VIRGIN ISLANDS RESOURCE MANAGEMENT COOPERATIVE

Biosphere Reserve Research Reports

No. 19 HISTORIC LAND USE IN THE REEF BAY, FISH BAY AND HAWKSNEST BAY WATERSHEDS ST. JOHN, U.S. VIRGIN ISLANDS (1718-1950)
by George F. Tyson, Jr.

No. 20 A GENERAL REVIEW OF SEDIMENTATION AS IT RELATES TO ENVIRONMENTAL STRESS IN THE VIRGIN ISLANDS BIOSPHERE RESERVE AND THE EASTERN CARIBBEAN IN GENERAL
by Dennis K. Hubbard

No. 21 SEDIMENTATION AND REEF DEVELOPMENT IN HAWKSNEST, FISH AND REEF BAYS, ST. JOHN, U.S. VIRGIN ISLANDS
by Dennis K. Hubbard, James D. Stump and Brian Carter

No. 22 BASIS FOR LONG-TERM MONITORING OF FISH AND SHELLFISH SPECIES IN THE VIRGIN ISLANDS NATIONAL PARK
by Ralf H. Boulon, Jr.

U.S. MAN AND THE BIOSPHERE PROGRAM

Virgin Islands National Park

August, 1987

The Virgin Islands Resource Management Cooperative (VIRMC) was formed in 1982. Signatories to the Memorandum of Understanding are: Virgin Islands National Park, the Department of Planning and Natural Resources of the U.S. Virgin Islands Government (Division of Fish and Wildlife and Division of Natural Resources Management), University of the Virgin Islands, West Indies Laboratory, Island Resources Foundation, Eastern Caribbean Natural Area Management Program, U.S. Geological Survey, U.S. Fish and Wildlife Service, Southern Forest Experiment Station, University of Puerto Rico (Sea Grant Program and the Center for Energy and Environment Research), Caribbean Fishery Management Council, the Ministry of Natural Resources and Labor of the British Virgin Islands Government, and the British Virgin Islands National Parks Trust.

The objectives of the cooperative are:

1. To establish a Virgin Islands Resource Management Cooperative for the purpose of providing coordinated research, extension, and educational support of programs to achieve full benefits of island forests, wildlife, water resources, the marine environment, and historic areas and their associated resources for their cultural, social, commercial, economic, and recreational utilization and enjoyment.

2. To provide for the direction and management of the Cooperative by forming an Executive Committee, comprised of one representative from each of the organizations who are parties to this agreement, which will a) elect annually a Chairman from the membership of the Executive Committee to serve for a term of one year, b) appoint an Executive Officer to a staff position to coordinate the work of the cooperative, c) appoint technical committees and project leaders, d) provide for the orderly process of development and implementation of policy, and e) foster cooperative activities and relationships among participating parties and with other agencies and institutions.

3. To coordinate and facilitate financial and other support for research on environmentally acceptable uses of forests, wildlife, the marine environment and historic areas, and their associated resources in order to provide for their better management.

4. To provide for the collective utilization of the unique attributes and resources (personnel, facilities, equipment, and other support services) of the parties as they may relate to objectives pursued under this agreement.

5. To plan for appropriate dissemination, publication, and application of research and information.

VIRGIN ISLANDS RESOURCE MANAGEMENT COOPERATIVE

BIOSPHERE RESERVE
RESEARCH REPORT NO.19

HISTORIC LAND USE IN THE REEF BAY, FISH BAY AND HAWKSNEST BAY WATERSHEDS ST. JOHN, U.S. VIRGIN ISLANDS 1718-1950

George F. Tyson Jr.
St. Thomas, U.S. Virgin Islands

U.S. MAN AND THE BIOSPHERE PROGRAM

Virgin Islands National Park

August, 1987

PN-ABH-589

HISTORIC LAND USE IN THE REEF BAY, FISH BAY AND HAWKSNEST BAY WATERSHEDS ST. JOHN, U.S. VIRGIN ISLANDS 1718-1950

1987

BIOSPHERE RESERVE REPORT NO. 19

GEORGE F. TYSON JR.
ST. THOMAS, 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

Historic land use and settlement patterns within the Reef Bay, Fish Bay and Hawksnest Bay watersheds were associated almost exclusively with export-oriented plantation agriculture introduced by European and African colonists after 1717. Aboriginal and post-emancipation peasant subsistence farming was not widely practiced in these study areas.

Energized by imported slave labor the plantations spread throughout the watersheds between 1718 and 1740. Field operations and population densities peaked in the 1770's, but continued at relatively high levels until about 1820. Thereafter, agricultual activities contracted steadily, permitting progressive reforestation of the watersheds. During the first half of the twentieth century no more than 5 percent of total watershed land remained in use.

Analysis of the historical record indicates that plantation agriculture had a profound, yet variable, impact on watershed environments. Plantation fuel, lumber and land requirements resulted in the initial loss of most, if not all, of the indigenous forest cover and its partial replacement with introduced vegetation. On the other hand, truncated plantation development and plantation land management strategies, such as terracing, watercourse controls and selective reforestation, allowed for the persistence of many native plant species and probably moderated soil erosion and sedimentation discharges associated with widespread land clearance and intensive use.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

INTRODUCTION

Human manipulation of the St. John landscape began some 2000 years ago with the arrival of seafaring aboriginal migrants. Since that time the limited terrestrial and marine resources of the 19 square mile island have been subject to almost continuous exploitation by successive waves of immigrant groups. Although the scope and intensity of land utilization varied considerably in accordance with the size and adaptive resource management strategies of each settlement culture, the cumulative impact has been the complete alteration of the pristine insular environment.

Today's landscape, despite its wilderness appearance, is largely a cultural landscape, in that it has been shaped as much by human activity as by natural processes and events. This intrinsic cultural dimension derives from two human systems: an export oriented plantation system and, to a lesser degree, a subsistence system practiced by a post-emancipation peasantry. The plantation system dominated the landscape for over a century (roughly 1718-1850). Thereafter, it shared St. John's natural resources with a small, but energetic peasantry until the advent in the 1950's of the contemporary systemic mode based on tourism and welfare state economics.

This study focuses on the land use patterns and practices of the plantation and peasant modes of production in three St. John watersheds - Reef Bay, Fish Bay and Hawksnest Bay - between 1718 and 1950. Its primary objective is to assess the extent and nature of human activity in these critical ecosystems in order to delineate the cultural and historical processes that have brought them to their present state of development.

The study is based primarily on archival research in hitherto untapped documentary sources found in the national archives of Denmark and the United States. Informant interviews, field surveys, cartographic analysis and secondary sources have been used to supplement the documentary material.

The most important historical documents consulted were the land tax registers (matriculs) maintained by the Danish Government. These records, which cover the years 1728-1733, 1736-1739 and 1755-1915, provide invaluable statistical information about ownership, size, land use and population for each unit of production on the island. While they pose certain problems for the researcher (Tyson 1984), their use, in conjunction with supplementary material, such as plantation inventories and special plantation censuses, makes it possible to reconstruct land use patterns and population densities during the era of Danish sovereignty with a high degree of accuracy.

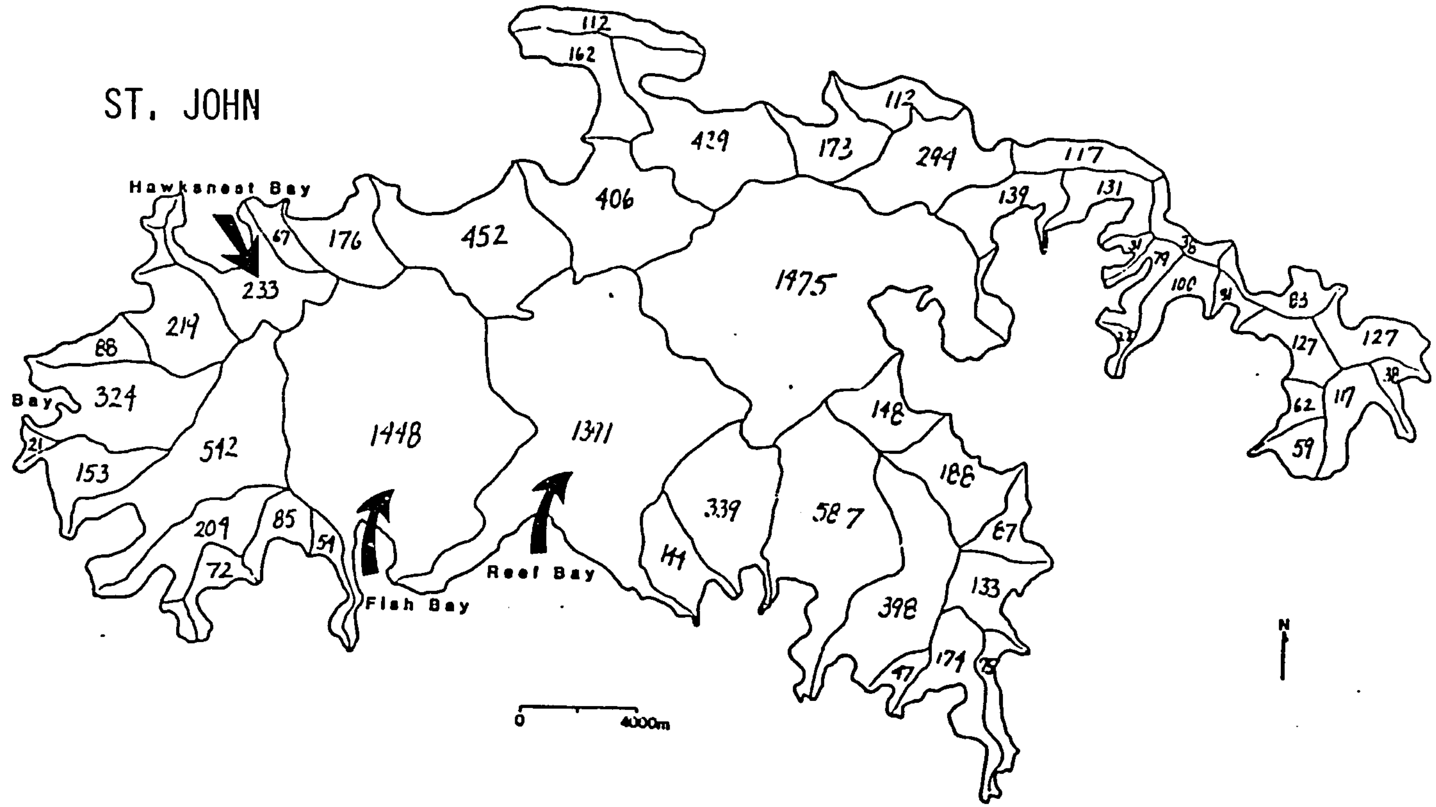


Figure 1. Watershed study areas (Hubbard 1987).

