VIRGIN ISLANDS RESOURCE MANAGEMENT COOPERATIVE

BIOSPHERE RESERVE
RESEARCH REPORT NO.21

SEDIMENTATION AND REEF DEVELOPMENT IN HAWKSNEST, FISH AND REEF BAYS, ST. JOHN, U.S. VIRGIN ISLANDS

Dennis K. Hubbard,
James D. Stump and Brian Carter
West Indies Laboratory
Fairleigh Dickinson University
St. Croix, U.S. Virgin Islands

U.S. MAN AND THE BIOSPHERE PROGRAM

Virgin Islands National Park

August, 1987

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DENNIS K. HUBBARD
JAMES D. STUMP
BRIAN CARTER
WEST INDIES LABORATORY
FAIRLEIGH DICKINSON UNIVERSITY
ST. CROIX, U.S. VIRGIN ISLANDS

U.S. DEPARTMENT OF THE INTERIOR
NATIONAL PARK SERVICE

AND

VIRGIN ISLANDS RESOURCE MANAGEMENT COOPERATIVE
VIRGIN ISLANDS NATIONAL PARK
P.O. BOX 7789, ST. THOMAS
U.S. VIRGIN ISLANDS 00801

LOCAL CONTRACTING AGENT
ISLAND RESOURCES FOUNDATION
RED HOOK BOX 33, ST. THOMAS
U.S. VIRGIN ISLANDS 00802
(NPS CONTRACT NO. CX-0001-3-0048)

ABSTRACT

In recent years, the potential impacts of sedimentation on reef development have been increasingly recognized. With ever-increasing development stress being placed on the upland areas of St. John, both the National Park and local residents have become concerned with the impacts of development on natural resources, and specifically on nearshore reefs. This study was conducted as a first attempt to evaluate the responses of nearshore reefs in three bays over the past two hundred years. Specifically, the impacts of land use on nearshore sedimentation levels were of special interest.

A theoretical study of runoff under natural conditions intimated that the present distribution of reefs around the island are primarily controlled by watershed size, bay geometry and exposure, with recent development exerting a secondary impact. It was established, however, that more frequent (10-25 yr) storms play a very important role in controlling the distribution of reefs around the island. Therefore, it is not necessary to invoke the catastrophic event (e.g. 100-yr storms) to explain the occurrence of modern reefs. From this, it can be argued that development can have significant impact under less than heavy runoff conditions.

Studies of the present distributions of sediment types and reefs in Hawksnest, Fish and Reef Bays point to controls identical to those identified by the more generalized study. Of critical importance in reef development was distance from sources of terrigenous runoff (the guts) and degree of exposure. On a local level, these both outweighed development at its present level. Over the long term, there appears to be a gradual decline in the reefs over the entire period of record, based on X-rayed cores through large coral heads. This may be related to a long-term compromise of the soil retaining capabilities of the upland watersheds following intensive cane farming in the 1700's and 1800's. With the exception of short-term degradation of the nearshore reefs in Hawksnest Bay, however, reef degradation could not be directly linked to any specific development activity.

Based on the findings of this study, specific management strategies are proposed. These include limiting development in main water courses, and establishing reasonable buffers to runoff related to upland construction. Recommendations for future research objectives are also offered.

ACKNOWLEDGEMENTS

This project was supported by the Virgin Islands Resource Management Cooperative and the National Park Service. The authors wish to further acknowledge the valuable assistance of Dr. Caroline S. Rogers and Ms. Vonnie Small (National Park Service) in carrying out the field aspects of the study. Mr. Michael Davis and Ms. Ellen Prager also assisted in the collection of field data. Thanks are also due to James Beets, Allen Putney, Vonnie Small, and George Tyson for helpful criticisms and input throughout the preparation of the manuscript. And finally, we wish to acknowledge all the members of VIRMC and the West Indies Lab staff for input and encouragement throughout the study.

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INTRODUCTION

The history of St. John (Fig. 1) is rich and varied. Since its settlement by Europeans in 1718, it has been the site of many kinds of development stress. From 1718 to 1850, the island was cultivated for agriculture, the primary crop being sugar cane. During this time period, cattle grazing was also important in certain areas. Through much of the late 1800's and early 1900's this environmental pressure was largely removed after the demise of the local cane industry in the late 1850's. In Reef Bay, cane production continued until the early 1900's, but at a greatly diminished capacity.

With the gift of land to the National Park Service in 1956, Laurance Rockefeller placed much of the island under federal control with the hope of preserving at least part of the natural beauty of the island. The remaining areas, however, are coming increasingly under new, and potentially more severe pressures. Developers, both large and small, have discovered the marketing potential of a tropical area wiht a National Park in its back yard. The influx of people has resulted in both direct development in the terms of new homes, condominiums, etc., and indirect development as an outgrowth of the developing infrastructure necessary to support population growth. And finally, the impact of the Park facility cannot be ignored. While the control exerted by the Park Service over parts of the island minimize the human impact, creating a facility for the public to appreciate those natural environments necessarily takes its toll.

Because the Park must operate within the overall community of St. John, it has raised justifiable concerns about minimizing the impact of Park operations, and development in adjacent areas, on the integrity of the Park itself. Likewise, St. John residents are concerned over the impact of the Park in the areas within and adjacent to its jurisdiction. Coincident with this concern is the existence of the Virgin Island Biosphere Reserve, which includes the entire Park area.

The purpose of this project was to assess the longer-term impacts of historical development in the area. To address the problem, three separate, but related studies were conducted. In the first, a theoretical approach was used to model runoff within individual watersheds on St. John. The purpose of this exercise was twofold. First, it was intended to establish the primary controls of reef occurrence on St. John. Secondly, it tested the usefulness of the technique as an interpretive tool.

The remaining studies were conducted on three bays that are different both in terms of natural environment, and presumed levels of development stress. Because of their different locations and histories, as well as varying degrees of control exerted by the Park Service, each bay presents a unique set of environmental and management problems. One study described the present character of the bays, and related that to the parameters identified above. The other measured changes in the bays over the past 100-200 years.

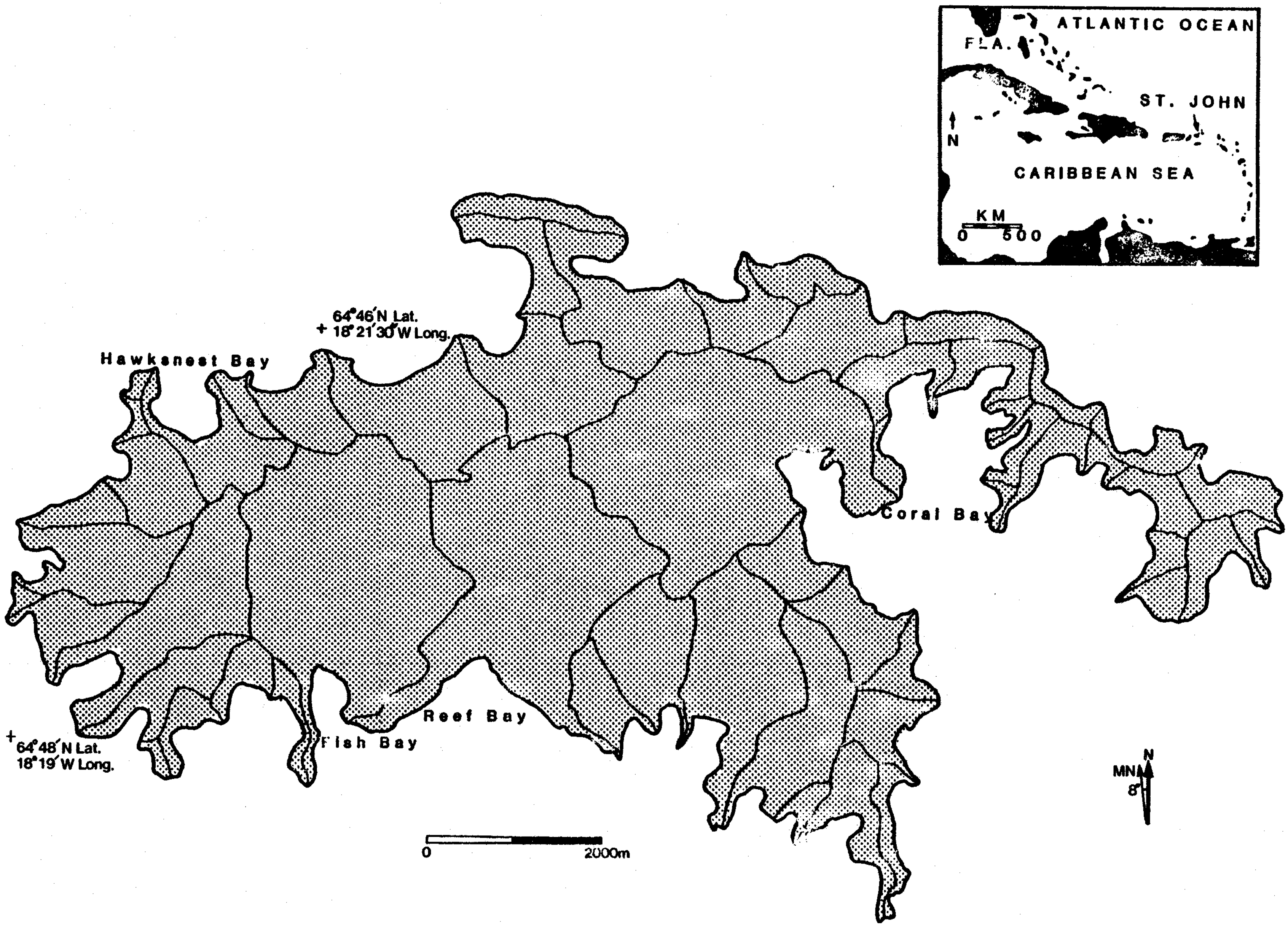


Figure 1. Map showing location of St. John and bays discussed in text.

Because of the relatively steep nearshore slope around St. John, reefs are confined to narrow strips close to shore. Because of their positions, these fringing reefs are very susceptible to environmental stresses related to upland areas. All three bays receive runoff from large watersheds (Hawksnest = 233 acres; Fish = 1448 acres; Reef = 1391 acres). During storms, rainwater flows through well-defined "guts" that empty into the bays so as to form a point source of upland sediment. The locations of these guts exert a profound effect on the distribution of reefs and live organisms within the bays.

The present condition of the reefs is the result of many complex factors in combination with one another. It is not always obvious which control is primary and which are secondary in nature. With respect to watershed management, the obvious point of interest is the degree to which changes in runoff will affect these factors. Therefore, it is important to be able to first, separate the effects of natural runoff from other controls of reefs development. Secondly we need to address what changes in the watersheds might impact those reefs, either positively or negatively.

In bays wholly within the Park boundaries, a posture of total protection of the watersheds might be appropriate. Within areas where at least part of the watershed is outside the control of the Park, and development is likely to occur, it is important to establish at what level those changes become a negative factor in the development of the reefs. Of critical importance here is understanding what levels of stress might result in degradation of the marine resource. Because our understanding of the organism-level responses of reefs to sediment stress is in its infancy, this study concentrates on documenting two things: 1) present environmental conditions within individual bays relative to coral distribution; and 2) changes in those reefs through historical time, which might reflect changes in environmental conditions over the period of record.

This investigation is only a very small first step in understanding sedimentary controls on reefs on St. John or in tropical areas in general. In addition to the more obvious limitations of cost, reef researchers will remain at a severe disadvantage until quantitative information is finally available about the metabolic responses of reef organisms to various types and levels of stress. Nevertheless, our nearshore environments are coming under severe and increasing stress in the meantime. This study is an attempt to address some very basic questions, albeit in a simplistic fashion, until those data eventually become available.

This report is divided into four sections. The first is a generalized discussion of the watersheds on St. John based on the theoretical calculations mentioned above. The second describes the three bays within which this study was concentrated. The primary focus is on reef character, sediment distribution, and the relationship between the two. The third section deals with changes in the environment over the recent past. Sediment cores were taken to examine changes in the amount of terrestrial material introduced into the bay over time. Cores through large coral heads record changes in the responses of reef organisms to those and other stresses. A final section briefly discusses elements of the study that are relevant to management strategies within the Park/Biosphere Reserve and surrounding environs. A discussion of future research stategies is also offered.

Throughout this report, metric units are generally used. One exception is the section on Watershed Analyses. Because all the nomograms, graphs and tables available are in English units, use of metric units within the text would create confusion between values cited in the text and those in the tables. Therefore, English units are used in this section, and conversion factors for all units used in the watershed studies are included as Appendix I.

The conclusions of this study must draw heavily on those of other companion VIRMC projects. Data on historic changes on St. John are derived from the work of George Tyson, a local historian. Generalized information on the location and character of reefs in bays not examined in this study is drawn from Beets, et al. (1985). It is hoped that by using this approach, we will be able to integrate information from many disciplines, and provide a reasonable picture of natural and man-induced controls on the reefs within the three bays. While an attempt is made to provide information that might be useful in watershed management within the Biosphere Reserve in general, great care must be taken in applying these recommendations beyond the three watersheds from which they were developed.

WATERSHED ANALYSES

The reef system surrounding St. John is an important ecological asset as well as an energy buffer zone which helps reduce beach erosion. With increased human development on St. John, this resource has come under increasing pressure. In this section, general patterns of runoff from St. John watersheds are discussed. The principal goal of this exercise was to evaluate whether the present pattern of reef development around St. John can be explained by variations in natural sedimentation, or whether obvious development impacts play the primary role.

At the outset it was recognized that sedimentation patterns around St. John are far too complex in their origin to be categorized with one model. Nevertheless, it was felt that some attempt to relate potential physical controls to reef development would be useful. The major problem in this approach is in separating all the different kinds of modern development activities into groups that would have equal impact on the reefs. In addition, it is impossible to accurately describe the levels of those activities over the time period during which the present-day reefs have developed.

Given an inability to accurately and objectively characterize development impact, an approach was chosen that eliminated those stresses from consideration. In our calculations, a condition of complete forestation (presumably the case prior to colonization) was chosen. It was felt that if the present-day pattern of reefs was responding on a large scale to recent development activities, then the reef distribution emerging from this exercise would vary noticeably from those occurring in nature today (i.e. in areas of development, reefs would be more poorly represented than under the forested conditions of the model).

Such an approach has obvious limitations. With the present data base, we can only reliably relate the hypothetical runoff patterns to the presence or absence of reefs in any given area. Valuable information exists in aerial photos and a recent report by Beets, et al. (1985). Information from these sources was used to extend the reef classes to "Absent, Scarce, Present or Abundant", but these are only qualitative terms, and this must be kept in mind throughout the discussion that follows. If we are to extend the usefulness of our exercise beyond general descriptive terms, data will eventually be needed that specifically quantify reef development in areas that are identified by this model as naturally stressed, or where man-induced stresses in recent times can be quantified.

Methods

Estimates of the peak rate of discharge and the average runoff volume for storms of various magnitudes were made, based on methodology outlined in the Engineering Field Manual for Conservation Purposes (Kautz, 1975). Variables used in the calculations included: 1) watershed area (in acres), 2) rainfall (in inches over a 24-hour period), 3) average watershed slope (in percent), 4) watershed vegetative cover, 5) the hydrologic soil group (e.g.

clayey soils with low infiltration and high runoff rates), 6) the antecedent moisture condition of the soil (from the previous 5-day accumulated rainfall) and 7) the conservation practices within the watershed (e.g. contouring and terracing of the land).

The relative importance of one factor over another, and the specific means used to measure them (e.g. using average vs. maximum slope below), can be argued for specific cases in individual watersheds. It should be recognized at the outset, however, that these methods represent a time-tested standard, and that redesigning this engineering methodology is well beyond the scope of this exercise. Furthermore, the purpose of this study was to evaluate whether the present distribution of reefs around St. John can be generally explained by runoff patterns under natural conditions. It was not to evaluate either specific impacts of development within individual bays or to establish critical levels of rainfall at which runoff will impact specific reefs. While these are important pieces of information, it is unreasonable to attempt these without substantial field data from each watershed and a much better knowledge of the specific sedimentation levels that given organisms can tolerate.

Watershed area was measured from the most recent USGS topographic map of the island. Watershed boundaries were delineated, and watershed acreages were measured using a Houston Instruments HiPad Digitizer and an Apple IIe computer. Watershed areas on the map were measured in square inches, and converted to acres using the topographic map scale (1:24000).

Rainfall data for St. John were acquired from U.S. Weather Bureau Atlases for 2-year, 5-year, 10-year, 25-year and 50-year frequency storms. 24-hour rainfall values for these storms on St. John were 3.9, 5.5, 6.6, 8.0 and 9.2 inches respectively. 100-year storms were not modeled, as relationships between runoff patterns and reef development had already emerged at lower levels of storm intensity. Given the accuracy of the runoff predictions, it was felt that the variability at the 100-year level would be too subtle to be discriminated by the technique.

Watershed slope was calculated using an average from at least two profiles within the watershed. Total relief was measured along each profile, and divided by the distance along that profile. Slope was expressed in percent.

Soil conditions (vegetative cover, hydrologic soil group, antecedent moisture condition of the soil, and conservation practices - Tables 1-4) were used to determine a runoff curve number (CN) for each watershed. This value is necessary to choose from a family of nomograms provided to determine discharge estimates. For a more detailed discussion of curve number, the reader is referred to Kautz (1975). All soils on St. John were considered to be in hydrologic soil Group D (Table 4), those soils with a high runoff potential (i.e. due to flashiness of rain, thin sediment cover and clay-rich soils, infiltration is generally low).

Table 1. Runoff curve numbers for agricultural areas. Higher curve numbers indicate less infiltration and increased runoff. From Kautz (1975).

Description	Hydrologic Condition	Hydrologic Soil Group A	B	C	D
Fallow					
Straight row	----	77	86	91	94
Row Crops					
Straight row	Poor	72	81	88	91
Straight row	Good	67	78	85	89
Contoured	Poor	70	79	84	88
Contoured	Good	65	75	82	86
Contoured & terraced	Poor	66	74	80	82
Contoured & terraced	Good	62	71	78	81
Small Grain					
Straight row	Poor	65	76	84	88
Straight row	Good	63	75	83	87
Contoured	Poor	63	74	82	85
Contoured	Good	61	73	81	84
Contoured & terraced	Poor	61	72	79	82
Contoured & terraced	Good	59	70	78	81
Sugar Cane					
Straight row	Trash burned	43	65	77	82
Straight row	Mulched	45	66	77	83
Contour	----	32	58	72	79
Straight row	Poor	49	69	79	84
Coffee					
No ground cover	----	48	68	79	83
Terrace & ground cover	----	22	52	68	75
No terraces	Good	25	55	70	77
Close-seeded Legumes or Rotation Meadow					
Straight row	Poor	66	77	85	89
Straight row	Good	58	72	81	85
Contoured	Poor	64	75	83	85
Contoured	Good	55	69	78	83
Contoured & terraced	Poor	63	73	80	83
Contoured & terraced	Good	51	67	76	80
Pasture or Range					
No mechanical treatment	Poor	68	79	86	89
No mechanical treatment	Fair	49	69	79	84
No mechanical treatment	Good	39	61	74	80
Contoured	Poor	47	67	81	88
Contoured	Fair	25	59	75	83
Contoured	Good	6	35	70	79
Meadow	Good	30	58	71	78
Woods	Poor	45	66	77	83
	Fair	36	60	73	79
	Good	25	55	70	77
Farmsteads	----	59	74	82	86
Roads, Including Rights-of-way					
Dirt	----	72	82	87	89
Hard surface	----	74	84	90	92

Table 2. Runoff curve numbers for urban areas with development completed and vegetation established.

Description	Hydrologic Soil Group A	B	C	D
Lawns, Parks, Golf Courses, Cemeteries, etc.	39	61	74	80
Pavement and Roofs - Commercial and Business Areas	98	98	98	98
Row Houses, Town Houses, and Residential with Lot Sizes 1/8 Acre or Less	80	85	90	95
Residential				
Lot sizes of 1/4 acre	61	75	83	87
Lot sizes of 1/2 acre	53	70	80	85
Lot sizes of 1 acre	60	68	79	84
Lot sizes of 2 acres	47	66	77	81

Table 3. Runoff curve numbers for urban areas with development underway and no vegetation established.

Description	Hydrologic Soil Group A	B	C	D
Newly Graded Area	81	89	93	95
Pavement and Roofs - Commercial and Business Areas	98	98	98	98
Row Houses, Town Houses, and Residential with Lot Sizes 1/8 Acre or Less	93	96	97	98
Residential				
Lot sizes of 1/4 acre	88	93	95	97
Lot sizes of 1/2 acre	85	91	94	96
Lot sizes of 1 acre	82	90	93	95
Lot sizes of 2 acres	81	89	92	94

Table 4. Hydrologic soil groups, based on infiltration and transmission rates.

Over 8,000 soils have been classified into four hydrologic soil groups as shown in Exhibit 2-1. The hydrologic soil groups, according to their infiltration and transmission rates, are:

A. (Low runoff potential). Soils having high infiltration rates even when thoroughly wetted. These consist chiefly of deep, well to excessively drained sands or gravels. These soils have a high rate of water transmission in that water readily passes through them.

B. Soils having moderate infiltration rates when thoroughly wetted. These consist chiefly of moderately deep to deep, moderately well to well-drained soils with moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission.

C. Soils having slow infiltration rates when thoroughly wetted. These consist chiefly of soils with a layer that impedes downward movement of water or soils with moderately fine to fine texture. These soils have a slow rate of water transmission.

D. (High runoff potential). Soils having very slow infiltration rates when thoroughly wetted. These consist chiefly of clay soils with a high swelling potential, soils with a permanent high water table, soils with a claypan or clay layer at or near the surface, and shallow soils over nearly impervious material. These soils have a very slow rate of water transmission.

Conservation practices - The procedure does allow for adjustments in the runoff calculations based on such things as terracing, paving, etc. As discussed above, however, because it would be difficult to 1) characterize general conservation practices by watershed, and 2) almost impossible to track these practices through historical time, a forested condition was chosen. In this sense, the model approximates "natural" conditions.

Peak discharge rates were derived for each watershed area using nomograms such as those shown in Figures 2 and 3. Rainfall (in inches per 24-hour period), drainage area (in acres), and the runoff curve number for the watershed areas are the variables used in these figures. Curve numbers for wooded areas in soil group D varied between 77 and 83 (Table 1). To model worst possible conditions (i.e. very flashy runoff), hydrologic condition was set at poor, and a curve number of 85 was chosen for all bays.

After a value was determined for peak discharge on the appropriate nomogram, that value was multiplied by the slope factor derived from Table 5. Average runoff volume (in cubic inches) was determined by multiplying runoff depth (Table 6) by the watershed area. Within each major watershed, sub-watersheds with separate drainage streams were defined. This exercise was undertaken to determine whether there were shoreline segments across which a relatively large percentage of an individual watershed was emptied of rainfall and sediment. The calculations described above were repeated for the sub-watersheds. The percentage of the watershed which drained into the bay along a designated length of shoreline was determined. This percentage was multiplied by the average volume of runoff from the entire watershed to determine runoff from the sub-watershed. This number, in cubic feet per second, was divided by the length of shoreline that drained each portion of the watershed.

There is a small degree of error in using this simplified approach, whereby each sub-watershed slope is derived from the previously calculated average slope for the entire watershed. The degree of error is not large enough to warrant the recalculation of the slope for each sub-watershed, however. Values recomputed for Fish, Reef and Hawksnest Bay sub-watersheds using the slope of each sub-area varied only 9% from those based on average slope of the entire watershed.

A ratio of watershed area to bay area was calculated to investigate whether there was a relationship between the presence or absence of reefs and this ratio. Bay area was defined by the water surface landward of the projecting headlands on either side. It was generally anticipated that the greater the ratio, the lower the probability of there being extensive coral reefs within the bay. Admittedly, bay volume would be a more sensitive parameter. Problems with this approach, however, include: 1) determining "average" depth for the bays given the poor data base on small-scale bathymetry around St. John, 2) assessing the impact of bay geometry on sediment retention, and 3) determining the effect of bay orientation on the ability of waves to affect flushing. In the absence of any way to objectively quantify these variables, bay area was considered equally appropriate for the general level of comparison in this study.

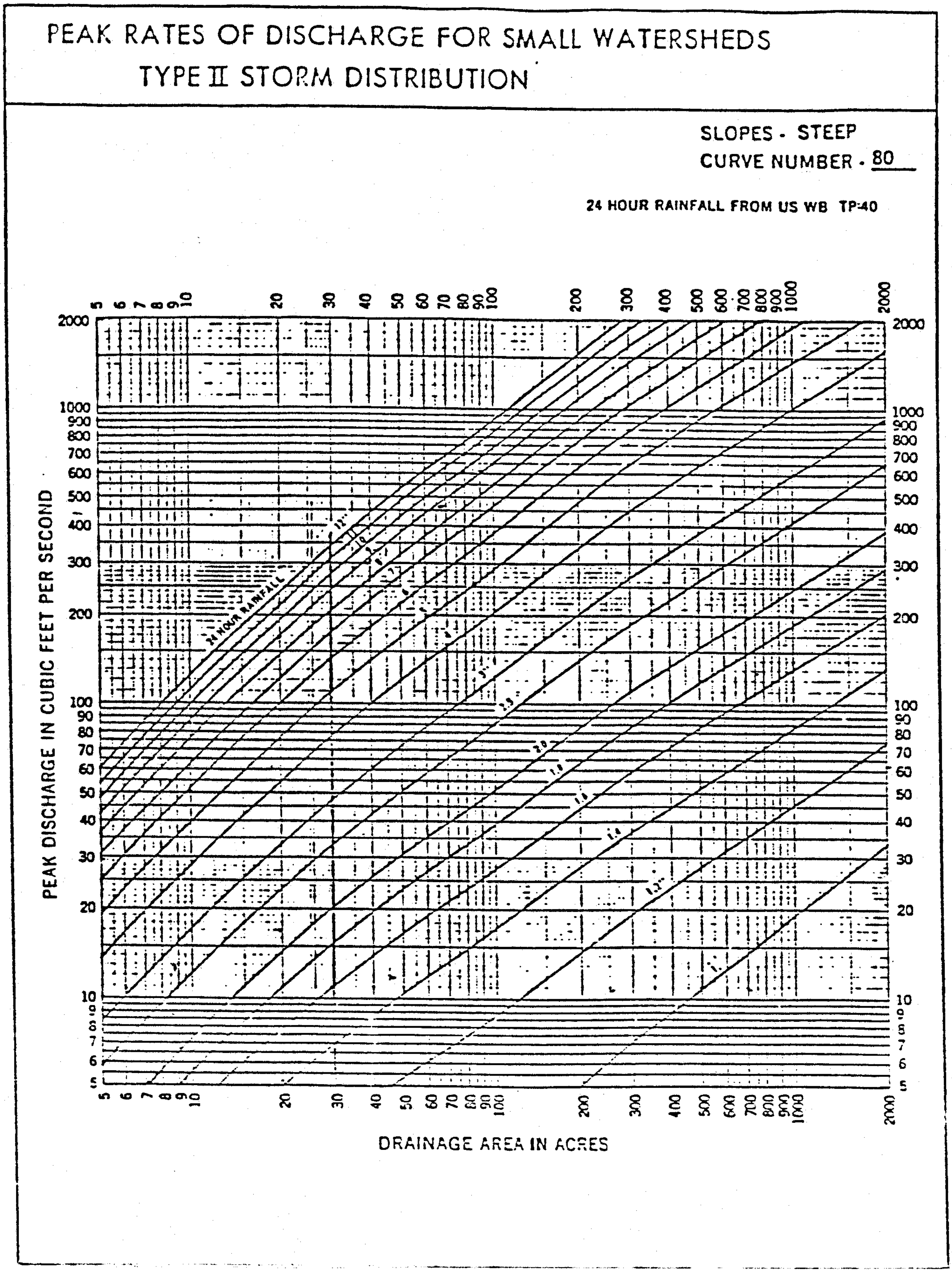


Figure 2. Nomogram used in calculation of peak discharge rates for watersheds with an average CN of 80.

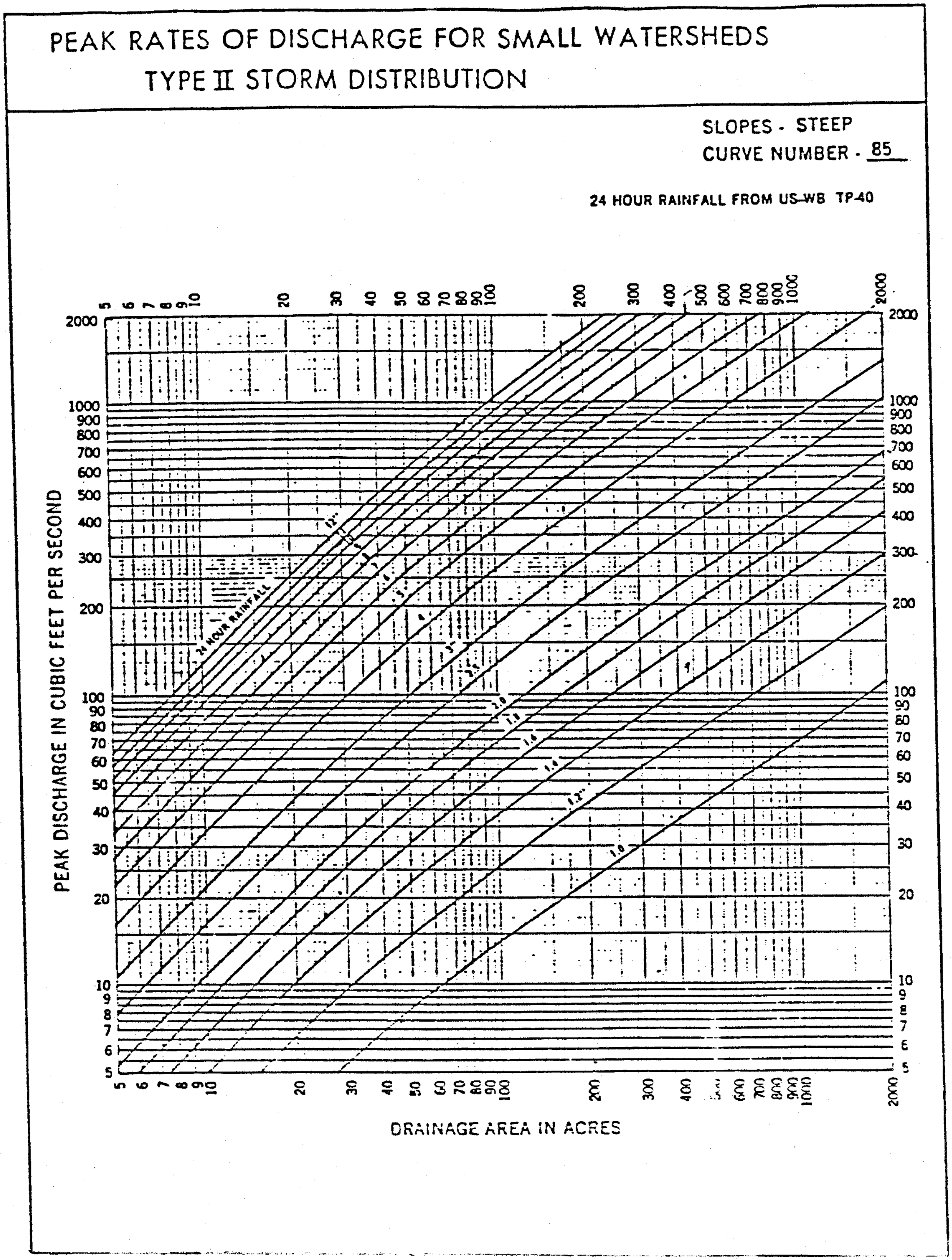


Figure 3. Nomogram used in calculations of peak discharge rates for watersheds with an average CN of 85. This nomogram was used for all calculations.

Table 5. Chart used to determine slope factor.

Flat Slopes - round to nearest % slope shown

(Use discharge values from ES sheets labeled "Flat")

Slope %	Acres 1-50	Acres 51-500	Acres 501-2000
.5	.80	.80	.78
.7	.87	.89	.91
1.0	1.00	1.00	1.00
2.0	1.13	1.16	1.18

Moderate Slopes - round to nearest % slope shown

(Use discharge values from ES sheets labeled "Moderate")

Slope %	Acres 1-50	Acres 51-500	Acres 501-2000
3	.96	.95	.94
4	1.00	1.00	1.00
5	1.04	1.05	1.06
6	1.07	1.10	1.11
7	1.09	1.13	1.15

Steep Slopes - round to nearest % slope shown

(Use discharge values from ES sheets labeled "Steep")

Slope %	Acres 1-50	Acres 51-500	Acres 501-2000
8	.92	.88	.83
9	.93	.90	.85
10	.94	.91	.87
11	.95	.93	.89
12	.96	.94	.91
13	.97	.96	.94
14	.98	.97	.96
15	.99	.99	.98
16	1.00	1.00	1.00
17	1.01	1.02	1.02
18	1.02	1.03	1.04
19	1.03	1.05	1.06
20	1.04	1.08	1.08
25	1.08	1.14	1.17
30	1.11	1.20	1.23
35	1.13	1.24	1.28
40	1.16	1.29	1.33
45	1.18	1.31	1.37
50	1.21	1.34	1.40
55	1.23	1.35	1.43
60	1.26	1.37	1.46
65	1.28	1.39	1.48
70	1.30	1.40	1.50
75	1.32	1.42	1.52

Example:

Given

1. D.A. = 1000 acres
2. Rainfall = 4"
3. C.N. = 80
4. Slope = 41%

Determine

Peak flow

Solution

1. Since the slope is greater than 8%, look up flow on ES 1027 - CN 80 - slope - steep = 1320 cfs
2. From table for steep slopes and under 501-2000 acres drainage area and on line with 40% slope (41 rounded to 40) find factor 1.33
3. Peak flow = 1320 x 1.33 = 1750 cfs

Table 6. Chart used to determine average runoff depth per 24 hours.

Rainfall (inches)	Curve Number (CN)[1]						
	60	65	70	75	80	85	90
1.0	0	0	0	0.03	0.08	0.17	0.32
1.2	0	0	0.03	0.07	0.15	0.28	0.46
1.4	0	0.02	0.06	0.13	0.24	0.39	0.61
1.6	0.01	0.05	0.11	0.20	0.34	0.52	0.76
1.8	0.03	0.09	0.17	0.29	0.44	0.65	0.93
2.0	0.06	0.14	0.24	0.38	0.56	0.80	1.09
2.5	0.17	0.30	0.46	0.65	0.89	1.18	1.53
3.0	0.33	0.51	0.72	0.96	1.25	1.59	1.98
4.0	0.76	1.03	1.33	1.67	2.04	2.46	2.92
5.0	1.30	1.65	2.04	2.45	2.89	3.37	3.88
6.0	1.92	2.35	2.80	3.28	3.78	4.31	4.85
7.0	2.60	3.10	3.62	4.15	4.69	5.26	5.82
8.0	3.33	3.90	4.47	5.04	5.62	6.22	6.81
9.0	4.10	4.72	5.34	5.95	6.57	7.19	7.79
10.0	4.90	5.57	6.23	6.88	7.52	8.16	8.78
11.0	5.72	6.44	7.13	7.82	8.48	9.14	9.77
12.0	6.56	7.32	8.05	8.76	9.45	10.12	10.76

1 To obtain runoff depths for CN's and other rainfall amounts not shown in this table, use an arithmetic interpolation.

Data on reef development were derived from recent aerial photographs, in conjunction with information from Beets, et al. (1985). Defining the degree of reef development was necessarily subjective. Reefs were categorized as Absent, Scarce, Present or Abundant.

Results

Watershed areas for St. John are shown in Figure 4. Table 7 summarizes the data on watershed character. Generally, the larger watersheds are located on the south shore of St. John (e.g. Fish Bay and Reef Bay). Peak discharges for 2, 5, 10, 25 and 50-year frequency storms are shown in Figures 5-9. Average runoff volumes of the St. John watersheds are shown in Figures 10-14.

As storm intensity increases, peak discharge and average rates of runoff volume also increase dramatically up to a certain point. Peak-discharge and runoff-volume rates do not increase as rapidly between 10 and 25-year or 25 and 50-year events as is the case between 2 and 10-year storms (Figs. 15-18). Likewise, there is a much greater change in runoff intensity per foot of shoreline between the 2 and 10-year frequency storms than between 10 and 50-year events (Figs. 19-21).

The shape of these curves (Figs. 15-18) is related primarily to the patterns of rainfall change between these storms. The rainfall increase between the 2 and 10-year frequency storm is from 3.9 to 6.6 inches per 24-hour period, an increase of 69%. The rainfall increase between the 10 and 50-year frequency storm is from 6.6 to 9.2 inches per 24-hour period, an increase of only 39%. This pattern is important, as the spatial variations in runoff that appear to control modern reef distribution can be largely established under higher-frequency conditions. While more severe storms (i.e. 100-year) can have substantial impact on individual reef areas, the general reef distribution around St.John appears more related to events with a periodicity of 10-25 years.

The three most critical factors for reef development around St. John appear to be: 1) runoff concentration, 2) exposure to wave energy and 3) the type and extent of development within individual watersheds.

Runoff - Two points are repeated at this time. First, vegetative cover was assumed to be uniform forest. This approach was taken to assess whether the present reef community could be explained by natural conditions or, conversely, whether development impact might be implied by anomalies in the data. Secondly, the runoff values and reef characterizations reported here are considered as only relative. It would be very difficult to accurately characterize variability in soil conditions and other factors that might impact runoff. Therefore, it is not realistic to take these runoff values as anything more than estimates of likely conditions. Nevertheless, the general relationships between runoff and reef distribution that emerge are still useful.

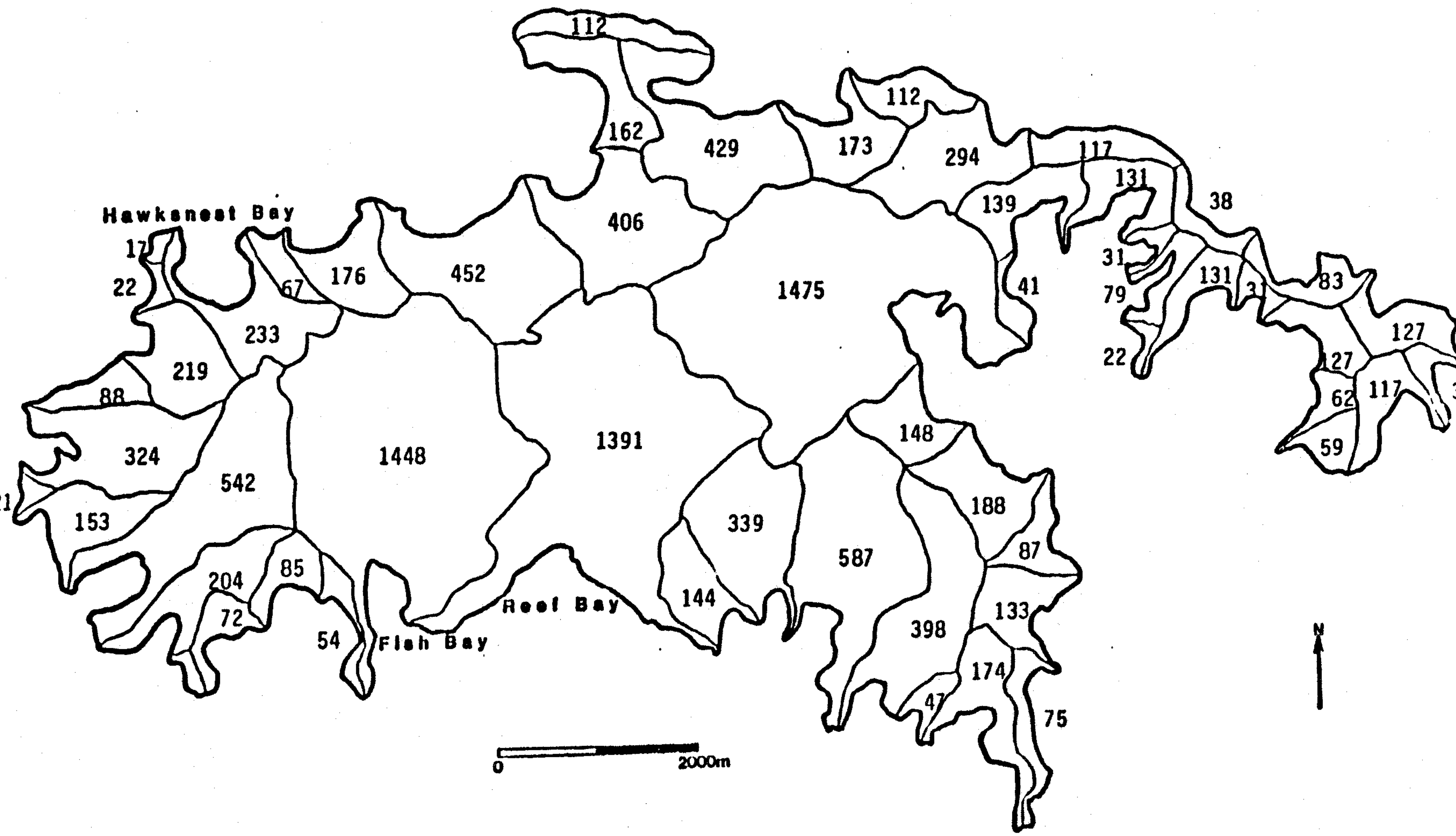


Figure 4. Map of St. John showing watershed areas in acres.

