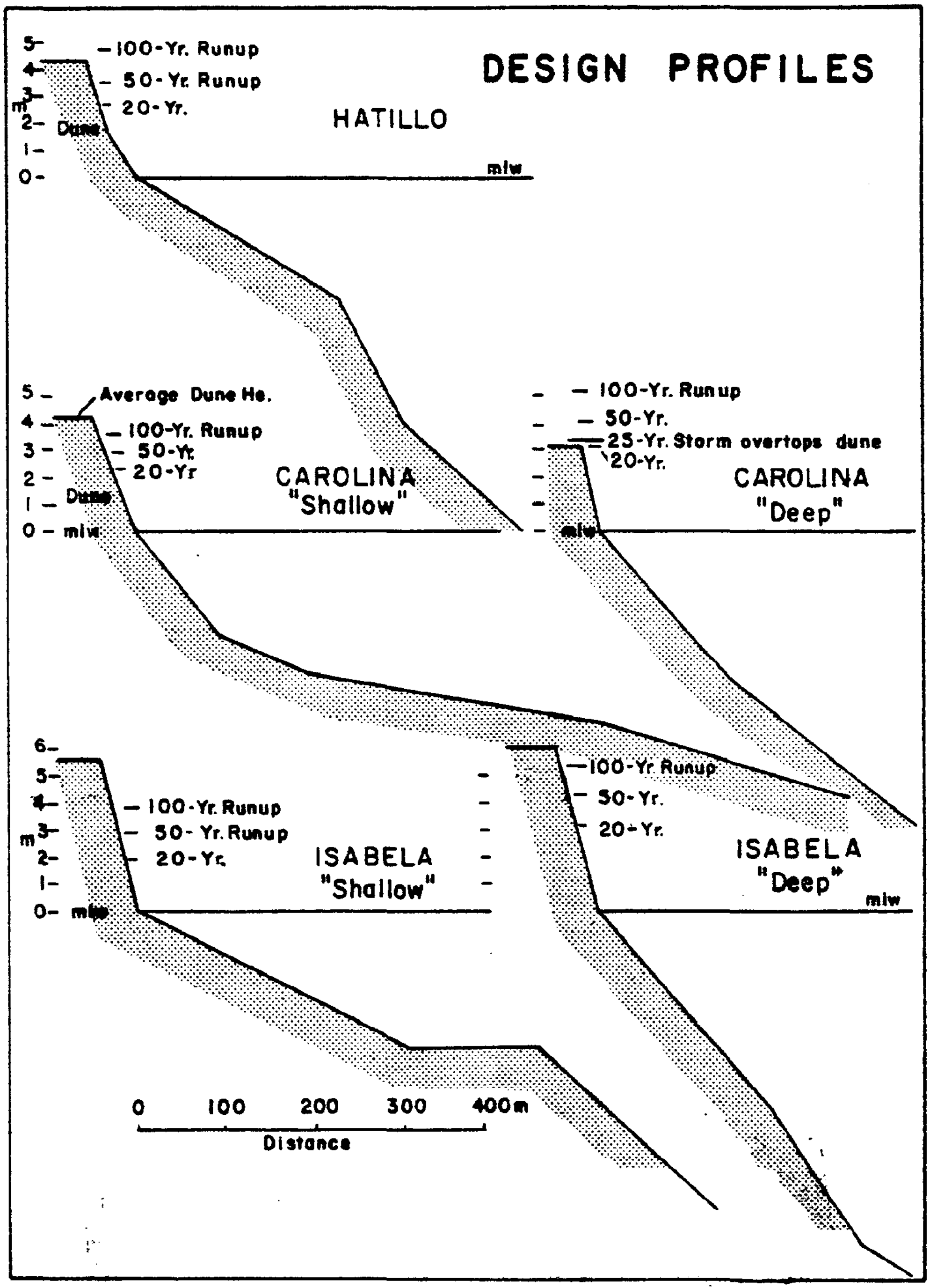

Figure 6-5. Design profiles used for runup predictions on selected segments of the coast. Predicted runup heights are taken from Table 5-9 and dune heights are averages for

narrow, 7 to 12 m, west of Pt. Maracayo, transects XXIV to V. In the vicinity of transect V, dunes less than 4 m wide were washed out by the storm of October 11-13. Farther east however, they were retained where widths were largely greater than 10 m even though heights were about the same, i.e. within the range of four to six meters. The dunes along Playa de las Tres Palmitas are all relatively wide, greater than 45 m, despite substantial erosion. If the average long-term erosion rates of 0.8 m per year continue at Tres Palmitas a minimal width of 45 m ideally will provide protection for 56 years. By contrast at Isabela where long-term erosion averages 0.4 m per year, the minimal widths of 12 m produced by extraction ideally will provide protection for 30 years. However, since the narrowed zones usually have reduced elevations, the degree of protection is mainly limited by dune height.

7. Beach and Dune Erosion Trends.

To predict the potential erosion that dunes must survive in the future, the historical record of shoreline changes is examined using sequential aerial photographs. By comparing the positions of the dunes and the shoreline on photographs taken at different times the amount of erosion for the time interval between two photographs is indicated. The photo coverage consists of vertical aerial photos obtained by the Puerto Rico Department of Highways in 1936, 1950, and 1962-1963 as well as by the Department of Natural Resources in 1977 at altitudes of 2,440 and 3,048 m (8-10,000 ft) respectively. Although more current coverage is desirable to examine changes between 1977 and 1982, the photos are sufficient to define long-term erosion rates over time spans of 27 to 41 years. This time scale is especially useful for designating the degree of protection required over periods of 20 to 100 years.

The procedures used follow conventional coastal engineering techniques (e.g. Stafford, 1971). They consist of three stages: first, the photos are enlarged about 3 to 4 times to a common scale of 1:5,000. Secondly, stable reference points on the photos are selected that are common to each photo taken from time to time. Thirdly, distances are measured from the reference points to the dune line, high and/or low water line. The difference in the position of these lines with respect to the reference points on photographs of different years, reveals the extent of erosion or accretion during the time interval of the photographs. By dividing the change in distance by the time interval, the average annual rate of erosion or accretion is computed.

In the analysis of photography, distances on the photos are proportioned from base topographic maps (1:20,000 scale) of the U. S. Geological

Survey. The reference points consist of cultural features such as road junctions or natural features such as nearshore rocks, all of which are close to the dune line. Distances are measured with a Gerber scale along a transect perpendicular to the dune line. Spacing of the transects is about 500 m at Carolina which has a straight dune line, and about 250 to 900 m at Hatillo and Isabela where the dunes are interrupted by rock headlands. Wherever possible the photo transects are established on the same transects as the ground transects. A few transects of Castillo (1980) are included.

Identification of the dune line and the high and low water lines is accomplished with aid of stero pairs from an auxilary set of photo prints at 1:20,000 scale. Usually the dune line can be recognized by an abrupt change in slope, Figure 7-1. The high water line can be identified by a distinctive change of grey tone that occurs between the dune line and the breakers. In some photos, the high water line is not observed because the prints and/or enlargements are over exposed for extreme reflectence of beach sand. In these cases, the high water line is not recorded. The low water line is the most difficult to identify because of the presence of transient white foam and irregularities of beach rock ledges and tide pools. Despite the problems, of delineating high and low waterlines, the mean

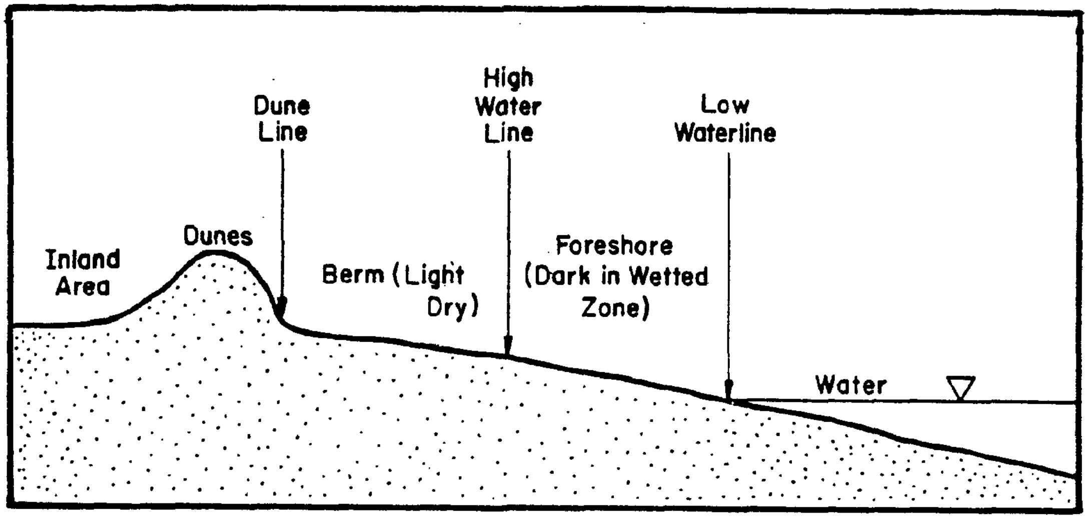

Figure 7-1. Idealized cross-section showing dune line, and low water line, from (Stafford, 1971).

error is less than 0.08 cm absolute or about 4 m on the ground. The dune line is positioned and measured with an error less than 0.4 cm absolute or 2 m on the ground. Seasonal changes in the high and low water lines are minimized by selecting photography from one season, winter, between December and March.

Long-Term Trends. The significant results of the photographic analysis are presented in Figure 7-2 and Table 7-1. For the purpose of presentation the rates of change for the dune line and for the water line are averaged for each transect into a composite value. Erosion of the dune line is most marked near Tres Palmitas, Carolina where rates reach 2.0 meter per year near transect 3. This is a zone of extensive sand extraction during the 1950's and a zone where offshore water depths are generally greater close to shore than in central and eastern sections. To protect this zone, an artificial breakwater consisting of scrap automobiles buried in sand was constructed but it failed to accrete and stabilize. The mean long-term erosion rate at Playa de las Tres Palmitas is 0.8 meter per year. As shown in Figure 7-2, composite values generally diminish with distance eastward.