For the period between 1917 and 1950, the record collections of various United States Government agencies involved in island administration were consulted. Information from these sources has been augmented by recollections of people who lived on St. John during the period.

The study will provide historical baseline information that will be integrated into scientific studies of vegetation, sedimentation rates, reef systems, and fisheries being conducted within the Virgin Islands Biosphere Reserve. It is further intended to contribute to our understanding of human ecology in Caribbean insular systems.

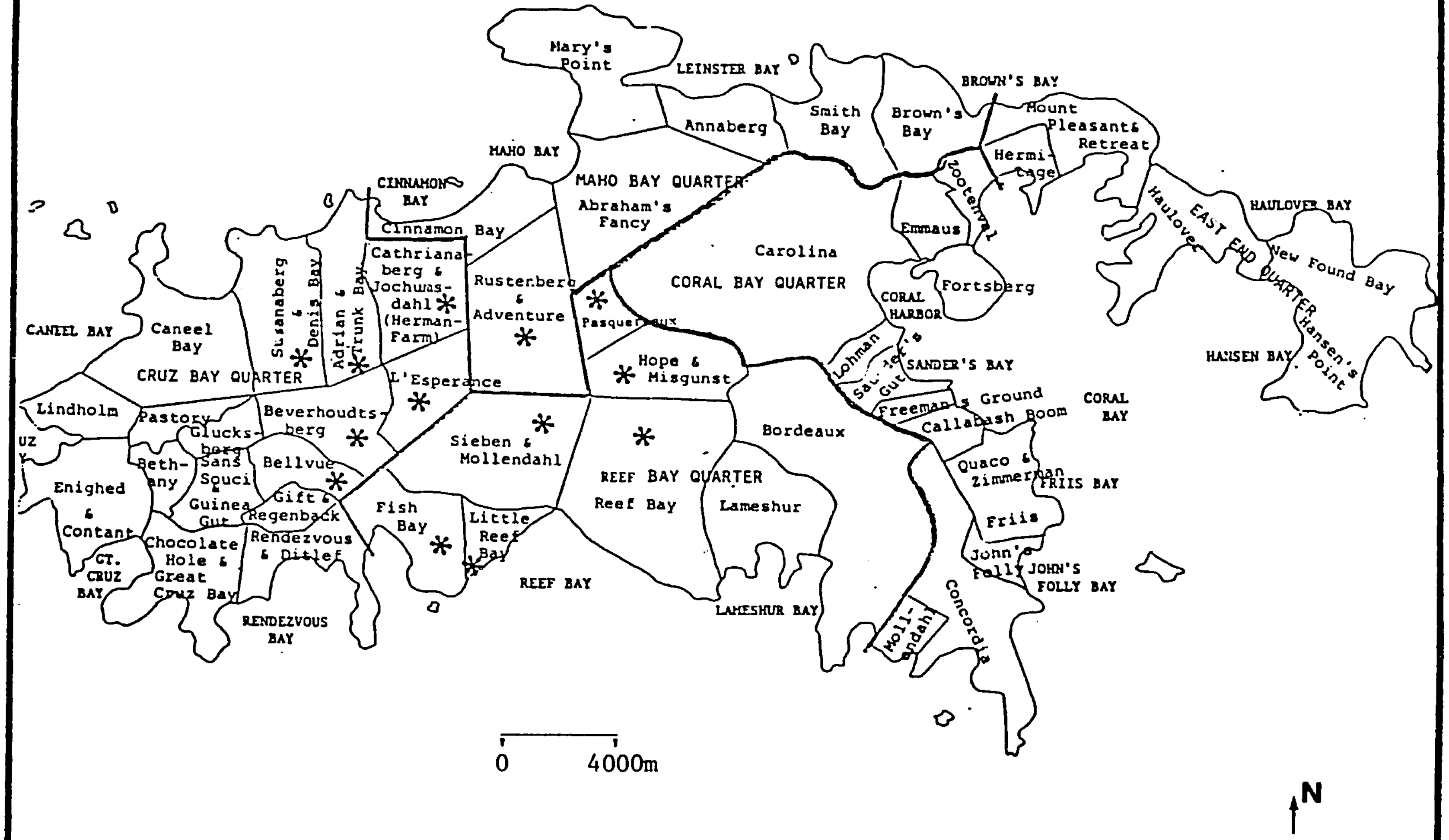


Figure 2. Location of watershed plantations (*).

HISTORIC OVERVIEW

Prehistoric Era

According to the archaeological record, human occupation of St. John began around A.D. 100-200, when seafaring aborigines belonging to the Arawak family of South America established at a settlement at Coral Bay.[1] Here they practiced a mixed subsistence economy that involved the exploitation of marine resources as a source of protein, but relied primarily upon the agricultural production of foodstuffs, such as potatoes, peppers, maize, beans and, above all, manioc. The cultivation technique of these early horticulturalists most likely consisted of "swidden" or "slash and burn" agriculture, rather than the establishment of permanent field systems characteristic of later Indian cultures found in the Greater Antilles (Bullen 1962; Bradstreet 1975; Figueredo 1982).

For reasons that remain unclear, sometime around 500 B.C. the locus of aboriginal settlement shifted from the southern to the northern side of St. John. The Coral Bay site was abandoned, while several contemporaneous settlements were established along the north shore between Cruz Bay and Francis Bay.

Archaeologists differ as to why this shift occured. Bullen (1962) attributes it to population change. Sleight (1962) stresses environmental factors, chiefly the desire to find more hospitable meterological and agricultural conditions. Bradstreet (1975) also emphasizes environmental factors, but believes that Coral Bay was abandoned because of recurring drought induced by increased land clearance. Johnston and Lunberg (1983) suggest that northside sites may also have been preferred because of growing inter-island trade networks.

All are agreed that the new settlement orientation reflected an adaptive shift in aboriginal subsistence pattern from primary emphasis on horticulture to primary reliance on the exploitation of marine resources, especially shellfish.

The impact of aboriginal subsistence economy on the terrestrial and marine resources of St. John during more than 1000 years of occupation is difficult to estimate. Available archaeological evidence indicates small populations and limited site distribution. To date a total of 23 prehistoric sites have been reported on St. John (Sleight 1962; Prokopetz and Hamilton 1977; Johnston 1981; Reeves 1987), but most seem to be special use sites and/or temporary camps rather than major settlements. All known sites are located at coastal bays or valleys, and there is little evidence that Indian settlement or agriculture extended far into the interior.

1. A 1986 archaeological survey conducted at Lameshur Bay by the Southeast Archaeological Center found evidence of a pre-ceramic midden that radio carbon tested to B. C. 770 (+/- 70) (Reeves 1987).

On the other hand, there must have been considerable land clearance and shellfish harvesting around the main coastal occupation sites at Coral Bay, Cruz Bay, Turtle Bay, Cinnamon Bay, Francis Bay and possibly Fish Bay. One local archaeologist (Figueredo 1986) believes that despite small populations, a millennium of shifting, slash and burn agriculture probably destroyed most, if not all, of the climax forest of St. John.

Proto-Historic Era (1493-1717)

St. John was among those Caribbean islands that Christopher Columbus encountered and claimed for Spain during his second voyage to the New World in 1493. His captains, who apparently did not make landfall, reported it as uninhabited. There is some evidence (Figueredo 1978) that Carib and Arawak refugees temporarily reoccupied St. John during the wars associated with the Spanish conquest of Puerto Rico and the pacification of the Caribs of St. Croix (1511-1530). However, it appears that aboriginal occupation ceased prior to 1550, leaving St. John uninhabited for over a century.

Between 1671 and 1717 small bands of mariners, woodcutters and agriculturalists from St. Thomas and surrounding British islands intermittently occupied St. John for short periods (Westergaard 1917; Larsen 1986). But, competing claims to the island by European powers prevented permanent colonization. Little is known about these early colonists, and no documentary or physical evidence respecting the location or nature of their settlements has yet surfaced. Their impact on the landscape must have been slight, for on the eve of Danish colonization a visiting English governor reported St. John as being heavily wooded and without evidence of human occupation (Public Record Office 1717).

The Plantation Era (1718-1850)

Immediately upon colonizing St. John in March 1718, Danish authorities began parcelling out the land for plantation development with the intention of producing profitable tropical crops for export into the emerging world market economy. Consequently, there was no development of subsistence agriculture, such as occurred in colonial Puerto Rico, or of small-scale yeoman farming, such as occurred on neighboring British and French islands.

By 1728 the entire island, except for some rocky headlands, had been subdivided into 91 plantation holdings (Larsen 1986). During the next decade some of these original tracts were subdivided by their owners, and headlands were parcelled out by the government so that by 1739 there were 110 plantations, averaging 110 acres and 15 residents each (Table 1).