Table 7. Data used in calculation of runoff for St. John watersheds.

Bay	Watershed Area	Average Slope
Borck Creek	139 acres	28%
Brown Bay	294	15
Caneel Bay	219	27
Chocolate Hole	204	25
Cinnamon Bay	452	34
Coral Harbor	1475	18
Cruz Bay	224	16
Denis Bay	67	21
Devers Bay	19	35
Drunk Bay	75	40
Durloe Channel SE	22	11
East End Bay	28	39
Elk Bay	100	26
Europa Bay	144	27
Fish Bay	1448	18
Francis Bay	162	34
Frank Bay	21	16
Friis Bay	87	29
Great Cruz Bay	542	14
Great Lameshur Bay	587	20
Grootpan Bay	298	40
Hansen Bay	127	36
Hart Bay	72	35
Haulover North	83	28
Haulover South	31	24
Hawksnest Bay	233	37
Johns Folly Bay	133	27
Johnson Bay	188	38
Kiddel Bay	47	8
Klein Bay	54	34
Little Lameshur Bay	339	22
Long Bay	62	37
Maho Bay	406	33
Mary Creek	429	23
Mary Point North	112	46
Mennebeck Bay	38	37
Monte Bay	85	47
More Hill North	117	38
Newfound Bay	127	37
Otter Creek	31	29
Pond Bay	59	36
Popilleau Bay	41	35
Princess Bay	131	34
Privateer Bay	117	33
Reef Bay	1391	19
Saltpond Bay	174	17
Sanders Bay	148	44

Table 7 (continued).

Bay	Watershed Area	Average Slope
Solomon Bay	88	38
Threadneedle Point	112	39
Trunk Bay	176	32
Turner Bay	153	24
Turner Point West	22	38
Turtle Bay	17	26
Water Creek	79	28
Watermelon Bay	173	33

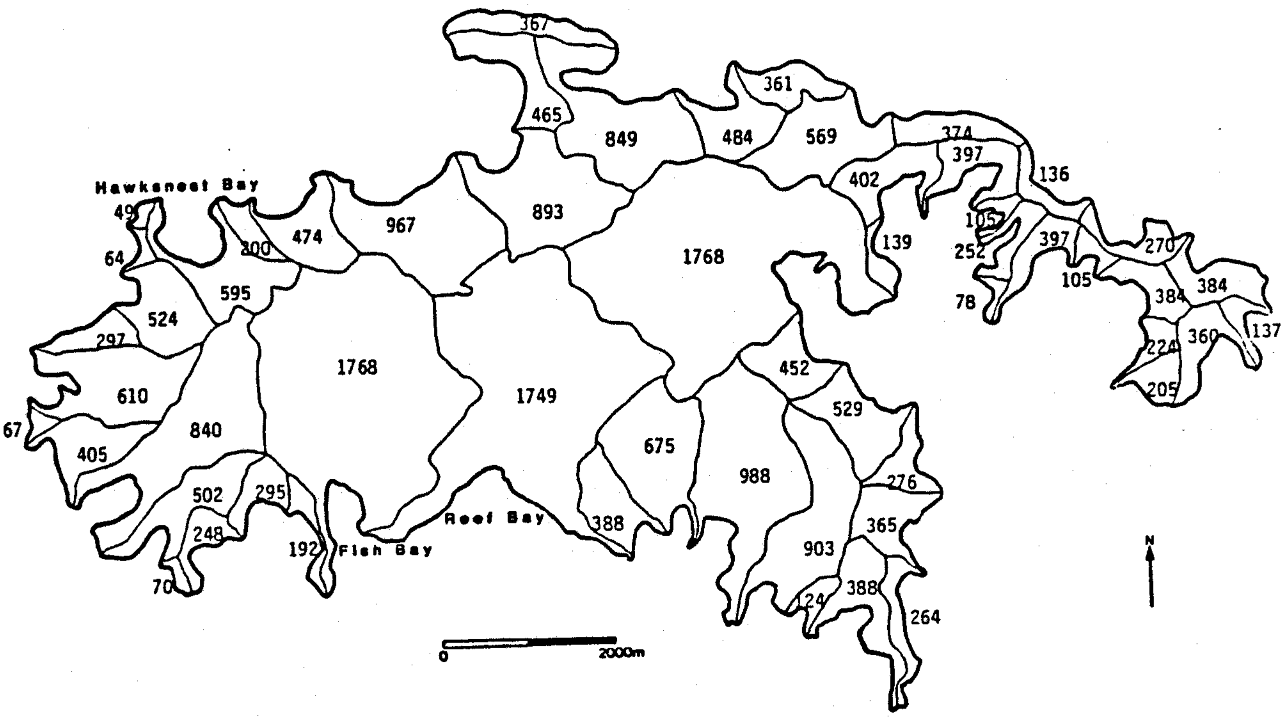


Figure 5. Peak discharge rates expressed in cfs for St. John watersheds during a 2-yr frequency storm (3.9"/24 hrs.).

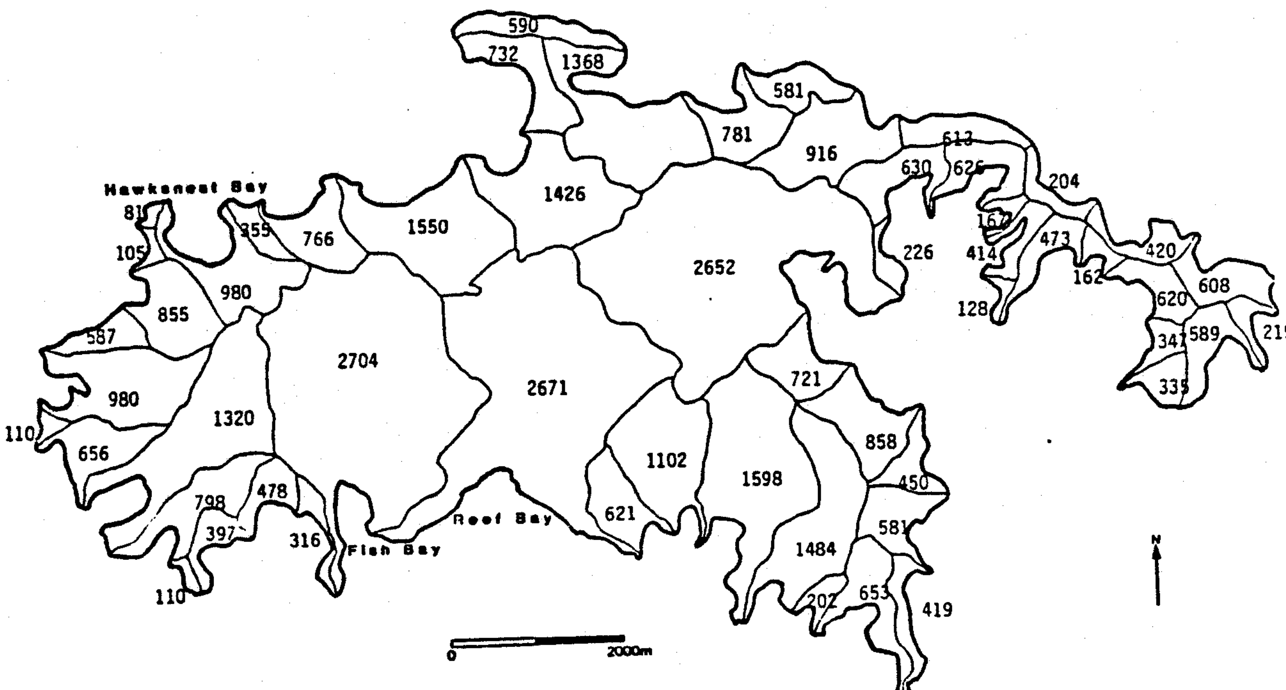


Figure 6. Peak discharge rates expressed in cfs for St. John watersheds during a 5-yr frequency storm (5.5"/24 hrs.).

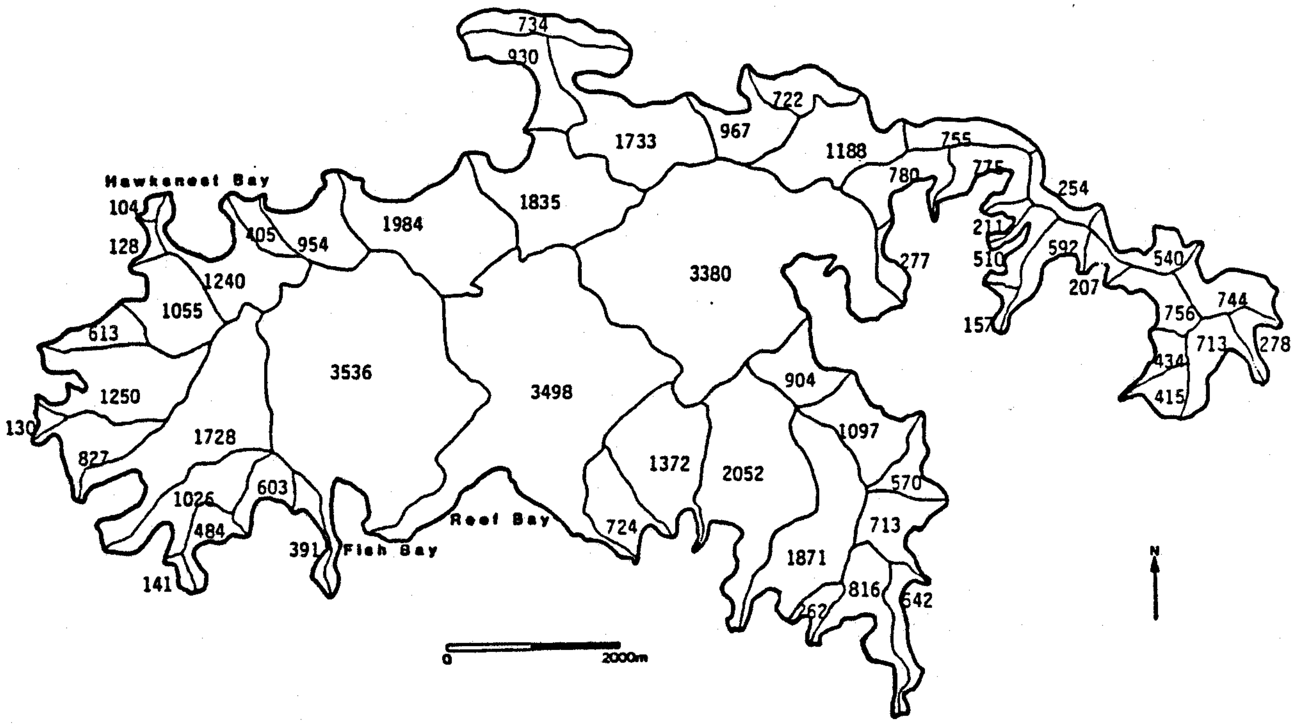


Figure 7. Peak discharge rates expressed in cfs for St. John watersheds during a 10-yr frequency storm (6.6"/24 hrs.).

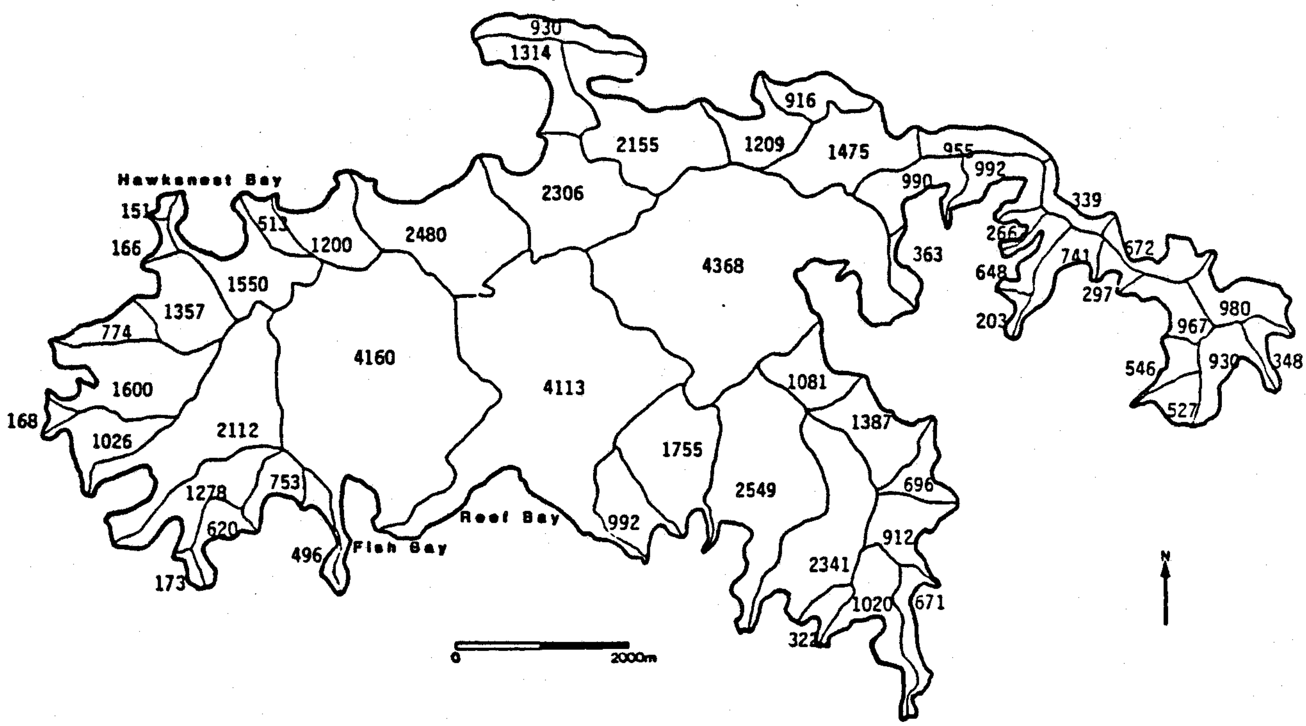


Figure 8. Peak discharge rates expressed in cfs for St. John watersheds during a 25-yr frequency storm (8.0"/24 hrs.).

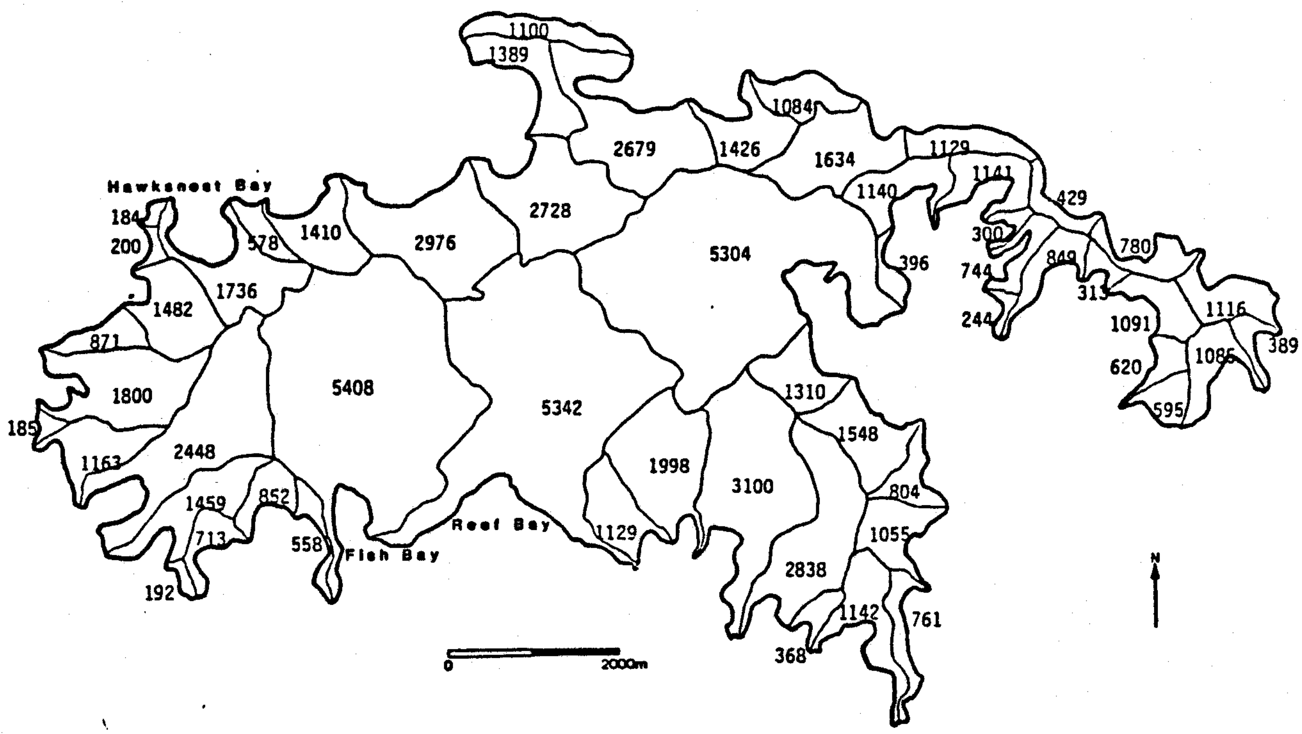


Figure 9. Peak discharge rates expressed in cfs for St. John watersheds during a 50-yr frequency storm (9.2"/24 hrs.).

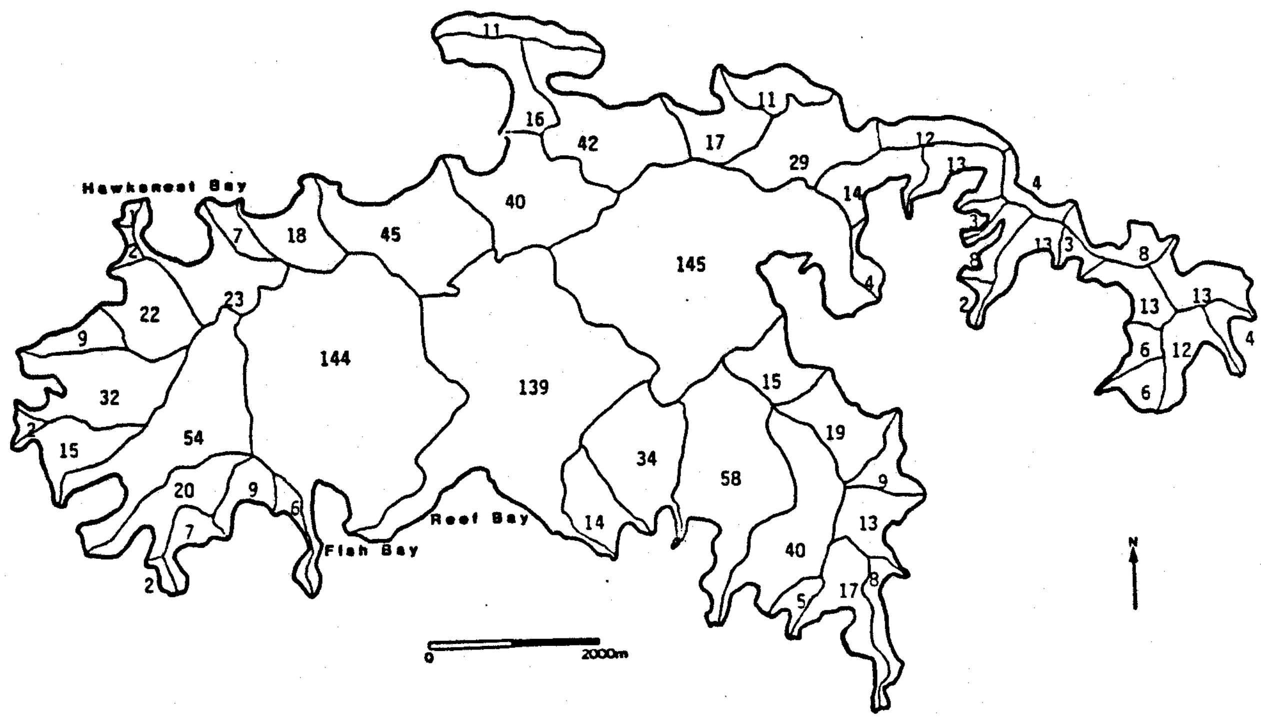


Figure 10. Average runoff volumes expressed in cfs for St. John watersheds during a 2-yr frequency storm (3.9"/24 hrs.).

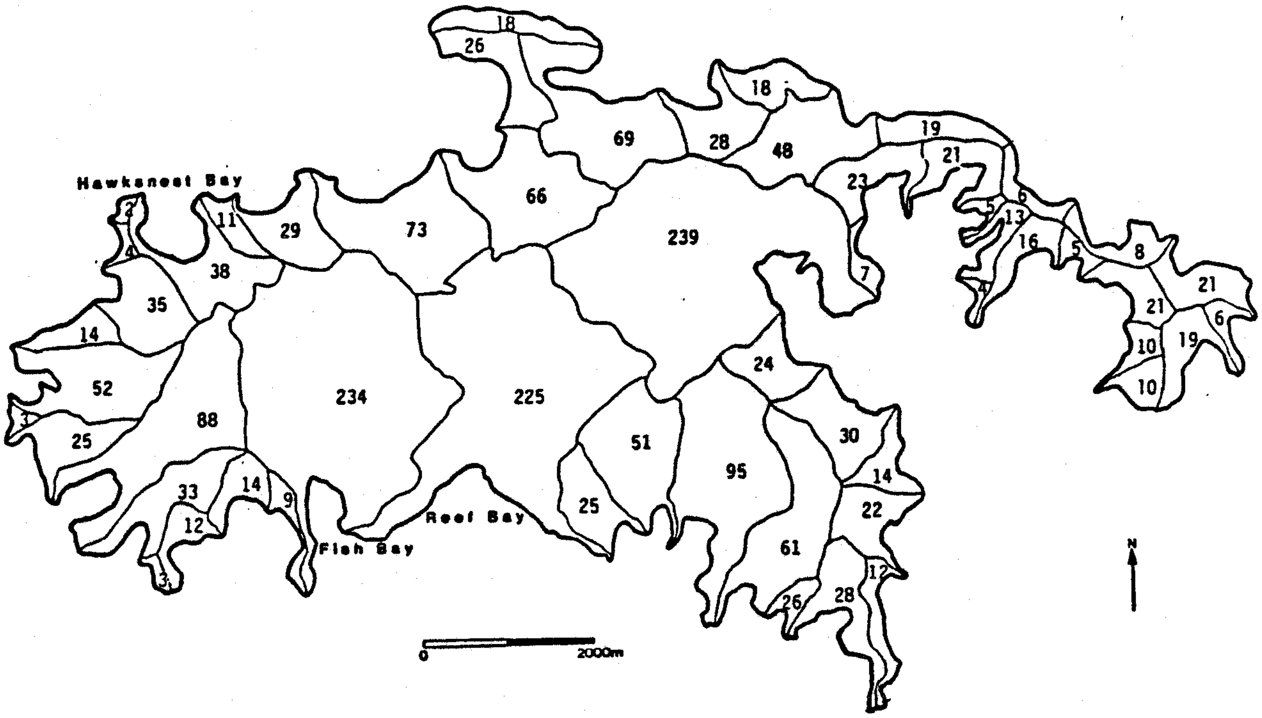


Figure 11. Average runoff volumes expressed in cfs for St. John watersheds during a 5-yr frequency storm (5.5"/24 hrs.).

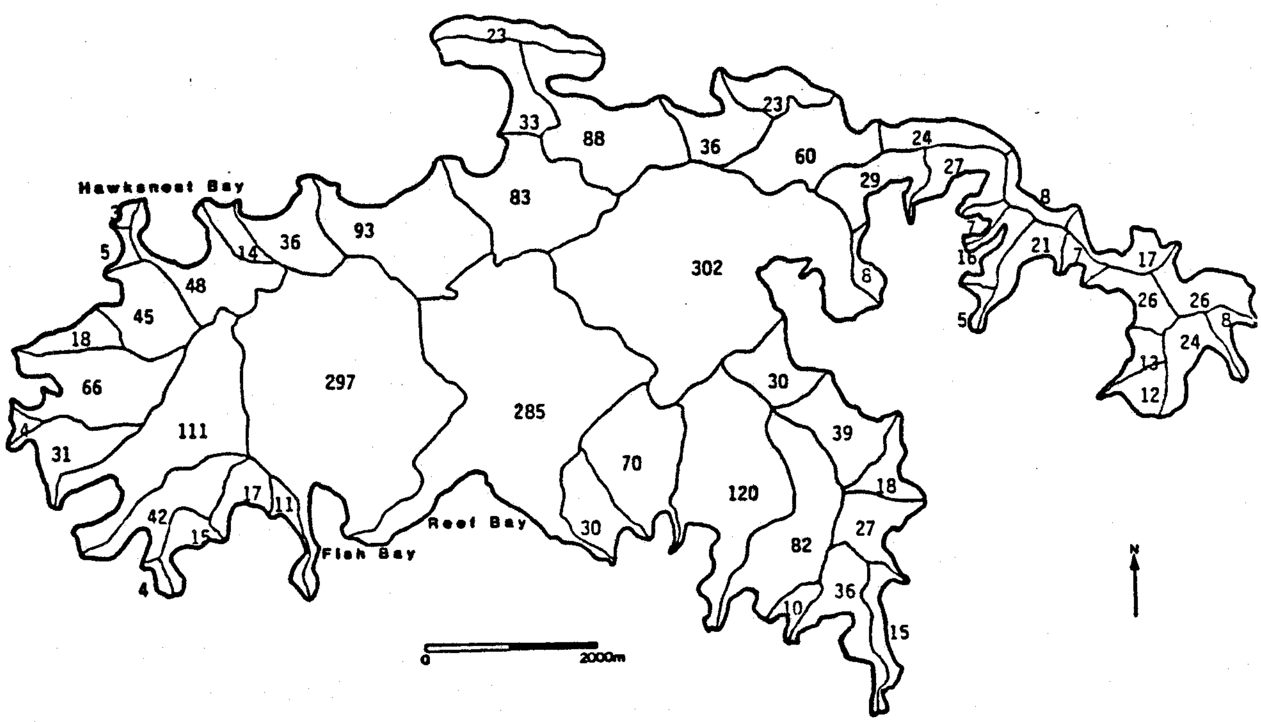


Figure 12. Average runoff volumes expressed in cfs for St. John watersheds during a 10-yr frequency storm (6.6"/24 hrs.).

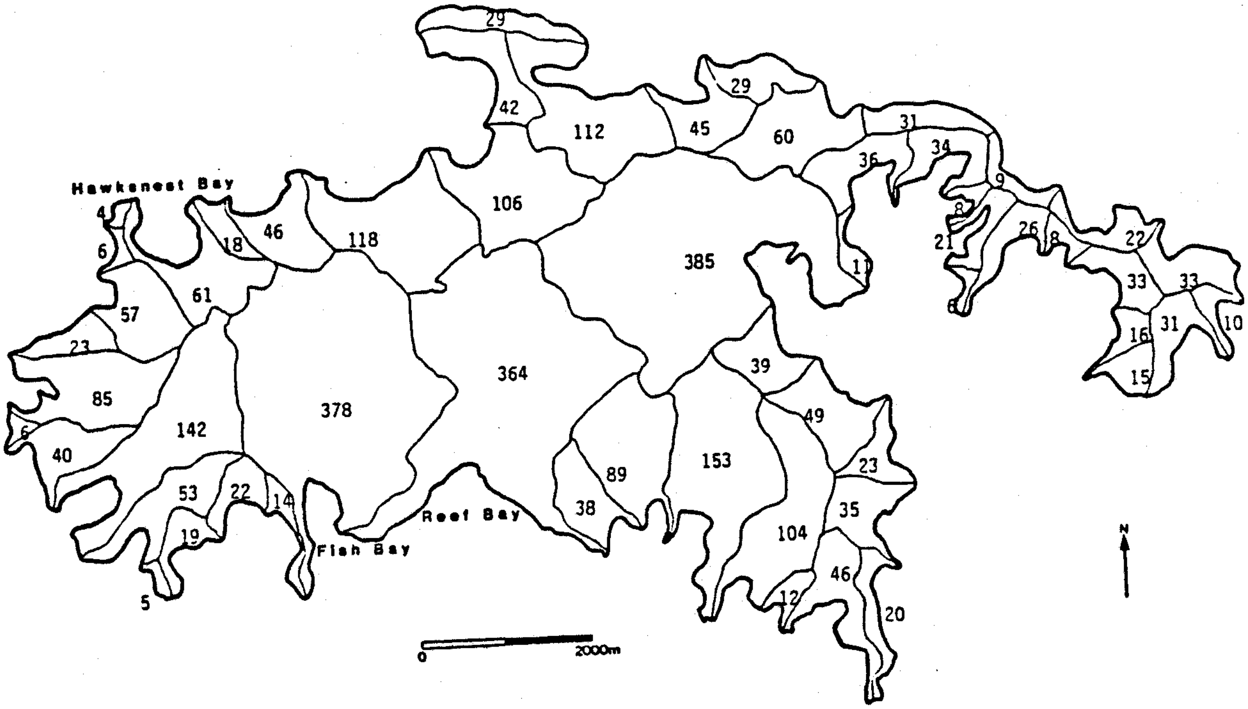


Figure 13. Average runoff volumes expressed in cfs for St.John watersheds during a 25-yr frequency storm (8.0"/24 hrs.).

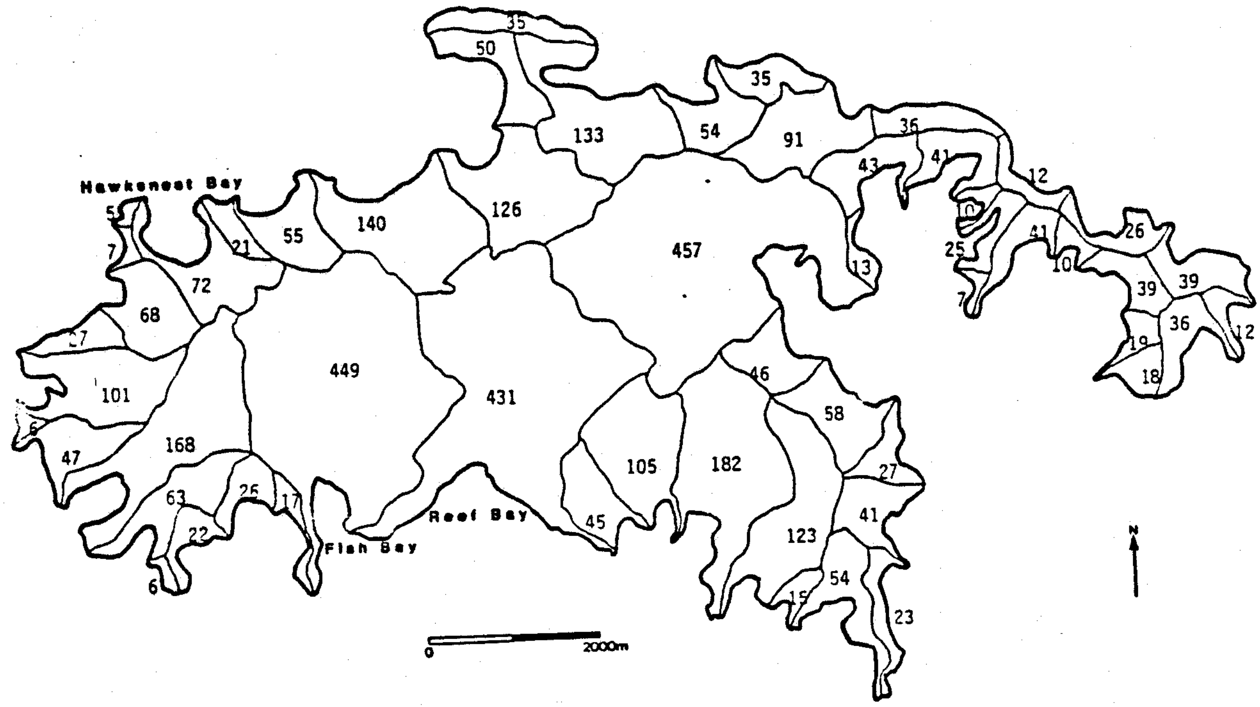


Figure 14. Average runoff volumes expressed in cfs for St. John watersheds during a 50-yr frequency storm (9.2"/24 hrs.).

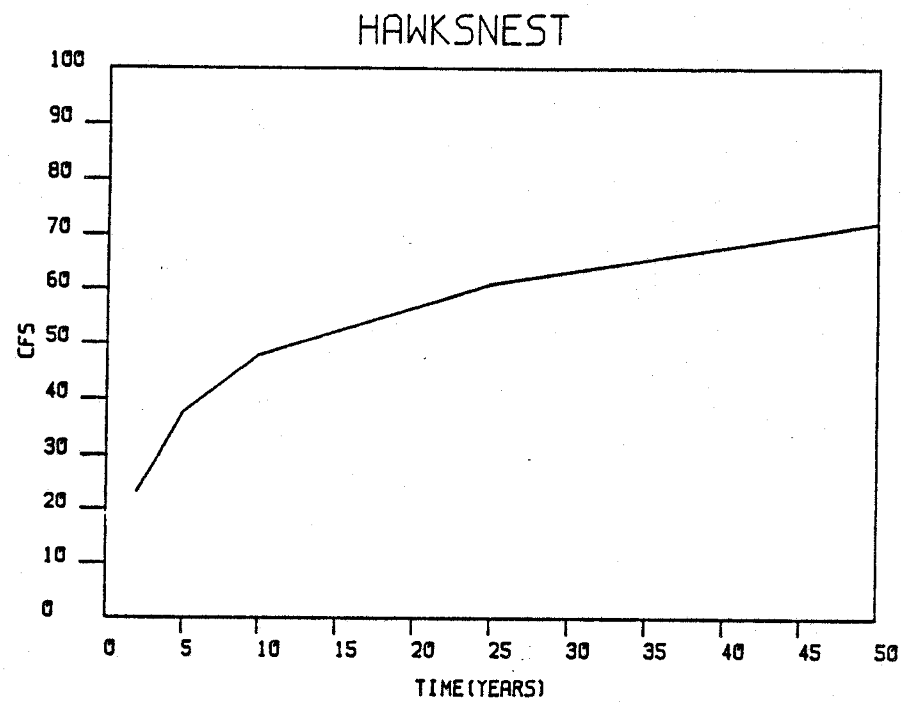


Figure 15. Average runoff volume expressed in cfs for Hawksnest Bay for different intensity storms. Note the consistent decrease in the slope of the curve with increasing storm intensity.

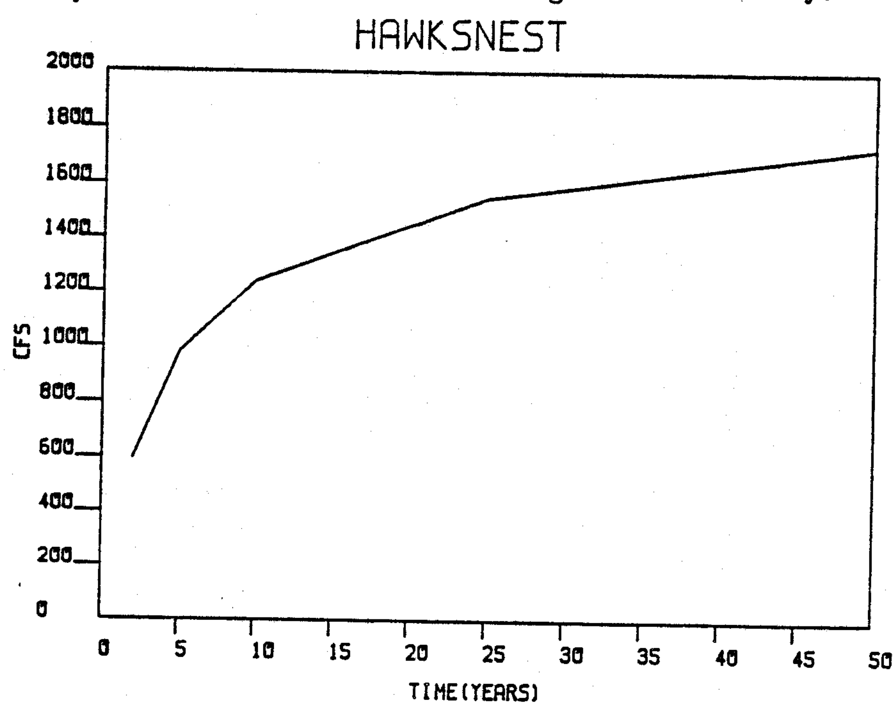


Figure 16. Peak discharge rate expressed in cfs for Hawksnest Bay for different intensity storms. Note the consistent decrease in the slope of the curve with increasing storm intensity.

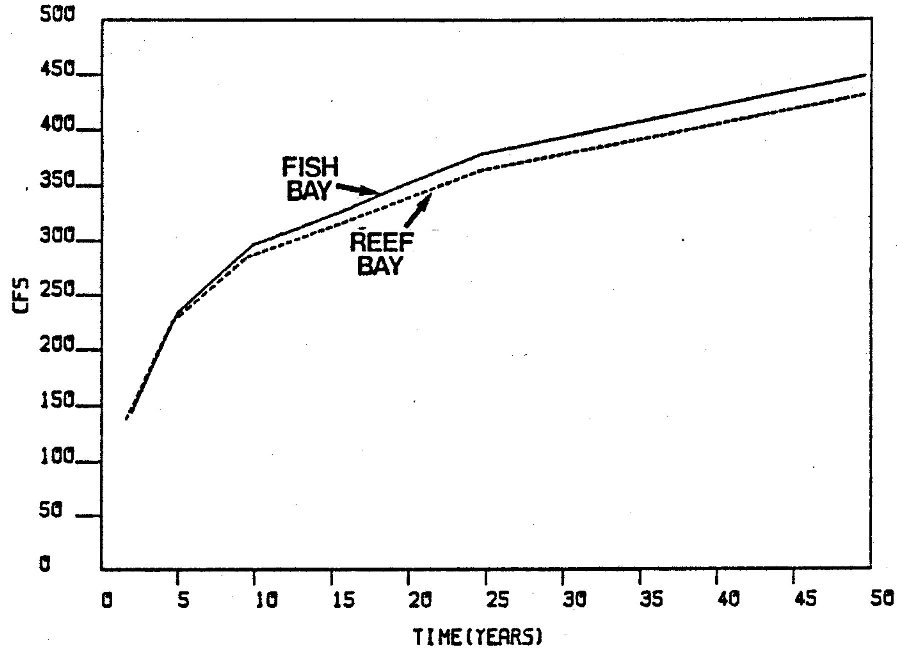


Figure 17. Average runoff volumes expressed in cfs for Fish and Reef Bays for different intensity storms. Note the consistent decrease in the slope of the curve with increasing storm intensity.

