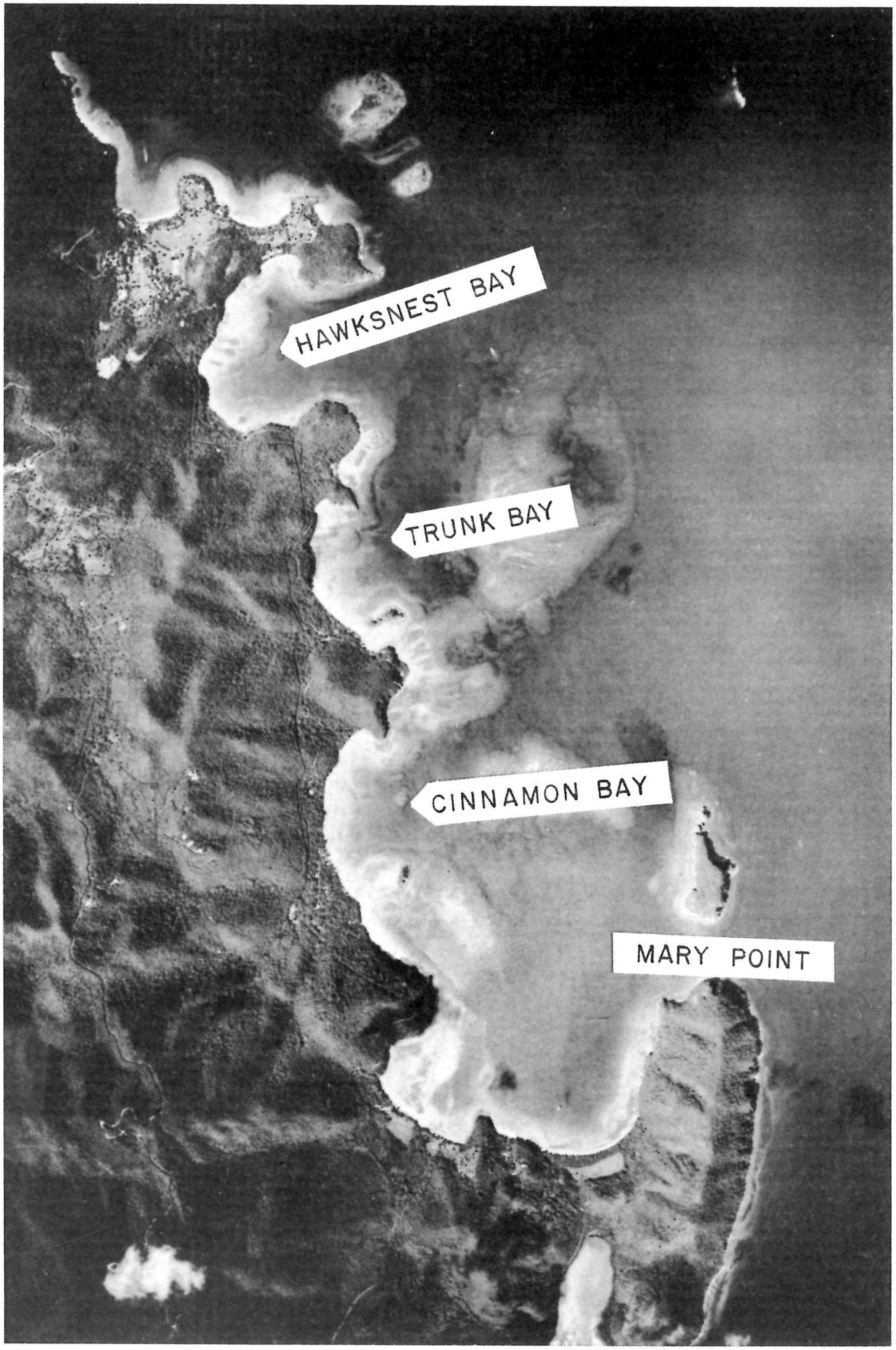
VIRGIN ISLANDS
BEACH PROCESSES INVESTIGATION
ST. JOHN, VIRGIN ISLANDS

OCCASIONAL PAPER NO. 1
FEBRUARY 1974

U. S. DEPARTMENT OF THE INTERIOR
NATIONAL PARK SERVICE
WASHINGTON, D. C.


HAWKSNEST BAY
TRUNK BAY
CINNAMON BAY
MARY POINT

VIRGIN ISLANDS
BEACH PROCESSES INVESTIGATION
ST. JOHN, VIRGIN ISLANDS

SCOTT HOFFMAN — ALAN ROBINSON — ROBERT DOLAN

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ACKNOWLEDGMENTS

The authors of this paper would like to extend their sincere appreciation to all the employees of the Virgin Islands National Park and the local citizens of St. John for their cooperation which helped make this project a success. In particular we want to thank Robert Stanton, Park Superintendent; Jim Lyles and Ray Kimple, Chief Rangers; Gene Casey and Jim Riddle, District Rangers; Jim Fisher, Maintenance Chief; and Sam Scatliffe, carpenter for their individual efforts.

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INTRODUCTION

Cinnamon Bay, located in the Virgin Islands National Park, St. John, U. S. V. I., is the primary center for visitor use within the Park (Fig. 1). Major recreational attractions include white sand beaches, clear blue water, and nearshore reefs. Camp sites and small cottages, some of which are located within 80 to 150 feet of the active shoreline, accommodate approximately 500 persons. Other attractions at Cinnamon Bay include a Danish warehouse of some historic importance and a large Kapok tree, both of which are very near the active shoreline.

The Virgin Islands National Park has been concerned about the beach erosion and preservation of the Danish warehouse on Cinnamon Bay for several years. In 1966, after waves had eroded the beach to within three feet of the warehouse, a rock revetment was constructed to prevent further shoreline recession (Fig. 2). Review by the National Park Service Denver Service Center in 1971 resulted in a proposal for the construction of an artificial reef which would function as an offshore breakwater. In 1973 additional erosion necessitated reinforcement of the revetment as the rock structure had degraded seriously in several places.

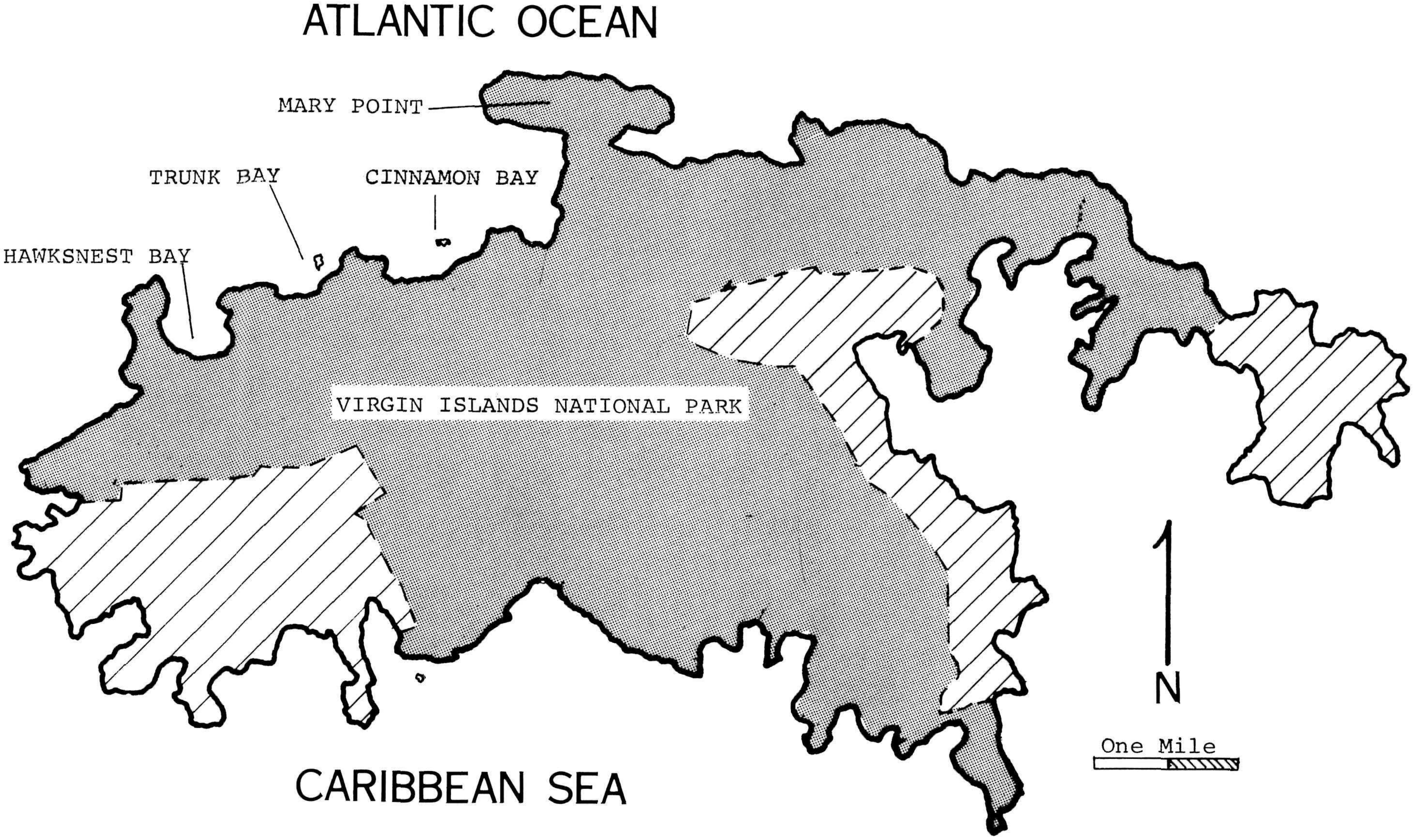


Figure 1. St. John, United States Virgin Islands.

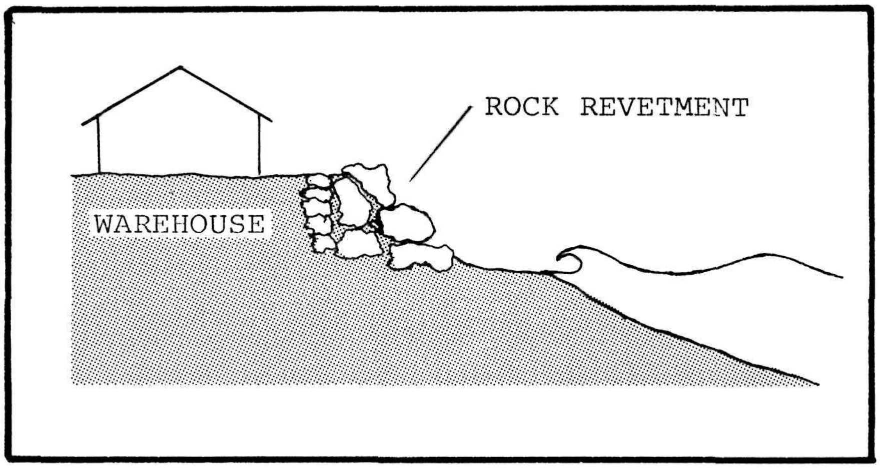


Figure 2. Cross-Section of Warehouse and Protective Rock Revetment at Cinnamon Bay West.

The Virgin Islands National Park, in conjunction with the Office of Natural Science, Washington, supported a one-year research program to study beach dynamics on St. John in order to provide basic information and to ascertain the possible environmental effects of an artificial reef structure on the beaches and reefs of Cinnamon Bay. During the eleven-month field investigation, data were systematically collected on wave heights, beach sediments, beach elevation, and offshore sediments at several bays.

The research program was designed by Dr. Robert Dolan, University of Virginia; coordinated by Alan Robinson, Virgin Islands National Park Marine Research Biologist; and carried out by Scott Hoffman, seasonal National Park Service Geologist and University of Virginia graduate student. The study period was from July, 1972, through May, 1973. Prior to this report, a preliminary document entitled *Virgin Islands Beach Processes Investigation, St. John, Virgin Islands* was submitted by Scott Hoffman, Alan Robinson, and Robert Dolan under National Park Service Contract Number CX5000031059. Focus of the preliminary report was on the reduction and the graphic presentation of data collected and the discussion, in general terms, of some of the basic engineering implications.

Material presented in this report examines specific relationships between surf-zone processes and beach changes as they occur in the reef-beach systems. A conceptual model was developed from previous literature and from our prior field studies in order to assess the significance of various elements within the system; a series of field experiments was then designed to test the hypotheses. Of particular concern to this project were the sediment-exchange processes of the subaerial beach and of the nearshore zone.

Although assessment of the sediment-exchange processes along the erosion-prone beach at Cinnamon Bay was a primary objective, the context of adjacent, apparently stable, reef-beach systems was fundamental to the investigation. Consequently, in addition to Cinnamon Bay, Hawksnest Bay and Trunk Bay were also included in the research program.