TABLE 1. St. John land use indices: 1739, 1760, 1800

St. John	1739	1760	1800
Total Plantations	110	83	65
Total Plantation Acreage	12046	12497	12497
Total Plantation Slaves	1455	1991	2359
Total Plantation Population	1620	2169	2616
Estimated Cropland (acres) [a]	2182	2987	3539
Population Density [b]	86	111	134
Av. Plantation Acreage	110	151	192
Av. Plantation Population	15	26	40
Av. Plantation Cropland Acres	20	36	54
Sugar Sector			
Number of Plantations	27	22	20
Plantation Acreage	4636	5993	7465
Plantation Slaves	734	1288	2167
Plantation Population	782	1471	2209
Estimated Cropland (acres) [a]	1101	1932	3251
Population Density [b]	108	157	189
Av. Plantation Acreage	172	272	373
Av. Plantation Population	29	67	110
Av. Plantation Cropland Acres	43	88	163
% Total Plantations	24.5	26.5	30.7
% Total Acreage	38.5	48.0	59.7
% Total Population	48.3	67.8	82.8
% Total Cropland	50.5	64.7	91.9
Non-Sugar Sector			
Number of Plantations	65	59	22
Plantation Acreage	5801	6219	3022
Plantation Slaves	721	703	192
Plantation Population	838	816	407
Estimated Cropland (acres) [a]	1081	1055	288
Population Density [b]	92	84	86
Av. Plantation Acreage	89	105	137
Av. Plantation Population	14	14	19
Av. Acres Cropland	17	18	13
% of Total Plantations	59.1	71.1	33.8
% of Total Acreage	48.2	49.8	24.2
% of Total Population	51.7	37.6	15.6
% of Total Cropland	49.5	35.3	08.1
Uncultivated Plantations			
Number of Plantations	18	2	23
Acreage	1609	285	2010
% of Total Plantations	16.4	02.4	35.4
% of Total Acreage	13.3	02.4	16.1

Source: Rigsarkivet 1728-1915
[a]Estimated at 1.5 acres per slave. [b]Persons per square mile

Like other West Indian plantations, those on St. John imported slave labor from Africa and other Caribbean colonies to clear the forest, build terraces, plant, harvest and process cash crops for export into the world market. The first island-wide census, taken in 1728, showed 806 slaves (Larsen 1986). In 1739 the slave population stood at 1455; in 1760 at 1991; in 1800 at 2359 (Table 1). Slave labor was essential to plantation enterprise, and it was universally acknowledged by the St. John plantocracy that the size of the slave population, more than any other factor, determined the extent of land clearance and cultivation (Rigsarkivet 1804a).

Given the absence of other types of relevant statistical information, the slave population curve provides the best index of agrarian land use activity on St. John prior to 1804. Slave population figures can also be used to estimate the amount of cropland before 1804. Information derived from St. John plantation inventories dating between 1767 and 1793, and from an island-wide plantation census of 1797 (Table 2), establish a ratio of at least 1.5 cultivated acres per slave during the 18th century, which compares to 1 acre per slave elsewhere in the Caribbean (Barrett, 1965).

In addition to importing labor, the plantations introduced a host of new plant species, including export crops like sugar cane, cotton, coffee, indigo, cocoa and tobacco; food crops such as bananas, plantains, coconuts, vegetables and a variety of citrus fruits; and forage crops such as guinea grass. They also imported domestic animals, most particularly horses, cattle, burros, sheep, goats and swine.

Like its Caribbean counterparts (Sheridan 1973), the St. John plantation system was not static. Rather it evolved through a development cycle consisting of four phases: foundation (1718-1740); consolidation (1740-1765); sugar monoculture (1765-1850) and decline (1850-1950). Data respecting the character of the plantation system in the first three of these phases is presented in Table 1.

During its first half century the plantation system practiced a diversified agricultural economy, closely adapted to prevailing environmental conditions. Sugar cane was cultivated on coastal plains, alluvial valleys, mountain spurs and the central upland plateau. Cotton was grown in the drier southwestern and eastern portions of the island. A few coffee estates were established along the cool mountain ridgelines between Bordeaux, Mamey and Camelberg peaks. Smaller properties on steep terrane concentrated on raising livestock or harvesting foodstuffs for sale to the sugar plantations (Tyson 1984). Some estates around Coral Bay produced indigo, but this fledgling industry was permanently destroyed by the great slave rebellion of 1733-1734 (Marfeldt 1765).

By 1740 the foundations of St. John's plantation economy had been firmly set in place. During this pioneer phase of development the plantation system spread throughout the entire island by a process of land distribution, in-migration, land clearance, terracing, cultivation and construction. A large percentage of forest was cleared and transformed into cropland. Additional areas of native vegetation were partially modified by African slaves cultivating foodstuffs on a shifting basis (Olwig 1986) and by herds of foraging livestock (mules, horses, cattle, sheep and swine) introduced by the plantation owners (Tyson 1984).

Between 1740 and 1765 the system of diversified plantation agriculture that had emerged in the 1730's matured into a fully developed economic order. During this period the number of plantations declined from 110 to 83, as landholdings were consolidated by enterprising planters into larger units of production. Non-sugar plantations prospered, with cotton and coffee competing with sugar as the leading crops. In 1760 the non-sugar plantations comprised 71% of all plantations and occupied 50% of the land (Table 1).

During this period the plantations achieved maximum internal and external expansion through increased inputs of capital, labor and technology. Most, if not all, of the remaining native forest was cut down, either because of its commercial value, or to make way for plantation agriculture and settlement. Stone terraces extended sugar cultivation to the mountain peaks in many areas.

In 1760 (Table 1) eighty-one operational plantations occupied 98% of the land surface. Much of the remaining area had been exposed to some level of cultivation before being allowed to revert to bush by its owners. Probably at no other time has the St. John landscape been subject to such extensive exploitation. In consequence of this agrarian enterprise, the pristine, tropical wilderness gave way to a cultural landscape whose features reflected the adaptive resource management strategies and syncretic cultural traditions of the new European and African inhabitants.

After 1765 the St. John plantation system underwent a major structural transformation, as its diversified agricultural economy gave way to one specializing in the production of a single staple: sugar. Between 1760 and 1800, as shown by Table 1, the sugar plantations progressively enlarged themselves and their control over the St. John landscape at the expense of the non-sugar sector. By 1800 the sugar plantations engrossed 60% of the land, 91% of all cropland and 83% of the population (Table 1).

Estates engaged in cotton and coffee cultivation virtually disappeared from the scene. Non-sugar properties that were not directly incorporated into the sugar sector functioned essentially as its economic satellites, producing ground provisions, livestock and possibly even slave laborers for sugar plantation consumption (Tyson 1984). Several estates were abandoned altogether. In 1800 (Table 1) there were 23 uncultivated plantations, aggregating 2010 acres. Most of these unproductive properties were located in the dry southwestern section of the island.

It should be noted that by 1800 most St. John sugar planters owned uncultivated plantation grounds outside the bounds of their sugar estates, which they utilized for wood, water, marine resources and pasture. For example, in 1800 the respective owners of Susanaberg, Adrian and Herman Farm, three sugar plantation in the central upland plateau, also owned a 350 acre plantation at Fish Bay, a 75 acre plantation near the village of Cruz Bay, and two plantations aggregating 375 acres at Chocolate Hole and Great Cruz Bay, all of which were classified as uncultivated in the tax records (Rigsarkivet 1728-1915).

Enlargement and consolidation of landholdings enabled sugar planters to practice economies of scale and to manage limited land, water and labor resources more efficiently. In practice this meant that cane cultivation was expanded to wherever soils, slope and precipitation could sustain it. Drier, rockier, steeper, less productive land was set aside for specialized purposes, such as slave provision grounds, pasture or wood harvesting. To concentrate labor on sugar production many planters scaled down or phased out these secondary activities, relying instead on imported food and lumber (Tyson 1984). The end result of this land management regime was intensive use of arable acreage, while marginal land was allowed to lapse into secondary growth.

The actual land use pattern prevailing on the sugar plantations at the end of the eighteenth century is shown in Table 2.

TABLE 2. Land use on St. John sugar plantations, 1797

Total Acreage	8355	(100%)
Cropland	2636	(31.5%)
Sugar Cane	1969	
Cotton	40	
Coffee	2	
Provisions	625	
Pasture	1678 a	(20.1%)
Woodland	4041	(48.4%)
Slaves	1805	
Cultivated Acres per Slave	1.5	

Source: Rigsarkivet 1797.
a. Reliable data could be obtained for 14 estates. It yielded an average of 84 acres per estate, which was the figure assigned to each of the six remaining estates.

According to these figures, derived from a special plantation census of 1797, just over half the total land area of the sugar plantations (4314 acres) was actually in agricultural use. The remaining 48.4% was classified as woodland. Of the land-in-use, cropland accounted for 61% and pasture for 39%. Caneland comprised 75% of all cropland, while provisions for plantation use took up 24% of the cultivated area. Not all of the caneland was planted. According to another census of 1804 (Rigsarkivet 1804b), 16% of the cane fields lay fallow. The woodland category included some cleared land, such as roads, trails, shoreline and the settlement site. Plantation settlement areas consisted of three activity zones:

1.	Great House Complex:	Owner's and/or manager's residence, kitchen and other service buildings, servants' quarters, wells, cisterns, privy, garden, cemetary.
2.	Factory Complex:	Grinding mill, boiling, curing and still houses(s), storerooms, stables, pens, shops, magoss house, hospital, overseer's rooms.
3.	Workers' Village:	Small houses, garden plots, burial grounds.

These three complexes were typically concentrated together on high ground near the center of the property. It is not possible to accurately determine the size of the settlement area from available information. However, the 1804 census shows that the 20 St. John sugar plantations allocated a total of 117 acres, or about 6 acres each, to their slave villages. It can be estimated that an equivilent amount of land was assigned to the remaining settlement structures. The settlement area on the typical St. John sugar plantation, therefore, aggregated about 12 acres, with perhaps an additional 3 acres in trails, paths and roads.

<u>The Mixed Economy (1850-1950)</u>

The period between 1780 and 1850 constituted the golden age of King Sugar, an era characterized by intensive, specialized land use, relatively high population densities, and island-wide land management by and for the great sugar complexes.