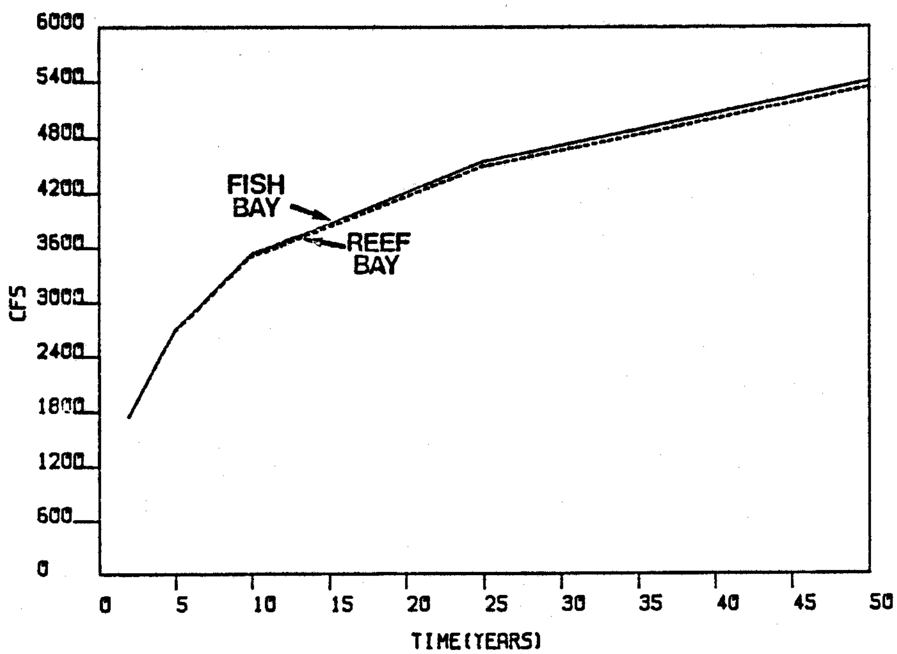


Figure 18. Peak discharge rates expressed in cfs for Fish and Reef Bays for different intensity storms. Note the consistent decrease in the slope of the curve with increasing storm intensity.

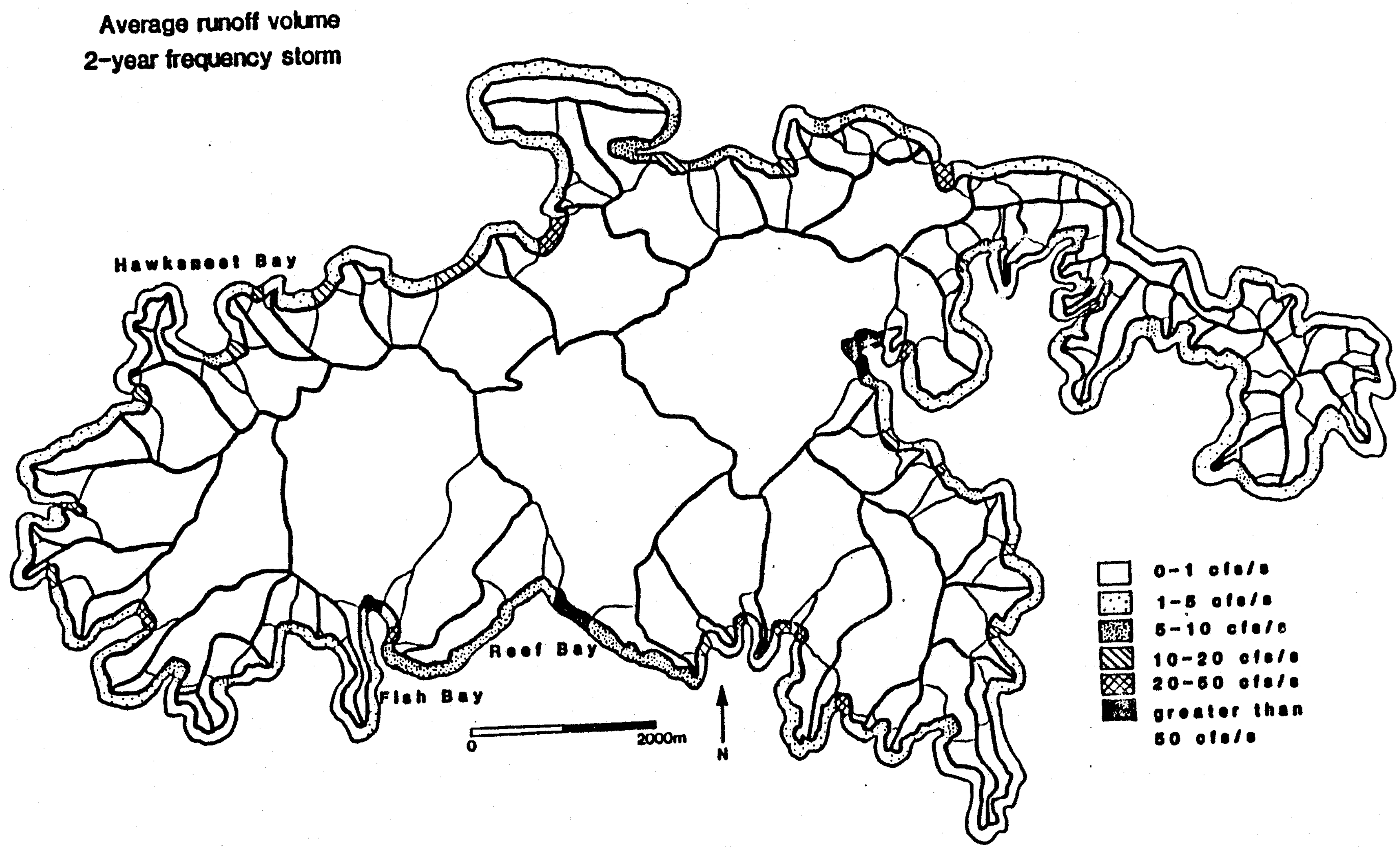


Figure 19. Map of St. John showing average runoff volume for shoreline segments for a 2-yr frequency storm. Dark symbols indicate high runoff values.

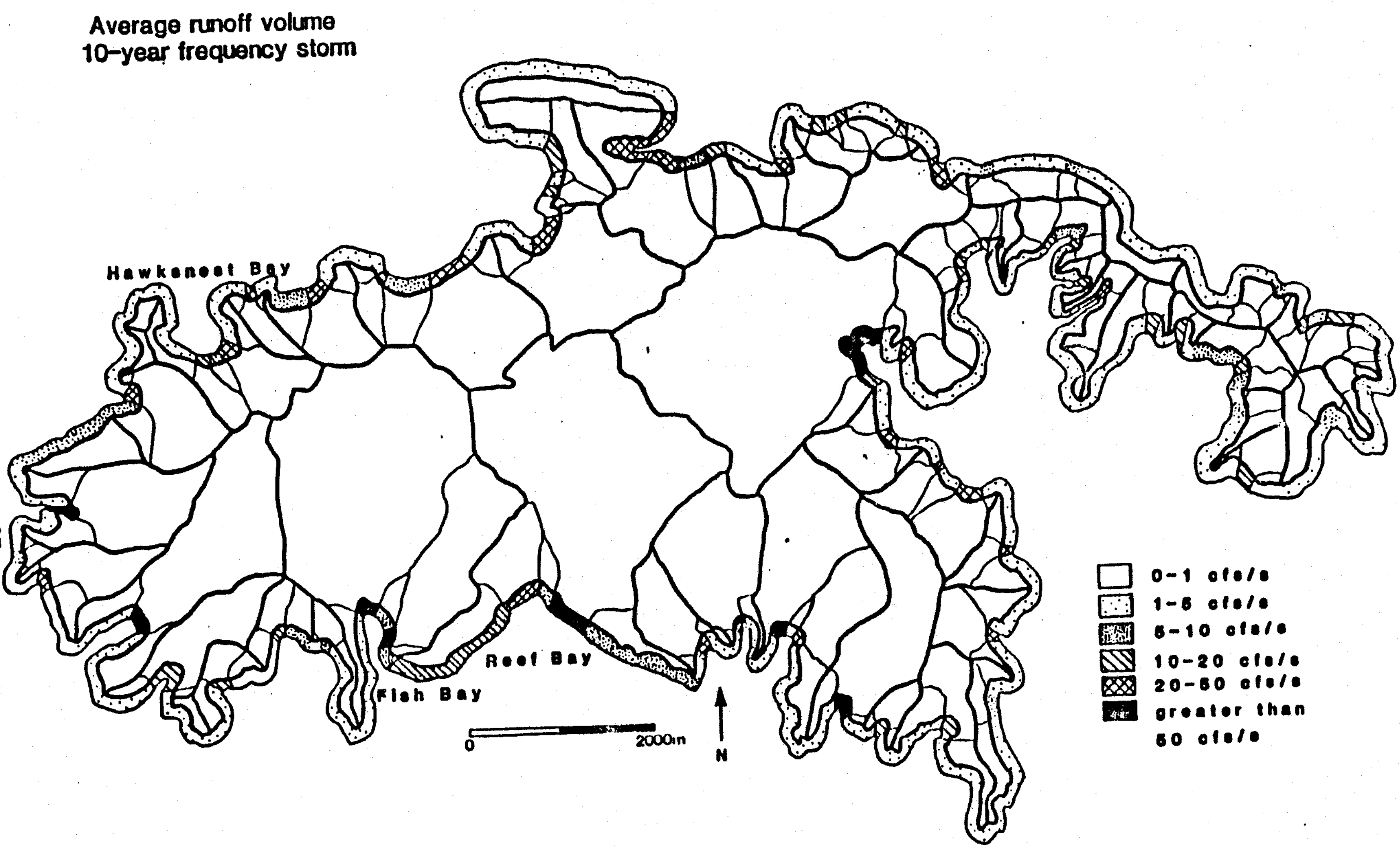


Figure 20. Map of St. John showing average runoff volume for shoreline segments for a 10-yr frequency storm. Dark symbols indicate high runoff values. The pattern of high-intensity runoff is significantly different than that shown for the 2-yr storm (Fig. 19), but is similar to that of more severe storms (e.g. 50-yr storm: Fig. 21).

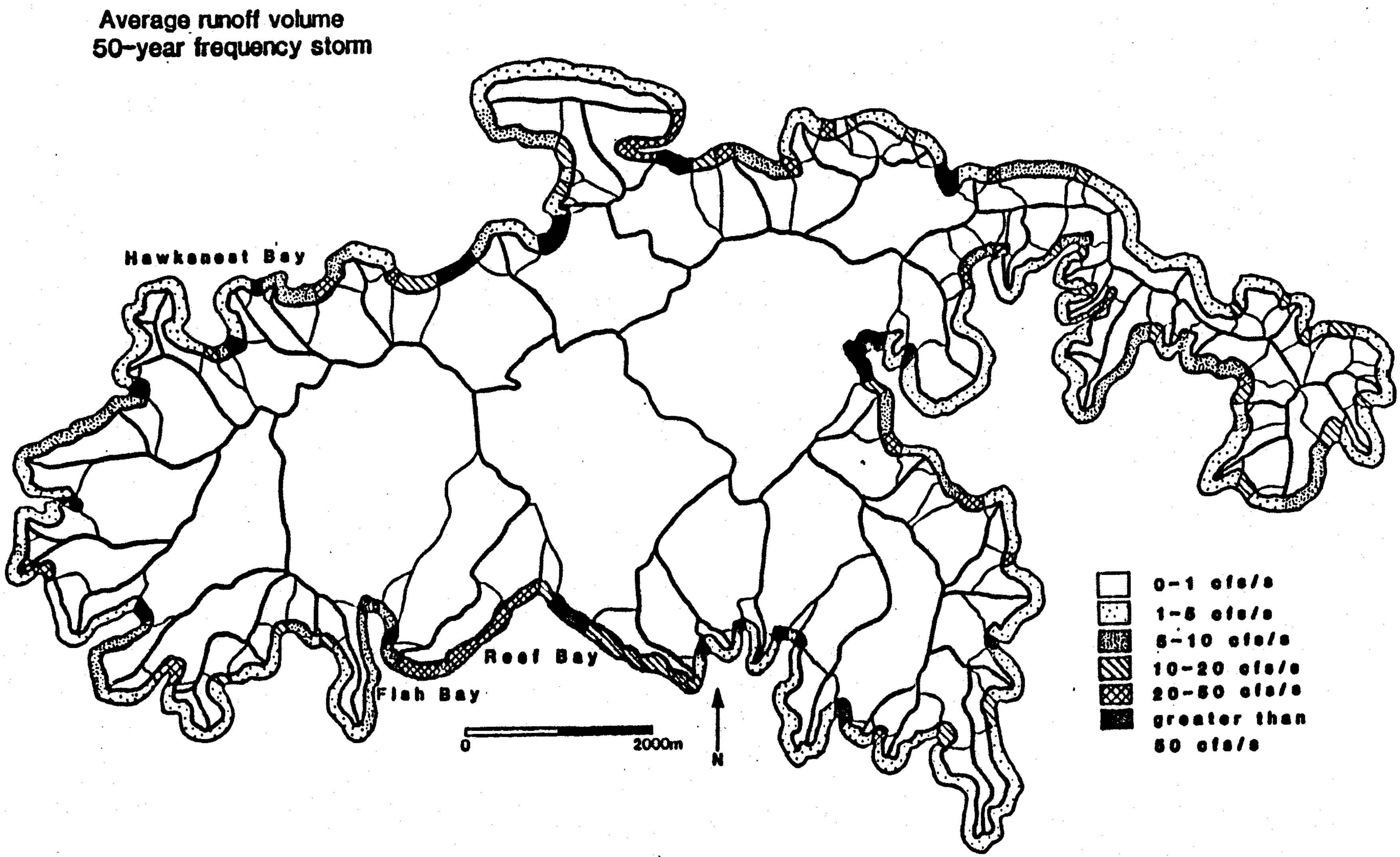


Figure 21. Map of St. John showing average runoff volume for shoreline segments for a 50-yr frequency storm. Dark symbols indicate high runoff values. Note the similarity to the pattern seen for less severe, 10-yr storms (Fig. 20).

Behind watershed size, geometry plays a critical role in determining the intensity of runoff within specific shoreline segments. Generally, the areas of highest runoff intensity are found in large watersheds with relatively high slopes. Also, these shoreline segments tend to drain areas that funnel a high percentage of the watershed through them. Shoreline segments with high runoff concentrations are listed in Table 8.

There is good correlation between areas of high runoff (greater than 50 cfs/ft) and the absence of reef development (generally at the heads of bays with moderate to large watersheds). In these areas, large amounts of sediment introduced into the adjacent bay waters during storms are detrimental to the reef organisms. Shoreline segments with low runoff intensity (less than 50 cfs/ft; ideally less than 20 cfs/ft) are more likely to contain better developed reefs in the nearby bay waters.

The watershed:bay-area ratio exerts a less predictable and secondary control upon reef development. Shore segments with no reef cover had an average value of 4.96 (Table 9). In areas with well-developed reefs, the ratio averaged 1.96. Ratios for the scarce and present categories were 4.21 and 3.76, respectively.

Lower values consistently occurred in areas where reef development was extensive. Although the ratio of watershed area to bay area decreased generally as reef abundance increased, numerous exceptions occurred and this ratio is not likely to be useful as a quantitative predictor of reef occurrence. As is discussed below, bay exposure exerts substantially more control than bay size.

Exposure - Wave energy is important as it affects resuspension and/or removal of fine-grained sediments. In protected areas such as inner Cruz Bay, Great Cruz Bay, inner Fish and Coral Bays (Fig. 1), waters can be very turbid as a result of both high runoff input and low prevailing wave energy. Along the eastern section of Hawksnest Bay, fine-grained bottom sediments in the eastern and central bay occur primarily due to sheltering from the point of land to the east. Sheltering within individual bays therefore provides for poor flushing during runoff events and subsequent settling and retention of fine-grained sediments in the interim.

Exposure can be affected by either the location, orientation or geometry of a specific bay. Bays on the western end of St. John subject to regular sediment input will tend to be more turbid because of the diminished wave action along that less-exposed coast. The inner areas of deeply incised bays, like Fish Bay, Hawksnest Bay and Coral Bay, receive lower levels of wave energy, and are therefore subject to poorer flushing.

As will be discussed in later sections, exposure plays a very prominent role in controlling the degree of reef cover in the three bays studied in detail. For example, the inner margins of Reef Bay are equidistant from a major gut that delivers runoff from the upland watershed. Yet, the more exposed reefs on the western side have noticeably higher coral cover than those to the east.

Table 8. List of bays containing shoreline segments with runoff values in excess of 50 cfs/ft under different storm conditions.

2-YEAR FREQUENCY STORM

Central Coral Harbor
Central Reef Bay
Central Fish Bay

10-YEAR FREQUENCY STORM

Central Coral Harbor
Central Reef Bay
Central Fish Bay
Central Grootpan Bay
West-Central Great Lameshur Bay
Central Little Lameshur Bay
South-East Fish Bay
Central Great Cruz Bay
Central Cruz Bay

50-YEAR FREQUENCY STORM

Central Coral Harbor
Central Reef Bay
Central Fish Bay
Central Grootpan Bay
West-Central Great Lameshur Bay
Central Little Lameshur Bay
South-East Fish Bay
Central Great Cruz Bay
Central Cruz Bay
East Coral Harbor
Central Johns Folly Bay
East-Central Great Lameshur Bay
Central Europa Bay
Central Caneel Bay
Eastern Hawksnest Bay
Central Denis Bay
Central Cinnamon Bay
Central Maho Bay
Central Brown Bay
Central Mary Creek

Table 9. Watershed:Bay-area ratio for St. John bays, and their relation to reef development.

ABSENT	WA/BA
Borck Creek	2.9
Caneel Bay	9.5
Coral Harbor	15.5
Cruz Bay	6.6
Francis Bay	1.6
Frank Bay	2.1
Friis Bay	3.8
Great Cruz Bay	5.6
Klein Bay	1.0
Little Lameshur Bay	10.3
Maho Bay	7.7
Otter Creek	2.1
Popilleau Bay	1.6
Sanders Bay	4.1

SCARCE	WA/BA
Brown Bay	4.3
Cinnamon Bay	3.7
Fish Bay	11.1
Monte Bay	2.4
Pond Bay	4.9
Princess Bay	2.1
Solomon Bay	4.0
Turner Bay	3.6
Water Creek	2.9
Watermelon Bay	3.1

PRESENT	WA/BA
Chocolate Hole	5.4
Denis Bay	6.1
Devers Bay	1.7
East End Bay	1.3
Elk Bay	1.5
Europa Bay	6.0
Great Lameshur Bay	6.5
Grootpan Bay	11.1
Hansen Bay	3.4
Johnson Bay	4.1
Kiddel Bay	5.2
Long Bay	3.0
Mary Creek	4.6
Saltpond Bay	1.4
Trunk Bay	3.5
Turtle Bay	2.1
South Haulover Bay	5.2
Threadneedle Point Bay	3.3
West Turner Point Bay	1.6
SE Durloe Channel	1.1

ABUNDANT	WA/BA
Drunk Bay	0.96
Hart Bay	1.4
Hawksnest Bay	1.7
Johns Folly Bay	2.3
Mennebeck Bay	0.79
Newfound Bay	3.6
Privateer Bay	1.6
Reef Bay	3.9
North Haulover Bay	1.4

Development - The degree of development within the watershed affects the potential for runoff absorption. In general, more intense development and construction translate into higher runoff intensities with large amounts of sediment input into the adjacent bays. It is often difficult to separate the effects of development from exposure, as development has typically centered around bays protected from wave action. Examples of this are Great Cruz and Cruz Bays on the western shore of St. John. These areas have been affected by recent development, and the reefs have likely suffered as a result. In Cruz Bay, this has involved dredging, port expansion and population growth. At Great Cruz Bay, dredging has created an artificially quiet area in which fine-grained sediment derived from runoff has been trapped. Periodic resuspension results in typically poor water clarity. Without adequate baseline data before development, however, it is difficult to assess the real magnitude of the environmental change, and to separate development impacts from stresses due to naturally low levels of wave energy and concentrated runoff.

Impacts on Modern Reef Development - The purpose of this exercise was not to provide thresholds for precisely predicting various levels of reef degradation in the face of development. Before any such accurate model even can be considered, we must come to grips with our impressive lack of knowledge concerning what types and levels of stress individual organisms can tolerate. What this study was able to do, however, was to examine the distribution of stresses from natural sedimentation and to relate that to the present-day pattern of reef development around St. John.

In general, the distribution and abundance of reefs can be explained as results of shelf configuration, runoff distribution and exposure to wave action. Fringing reefs dominate because of the abrupt drop in the shelf close to land. Accordingly, these reefs are highly susceptable to natural levels of sedimentation stress. While exceptions do occur on a small scale, the position and character of the reefs around St. John generally follow a pattern that would be expected under natural conditions of total forest cover. It would be naive to say that development bears no influence on modern reefs, but development impacts appear to still be exerting a secondary control behind the factors of watershed size and geometry.

While not directly addressed by the model, very important in runoff retention and therefore reef development, are shoreline features such as ponds and mangrove complexes. In several instances, lowered watershed slopes in our calculations reflect substantial areas behind the shoreline occupied by these features. Their most important roles with respect to this discussion however, are as sediment-retention features. It has become common practice in recent decades to fill these areas to either create new land or to remove standing water that breeds insect larvae. In addition to the ecological losses whose enumeration is beyond the scope of this discussion, substantially increased runoff and nearshore sedimentation can result from their removal. Their role in a natural setting is probably reasonably approximated by the slope reductions in the model. Because of their tremendous importance in a development setting however, they bear special mention.

PRESENT-DAY REEF ENVIRONMENTS

Introduction

From a management perspective, the simpified model described above, and a little logic give us a reasonable starting point for assessing potential future impacts. The present condition of the reefs infers the ability of these communities to have at least in part withstood the levels of stress over time. The key to addressing the question of "thresholds" of impact, therefore, lies in:

1) separating real from perceived impact in areas of purported change

2) determining the changes in environmental conditions that might be responsible for real changes (i.e. are they cyclic changes or real stress events?)

3) greatly broadening our knowledge base concerning the responses of specific organisms to types and levels of stress that are likely under conditions of development (e.g. How much sedimentation stress is "shading" vs. "smothering" of organisms? Is sand or mud more harmful to corals?).

The remainder of this report addresses the first two points in three bays studied in detail. Unfortunately, the third element must await a time when our basic research on reef metabolism catches up to our applied needs.

This section describes three bays as they exist today. The purpose of studying these bays was twofold. First these bays are of specific interest to the National Park Service, and this investigation, therefore, provides useful baseline data. Secondly, the study uses new methods to assess changes in those bays over time. The investigation thus provides a critical test of these methods, and illustrates the kinds of inferences that can be made.

The three study sites were: 1) Hawksnest Bay, on the north shore, 2) Fish Bay, on the south shore, and 3) adjacent Reef Bay (Fig. 1). Hawksnest Bay was chosen because it is presently under use by the Park Service, and had recently come under presumed increases in sediment stress with the initial construction of the St. John Medical Clinic near the head of the watershed in 1981. Fish Bay is bordered by both Park Service land and private property. Indications of imminent and potentially substantial development within this large watershed made it an obvious candidate for study. And finally, Reef Bay is at the terminus of a large watershed, in this case however, controlled almost entirely by the Park. It is unlikely that this area will come under substantial development pressure in the near future, and its management is tied more solely to the operation of the Park. Thus, each bay is associated with a large watershed, but has a different natural and management situation.

Methods

Three to six transects were established across representative environments in each bay (Figs.22-24). A tape measure, compass and depth

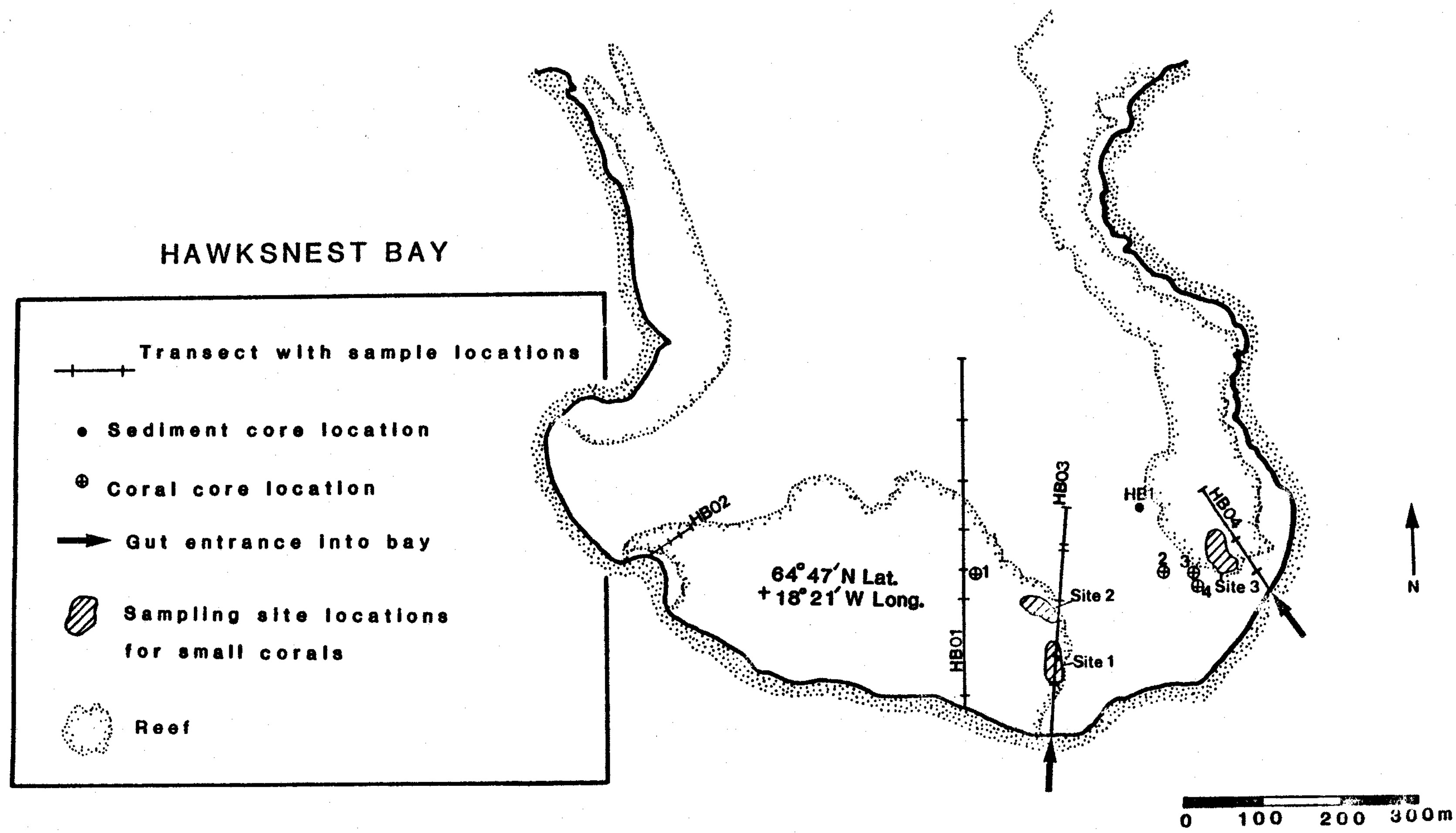


Figure 22. Base map of Hawksnest Bay. Locations of transects, sediment samples and coral cores are shown. Arrows delineate entrances of major guts into the bay.

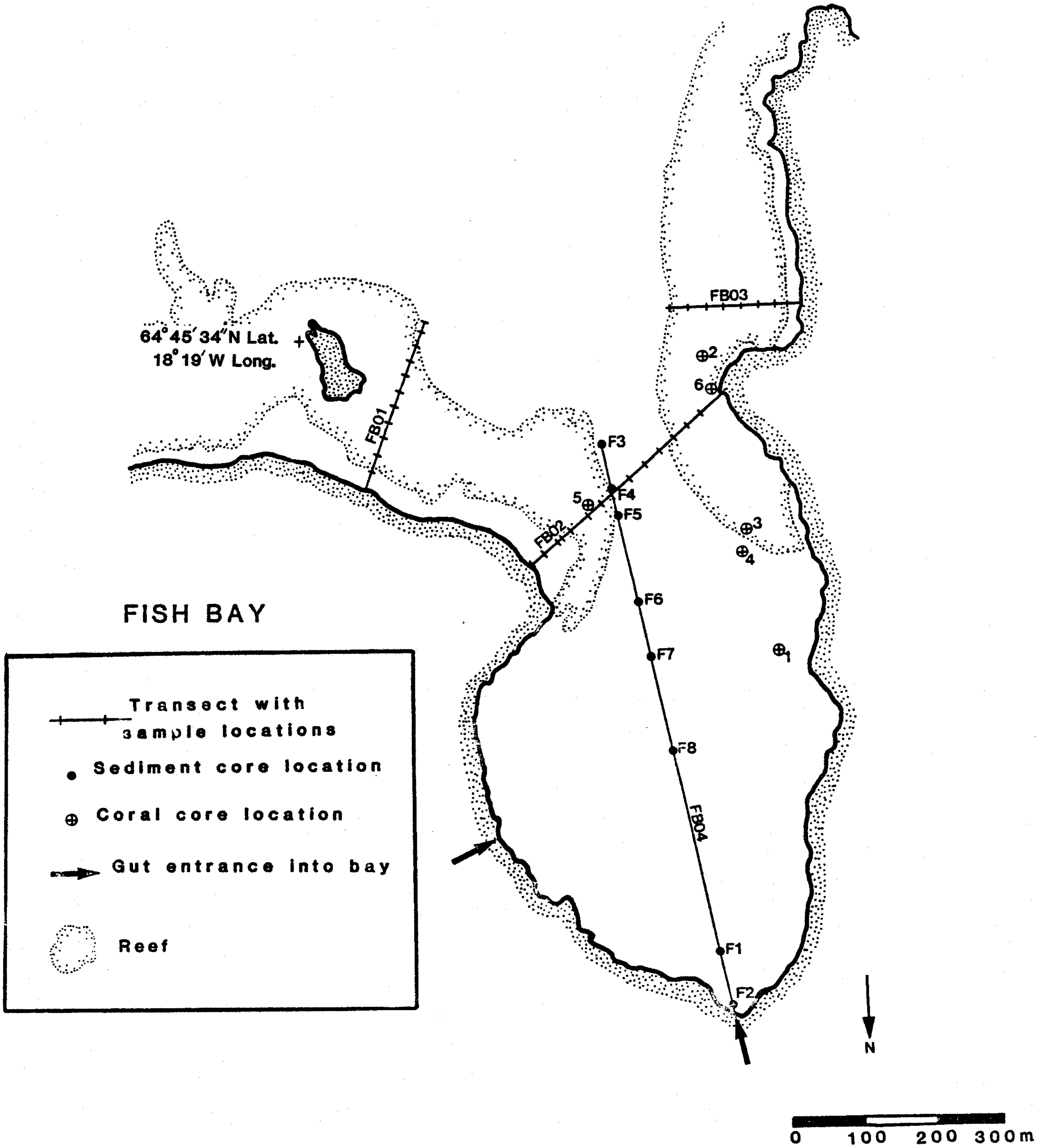


Figure 23. Base map of Fish Bay. Locations of transects, sediment samples and coral cores are shown. Arrows delineate entrances of major guts into the bay.

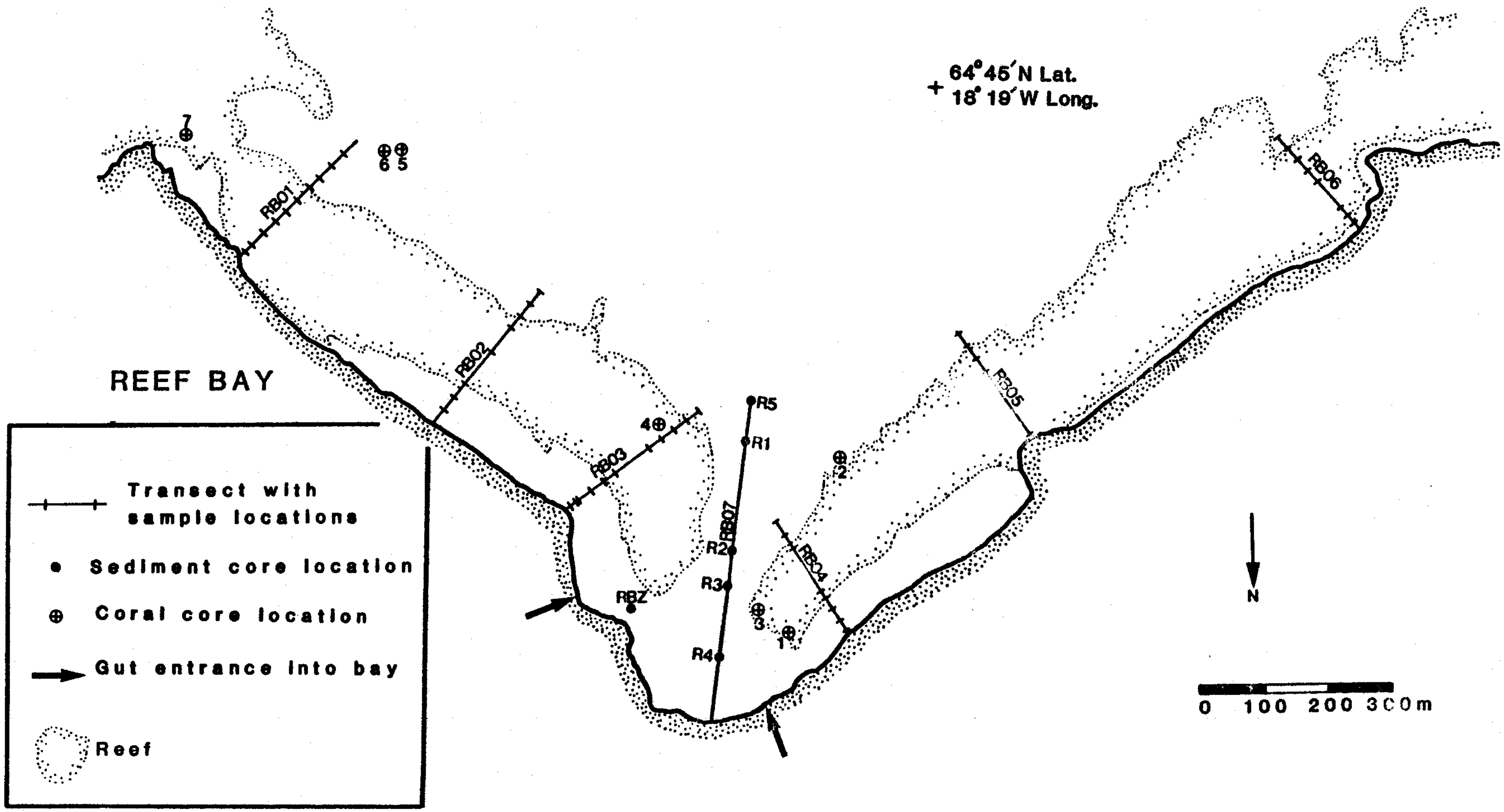


Figure 24. Base map of Fish Bay. Locations of transects, sediment samples and coral cores are shown. Arrows delineate entrances of major guts into the bay.

gauge were used to measure distance, transect orientation and water depth. Along each profile, observations of general bottom character, type and extent of living cover and water depth were made. Surface sediments were sampled with a 15-cm piston-core tube at 25 m intervals along the transect. Approximately 100-150 grams of sediment were collected at each site.

Sediment-sample treatment is summarized in Table 10. Samples containing large quantities of mud were wet-sieved through a .0625 mm screen to separate the sand from the mud. Each fraction was dried and weighed to determine its importance in the sample. A representative subsample of each fraction was exposed to 10% HCl to dissolve the carbonate fraction. The remaining insoluble residue was dried and weighed to yield the amount of terrigenous material in each sample. 50-100 grams of the sand fraction were dry-sieved at 0.5-phi intervals (Folk, 1974) to determine mean grain size and sorting (calculations assume a mean grain size of 0.044 mm for the material removed by wet-sieving). Sediments with low mud contents were dry-sieved intact, and terrigenous content was determined for sand and mud as a single group.

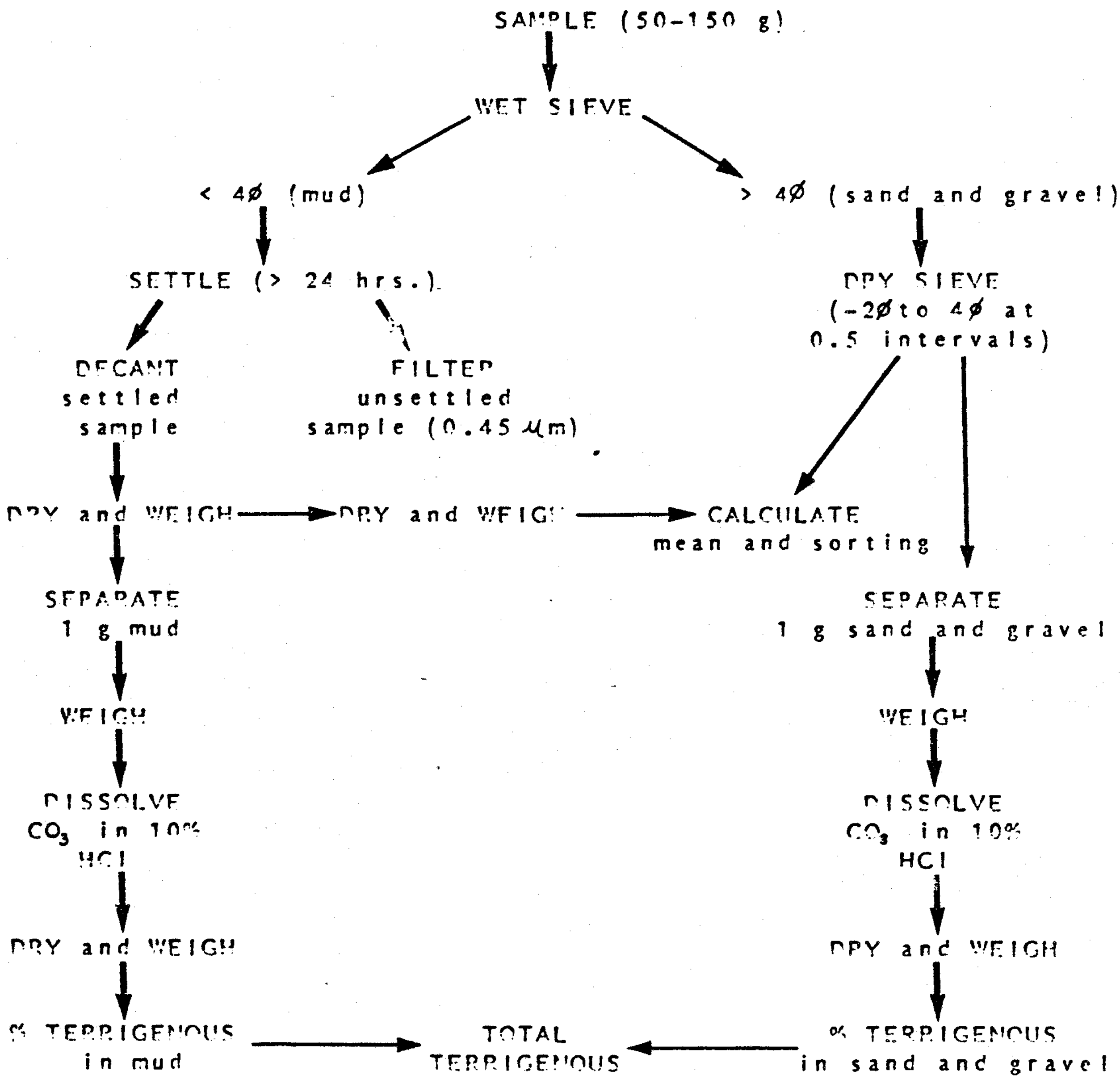
Hawksnest Bay (Figs. 25-30)

Sediments - A total of 21 surface-sediment samples were collected along four transects at this study site (Fig. 22). A decrease in grain size was observed with depth on all four transects (Fig. 25). The coarsest sediments were observed just seaward of the reefs where most of the fine-grained material had been removed by waves. However, these sediments were not particularly well-sorted due to a dominance of gravitational transport of the coarse-grained sediments down the reef front into the lower energy forereef. Similarly, nearshore environments were a mix of fine-grained sediment characteristic of a low-energy environment and coarse materials periodically introduced by wave action over the reef crest.