Along the coast east of Hatillo erosion and accretion rates are low averaging 0.2 meters per year along the dune line, Table 7-1. Locally, erosion reaches 0.85 meter per year at transect II whereas slight accretion occurs west of Punta Maracayo (Figure 7-2).

The coast at Isabela is dominantly erosional; rates average 0.4 meters per year. Erosion is generally faster west of Punta Jacinto than in the embayed coast east of Punta Jacinto (Figure 7-2). Because of massive sand extraction and consequent blowouts and washovers, it seems likely that the dune face is sensitive to further losses and erosion will accelerate. Because sand extraction in most of the Isabela area has proceeded mainly in the last

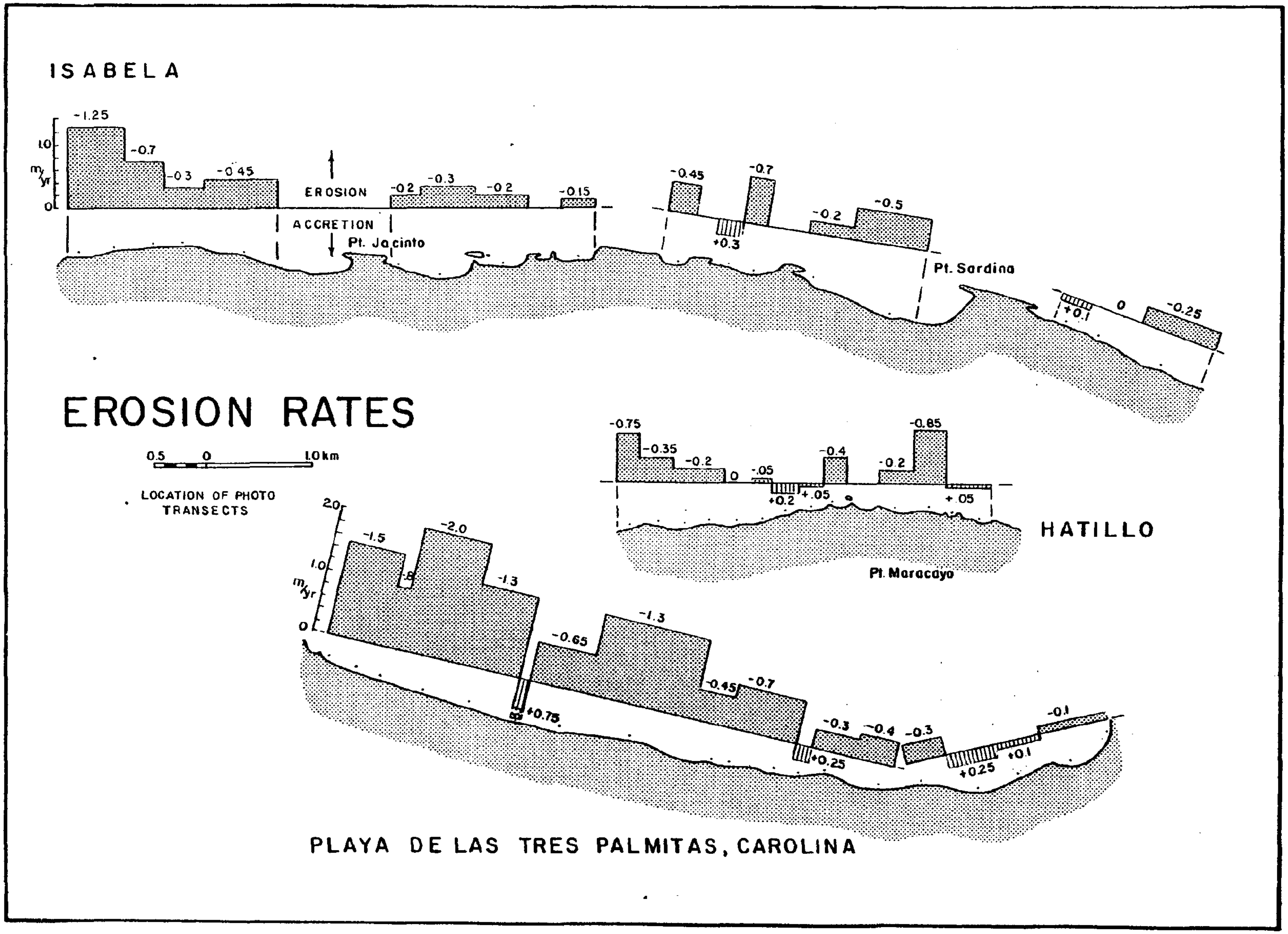

Figure 7-2. Long-term erosion and accretion rates presented as a composite average of dune line and water line change in meters per year. Based on aerial photos, see text.

10 to 12 years, a period of relatively few storms on the north coast, significant post-extraction erosion, such as observed in western Tres Palmitas, has not set-in yet.

Table 7-1. Long-term erosion and accretion rates along the north coast in meters per year. From aerial photos, 1:5,000 scale, 1936-37, 1950 and 1977 for Hatillo and Carolina and 1950-1977 for Isabela. Negative value is erosion landward; positive is accretion seaward.

	Change in m/yr		
Location/Transect	Dune Line	Low Water Line	Width, W, in m
Carolina			
1	-1.3	-1.7	57
2	-0.7	-1.0	95 (washover)
3	-2.0	-1.9	138 (washover)
3a	-0.9	-1.7	45
12	+0.6	+0.9	>150
12a	-0.8	-0.5	55
12b	-1.5	-1.4	62
11	-0.8	-0.1	83
10	+0.1	+0.4	60
9	-0.4	-0.2	92
9a	-0.4	-0.4	>150
9b	-0.4	-0.2	>160
8	±0.0	+0.5	116
6	-0.1	+0.2	65
5	-0.2	+0.1	92
4	-0.2	±0.0	66
Hatillo			
I	+0.2	±0.0	16
IIa	-0.9	-0.8	12
II	+0.5	-0.7	59
III	+0.1	-0.5	85
XXIV	+0.1	±0.0	12
IVa	+0.2	+0.2	9
IV	+0.1	±0.0	46
Va	±0.0	±0.0	10
V	-0.1	-0.3	7 (washover)
VIa	±0.0	-0.4	4
VI	-0.4	-0.3	19
VIb	-0.8	-0.7	10
		High Water Line	
Isabela			
VII	-0.3	-0.2	27
VIIa	-0.2	+0.2	
VIII	-0.1	+0.2	27
XXIII	-0.3	-0.1	16
XXI	+0.3	+0.3	16
XX	-0.3	-0.6	12
XIX	-0.3	0.0	55
XVIII	-0.2	-0.2	-
XVII	-0.3	-0.3	17
XVI	-0.3	-0.1	16
XIa	-0.8	-0.6	17
XIII	-0.4	-0.5	37
XII	-0.5	-0.1	33
XI	-1.4	-1.1	18

Storm of October 11-13, 1982. Large waves generated by a broad low pressure system in the central Atlantic Ocean, Figure 7-3, attacked the north coast for more than three days. Beaches were eroded, dunes overtopped and sand washed into extraction areas. This section records short-term effects of a 5-year to 8-year northerner. The new information was gained from overflight photography and ground observations during the storm as well as from post-storm observations and elevation profiles surveyed between October 21-24, 1982. The elevation profiles were surveyed on the same transects surveyed before the storm in July and September, 1982. Additionally, maximum wave swash heights and the height of overtoppings were surveyed at each transect and at additional points where they were observed.

The storm waves traveled more than 1200 miles before breaking on the north coast. Travel time is estimated at 24 to 30 hours. Movement of the low pressure system was relatively slow so that the period of wave attack was relatively long compared to a tropical hurricane. Deepwater wave periods reported by the National Weather Service from ships north of the Puerto Rico vicinity were 12 to 14 sec on October 12th and 13th. Deepwater wave heights from ship reports ranged mostly 2 to 3 m and wave lengths are estimated at 260 m. Using the CERC runup procedures as used in section 5, breakers at Hatillo, transect 4, are estimated to reach 3.9 m high and to break in water depths of 4.3 m or 143 m offshore. Since local winds were weak there was no wind set-up on the north coast and the wind direction changed verly little despite a long cold front extending toward Puerto Rico from the north (Figure 7-3). Storm surge reached only 15 cm 10.5 feet at 6 p.m., October 12th on the NOS tide guage in San Juan harbor, a value that is the "excess" height observed above normal predicted high water. Tidal elevations returned to predicted heights by October 14th. Since wind was low and the storm distant,

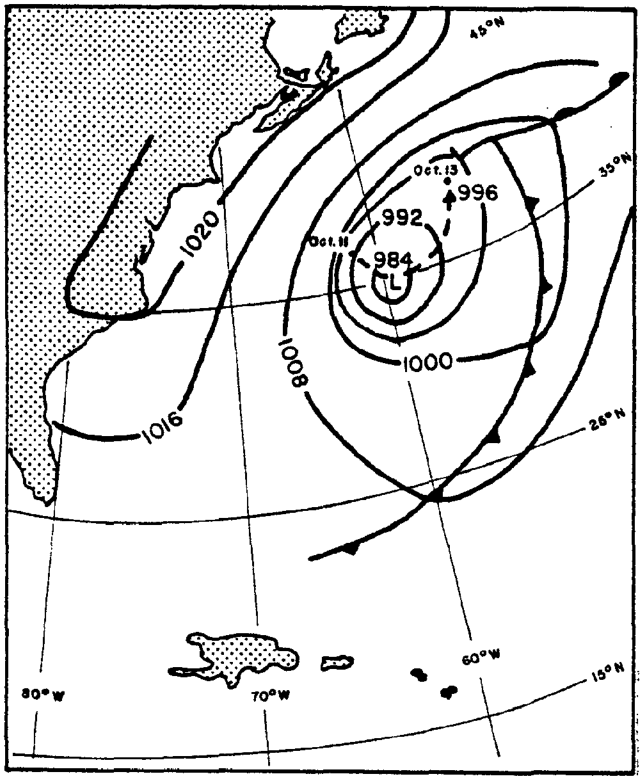

Figure 7-3. Weather map of the Atlantic Ocean, October 12, 1982.

the storm surge must have been created by wave set-up.