After 1840 several factors combined to undermine the St. John sugar economy and vitiate the plantation system. These impairments included declining soil fertility, mounting production costs, falling prices and scarcity of investment capital (Tyson 1984). Slave emancipation in 1848 accelerated the decline, as many laborers evaded the oppressive contract Labor Act of 1849 by leaving St. John for greater economic opportunities and personal freedom on the neighboring islands of St. Thomas and Tortola (Olwig 1986). Overall population on St. John plunged from 2450 residents in 1846 to just 944 in 1880. During the same period the

UNITS OF PRODUCTION

YEAR	50 ACRES OR MORE: SUGAR	50 ACRES OR MORE: NON SUGAR	50 ACRES OR MORE: UNCULTIVATED	50 ACRES OR MORE: TOTAL	UNDER 50 ACRES: CULTIVATED	UNDER 50 ACRES: UNCULTIVATED	UNDER 50 ACRES: TOTAL	TOTAL UNITS	LAND USES (ACRES): SUGAR CANE	LAND USES (ACRES): OTHER IMPROVED	LAND USES (ACRES): WOODLAND	LAND USES (ACRES): TOTAL	RURAL POPULATION
1805	21	22	20	63	1	1	2	65	1788	730[a]	9988	12506	2577
1810	21	19	21	61	1	0	1	62	1690	805[a]	10337	12832	2386
1815	18	15	19	52	0	3	3	55	1561	433 ½[a]	10477 ½	12472	2306
1820	18	15	20	53	0	3	3	56	1455	280 ½[a]	11164 3/4	12900 ¼	2257
1825	17	18	18	53	2	4	6	59	1211	241 ½[a]	11457 3/4	12910 ¼	2224
1830	16	21	15	52	20	4	24	76	1116	270[a]	11530 ¼	12916 ¼	2319
1835	16	21	15	52	21	8	29	81	995	327[a]	11583 ¼	12910 ¼	2435
1840	16	21	16	53	22	4	26	79	950	851	11109 ¼	12910¼	2161 (1841)
1845	15	19	17	51	16	9	25	76	839	780	11291 ¼	12910 ¼	2113
1850	16	18	17	51	25	6	31	82	976	1022 ¼	10900	12898 ¼	1325
1855	13	11	28	52	na	na	39	91	635	893 ½	11457 ¼	12898 ¼	1633
1860	13	14	24	51	na	na	47	98	562	1327 3/4	11096	12985 3/4	1427
1865	11	17	21	49	22	60	82	131	559	1192 1/3	11242 5/8	12993 3/4	na
1870	4	22	24	50	19	63	82	132	136	1078	11779 3/4	12993 3/4	955
1875	6	17	29	52	14	79	93	145	88	599	12306 3/4	12993 3/4	na
1880	1	24	26	51	20	72	92	143	78	564	12421 3/4	12933 3/4	854
1885	5[b]	20	28	53	70	69	139	192	106	500	12387 3/4	12993 3/4	na
1890	4	27	22	53	83	78	161	214	82	631 ½	12355 3/4	13069 ¼	924
1895	5	21	25	51	102	66	168	219	26	499 3/4	12543 ½	13069 ¼	na
1900	3	26	22	51	125	64	189	240	10 ½	824 3/4	12237 ½	13069 ¼	872 (1901)
1905	2	25	25	52	117	74	191	243	7 ½	726	12335 3/4	13069 ¼	na
1910	1	29	20	50	125	81	206	256	14	807	12248 ¼	13069 ¼	914 (1911;
1915	1	30	23	54	172	72	244	298	10	1044	12208 ¼	13262 ¼	na

Sources: Rigsarkivet 1728-1915; Rigsarkivet 1835-1911. [a]Excludes pasture. [b]Includes Adrian 1886

Table 3. St. John land use data, 1805-1915.

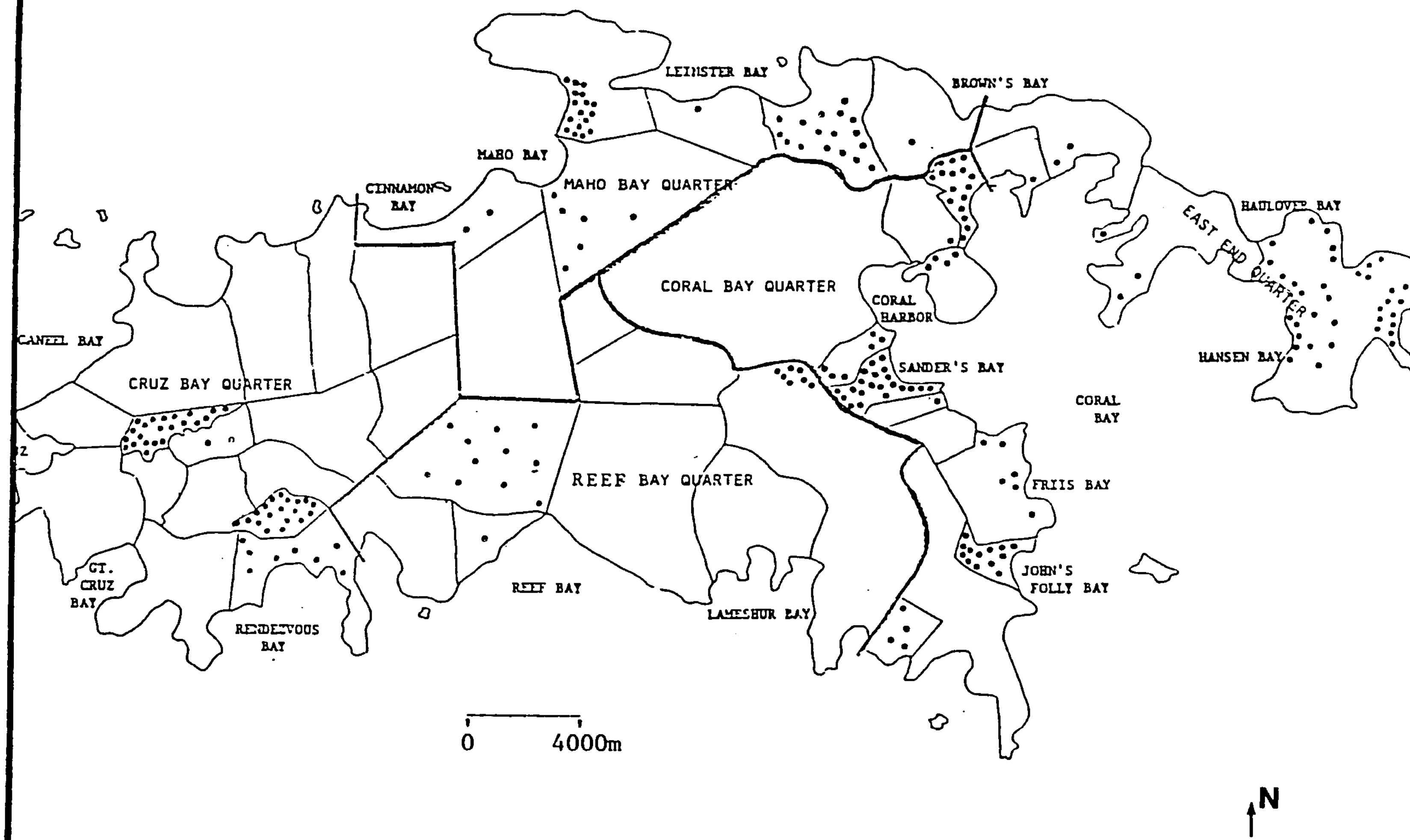


Figure 3. Distribution of St. John small-holdings, 1915. ● denotes one small-holding.

amount of caneland shrunk from 839 to 8 acres (Table 3). By 1915 only Par Force plantation in Reef Bay Quarter still cultivated sugar cane commercially.

The St. John plantation system buckled under the impact of slave emancipation and the demise of the sugar industry, but it did not collapse. It adapted to changing conditions by converting to small-scale, labor extensive, diversified agricultural pursuits, such as provision farming, fruit growing (limes, mangoes, guava, bananas), bay leaf harvesting/processing, and, most importantly, livestock (cattle and sheep) raising (Tyson 1984). In 1915 there were still 31 operational plantations with combined landholdings of 12,114 acres. However, only 729 acres were actually being farmed, chiefly as pasture. Much of the remainder had reverted to secondary forest.

Although the plantations controlled 91% of the land in 1915, most of the rural population lived outside their boundaries. The plantations survived into the twentieth century largely because their owners began sharing land resources with the newly emancipated labor force, thus laying the foundations of a freeholding peasantry unique in the Danish West Indies. Much of the impetus toward agricultural diversification after 1850 came from the mixed subsistence economy practiced by these resourceful peasant cultivators.

Data presented in Tables 3 and 4 shows that between 1805 and 1915 the number of small-holdings (50 acres or less) on St. John rose from 2 to 244. In the latter year 75% of the population lived on these plots, which engrossed 9% of the land, and accounted for 31% of all land-in-use. Figure 3 shows the distribution of small-holdings in 1915.

TABLE 4. Acreage and Land Use on St. John Small-holdings, 1805-1915

Year	Units	Sugar Acres	Pasture & Provisions	Unused	Totals
1805	4	0	1	31	32
1830	24	0	28	153	181
1860	47	0	43	312	355
1885	139	1	158	676	835
1915	244	0	325	823	1148

Source: Rigsarkivet 1728-1915

The impact of the peasant sector on the landscape exceeded actual land ownership, because in addition to parcelling out land, the planters frequently entered into rental or sharecropping arrangements, allowing peasants access to unused estate land (Olwig 1986).

The St. John peasantry practiced a subsistence economy involving a combination of occupational activities, including shifting provision cultivation, rearing small numbers of livestock, charcoal production, boat building, fishing, sailing, sand and ballast rock harvesting, basketry and part-time plantation labor. A discrete Afro-Caribbean culture, based on traditions of cooperation, sharing and reciprocity, crystallized around these diverse economic pursuits (Olwig 1986).

Within fifty years after Emancipation a distinctive socio-economic order based on small-scale, diversified agriculture, synergistically practiced by a relatively small population of plantation owners and peasants had evolved on St. John. In this system of integrated resource management people's energies were directed not toward rearranging the environment, but to making the most effective use of microhabitat and natural phenomena. A balance had been reached between production for the market and production for domestic use, which ensured the inhabitants a modest livelihood and a high degree of cultural autonomy. The development of this mixed economy significantly altered the land use situation, as can be seen from a review of the data presented in Table 3.