The fine sediments encountered on the seaward ends of all four transects are the result of both bay morphology and water depth. The eastern portion of the bay is protected from most wave activity by the point of land east of the bay (Fig. 22). This provides a low-energy environment in the eastern and central parts of the bay, and fine-grained sediments are deposited. Seaward of the nearshore reefs, water depths drop substantially, and the sea floor lacks an appreciable coral population which might act as a source of coarse-grained sediment.

Terrigenous content of the surface sediments within the bay varied between 0.8 and 13.3% (Fig. 26). Along Transect HB-02, there was a higher terrigenous content (mostly in the sand-size range) in the nearshore area relative to the remaining samples. This can be explained due to the proximity of a rocky headland on shore. Along Transects HB-01, HB-03, and HB-04 (Figs. 27, 29 and 30), terrigenous content was slightly higher closer to shore with a decrease midway through the transects. Terrigenous content increases along the seaward ends of the transects. This likely reflects the offshore transportation of fine-grained sediments, and their deposition in deeper, more quiet areas of the bay.

Table 10. Sediment sample treatment procedures.



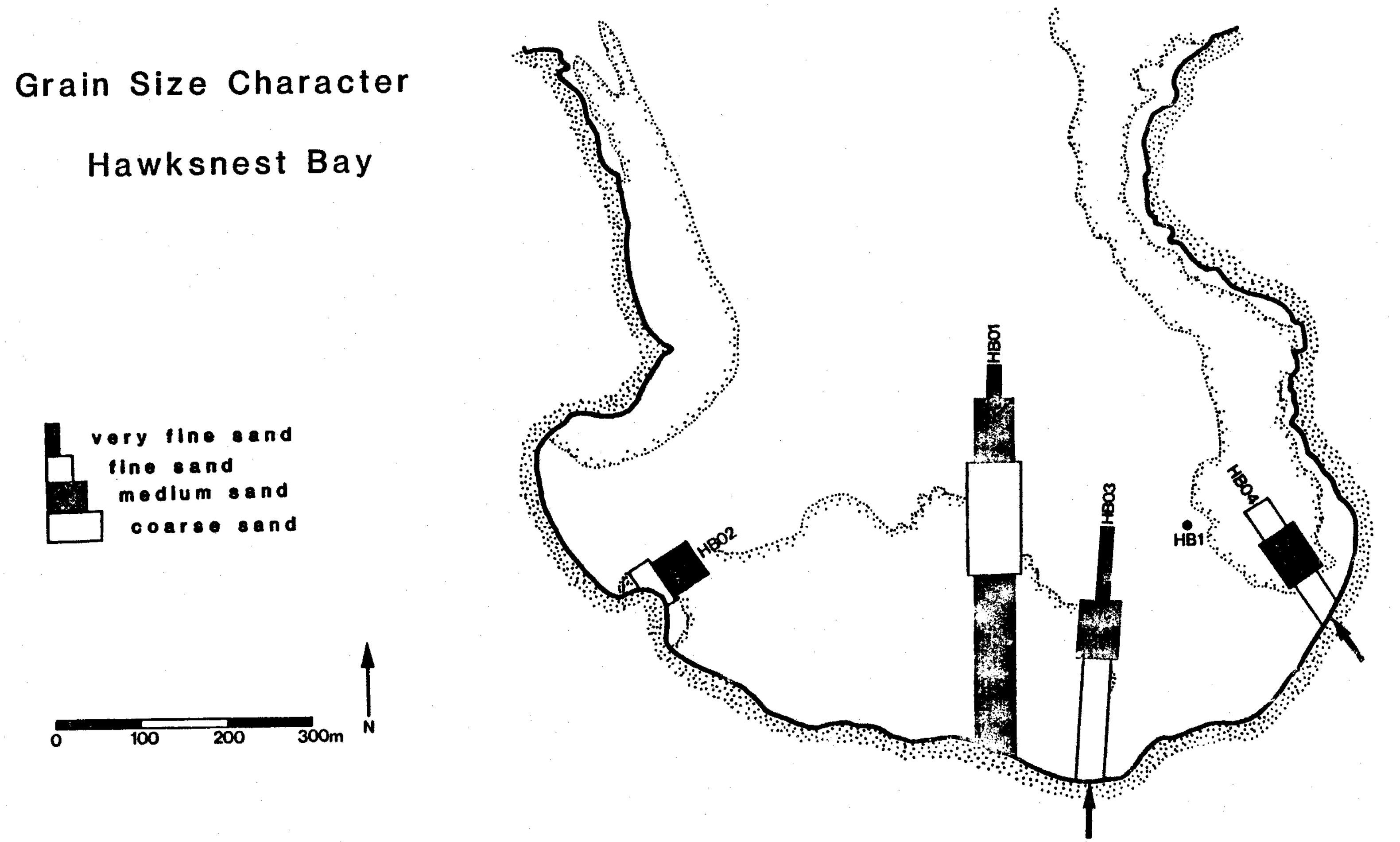


Figure 25. Map of Hawksnest Bay showing grain-size characteristics of surface sediments along each transect.

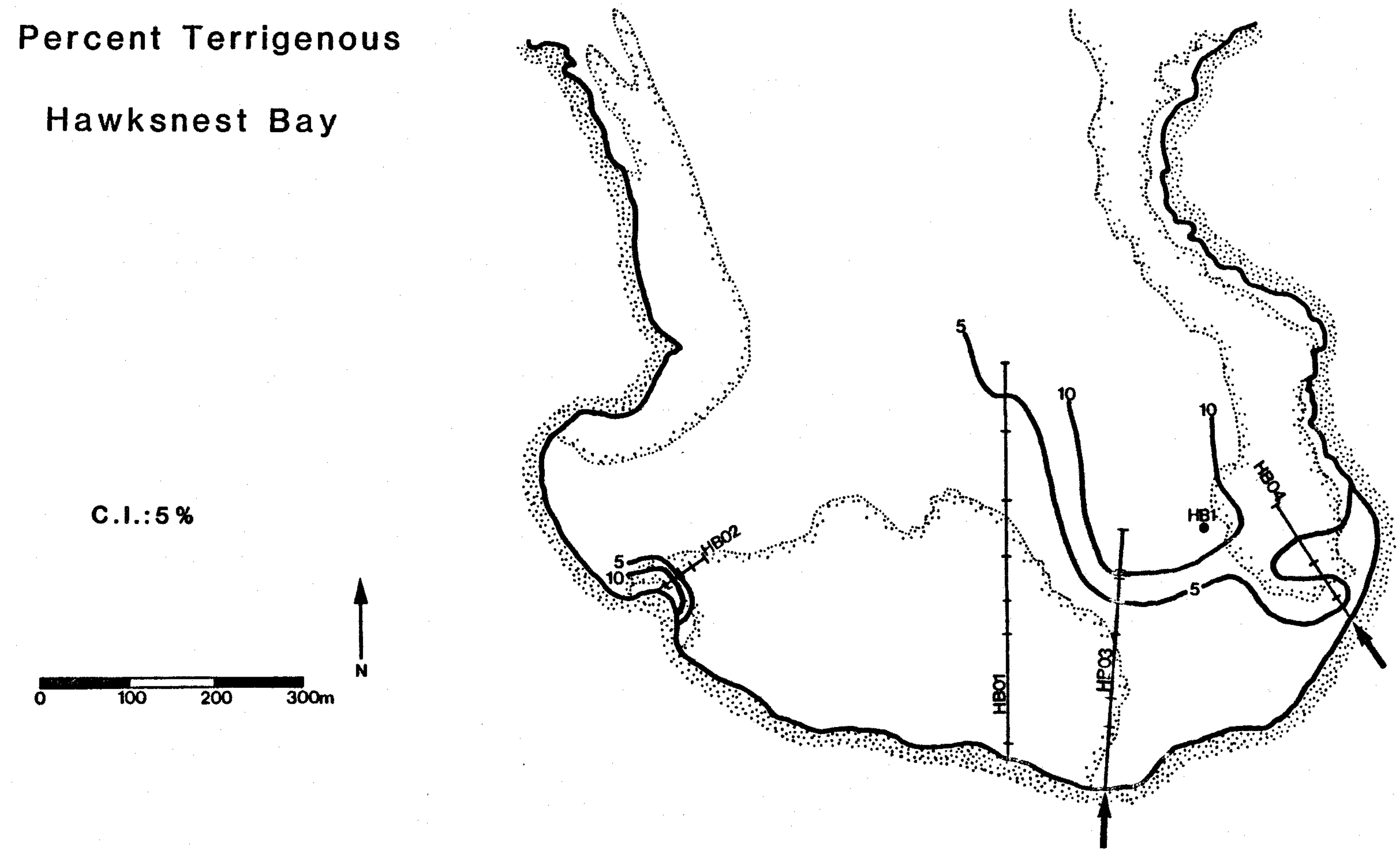


Figure 26. Map of Hawksnest Bay showing the percentages of terrigenous material in the surface sediments.

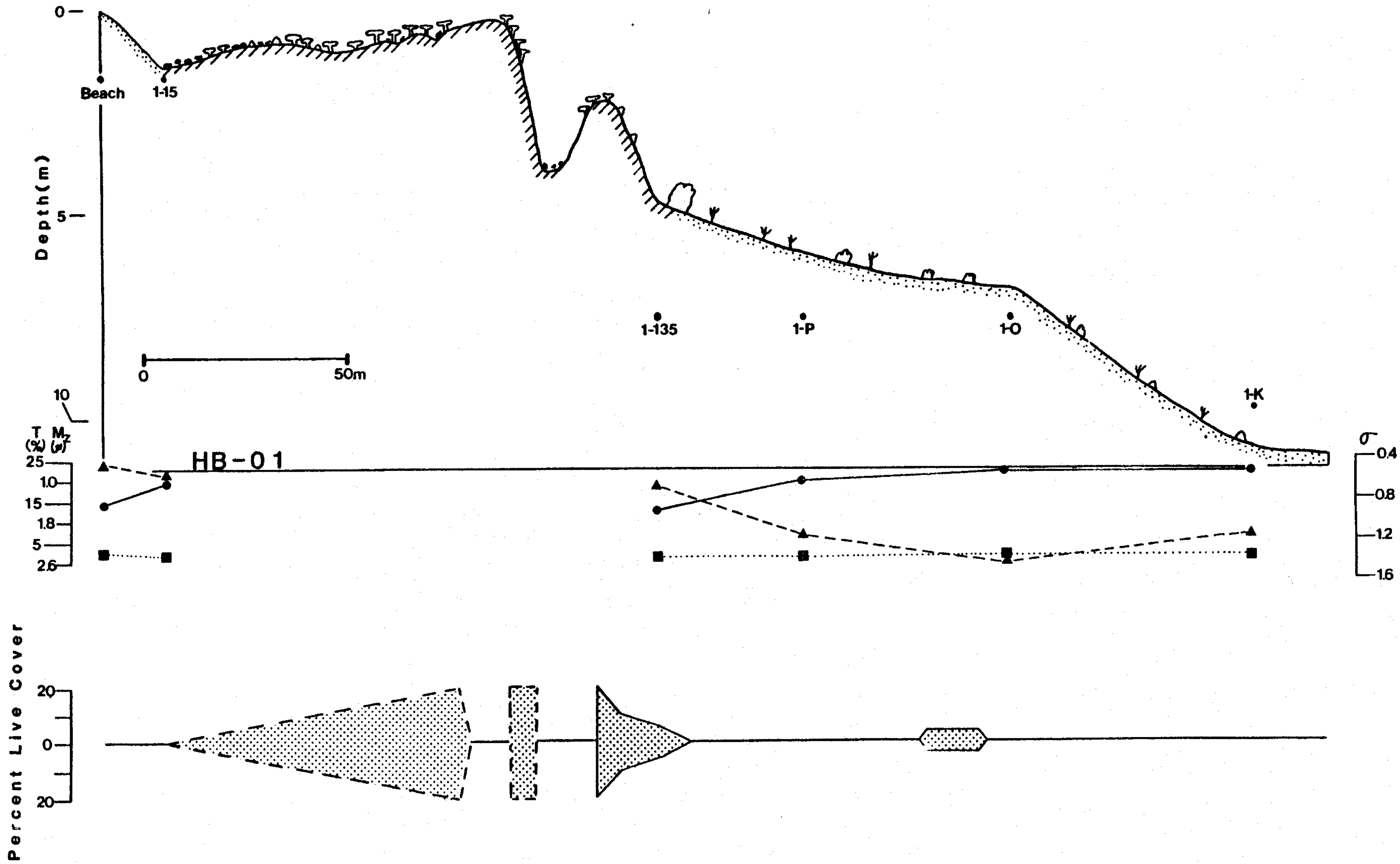


Figure 27. Hawksnest Bay profile HB-01. A key to profile symbols is included in Figure 28.

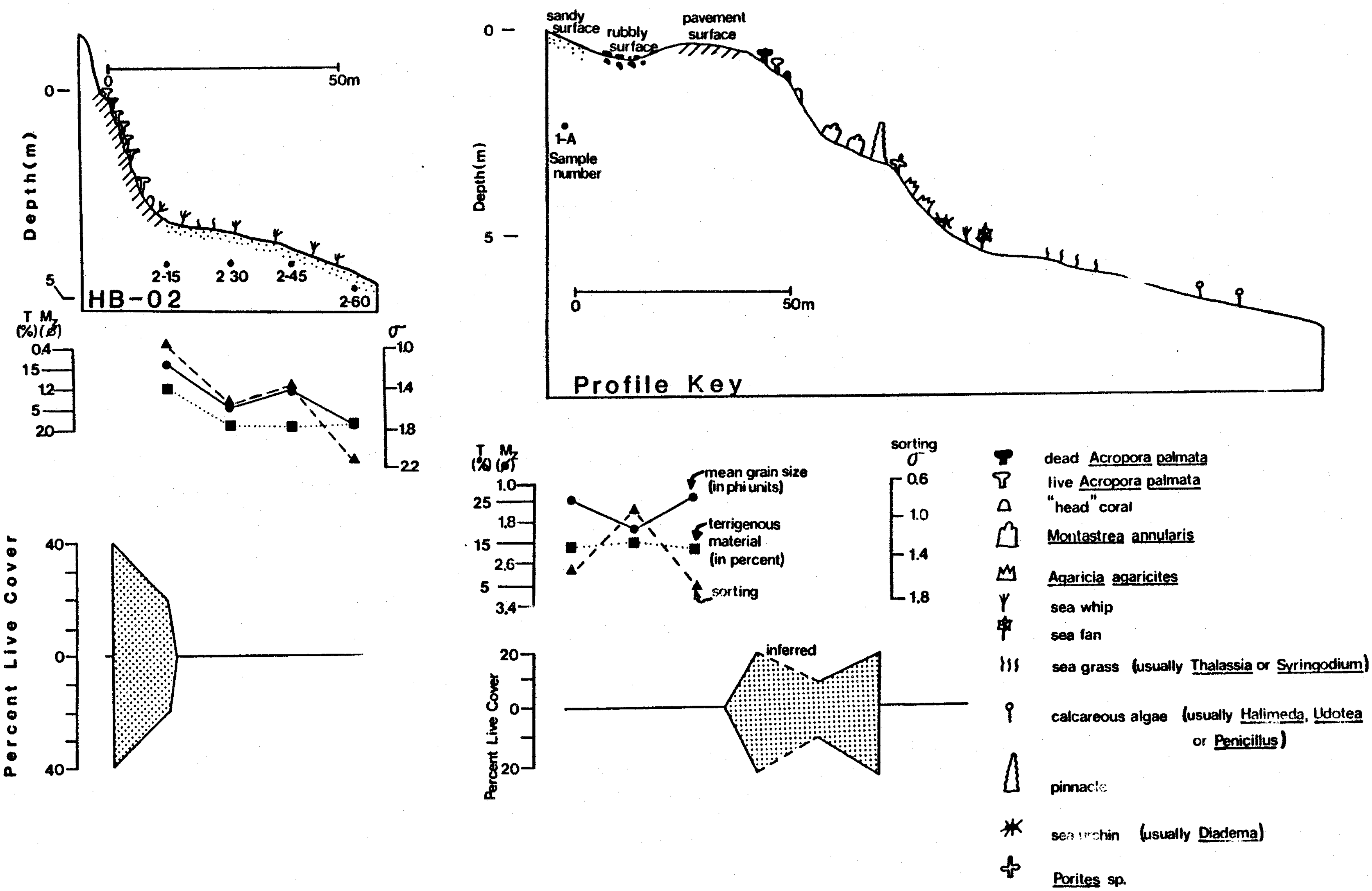


Figure 28. Hawksnest Bay profile HB-02 (left). The symbols shown in the key (right) are consistent on all profiles in this report.

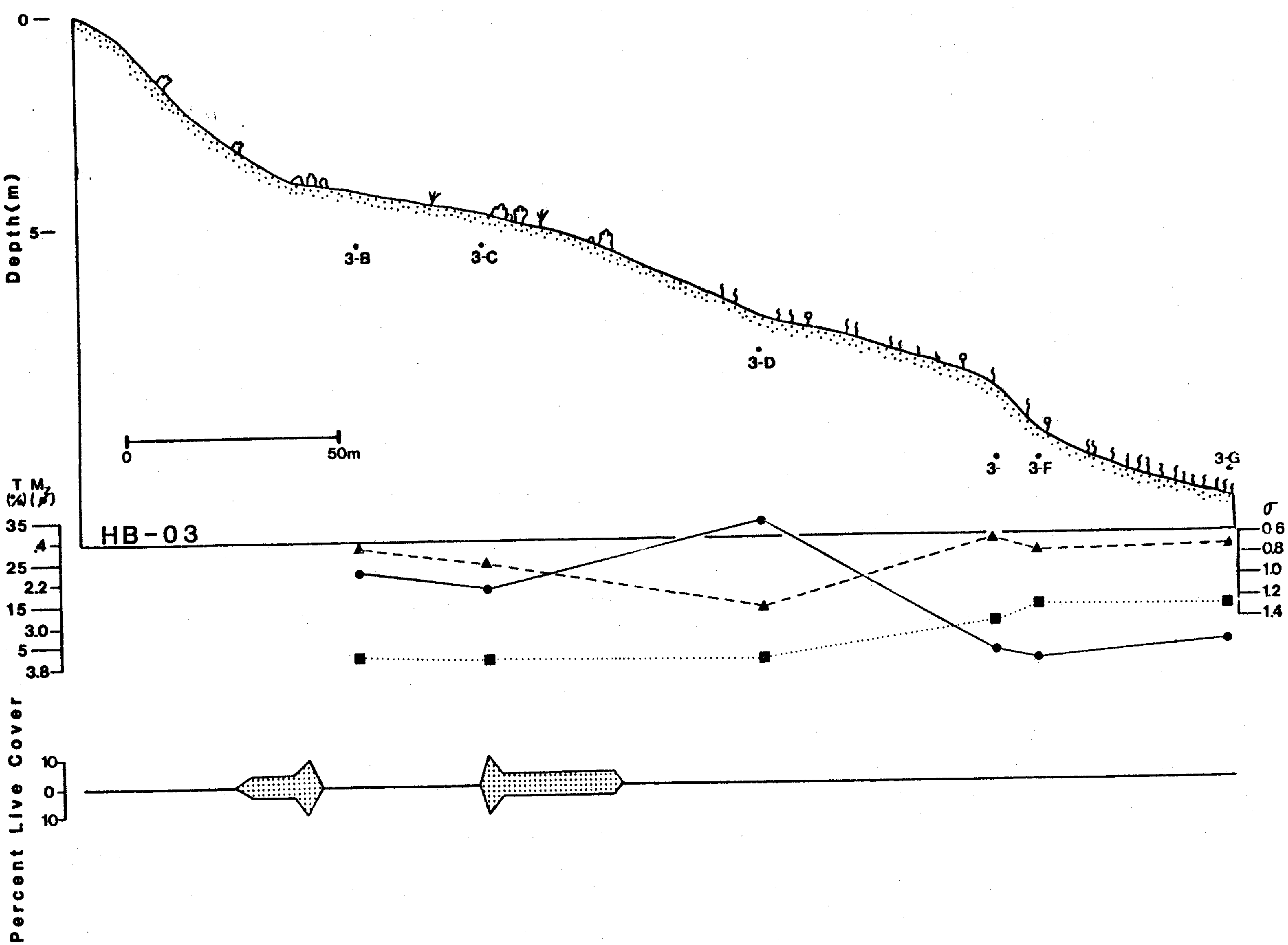


Figure 29. Hawksnest Bay profile HB-03. A key to profile symbols is included in Figure 28.

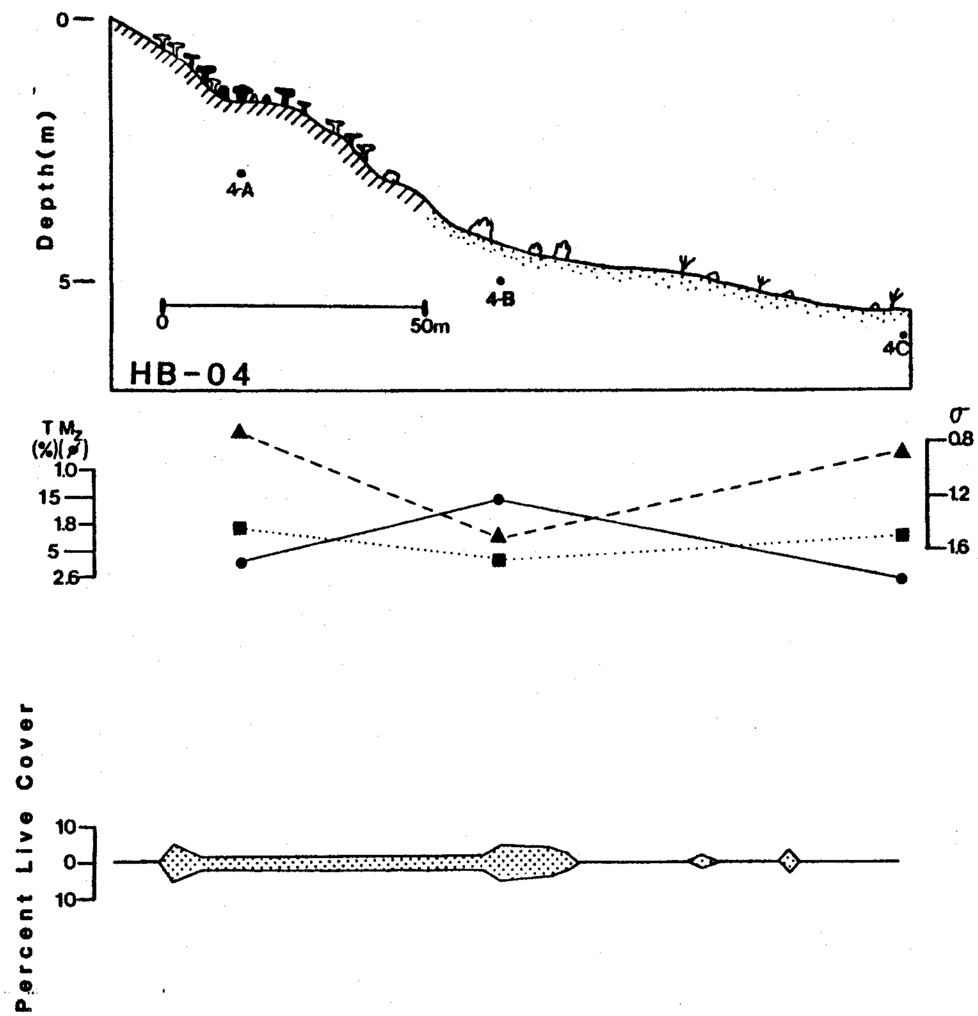


Figure 30. Hawksnest Bay profile HB-04. A key to profile symbols is included in Figure 28.

Terrigenous content appears to be related to two factors: 1) wave energy and 2) proximity to the source. In general, sediments highest in terrigenous material were located in low-energy, deep-water areas. The most terrigenous-rich sediments were located in the deep, highly protected eastern portion of the bay (Fig. 26). This environment is conducive to sedimentation by fine-grained material characteristic of much or most of the land-derived sediments.

With respect to source, an eroding volcanic headland near Transect HB-02 is probably responsible for the high percentages of mostly sand-sized terrigenous grains found there. Similarly, the seaward ends of Transects HB-01, HB-03 and HB-04 extend into an area along which a major drainage gut empties into the bay (Fig. 22). The abundance of land-derived, fine-grained material, in combination with the relatively low-energy area along the eastern edge of the bay, results in significant terrigenous-sediment deposition in the central part of the bay.

Reefs - Of the three bays, reef cover is least developed in Hawksnest Bay. The best developed reefs are along the central and eastern shore. Profile HB-01 (Fig. 27) traverses the middle reef along the central shore (Fig. 22), and is dominated by *Acropora palmata*. The corals along the reef crest are a mixture of columnar fragments and upright live and dead colonies. Live cover reaches 20% immediately in front of and behind the main reef crest (Fig. 27), and drops rapidly on either side. The forereef, out to a depth of about 20 m, is a carbonate hardground occasionally covered by a thin veneer of sand or rubble. Cover is light and dominated by widely scattered, meter-sized heads of *Montastrea annularis*, with a sharp decline seaward of the swimming-area boundary.

The channels on either side of these reefs (e.g. profile HB-03; Fig. 29) are areas of low coral cover. The presence of several colonies of "knobby" *M. annularis* in the area along Transect HB-03 likely reflects high periodic stresses as will be discussed below. The lack of cover between the central and eastern reefs is related to the presence of two major drainage guts from the Hawksnest watershed. The eastern, larger gut has been the site of the construction for the St. John Medical Clinic. The potential impact of this recent development is discussed in a later section.

The eastern reef complex is much more poorly developed. This is a response to both lower energy levels and the proximity to the major drainage gut. Percent cover is generally low (ca. 5%), and is discontinuous in nature. The bottom is primarily hardgrounds with a thin sediment veneer.

To the west, bottom slopes are much steeper. Despite the higher wave energy, the slope provides a relatively narrow zone of reef growth, and cover is generally low. A possible exception to this occurs along the seawardmost point of the western shore. The most recent NOAA aerial photogragh shows a deeper reef separated from the shore. Beets, *et al*. (1985) estimated coral cover in this area at 25-30%. As this area was not likely to reflect sedimentation stress from the guts primarily to the east, it was not examined.

Fish Bay (Figs. 31-36)

Sediments - A total of 41 surface samples were collected along four transects within Fish Bay (Fig. 23). Two transects (FB-01 and FB-03) are located on the southern, more-exposed portion of the bay and extend perpendicular to the shoreline. Transect FB-02 extends across the narrow opening which separates the inner and outer bays. Transect FB-04 dissects the interior bay, and extends slightly into the outer bay.

Sediments along Transects FB-01 and FB-03 are composed of predominantly poorly-sorted coarse to very coarse sands (Fig. 31). The character of these sediments reflects both the proximity of the reefs and the high wave energy of these environments.

Along Transect FB-02, the coarsest sediments are similarly associated with the reefs. Behind the eastern reef, sediments are poorly-sorted, medium to coarse-grained sands. Grain size increases over the emergent reef, with a gradual increase in sorting seaward. Beyond a distinct slope break at the base of the forereef, the channel-floor sediments are the finest and most well-sorted (fine to medium sands) found along the transect. The absence of coarse-grained, reef-derived sediments in this area contributes to the fine-grained, well-sorted nature of the sediments. Along the western reef, sediments increase in grain size and decrease in sorting.

Sediments found along Transect FB-04 (Fig. 36) are the finest-grained, most poorly-sorted of any observed in Fish Bay. Coarse sands dominate the landward end of the transect. Deposition along this end of the transect is influenced by runoff from the major gut from the watershed. A small delta has developed where the coarse sediments carried through the gut have settled in the bay (sediment-core samples FB-01, FB-02; Fig. 23). The seaward end of this transect is also coarse and moderately well-sorted, reflecting an increase in energy and proximity to the reefs of the outer bay.

Beyond the influence of the delta, sediments become progressively finer in a seaward direction. A lack of appreciable energy levels within this part of the bay causes deposition of poorly-sorted, fine to very fine sands. Because of the narrowing of the bay (near Transect FB-03) which restricts wave energy, and the rapid settling of coarser sediments in the delta, the only sediments available to this portion of the bay are fine-grained. There are few reef-derived sediments found in the interior portion of the bay. The sediments are either derived from terrestrial sources carried into the bay through the guts or are formed *in situ* by epibionts within grassbeds or by the breakdown of calcareous algae.

The higher terrigenous content of inner Fish Bay sediments may in part be due to increased construction activity in the area over recent years. This includes bulldozing of numerous roads and clearing of mangrove areas near the bay head. While this activity has undoubtedly had some impact, two lines of evidence indicate that the primary controls of sedimentation patterns within the bay are still natural. First, the terrigenous content within the cores

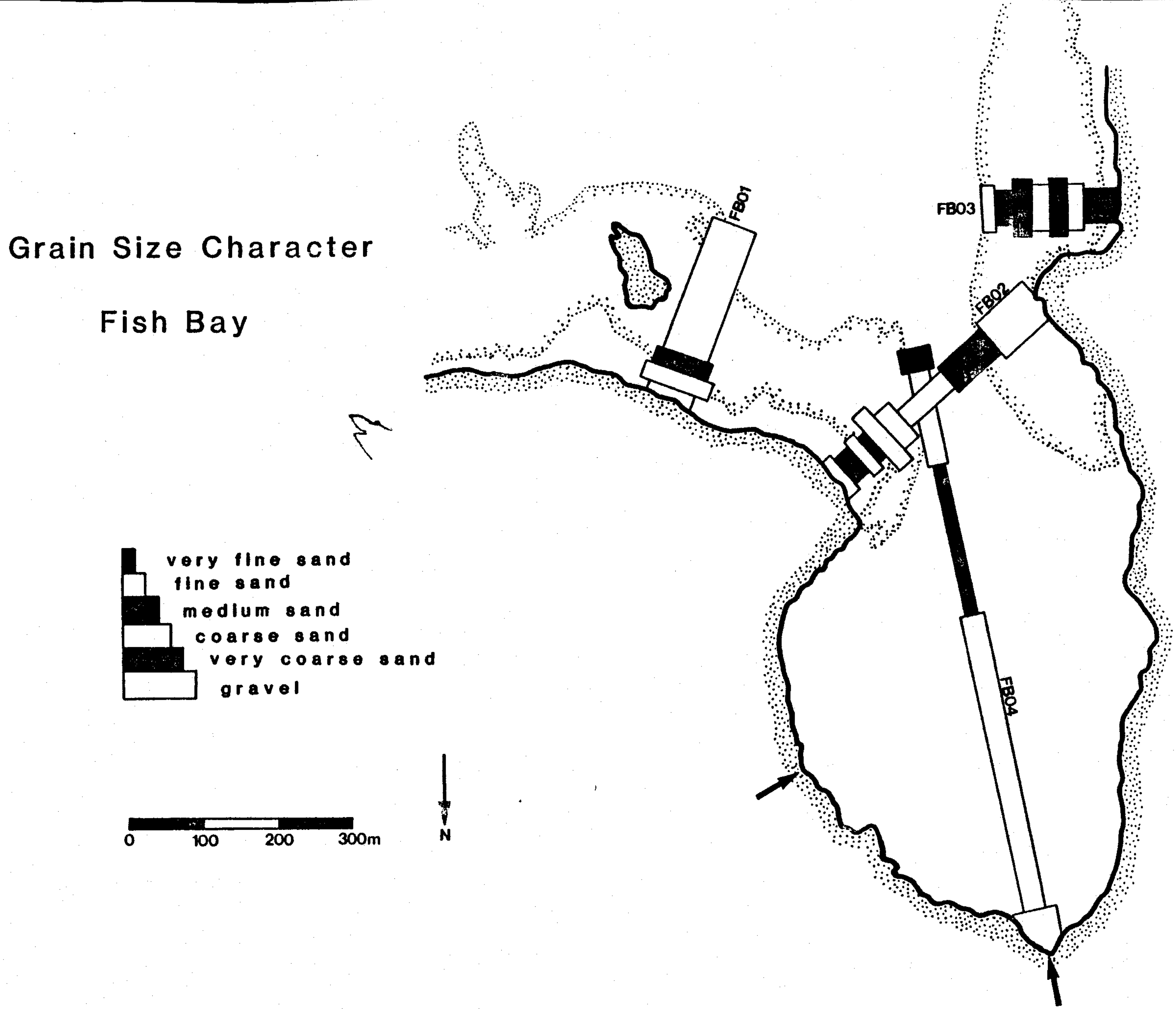


Figure 31. Map of Fish Bay showing grain-size characteristics of surface sediments along each transect.

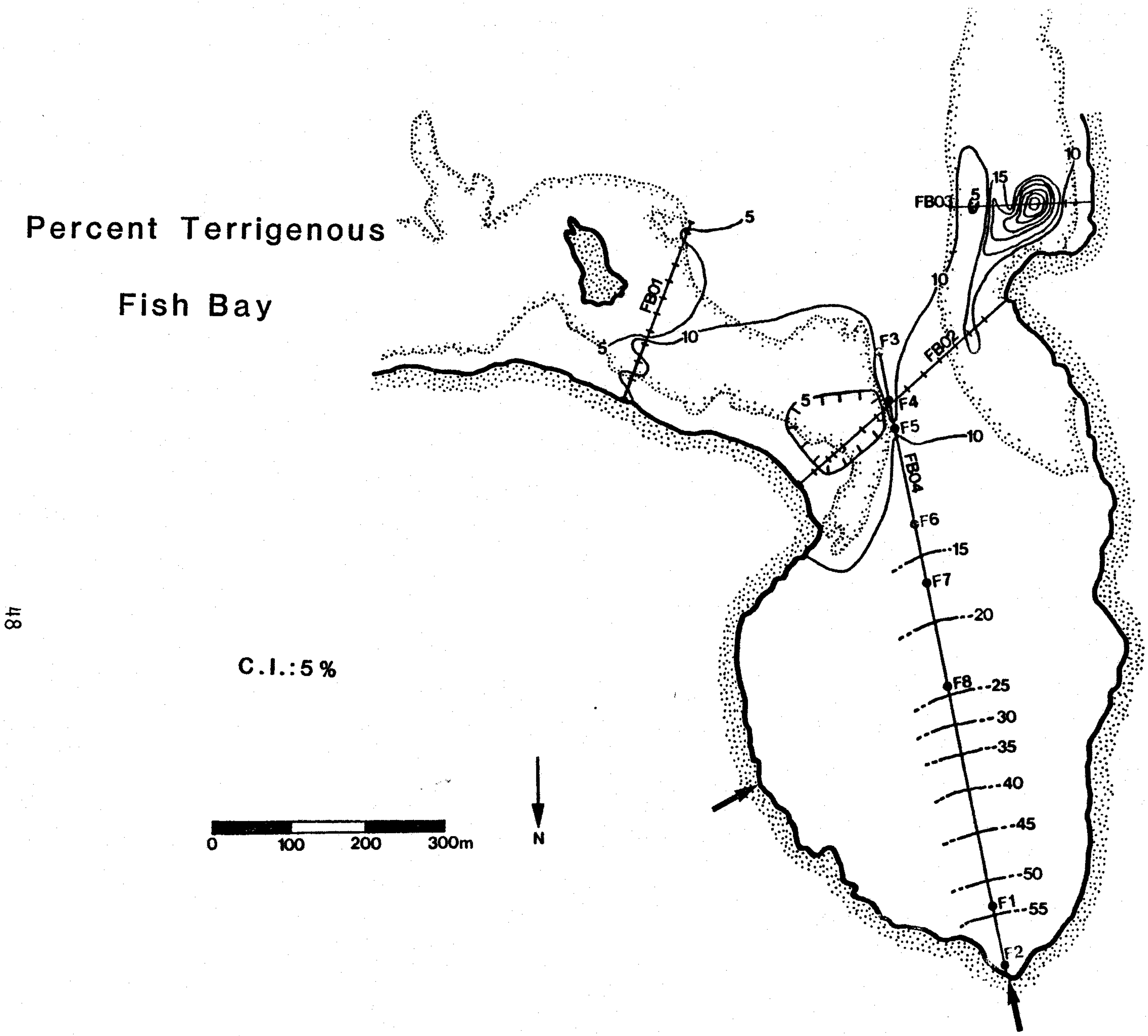


Figure 32. Map of Fish Bay showing the percentages of terrigenous material in the surface sediments.