Wave swash heights, i.e. the highest points reached by wave swash are listed in Table 7-2. These elevations are recorded by the upper limit of debris or trash on the beach/dune or by current washed vegetation and swash marks on the sand surface. The heights are referred to mean low water by correcting the local still water level estimated in the surf using predicted tide tables. As revealed by Table 7-2, the wave swash elevations are higher in the Isabela sector east of Punta Jacinto than elsewhere. Elevations range from 3.9 m to 6.3 m with the highest value at transect XVIII, an embayment with relatively deep water nearshore. West of Punta Jacinto where the coast is more regular than to the east, elevations vary within narrow limits, 3.4 m to 4.2 m. At Hatillo, where dunes collapsed during the storm, a swash height

Table 7-2. Wave swash heights and overtopping elevations measured October 21-24, 1982 after the storm of October 11-13, 1982.

Location/Transect	Swash Height, m	Overtopping Elevation, m
Carolina		
4a	2.4	2.4
5	2.8	-
8	3.7	-
9a	3.6	-
9	3.9	-
11a	4.3	-
12a	4.3	3.8
3a	3.1	3.1
3	3.6	3.1
2	-	-
1	4.2	4.0
Hatillo		
I	4.4	3.8
Ia	4.7	-
II	3.6	-
III	3.5	>2.4
XXIV	5.2	>2.4
V	-	3.2
VI	-	>3.7
Camuy		
XXV	-	4.1
West	5.1	4.7
Isabela		
VII	5.9	-
VIII	4.8	4.5
IX	5.4	4.0
X	5.9	4.5
Xa	5.0	4.7
XXI	5.4	<5.4
XX	4.8	-
XIX	5.7	-
XVIII	6.1	-
XXII	3.9	3.7
XVII	6.3	5.8
XVI	3.6	2.8
XV	3.4	3.1
XIV	4.2	-
XIII	3.6	-
XII	3.4	-
XIa	3.8	3.4
XI	3.8	3.8
Los Cedros River Mouth	4.2	-

of 5.2 m was measured on transect XXIV while west of Camuy a height of 5.1 m was recorded. At Playa de las Tres Palmitas, Carolina, swash heights generally increase with distance westward from Punta Vacia Talega; e.g. from 2.4 m on transect 4 at the east end, to 4.3 m on transects 12 a and 11 a, just east of Pinones. In the extensive washover area west of Pinones, transects 3 and 3 a, the elevations, i.e. 3.1 m and 3.6 m, are less than to the east. Evidently overwashing reduced runup heights in this sector.

When the wave swash heights are compared with those measured by Fields and Jordan (1972), the heights have an estimated frequency of recurrence in Carolina of one in five years, and in eastern Isabela, one in eight years. The points surveyed in this survey however, differ from those of Fields and Jordan so that an accurate comparison cannot be made.

Dune overtopping is recorded at 23 points, Table 7-2, Figures 7-5A, 7-5B. Overtopping elevations are the height of breaches and gaps between the dunes that give evidence of flowing water through the beach into low lying areas behind the dunes Figures 7-4A, 7-4B. Generally, these are minimal heights for overtopping because erosion of the gap removed the initial overtopping height. Like the distribution of swash marks along the coast, overtopping elevations are generally higher east of Punta Jacinto than elsewhere. In this sector elevations range 3.7 to 5.8 m with the highest value at transect XVII. Generally, overtopping elevations are 0.3 to 0.6 m lower than nearby swash marks elevations. The elevations of major breaches having significant washover fans are generally 1.0 to 1.4 m lower than nearby wave swash elevations.

Major washovers with extensive sand deposition landward are recorded in three sections: (1) west of Pinones, transects 2, 3, 12; (2) east of Hatillo, transects V and VI; (3) seaward of the village of Camuy extending along shore 1700 m, Figure 7-5B. These are all former sites of sand extraction. West of Pinones

Figure 7-4A. Aerial view southeast toward village of Camuy showing dune overtopping and breaching (foreground) during high waves, Oct. 13, 1982. Extraction sites behind dunes are flooded.

Figure 7-4B. View east showing surf overwash along a former dune line, Oct. 13, 1982. Rock debris is resistant eolianite formed near base of former dune.

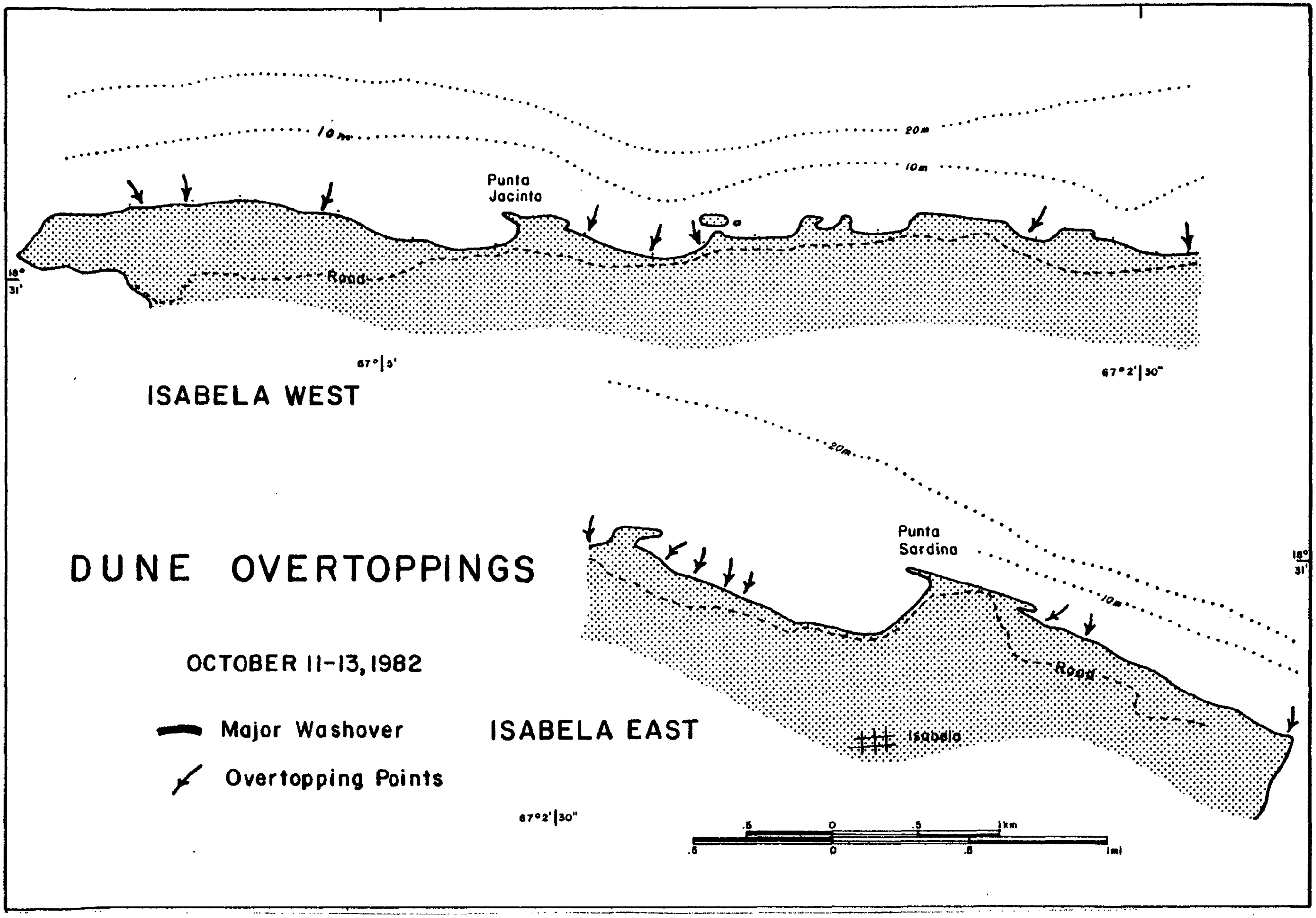

Figure 7-5A. Distribution of dune overtopping points and washover zones observed after the storm of October 11-13, 1982 at Isabela.