Between 1805 and 1915 the amount of land-in-use on St. John decreased by 58%, from 2158 to 1054 acres. Whereas in 1800 about 34% of the island was subject to intense exploitation, by 1915 only 8% remained in agricultural use. During this period the cultivation of sugarcane virtually ceased and there was a fundamental shift in land use from cropland to pasture. Population pressure on land resources eased considerably as the number of inhabitants fell from 2577 to 905, a net loss of 65%. Overall population density dropped from 134 to 47 persons per square mile.

In 1917 the United States took possession of St. John along with the other Danish West Indian colonies. Although American rule did not significantly alter the prevailing system of land tenure before 1950, it did disrupt post-emancipation patterns of land distribution and land use.

The basic contours of the plantation system remained intact, primarily because large landowners held on to their properties for speculative, rather than agricultural, purposes. Land distribution to smallholders was curtailed, and landholdings were concentrated into fewer hands, so that in 1950 just 14 owners held 10,480 acres, or 82% of St. John (Tyson 1984). Between 1930 and 1950 most plantations ceased commercial farming and fell into ruin. The once promising forestry industry collapsed. Livestock farming also suffered a downturn, although it persisted on a few estates.

After 1930 peasant subsistence activities also contracted, and many settlement sites were abandoned by their owners. Between 1917 and 1950, the rural population, which had been fairly stable since 1880, dropped from 900 to around 700. By 1950 smallholders probably had no more than 100 acres under cultivation. Charcoal production continued to be the chief source of peasant income during this period, but by 1950 it too had almost ceased (Tyson 1984).

The post-emancipation productive system, which began disintegrating during the 1930's, has been totally transformed by the establishment of an open tourist economy and the St. John National Park in the 1950's and 1960's. During the past 35 years, most of the old plantation land has been incorporated into the National Park system, which has shut it off to traditional agricultural and forest uses. Concurrently, small cultivators have abandoned the land as a source of livelihood, although some St. Johnians continue to engage in ground provision cultivation and artisanal fishing in order to supplement their government or tourist related incomes (Olwig 1986; Koester 1986). A way of life has disappeared, while much of the landscape has been deliberately managed to a wilderness state that obscures its cultural dynamic.

LAND USE IN REEF BAY WATERSHED

Geographical Setting

The Reef Bay watershed, located on the south side of St. John (Figure 1), drains 1391 acres (Hubbard, et al. 1987). The watershed is characterized by steep slopes rising to heights of 1000 to 1200 feet on three sides of a narrow, alluvial valley that opens broadly to the sea at Reef Bay on the south. The northern boundary is defined by the island's central east-west oriented mountain ridgeline, culminating at Mamey Peak (1147 feet). The eastern border is defined at its upper elevation by the Bordeaux mountain spur stretching north-south toward Bordeaux Peak (1277 feet), thence meandering along a subsidiary spur toward White Point on the eastern side of Reef Bay. The western border is defined by another north-south trending mountain spur that incorporates Camelberg Peak (1193 feet) before arcing in an ENE-WSW direction toward a shallow headland (Oyens or Owens Hill) that separates Reef and Fish Bays.

Reef Bay Gut, the second longest drainage basin on St. John, completely bisects the watershed, running 1.7 miles from Mamey Peak to Reef Bay. It is paralleled on the west by Rustenburg Gut, which extends 1.1 miles before joining it on the valley floor. Water flows in these two guts are intermittent.

Most of the watershed has slopes of 40-60 degrees. Cramer variety soils predominate in the uplands, San Anton varieties on the valley floor (Rivera, et. al. 1970).

Prehistoric Land Use

There is little evidence of significant land use in the Reef Bay watershed prior to the historic epoch. Two prehistoric sites have been found in the Reef Bay valley by surface surveys, but only limited cultural remains have been encountered, leading archaeologists to speculate that Reef Bay was not heavily populated or utilized by aborigines (Sleight 1962; Prokopetz and Hamilton 1977; Johnston 1981). It is entirely possible, however, that other evidence of prehistoric settlement may have been destroyed/buried by the dynamic of upland erosion and lowland sedimentation generated by historic agricultural activities.

Historic Land Use

Whatever the level of prehistoric activity, there can be no doubt that the greatest human impact on the Reef Bay watershed occurred during the historic era, through the medium of the plantation system. All of the land within the Reef Bay watershed was parcelled out for plantation development during the first decade of Danish occupation. A total of 12 plantation grounds, comprising approximately 1455 Danish acres, were distributed by Danish authorities between 1718 and 1726 (Table 5).

TABLE 5. Plantation development in Reef Bay watershed, 1718-1728

Plantation	1728 Owner	Year Laid Out	Acres (Danish)
Adventure A	Jan Vlack	1718	150
Rustenburg A	Jacob Magens	1718	150
Rustenburg B	Jacob Magens	1718	150
Pasquereaux	Pasquereaux heirs	1721	158
Hope A	Adrian v. Beverhoudt	1721	150
Hope B	Adrian v. Beverhoudt	1721	75
Misgunst	Reis David	1724	112
Par Force A	Andreas Tortensen	1721	150
Par Force B	Jochim Stolley	1721	150
Par Force C	Bertel Swennings	1721	113
Par Force D	Anthony Kambeck	1724	97
Little Reef Bay	Phillip Diedrich	1726	75

Source: Rigsarkivet 1728-1915

Between 1725 and 1800, 11 of these original plantation grounds were progressively consolidated into 4 large units: Rustenburg/Adventure (450 acres), Pasquereaux (175 acres), Hope/Misgunst (275 acres), Par Force (500 acres). Little Reef Bay (75 acres) was the only plantation unaffected by the consolidation process. Thereafter, the plantations retained these acreages until their acquisition by the National Park Service in the 1950's.

It should be noted that plantation boundaries do not coincide exactly with watershed boundaries. Three upland plantations - Sieben, Maria's Hope (Vessup), and Bordeaux - each having some land within the watershed, have been excluded from this study because the majority of their property was outside the watershed. Sieben plantation, with considerable acreage on the ridgelines and slopes in the southwestern quadrant of the watershed, has been been excluded because after 1755 land use and population data relating to it was combined with that of Mollendal plantation in the land tax records. The Sieben/Mollendal plantation has been included in the Fish Bay watershed, which is discussed in the next section, since most of its land lies within those boundaries. The reader should bear in mind, therefore, that the Reef Bay watershed experienced somewhat greater human manipulation than is statistically indicated in this discussion.

The statistical distortion is offset somewhat by the fact that Adventure, a 150 acre plantation located outside of the watershed, has been incorporated into it by this study. This inclusion became necessary because after 1772 Adventure was combined with Rustenburg and so lost its independent listing in the tax records.

TABLE 6. Reef Bay land use indices: 1739, 1760, 1800

	1739	1760	1800
Total Plantations	11	8	5
Total Plantation Acreage	1475	1475	1475
Total Plantation Slaves	242	383	267
Total Plantation Population	253	387	275
Estimated Cropland (acres) [a]	363	575	401
Population Density [b]	110	168	119
Av. Plantation Acreage	134	184	295
Av. Plantation Population	23	48	55
Av. Acres Cropland	33	92	80
Sugar Sector			
Number of Plantations	4	5	4
Plantation Acreage	600	1100	1400
Plantation Slaves	130	349	267
Plantation Population	133	352	275
Estimated Cropland (acres) [a]	195	524	413
Population Density [b]	142	205	126
Av. Plantation Acreage	150	220	350
Av. Plantation Population	33	70	69
Av. Acres Cropland	49	105	103
% Total Plantations	36.3	62.5	80.0
% of Total Acreage	40.7	74.6	94.9
% of Total Population	52.0	91.0	100.0
% of Total Cropland	53.7	91.1	100.0
Non-Sugar Sector			
Number of Plantations	6	3	0
Plantation Acreage	725	375	0
Plantation Slaves	112	34	0
Plantation Population	120	35	0
Estimated Cropland (acres) [a]	168	51	0
Population Density [b]	106	60	0
Av. Plantation Acreage	121	125	0
Av. Plantation Population	20	12	0
Av. Acres Cropland	28	17	0
% of Total Plantations	54.5	37.5	0
% of Total Acreage	49.1	25.4	0
% of Total Population	48.0	0.09	0
% of Total Cropland	46.3	0.09	0
Uncultivated Plantations			
Number of Plantations	1	0	1
Acreage	150	0	75
% of Total Plantations	.09	0	20
% of Total Acreage	10.1	0	0.05

Source: Rigsarkivet 1728-1915
[a]Estimated at 1.5 acres per slave. [b]Persons per square mile

Data summarizing land use and population trends in the Reef Bay watershed during the eighteenth century is presented in Table 6. Comparison with simillar data in Table 1 demonstrates that watershed plantations were generally larger, more densely populated and more extensively cultivated than most St. John plantations. For example, in 1739 they contained 18% more acreage, were 22% more densely populated and had 39% more cropland than the island-wide average. By 1760 these figures stood at 18%, 34% and 61% respectively.

Prior to 1740 watershed plantations practiced a diversified agricultural economy centering around the cultivation of sugarcane and cotton, but also involving provision farming, stock grazing and coffee growing. Jacob Magens, owner of Rustenburg, reportedly introduced the latter crop to St. John (Marfeldt n. d.).

Comparison of Table 6 with Table 1 shows that the statistical deviations from island-wide norms in 1739 and 1760 were largely attributable to the relative strength of the sugar plantations. Cane was being grown on Rustenburg, Adventure and Hope plantations from the 1720's. Misgunst shifted from cotton to sugar around 1735. However, before 1740 land use features within the watershed were also strongly determined by the non-sugar plantations, nearly all of which cultivated cotton. In 1739 the non-sugar plantations contained 24% more land and 30% more residents than those outside the watershed.

Between 1740 and 1760 sugarcane cultivation expanded significantly within the watershed, while non-sugar acreage contracted. By 1760, and probably earlier, five large sugar plantations occupied 75% of the watershed and held 92% of the population. Cane was also being grown on watershed uplands belonging to Sieben, Maria's Hope and Bordeaux.