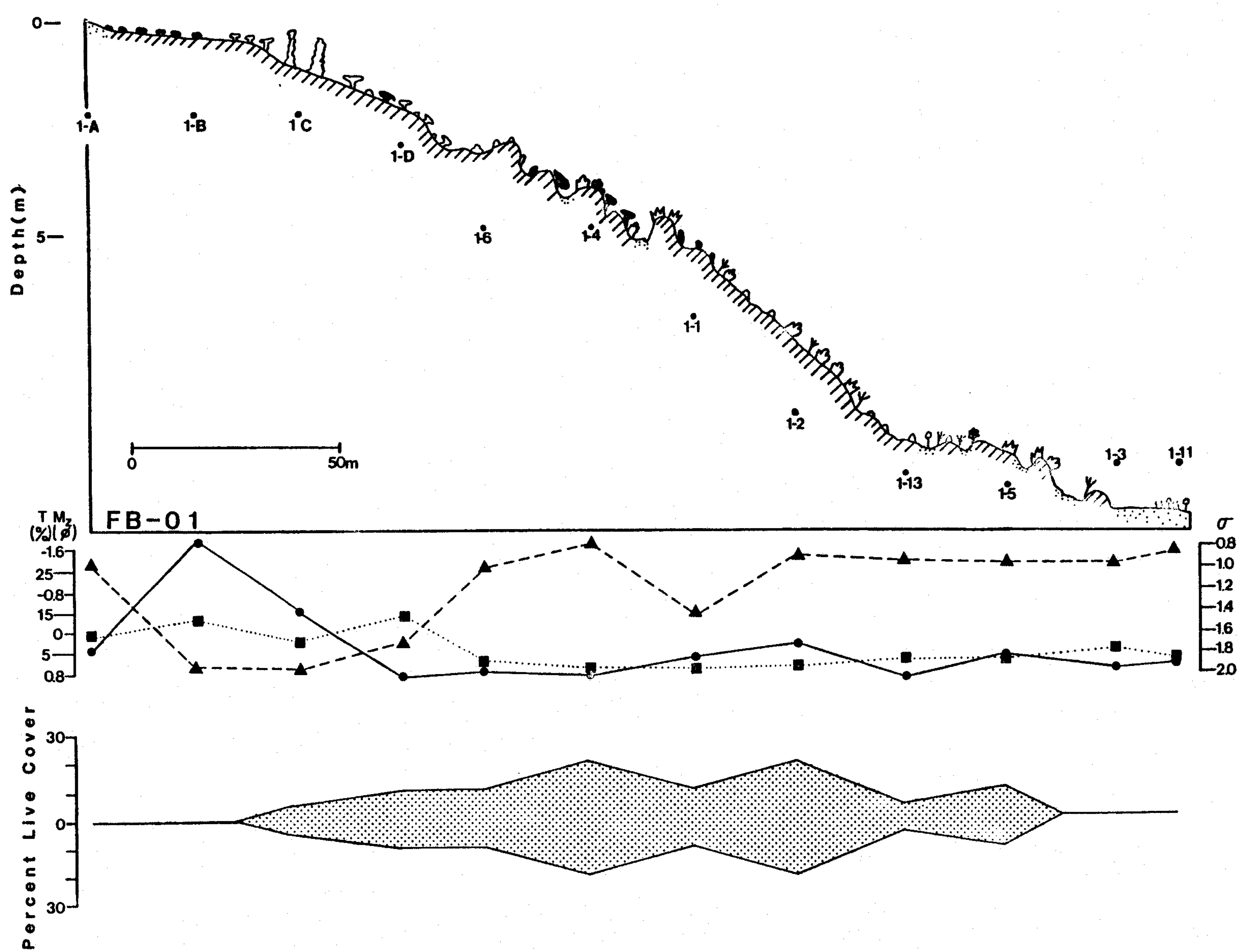


Figure 33. Fish Bay profile FB-01. A symbol key is included in Figure 28.

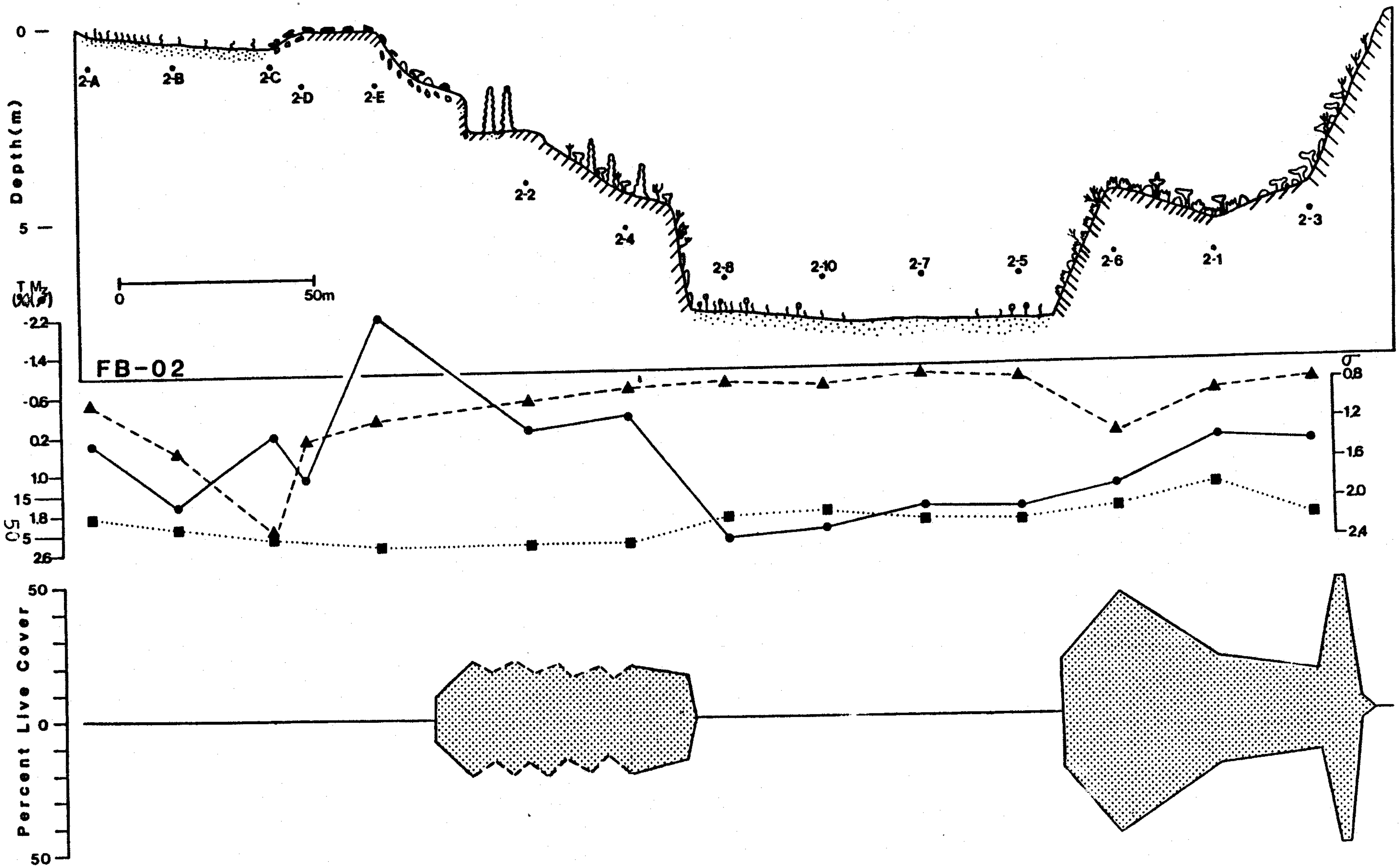


Figure 34. Fish Bay profile FB-02. A symbol key is included in Figure 28.

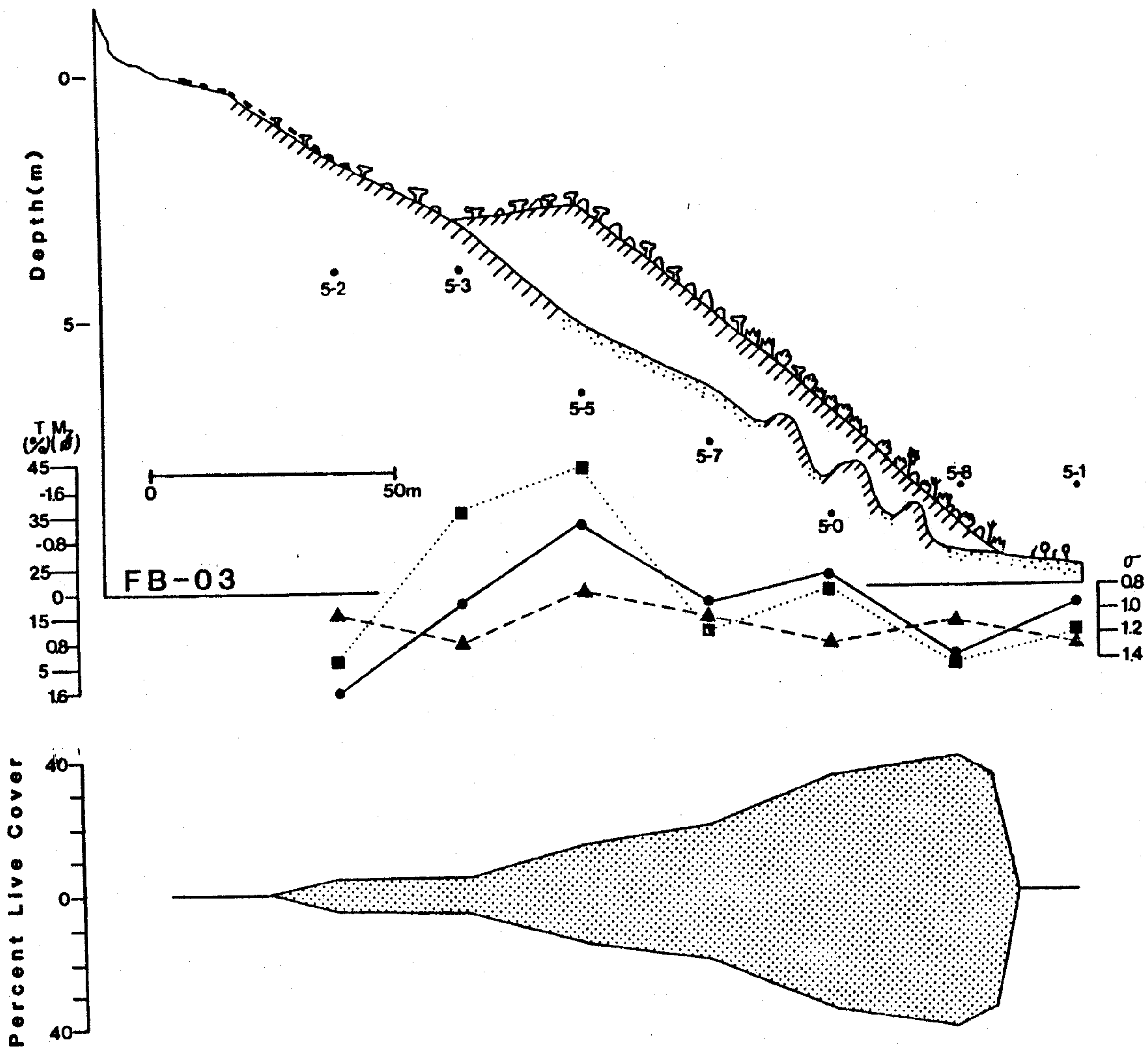


Figure 35. Fish Bay profile FB-03. A symbol key is included in Figure 28.

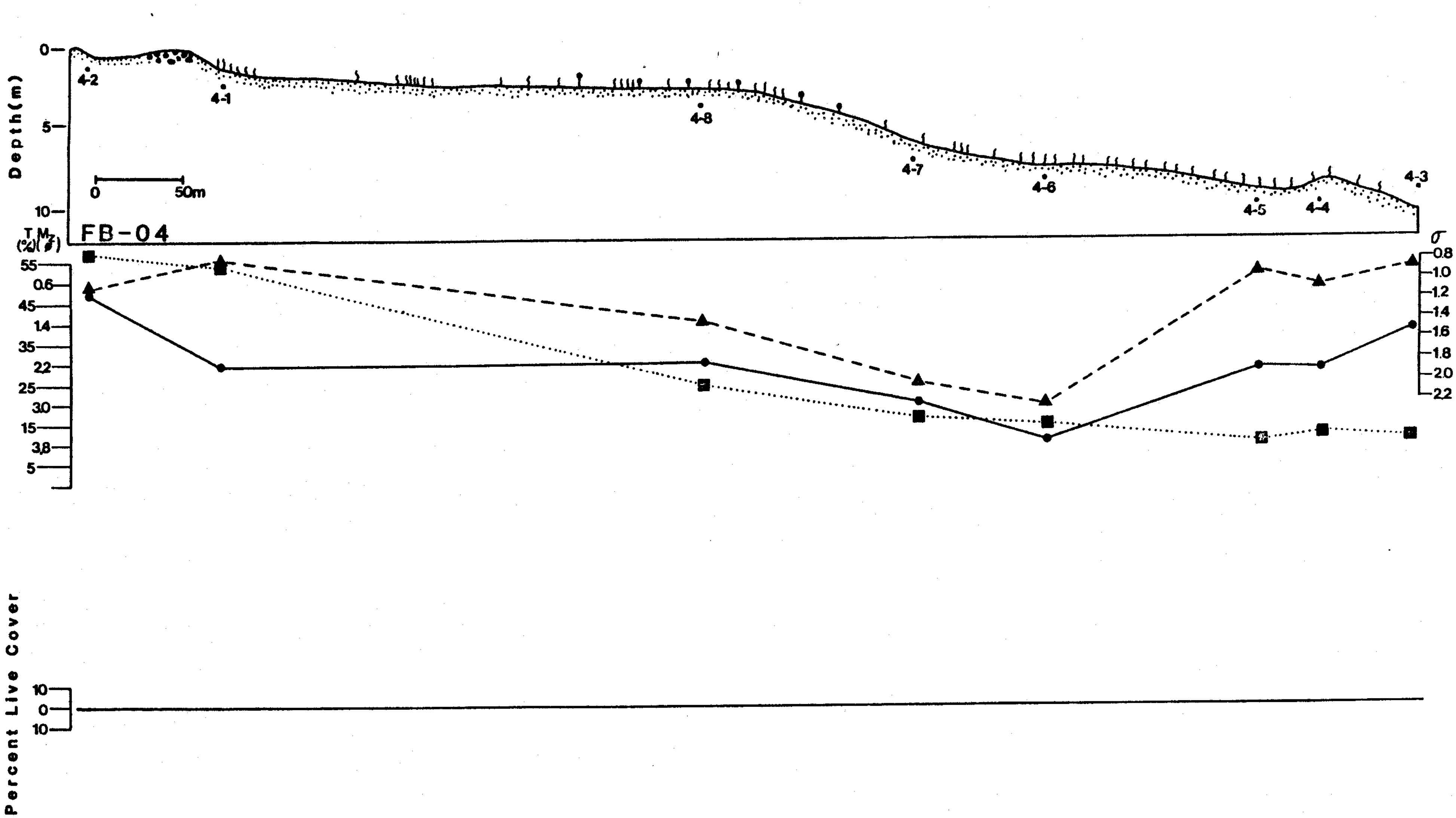


Figure 36. Fish Bay profile FB-04. A symbol key is included in Figure 28.

taken from the bay floor does not show a dramatic increase near the sediment surface. Second, the distribution of coral types within the bay (revealed by coral cores - discussed later) intimates that the general pattern of turbidity has remained relatively constant over the past 100-200 years.

Terrigenous content of Fish Bay sediments (Fig. 32) was as much as three times higher than that from any of the other areas studied. Terrigenous percentages in Fish Bay ranged from greater than 57% at the landward edge of Transect FB-04 to less than 2% in several places in the outer bay. The most dominant trend is a constant decrease in terrigenous sediment in a seaward direction across the inner bay. High terrigenous content is related to the influence of the major gut draining the watershed, and the morphology of the bay. Inner Fish Bay is a semi-enclosed bay protected from most wave activity. The gut at the landward end of Transect FB-04 (Fig. 23) drains 1057 acres of land. During heavy rains, nearly 300 million gallons of rain fall on the watershed in a 24-hour period and must be ultimately absorbed or exported through the gut. The coarse fraction of the sediment being carried is deposited in the delta at the head of the inner bay. The fine-grained, terrigenous sediments settle out in the quiet environment beyond, and cause the high terrigenous component seen in samples FB-07 and FB-08 (Fig. 32).

Although quantitative data regarding the actual output of terrigenous sediments through the gut are lacking, some generalizations can be made. While Reef Bay to the east has a comparably sized drainage basin, terrigenous percentages within sediments from that bay are much less than those observed in Fish Bay (see discussion below). Therefore, it appears that bay morphology is a major factor in terrigenous sedimentation in inner Fish Bay.

Terrigenous content decreases dramatically near the mouth of the bay (Fig. 32), and is comparable to that at similar locations in Hawksnest and Reef Bays. Energy is again the major factor influencing depositional patterns, as increases in wave and current activity preclude the deposition of mostly fine-grained terrigenous sediments. Values in the outer bay vary between 1.5 and 14%.

Exceptions to this pattern can be seen in the southwest portion of the bay where abnormally high values, some greater than 40%, occur. In this instance, the high terrigenous component is dominantly confined to the coarse fraction. The sample sites are located near a rocky headland where an abundant supply of sand-sized terrigenous material is produced. The degree of protection provided by the surrounding topography prevents the movement of most of the sand-sized terrigenous component of the sediment.

Reefs - Fish Bay is comprised of two bays, an outer, exposed body of water and an inner, more protected one (Fig. 23). Within the inner bay, levels of turbidity are much higher, primarily due to the quieter environment. The coral community within the inner bay is sparse, and is confined to a few colonies of *M. annularis* and *Siderastrea* sp. in shallow water along the western shore, and scattered heads of *Manicina* and

Meandrina (V. Zullo, pers. comm.) in nearby grassbeds.

In the outer bay, wave exposure is higher, and levels of terrigenous sediment are correspondingly lower. The best coral cover is generally separated from shore and on the forereef slope in somewhat deeper water. Along the eastern shore, the reefs are generally separated from land by a shallow lagoon or a submerged reef flat covered with cobble-sized coral debris (Figs. 33 and 34). To the west, the reefs form veneers over steeply sloping bedrock. Variations from a uniformly sloping profile (e.g. central portion of profile FB-03; Fig. 35) are probably the result of accretion by corals, and are associated with channels which store and serve as pathways for the removal of sediment produced locally.

Reef growth is most active along the western, more-exposed margin. Along both Transect FB-02 and the western end of FB-03 (Figs. 34 and 35), the highest degree of cover is related to exposed areas of high slope near the base of the forereef. With the exception of a narrow band of A. palmata close to the shore on western Transect FB-03 (Fig. 35), these areas of higher cover are associated with head corals and Agaricia sp.

Reef Bay (Figs. 37-45)

Sediments - Within Reef Bay, 56 surface samples were collected along seven transects (Fig. 24). Along the high-energy northeast side of Reef Bay near the White Cliffs area (Transect RB-01; Fig. 39), no lagoon environment occurs. The sediments range from a very coarse sand on the landward end of the transect to a medium sand on the seaward end of the transect. Sorting decreases seaward from a moderately well-sorted sand landward to a poorly sorted sand seaward.

Transects RB-02 and RB-03 (Figs. 40 and 41) differ from RB-01 in that they each have a shallow lagoonal environment behind the reef crest. In both instances, lagoonal sediments are coarse to very coarse sand, and the most poorly-sorted found along the transect. This is probably due to accumulated "backreef rubble" in this environment. Along the forereef, grain size decreases slightly seaward until, at the base of the reef, medium sand dominates. Sorting is generally poor with only a slight increase downslope.

On the west side of Reef Bay, Transect RB-04 (Fig. 42) is similar to RB-02 and RB-03. The sediments in the lagoonal environment are analagous to those encountered in similar environments on the east shore. Mostly poorly-sorted, coarse sands are again the result of accumulated backreef rubble. In a seaward direction, the sediments become slightly more well-sorted and finer-grained. Just seaward of the forereef, a slight depression (1 m relief) occurs where the sediments are extremely poorly sorted and much finer-grained than the surrounding sediments. This area seems to be a small depository for fine-grained sediments which probably flow through the channel that separates the eastern and western reefs. Seaward of this depression, the sediments are moderately-sorted, medium sands.

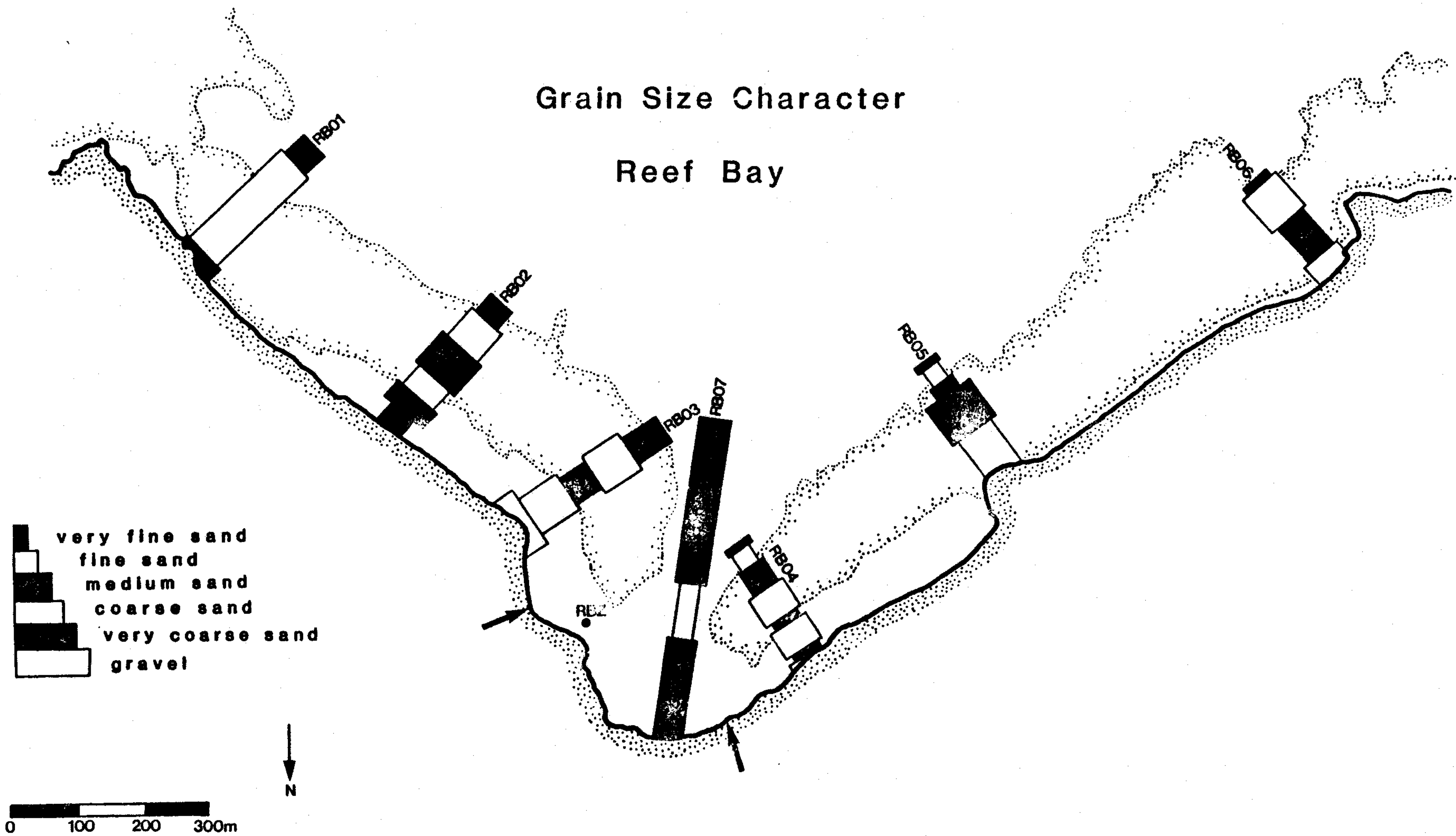


Figure 37. Map of Reef Bay showing grain-size characteristicsofsurface sediments along each transect.

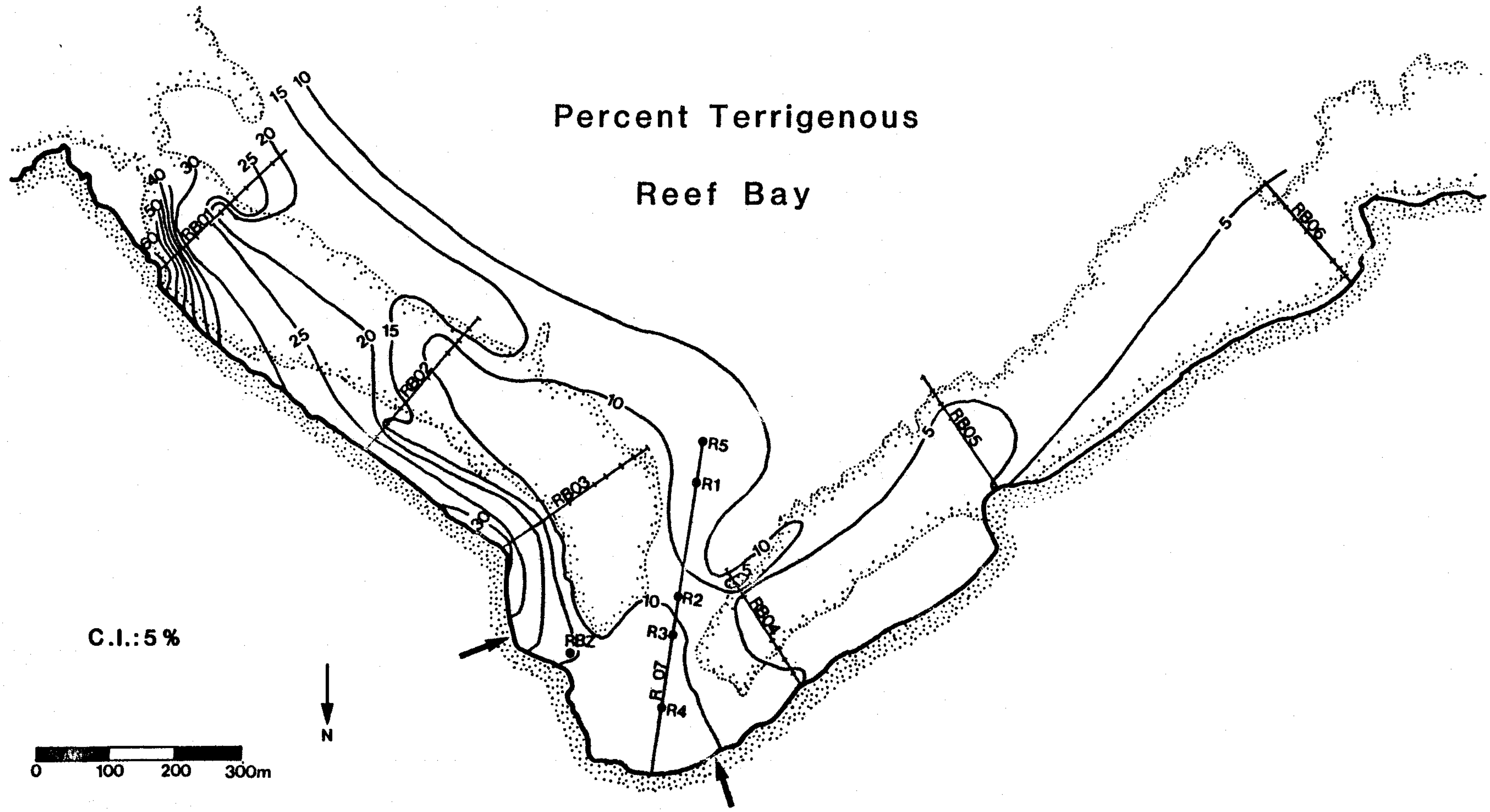


Figure 38. Map of Reef Bay showing the percentages of terrigenous material in the surface sediments.

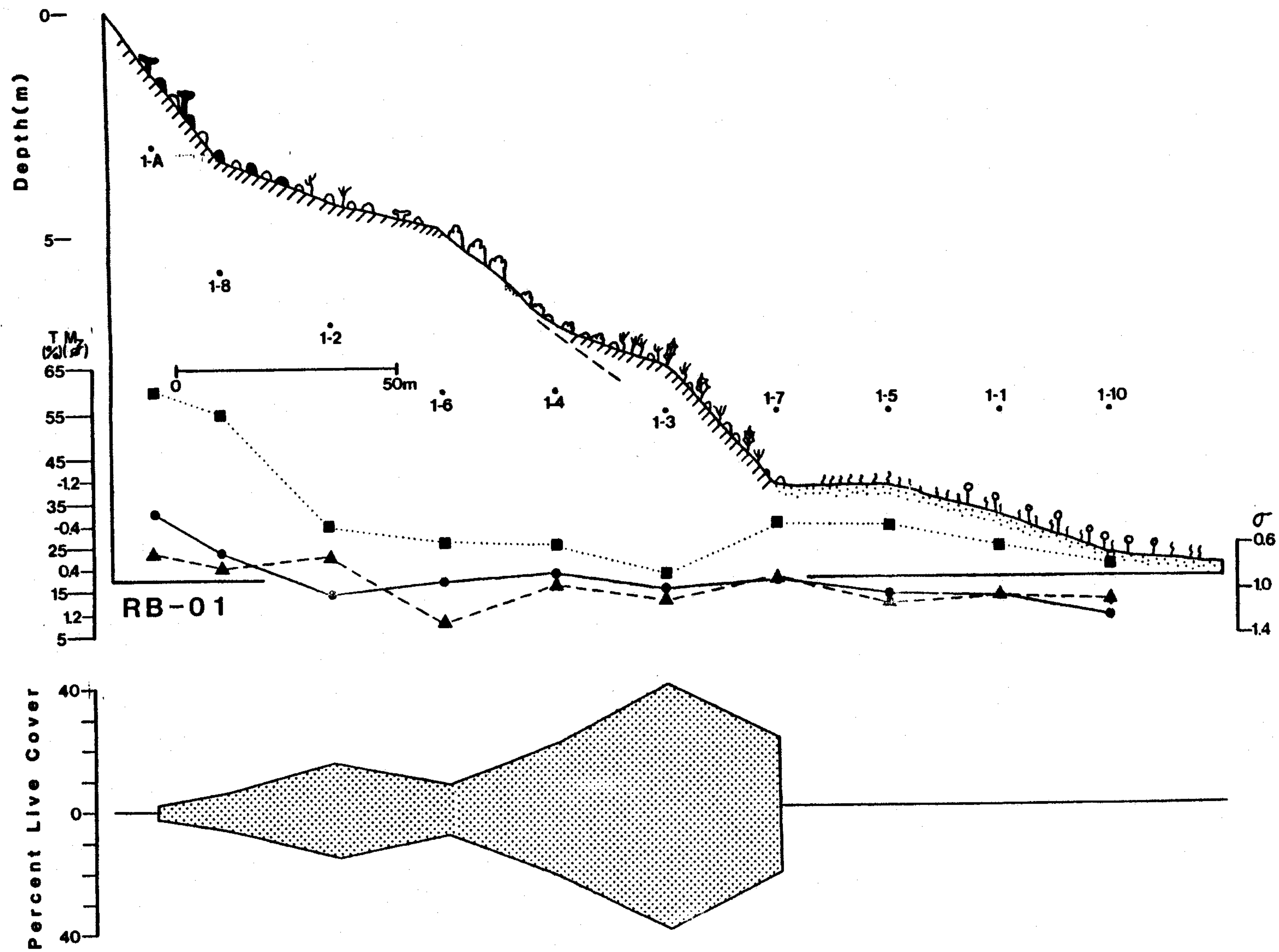


Figure 39. Reef Bay profile RB–01. A symbol key is included in Figure 28.

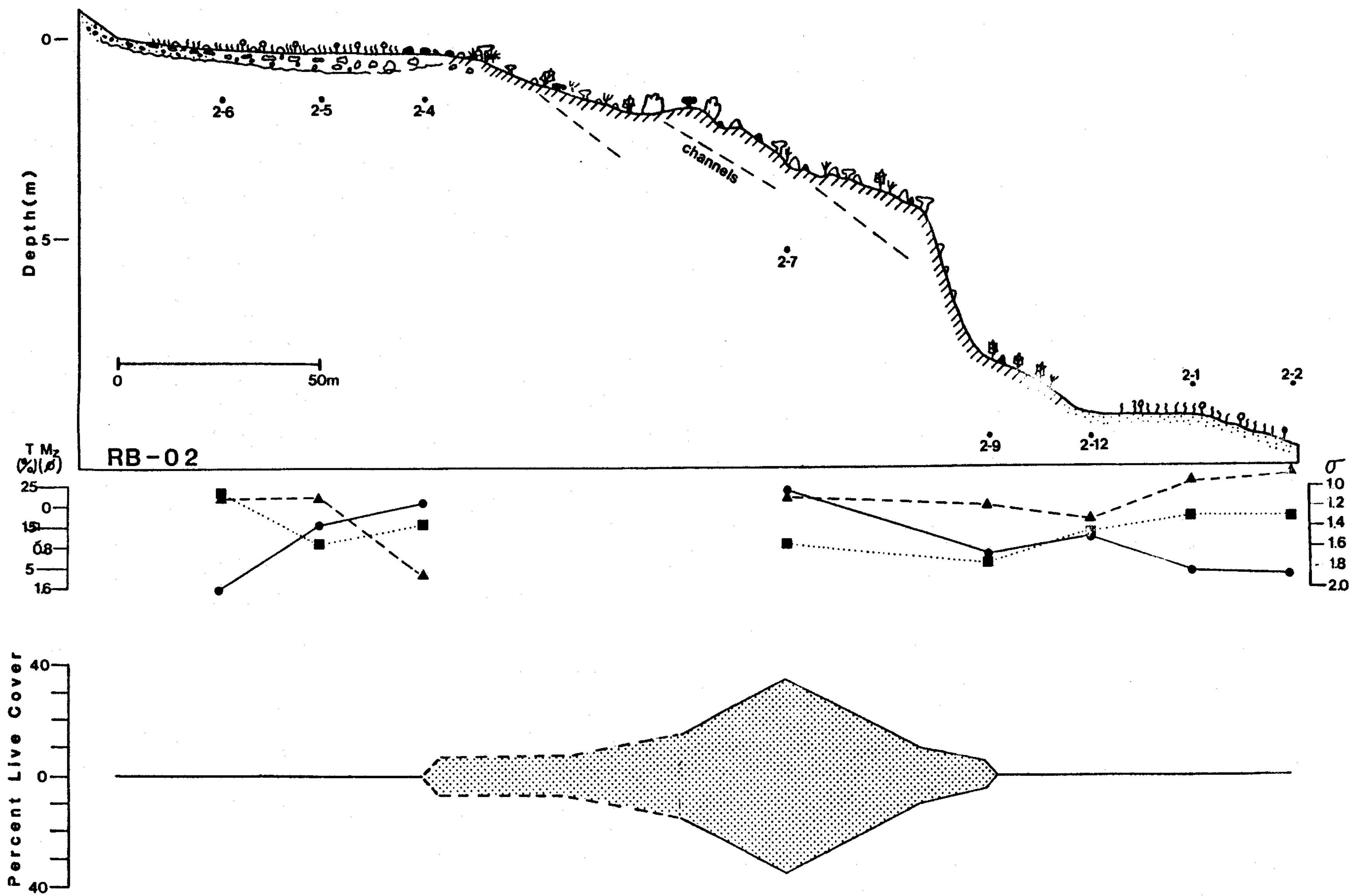


Figure 40. Reef Bay profile RB-02. A symbol key is included in Figure 28.

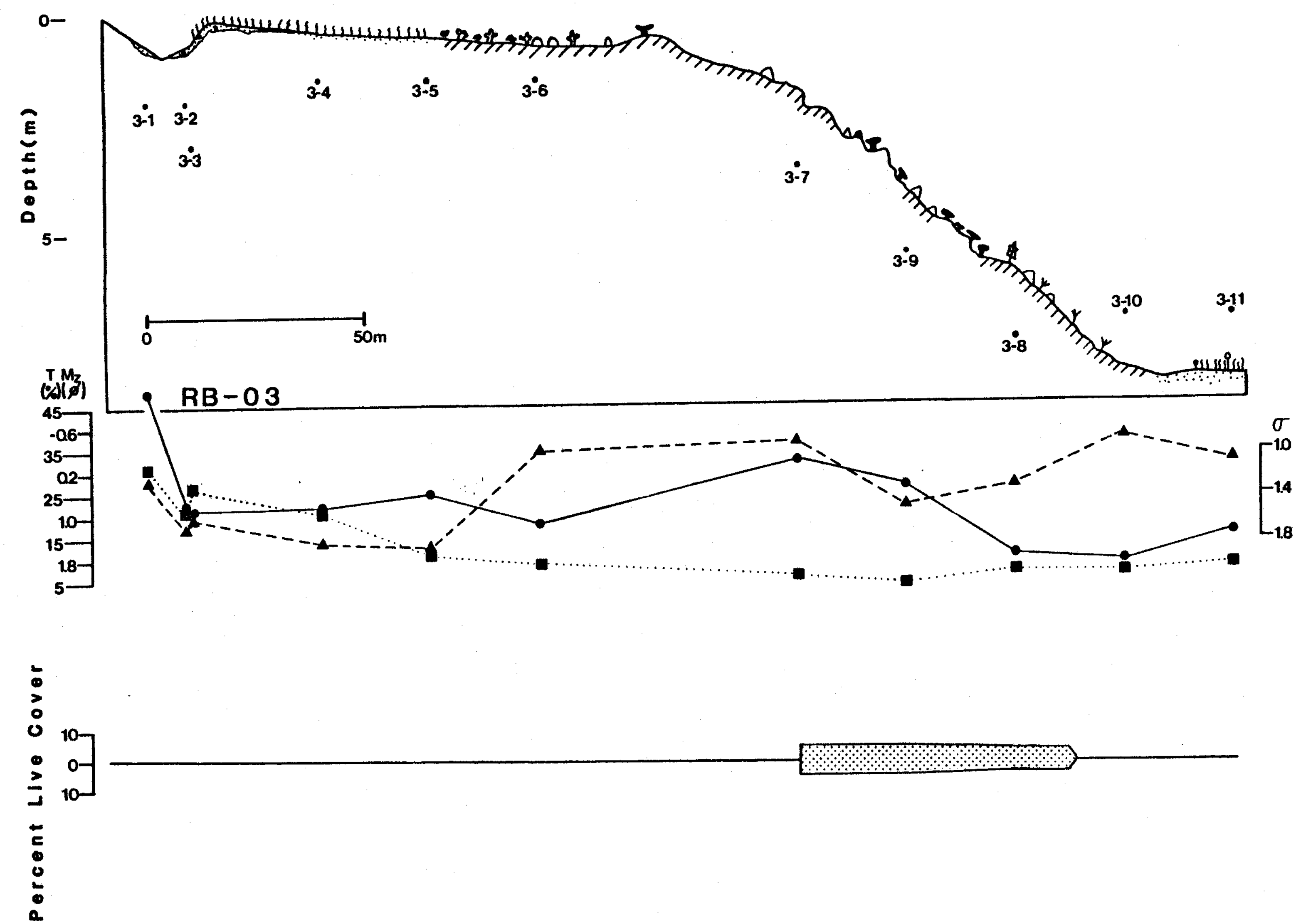


Figure 41. Reef Bay profile RB-03. A symbol key is included in Figure 28.