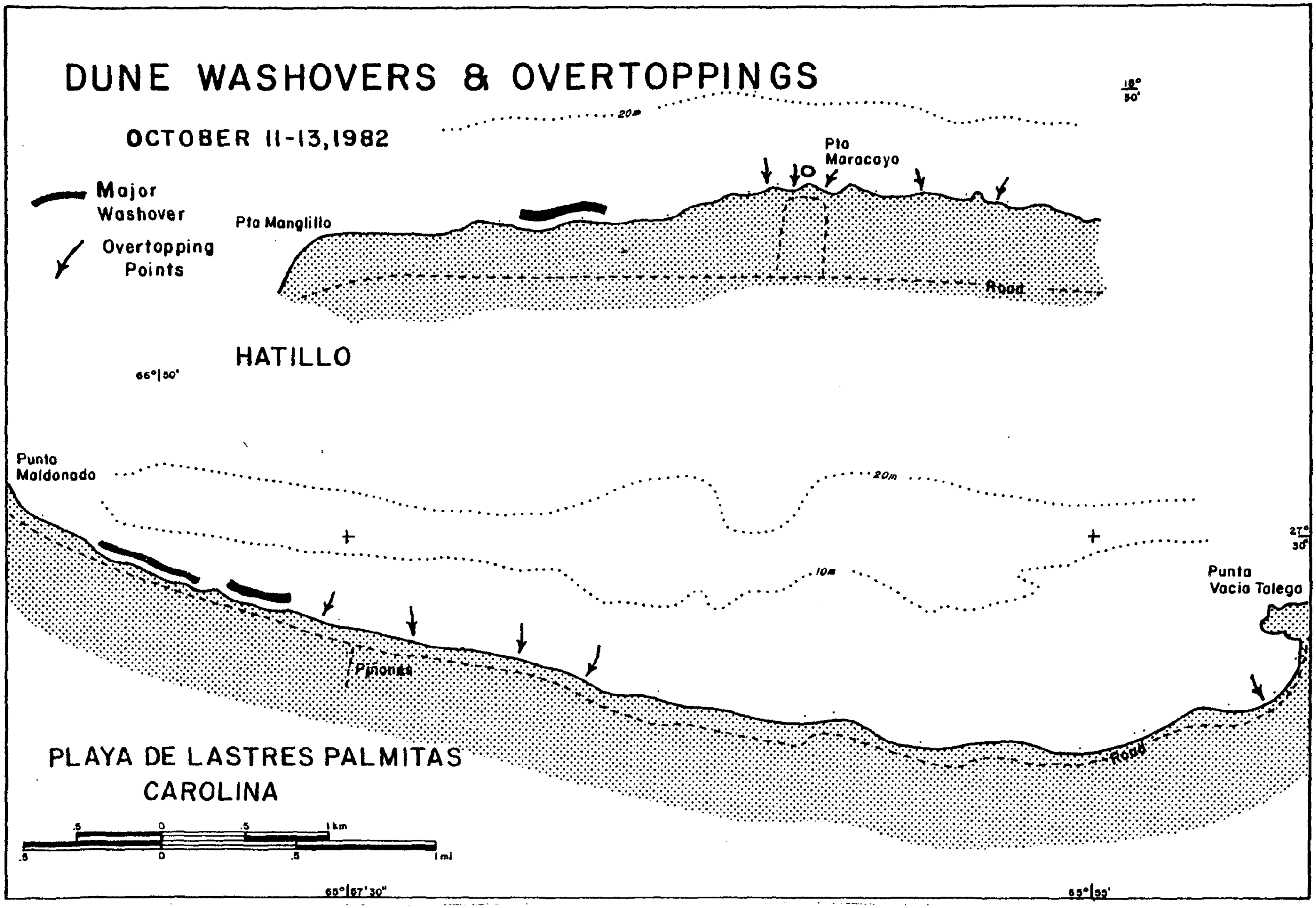

Figure 7-5B. Distribution of dune overtopping points and washover zones observed after the storm of Oct. 11-13, 1982 at Hatillo and Playa de las Tres Palmitas, Carolina.

the washovers extend landward from the low water line 120 to 180 m, Figure 7-6A, and bury mangroves behind the beach for a distance of 1150 m along the backshore. Leveling of debris heights in mangrove branches suggests water elevations diminish rapidly with distance landward e.g. from 3.6 m on the dune ridge to 0.7 m at a distance of 188 m landward from the low water line. East of Hatillo, a washover penetrated 53 m landward from the low water line and covered a grass pasture and campground, Figure 7-6B. The largest washover zone lies seaward and west of Camuy where former extraction sites were flooded and partly filled with sand 146 m landward from the low water line. Since the dunes were almost completely destroyed, the village of Camuy lacks protection from future storm waves and flooding.

Figure 7-6A. View west of washover zone left, west of Pinones, Carolina, Oct. 24, 1982. Beach road was destroyed and mangroves buried in this sector.

Figure 7-6B. View west toward Hatillo, transect V showing extensive washover zone, Oct. 13, 1982.

8. Dune Design for Protection and Sand Resources

Having defined the present status of the dunes with respect to their stability, height and width and having shown from wave predictions and storm observations that the dunes are inadequate for long-term protection in many places, it remains to designate what size and height dune is actually required to protect the coast over a given time span. Protection is needed for the following reasons:

a) The dunes are the first line of defense against the sea. Protection is needed to preserve the natural function of dunes as a barrier to storm waves.

b) To provide a reservoir of sand, which when released by erosion, can nourish and build up beaches of use for recreational activities.

c) To protect human life and welfare as well as to minimize damage to real estate, agriculture lands and public facilities.

d) To minimize ponding of salt water behind the dunes and resulting breeding of mosquitoes.

e) To minimize expenditure of public and private funds for costly shore repair work and restoration projects.

Without dune protection the shore front will be degraded by extensive washover sand deposits. Agriculture lands will be buried and waterfront property will be devalued. Shorefront roads will need repair, rebuilding or relocation along other routes. Human life in coastal villages will be threatened. Beaches will be narrowed or reduced to sandy tidal flats limiting aesthetic quality. Salt water flooding of low lying areas will breed swarms of mosquitoes. Tourists will go elsewhere to find relief as well as better beaches. Landowners are likely to seek costly shore repair and engineering works for protection as well as road maintenance for adequate access. The task now is to designate a degree of protection and to restore and maintain the dunes in their best achieveable condition.

Since the type and status of the dunes varies widely with natural conditions and with the magnitude of prior extraction and development, different management approaches must be considered: (1) let the natural processes prevail, (2) modify the natural processes to maintain or restore the dunes, (3) rebuild the dunes artificially.

To let natural processes prevail, the coast must be managed in a manner that is compatible with the migration trends and historical erosion rates. This requires design of a buffer zone landward of the shore which allows the processes, which produce migration and erosion, to operate without interference. The approach is not to exclude sand extraction or development but to control it in such a way as to minimize interference with natural processes and to provide a degree of protection. This approach takes advantage of the natural processes that tend to build dunes and of the protection they offer. It remains to determine how much protection is desired for different coastal land-uses.

To manage the dunes so that natural processes prevail and dunes are kept intact, a setback or dune management zone needs to be organized. This is defined by the existing dune dimensions, stability or migration trends and by the long-term historical erosion rates. Width of the zone is prescribed by the product of the annual erosion rate and the time span of the desired protection or planning period. For migrating dunes the present-day dune width, measured from the frontal dune face line, is added to the foregoing product. For shores with former dunes, now transformed into washovers, the width is taken from the former dune line as defined on aerial photos and the landward extent of the present-day washover. Since landward migration rates of the washover are unknown, the limit will have to be redesignated as future migration develops with erosion of the shore. By establishing a dune management or setback zone, future extraction and vehicular activities, as well as development, can be directed inland from the active part of the dunes. A number of states and local units have successfully responded to dune problems in this way; for example,Texas has a "dune protection line" based on vegetation, New Jersey has "dune management districts", Florida is establishing individually surveyed set-back lines for each coastal community.

Natural processes can be modified to maintain and restore dunes by planting grass or vegetation and simple structures of fencing or debris. A large short-term benefit can accrue at relatively low cost by focusing on gaps and breaches. Because such an effort is simple and inexpensive, it can be undertaken by property owners, or community groups. On an eroding shore however, such an effort can be counterproductive because stabilization "traps" sand needed to nourish beaches and other dunes downwind. Consequently beaches may become narrow and waves may erode the dune face. Therefore, this approach is most useful on coasts with slow erosion rates and where beach sand is supplied from sources other than dunes.

In the eastern section of Playa de las Tres Palmitas, Carolina, between transects 9 and 5, dune height which averages 4.2 m, is adequate for "200-year" hurricane runup protection and widths ($\geq$40 m) are sufficient to provide 100-year protection at long-term erosion rates less than 0.4 m per year. Since width in the vicinity of transects 9 and 8 exceeds 40 m, a reservoir of sand is available landward of the dunes for extraction. The best practice in this segment is to protect the zone from the dune face 80 m landward, from development and let natural processes prevail. Since it is likely longshore transport is westward, erosion can benefit beach and dunes "downstream", i.e. west of transect 9, by providing nourishment.

In the central section of Tres Palmitas, between transects 10 and 12a, dune height is adequate for 100-year runup protection except locally in gaps and breaches where heights are insufficient for 50-year protection (Figure 6-4). Consequently, natural processes need to be modified by building up height of the gaps to 3.6 m through vegetative planting. Further lowering can be arrested by control of vehicle and pedestrian traffic on the main dune ridge. Where dune sand is actively migrating, fencing will accelerate the initial build up. Alternately, natural processes can be allowed to proceed with washovers into the mangroves, a trend that will interfer with transport along the main coastal road. Because long-term erosion rates exceed 1.0 m per year and widths are 55 to 83 m, a dune management zone, or setback should be established from the dune line landward to the limit of mangroves, or limit of future washovers as they develop.

In the Tres Palmitas Sector west of Piñones where extensive washovers have occurred, a large expenditure of effort is needed to rebuild the dunes artificially. It is the authors impression that the beach and dunes lack sand nourishment from either longshore or offshore sources. Therefore, modification of natural processes will yield little benefit except locally on the few remaining dunes. Prior attempts to rebuild these dunes failed partly because of inadequate materials. Junk autos rust quickly in salt water and dune sand size needs to be close to natural sizes to stabilize the ridge. Therefore, a large-scale beach-dune nourishment combined with stabilizing vegetation, is required. Local sources of sand for nourishment however, need to be identified. Because washovers are active and loss of sand is great, the entire area will benefit by a setting a beach/dune setback or management zone and rerouting the coastal road.

Most of the coast around Punta Maracayo east of Hatillo, has dune heights sufficient for 100-year storm runup protection except locally in gaps and washovers breaches (Figure 6-4). A substantial benefit could accrue by building up these sites utilizing a combination of fencing, vegetation and artificial nourishment. Since erosion rates are relatively low, except for one transect west of Ia, landward migration of the coast is limited. Further stabilization of the dunes therefore, should not cause substantial loss of sand to the beach. A setback of 30 m from the dune face is needed to control development and vehicle traffic and protect the remaining ridge.

The western sector of the Hatillo coast, transects V and VI, has substantial erosion (Figure 6-4). The beach is narrow and the shortage of beach/dune sand is enhanced by recent "loss" of sand in washovers produced by northern swells of the October 11-13 storm. Although, nearshore beachrock outcrops offer partial wave protection near transect VI, erosion is likely to increase and threaten a housing development built close to the narrow residual dune. It seems possible a foredune will rebuild naturally on seaward parts of the washover but rates will be very slow. Backdunes can be started on the washover by planting vegetation in patches rather than a continuous dune line. Developing dune nuclei on an open plain stand a better chance of survival during successive storm overwash than a continuous barrier. Also, the creation of small patches will facilitate more rapid dune accretion which is important for dune formation on a low surface. Formation of a continuous dune could follow successful accretion of the dune nuclei. A similar approach is feasible for Camuy. Dune management at Hatillo should embrace the entire washover zone, 50 m landward from the old dune line, in order to limit use of the area for extraction, vehicle traffic, and allow natural rebuilding.

In the eastern sector of Isabela, between transects VIII, VII, east of Punta Sardina, dune height averages 7.4 m, a height greater than the 100-year predicted runup elevation (Figure 6-5). Two small gaps need to be filled to assure better protection. Dune widths average 27 m and are sufficient to provide protection for 100 years at long-term erosion rates of

0.25 m per year. Because extraction is relatively recent, the erosion rates may not reflect the impact of extraction yet, and thus they may be conservative. A dune management setback zone of 60 m is recommended to protect the remaining dune ridge. Vehicular traffic and future extraction activities should be directed into areas landward of the 60 m setback.