Watershed sugar plantations - Rustenburg/Adventure in the northwest corner, Par Force on the valley floor and Hope/Misgunst on the western slopes of Bordeaux Mountain - were about the same size as their counterparts elsewhere on the island; but, in 1760 they had larger than average populations and population densities. And, because of their higher number of slaves, they undoubtedly had more land under cultivation than the norm. For example, in 1767 all 150 acres of Rustenburg plantation were being exploited: one hundred acres were planted in cane, 20 acres were planted in provisions and the remainder was in "negro plantation" (Rigsarkivet 1763-1775). Evidence survives of considerable terracing around Rustenburg and along the watershed's eastern slopes between Misgunst and Pasquereaux.

The three non-sugar properties in 1760 were Pasquereaux, in the upper northeastern corner, which concentrated on coffee cultivation until shifting to sugar at the end of the eighteenth century; Par Force B in the southeastern corner, which cultivated cotton until 1765, when it was absorbed into the Par Force sugar plantation; and Little Reef Bay in the southwestern corner, which grew some cotton, but emphasized the production of foodstuffs and livestock for sale to the surrounding sugar plantations. Coffee was also cultivated along with sugar on Rustenburg and Hope plantations during the second half of the eighteenth century (Tyson 1984), while some cocoa was cultivated on Rustenburg, Maria's Hope and possibly Pasquereaux along the watershed's upper northern slopes (Rigsarkivet 1763-1775).

Figure 4, which depicts the size of the watershed slave population between 1730 and 1800, shows that the highest slave densities, and, by correlation, the most intense agricultural land use, occurred during the two decades between 1755 and 1775. During this period the slaves were more or less equally distributed among watershed sugar plantations (Table 7), indicating roughly the same degree of environmental modification. While agricultural activity, along with the slave population, fell off somewhat after 1775, it remained at a relatively high level into the first decade of the nineteenth century.

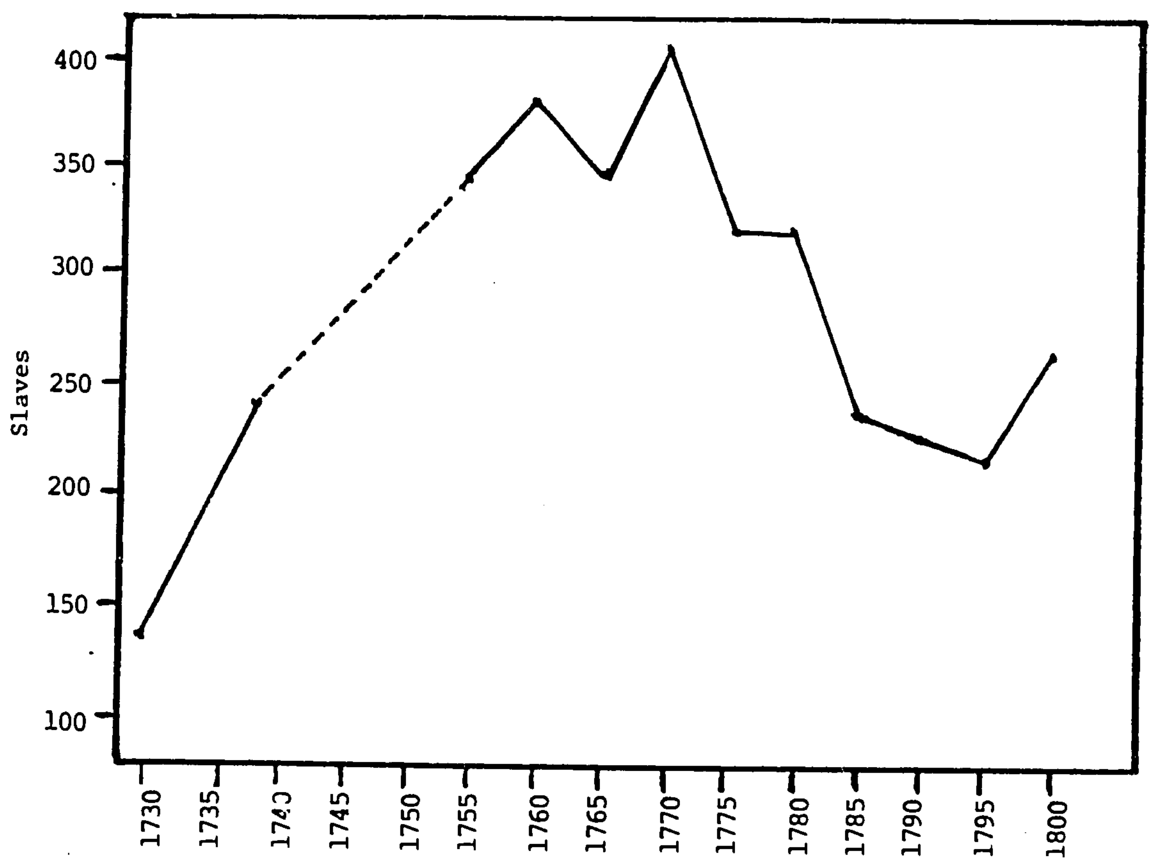


Figure 4. Reef Bay slave population trends, 1730-1800.

Figure 5. Reef Bay watershed in 1800 (Oxholm 1800).

The nature of plantation land use and extent of land clearance in the Reef Bay watershed around 1800 can be rather precisely established from data presented in Table 7, and examination of Peter L. Oxholm's 1800 map of St. John (Figure 5).

TABLE 7. Plantation land use in Reef Bay watershed, 1797

Plantation	Cane Land	Other Crops	Pas- ture	Wood- land	% Im- proved	Popula- tion	Live- stock
Rustenburg/Adv.	70	30	84	266	41%	112	98
Par Force	90	40	40	330	34%	70	44
Hope/Misgunst	40	5	60	195	35%	55	33
Pasquereaux	50[a]	40[a]	2	58	61%	53	14
Little Reef Bay	0	3	72	0	100%	10	39
Totals	250	118	258	849	42%	300	228

Sources: Rigsarkivet 1728-1915; 1797
[a]1804 figures

According to the data presented in Table 7, 42% of watershed land was improved in 1800, compared to an island-wide figure of 35%. Cropland accounted for 59% of the improved land, with pasture making up the remainder. Caneland comprised over two-thirds of the cropland. Most other cropland was planted in provisions, except for a few acres of coffee still being grown at Pasquereaux. Comparison with island-wide statistics presented in Table 2 reveals that despite greater than normal land clearance within the watershed, all forms of agricultural activity on watershed sugar plantations were less extensive than on sugar properties elsewhere.

Oxholm's map (Figure 5), which shows roughly half of the watershed in vegetation, confirms and particularizes the statistical data. It shows extensive clearance around all plantations, except Pasquereaux, which was just being opened up for sugar cultivation in 1800. According to Oxholm there were two large concentrations of woodland: one covered the long, dissected mountain spur abutting the western side of the Reef Bay Gut; the other extended along a mountain spur stretching between White Point and Bordeaux Peak in the southeastern corner of the watershed.

It is likely that some part of both of these woodland areas had previously been under cultivation. The old Par Force D plantation was located somewhere in the first woodland cluster, while Par Force B occupied the second. In all probability Rustenburg/Adventure cultivation once extended into some of the woodland area in the north-central part of the watershed.

TABLE 8. Reef Bay plantation land use trends, 1797-1915

	1797	1836	1875	1915
<u>Caneland</u>				
Rustenburg/Adventure	70	40	0	0
Pasquereaux	50[a]	0	0	0
Par Force	90	60	10	10
Hope/Misgunst	40	50	0	0
Little Reef Bay	0	0	0	0
Total (Danish acres):	250	150	10	10
<u>Other Improved Land</u>				
Rustenburg/Adventure	114	30	30	0
Pasquereaux	40[a]	0	0	0
Par Force	80	60	47	24
Hope/Misgunst	65	50	20	4
Little Reef Bay	75	10	0	4
Total (Danish acres):	374	150	97	32
<u>Woodland</u>				
Rustenburg/Adventure	266	380	420	450
Pasquereaux	60[a]	175	175	175
Par Force	330	380	443	466
Hope/Misgunst	195	175	255	271
Little Reef Bay	0	65	75	71
Total (Danish acres):	851	1175	1368	1433
<u>Population</u>				
Rustenburg/Adventure	112	62	16	0 (1911)
Pasquereaux	53	0	0	0 (1911)
Par Force	70	83	15	27 (1911)
Hope/Misgunst	55	117	0	0 (1911)
Little Reef Bay	10	18	0	0 (1911)
Total:	300	280	31	27 (1911)

Source: Rigsarkivet 1728-1915; 1797. [a]1804

Data presented in Table 8, summarized in Figure 6, shows that Reef Bay experienced a significant decline in agricultural land use between 1797 and 1915. During this period sugar production and other kinds of agricultural activity ceased on all plantations except for Par Force and Little Reef Bay. Despite the failure of commercial agriculture, plantation owners held on to their properties, so smallholders never established themselves in the watershed.