THE REEF-BEACH SYSTEM

The general dynamics of the reef-beach system can be described in terms of four elements (Fig. 3):

1. The Offshore Zone

In deep-water areas of the offshore zone, wave motion is oscillatory and wave interaction with the bottom is minor. The offshore bathymetry in the Virgin Islands is

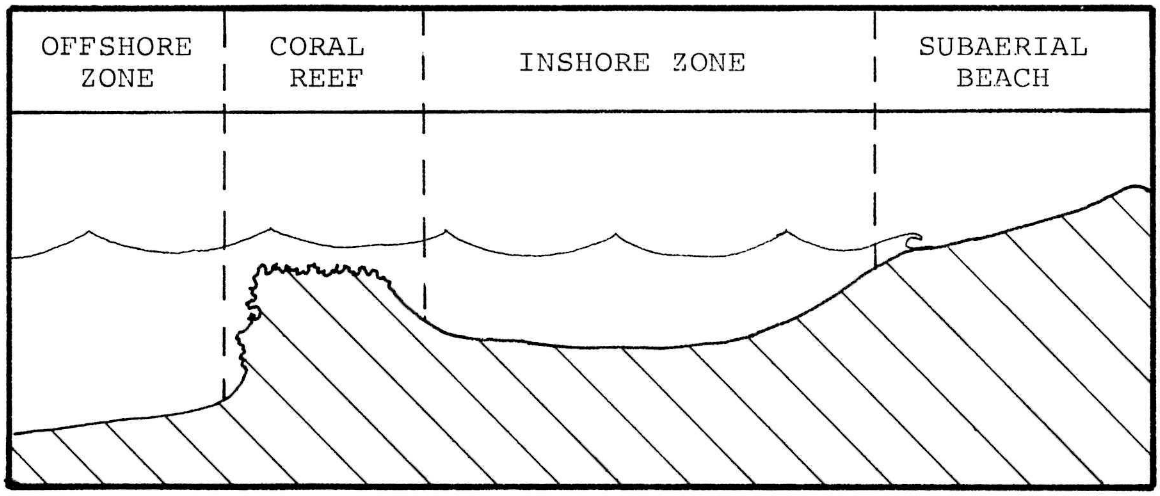


Figure 3. Cross-Section of the Reef-Beach System.

highly complex, a manifestation of the complex geology and topography of the region as well as a manifestation of the coraline-growth forms. As the waves move onshore from deep water, energy is transmitted to the reefs, to the inshore bottom, and to the subaerial-beach deposit.

Maximum excitation of these northward facing reef-beach systems occurs during the period of October through April when large waves, generated as extratropical storms move offshore along the mid-Atlantic coast of North America, reach St. John. During the period of May through October, the trade winds become stronger, the sub-tropical high intensifies, and fewer storms occur in the mid-Atlantic. Waves reaching the north shore of St. John during the May-October period are in the one-foot range except when tropical storms move through the Caribbean (Fig. 4).

2. The Reef

Reefs play an important role in the overall balance of the reef-beach system. Most of the beach sediments are coraline, derived from local fringing and patch reefs, and are transported to the beach by wave action. In addition, the reefs act as an energy buffer: As waves move across

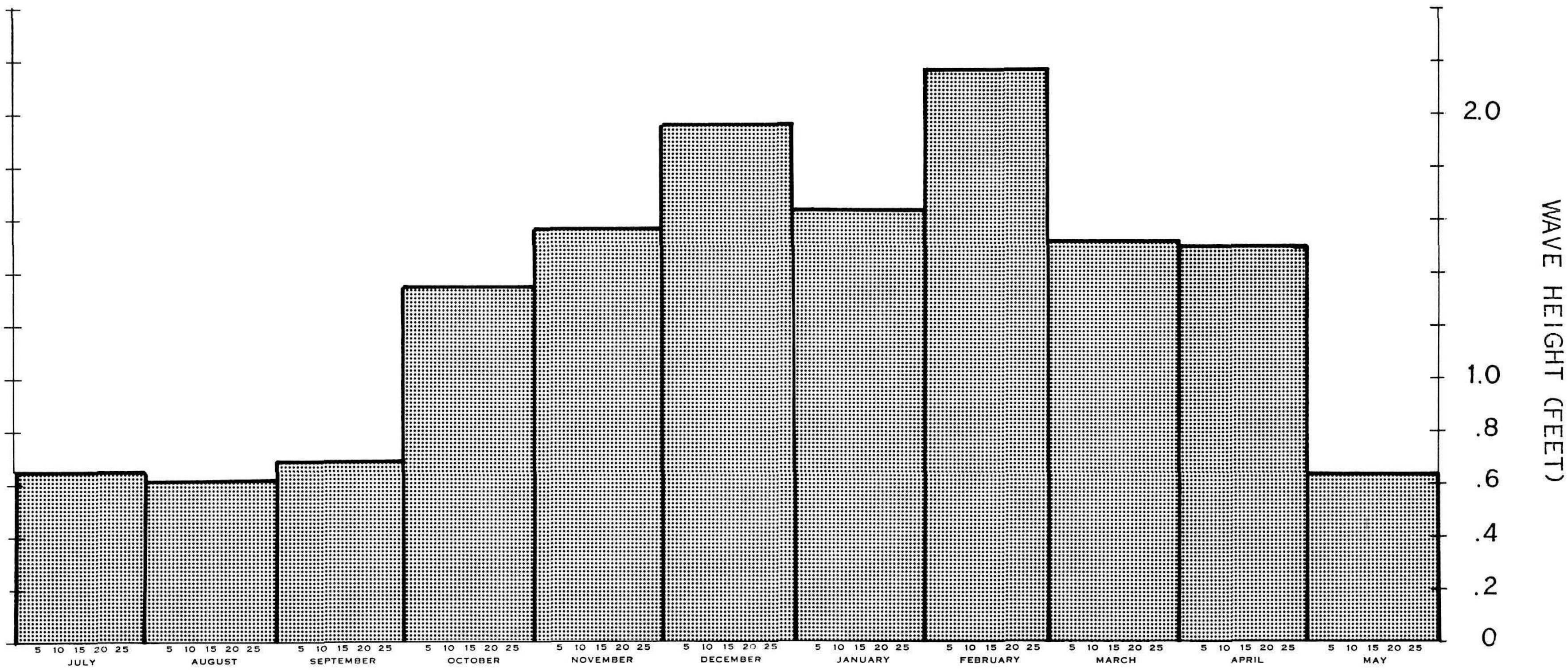


Figure 4. Mean Monthly Wave Height at Cinnamon Bay From July, 1972 Through May, 1973.

the reefs, they shoal or break, dissipating energy which would otherwise reach the subaerial beach.

Since the reef is a living entity, constant growth is an essential characteristic. One of the most important variables in reef health is water quality. The algal component of the coral polyps is light dependent, so turbid water can be detrimental. Excess suspended sediments and detrital material from adjacent terrestrial sources can cause retardation in reef growth resulting in deeper water over the reef and thus exposure of the beaches to high-wave energies.

3. The Inshore

The coraline materials that are removed from the reefs are deposited in the inshore zone, or bay bottom. During periods of high energy, the bay bottom also acts as a sediment reservoir for sands moved from the subaerial beach. As the storm waves dissipate, deposits from both sources move onshore to be incorporated in the subaerial beach deposit. Observation of sediment movement under low-wave conditions indicates that currents circulating between the bays and the offshore zone also play a role in sediment exchanges. Sediment loss to the offshore area caused by these currents may be significant.

4. The Subaerial Beach

The subaerial beach includes sand deposits that are acted upon by the swash of waves which break near the shoreline. Here hydraulic action differs appreciably from that in other parts of the reef-beach system: Sheet-like masses of translatory water move upward and, after reaching a stillstand, return down the beach face with increasing acceleration. The linear to-and-fro swash constantly redistributes the beach-face sediment. If the quantity of material carried by the uprush is in balance with that moved by the backwash, equilibrium exists; however, when the reef-beach system is excited by storm waves, swash action moves great quantities of sediment down the beach face and into the nearshore zone.

This exchange process results in a constant transfer of beach material from one part of the system to another. In the process, some of the material is lost to the deep-water zone, some is pushed landward over the beach berm in the form of overwash deposits, and some is mechanically reduced in size in the surf zone and then is transported out of the system. Therefore, balance within the system depends upon a constant resupply of sediment from the reefs and from the inshore sediment reservoir.

In summary, the reef-beach system indicates relationships between wave energy, reefs, inshore zones, and subaerial beaches. The object of the Cinnamon Bay investigation was to quantify certain of these relationships by measuring the configuration and sediment characteristics of the subaerial beach. The field experiments were conducted during the period July, 1972, to June, 1973.

THE DESIGN

Most of St. John's sand beaches are within embayments which are irregular in shape and bounded by rock headlands. Fringing reefs at the base of the headlands and patch reefs directly offshore are the sediment sources for these beaches (Fig. 5). Field experiments were conducted at three National Park Service bays that face northwest (Fig. 1).

Hawksnest Beach (Table 1), varying in width from 15 to 40 feet, is 600 feet in length. The eastern 450 feet are carbonate sand that has a mean grain size of 0.30 mm. The western 150 feet is mostly composed of beach rock and of cobble-size material.

Trunk Bay Beach (Table 2), varying in width from 20 to 50 feet, is approximately 1,200 feet long. There is a

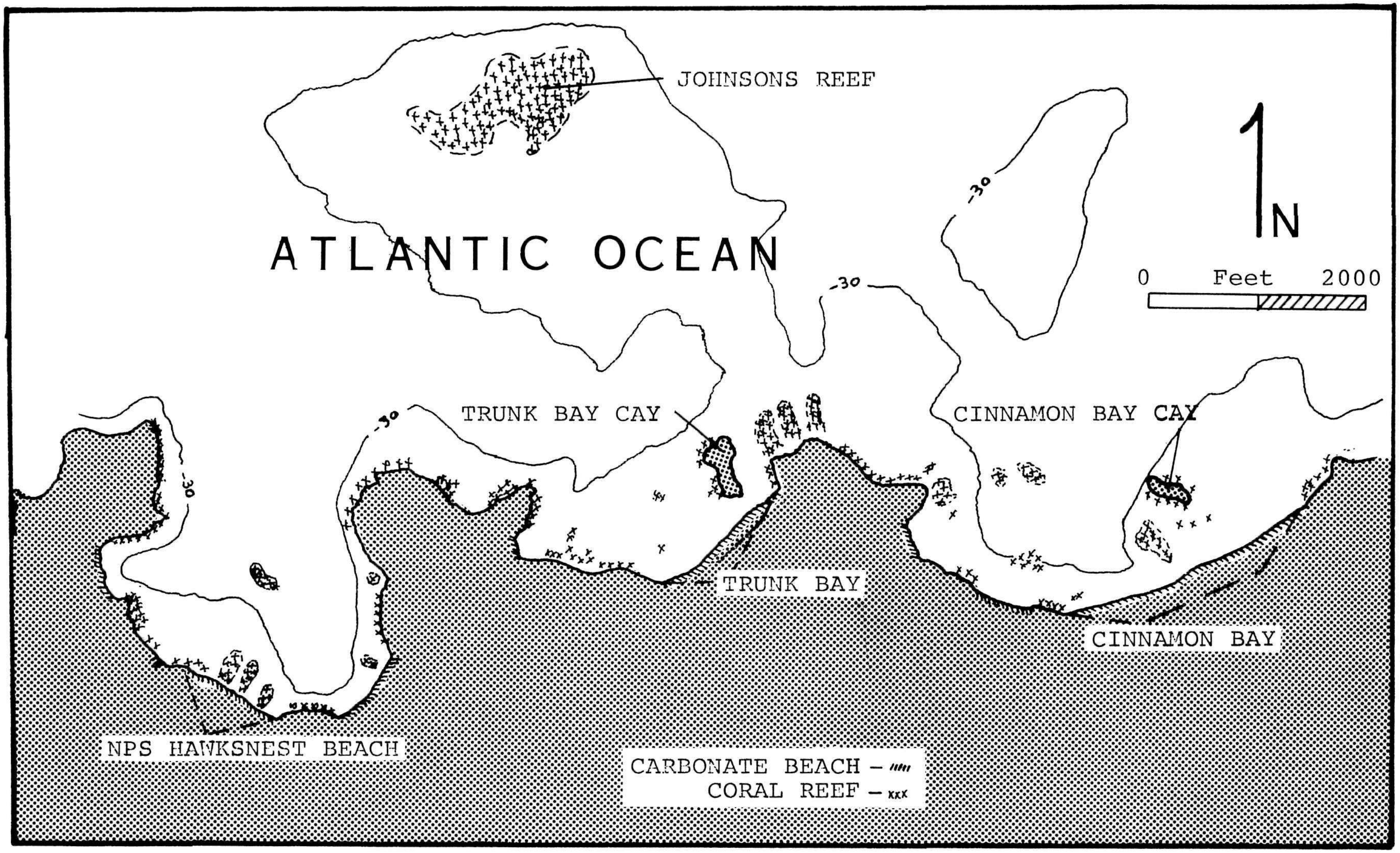


Figure 5. Hawksnest, Trunk, and Cinnamon Bays.