The embayments immediately west of Punta Sardina and Punta Jacinto have adequate 100 year hurricane runup protection on their eastern and central section. In the vicinity of transect XXIII however, dune gaps, local washovers and blowouts need to be stabilized by combined fencing and vegetation. Backfilling of the extraction trenches with upland fill should be encouraged and vehicular traffic controlled with a management zone extending from the dune face to the 5 m upland contour. Elsewhere, between transects XXIII and Punta Jacinto, there are five gaps exposing the coast to 100 year hurricane wave runup. Natural processes need to be modified to build up the gaps to 5.3 m by combined fencing (initially) and vegetative planting. Where the dunes are backed by an upland nearby and free of development, natural process can be allowed to proceed with gradual landward migration. Since erosion is relatively slow (<0.45 m per year) except at transect X, a dune setback management zone of 65 m extending landward from the dune line should be adequate for long-term protection of the dune ridge and low lying land behind the dunes.

In the blowout zone west of Punta Jacinto, vicinity transect XIII, dune heights are inadequate in gaps for 100 year runup protection. These can be filled relatively quickly with fencing and vegetative cover if vehicular dune traffic thru the gaps is controlled. Since long term erosion is less than 0.45 m per year and width averages 35 m, a 70 m setback zone is adequate for 100 year long-term erosion and washover protection. Blowout deposits filling old extraction sites landward of 70 m from the dune line should be made available for dune buggy traffic or for sand extraction.

The west end of Isabela, vicinity of transects XI and XIa, is subject to marked changes by future storms. The dune ridge which is about 3.8 m high, is inadequate for 50 year runup protection, the beaches are narrow having eroded at rates of 0.6 to 1.1 m per year, and the dune ridge is less than 18 m wide on the average. This provides erosion protection for 16 to 30 years. The ridge is stabilized by vegetation except locally in swales and gaps. By holding the ridge in place, waves reach the dune face and cause considerable erosion; but longshore currents carry the eroded sediment away thereby leaving a narrow beach and little replenishment for the dunes. Since development is limited, natural processes should be allowed to run their course. They will destroy the dune ridge by scarping and washovers, and eventually establish a new beach and dune ridge. A setback of 80 m for dune management should provide sufficient space for processes to operate without interference.

The foregoing discussion and recommendations have focused on a design hurricane having a 100 year recurrence interval. A decision must be made however, as to the actual degree of protection required. The advantage of selecting a 100 year design is that a 100 year ridge height should provide protection against 100 year hurricane storm surge and runup as well as many northern swells. Additionally, hurricanes having an intensity associated with a 50 to 100 year recurrence interval are usually responsible for major erosion, washovers and flooding. The present status of the dunes is such that only a limited amount of upbuilding of the foredune ridge is necessary, mainly in gaps, to reach a height attained by "100 year" storm surge and runup. Therefore, implementing this degree of protection is a reasonable goal in terms of cost and effort except in washover zones. If a "200 year" design is selected then a great expenditure of effort and money will be needed to build the dunes to the required height. Another advantage is that a 100 year design allows a buffer zone for natural processes to operate, i.e. for dunes to migrate, washovers to occur and for dunes to rebuild, as sea level rises over many years. Whatever design storm and dune height is adapted, a dune height code and setback width will have to be enforced. Additionally, the design dune dimensions should be reviewed every 10 to 20 years as the coast readjusts to long-term impacts of extraction. For future decisions on sand extraction permits in dunes other than those considered in this report, it is recommended that protection requirements be established from new predictions of hurricane and northern swell wave heights, from migration trends and historical erosion rates.

9. Assessment of Submarine Sand Extraction.

The sand resources of Puerto Rico are not restricted to the narrow fringe of dunes and beaches but they extend offshore on spits and parts of the inner insular shelf. Exploiting this resource is an attractive alternative for the concrete-based construction industry in order to relieve pressure on dunes and beaches that are needed for protection and recreation. For sand extraction to proceed, however, it is necessary to reconcile prospective alterations of the offshore bed with prospective damage to the beach. This is necessary because the offshore deposits are often linked to beach and inshore sand transport systems by physical processes.

Plans for extraction of sand from offshore raise three fundamental questions with respect to impacts on the nearby shore:

1. Can the depression created by extraction intercept the onshore movement of sand that feeds a beach by current or wave action? This problem is recognized as "sediment interception".
2. Can the depression, or a lowering of protective offshore shoals by extraction, act to increase wave activity at the shoreline and thereby induce beach erosion?
3. Can the depression created by extraction serve as a sink for beach or nearshore sand and thereby cause beach erosion? This problem is called "beach drawdown". In other words, what distance offshore, or what depth of water is required to assure an extraction site is outside the beach/nearshore transport system?

This section aims to assess these questions with the greatest degree of confidence permitted by the existing data.

To assess the possible impact of offshore sand extraction, it is essential to appreciate the dependency of beach transport on the nearshore and offshore zones. Beach processes begin to operate at the base of the nearshore zone where landward directed waves first interact with the bed. Waves first feel bottom at a depth approximately one-half the wave length. For practical purposes however, significant modifications do not occur until the depth is 0.25 times the wave length. Most sand transport is done in the surf zone where most wave energy is expended. The position of surf-zone regime mainly depends on the deepwater wave climate and partly on the degree waves are modified and altered before reaching the breaking point.

Sediment interception by dredging can occur if a beach is being fed from offshore by wave and current action and if a portion of the sand is trapped in the dredged depression. Onshore transport is likely in embayments enclosed by headlands and during post-storm periods when beaches tend to recover naturally. It is very important therefore, that dredging be excluded from zones of actively moving onshore-offshore transport. Lacking observations of sediment mobility on the sites of concern, one can only estimate the orbital velocities expected at a particular depth under worst-case storm conditions, and then estimate the threshold of movement from particle size data using criteria of Komar and Miller (1977), Figure 9-1.

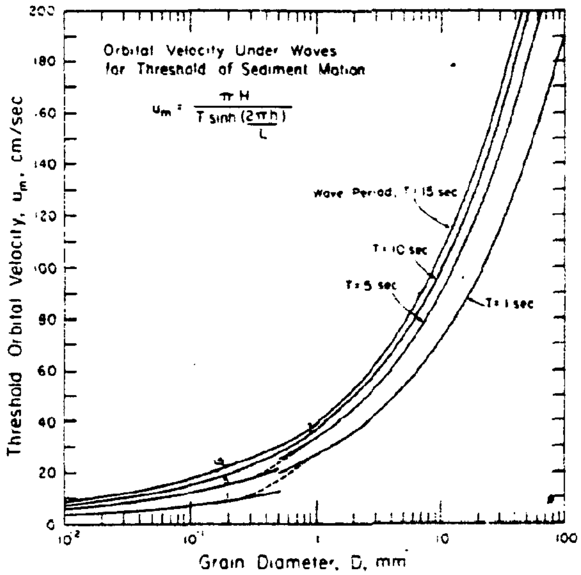

Figure 9-1. Threshold orbital velocity maxima (max) in relation to particle size, from Komar and Miller (1975).

Another approach, is to apply observations made elsewhere to Puerto Rico. For example, off the south and east coast of Britain, sediment interception is avoided by designating a minimum water depth for dredging of 18 meters (Price et. al. 1979); and off Broken Bay, Australia, 20 meters is recommended (Wright et. al 1980). For any given site, the maximum depth of sediment disturbance is variable and should be defined statistically in terms of the long-term wave climate and in terms of the probability of sediment at any point on the nearshore profile being disturbed by wave action.

Since waves travel with a group velocity that depends on their period and depth of water, a permanent increase in water depth caused by dredging can increase the wave velocity and change the direction of wave approach on the beach. Such a change can change the rate of longshore drift and cause beach erosion. Similarily, when offshore shoals that help protect the shore, are lowered permanently by dredging, wave intensity can increase and direction of approach on the shore can change thereby inducing erosion. Like the foregoing case of a depression, the wave change is dependent on water depth which in turn determines the wave height and angle at breaking as well as the rate of alongshore transport. In the presence of strong tidal currents and sand waves on the shoals, the value of the friction factor to be used in wave height calculations is uncertain.

Beach drawdown usually occurs during storms due to the action of high steep waves that erode the beach and transport sand offshore. If the dredge site is too near the shore, the depression will trap sand and prevent its return to the beach during periods of normal weather and waves. An indication of the depths of offshore-onshore interchange of beach sand is recorded at La Jolla, California (Inman and Rusnak, 1956) where a change in sand level on reference rods over a three year period reached 9.1 meter water depth. Since the seasonal wave climate of Puerto Rico is generally less severe than that of La Jolla, it is believed that water depths greater than 10 meters will not result in beach drawdown associated seasonal onshore-offshore movement.

Whereas deepwater waves are a prime source of energy that produce onshore-offshore sand transport, it is the shallow water modifications which occur as a consequence of the bed geometry and coastal configuration that are responsible for spatial contrasts in beach sensitivity. On beaches where longshore drifting of sand is active a net transport of sand can result in a net storage of sand in the form of a spit, bank or shoal, at the downstream end of the system. If dredging on the downstream end removes an amount equal to the upstream input, no net change in storage volume will result and the deposit is renewable. Even if more sand is removed downstream than is introduced upstream, shore erosion will be induced as the sand sink is downstream of the supply. However, dredging can create an imbalance if it intercepts the natural alongshore transport at an amid-stream location. This mechanism is analogous to the natural "loss" of beach sand in a trough or canyon that extends landward of the breaker zone.

The data sources used in this assessment consist of:

1. Bathymetric charts of NOS and revised by U. S. Geological Survey; e.g. Grove and Trumbull (1978); Shiedeler (1980); and Trumbull and Trias (1982).
2. Location and sediment characteristics of the deposits; e.g. Grove and Trumbull (1978); Shidler (1980); Trumbull and Trias (1982).
3. Wind and deepwater wave climate data; e.g. predictions from section 5 of this study; Ho (1975); NOAA (1978); Rodriguez (1979).
4. Beach changes and shoreline morphology; e.g. prior section of this study, no. 7, Briggs (1961); Cintron and Pool (1976); Morelock (1980); Olivieri (1956); Rodriguez (1979).