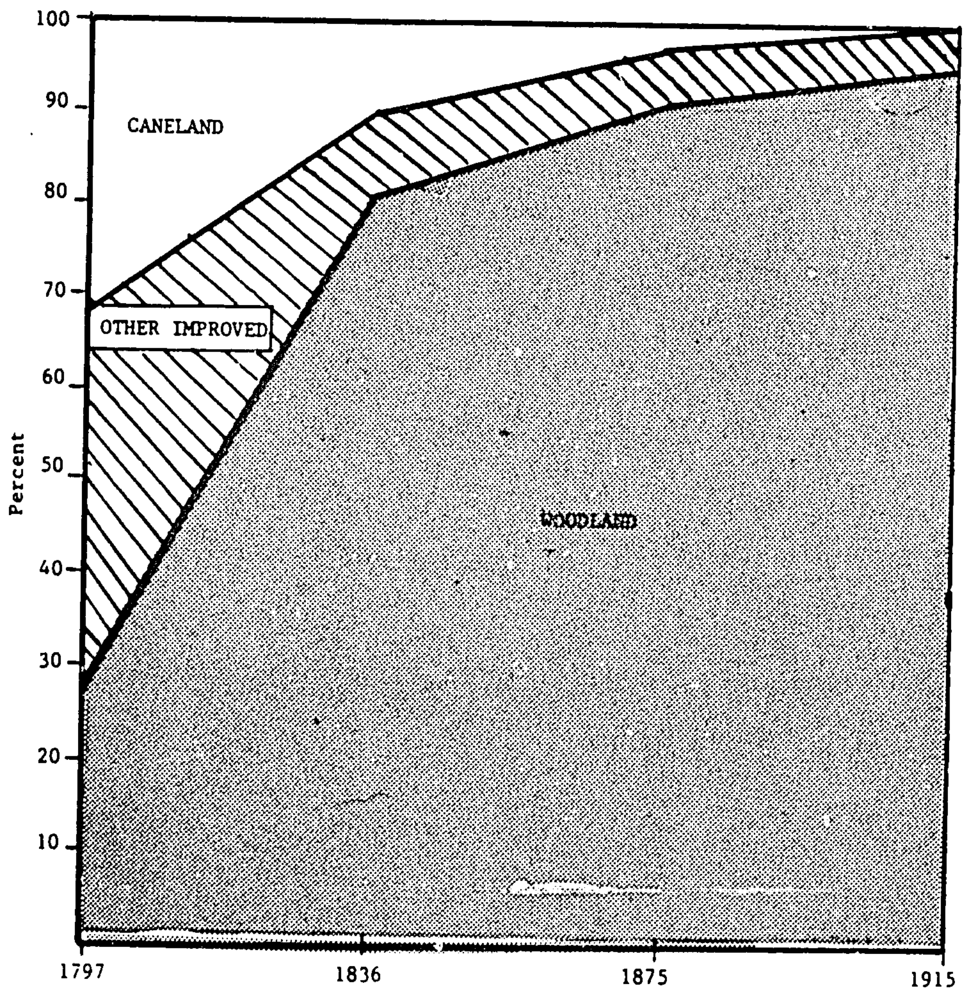


Figure 6. Land Use trends in Reef Bay watershed, 1797-1915.

Sugarcane cultivation ceased on Pasquereaux in 1813, on Hope/Misgunst in 1849 and on Rustenburg/Adventure after the hurricane of 1867. The latter plantation had an average of 60 acres planted in cane between 1845 and 1865, but apparently its owner could not raise sufficient capital to repair the hurricane damage to his sugar works.

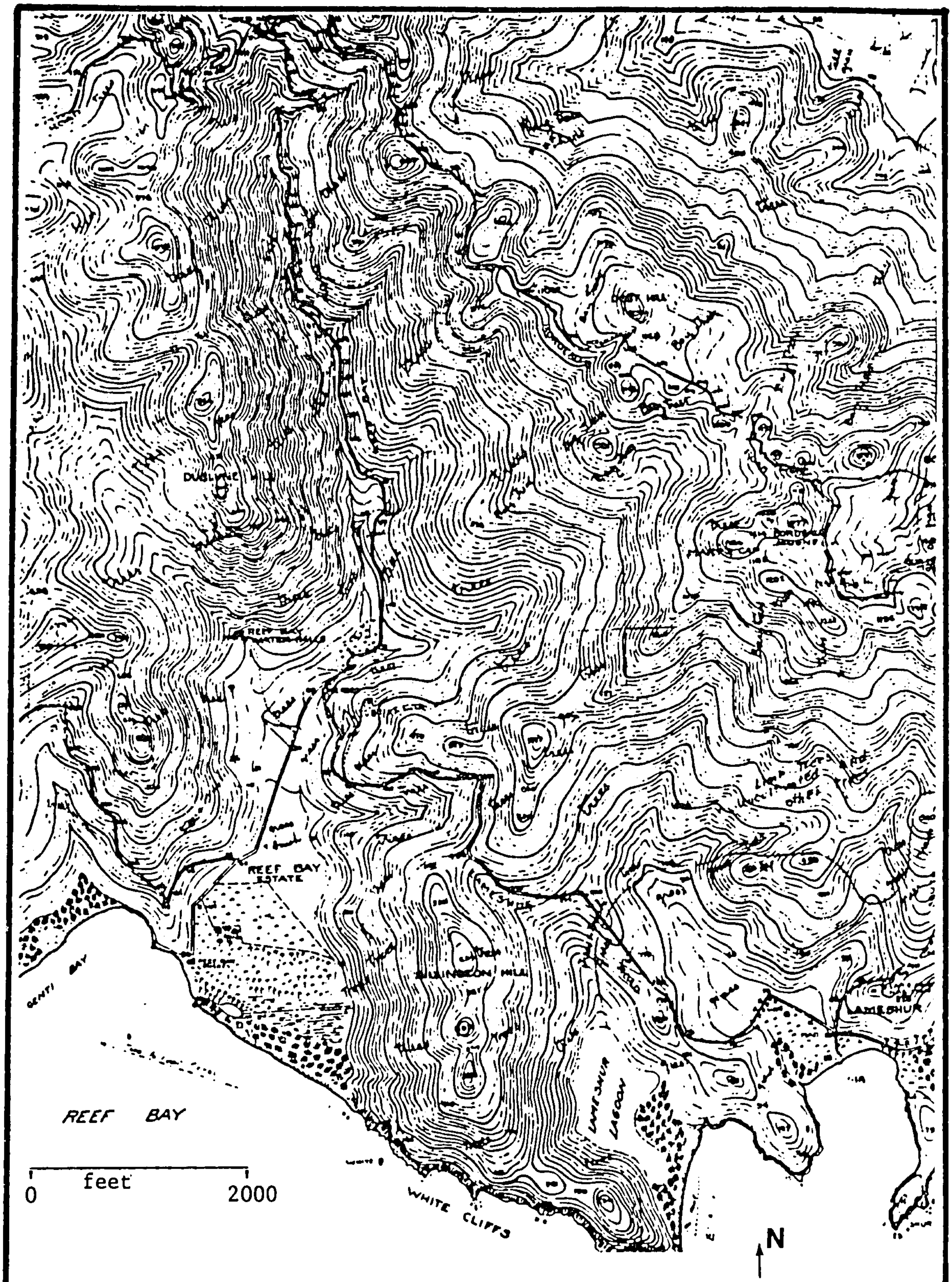


Figure 7. Reef Bay watershed in 1919 (USCGS 1919).

As sugar production proved increasingly unprofitable, watershed planters shifted to other agricultural pursuits, particularly stock farming. But these new ventures enjoyed little success, and within a few decades operations ceased altogether, except on Par Force. Pasquereaux was abandoned in 1826, Hope/Misgunst in 1887, Rustenburg Adventure in 1898. Little Reef Bay, without the sugar plantations to cater to, also fell on hard times, going unoccupied for 40 years (1869-1909) before being reactivated as a stock estate by William Henry Marsh, owner of Par Force.

Post-sugar era livestock herds were rather small. In 1860, for example, the watershed contained a total of 112 adult cattle, 31 sheep and 32 goats. By 1877 there were only 57 cattle and 6 goats, but the sheep population had grown to 68 (Rigsarkivet 1728-1915). Rustenburg and Par Force were the leading stock estates, even while they cultivated sugar. Although some grass pastures were planted and fenced, open range grazing was commonplace.

After 1900 only Par Force and Little Reef Bay remained operational. They supported a population of some 25 residents, who cultivated from 7 to 10 acres of sugar cane, grazed small herds of cattle, and harvested some fruit, coconuts and vegetables (Rigsarkivet 1728-1915).

According to an informant (Pickwood 1986) who lived on Par Force between 1895 and 1905, plantation operations extended over the entire valley floor. Sugarcane was planted just behind the marshy area north-east of the factory; fruit and coconut trees, used solely for domestic consumption, abounded; provision grounds for the plantation household and the estate laborers were located around the worker village and great house at the northern end of the valley floor. Although three or four enclosed grass pieces were set aside for sheep and cattle, most of the time plantation livestock roamed freely in the thickly wooded hills surrounding the settlement.

A detailed fieldmap of the Reef Bay watershed, prepared by the United States Coast and Geodetic Survey in 1919 (Figure 7), confirms the informant's memory. It shows watershed slopes covered with trees and a cleared valley floor planted in grass and cane, with a banana patch and coconut grove behind the Reef Bay shoreline. Sugar and rum were still being processed at the estate factory (Swainson 1919).

Little information respecting land use in the Reef Bay watershed between 1920 and 1950 has been located. It has been established through local informants and fragmentary documentation that Par Force and Little Reef Bay plantations remained occupied and marginally operational into the 1940's. During this period the locus of agricultural activity shifted somewhat from the Reef Bay valley to the slopes around Little Reef Bay. But, the overall amount of land in use appears to have remained fairly constant at 30 to 40 acres.

In 1930 five persons lived on Par Force (Shaw 1940). An agricultural census return of that year (U.S. Bureau of the Census 1930) showed that cane cultivation had ended, and that only 2 acres of improved land remained. A herd of 44 cattle grazed the property. The owner (Anna Marsh) sold small amounts of milk and fruit (limes, mangoes, guava and oranges). Little Reef Bay contained 30 improved acres, and a herd of 25 cattle in 1930. Its owner (A. A. Richardson, the island Administrator) sold small amounts of milk, fruit (mangoes, bananas, limes) and coconuts (U.S. Bureau of the Census 1930).

No returns were submitted in 1930 for the other watershed properties, indicating that they remained unimproved. However, some forest industry did occur there. In 1904 Baron de Castenskjold, a Danish nobleman who owned Lameshur and Bordeaux plantations, acquired Misgunst, Hope and Pasquereaux from the Marsh family. The Baron allowed a few families to settle on Bordeaux Mountain so that they could harvest leaves from bay tree groves. A number of these bay trees were located in the upper reaches of the watershed around Hope and Misgunst plantations (Figure 7). Herman O. Creque, who purchased Castenskjold's holdings in 1922, continued this practice, at least into the 1930's (NARS 1933). Bay leaf harvesting also occurred around Rustenburg during the same period. Field surveys confirmed extensive bay tree orchards in all these upland areas, as well as several old charcoal pits, indicating that the pickers also cut and burnt estate wood.