TABLE 1

Bay:	Hawksnest
Beach Length:	600 Feet
Beach Width:	40 Feet
Mean Wave Height: Period:	1.0 Feet 5.0 Seconds
Maximum Wave Height: Period:	6.0 Feet 7.8 Seconds
Minimum Wave Height: Period:	0.1 Feet 2.3 Seconds
Mean Grain Size:	1.8ø (0.30mm)
Standard Deviation:	0.14 (ø Scale)
Grains With Mean Diameter Less Than 125 Microns:	1.25%
Mean Beach Elevation:*	1.83 Feet
Maximum Beach Elevation:*	2.92 Feet
Minimum Beach Elevation:*	1.26 Feet

*Above Reference Point at Permanent Pipe #3

TABLE 2

Bay:	Trunk Bay West	Trunk Bay East
Beach Length:	950 Feet	275 Feet
Beach Width:	50 Feet	30 Feet
Mean Wave Height : Period:	1.3 Feet 5.8 Seconds	0.7 Feet 3.8 Seconds
Maximum Wave Height : Period:	10.0 Feet 13 Seconds	6.0 Feet 8 Seconds
Minimum Wave Height : Period:	0.1 Feet 2.3 Seconds	0.1 Feet 2.2 Seconds
Mean Grain Size:	2.18ø (0.22mm)	2.11ø (0.23mm)
Standard Deviation:	0.59 (ø Scale)	0.41 (ø Scale)
Grains With Mean Diameter Less Than 125 Microns:	4.34%	5.54%
Mean Beach Elevation :*	1.89 Feet	3.23 Feet
Maximum Beach Elevation :*	3.51 Feet	4.38 Feet
Minimum Beach Elevation :*	0.73 Feet	2.09 Feet

*Above Reference Point At Permanent Pipe #3

small island or "cay" immediately offshore which forms a natural east-west division of the beach (Fig. 5). Within Trunk Bay, there are several large reefs, mostly fringing the rock headlands and the cay. The beach to the east of the cay (Trunk Bay East) is 275 feet long, is 30 feet wide, and contains sediment with a mean grain size of .23 mm. It is protected from high-wave energy by the narrowness of the bay mouth and by a reef complex to the east (Fig. 5). The eastern side of Trunk Bay East is bounded by a cliff; the western side is bounded by a sand point caused by wave diffraction around the cay. The beach to the west of the cay (Trunk Bay West) is 950 feet long, ranges in width from 25 to 50 feet, and contains sediment with a mean grain size of .22 mm. The western side is bounded by a rock headland.

On St. John, Cinnamon Bay (Table 3) contains one of the largest National Park Service beaches with a total length of 2,300 feet. Like Trunk Bay, Cinnamon Bay has a small cay offshore, faces northwest (Fig. 5), and has fringing reefs around the cay and the headlands. There are also patch reefs immediately offshore.

Cinnamon Bay East is 1,100 feet long, 85 feet wide, and contains sediment with a grain size of .21 mm. It is

TABLE 3

Bay:	Cinnamon Bay West	Cinnamon Bay East
Beach Length:	1200 Feet	1100 Feet
Beach Width:	15 Feet	85 Feet
Mean Wave Height : Period:	1.3 Feet 5.8 Seconds	1.6 Feet 6.4 Seconds
Maximum Wave Height : Period:	9.0 Feet 12 Seconds	10.0 Feet 13 Seconds
Minimum Wave Height : Period:	0.1 Feet 2.3 Seconds	0.1 Feet 2.4 Seconds
Mean Grain Size:	2.5ø (0.18mm)	2.24ø (0.21mm)
Standard Deviation:	0.68 (ø Scale)	0.76 (ø Scale)
Grains With Mean Diameter Less Than 125 Microns:	18.71%	13.37%
Mean Beach Elevation :*	1.4 Feet	1.94 Feet
Maximum Beach Elevation :*	3.05 Feet	4.49 Feet
Minimum Beach Elevation :*	0.15 Feet	1.94 Feet

*Above Reference Point at Permanent Pipe #3

bounded on the east by rock cliffs and on the west by the break in trend of the beach caused by the cay. Cinnamon Bay West is the one beach area on St. John that has a serious erosion problem: The entire beach front (1,200 feet) is receding. The beach varies in width from 5 to 15 feet and contains sediment with a mean grain size of .18 mm. An erosional scarp which separates the active beach from the older sand deposits varies from one to four feet in height (Fig. 6).

The conceptual relationships developed in an earlier section between components of the reef-beach system presented a greatly simplified explanation of a highly complex biophysical system. However, testing and measurement of even this general model is difficult. Although any one component of the reef-beach system could be investigated, the role of waves in the material-exchange processes of the subaerial beach has been demonstrated to be important (Waddell, 1973). Also the subaerial beach is the most convenient segment of the system to study.

In the St. John experiments, the beach below the lowest tide level was physically beyond the range of routine measurements; therefore, quantifications of changes within the inshore zone could only be estimated from occasional

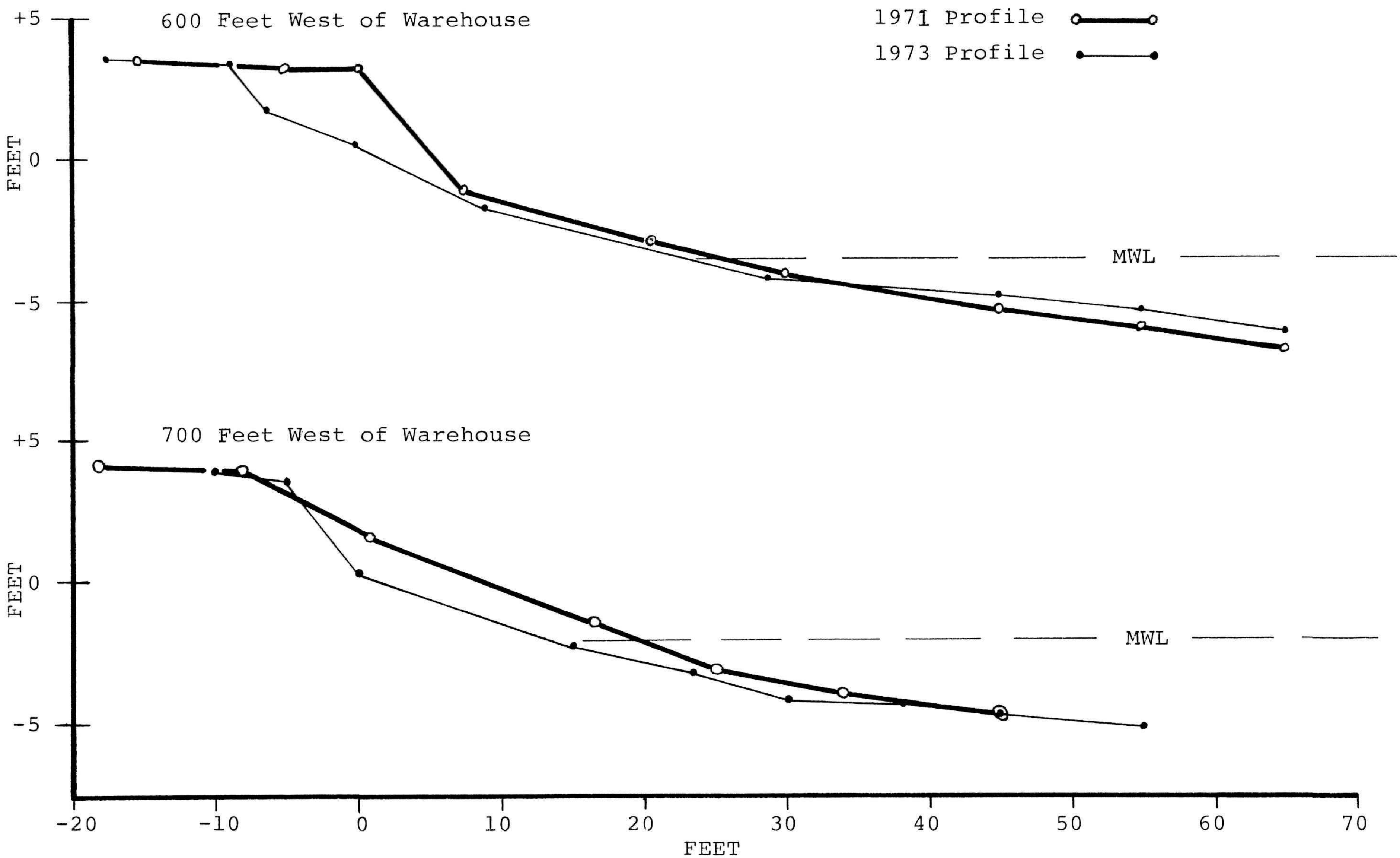


Figure 6. Beach Profiles at 600 and 700 Feet West of Cinnamon Bay Warehouse Illustrating Beach Recession and Erosional Scarp.

measurements and from samples collected by SCUBA diving techniques. Our studies of subaerial-beach responses to process changes were thus restricted to the area between low-tide level and the upper limit of wave uprush. Also, because of the lack of a theoretical understanding of swash processes and the technical difficulties associated with empirical studies of beach-face processes (Waddell, 1973a), assessment of the uprush and backwash was excluded from the experiments.

Finally, consideration of the complete reef-beach system, as demonstrated by Dolan _et al_. (1969), ideally should include the continuous nature of energy applications and of beach response; however, during the investigation on St. John, sampling was limited to a selected set of variables sampled periodically (Table 4). In limiting the measurements to these variables, it is understood that a significant number of interactions were defined out of the experiments and that a higher noise level is no doubt introduced; however, if the variables selected are the most significant, then the fundamental relationships can be quantified.

The Processes

The energy delivered to the reef-beach system was estimated from measurements of breaking waves: Thirty to forty

TABLE 4

Primary Process and Response Data

Variable	Frequency of Measurement
Wave Height	Daily
Wave Period	Daily
Beach Response Under One Tidal Cycle	Weekly
Beach Response Under Storm Conditions	After Each Storm
Beach Elevations	Daily

waves at a minimum of two beaches were measured daily by using a graduated staff to measure the distance from the trough to the crest as the waves peaked before breaking. Waves higher than five feet were estimated from the shore, an event which occurred only eight times during the study period. Wave period was measured by using a stop watch to record the period of time it took thirty waves to pass fixed points on each bay.

The Responses

Beach responses to various energy conditions were measured during the semi-diurnal tidal cycles and under storm conditions. Sediment characteristics and sand-level changes within 12-hour tidal cycles were measured weekly at two beaches selected at random. Twenty sample points were established within a fifteen- by seventy-five-foot grid area; elevation-control stakes were measured at each of the twenty sampling points. The stakes were placed in a regular pattern: Four rows, twenty-five feet apart, of five stakes each, three feet apart, were placed perpendicular to the shoreline (Fig. 7) covering the tidal zone of the beach-face. This set-up was installed at low tide and the position of the stakes nearest the water was determined by the average uprush of the swash. When the stakes were

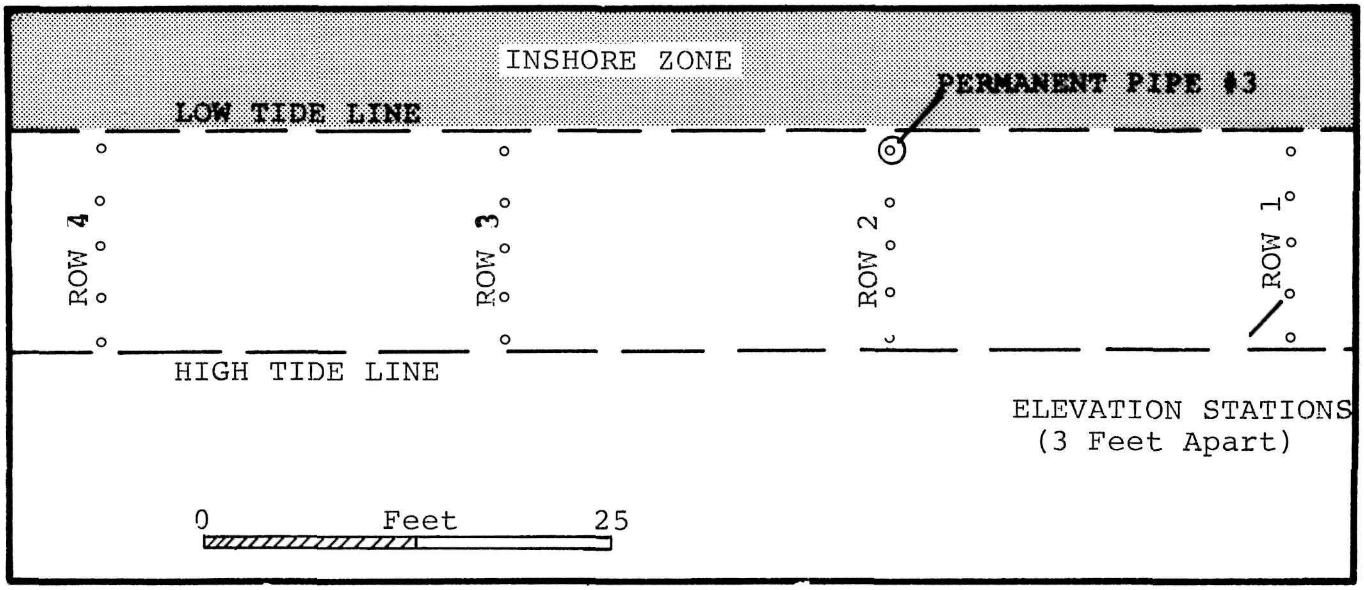


Figure 7. Plan View of a Tidal-Cycle Measurement Set-up.

placed, the height from the top to sand level was measured. At the following low tide, 12 hours later, the distances from the stake tops to sand level were again measured. The difference between the last and the first measurement was the gross change in the sand level within a tidal cycle. At the same time the stakes were placed, a small plug of sand (which had been spray-painted red) was inserted into the beach near each stake. At the following low tide, this red plug of sand was dissected so as to reveal its position relative to the beach section. The top of the red plug represented the low point of the beach (erosion) during the tidal cycle and any material positioned above the plug represented sediment deposited by the falling tide. This sampling method was conducted simultaneously at two bays for two consecutive tidal cycles each week during the investigation (Fig. 8).