The sites considered for submarine assessment are shown in Figure 3-1 in relation to nearby beaches of concern. Table 9-1 lists the sites considered, their range of water depth and relevant assessment data.

Isabela. Although the location of the Isabela offshore sand deposits have not been pin-pointed according to their extractable size and grade, they are believed to lie on offshore terraces in water depths from less than 16 m to more than 34 m, equivalent to distances of 400 to 2700 m offshore, respectively. Sediment characteristics indicate terrigenous sand extends 1800 m offshore east of Punta Jacinto whereas west of Punta Jacinto it extends 450 m offshore. Since the composition of this sand is similar to beach, dune and river sand onshore, the seaward extent of this sand type is interpreted to indicate the seaward extent of beach and nearshore long-term transport, a case that assumes the sand unit is contemporary and not relic. Interchange is further evidenced by the dominance in the beach and inner shelf of rounded skeletal fragments having abrasion polish. This suggests some newly formed skeletal fragments are carried to the beach from offshore. Farther seaward beyond 1800 m offshore, at depths of 34 to 50 m, the occurrence of algal nodules give evidence of an unstable bottom, i.e. where waves and/or currents are active.

Lacking wave and current observations for the Isabela shelf, prospective dredging impacts are necessarily inferred from the foregoing sediment characteristics or from numerical wave predictions and physical processes observed in nearby areas. For example, in a study of shelf sediments off the Rio de la Plata, 70 km east of Isabela, Pilkey et. al. (1978) observed shifting mud blankets at water depths of 10 to 40 m or between 600 and 1200 m offshore. Cross-shelf transport of mud, and winnowing of mud from sand, are believed to be accomplished by post-storm processes of normal wave activity and shelf currents, or by minor storms. Additionally, in the Punta Borinquen-Aguadilla area of the west coast adjacent to Isabela, Grove (unpublished) reports longshore transport moves beach and inner-shelf sand offshore onto the insular slope to a water depth of 200 m where sand deposition is active. These studies suggest that sediment can move from the shore onto the shelf as well as across the shelf.

The beaches of Isabela are subject to substantial temporal variation as well as moderate long-term erosion averaging 0.4 m per year. Aerial photographs show that beaches both east and west of Punta Jacinto have narrowed between 2 to 7 meters between 1936 and 1977. Additionally, aerial photo analyses reveal that sand is less extensive on the nearshore bed in 1977 than in 1936. Because of massive sand extraction of the Isabela dunes during the 1970's, storm wave attack has resulted in a loss of sand from the beach/dune system by blowouts and by overtopping, and overwash. Consequently, the beach is less nourished than prior to sand extraction and it is likely that it is sensitive to further losses. Because the nearshore and breaker zone are relatively steep, with slopes ranging 1:30 to 1:16 the beach responds to wave action more like a reflective beach than a dissipative beach. A portion of the incident wave energy is reflected back to sea resulting in standing wave motions with high runup on the beach, particularly in embayments. Therefore, the surf zone is narrow, beaches store little sand and they are thus susceptible to erosion with increasing energy.

Wave calculations for Isabela, section 5, show that for a 10-year hurricane and relatively steep off-shore slopes of 0.03 to 0.06 the breaker zone (between the breakers and the shore) will lie at 155 m offshore or at a water depth of about 6.4 m. For a 100-year hurricane, the breaker zone will lie 225 m offshore or at a depth of 10.6 m. This represents a zone in which longshore currents can transport sediment. Onshore-offshore transport induced by deep-water wave orbital velocities on the bed for a 100-year hurricane, are estimated to reach 20 to 38 cm per sec at water depths of 30 to 32 meters or about 1800 to 80 m offshore. These orbital velocities are required to move the observed surface sediments having 0.2 to 1.0 mm particle size diameter.

The implications of the foregoing data for offshore dredging are that removal of sand from depths greater than 22 m west of Punta Jacinto, and 30 m depth east of Punta Jacinto, may be considered safe to avoid interception of seaward moving sand or for beach drawdown under conditions of a 100-year storm. This assumes that dredging will follow the present depth contour alignment. At depths less than 11 m a dredged depression could act as a sink for sand transported alongshore. Wave modification for 100-year storm waves begins at about 47 m but information at hand is insufficient to predict impacts on the beach.

Cabo Rojo. The Cabo Rojo west sand deposit lies in a shallow trough at depths of 10 to 16 m extending about one km southwest and 4 km west of the southwesternmost tip of Cabo Rojo. The deposit is flanked on the southwest side by a low rock bank at depths of 8 to 10 m. Under normal conditions waves approach the coast from the southeast. East of Cabo Rojo westward sand movement is revealed by an active sand wave field whereby the crests reportedly migrate to the southwest (Grove and Trumbull, 1978). West of Cabo Rojo littoral drift is reportedly southward (Morelock, 1980). The sand transport system therefore seems to converge south and west of the Cape. Fine sand accumulates inshore just west of the Cape at less than 6 m water depth, while medium and coarse sand is found at greater depths including the deposit of concern. Lack of sediment thickness and occurence of exposed rock in a 16 m deep trough, one to two km south of Cabo Rojo, suggest this is a zone of relatively strong current and sediment bypassing. Data are not sufficient to indicate if the main sand body is relic or accumulating at present. In any case the seaward limit of the non-carbonate sediment fraction, most probably terrigenous, is limited to the 10 m depth curve or 2.5 km west of Cabo Rojo.

Table 9-1. Submarine extraction sites, corresponding range of water depth, distance offshore and relevant assessment data in terms of the estimated minimum water depth or inner water depths at which dredging is unlikely to affect nearshore sand transport and beach erosion.

		Site	
	Isabela	Cabo Rojo	Escollo de Arenas
Characteristics			
Estimated Water Depth of Deposit, m	16 to >34 m	10 to 16 m	1 to 7 m
Distance of Deposit Offshore, m	400 to >2700 m	2400 to 5000 m	10 to 6000 m
Assessment			
Sediment Interception, Onshore-Offshore	>22 m unlikely	>18 m unlikely	N.A.
Beach Drawdown	>16 m W. of P. Jacinto >30 m E. of P. Jacinto	Insufficient data	N.A.
Longshore Sink and Interception	>11 m unlikely	>10 m unlikely	>10 m unlikely
Storm Wave Modifications	No protective banks >47 m unlikely	>12 m unlikely	>12 m unlikely

N.A. = not applicable

The beaches of concern lie along the central and western part of Bahia Salinas northwest of Cabo Rojo. Beach sand is predominately calcium carbonate with less than 10 percent quartz, Morelock (1980). The beach is low about 30 m wide and there is little evidence of erosion. The beach zone most sensitive to offshore modifications during storms lies near the high energy or western part toward Punta Aguila. Also, of concern is El Combate beach north of Punta Aguila. It mainly consists of quartz sand with admixtures of carbonate, less than 20 percent, and extends about 35 m wide. There is no evidence for erosion (Morelock, 1980) but its southern part, near Punta Aguila, is expected to be more sensitive to storm waves under offshore modifications than elsewhere. Because nearshore bed slopes are relatively low; 1:200 or 0.005, the beach and nearshore act to dissipate energy under steep storm wave conditions. Sand tends to be stored in the surf zone and hence acts to dissipate wave energy and restore sand lost from the beach. Normal wave engergy is relatively low on these beaches because they are largely protected by Cabo Rojo from easterly waves and partly protected from southwesterly storm waves by a 10 m depth offshore bank. The beaches however, are exposed to hurricane waves refracted around Cabo Rojo from the south.

Lacking wave and current observations in the vicinity of the Cabo Rojo deposit, prospective dredging impacts are necessarily inferred mainly from the foregoing bathymetry and sediment characteristics as well as from numerical wave predictions. The implications are that interception of onshore-offshore sand movement is limited, except possibly during 100-year deepwater hurricane waves from the west, to water depths less than 18 m. It is estimated that 100-year storm waves directed from the west will break at the 9 m depth or a distance of 1450 km from the central Bahia Salinas beach. Since sand of probable terrigeneous origin (more than 4 percent of the total content) is found within the 10 m depth curve, it seems that deposits lying greater than 10 m depth are not likely to create a longshore sink. Moreover, if the nearshore transport converges west of Cabo Rojo, any extraction from the downstream end is not likely to affect the shore unless the protective 8 to 10 m rock ridge northeast of the deposit, is lowered. Data are insufficient to assess possible impact of beach drawdown by offshore transport during storms. Wave modifications induced by lowering the 10 m bank which constitutes the apex of the deposit, requires a detailed wave refraction analysis under storm conditions because the geometry of the area is so complicated. It seems likely that this bank is too deep, too small and too far from shore to provide much protection from hurricane waves. Additionally, its removal is not likely to increase wave activity on the shore. If sand is removed, some protection is still provided by a discontinuous ridge to the northeast at the 10 m depth. This ridge also acts to remove the dredge site from the nearshore transport system. In any case, if dredging were to proceed, the safety factor would be increased many times if dredging is limited to the 12 m depth curve and if it follows the alignment of the natural depth contours.

Escollo de Arenas. The Escollo de Arenas spit is a linear sand body extending 6 km northwest from Punta Arenas Vieques. Water depths increase seaward along the axis from one m nearshore to 7 m on the distal end. Surface of the spit is broken by prominent sand waves with crests mainly oriented parallel to the spit axis. The sand waves have wavelengths of about 100 meters and amplitudes of 2 to 3 meters. They are very dynamic and change asymmetry with ebb and flood of the tide, i.e. northeasterly to southwesterly. Tidal currents over the shoal reach 150 cm per sec. They not only are responsible for generating the sand waves but induce a small resultant transport northwestward. It is likely their net movement holds the sand body in place; otherwise, the sands would disperse over a wide area and the spit would erode. Normal wind and gravity waves reportedly do not affect the morphology or sand transport (Rodriquez, 1979). However, hurricane waves directed from the southwest or northeast can have some effect.