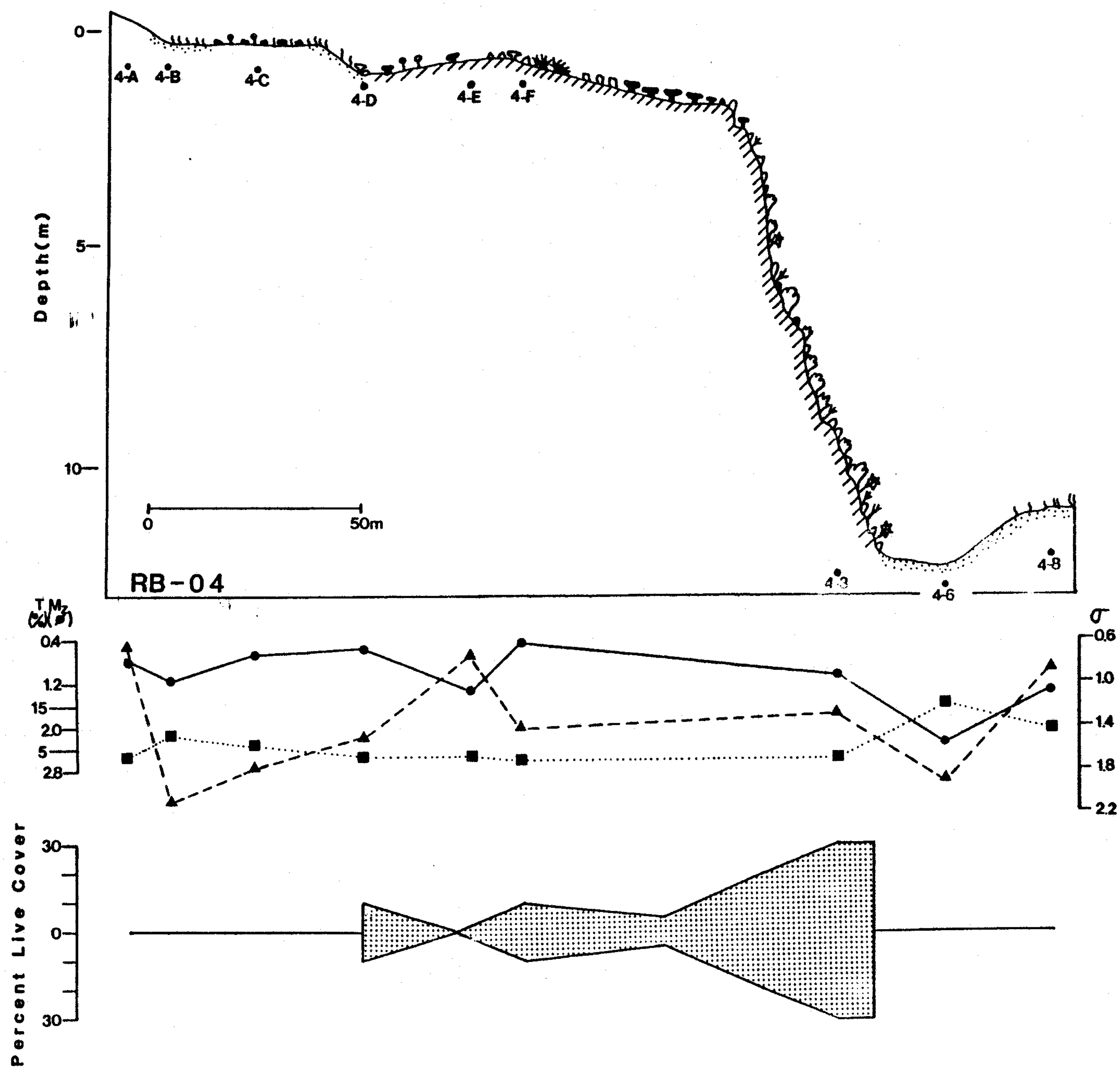


Figure 42. Reef Bay profile RB-04. A symbol key is included in Figure 28.

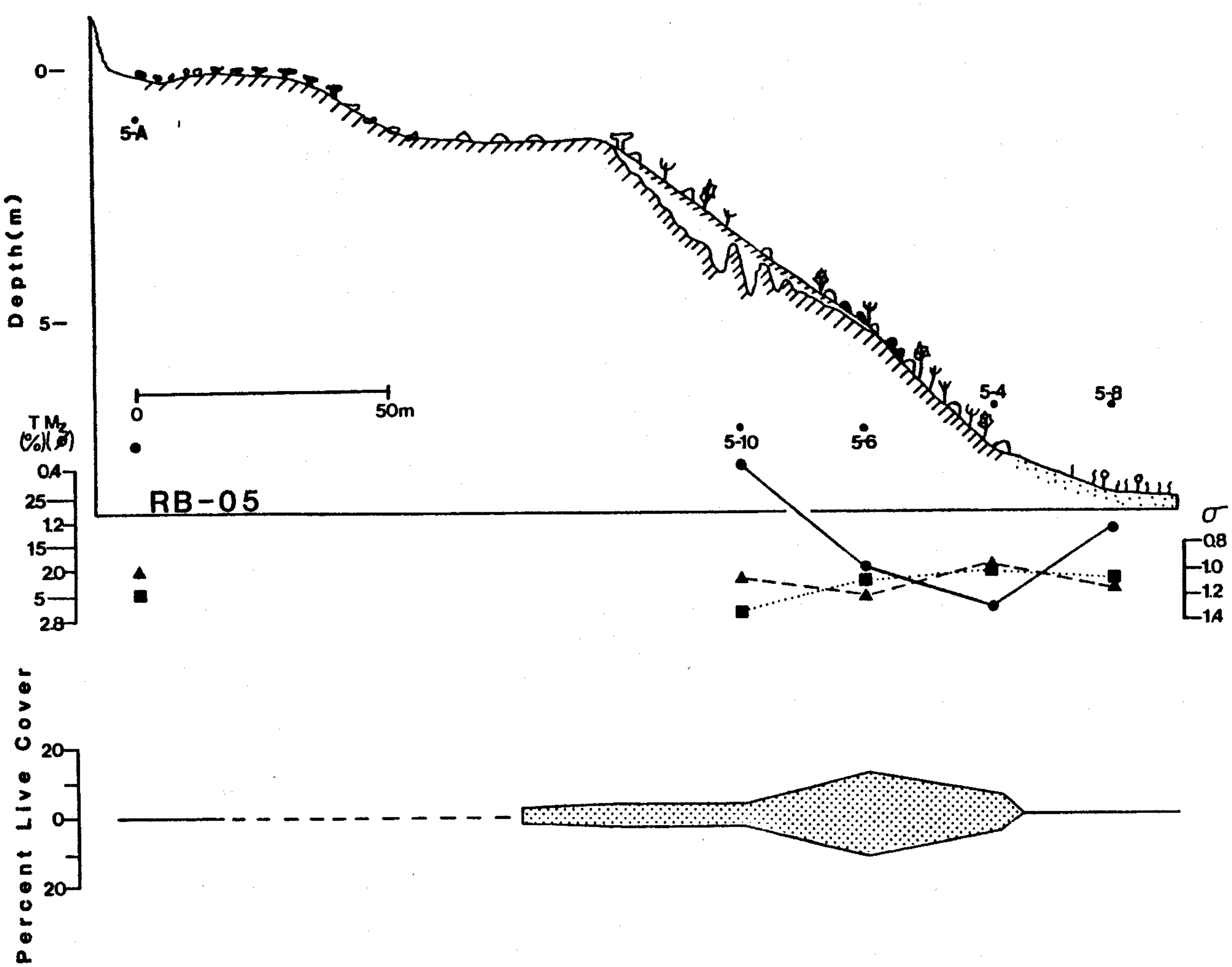


Figure 43. Reef Bay profile RB-05. A symbol key is included in Figure 28.

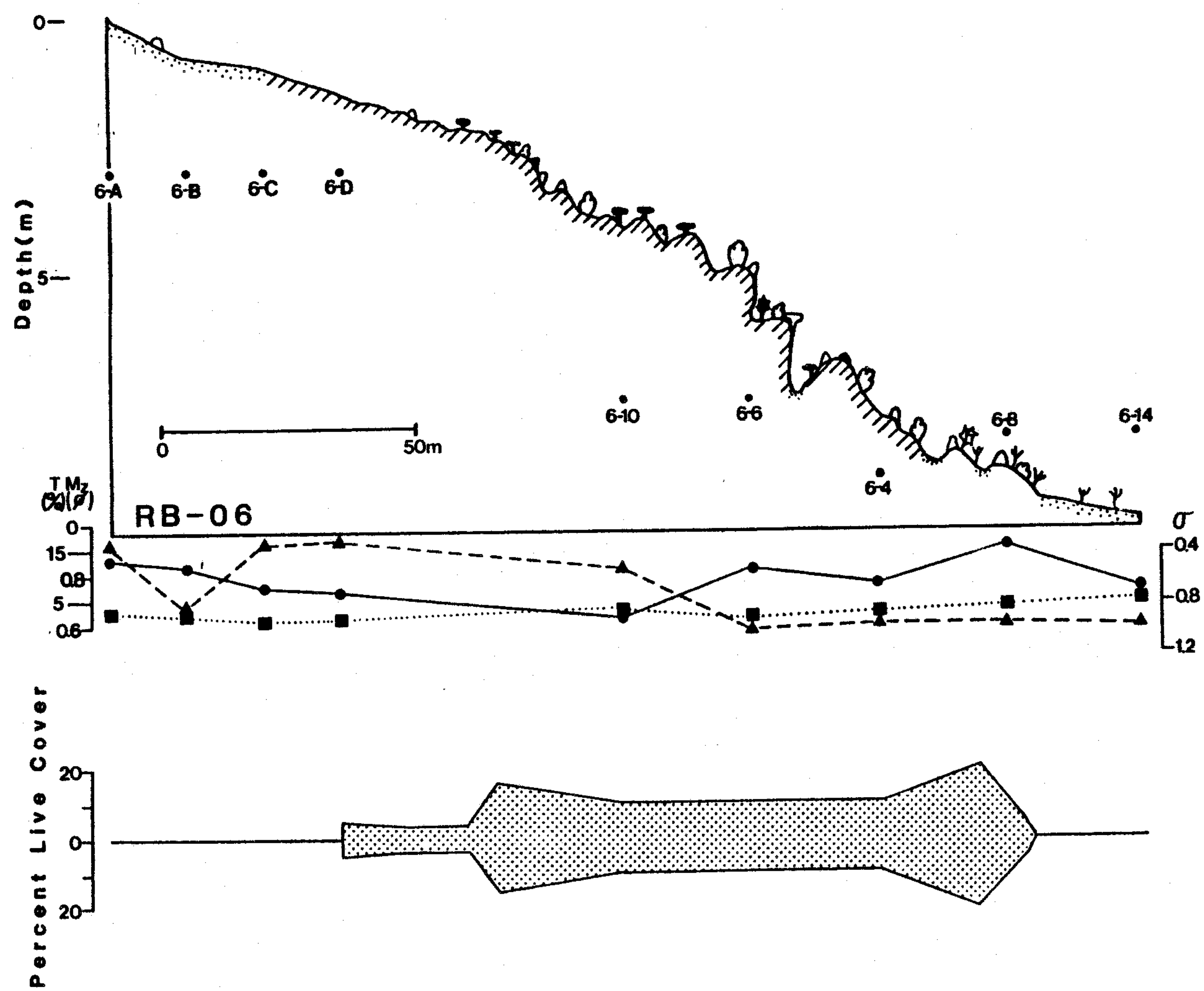


Figure 44. Reef Bay profile RB-06. A symbol key is included in Figure 28.

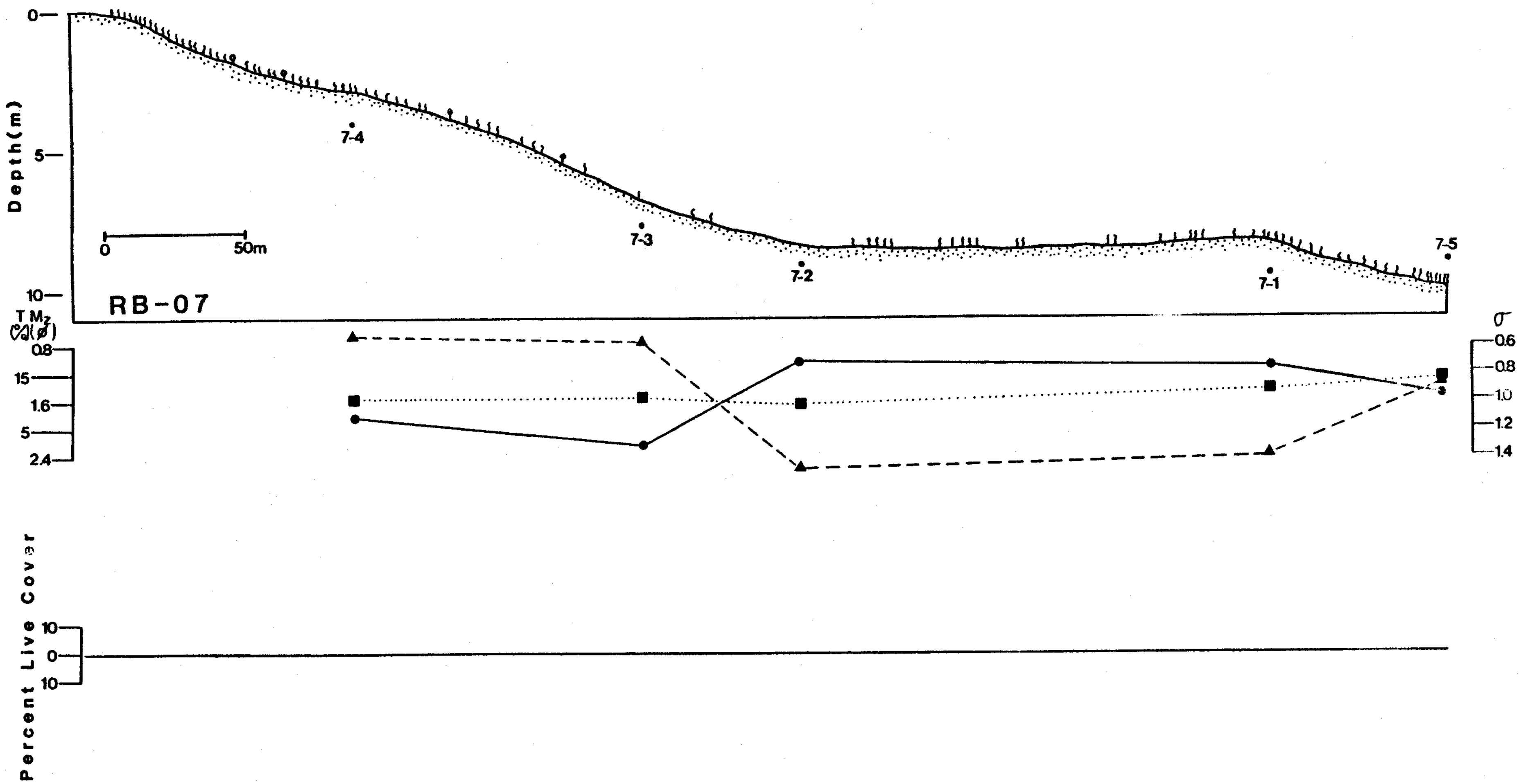


Figure 45. Reef Bay profile RB-07. A symbol key is included in Figure 28.

Transects RB-05 and RB-06 (Figs. 43 and 44) are both located on exposed headlands, in areas of high wave action. The landward ends of the profiles are typically barren, encrusted pavements with no lagoon. Reef growth starts in 1-3 m of water. Very little sediment is encountered along the reef crest or upper forereef environments. Seaward of the pavement surface, sediments range from very coarse or coarse sands on the lower forereef to a medium sand along the bay floor. No appreciable change in sorting values exists along the transects. All sediments are poorly-sorted.

Transect RB-07 (Fig. 45) is located in the channel separating the east and west reef systems. The surface sediments are mostly medium and fine sands, and are constant in character along the transect. Sediments along the inner transect are moderately well-sorted. Sediments found near the break in the reef contain appreciably more coarse-grained material (probably small amounts of reef detritus), and are thus more poorly-sorted.

In summary, general trends in mean grain size and sorting of sediments within Reef Bay are predictable. In areas where there is a lagoonal environment behind the reef crest (RB-02, RB-03 and RB-04), very poorly-sorted sediments are found. This occurrence is due to coarse-grained backreef rubble mixing with the generally fine sediments occupying this low-energy area. In areas where there is no lagoonal environment present (RB-01, RB-05 and RB-06), the best-sorted sediments are generally found along the landward end of the transect. High wave energy causes well-sorted material to deposit in the nearshore environment. On the reef itself, grain size tends to decrease in a seaward direction from coarse to very coarse sands along the reef crest to medium sands at the base of the forereef.

Percent terrigenous material in the surface samples shows several marked trends (Fig. 38). Values on the eastern side of Reef Bay are consistently higher than those on the western side. Values of greater than 60% terrigenous material occur on the landward end of easternmost transect RB-01, while values along the western shore rarely exceed 5%, and are often nearer 2%. Terrigenous sedimentation from the White Cliffs area on the eastern shore has a dramatic effect on terrigenous content in the surface sediments. This probably reflects deposition in the lee of the exposed point to the southeast. Terrigenous material on the western shore of Reef Bay is relatively scarce. The western shore contains no major drainage guts. Those guts that are present drain only a small percentage of the basin, and would not be expected to carry large amounts of terrigenous material. Despite extensive construction near the point on the western shore, terrigenous content along Transect RB-06 (Fig. 24) remained below 5% (Fig. 44).

Terrigenous content of sediments near the bay mouth adjacent to the major guts ranges from 5-15% (Fig. 38). Much of the terrigenous sediment in the bay mouth area is due to runoff from the guts, but some of the sediments are due to lagoonal currents carrying in material from the White Cliffs area. Because this area is more exposed than inner Fish Bay, sediments can be attributed to lagoonal currents carrying in material from the White Cliffs area. Because this area is more exposed than inner Fish Bay, the flushing action by the waves results in lower percentages of terrigenous material.

Reefs

Large-scale bay geometry is related to the underlying antecedent topography. The shape of the embayment is such that it is deepest along a line bisecting the bay and shallower to each side. Reasonably continuous fringing reefs form veneers along the steep sides of the bay. A channel which separates the two reef complexes is related to the major gut draining the upland watershed. The reef development on either side of the channel illustrates the effect of exposure on reef development. Profiles RB-03 and RB-04 (Figs. 41 and 42) are located on either side of the channel (Fig. 24), approximately equidistant from a large gut draining the adjacent watershed. Coral cover on the more exposed western transect (RB-04; Fig. 42) reaches 30% while on RB-03 (Fig. 41) it never exceeds 5%.

With the exception of the outermost profile, the eastern reef complex is characterized by a shallow lagoon, a narrow, exposed reef crest dominated by dead and encrusted corals (primarily *Porites* sp. and *A. palmata*), and a sloping forereef. In general, reef cover increases toward the southeast, in part a response to increasing wave action, but more likely as a response to increasing distance from the major drainage gut at the bay head. Maximum coral cover is 40% and corresponds to the head coral zone along Transect RB-01 and mixed head corals and *A. palmata* along profile RB-02.

The western reef is a veneer over the underlying bedrock, similar to that found in western Fish Bay. Given the exposure of this shore, the low coral cover is surprising. This may be related to the lack of a lagoon to separate the reef face from shore effects. Probably more important is the higher turbidity observed on several occasions along this shore. This suspended material is probably derived from the lagoon to the east, and is held up against the reef face by incoming waves, as illustrated in Figure 46. Reef cover is highest along the inner section of the margin. In this area, the steep slope, which is probably related to erosion by the central channel, provides an environment where sediment settling on the reef is easily shed. As in Fish Bay, the richest cover is related to higher slopes in the lower forereef, removed somewhat from nearshore processes.

A distinctive morph of *M. annularis* predominated along the innermost portion of the western bay. Coral colonies were composed of a selection of "knobs" which effectively divided each colony into smaller sub-colonies. Because of the environmental conditions associated with these corals (higher turbidity, and proximity to a source of terrigenous bedload material), this morphology is felt to be an adaptation to sediment stress. It is possible that this partitioning of the colony surface results in a shorter path along which to move settled sediment. Whatever the explanation, this colony type seems confined to areas of high sedimentation near the bay head. The persistence of this morph in the area over the time period represented in our coral cores intimates that the present levels of sediment stress have prevailed in this area for a considerable length of time. This is discussed in more detail in the next section.

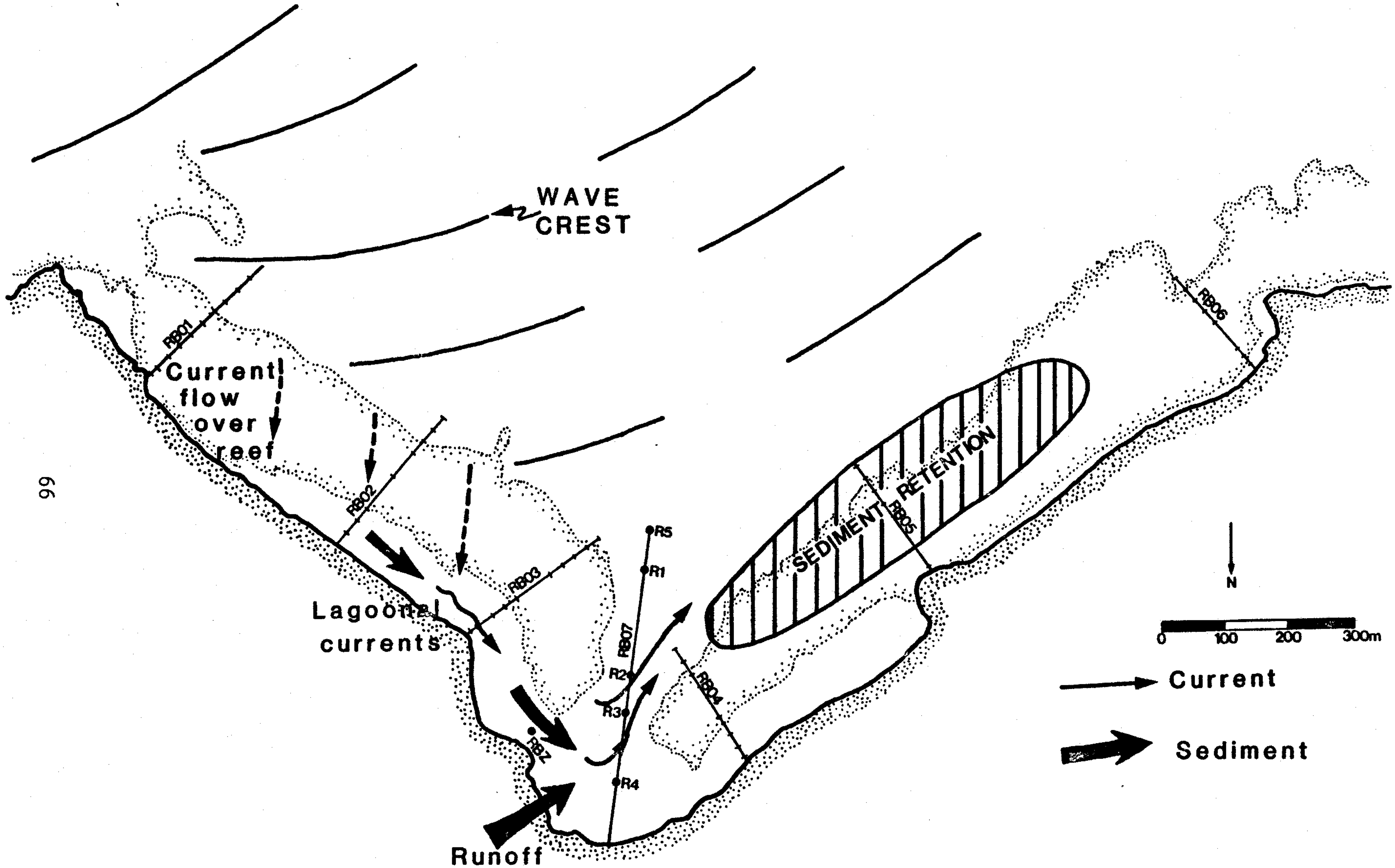


Figure 46. Generalized circulation within Reef Bay. To the east, wind and wave-driven currents carry turbid lagoonal waters toward the bay head. This sediment, along with that derived from runoff, flows toward the western reef face where it is confined by incoming waves. This flow pattern likely accounts for the often-turbid conditions encountered in this region. Flow vectors are based on observations during several field visits.

ENVIRONMENTAL CHANGES

The final part of this study examined the three bays described above with respect to possible changes in environment over time, and related those perceived stresses to temporal variations in the reefs. This study focused on two things: 1) changes in the amount of terrigenous material in the sediments over time, and 2) changes in the growth rates of individual corals on the reefs.

Sediment Cores

Methods - Sediment cores were extracted from each of the study areas, six from Reef Bay, eight from Fish Bay and one from Hawksnest Bay (Figs. 22-24). These cores were taken to determine 1) the controls of the sediment distribution within the bays, and 2) whether there has been a sudden increase in terrigenous sedimentation associated with recent development. Three-inch (7.6 cm) irrigation pipe was pounded into the sediment by hand. A rubber piston attached to a fixed vertical staff provided suction during coring and extraction. Core penetration reached lengths of over 1.6 m in some cases.

On the surface, the length of each core was measured, and the sediments were extruded. At 15 cm intervals, 100-150 gram samples were collected. As a result of the extrusion procedure, the cores became compacted. Compaction was considered as the difference between core penetration and the length of core recovered. The sample locations within the cores shown in Figures 47-50 have been corrected using these values and assuming compaction was uniform throughout each core.

Samples from the cores were wet-sieved through a .0625 mm screen to separate the sand from the mud (Table 10). Each fraction was dried and weighed to determine its importance in the sample. A representative subsample of each fraction was exposed to 10% HCl to dissolve the carbonate fraction. The remaining insoluble residue was dried and weighed to yield the amount of terrigenous material in each sample. 50-100 grams of the sand fraction was dry-sieved at 0.5-phi intervals (Folk, 1974) to determine mean grain size and sorting (calculations assume a mean grain size of 0.044 mm for the material smaller than 4-phi). Data on grain-size, sorting and terrigenous content are summarized in Figures 47 and 48.

Hawksnest Bay - A 1-m long core was recovered near the seaward end of Transect HB-03 in approximately 10 m of water (Fig. 22). Only one core was taken, as this was the only area with sufficiently thick sediment for coring. The sediment becomes finer-grained and more well-sorted toward the top of the core (Fig. 47). Terrigenous content increases slightly upward from 11.0% at the base to 13.7% at the top of the core. These values are similar to the terrigenous content of nearby surface samples.

The eastern edge of Hawksnest Bay is an important site for fine-grained, terrigenous sediment deposition because of its protected location and its proximity to the gut on the eastern shore of the bay. This is reflected in the relatively thick (at least 3 m) deposits of terrigenous-rich,

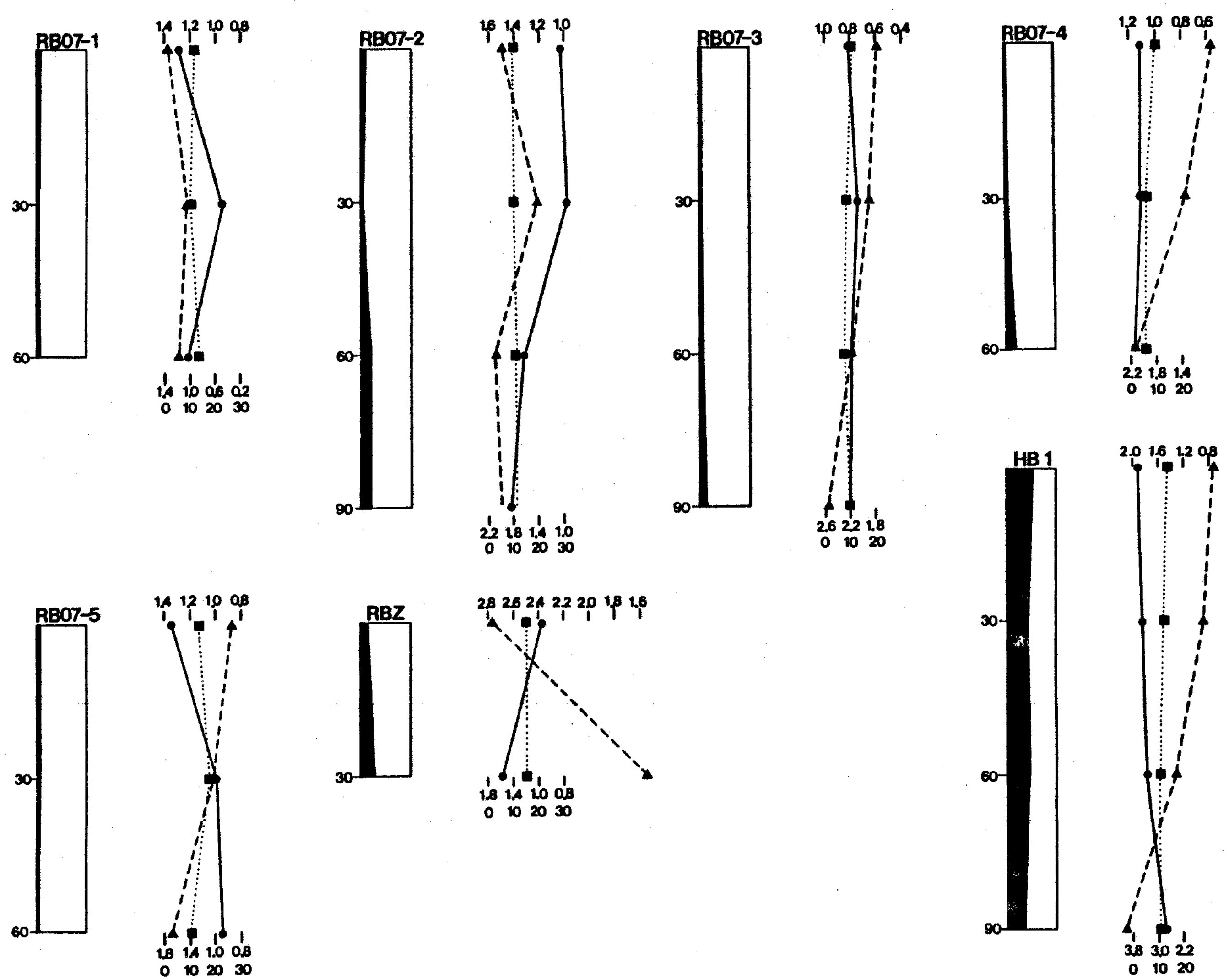


Figure 47. Sediment cores from Reef and Hawksnest Bays. See Figure 48b for key to symbols for core logs.

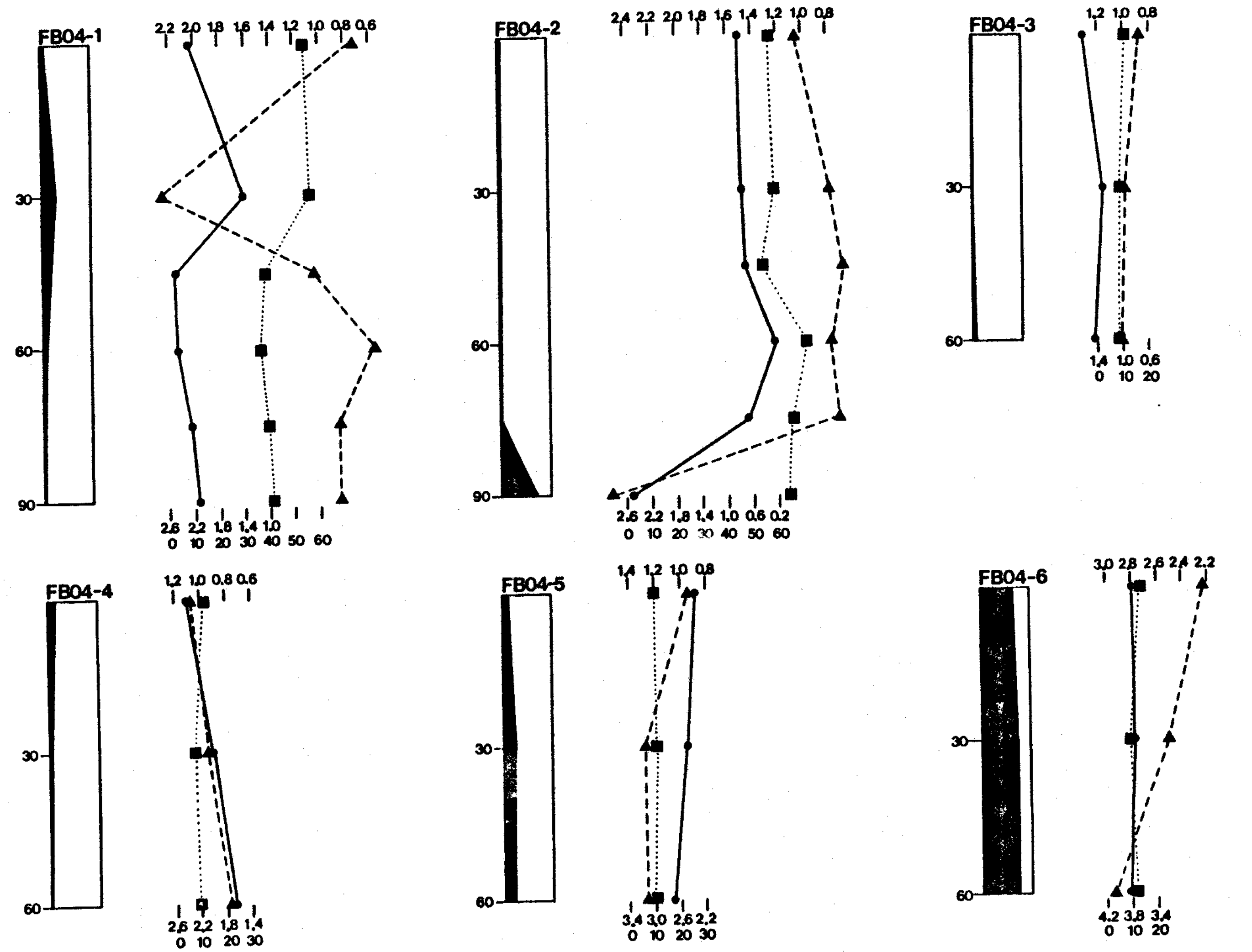


Figure 48a. Sediment cores from Fish Bay. See Figure 48b for key to symbols for core logs.

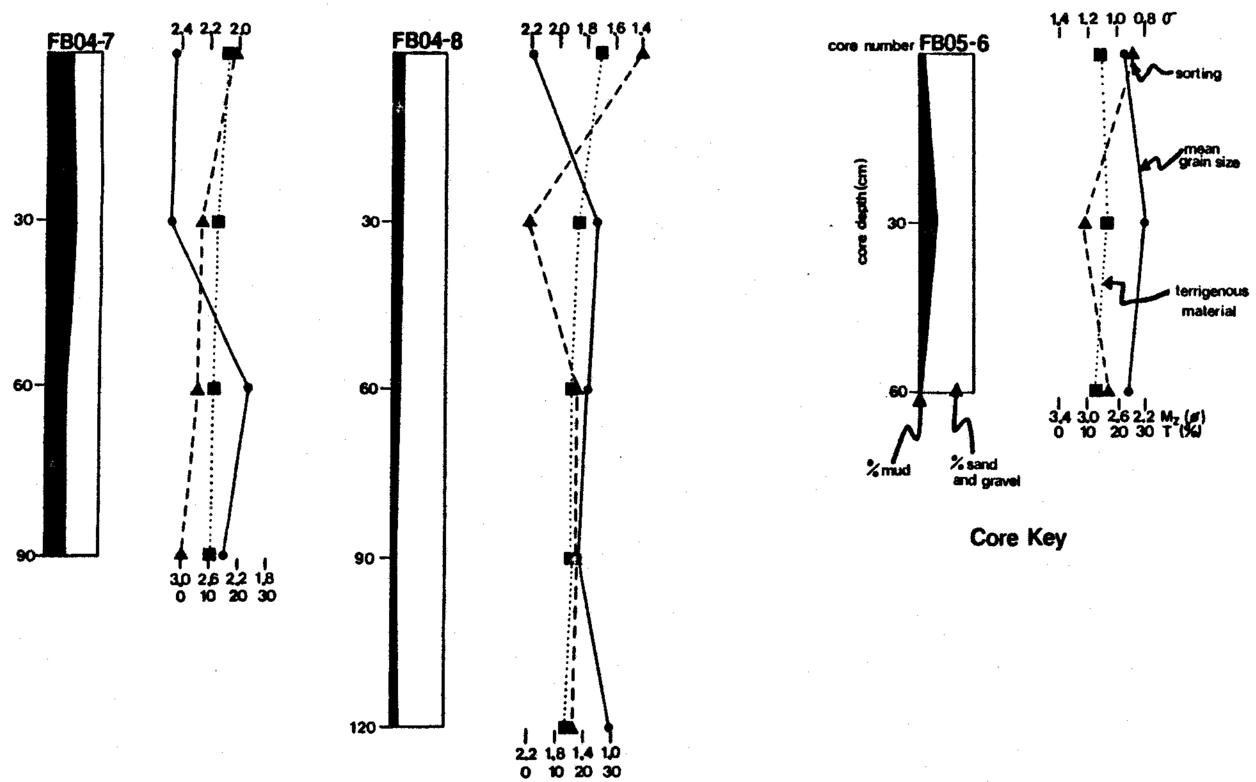
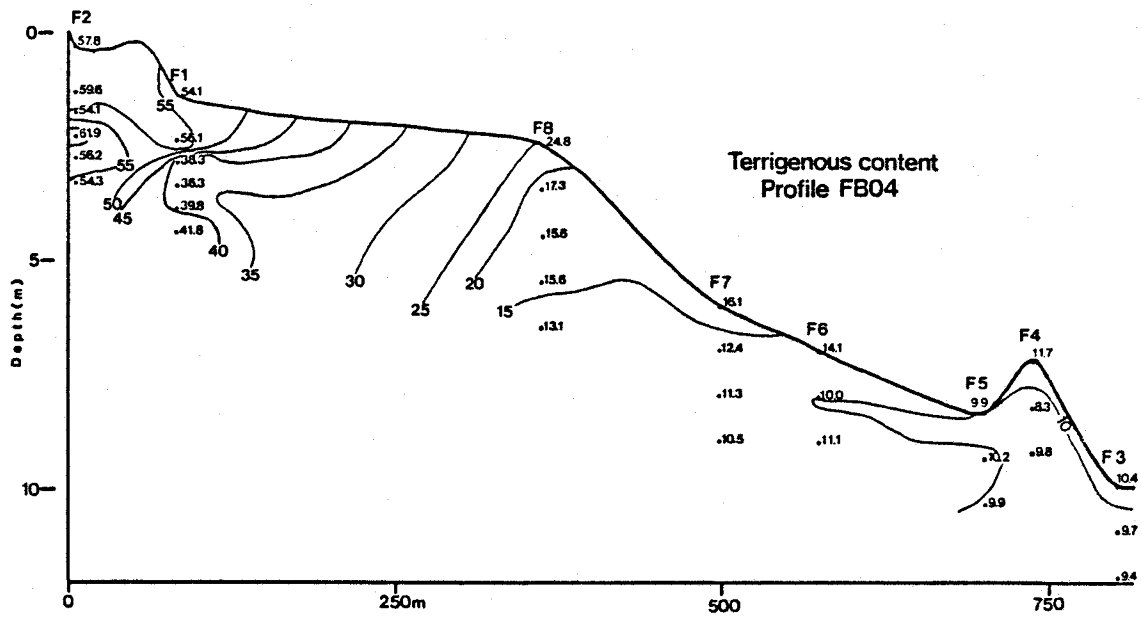


Figure 48b. Sediment cores from Fish Bay (continued) on left. A key to symbols in Figures 47 and 48a is located on the right.