Characteristics of sediments moved under different storm conditions were measured in a similar manner except that the stakes and the colored sand plugs were larger and the stakes were permanent: Two polyethylene pipes and one steel pipe were installed in the subaerial beach and held in place by concrete footings. The pipes were equally spaced along a line perpendicular to the shoreline (Fig. 9)

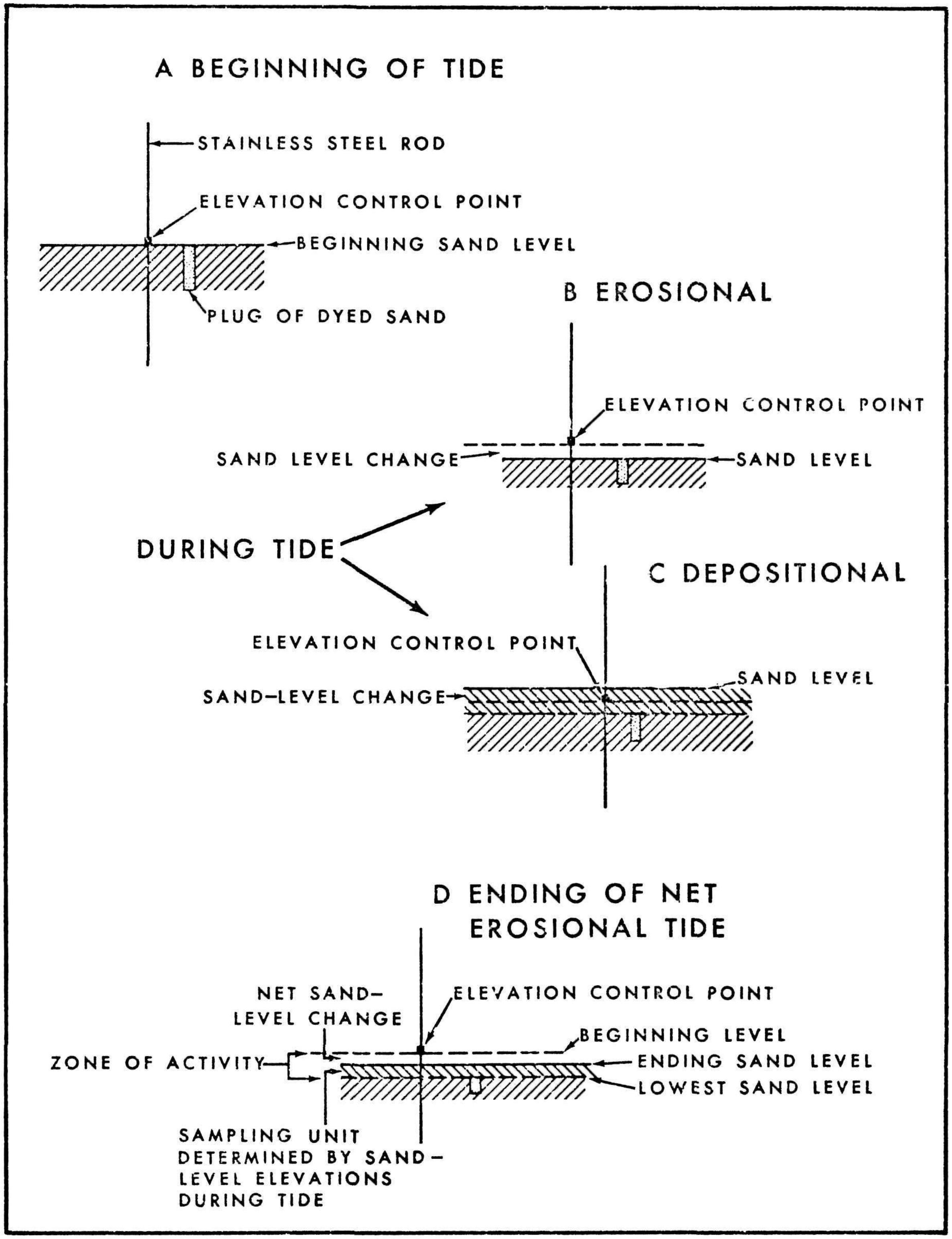


Figure 8. Method for Determining Sand-Level Changes.

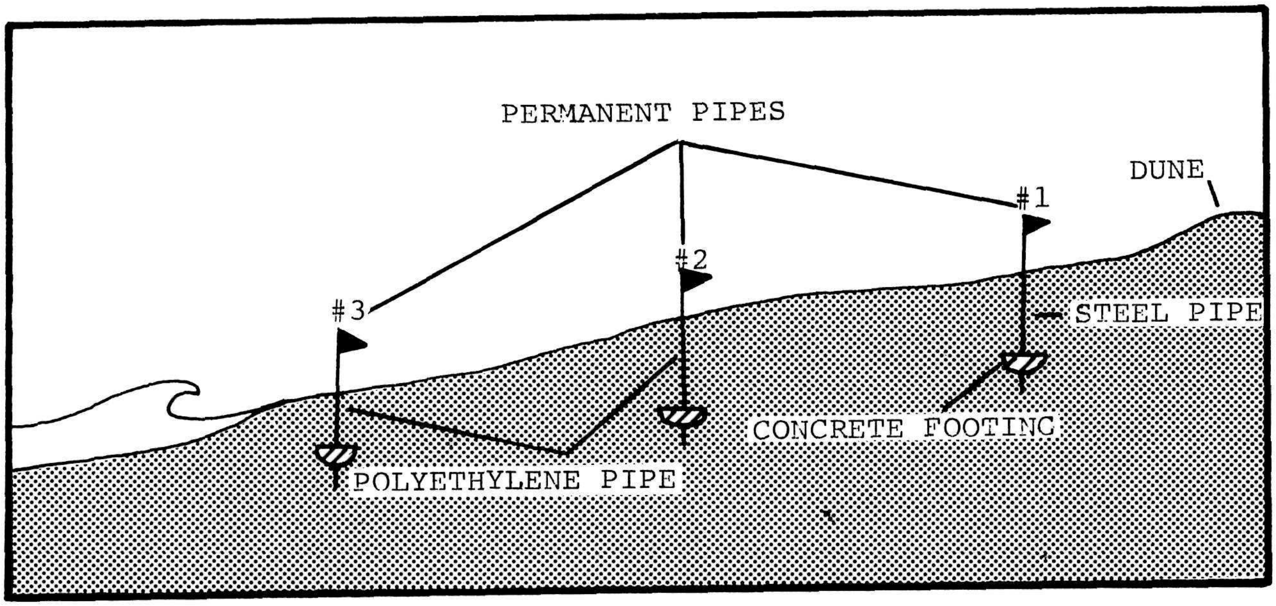


Figure 9. Profile of Permanent Elevation Control Pipes.

and were measured daily to determine gross sand-level changes. A large (three-foot long) plug of red sand was inserted in the beach near each pipe in order to record the lowest level to which the beach had been reworked during a storm. After a storm, the plug was viewed in profile, the amount of sand above the top of the plug was measured and sampled, and a new plug of red sand was inserted into the beach.

The following periodic measurements were also taken (Table 5):

1. In order to monitor gross seasonal variations in grain size along or across the subaerial beach at each bay, sediment samples were collected every 3 months from the top 2.5 inches of the dune, berm, and swash zones along 200-foot spaced lines. By surveying bimonthly profiles along these same lines, seasonal variations in subaerial beach profiles were also monitored.

2. Since most response data were collected in the subaerial tidal zone, the relationship between subaerial-beach response and inshore-zone characteristics was investigated to establish at least a qualitative relationship of this section of the reef-beach system. Data was collected by quarterly offshore reconnaissance using SCUBA techniques. To describe the relationships water depth, bottom characteristics, and sediment samples were taken at 100-foot intervals to a distance 1,000 feet directly offshore from the permanent pipes on each beach.

3. The relationship between beach change and the stability of the Cinnamon Bay Warehouse was of

TABLE 5

Secondary Response Data

Variable	Frequency of Measurement
Seasonal Grain-Size Variation	Every Three Months
Seasonal Beach-Profile Variation	Bimonthly
Inshore-Zone Sediment Size and Configuration	Every Three Months
Cinnamon Bay West Beach Configuration	Weekly (After 1/1/73)
Rate of Beach Erosion at Cinnamon Bay West	August 1971 and May 1973

primary interest to the Virgin Islands National Park. Therefore, two subaerial beach profiles, one from each side of the warehouse, were taken weekly at Cinnamon Bay.

4. Finally, in order to provide documentation of the rates of beach retreat at Cinnamon Bay West, a set of profiles was surveyed in May, 1973, along the same lines that had been surveyed by the NPS Denver Service Center in August, 1971.

ANALYSIS AND RESULTS

Although the conceptual model of the reef-beach system can provide general explanations for the interaction of various elements, statistical analyses of the data sets collected on St. John provide quantitative verification of both the actual existence and the degree of these interactions. The analyses were designed to answer these questions:

1. Is there any significant variation of beach-material size and of beach elevation along and/or across the beach faces within semi-diurnal tidal cycles?
2. Is there any significant seasonal variation in beach configuration as measured by beach elevation and beach-material size?
3. Is there significant variation of subaerial-beach grain size and elevation between Trunk Bay, Cinnamon Bay, and Hawksnest Bay?
4. Is there a significant correlation between wave energy and grain size or wave energy and beach elevation?

To answer the above questions, the following statistical analyses were used:

1. Variation within a tidal cycle was tested using a two-way classification analysis-of-variance (ANOV) model. Data points on the beaches were assigned corresponding positions in the analysis matrix and the model tested the variation along the beaches (between columns) and across the beaches (between rows).

2. Significant seasonal variation in grain size and beach elevation within each of the five beaches was tested using a one-way classification ANOV model. This one-way classification ANOV model was also used to test grain-size and beach-elevation variations within Trunk and Cinnamon Bays and between Trunk, Cinnamon, and Hawksnest Bays.

3. Correlation coefficients for relationships between wave height and sand grain size were calculated using a Hewlett-Packard regression-correlation program.

These statistical analyses yielded the following results:

1. In 64 out of 68 cases, there was no significant variation (at the .05 level of significance) between grain sizes across the beach face at any of the five beaches; and in 67 of the 68 cases, there was no significant variation along the beaches (Table 6). The F ratios for rows ranged from 0.05 to 22.1, with only one value suggesting rejection of the null hypothesis.

   The beach-elevation change within tidal cycles varied significantly across the beaches but did not vary along the beaches (Table 7). There were decreasing beach-elevation changes moving up the beach faces ranging from 0.10 feet (a grand mean for all five beaches) at the lowest

TABLE 6

Analysis-of-Variance Table for

Grain Size Within Site

All Bays

Source	Sum of Squares	Degrees of Freedom	Mean Square	F Ratio
Rows	0.001	4	0.0002	F = 0.52
Columns	0.002	3	0.0008	F = 1.6
Residual	0.006	12	0.0005	$F_{.95(4,12)} = 3.26$
Total	0.009	19		$F_{.95(3,12)} = 3.49$

TABLE 7

Analysis-of-Variance Table for

Beach Elevation Within Site

All Bays

Source	Sum of Squares	Degrees of Freedom	Mean Square	F Ratio
Rows	0.020	3	0.007	F = 4.68
Columns	0.006	4	0.002	F = 1.11
Residual	0.018	12	0.001	$F_{.95(3,12)} = 3.49$
Total	0.044	19		$F_{.95(4,12)} = 3.26$

point within the tidal area to 0.01 feet at the highest point within the tidal area. The maximum beach-elevation change during a tidal cycle was 0.9 feet (at Cinnamon Bay West) and the minimum was 0.005 feet (at all bays).

2. There was no significant seasonal variation in the mean grain size of the beach sediment at any of the five beaches throughout the study period (Tables 8-12) with the exception of Hawksnest Bay. Analysis showed that 95 per cent of the time the mean grain size is between 0.21 mm and 0.37 mm at Hawksnest Bay, between 0.15 mm and 0.21 mm at Cinnamon Bay West, between 0.17 mm and 0.25 mm at Cinnamon Bay East, between 0.21 mm and 0.25 mm at Trunk Bay East, and between 0.20 mm and 0.24 mm at Trunk Bay West.

   At Trunk Bay East (Table 13), Hawksnest Bay (Table 14), and Cinnamon Bay East (Table 15), seasonal variation in beach elevation, because of storm conditions, was significant at the 0.05 level. Analysis of variance indicated that there is no significant seasonal variation in beach-elevation differences due to tidal or storm conditions at Cinnamon Bay West (Table 16) or Trunk Bay West (Table 17).