According to Rodriguez (1979), the landward part of the shoal receives terrigenous sediment from the north and west coast of Vieques, which is transported to the shoal by longshore currents. Transport farther seaward is promoted by resultant movement of bedforms. The terrigenous fraction of sand from the distal end of the shoal constitutes about 10-20 percent of the total sediment content. It is uncertain whether terrigenous sand at the distal end of the shoal is relic or transported there from Punta Arenas. Formerly, most longshore transport of terrigenous sand feeding the shoal came from the north coast. Since construction of Mosquito Jetty east of Punta Arenas, the north coast supply has been reduced and the northwest shore is eroding. Consequently, the relative importance of supply from the west coast has probably increased though the total input to the spit via Punta Arenas probably is reduced by the jetty.

The foregoing information implies that if dredging the central shoal surface were to proceed, an area where replenishment is better than on the distal end, to depths of one or two meters below the sediment surface, there would be little impact on the longshore sediment transport since it is at the downstream end, or largely beyond the offshore extent of converging longshore transport system during normal conditions. Although seaward transport along the shoal may be coupled to the longshore transport system and maintains a dynamic equilibrium, shore erosion would not increase even if the rate of extraction (of the terrigeneous fraction) greatly exceeds the rate of supply. Observations are needed to confirm the continuity of the longshore-shoal sediment transport "stream" especially during storm conditions and to distinguish the relative age of the terrigeneous fraction regarding its relic or modern origin. Impacts from beach drawdown and interception of onshore-offshore transport as induced by normal waves, are not applicable to Escollo de Arenas since tidal currents dominate sand transport. During hurricane conditions, the shoal probably attenuates incident wave energy from the southwest or the northeast and controls the pattern of wave refraction around Punta Arenas. If dredging removes sand from the crest, storm wave activity is likely to increase on the adjacent shelf floor and the position of wave attack on the shore around Pt. Arenas will shift. Numerical calculations of 100-year hurricane wave characteristics show that waves will break at the 10 m depth curve. Because nearshore slopes are low the breaker zone would extend 1800 m off the north coast of Vieques. The entire Escollo de Arenas would become a breaker zone and hence tied to accelerated longshore transport generated by the storm waves. During storms the shoal must become an avenue for offshore transport. Onshore impacts of dredging associated with refraction and longshore transport are likely to diminish with distance offshore from Punta Arenas. In the event that the coast of Vieques experiences abnormal erosion during or after dredging, contingency plans should be made available to transfer dredged sand from the shoal to the affected beaches

10. Summary of Findings (continued)

j. Of the three submarine sand deposits assessed, the Cabo Rojo west deposit has a lower risk of impact on beaches than other sites.

11. Acknowledgements.

The work of this investigation was accomplished as follows: Carl Cerco performed most of the wave computations; Ramon Martinez of the Puerto Rico Department of Natural Resources performed many of the elevation transects and depth profiles assisted by Lucy Cruz, William Ortiz Carrasquillo and Jose Berrios and Emilia Medina. Aerial photography was provided by the Department of Natural Resources and the Department of Highways and analyzed for erosion rates by Reinaldo Morales-Alamo.

We thank Ferdinand Quiñones and Rafael Rodriguez of the U. S. Geological Survey for hydrologic and geologic information. Mr. Robert Calversbert of the National Weather Service, San Juan, provided climatologic information. Mr. Josa Martinez of the U. S. Army Corps of Engineers also provided information. Teresa Haynes converted rough drafts into reports and Peggy Peoples drafted most of the figures.

Mr. Gilbert Cintron of the Department of Natural Resources acted as general program manager and provided essential personal equipment to accomplish the field surveys.

12. Future Research Needs.

a. To improve storm surge predictions and verify hindcasting techniques, better historical data are needed to check how well the properties of a given hurricane surge represent the total storm population. Present day surge models suffer from a paucity and quality of historical data, especially wind velocity and water level elevations needed to specify the wind field and surge distributions of individual hurricanes. Additional tide gauges are needed for several sites along the north coast. The NOAA San Juan gauge needs to be run for another tidal epoch (18 years) and equipped for measuring heights greater than two meters. Besides verifying surge models long-term tide gauge records are of direct use for predicting storm surge from a frequency analysis of tidal heights.

b. The wave runup predictions assume the dunes are impermeable, flexible structures according to engineering practice. This provides a conservative runup height that is considered acceptable at the present state of the art. To increase the accuracy of runup predictions however, experimental and field studies need to be conducted to evaluate the engineering model for sand dunes. Additionally, studies should observe the progressive changes that occur in runup as a dune is breached and/or "collapsed" into a washover deposit. This investigation suggests wave heights diminish markedly with distance landward across a washover fan. Consequently, a frequency analyses for flooding needs to be accomplished in addition to the runup analyses completed here.

c. Since this investigation shows a substantial variation in runup heights from site to site, there is a need to predict runup heights using similar procedures, for each new site where future sand extraction is anticipated.

d. Inasmuch as northerners like that of the October 11-13, 1982 storm generate overtoppings as high or higher than predicted heights of 50-year or 100-year hurricanes, hindcast and runup procedures need to be applied to northern waves especially to cover the range of recurrence intervals greater than one in 20 years that are not covered by Fields and Jordan (1972). Additionally, post-storm field surveys of swash marks and overtoppings are needed to verify runup predictions for northern waves. This should be combined with wave and erosion measurements during the storms to relate the erosion to waves and runup acting on the dune. If erosion rates are coupled to individual storm and wave runup conditions, it would be possible to predict the dune widths required from the erosion rates. Such an approach is compatible to the approach used for frequency heights as used in this investigation.

e. Short-term beach cut and fill related to seasonally alternate retreat and advance of a dynamic beach/dune system can pose as great a threat to dune stability as the long-term "nibbling" of progressive shore retreat. Consequently, short-term seasonal changes need to be measured by repetitive elevation profiling and by more frequent aerial photo coverage at a scale of 1:10,000 or larger. Monitoring of coastal erosion patterns and associated hazards is highly desirable for Commonwealth organizations concerned with control and protection of the coastal zone.

f. This study treats dune height and dune width as separate protective elements for the purpose of computation and designating protection. The two elements however, act together to provide protection. Ideally, the storm frequency analysis should apply to both height and width. Therefore, erosion rates associated with a series of individual storms need to be determined together with wave swash and overtopping elevation.

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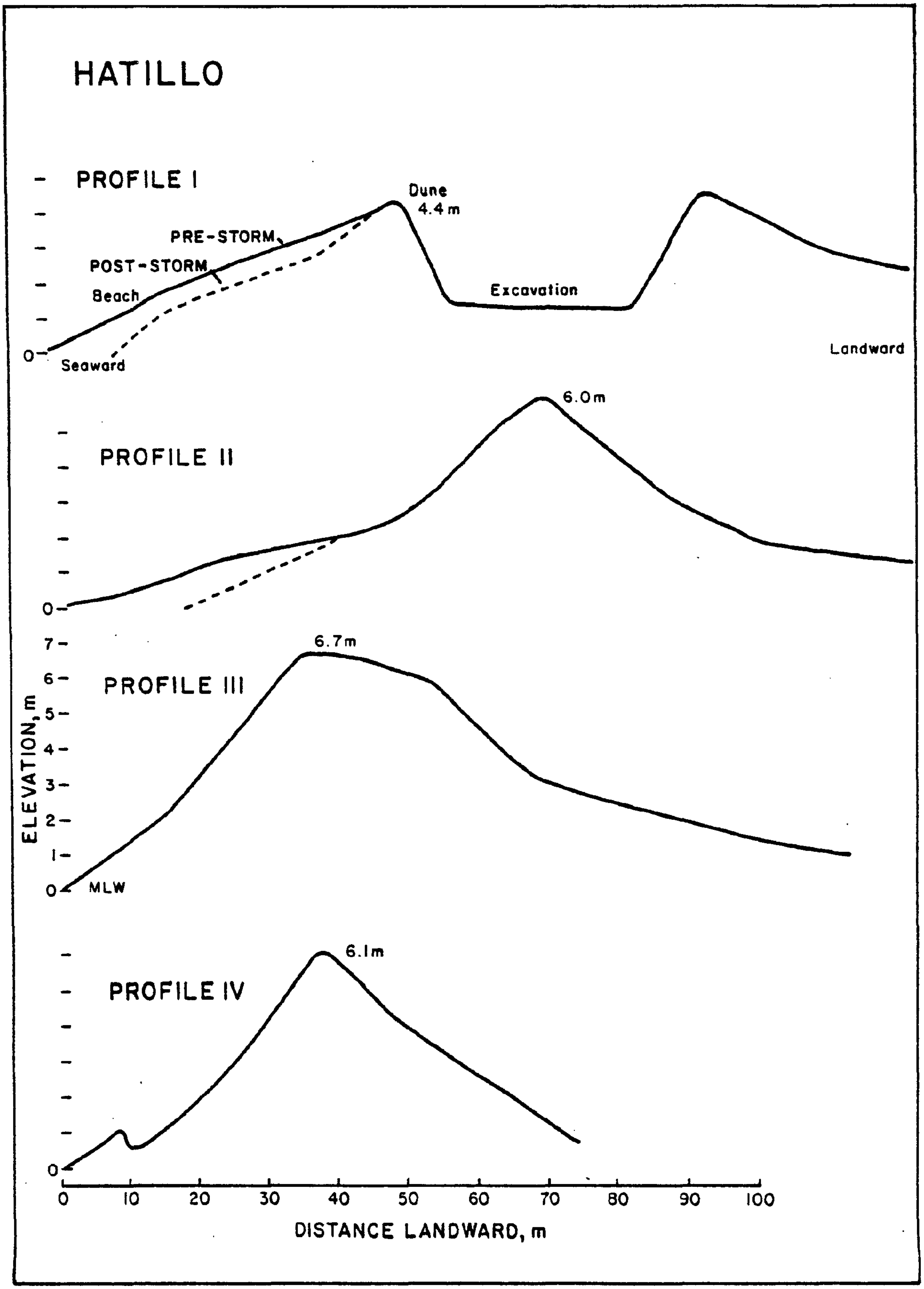
APPENDIX A. Location of Reference Markers Used for Transects of the Ground Survey