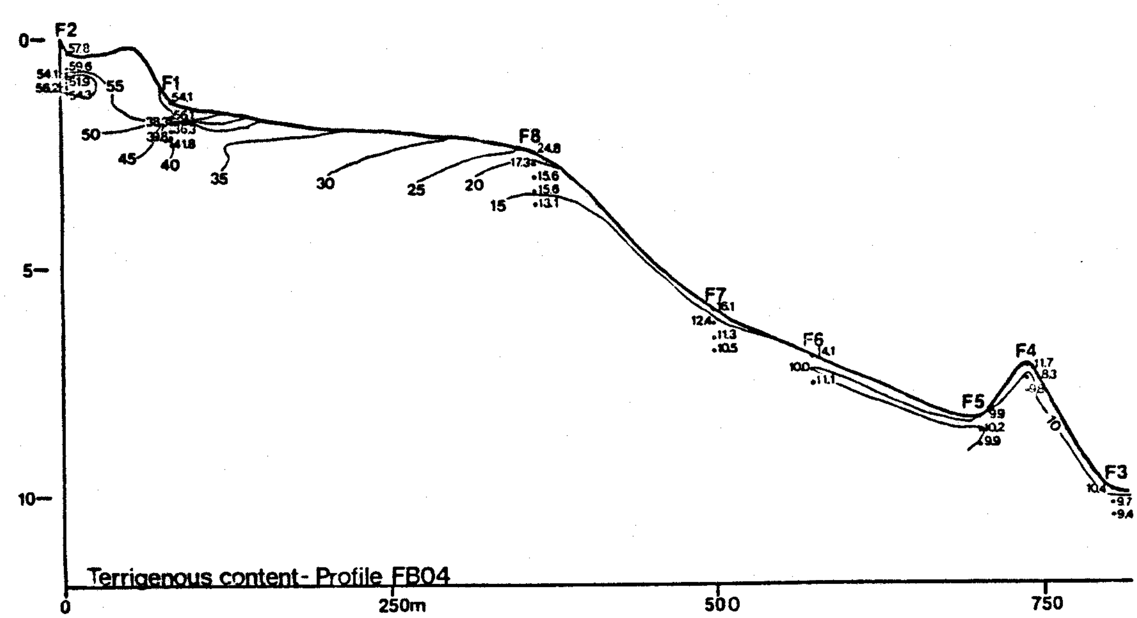


C.I.: 5%

Vertical exaggeration (profile): 35x

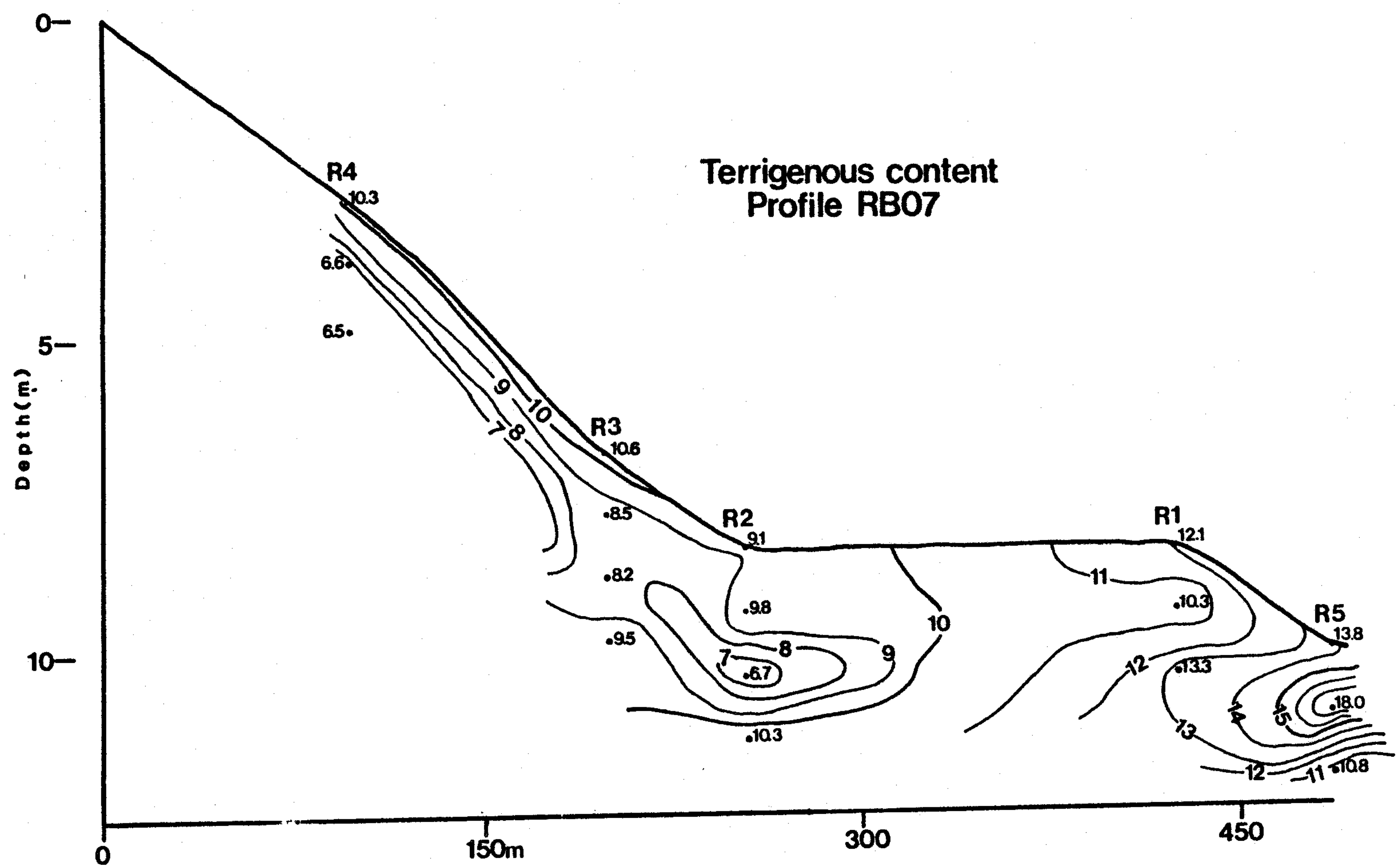
Vertical exaggeration(cores): 116.7x

Figure 49a. Fish Bay profile FB-04 showing percent terrigenous material horizontally in cores. Note: Cores are exaggerated vertically to enhance clarity of contour lines.



C.I.: 5%

Figure 49b. Fish Bay profile FB-04 showing percent terrigenous material horizontally in cores.



C.I.: 1%

Vertical exaggeration (profile): 25x

Vertical exaggeration(cores): 83.3x

Figure 50. Reef Bay profile RB-07 showing percent terrigenous material in sediment cores. Note: Cores are exaggerated vertically to enhance clarity of contour lines.

fine-grained sediments found here. Although it is difficult to reach any far-ranging conclusions based on data from one core, the upward increases in both fine-grained sediment and terrigenous content are not sufficient to make a case for significant environmental change over time.

Fish Bay - Eight sediment cores were taken from Fish Bay along Transect FB-04 (Figure 23). Cores were taken in water depths ranging from 1 m in the interior portion of the bay to over 10 m at the seaward end of the transect. The percent of terrigenous material in these cores was the highest encountered in any of the three bays studied, ranging from less than 9% in the seaward cores to greater than 60% in the interior cores (Fig. 49).

As discussed for surface sediments, grain size and sorting generally correspond to differing energy levels within the bay. In the nearshore environment near the major gut, cores FB2 and FB1 (Fig. 48) are composed of fairly well-sorted, medium to coarse sand. Cores FB6, FB7 and FB8 located in the central part of the inner bay contain the poorest-sorted and finest-grained sediments along the transect. These sediments are positioned in a low-energy environment, away from heavy influence of the major gut and protected from most wave activity by the geometry of the bay. In the more exposed channel between the inner and outer bays (cores FB3, FB4, and FB5; Fig. 48) the sediments again coarsen and become much better sorted.

Laterally, there is an expected decrease in terrigenous percent away from the gut. This trend occurs at the surface as well as at corresponding levels within all cores. The two most interior cores (FB2 and FB1; Fig. 48), contain almost 60% terrigenous material. In the channel cores (FB3, 4, 5 and 6), that value drops to less than 10%.

More significant, however, is an upward increase in the percentage of terrigenous material in each core. Exceptions are the landwardmost core, FB2, and core FB5, which have fairly consistent values throughout. This trend may be explained by an increase in the amount of fine-grained terrigenous runoff from the major guts within the bay over recent time. Alternately, reef development on the southeast shore of the bay may have reduced wave energy, thus inhibiting the removal of the terrigenous material from the bay. If this is the case, and the trend continues, then inner Fish Bay would eventually become a stagnant salt pond, completely separated from open-ocean circulation. Without conclusive data on 1) the time span represented in the sediment cores (i.e. radiocarbon dates) and 2) the development of the bay morphology during that period (i.e. longer cores through the entire reef system), choosing between the two alternatives is difficult.

Reef Bay - Six sediment cores were extracted from Reef Bay, five along the N-S Transect RB-07 and one inside the reef complex (Fig. 24). Water depths ranged from near 1.5 m at core RBZ to approximately 10 m at core RB5. Percent terrigenous material in the cores ranges from 6.5% at the base of the landwardmost core to 18% in the middle of the seawardmost core (Fig. 50). Grain size within cores along Transect RB-07 increases slightly in a seaward direction (Fig 47). The landward cores are composed primarily of fine sand while the seawardmost cores are predominantly medium to coarse sands. There is little grain-size variation within the cores. Sorting along the transect tends to decrease seaward. The finest, most well-sorted sediments are found in the landwardmost cores.

Terrigenous content is significantly lower than in Fish Bay despite a similar watershed area. This is probably due mostly to the differing degrees of exposure in the two bays. Fish Bay is protected, and fine-grained sediment from the major guts can settle out in a relatively quiet environment. Reef Bay is more open. Nevertheless, there is sufficient sheltering of the innermost portion of the bay head to allow fine-grained sediments to be deposited at stations RB3 and RB4 (Fig. 45).

Terrigenous percentages within the cores increase in a seaward direction, most likely a function of water depth. Closer to shore, there is a slight increase in terrigenous content toward the sediment surface, but percentages remain low throughout the cores. The seaward cores reflect relatively constant conditions and no systematic variation in terrigenous content was seen.

Coral-Growth Study

Methods - Fifteen large (greater than 1 m) coral heads were cored in the three bays (Figs. 22-24). The sites were located to provide representative samples of the diverse habitats and marine conditions in the area. These include: (1) proximity to drainage guts, (2) wave exposure on alternate sides of the bays (3) openess of the bays and, (4) water depth. The largest available corals were selected in order to maximize the length of time recorded by their growth.

In highly stressed areas, *Montastrea annularis* often grows in a knobby morphology. Rather than a single hemisphere, the colony is subdivided into numerous, smaller lobes. Cores through these provided a very discontinuous record due to the segmented character of the colony, and porous nature of the skeleton. Therefore, during the latter part of the coring program, only massive forms were cored.

The cores were taken with a hydraulic drill similar to that described by MacIntyre (1975). The cores were slabbed longitudinally along the bias of the corallites. 5 to 6-cm thick slices were X-rayed on a Faxitron X-radiograph machine using Dupont Cronex 4 medical X-ray film. Positive contact prints were made from the negatives, and the spacing of the annual growth bands was measured using a Houston Instruments HiPad digitizer.

A typical core segment is included as Figure 51 to illustrate the bands revealed by X-rays. This banding pattern has been shown to be annual in *M. annularis* (Knutson, *et al.*, 1972). Density-band analyses have been used elsewhere to interpret environmental controls in both modern (Hudson, *et al.*, 1976; Dodge and Vaisnys, 1977) and ancient (Runcorn, 1967; Hubbard, *et al.*, 1985, in press) corals. The underlying principal is that any degradation of the water quality (here, a decrease

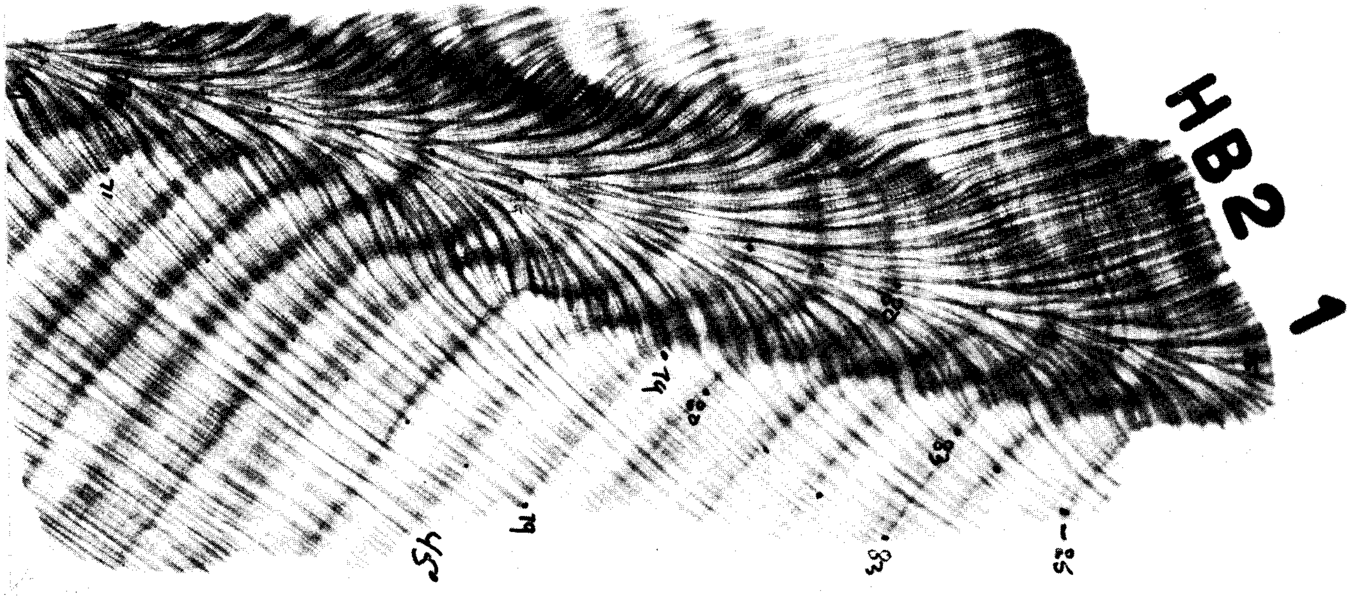


Figure 51. X-ray positive of a typical core segment showing annual growth bands.

in light due to an increase in turbidity or sedimentation rate) will result in compromised coral metabolism and lowered growth.

The age of an individual coral was calculated by counting the annual bands. Continuous segments of the cores were assigned absolute ages. Where intervals between segments were ground away by drilling, growth bands were matched as well as possible across the discontinuity. In extreme cases, a reasonable estimate was made of the period missing based on the length of the core recovered versus the penetration by the drill. The total ages of such discontinuous cores were calculated by adding the number of years from each individual segment. This undoubtedly introduced minor errors in the actual dates towards the bottom of some cores. The ages of colonies with the knobby morphology, therefore represent minimums, while those from the more massive corals are closer to absolute.

Growth rates were plotted for all corals against colony age for 5-year average intervals (Figs. 52-54). Selected colonies (R1, R2, R6, F2, H3) were plotted annually (Fig. 55). Corals will vary their growth rates under normal conditions in response primarily to light (usually with depth). Therefore, it is difficult to compare growth rates between corals, because those growth rates are expected to be different, with or without stress. To eliminate this variability, the raw data were normalized for each coral by dividing the

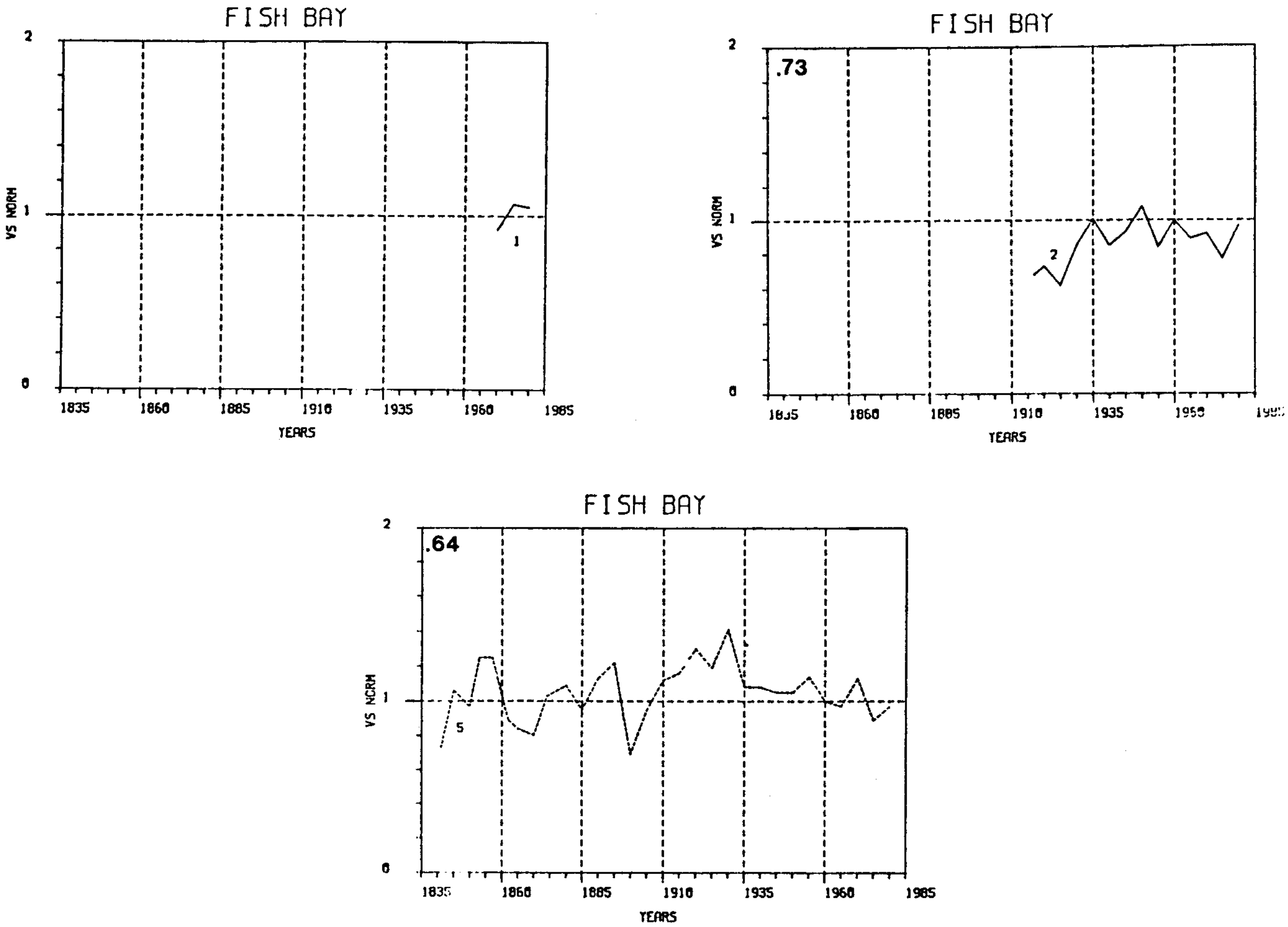


Figure 52. 5-year average growth rate for cores from Fish Bay. All values have been normalized to remove variability between corals due primarily to depth of occurrence. To obtain actual growth rates, multiply values derived from the graph by the number in the upper left-hand corner.

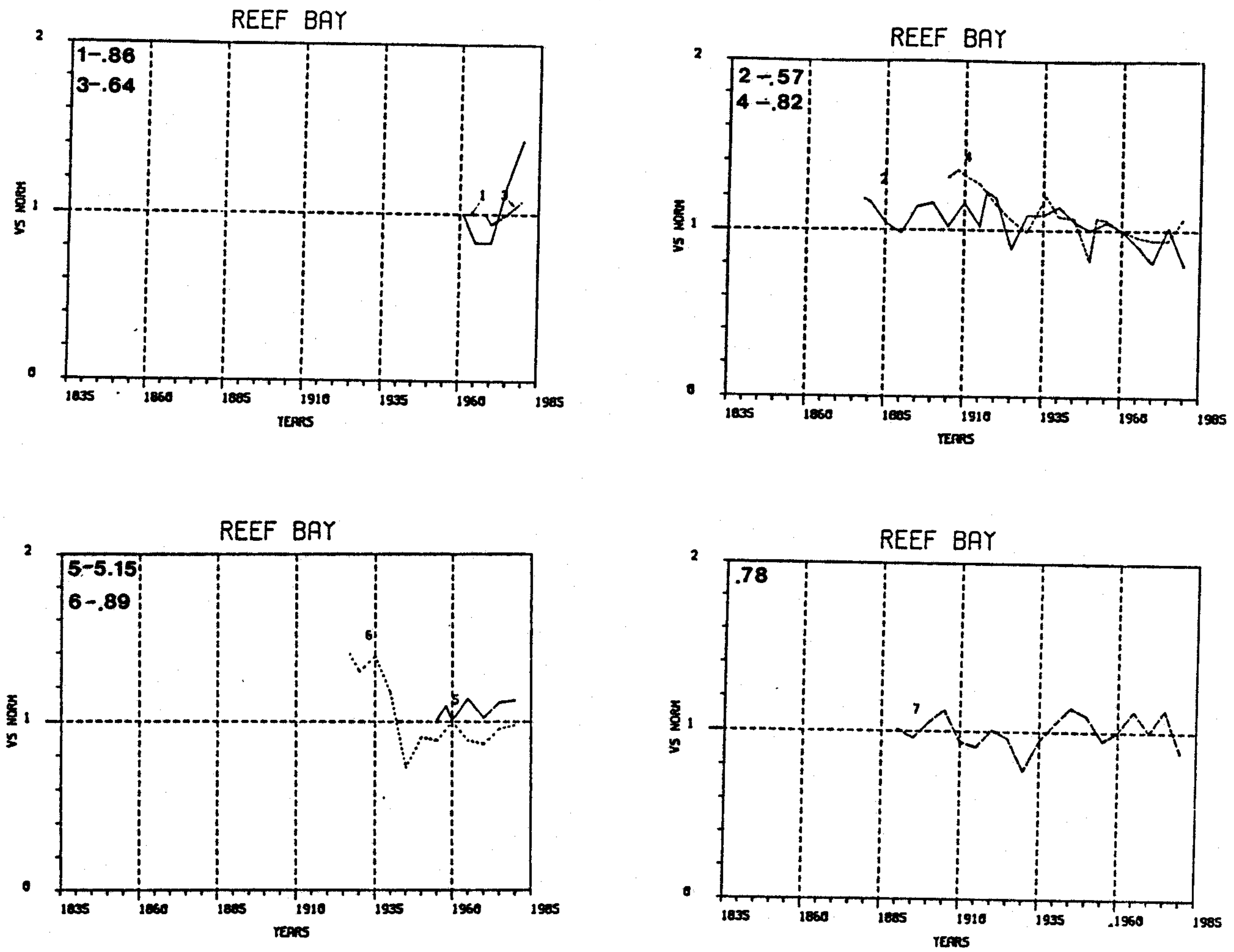
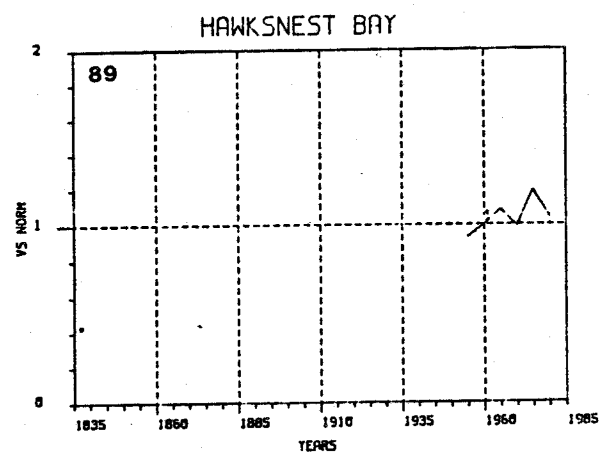
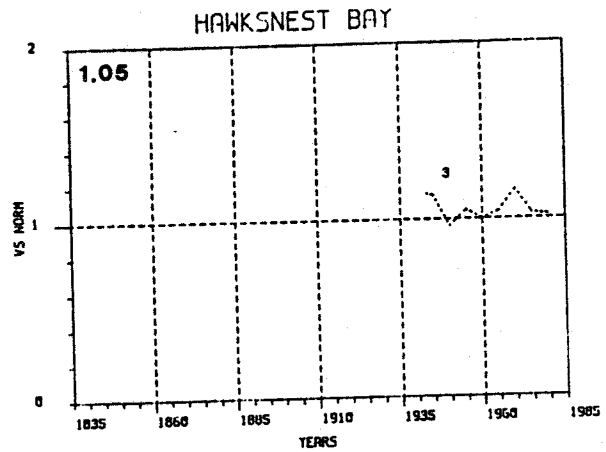


Figure 53. 5-year average growth rate for cores from Reef Bay. All values have been normalized to remove variability between corals due primarily to depth of occurrence. To obtain actual growth rates, multiply values derived from the graph by the number in the upper left-hand corner.





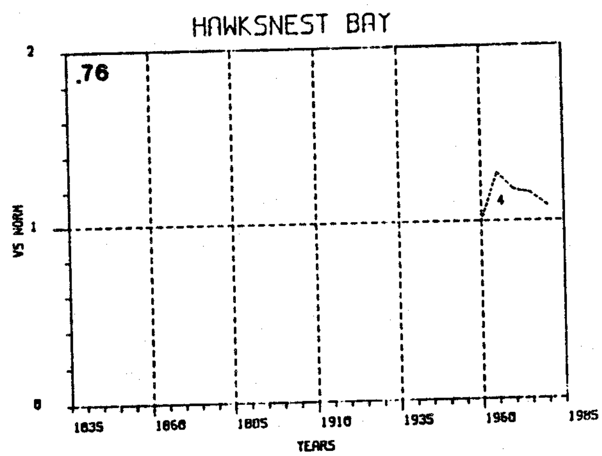


Figure 54. 5-year average growth rate for cores from Hawksnest Bay. All values have been normalized to remove variability between corals due primarily to depth of occurrence. To obtain actual growth rates, multiply values derived from the graph by the number in the upper left-hand corner.

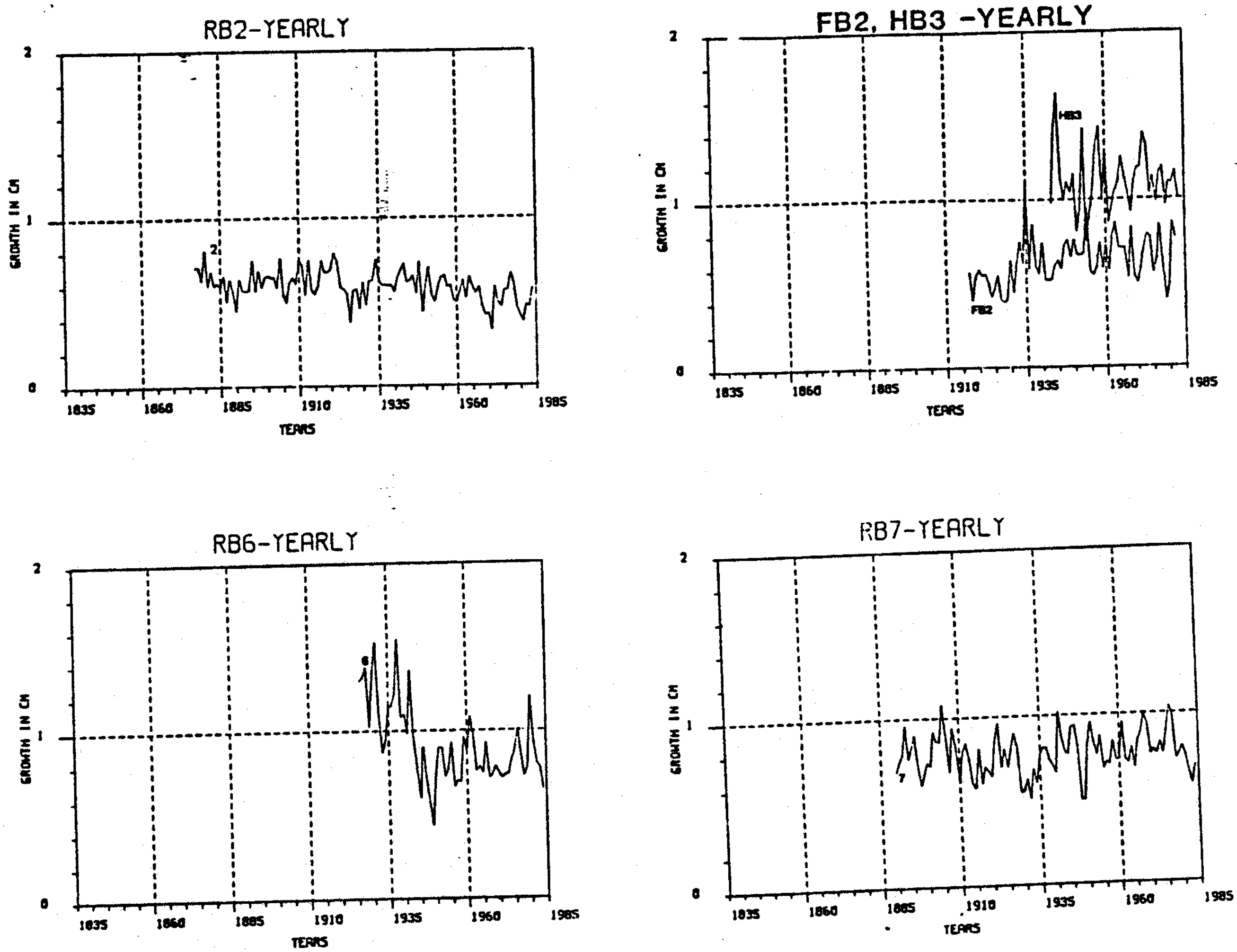


Figure 55. Annual plots of growth rates for selected corals from the three bays.

growth rate in any given year by the average growth rate between 1960 and 1964 for that colony. Rainfall was low during this time period, and it was felt that under these conditions, the effects of land-derived runoff would be minimal and uniform among the three bays. The 1960-64 growth rate for each coral is given on the figures. To convert normalized growth rate to actual growth rate, the reader should multiply the value from the graph by the normalization factor provided.

Rainfall data provided by the National Park Service on St. John were averaged in a similar manner, and are summarized in Figures 56 and 57. The raw data were inspected to identify months in which more than 9 and 12 inches of rain fell on St John (not to be confused with 9 or 12 inch/24 hour storms). Figures 58 and 59 summarize the rainfall under those conditions on an annual basis.

The nature of the study also required the comparison of the growth rates with selected historical periods having characteristic patterns of land use. Based on discussions with George Tyson, the following periods were chosen:

Early cultivation period:	pre-1910
Post-cultivation period:	1910-1949
Modern (development) period:	1950-1985

For each coral core, the means of the growth rates within each period were statistically compared to each other for significant differences by a one-sided t-test.

In Hawksnest Bay, 12 smaller corals were also collected intact. These coral heads were collected from three sample sites within the bay (Figure 22). Annual growth rates were determined for these corals in the same manner as for the cores. Growth rates from the small coral heads were compared to recent rainfall data to determine if the small coral heads were more susceptible to runoff influence (Fig. 60).

<u>Results</u> (cores) - Fifteen <u>Montastrea annularis</u> cores were taken in Hawksnest, Fish and Reef Bays (Figs. 22-24, 52-55). Seven of the cores provide a continuous record into the 1910-1949 post-cultivation period, and four cores (R2, R4, R7,F5) extend into the cultivation period prior to 1910. In addition, some of the cores have discontinuous records that, although not precisely datable, do provide a record of minimum ages prior to the turn of the century.

The ages of the cores are shown in Figure 61. The youngest cores are those from Hawksnest Bay (post-1910's) and those from corals with a knobby morphology in Fish and Reef Bays. The absolute ages of the latter may be somewhat biased, due to the discontinuous nature of the cores.

The oldest cores tend to be present at greater depths and further from the gut (Fig. 62). This patern reflects significant stress events during more recent time near the shallower corals closer to shore.

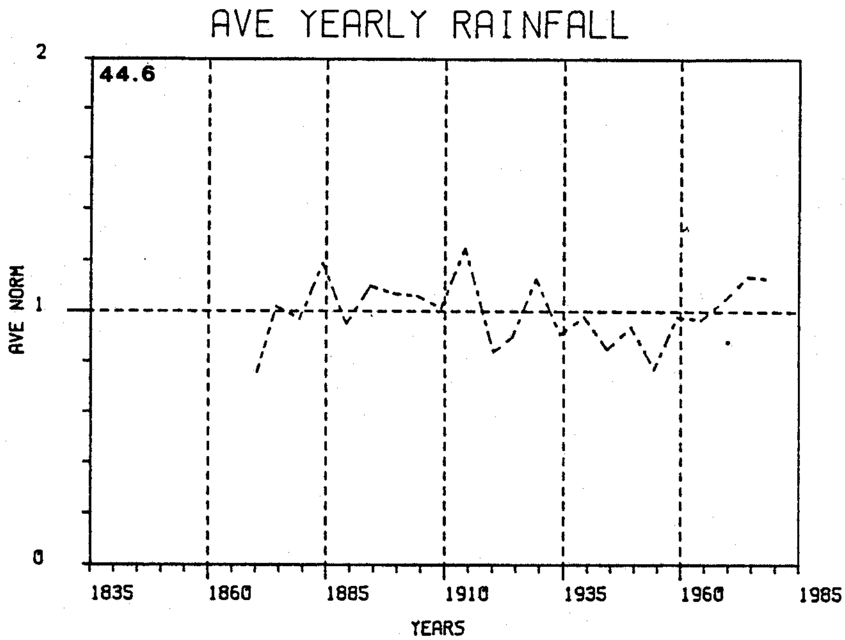


Figure 56. Average yearly rainfall for St. John. Each point is a 5-year average of data provided by the National Park Service on St. John. Data are normalized in the same fashion as for coral growth. To obtain actual rainfall, multiply values derived from the graph by the number in the upper left-hand corner.

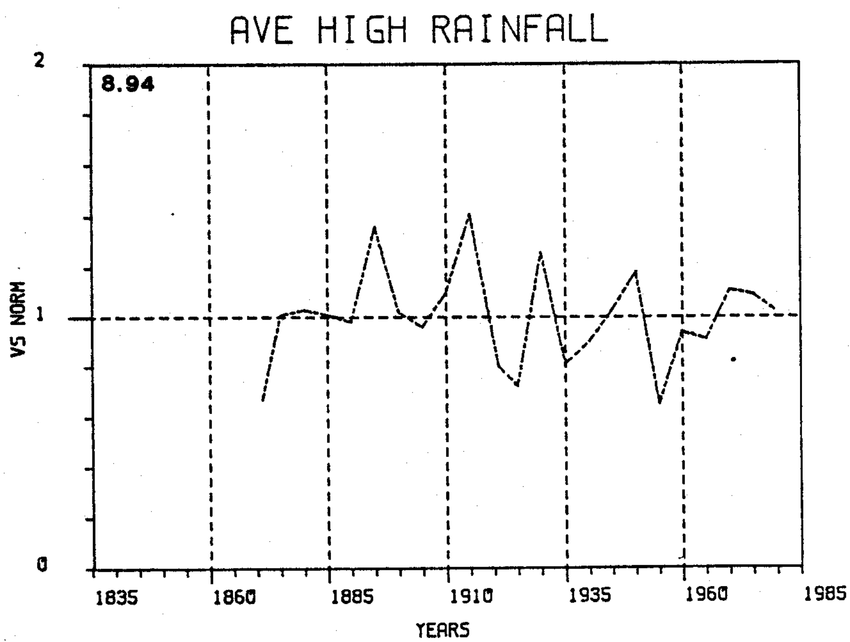


Figure 57. Maximum yearly rainfall for St. John. The maximum monthly rainfall was averaged over five-year periods. Data are normalized in the same fashion as for coral growth. To obtain actual rainfall, multiply values derived from the graph by the number in the upper left-hand corner. Data provided by the National Park Service on St. John.

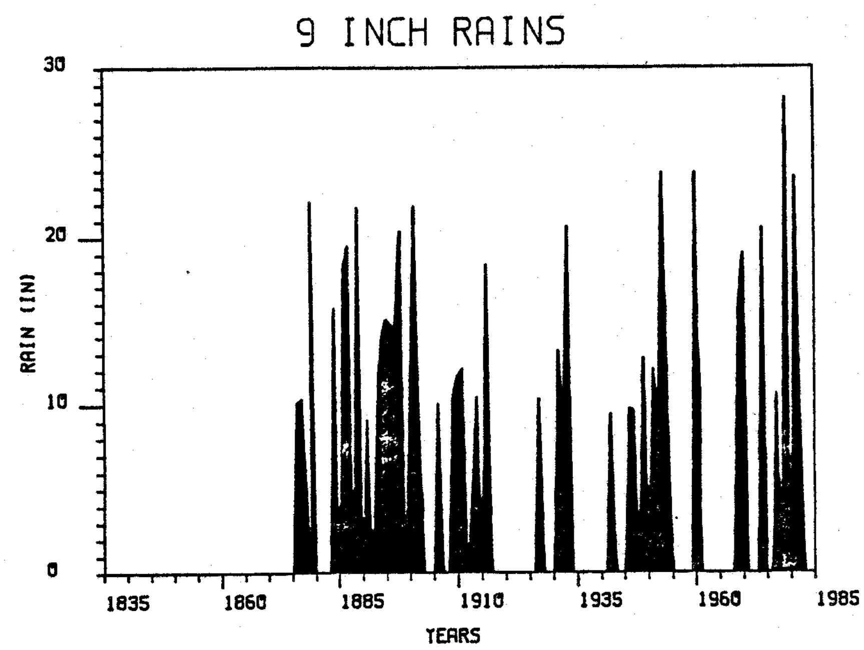


Figure 58. Graph displaying amount of annual 9" rainfall. The value reported is the sum of all monthly rains equal to or exceeding 9".

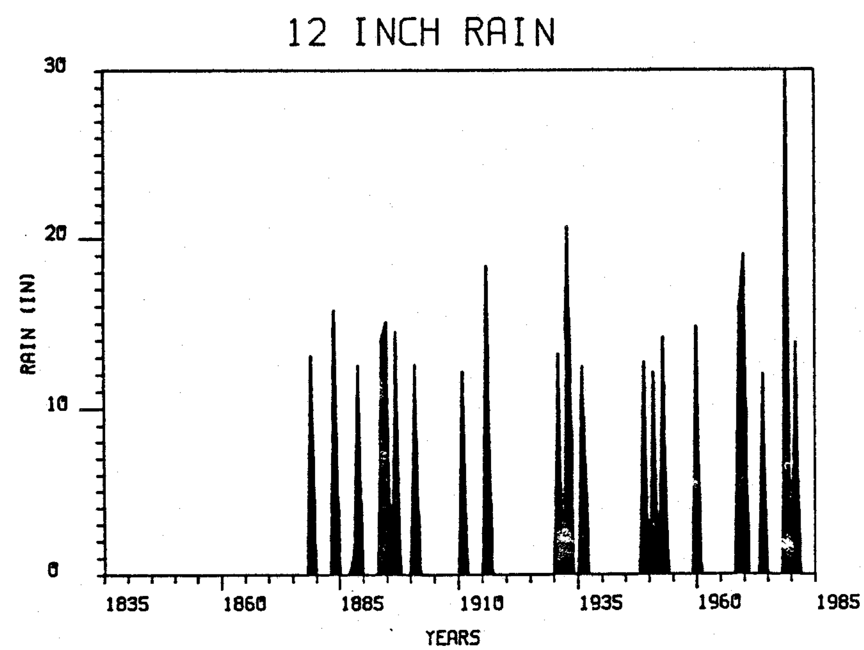


Figure 59. Graph displaying amount of annual 12" rainfall. The value reported is the sum of all monthly rains equal to or exceeding 12".