3. There was significant variation (at 0.05 level) in grain sizes within Cinnamon Bay (Table 18). This indicates that the mean grain size at Cinnamon Bay West (0.18 mm) is significantly different than the mean grain size at Cinnamon Bay East (0.21 mm). The mean grain size at Trunk Bay East (0.23 mm) did not vary significantly (at 0.05 level) from the mean grain size of Trunk Bay West (0.22 mm) (Table 19).

   No significant variations in beach elevation were caused by tidal or storm conditions <u>within</u> Trunk Bay (Table 20); however, the beach-elevation differences caused by tidal and storm conditions at Cinnamon Bay West were not equal to those at Cinnamon Bay East (Table 21). The mean beach-elevation difference caused by storm and tidal conditions at Trunk Bay was 0.5 feet with a range of 2.29 feet to 0.01 feet. The mean was 0.39 feet at Cinnamon Bay and ranged from 2.29 feet to 0.02 feet.

TABLE 8

Analysis-of-Variance Table for

Grain Size Within Bay

Cinnamon Bay East

Source	**Sum of Squares**	**Degrees of Freedom**	**Mean Square**	**F Ratio**
Category Means	0.005	3	0.002	$F = 0.88$
Within	0.05	26	0.002	$F_{.95(3,26)} = 2.98$
Total	0.055	29		

TABLE 9

Analysis-of-Variance Table for

Grain Size Within Bay

Cinnamon Bay West

Source	Sum of Squares	Degrees of Freedom	Mean Square	F Ratio
Category Means	0.005	3	0.002	F = 1.6
Within	0.03	31	0.001	$F_{.95(3,31)} = 2.90$
Total	0.035	34		

TABLE 10

Analysis-of-Variance Table for

Grain Size Within Bay

Trunk Bay East

Source	Sum of Squares	Degrees of Freedom	Mean Square	F Ratio
Category Means	0.001	3	0.0004	F = 0.76
Within	0.009	19	0.0005	$F_{.95(3,19)} = 3.13$
Total	0.010	22		

TABLE 11

Analysis-of-Variance Table for

Grain Size Within Bay

Trunk Bay West

Source	Sum of Squares	Degrees of Freedom	Mean Square	F Ratio
Category Means	0.005	3	0.002	F = 1.9
Within	0.03	40	0.0008	$F_{.95(3,40)} = 2.84$
Total	0.35	43		

TABLE 12

Analysis-of-Variance Table for

Grain Size Within Bay

Hawksnest Bay

Source	Sum of Squares	Degrees of Freedom	Mean Square	F Ratio
Category Means	0.16	3	0.05	F = 9.19
Within	0.12	20	0.006	$F_{.95(3,20)} = 3.1$
Total	0.28	23		

TABLE 13

Analysis-of-Variance Table for

Within-Bay Beach Elevation

Trunk Bay East

Source	Sum of Squares	Degrees of Freedom	Mean Square	F Ratio
Category Means	4.08	3	1.36	F = 29.6
Within	1.01	22	0.05	$F_{.95(3,22)} = 3.05$
Total	5.09	25		

TABLE 14

Analysis-of-Variance Table for

Within-Bay Beach Elevation

Hawksnest Bay

Source	Sum of Squares	Degrees of Freedom	Mean Square	F Ratio
Category Means	2.39	3	0.79	F = 14.16
Within	1.58	28	0.06	$F_{.95(3,28)} = 3.34$
Total	3.97	31		

TABLE 15

Analysis-of-Variance Table for

Within-Bay Beach Elevation

Cinnamon Bay East

Source	Sum of Squares	Degrees of Freedom	Mean Square	F Ratio
Category Means	0.93	3	0.31	$F = 3.1$
Within	2.72	27	0.10	$F_{.95(3,27)} = 2.98$
Total	3.65	30		

TABLE 16

Analysis-of-Variance Table for

Within-Bay Beach Elevation

Cinnamon Bay West

Source	Sum of Squares	Degrees of Freedom	Mean Square	F Ratio
Category Means	1.11	3	0.37	F = 2.48
Within	5.70	38	0.15	$F_{.95(3,38)} = 2.85$
Total	6.81	41		

TABLE 17

Analysis-of-Variance Table for

Within-Bay Beach Elevation

Trunk Bay West

Source	Sum of Squares	Degrees of Freedom	Mean Square	F Ratio
Category Means	0.64	3	0.21	F = 1.01
Within	8.64	43	0.20	$F_{.95(3,43)} = 2.83$
Total	9.28	46		

TABLE 18

Analysis-of-Variance Table for

Grain Size Within Bay

Cinnamon Bay

Source	Sum of Squares	Degrees of Freedom	Mean Square	F Ratio
Category Means	0.04	1	0.04	F = 23.3
Within	0.10	62	0.002	$F_{.95(1,62)} = 4.0$
Total	0.14	63		

TABLE 19

Analysis-of-Variance Table for

Grain Size Within Bay

Trunk Bay

Source	Sum of Squares	Degrees of Freedom	Mean Square	F Ratio
Category Means	0.0003	1	0.0003	F = 0.43
Within	0.04	54	0.0007	$F_{.95(1,54)} = 4.03$
Total	0.0403	55		

TABLE 20

Analysis-of-Variance Table for

Within-Bay Beach Elevation

Trunk Bay

Source	Sum of Squares	Degrees of Freedom	Mean Square	F Ratio
Category Means	0.06	1	0.06	$F = 0.19$
Within	11.28	34	0.33	$F_{.95(1,34)} = 4.1$
Total	11.34	35		

TABLE 21

Analysis-of-Variance Table for

Beach Elevation Within Bay

Cinnamon Bay

Source	Sum of Squares	Degrees of Freedom	Mean Square	F Ratio
Category Means	0.02	1	0.02	F = 7.74
Within	13.70	50	0.27	$F_{.95(1,50)} = 4.04$
Total	13.72	51		

4. Analysis of variance for between-bay variations in grain size (Table 22) indicates that the null hypothesis of equal means should be rejected; the mean grain size between bays is significantly different at the 0.05 level. The beach-elevation differences caused by storm and tidal conditions were approximately equal at all three bays (Table 23).

5. Correlation coefficients for wave height versus grain size ranged from .003 at Cinnamon Bay East to 0.49 at Cinnamon Bay West. Trunk Bay West (r=0.15) and Cinnamon Bay East (r=.003) had correlation coefficients suggesting no relationship (at 0.05 level of significance) between variations in wave height and changes in sediment size. Cinnamon Bay West (r=0.49), Trunk Bay East (r=0.46), and Hawksnest Bay (r=0.48) had correlation coefficients which suggest very weak relationships (at 0.05 level of significance) between increasing wave height and coarser grain sizes.

6. Wave energy correlated significantly with beach-elevation differences at all five beaches investigated:

   a. Cinnamon Bay West, r = 0.75;

   b. Cinnamon Bay East, r = 0.84;

   c. Trunk Bay West, r = 0.48;

   d. Trunk Bay East, r = 0.45;

   e. Hawksnest Bay, r = 0.63.

   Beach elevation and wave heights for each of the five beaches are shown in Figures 10-14. These figures emphasize the relationship between beach accretion and/or degradation and periods of high-wave energy.

Statistical analysis provides quantification of the degree of variability of the reef-beach system, adding

TABLE 22

Analysis-of-Variance Table for

Grain Size Between Bays

All Bays

Source	Sum of Squares	Degrees of Freedom	Mean Square	F Ratio
Category Means	0.69	4	0.17	F = 26.7
Within	0.99	154	0.006	$F_{.95(4,154)} = 2.37$
Total	1.68	158		

TABLE 23

Analysis-of-Variance Table for

Between-Bay Beach Elevations

All Bays

Source	Sum of Squares	Degrees of Freedom	Mean Square	F Ratio
Category Means	1.12	4	0.28	F = 0.58
Within	40.12	83	0.48	$F_{.95(3,83)} = 2.47$
Total	41.24	87		

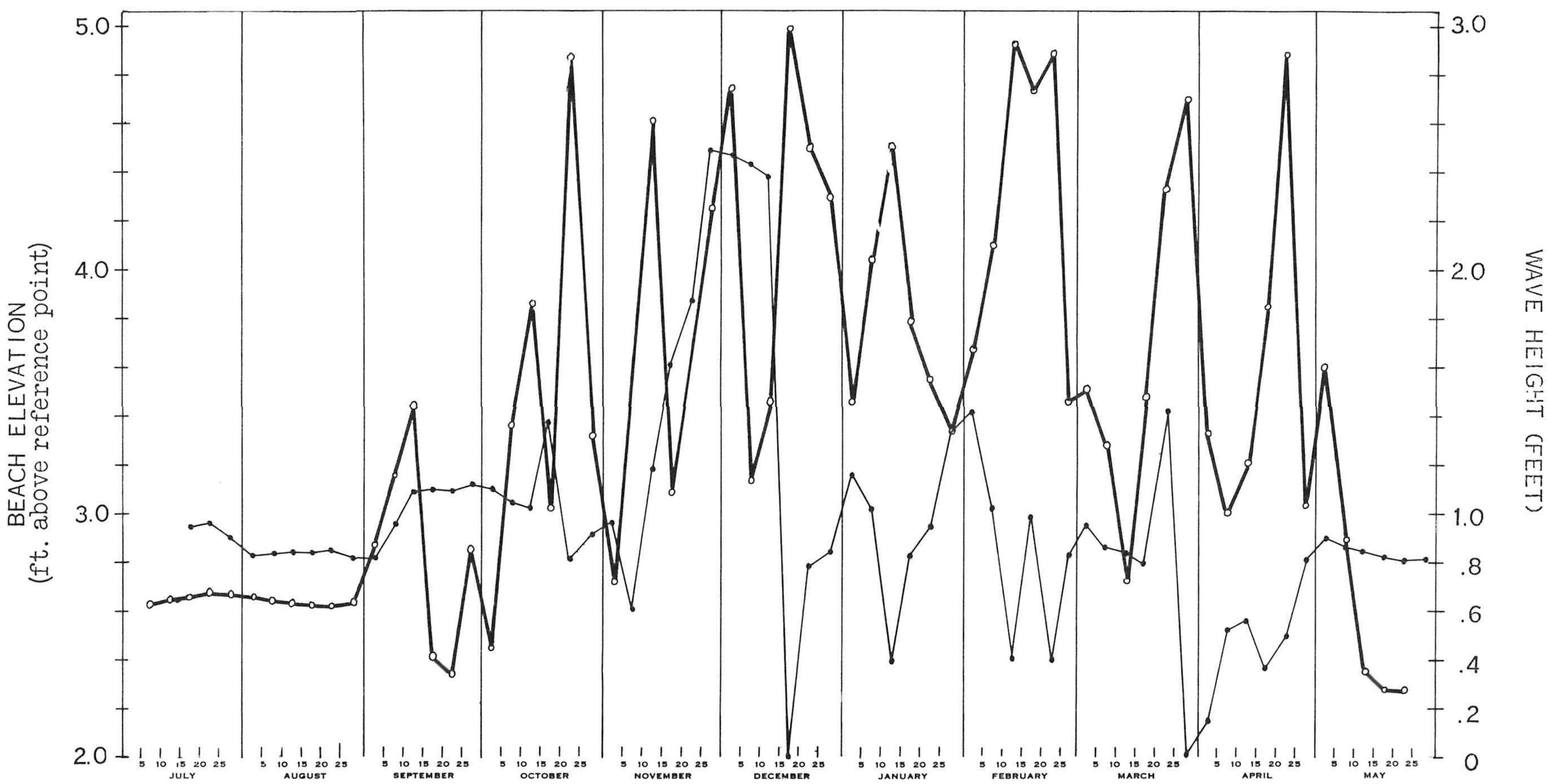


Figure 10. Wave Height vs. Beach Elevation at Cinnamon Bay East From July, 1972 Through May, 1973.