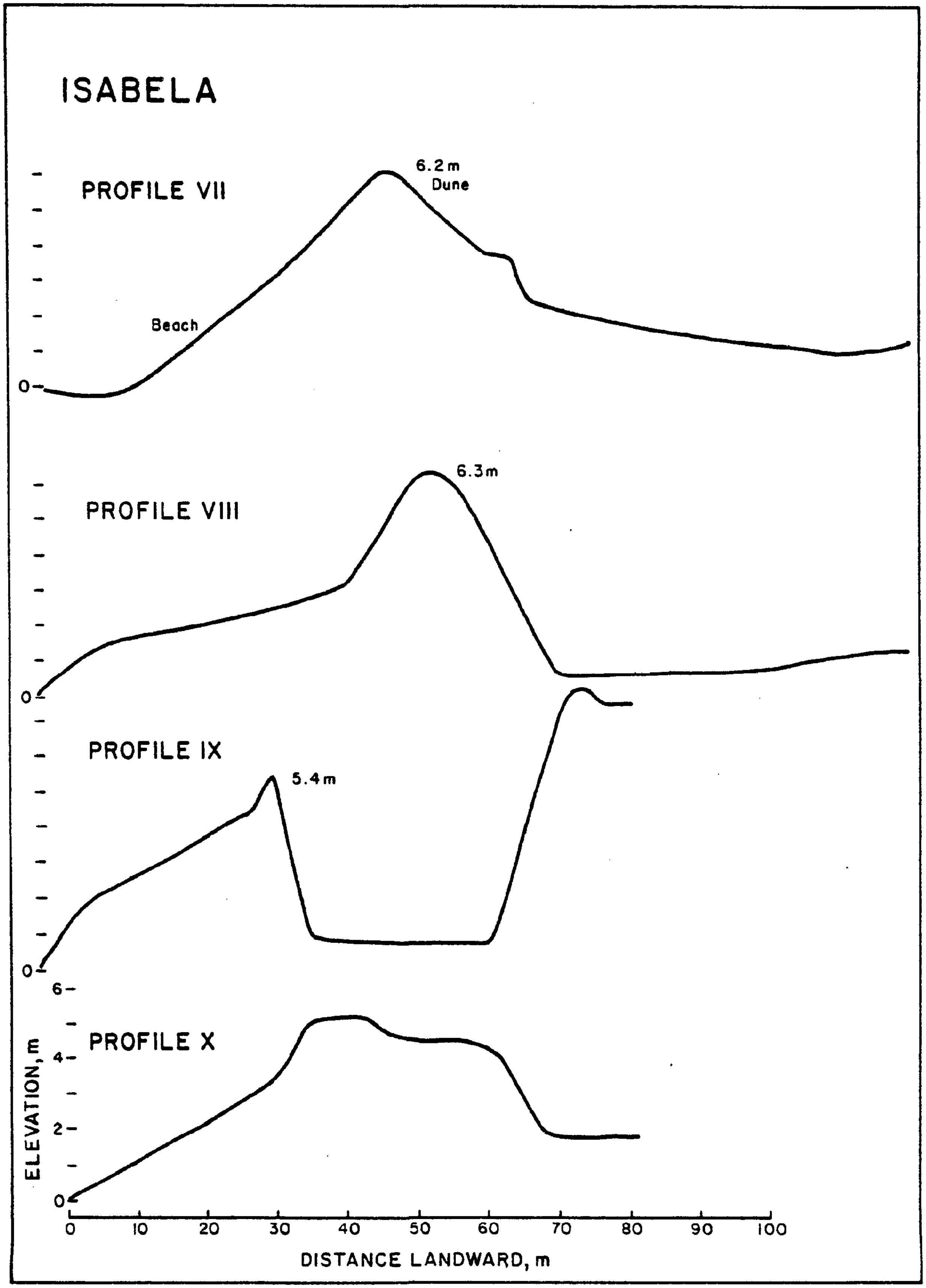
Profile No.	Elevation, m*	Description of Location**
Hatillo		
I	4.47	Steel rod in ridge crest on transect line landward of prominent rock oriented vertically.
Ia	7.09	Steel rod on top of prominent knoll in dune ridge; 11.8 m east of transect line.
II	6.07	Steel rod at base of prominent stump on knoll in dune ridge and on transect line.
III	6.69	Cement slab base on ridge crest at northeast of trailer campground and on transect line which extends along north-south road down landward side and in east part of trailer-park campground.
XXIV	2.05	Steel rod along fence and property line at landward base of dune and on east side of palm tree.
V	3.67	Cement base of swimming pool surface at northwest corner along steel post supporting wire fence. Resurvey elevation October 21, 1982 was 4.09 m which varies with elevation of September 17, 1982 (3.67 m).
VI	1.63	Steel rod at 22 m landward from back of dune base and in grass of extraction floor on transect line.
Isabela		
VIII	1.37	Steel rod adjacent to old tree stump on landward side of dirt road.
IX	7.00	Seaward edge of paved road surface at gentle bend in road.
X	2.20	Steel rod at base of 5 m high palm tree which is the third palm to the west of excavation in a east-west line of palms.
Xa	6.41	Steel rod at base of high palm tree near southeast of sand extraction pit and near dirt road.
XXI	1.78	Steel rod 10 m seaward of single tall palm tree (with nail in base), located along a property line marked by logs of palms lioto 1.5 m high.
XX	1.49	Steel rod at base of coconut palm stump (with nail in base) 8.7 m seaward of dirt road.

Profile No.	Elevation, m*	Description of Location**
Isabela (Cont'd)		
XIX	6.25	Steel rod on west side of palm tree which is 21.3 m landward of a power pole.
XVIII	6.60	Steel rod along private property line next to the fifth cement post 12.6 m landward from bulkhead supporting 2 m high steel fence with barbed wire on top. House inside fence has prominent cement block terrace built landward of foreshore.
XVII	9.52	Steel rod driven near seawardmost concrete post at end of paved road which extends west to excavations.
XVI	2.72	Steel rod about 1.0 m east of tall palm tree (with nail in base) along landward side of dirt road and about 8.0 m seaward of power pole.
XV	3.46	Paved road center about 50 m east of restaurant and landward of small cement buildings near beach; directly seaward of power pole.
XIV	4.10	Steel rod driven in dune ridge (in a swale) next to a concrete property corner post with two supports.
XIII	1.40	Steel rod in extracted back dune area at base of prominent isolated palm stump with old fence wire attached to it.
XII	2.75	Steel rod 1.65 m east of small palm tree (having nail in base) which is 29.4 m east of fence with concrete posts and is the northwesternmost tree in area.
XI	2.57	Cement base on west side of two-story hog house. Also, a steel rod at fence post corner 8.35 m west of cement base with elevation of 1.35.

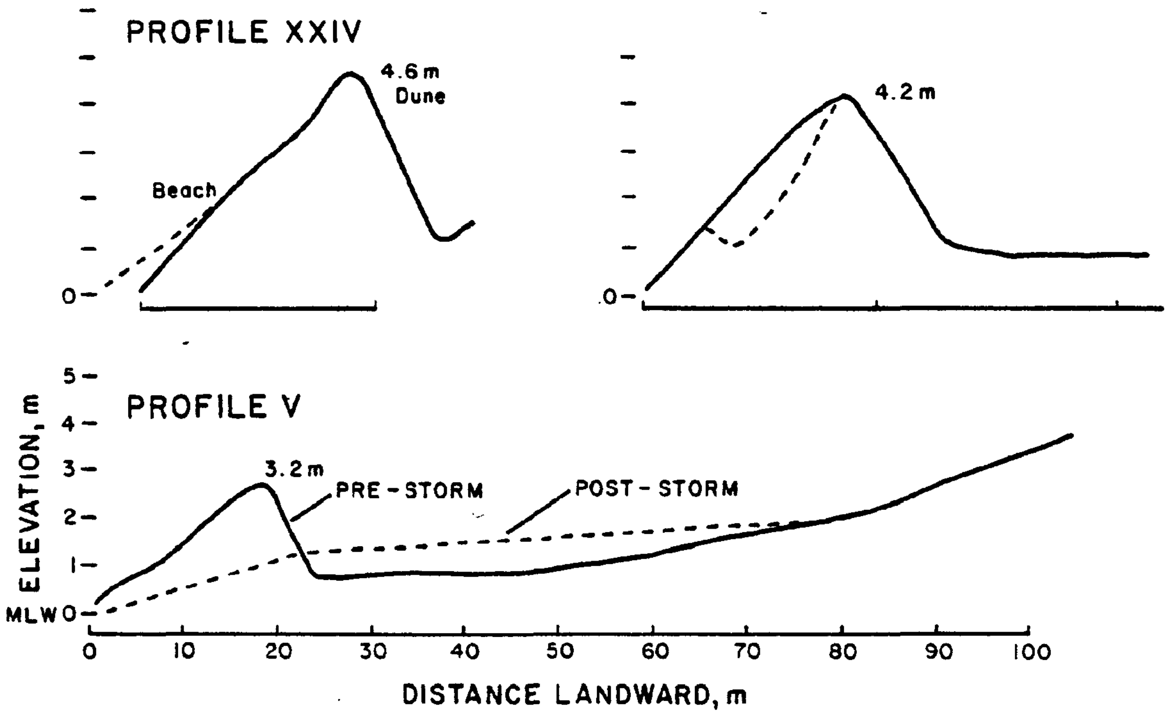
*For steel rods, elevation is taken at top of rod which is driven in ground 0.4 to 1.0 m.

**Most locations mark the landward end of the transect line.


HATILLO
PROFILE I
Dune
4.4 m
PRE-STORM
POST-STORM
Beach
Excavation
Seaward
Landward
0
PROFILE II
6.0m
0
PROFILE III
6.7m
ELEVATION, m
7
6
5
4
3
2
1
0
MLW
PROFILE IV
6.1m
0
0
10
20
30
40
50
60
70
80
90
100
DISTANCE LANDWARD, m


ISABELA
PROFILE VII
6.2 m
Dune
Beach
0
PROFILE VIII
6.3m
0
PROFILE IX
5.4m
0
6
PROFILE X
4
2
0
ELEVATION, m
0
10
20
30
40
50
60
70
80
90
100
DISTANCE LANDWARD, m

HATILLO


PROFILE XXIV
4.6 m
Dune
Beach
0
4.2 m
.0
PROFILE V
5
4
3
2
1
MLW 0
ELEVATION, m
3.2 m
PRE - STORM
POST - STORM
0
10
20
30
40
50
60
70
80
90
100
DISTANCE LANDWARD, m