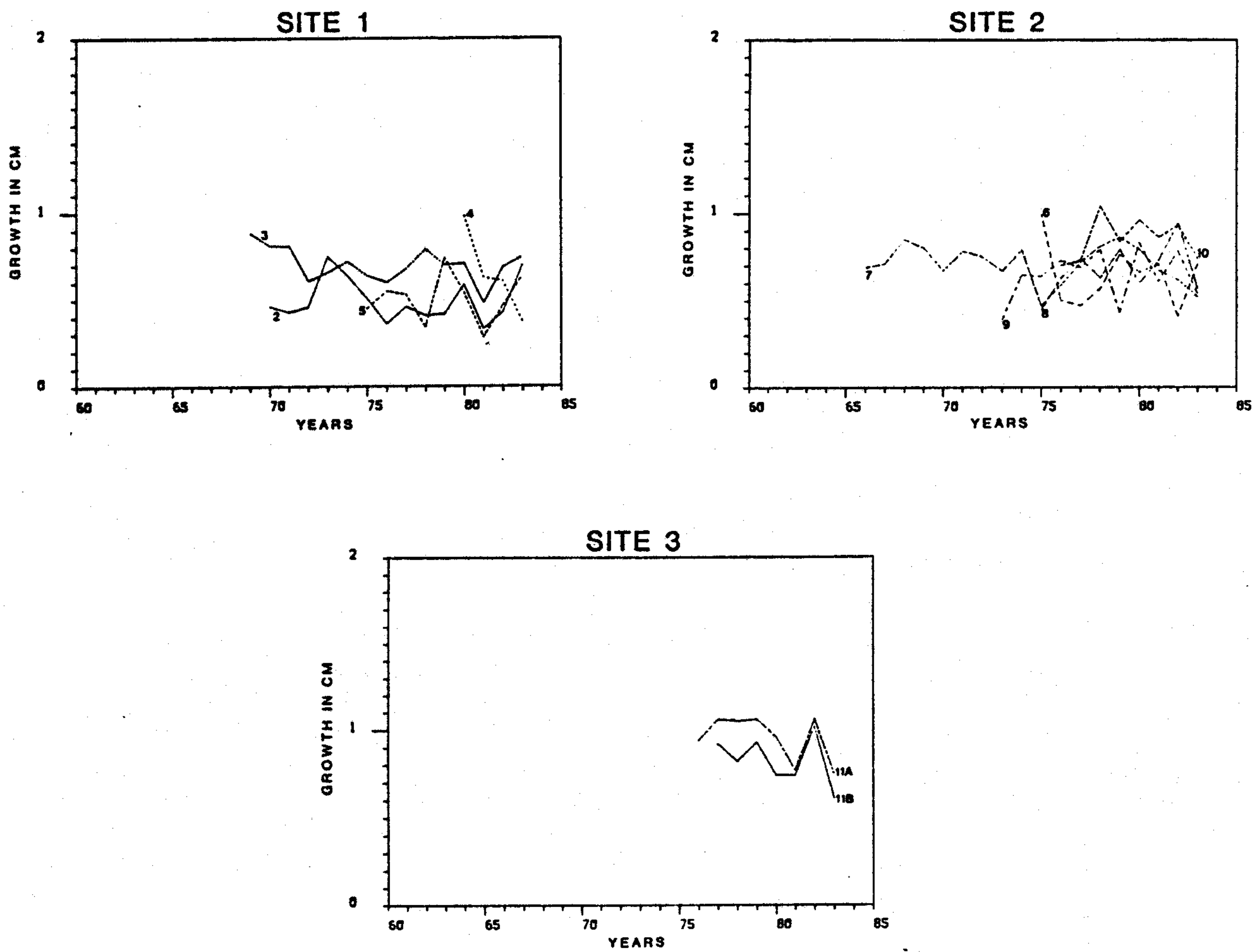


Figure 60. Annual growth rates for small coral heads collected from three sample sites in Hawksnest Bay (for sample-site locations, see Figure 22).

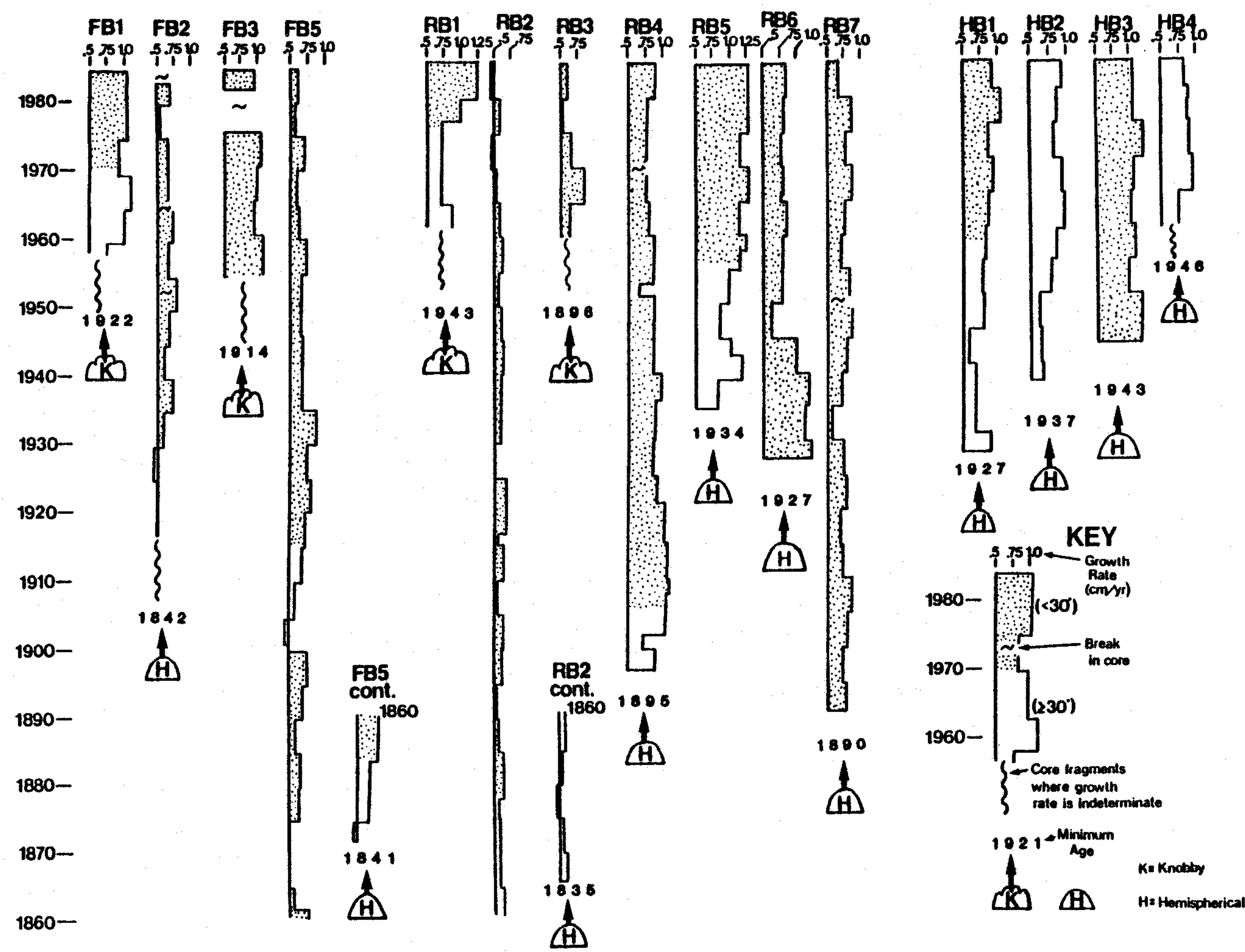


Figure 61. Summary of annual growth data from coral cores in the three bays on St. John. Within 5-year periods, growth rates are grouped in intervals between 0-0.5, 0.5-0.75, 0.75-1.0 and >1.0 cm/yr. Variations in the direction of coral growth relative to the axis of the core are shown by the solid white and stippled pattern in the histograms. Data from slabbed coral heads indicate that growth rates derived along axes within 30 degrees of vertical are essentially identical. Therefore, only those values (stippled) were used in the growth-rate comparisons. The dates within the core intervals (e.g. 1943 for HB3) indicate the minimum age of the coral. This number is based on summing the number of growth bands in all core segments. The symbol at the base of the core indicates the morphology of the cored colony.

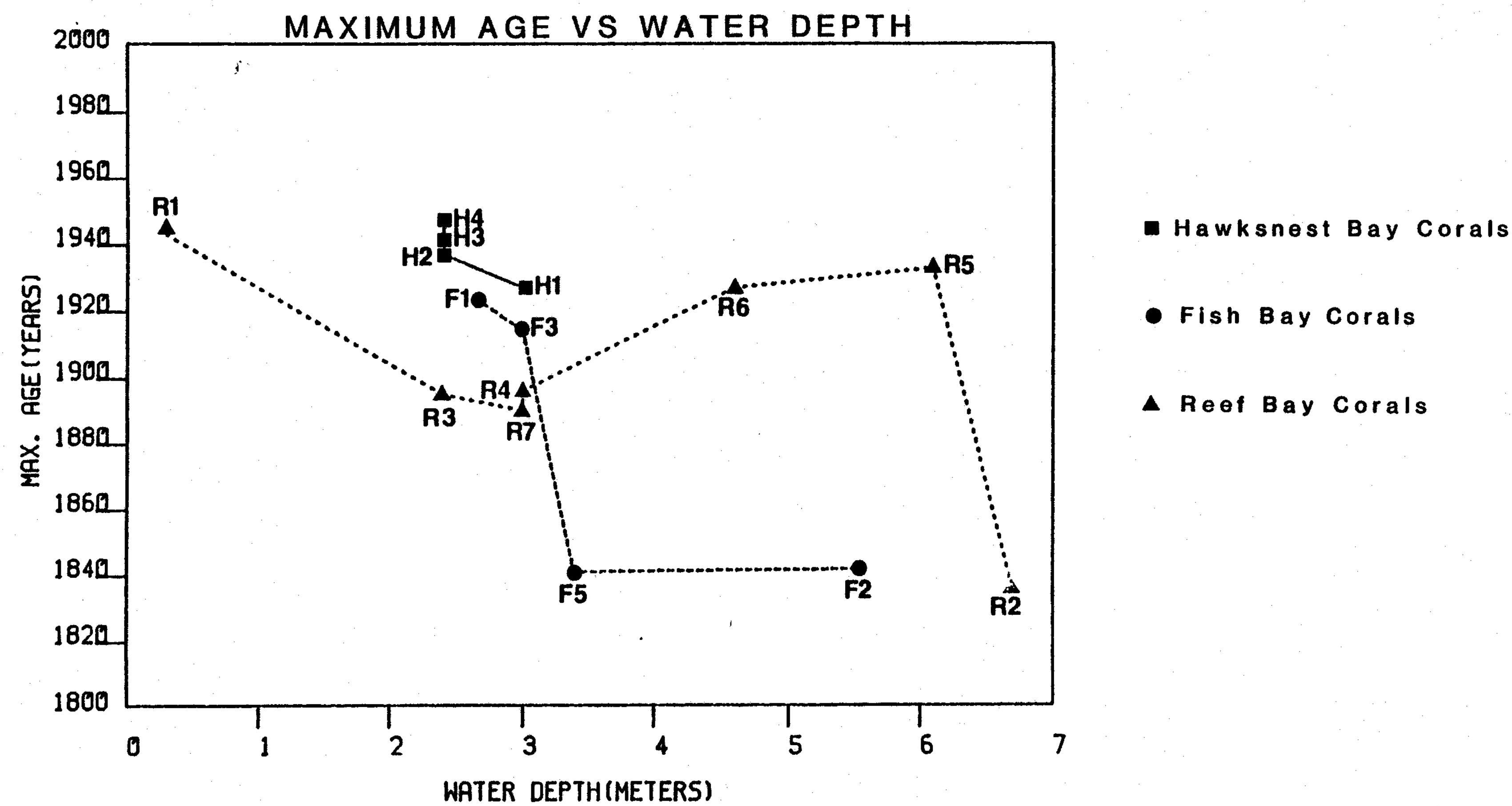


Figure 62. Graph of maximum coral age versus water depth in the St. John cores. Note the trend toward increasing age with depth (and away from sources of runoff).

The absolute growth rates for the corals during the modern period (1950-1985) are similar to those cited in the literature (Dustan, 1975; Gladfelter, et al., 1978). Figure 63 shows a clear decrease in growth rate with increasing depth for the modern period (1950-1985). At any depth, there is a 10-20% difference in growth rates for corals from the three bays. Nearly all the corals have present-day growth rates similar to corals from the open-shelf margin of Cane Bay on St. Croix (Hubbard and Scaturo, 1985).

Short-term fluctuations in coral-growth rate likely represent acute variations in water clarity. These short-term fluctuations were compared to rainfall records to determine whether extreme runoff events from major storms could be correlated with decreases in coral growth. Within some cores, decreases in growth rate can be correlated with rainfall events on occasional instances. The relationship, however, is by no means consistent, nor can similar patterns be discerned in even adjacent cores. For example, cores R2 and R7 (Fig. 53) do show reasonable correlation with some rainfall events, but are located well away from gut-related sediment sources. While the apparent correlation in coral R2 might be explained by currents during heavy rains depositing excess sediments at that site, this is difficult to imagine at site R7 (Fig. 24) on the exposed east point of the bay. The patterns of growth occurring in adjacent cores R5 and R7 (Fig. 53) are almost completely opposite to one another. Also, corals located near guts, such as R1, R3, F1, F3, and H1-4 (Figs. 52-54), all have ambiguous records when they should be expected to display the most profound effects.

On a time scale greater than 20 years, more consistent trends emerge. The mean growth rates for each of the three time periods listed above are summarized in Figure 64. Based on a one-sided t-test, five cores (R2: .005, R4: .005, R6: .005, F5: .005, H3: .15) have significantly diminished growth rates of 10-20% between the post-cultivation period and the present. Coral F2, showed no significant difference, and coral R7 had higher growth rates in recent times.

It is tempting to atrribute this decrease in growth rate in 5 of the 7 cores to recent development. However, in four of these corals that extend back further into the cultivation period, three had higher growth rates during cane production. Thus, the long-term trend appears to be one of a gradual decrease in growth over time, regardless of land use.

To test whether changing temporal boundaries between land-use periods would affect the trends just discussed, the initiation of the post-cultivation period was extended back to 1860, and the recalculated means were compared. The overall pattern remained the same (Fig. 64). With the exception of core R7, the growth rates in the latter part of the 1800's and early part of the 1900's were significantly higher (by 10-20%) than the present (1950-85) growth rates, and a pattern of consistently decreasing growth rates through time was still evident. If this is to be related to man's influence, then some mechanism must be recognized whereby sedimentaiton has gradually increased over the past 100-200 years. This is clearly contrary to our initial hypothesis that reef development would have been greatest during the post cultivation fallow period (1910-1949), and lessened by more intense land use on either side.

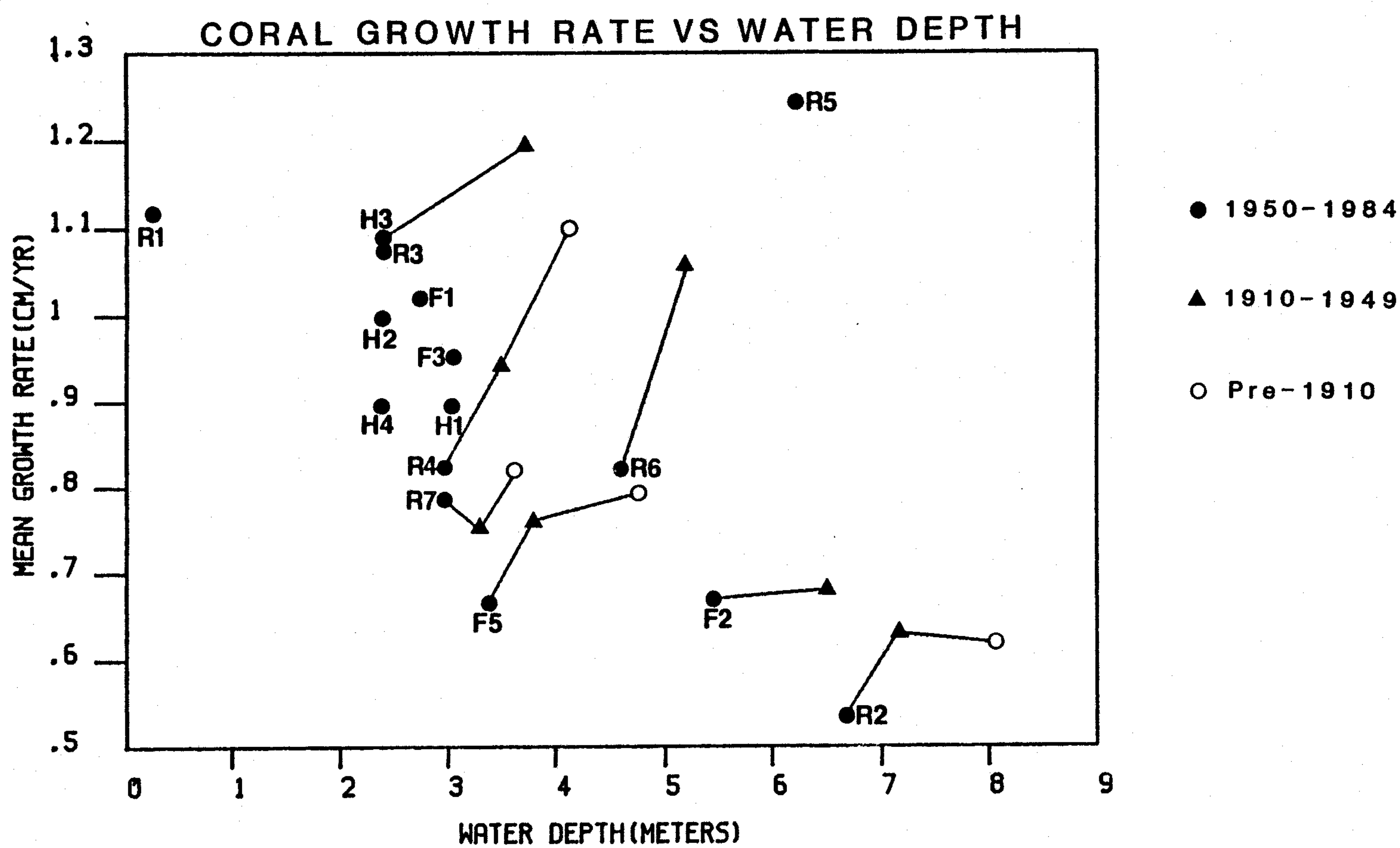


Figure 63. Graph of coral-growth rate vs. depth in the St. John cores. The dashed line describes the range of growth rates for corals from simlar depths at Cane Bay on St. Croix (Hubbard and Scaturo, 1985). Changes in average-growth rate during the three development periods are also shown.

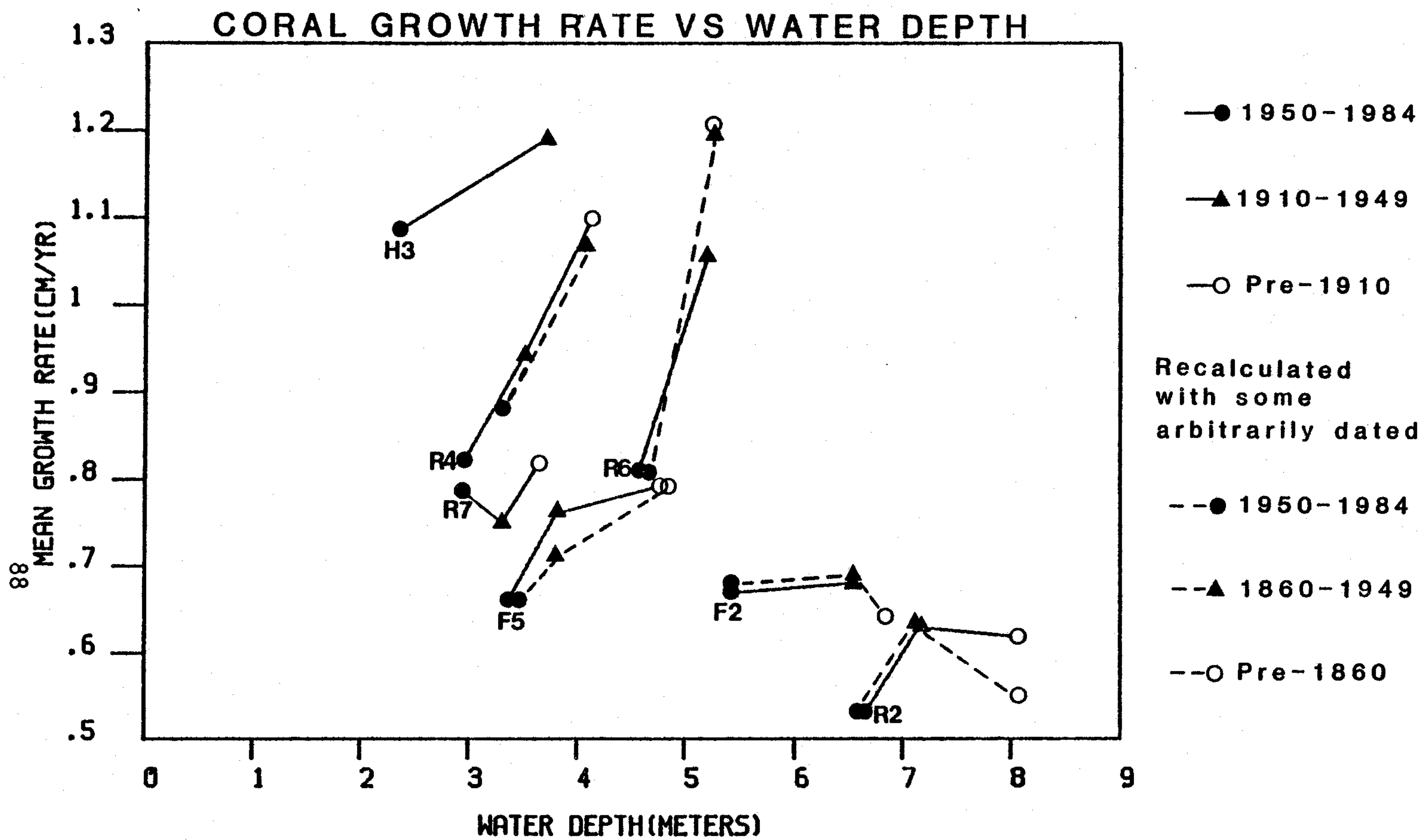


Figure 64. Graph of coral-growth rate vs. depth in the St. John cores. Points connected by solid lines are taken from Figure 63. Points connected by a dashed line are those based on different boundaries between the three development periods. Note that despite changed temporal boundaries, the trends remain the same. To extend the range of some cores beyond 1860, it was necessary to use data from coral segments where the growth axes varied more than 30 degrees from the vertical (i.e. growth rate drops off on either side of the vertical axis). Therefore, older growth rates (open circles) are minimum values

A long-term response to intensive agriculture in the 1800's is a probable cause, but it is puzzling that the decline to the present growth rates typically started in the post-cultivation era, when the direct effects of cane should have been at a minimum. At this point, the most promising possibility is that early forest succession since the end of cultivation may have been detrimental to the ground-holding understory, and thereby caused increased erosion. This, coupled with the degradation of any water-retaining terraces built for cultivation could explain the long-term decrease in coral growth. This is supported by several lines of evidence. First, the curve numbers (CN) ASSIGNED TO "woods" are slightly higher than those for "meadow" (Table 1; a higher CN corresponds to greater runoff). Also, recent experiments at Coweeta Experimental Forest in Franklin, North Carolina have shown that "grass cover in a watershed results in less sedimentation than forest" (A. Putney, written comm.). It is thus possible that the gradual reforestation of the former plantation areas lies at the heart of the pattern seen in the coral cores. In light of this, VIRMC studies of forest succssion being conducted on St. John by the College of the Virgin Islands take on particular significance.

Coral heads - No significant long-term trends for annual-growth rates of the smaller coral heads in Hawksnest Bay can be established over the 10-20 years that they record. There is a strong indication from the data, however, that recent construction within the watershed has had important short-term effects. There was a significant decrease in annual growth rates of corals found in sites 1 and 3 (Fig. 22) during 1981 and 1983. These declines correspond with relatively high rainfall values within the same time frame (e.g. Figs. 56 and 57: 13.87" rainfall in May, 1981, 9.72" rainfall in December, 1981, 13.58" rainfall in April, 1983). Within the same corals, however, no decrease in growth rate corresponded to the much more severe rains in 1979 (13.34" in May; 16.64" in September; 11.55" in November).

During October, 1980, ground was broken for the construction of the hospital at the head of the Hawksnest Bay watershed. Guts which drain the construction site flow into Hawksnest Bay near sample sites 1 and 3. The fact that the post-construction rains in 1981 and 1983 corresponded to drops in growth rate, while pre-construction rains showed no consistant correlation, strongly intimates higher levels of runoff and lowered water quality after clearing of the upper watershed.

Direct comparison of the record of these small corals with larger colonies is impossible as cores could not be obtained from within the swimming area close to the presumed stress. Core H3 from just beyond the eastern swimming area, however, did not show a drop in 1981 corresponding to that of the smaller corals closer to the gut. Therefore, if an impact to the larger heads has resulted, it appears to be confined to the immediate vicinity of the eastern Hawksnest guts.

It is encouraging to note that in most instances, the coral-growth rates have shown recovery since the decreases discussed above. It is likely that subsequent revegetation of the upper watershed has returned its sediment-retaining properties to near normal. Thus, this example has demonstrated both the potential for upland development to cause a short-term degradation of the nearshore environment, and the ability (at least in this case) for the natural environment to mitigate the distrubance over time. At the heart of assessing the potential impact of this kind of spot development is the ability to determine 1) the extent of the short-term environmental response (e.g. will the corals just slow down or will they be killed?), and 2) the time frame within which the system will return to "normal".

There is evidence that significant levels of sediment stress have occurred at least twice at Hawksnest in the recent past. The initial coral growth reflected in the core's clusters just after the 1910's. This likely represents an episode of recolonization after chronic stress related to either cane cultivation, which ended at that time, or to reef destruction by the 1916 hurricane. The dominance of 10 to 20-year-old corals in the nearshore zone may reflect yet another resurgence of the reef after a prior stress event.

SUMMARY

General

The position of the U.S. National Park within the overall community of St. John has raised concerns on both sides over the impacts of development activities (including those of the Park) on the nearshore environments around the island. With increasing development pressure, we seem to constantly find ourselves in the quandary of predicting environmental impact with frighteningly little data. At the crux of the problem is separating real from perceived change in the absence of any baseline data with which to start.

This project was a first attempt to investigate ways that we might assess long-term environmental changes given these extreme limitations. In the first section of the report, a methodology generally accepted within the engineering community was used to evaluate runoff patterns on the island in general. With the lack of quantifiable information on the impacts of specific development practices (e.g. what is the impact of a condominium development vs. construction of single-family dwellings? What are the relative impacts of 10 vs. 20 homes per square mile?), a hypothetical case of no development (i.e. 100% forest cover) was evaluated. Inasmuch as the pattern of reef occurrence predicted by the runoff calculations for a "natural" system reasonably matched that of the present-day reefs, it is likely that watershed size, bay geometry and exposure still maintain the primary control over runoff and, therefore, reef development.

That is not to say that recent construction practices are without impact or that they are of small significance in causing localized degradation. Ideally, the runoff data should be compared to information on not only reef distribution, but reef character as well. Reef data available at this time for St.John, however, are not sufficiently detailed to address island-wide reef development on anything but this gross scale.

In three specific bays, surveys were conducted to describe the distribution of reefs and reef-associated environs within those bays. The purpose of the study was twofold. First, it provided baseline data on these bays of interest to the Park Service. Second, it tested whether sufficient data could be gathered on a bay-by-bay basis to explain localized patterns of reef development (and "quality") in light of natural and man-induced stresses.

As was the case in the larger-scale study of the entire island, the degree of reef development is primarily controlled by the size of the watershed and the location of the natural guts that funnel water and sediment into the bays. Also important is the degree of exposure within different areas of the bays. Terrigenous content of the sediments (which presumably reflects sediment stress near the sample sites) varies between and within bays primarily as a function of their degree of exposure and flushing ability. While features such as mangroves and low-lying areas behind the beach exert controls on the total amount of sediment entering each bay, they appear to be less important in determining the distribution of those sediments once they reach open water. For example, the low-energy environment of inner Fish Bay is often turbid, despite being totally surrounded by mangroves. In Reef Bay, cover along profile RB-03 is poor, despite the low-lying area between it and the nearest source of terrigenous runoff. In both these instances, bay geometry and exposure play the dominant roles in dictating the patterns of circulation, and therefore, reef development.

While development in the upland watersheds has likely affected runoff characteristics, it is not readily apparent in the distribution of land-derived materials found in the bay sediments. Terrigenous content of the sediments along western Reef Bay remains low despite recent clearing of land in that area. A substantial increase in runoff is clearly evident from the slumps and scars at the development site. The higher wave energy and flushing levels seem to be able to counter this, however, at the present level of development.

The growth patterns within the coral cores (Figs. 52-55) provide information about the way those corals, and hence the reefs they form, have fared through the last two hundred years. When plotted against water depth, the ages of the corals generally increase with increasing water depth and distance from sources of runoff, demonstrating consistent responsiveness of those organisms to change in environment.

The long-term decline of coral-growth rates in all three bays appears to reflect a long-term response to forest succession. If this is the case, then exceedingly long-term repercussions of extensive agriculture clearly (e.g. historic cane clearing on St. John; present clearing for agriculture on St. Croix) emerge as important controls over the amount of sediment reaching nearshore reef environments. The consistent decline in coral-growth rates in all three bays clearly dominates over any patterns that might be related to recent development.

This is further supported by the apparent constancy in zonation of *Montastrea annularis* over time. In Reef and Fish Bays, multi-lobed or "knobby" morphs of *M. annularis* consistently occur near the bay heads, closer to the sources of sediment stress. The common occurrence of this morph on backreef environments and opposite drainage paths in many other reefs implies a possible link to sediment stress.

Since these potential indicators of high sediment flux formed in and persisted through the post-cultivation period, they seem to deny any recent and dramatic worsening of conditions, and suggest that chronic sediment runoff problems are a persistent component of these inner bay environments. Even if a direct link between sedimentation and colony morphology is not the case, the shape of the corals is nevertheless the direct result of some environmental factor(s), and they have recently remained constant.

Management Implications

The watershed analysis revealed generalized patterns of reef occurrence consistant with runoff under conditions of total forestation (i.e. the reefs are still responding to primarily natural controls). Within the three watersheds investigated, both the large-scale reef configuration and the distribution of live organisms on those reefs are again consistent with the presumed pattern of natural sediment stresses within the bays.

The sediment cores do show a gradual increase in terrigenous content over time. Given probable rates of sedimentation, however, it is more likely that this reflects changes over hundreds or thousands of years. Corals show a general decrease in their growth rates over time, which appears to relate to gradual changes in ground cover since cane cultivation.

Despite their colonization at differing times and presumably under very different conditions of land use, the initial morphology of individual corals is consistently comparable to both the present morphology of that colony as well as that of surrounding colonies of varying ages. The inescapable conclusion is that the distribution of sediment stresses within the bays have not changed sufficiently over the past two centuries to noticeably alter that large-scale zonation pattern. While impacts of local development are suspected, they occur at a very small scale, and cannot be separated from larger-scale, natural controls.

The only impact that could be readily attributed to recent development is the decline in growth rates in the Hawksnest Bay corals after 1980. Even in this case, however, coral-growth rates subsequently recovered, and the temporary declines were quite localized.

At this point, the crux of the problem is twofold. First, we must separate real from perceived changes in reef conditions. Everybody always remembers "the good old days" of healthier corals and more reefs. Without quantitative and repeatable baseline data, this problem cannot be addressed. The second part of the problem relates to equating change with degradation. Many changes on the reefs are cyclic in nature (e.g. the recent *Diadema* mortality, El Nino, etc.). Even with reliable baseline data, we must be careful in assigning blame for real changes in reef conditions over time periods of a few tens of years.

With respect to either of these problems, the data from this study hint at a long-term decrease in the growth rates of the corals within the three bays studied. And in Hawksnest Bay, there is strong evidence for short-term reef damage related to development. Great care must be taken however, in moving from these conclusions to management strategies within the entire Biosphere Reserve. Management strategies and potential development impact must be assessed on an individual basis. Nevertheless, some generalized recommendations can be made.

It is common to link environmental damage to very large, infrequent storms. Under natural conditions, this is often the case. Nevertheless, our runoff calculations have shown that large-scale reef distribution is responding to much smaller, more frequent events (ca. 10-25 yr storms). Given this fact, it is likely that substantial damage is done by smaller storms, but at a level more subtle than we can easily detect in the time scale of most biological studies. This fact, combined with the tendency for developers (and some scientists) to rationalize that big events are going to destroy everything no matter what we do (e.g. the recent drainage plan for the development of Fountain Valley on St. Croix), lies at the heart of many potential problems with future development on St. John.

Development in major water pathways must be discouraged. Any compromise in the water and sediment-holding capabilities of these areas will likely result in the long-term degradation of water quality in adjoining bays. At Hawksnest Bay, construction near the head of the watershed appears to have adversely impacted nearshore reefs for several years. The subsequent recovery of the reefs is related to the fact that 1) siltation was not sufficient to kill major coral populations, and 2) the watershed was able to recover over a relatively short period of time.

The confinement of siltation to levels below lethal values is likely related to two factors. First a high location of the construction within the watershed minimized the amount of water traveling through the disturbed area. Secondly, the maintained integrity of the lower watershed was apparently sufficient to buffer the effects (although not totally) of the increased runoff and erosion. Critical points from this example are:

1) Try to discourage development in the major drainage guts of larger watersheds, especially those that funnel water into confined areas (i.e. high runoff values in Figures 19-21).

If development must occur in such areas:

2) Try to limit the acreage of the development (i.e. high density <u>may</u>, in some instances, be better than a wider spread, less dense development).

3) Attempt to locate the development as high in the watershed as possible.

4) Attempt to preserve the integrity of the lower watershed. In these situations, the buffering ability of the lower watershed is the last defense against reef damage. Included in this is the retention of nearshore ponds and mangroves that efficiently trap substantial quantities of runoff within relatively small areas.

5) Consider accentuating the water and sediment-holding capabilities of the watershed. This involves things like weirs to slow down flow, ponds to collect water and sediment, etc. Specific suggestions are not offered here, as this is a <u>very</u> complex undertaking, and must be studied very carefully before proceeding.

6) To the extent possible, confine ground-clearing activities to just after "rainy seasons". Then, attempt to replant ground cover prior to periods where heavy rainfall might be expected. This approach minimizes the potential for heavy runoff and siltation during construction, while speeding up thes recovery of the upland watershed. If ground clearing must continue through rainy periods, some sediment-retaining structures should be considered until the watershed has returned to its prior state naturally.

Development in watersheds emptying into low-energy embayments should be discouraged. The highest levels of turbidity and terrigenous material found in the three bays studied occurred in inner Fish Bay, where wave energy is low and flushing is poor. Likewise, in the general, island-wide calculations, such low-energy areas typically correspond to poor reef conditions.

Such development along the shoreline in low-energy areas should be carefully examined before being allowed. This is one of the most difficult areas for which to provide hard-and-fast rules. Areas where poor circulation has resulted in nearshore environments of little ecological value might be acceptable for development. The problem here is deciding on "ecological value" (e.g. the unwise infilling of Krauss Lagoon on St. Croix and the many stagnant nearshore ponds all around the Virgin Islands). At the other end of the spectrum, high-energy areas can often mitigate sedimentation by rapid removel of terrigenous debris. For example, recent development near the western point in Reef Bay appears to have had little impact on nearby reefs. The decision to develop in these instances necessarily falls upon criteria other than nearshore sediment damage.

The crux of the problem lies in those intermediate areas where the nearshore environment is of considerable worth (criteria for this "worth" are beyond the scope of this discussion), and increased sedimentation under protected local conditions could cause significant environmental damage. Therefore, an immediate research goal in this respect would be to:

1) Identify areas with low to moderate flushing under conditions likely to accompany severe rainfall events. This can be done without extensive field work, given some knowledge of basic oceanographic processes.

2) Assess the natural environments within the nearshore zones of those bays.

3) Designate development areas only in those regions that either:

   A. occur in high-energy zones, or

   B. occur in areas of already degraded environment.

The main problem with this approach, is that prime areas for development are those with low enough energy levels to allow water-related sports, and pristine nearshore environments that are aesthetically pleasing. In other words, development will tend to accumulate in those areas where one might least want to place it in this context.

The final point of discussion relates to the relative impacts of high-density development vs. less dense, but more extensive, land use. The example from Hawksnest Bay illustrates the ability of the watershed and nearby marine environments to at least partially mitigate localized development. At the same time, the long-term but gradual decrease in the growth rate of corals in all three bays studied demonstrates the long-term impact of large-scale ground clearing. In the case of cane cultivation on St. John, the aftermath of the cane industry appears to be more significant than the impacts during cane farming itself.

The importance of these two examples relates to the size of the development activity as opposed to its intensity. On St. Croix, large tracts of land are cleared, ostensively for agricultural purposes. The apparent lack of concern for this type of activity is evidenced in the exemption of agriculture from the Coastal Zone Management permitting process. If we are to learn anything from this exercise, it is likely to be the potential long-term impacts of such activities. This is in addition to the concern that should be raised by the often-extensive sediment plumes emanating from those areas that are typically cleared just before the rainy season to maximize the revegetation potential.

The worst case lies in extensive, and often excessive clearing of entire watersheds or drainageways prior to commercial development. Developers often clear entire lots rather than selectively removing ground cover only in areas of construction. This permits easier access for contractors, and requires substantially less foresight in clearing. The cost, however, is often environmental damage. In this respect, the following recommendations are made:

1) Limit large-scale agricultural clearing to situations where it is absolutely necessary, probably never on St. John.

2) Provide substantial sedimentation buffers below areas where clearing is allowed on this scale. This may include artificial sedimentation ponds.

3) Require (or, outside the Biosphere Reserve, request) that the larger developments institute a clearing plan that restricts vegetation removal to areas of construction and access. It may be necessary to restrict development from areas where this approach cannot reasonably mitigate erosion.

4) Confine clearing activities to low-rain periods, and require revegetation strategies, as discussed above.

Future research strategies should center around two areas:

1) Establishing permanent monitoring areas that can be resurveyed in such a way as to permit <u>quantitative</u> comparison at some future date. The transects measured during this study probably represent the absolute

minimum of reproducibility required. While the transects were accurately located, and points of observation were carefully measured and recorded on the profiles, reef cover was only estimated. This is useful for documenting gross changes, but will miss more subtle variations often important in assessing environmental damage. Permanent quadrats should be established with reference to these transects, and careful documentation of those quadrats should follow. The objective of this study was not to establish permanent transects, but the existing transects do provide an opportunity to do so in an area where generalized reef distribution has been documented and related to physical factors.

2) Determining the levels of stress in a field setting that will adversely impact reef quality. While runoff volume, bay circulation, and other factors that impact water quality are not without use, they cannot be related to reef damage (except in the most basic way....post-mortem) until the levels at which sedimentation becomes detrimental at the organism level are understood. This is not to say that VIRMC should ignore such factors, or not be interested in programs that might monitor them over time. The point here is that, if reef degradation due to sedimentation is to remain an interest of VIRMC and the Park, then the first priority should be to determine specifically at what levels stress will do damage. Only at that point will all these other studies of contributory processes become applicable in a predictive way. Of critical importance are:

   A. What are the metabolic responses of reef organisms to varying concentrations of suspended matter?

   B. How does the character of those suspended materials (i.e. size, composition) affect the level of impact?

   C. What are these levels <u>near the organisms</u> under natural conditions and during storms of various intensities? This last measurement is both more crucially tied to reef development and easier to measure than runoff from adjacent watershed areas, or the host of environmental factors such as currents or flushing that link runoff to the nearshore reefs.

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APPENDIX I. Conversion factors for English units used in discussions of engineering calculations.

1 inch = 2.54 cm = .0254 m

1 acre = 4046 m^2

1 foot = 0.305 m

1 cfs = 2.832 x 10^{-2} m^3/sec

1 cfs/ft (in diagrams cfs/s) = 9.29 x 10^{-2} m^3/sec-m