Wave Height

Beach Elevation

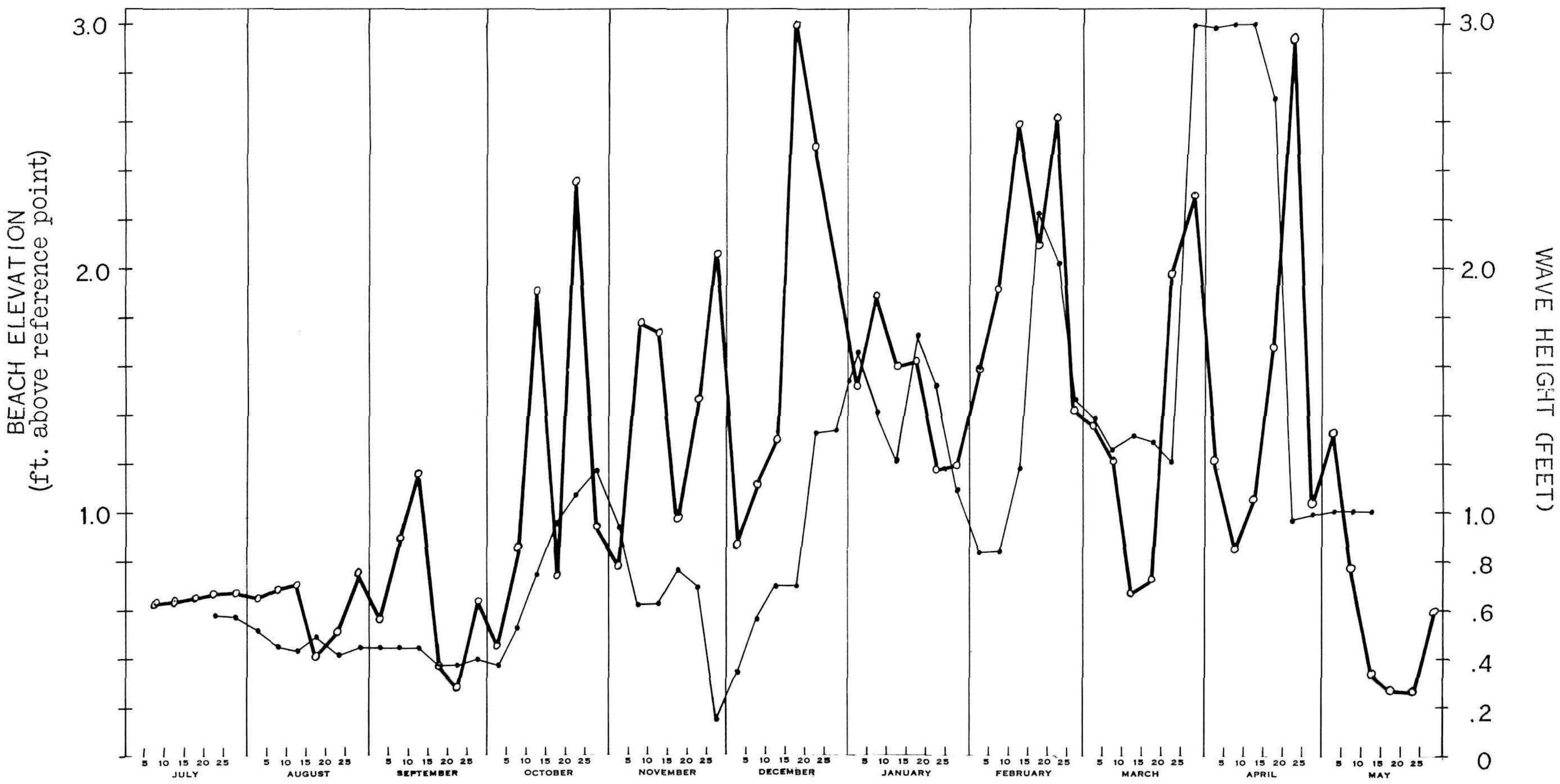


Figure 11. Wave Height vs. Beach Elevation at Cinnamon Bay West From July, 1972 Through May, 1973.

Wave Height Beach Elevation

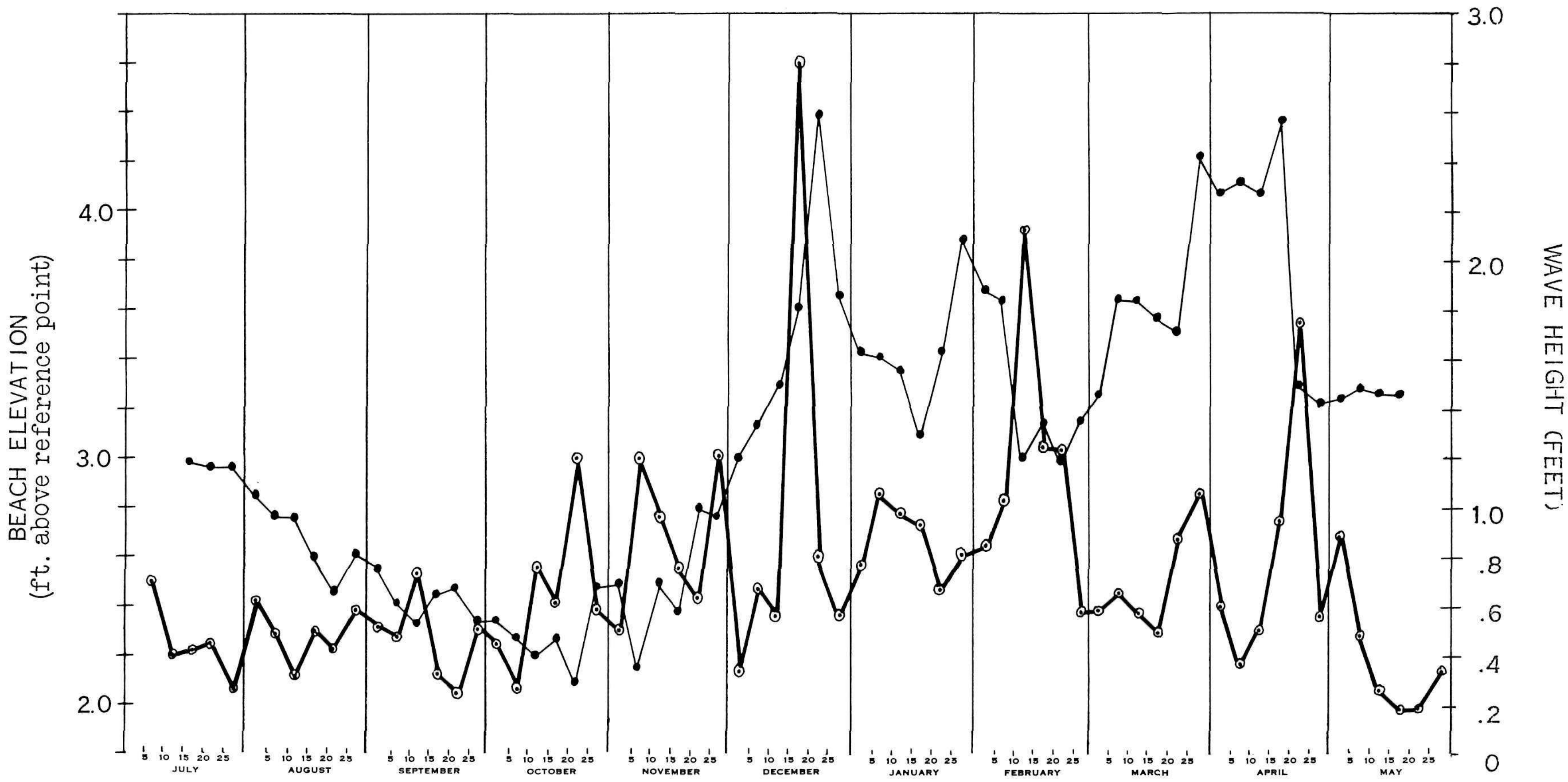


Figure 12. Wave Height vs. Beach Elevation at Trunk Bay East From July, 1972 Through May, 1973.

Wave Height ⸺ Beach Elevation ⸺

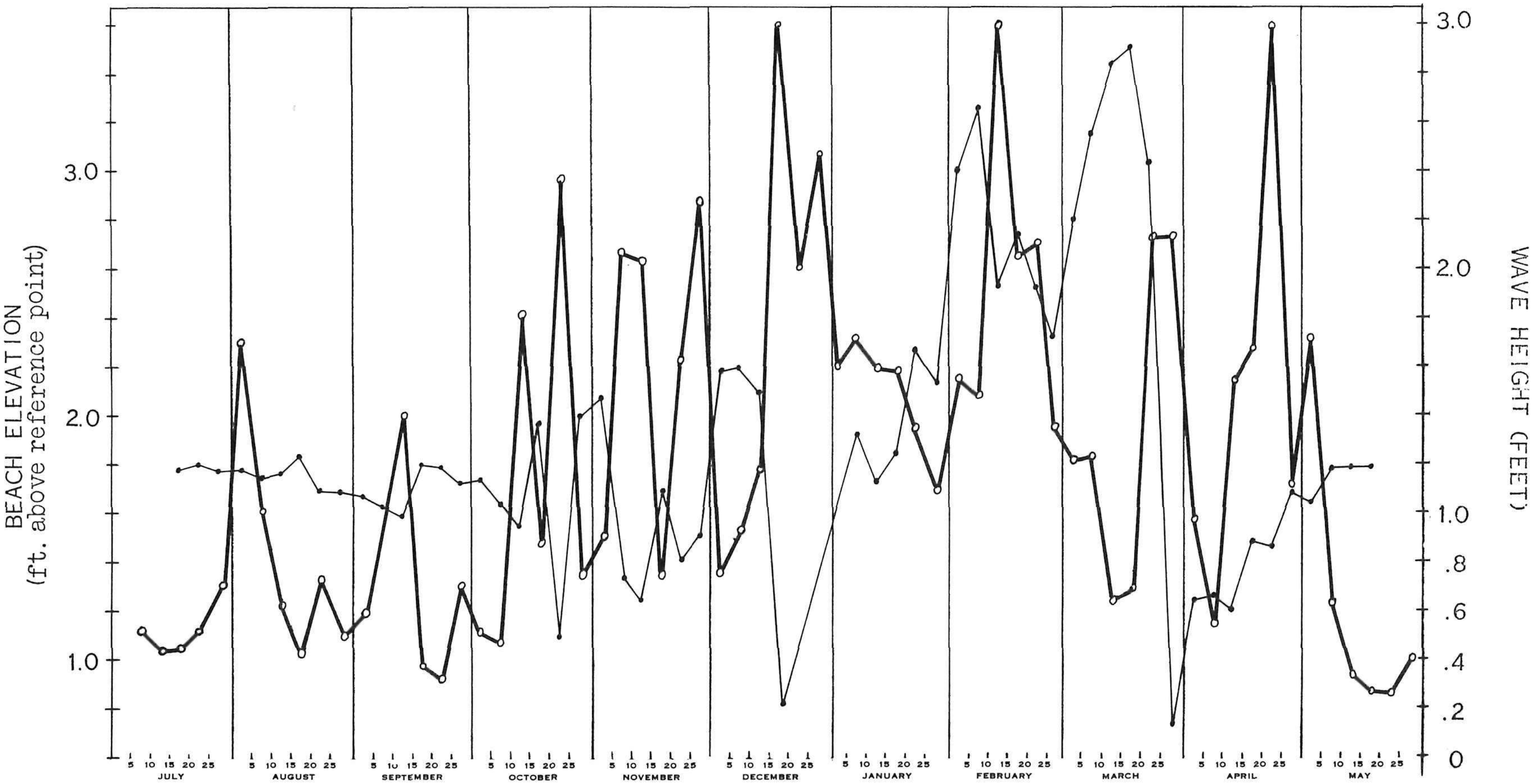


Figure 13. Wave Height vs. Beach Elevation at Trunk Bay West From July, 1972 Through May, 1973.

Wave Height ○——○ Beach Elevation •——•

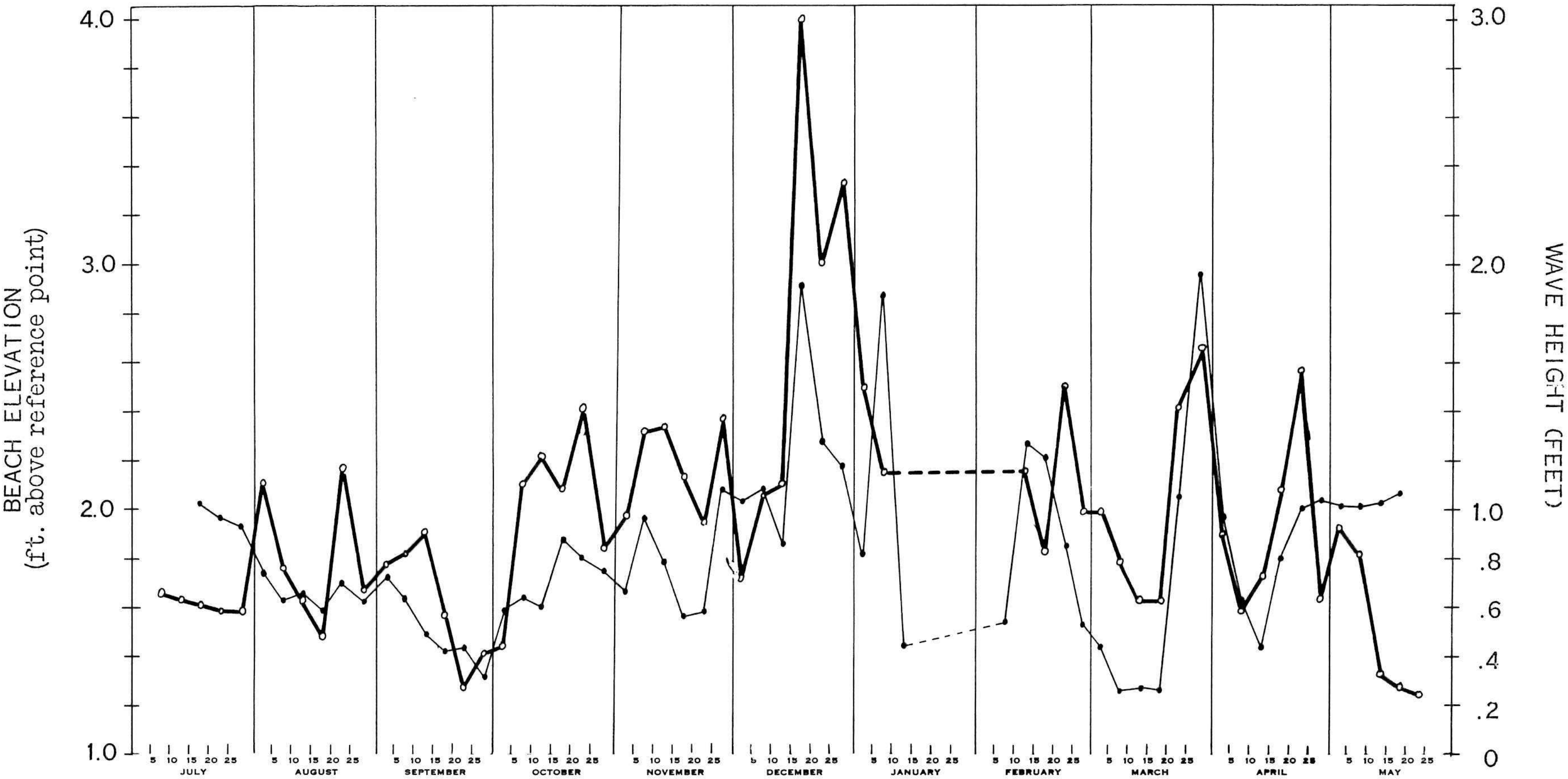


Figure 14. Wave Height vs. Beach Elevation at Hawksnest Bay From July, 1972 Through May, 1973.

Wave Height ○━━━○ Beach Elevation ●———●

dimension to the magnitude of change and adding absolute values to the data. Table 24 presents the results in terms of significant and non-significant variation. Summarizing the results: For each of the beaches studied, Hawksnest Bay, Trunk Bay East, Trunk Bay West, Cinnamon Bay East, and Cinnamon Bay West, sediment-size characteristics were uniform along and across the beaches, and each bay experienced beach-elevation changes during periods of high waves. Although the variations in grain size within the bays were not significant, variations in grain size between the five beaches studied were significant. The most notable variation was at Cinnamon Bay West where finer sands dominated.

Swell from extratropical storms in the mid-Atlantic excited the reef-beach systems on the northwest coast of St. John thus setting into motion the sediment-exchange processes. These processes were manifested as changes in beach elevations and were recorded at all bays studied. The most significant changes caused by storm waves were recorded at Trunk Bay East, Cinnamon Bay East, and Hawksnest Bay.

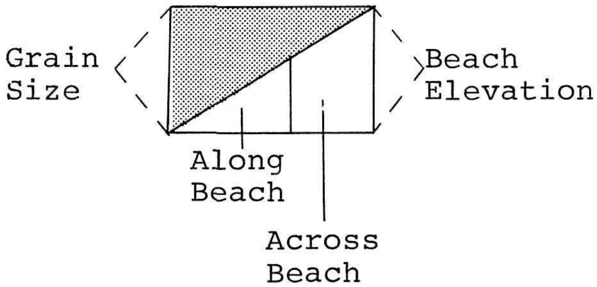
The sorting of beach sands by grain size, a characteristic beach-storm response, was absent from Cinnamon Bay

TABLE 24

Statistical Results

BAY	BEACH CHARACTERISTIC VARIATION				
	WITHIN TIDE	SEASONAL	WITHIN BAYS	BETWEEN BAYS	CORRELATION WITH WAVE HEIGHT
CINNAMON WEST	NS / NS, S	NS / NS	S / S	S / NS	S / S
CINNAMON EAST	NS / NS, S	NS / S	S / S	S / NS	NS / S
TRUNK WEST	NS / NS, S	NS / NS	NS / NS	S / NS	NS / S
TRUNK EAST	NS / NS, S	NS / S	NS / NS	S / NS	S / S
HAWKSNEST	NS / NS, S	S / S	NS / NS	S / NS	S / S

S - Significant
NS - Not Significant



East and Trunk Bay West, although each of the two bays underwent beach-elevation changes during periods of storm waves. At Cinnamon Bay West, Trunk Bay East, and Hawksnest Bay, the beach sands were significantly coarser following high waves than they were at other times; therefore, the transport processes were proportional for all grain classes.

The mean grain size of beach sand along Cinnamon Bay West is significantly smaller than that recorded for Cinnamon Bay East. In addition the beach-elevation changes at Cinnamon Bay West were consistently greater than along Cinnamon Bay East; however, the changes at Cinnamon Bay East were seasonal, whereas those at Cinnamon Bay West occurred throughout the year.

At Trunk Bay there is a similar configuration to the west and east portions; however, mean grain sizes for beach sand along the two portions of the bay, unlike those for Cinnamon Bay East and West, are indistinguishable. During storms, recorded beach-elevation changes were similar and no sorting of beach materials was recorded.

UNEXPLAINED VARIANCE

Numerous processes are involved in the balance of the reef-beach system. Assessment of the role of different components necessarily varies according to the state of the system. Under equilibrium conditions each component must be monitored simultaneously; when the system is in disequilibrium, the departure from equilibrium may be assessed by careful study of that component of the reef-beach system which has experienced a progressive change; i.e., a trend. Such was the case in our St. John studies.

A prevailing erosional trend at Cinnamon Bay West was documented. In order to assess this unstable system, the sediment-exchange processes of the beach were studied and compared with adjacent reef-beach systems for which there was no evidence of a trend state. Although a limited set of experiments could be designed to answer a specific set of questions about one component of the reef-beach system, detailed assessment of the dynamics of the entire system was impossible. This trade-off is reflected in the amount of variance based on collected data. From assessment of the unexplained variance, probably the three most important contributing factors are:

1. The unexplained variance associated with grain-size sorting, especially at Cinnamon Bay East and Trunk Bay West, which may be due to differences in swash-zone processes within and between the bays.

2. The unexplained variance between sediment-exchange processes within and between bays which is

associated with the wave environments may be attributable to the differences in wave-approach directions related to the fringing and patch-reef configurations. Small differences in wave-approach direction thus may have marked differences in energy received at the beach.

3. The unexplained variance between sediment-exchange processes within and between bays which may be attributable to lags in reef-beach system responses inherent to each bay. Because our studies focused on simultaneously recorded process-response changes, changes involving a lagged response beyond our sampling period could not be treated.

Although each of these processes may be significant, their inclusion in the experimental design would have resulted in only marginal gains given the magnitude of the variance which was explained with the experimental methods used.

CONCLUSIONS AND DISCUSSION

Perhaps the most significant documentation of our study was the excitation of north-shore beaches of St. John by waves generated by extratropical storms moving offshore along the mid-Atlantic coast well to the north of the Virgin Islands. This responsiveness to extratropical storms sets these areas apart from general tropical reef-beach systems and unites them, from a dynamic perspective, with the temperate-latitude beaches of the mid-Atlantic coast. Much of the knowledge gained over past decades about beach processes and shoreline variability become to some degree applicable to the reef-beach systems of the north shore of St. John if they are classed with the temperate-latitude beaches. This is not to imply, however, that management of these systems should be similar to that of the sand beaches and the barrier islands of the north. The existence of the reefs alone clearly sets these sites apart.

Two coupled variables of the reef-beach system are central to the management question. The first is the form of the reef shadowing the beach. Along the north-shore beaches west of Mary Point (Fig. 1) the reef form is characterized by distinct shallow-water fringing reefs adjacent to the major points and deeper, sloping fringing reefs of scattered coral heads. There is also a system of extensive patch reefs rising to within 5 to 20 feet of the surface. Along much of the southward- and the eastward-facing shores, the water depth increases more rapidly offshore and much of the shallow-water coral growth consists of scattered colonies on hard rock. Few significant offshore patch reefs are found.

The second variable is that of the area's wave climate. The north-shore bays containing patch and fringing reefs are in areas characterized by occurrences of waves generated by extratropical storms to the north; whereas, scattered colonies along the southern and eastern shores are in areas largely under the domination of waves generated by the trade-wind systems and are devoid of storm waves. Those areas without reefs are shadowed from extratropical storm and/or trade-wind waves; that is, they are only exposed to small, locally generated waves.

The beaches fronted by scattered coral formations and under the influence of trade winds undergo adjustment on a continual basis because of the consistency of the wave environment. In contrast, the beaches fronted by patch and fringing reefs and responsive to extratropical storm waves respond and adjust at periodic intervals. Beach-sediment changes in these systems are, therefore, episodic in contrast to the evolutionary changes of those areas dominated by trade-wind waves.

The north-shore bays of St. John exhibit similar responses to the episodic, high-energy conditions which occur approximately ten times each year. During these meteorological events, morphological changes within the system cause large volumes of sediment to be exchanged between the inshore zone and the subaerial beach. Grains of sediment with a mean diameter of less than 125 microns (fine sands, silts, and clays) are most easily placed in suspension by the stresses associated with breaking waves.

The average percentage of beach material less than 125 microns is given in Table 25 for all samples taken at each bay. From the data gathered on beach-elevation changes during the high-energy periods, the volume of sediment that was moved off and onto the beach face during each storm period was calculated. In this way, estimates can be made of the volume of suspended material involved in the exchange process (Tables 26-30).

Under natural conditions, the reefs on the north shore of St. John barely tolerate present volumes of fine sediment; this is clearly evident from the present marginal health of the reefs. If an alteration of the exchange process were to occur, more of the fine fraction could very easily be winnowed out of the subaerial beach and moved across the inshore zone onto the reefs or into the offshore zone. This would result in major changes in the beach configuration as well as significant damage to the reefs.

Any alteration to the system, such as the rock revetment in front of the warehouse on Cinnamon Bay, can cause

TABLE 25

Sediment Less Than 125 Microns

In Mean Diameter

Bay	Percent
Hawksnest	1.25
Trunk West	4.34
Trunk East	5.54
Cinnamon West	18.71
Cinnamon East	13.37

TABLE 26

Sediment Transported Under High-Energy Conditions

Hawksnest Bay

Date	Total Volume Transported (Cu. Feet)	Suspended Volume (Cu. Feet)	Mean Grain-Size Transported (mm)
12/19/72	5,922	74	0.34
12/29/72	1,419	18	0.33
2/3/73	1,650	21	0.38
2/13/73	8,004	100	0.60
3/25/73	11,748	147	0.45

TABLE 27

Sediment Transported Under High-Energy Conditions

Trunk Bay West

Date	Total Volume Transported (Cu. Feet)	Suspended Volume (Cu. Feet)	Mean Grain-Size Transported (mm)
10/24/72	11,156	502	0.29
11/9/72	4,218	190	0.26
11/13/72	5,716	257	0.26
11/26/72	2,275	103	0.33
12/19/72	30,747	1384	0.25

TABLE 28

Sediment Transported Under High-Energy Conditions

Trunk Bay East

Date	Total Volume Transported (Cu. Feet)	Suspended Volume (Cu. Feet)	Mean Grain-Size Transported (mm)
11/26/72	1,380	76	0.26
12/19/72	6,060	333	0.23
1/15/73	1,740	96	0.26
2/3/73	2,580	142	0.26
2/13/73	570	31	0.25
4/23	3,375	186	0.28

TABLE 29

Sediment Transported Under High-Energy Conditions

Cinnamon Bay West

Date	Total Volume Transported (Cu. Feet)	Suspended Volume (Cu. Feet)	Mean Grain-Size Transported (mm)
11/9/72	2,625	492	0.24
11/26/72	4,650	871	0.25
12/19/72	6,225	1,167	0.25
12/29/72	975	182	0.25
2/13/73	10,350	1,372	0.22
2/23/73	5,700	1,068	0.28
3/25/73	13,650	2,559	0.29
4/23/73	12,825	2,404	0.25

TABLE 30

Sediment Transported Under High-Energy Conditions

Cinnamon Bay East

Date	Total Volume Transported (Cu. Feet)	Suspended Volume (Cu. Feet)	Mean Grain-Size Transported (mm)
10/24/72	8,833	1,192	0.26
11/13/72	7,986	1,078	0.25
11/26/72	19,118	2,580	0.31
12/19/72	64,251	4,263	0.24
1/15/73	4,598	620	0.24
2/13/73	14,157	1,911	0.25
2/23/73	5,808	784	0.28
3/25/73	16,819	2,270	0.26
4/23/73	6,050	816	0.26

even more dramatic changes. This wall causes wave reflection rather than energy dissipation and thus increases scour at the base of the wall; sediment plumes directly offshore from the warehouse are significantly larger than plumes found under natural conditions. Weekly beach profiles taken on each side of the warehouse during 1973 are shown in Figure 15. At the lowest point, the beach was completely subaqueous during high-energy conditions and the sediment losses were significant. When profiles were compared with the National Park Service surveys made in 1971 (Fig. 6), the results showed that the beach along Cinnamon Bay West had retreated approximately six feet within the past three years except directly in front of the warehouse where the rock revetment retarded beach erosion.

The prevailing erosional trend at Cinnamon Bay West, coupled with the results of this investigation, suggest that the volume of fine sands removed from the beach during storms exceeds the volume returned during fair weather. The surplus material either remains in the inshore zone or is subsequently transported beyond the reef to the offshore zone where it is effectively lost from the reef-beach system.

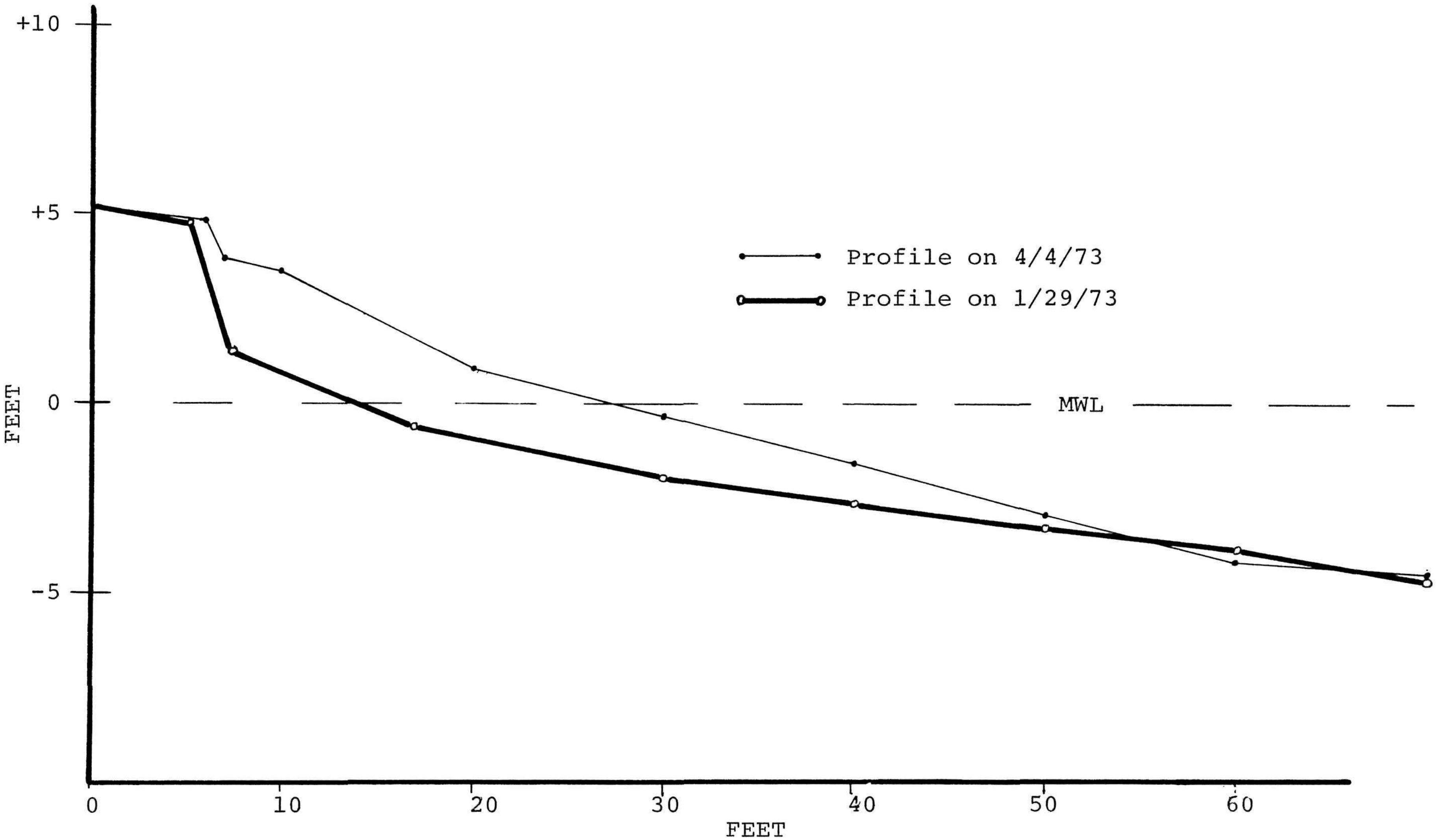


Figure 15. Sediment Envelope at East Side of Cinnamon Bay Warehouse.

In our opinion, further engineering could cause even greater amounts of sediment to move from the inshore zone and/or the subaerial beach to the reefs or past the reefs to deeper, offshore waters. In either case, dramatic changes in the subaerial beaches will occur with, possibly, complete destruction of the already marginal reefs along the north shore. Because of the evidence pointing towards these probable results, it is our recommendation that no structures be used for beach-management purposes on north-shore beaches within the Virgin Islands National Park.

RECOMMENDATIONS

The only shoreline erosion problems within the Virgin Islands National Park that might require "management" are those at Cinnamon Bay West where local archeological sites, the Danish warehouse, and a large Kapok tree (Fig. 16) are in the immediate vicinity of the active shore zone.

If the National Park Service decides that these features are critical to the interpretive programs, then some form of erosion control will eventually be required. On the other hand, if these features are considered temporary and expendable, the erosion problem is, of course, solved.

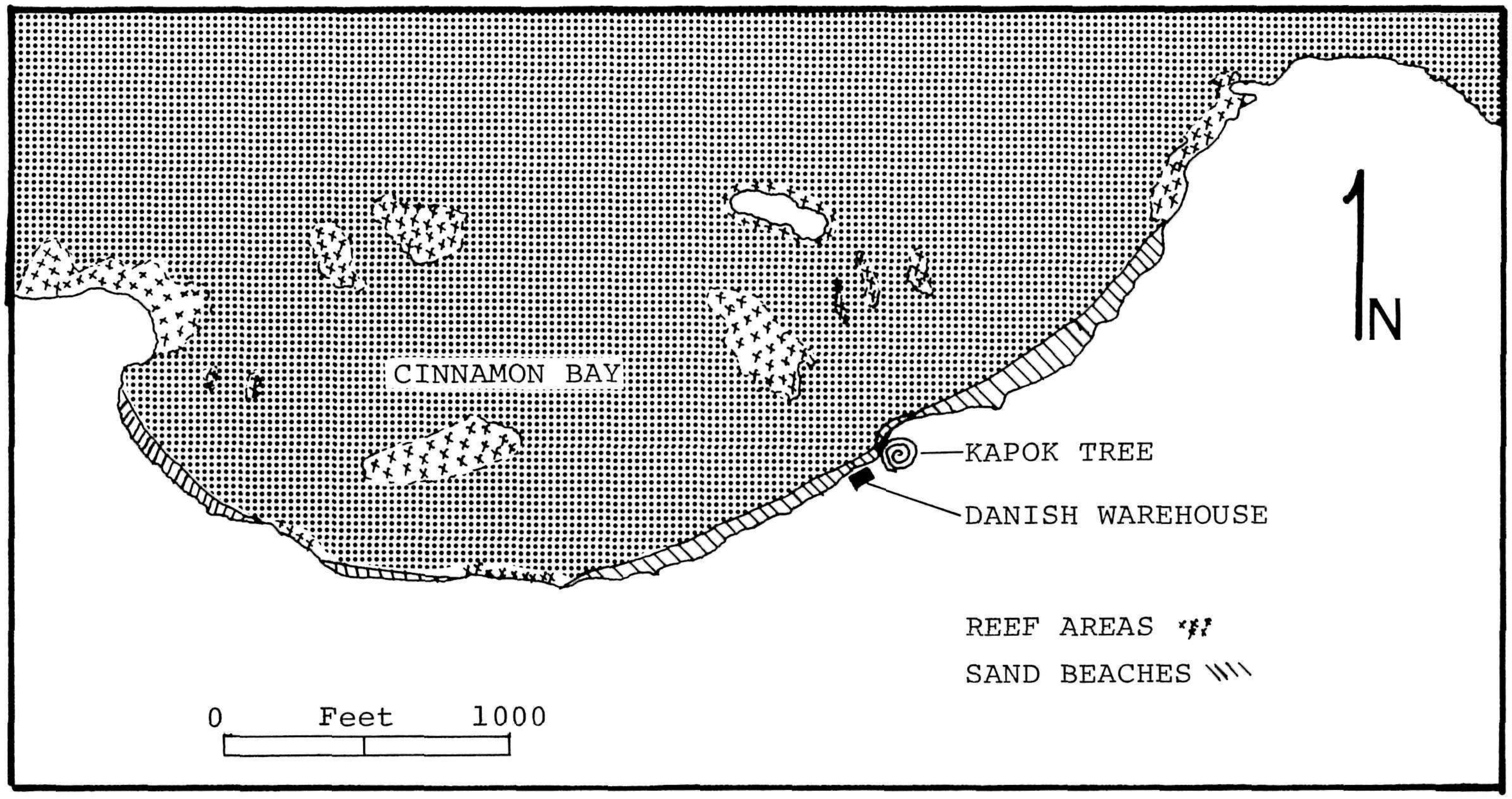


Figure 16. Location of Danish Warehouse and Kapok Tree at Cinnamon Bay. Warehouse, Tree, and Beaches are Not to Scale.

We are convinced that the best management strategy is to recognize that beaches are ephemeral features of the landscape and that any structure resting within the range of this system's intermediate and/or long-term fluctuations should not be considered a permanent addition to the landscape. This is particularly sound management strategy within the Virgin Islands when the possible consequences of shoreline engineering are considered. Therefore, it is our recommendation that the National Park Service:

1. Relocate or demolish the Danish warehouse at Cinnamon Bay in the near future.

2. Remove the rocks that now serve as a temporary revetment, since this structure is not only unsightly and a visitor safety hazard but also contributes to accelerated erosion via wave reflection.

3. Assume a policy that <u>all</u> natural features, as well as archeological sites, located in the vicinity of the active shore zone, including such individual plant specimens as the Cinnamon Bay Kapok tree, are temporary elements of the landscape and, therefore, expendable.

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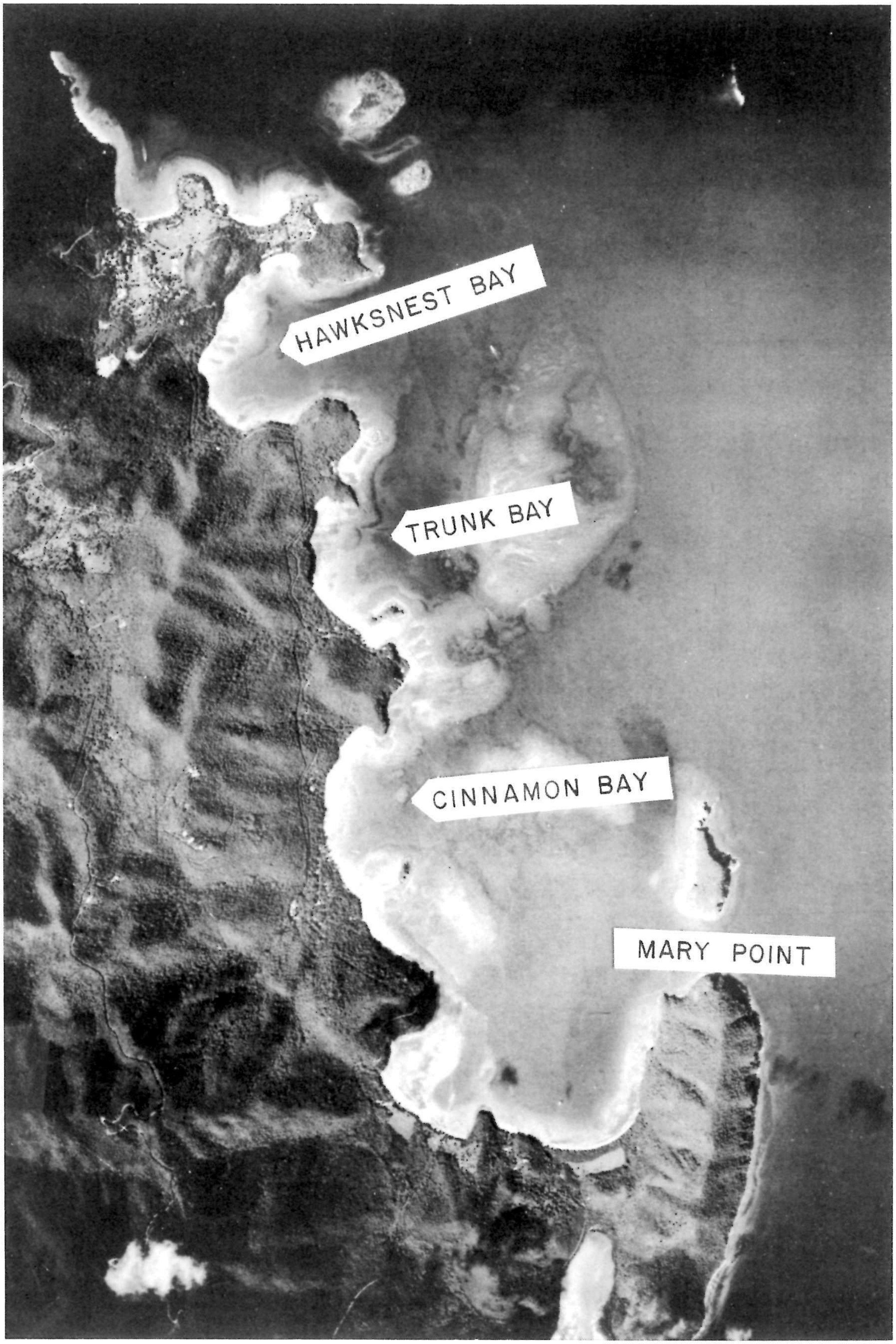
HAWKSNEST BAY
TRUNK BAY
CINNAMON BAY
MARY POINT