This pattern of limited occupation and land use continued through the 1940's. Aerial photographs of 1947 (U.S. Air Force 1947) show the watershed covered with vegetation, except for a few small patches of clearance along the upper slopes of Bordeaux Mountain, at Rustenburg and near the Par Force factory. Sizable areas on the hillsides above the Little Reef Bay settlement and along the crest of Billington Ridge, south of the Par Force great house, seem to have been partially cleared, probably for use as pasture. Of the vegetated area only about 20%, located primarily along the western slope of Bordeaux Mountain, could be classified as forest. The remainder appears to be scrub, indicating intensive prior land use.

By the mid-1950's, according to aerial photographs (U. S. Geological Survey 1954) and a USGS topographic map (U. S. Geological Survey 1958), most of the cleared or partially cleared patches had reverted to bush, while the forested area had expanded. Par Force seems to have been abandoned, and residential usage was restricted to three buildings at Little Reef Bay.

LAND USE IN FISH BAY WATERSHED

Geographical Setting

The Fish Bay watershed, draining a total of 1448 acres (Hubbard, et. al., 1987), features several diverse terrains. In the north is a gently sloping upland plateau, roughly 2000 feet wide and 7000 feet in length. Cramer soils, in association with Isaac and San Anton varieties, predominate here. The eastern part of the watershed consists principally of a long mountain spur, with relatively gentle upper slopes, slanting southward from Camelberg Peak Ridge toward the sea. The watershed's southern portion is characterized by steep, rocky terrain, except for some small alluvial fans with San Anton soils in the narrow lowland valleys immediately behind Fish Bay (Rivera 1970).

Two major watercourses drain the central uplands into Fish Bay: Battery Gut, originating at Herman Farm, and Fish Bay Gut, beginning at L'Esperance. They converge at the northern end of the Fish Bay valley before emptying into a mangrove swamp behind Fish Bay. A shorter gut, originating in the hills between Sieben and Mollendal and entering Fish Bay from the east, drains the southeastern quadrant of the watershed. The three guts flow intermittently, but there are standing pools of water year-round in Fish Bay and Battery guts. Reportedly, the gut between L'Esperance and Fish Bay was never dry during the second half of the eighteenth century (Rigsarkivet 1804).

Prehistoric Land Use

Four prehistoric sites have been found by surface surveys in the Fish Bay watershed. All of these sites are located around Fish Bay. One is on the west side of Ditlef Point. Another is on Owens Hill. Two sites are in the central Fish Bay valley, on either side of Fish Bay Gut. No sites have been reported in the upper part of the watershed (Sleight 1962; Prokopetz and Hamilton 1977; Johnston 1981).

None of the sites appear to be extensive; but collectively they suggest a relatively high level of prehistoric activity. From the number of shells present it can be conjectured that aboriginal inhabitants selected the area more for its marine resources than its agricultural potentials.

Historic Land Use

Land in the upper parts of the Fish Bay watershed was completely taken up by aspiring planters within three years after Danish colonization commenced. Plantation development came somewhat later to the lower section around Fish Bay, indicating the poor agricultural value of this area. By 1729, however, as shown by Table 9, the entire watershed had been organized into 20 plantations.

TABLE 9. Plantation development in Fish Bay watershed, 1718-1729

Plantation	1728 Owner	Year Laid Out	Acres (Danish)
Jochumsdahl A	J. Delicat Jr. heirs	1718	75
Jochumsdahl B	Jacob Delicat	1718	75
Catharinaberg	Judith Ann Delicat	1718	150
L'Esperance A	Eric Bredal	1721	150
L'Esperance B	Christian Crabbe	1725	150
Adrian A	Adrian Runnels	1718	150
Adrian B	Adrian Runnels	1725	37
Susanaberg A	Isaac Runnels	1721	200
Susanaberg B	Abraham Runnels	1721	113
Beverhoudtsberg A	Johannes v. Beverhoudt	1721	150
Beverhoudtsberg B	Johannes Runnels	1718	75
Bellvue	Anna Maria v. Hoeten	1721	150
Fish Bay A	William Carstensens	1729	44
Fish Bay B	Ditlef Madden	1727	22
Fish Bay C	Volkers & v. Hermall	1721	150
Fish Bay D	Diedrich v. Stell	1726	70
Mollendal A	Adrian Charles	1727	113
Mollendal B	Gerard Moll	1721	112
Sieben A	Elizabeth Friis	1727	75
Sieben B	Johan v. Sieben	1721	150

Source: Rigsarkivet 1728-1915

Between 1730 and 1800 all but one of these original plantation grounds were progressively consolidated into 7 large units: L'Esperance (225 acres), Jochumsdahl/Catharinaberg, called Herman Farm (300 acres), Adrian (225 acres), Susanaberg/Denis Bay (300 acres), Beverhoudtsberg (225 acres); Fish Bay (350 acres); Sieben/Mollendal (400 acres). Bellvue (150 acres) was the only plantation uneffected by the consolidation process, although it was often affiliated with neighboring Beverhoudtsberg. Most plantations retained these acreages into the 1950's. A 25 acre tract called Grunwald was permanently separated from Bellvue in 1871. Susanaberg had a 75 acre tract (Denis Bay) split from it in 1877. Sieben/Mollendal transferred 49 acres to smallholders between 1879 and 1913. For statistical purposes, however, these smaller tracts have been grouped with their parent plantation throughout this study.

Plantation boundaries do not coincide exactly with watershed boundaries. As noted in the preceding section, some Sieben land actually lay within the Reef Bay watershed. About one-third of the land belonging to Herman Farm, Susanaberg and Adrian also fell outside the watershed. Given the organization of the land tax records, it was not possible to

TABLE 10. Fish Bay land use indices: 1739, 1760, 1800

	1739	1760	1800
Total Plantations	18	12	10
Total Plantation Acreage	2225	2225	2225
Total Plantation Slaves	400	622	649
Total Plantation Population	435	656	664
Estimated Cropland (acres) [a]	600	933	996
Population Density [b]	125	189	191
Av. Plantation Acreage	124	185	223
Av. Plantation Population	24	55	66
Av. Acres Cropland	33	78	100
<u>Sugar Sector</u>			
Number of Plantations	9	7	6
Plantation Acreage	1525	1750	1750
Plantation Slaves	318	514	649
Plantation Population	340	533	664
Estimated Cropland (acres) [a]	477	771	996
Population Density [b]	143	195	243
Av. Plantation Acreage	169	250	292
Av. Plantation Population	38	76	111
Av. Acres Cropland	53	110	166
% Total Plantations	50.0	58.3	60.0
% of Total Acreage	68.5	78.7	78.7
% of Total Population	78.2	81.2	100.0
% of Total Cropland	79.5	82.6	100.0
<u>Non-Sugar Sector</u>			
Number of Plantations	8	5	0
Plantation Acreage	625	475	0
Plantation Slaves	82	108	0
Plantation Population	95	123	0
Estimated Cropland (acres) [a]	123	162	0
Population Density [b]	97	166	0
Av. Plantation Acreage	78	95	0
Av. Plantation Population	12	25	0
Av. Acres Cropland	15	32	0
% of Total Plantations	44.4	41.7	0
% of Total Acreage	28.1	21.3	0
% of Total Population	21.8	18.8	0
% of Total Cropland	20.5	17.4	0
<u>Uncultivated Plantations</u>.			
Number of Plantations	1	0	4
Acreage	75	0	475
% of Total Plantations	05.6	0	40.0
% of Total Acreage	03.4	0	21.3

Source: Rigsarkivet 1728-1915
[a]Estimated at 1.5 acres per slave. [b]Persons per square mile

eliminate this acreage statistically from watershed holdings. On the other hand, nearly all arable land belonging to these properties fell within the watershed, so data respecting land use has not been badly distorted.

Data summarizing land use and population trends in Fish Bay watershed during the eighteenth century is presented in Table 10. Comparison with similiar data in Table I demonstrates that from the outset watershed plantations, were larger and more densely populated than most on St. John. As illustration, in 1739 they contained 11% more acreage, were 31% more densely populated, and had 39% more cropland than the island-wide norm. In 1760 these figures had increased to 18%, 41% and 54% respectively. It can be inferred from this data that the watershed experienced far greater human modification and use than other parts of the island during the eighteenth century.

The deviations from island-wide norms are largely attributable to the early predominance of sugar plantations within the watershed. Due to its gently sloping terrain, relatively deep, rich soils and high rainfall, the central upland plateau constituted the premier sugar producing area on St. John. Peter Oxholm declared that its soil was "excellent and produces much better and finer sugar than either of the other two Danish islands" (Oxholm 1780). Area plantation owners seconded this assessment (Rigsarkivet 1804a).

Sugarcane cultivation started in the upland region almost immediately after Danish occupation. Catharinaberg was harvesting cane as early as 1721, and had a sugar factory a year later (Larsen 1986). In 1739 nine watershed plantations accounted for 33% of the land and 44% of the population within the entire sugar sector.

By 1760 cane was being grown on all upland watershed properties, except Bellvue. Although watershed sugar plantations - Herman Farm, Adrian, Sieben/Mollendal, Susanaberg, Beverhoudtsberg, L'Esperance - tended to be of average size, they were more densely populated and extensively cultivated than the norm. Indeed, it appears that by the second half of the eighteenth century, if not earlier, sugarcane blanketed virtually the entire central plateau. Plantation inventories dating between 1767 and 1780 show that cane cultivation extended over all of Catharinaberg, nearly all of Beverhoudtsberg, three-quarters of Adrian and two-thirds of Jochumsdahl. Most of the remaining land was planted in provisions (Rigsarkivet 1765-1786; 1775-1796).

Non-sugar plantations within the watershed were concentrated in the southern portion around Fish Bay. Like their counterparts elsewhere on the island they had small populations and limited amounts of land in use. It is difficult to determine from available documentation exactly what types of agricultural activity they engaged in. Bellvue cultivated cotton for a while, as did Fish Bay D. Both estates also pastured live-earlier, raised cattle (Rigsarkivet 1763-1775). Fish were also harvested by dragnets in the bay, hence its name (Marfeldt 1765).

Commercial agriculture lasted for less than sixty years on the non-sugar properties. Between 1750 and 1765 the four Fish Bay plantations and Sieben A were acquired by upland sugar planters, who apparently discontinued cultivation and used them to support the grazing and lumber needs of their sugar plantations. The land tax records show Fish Bay as being unoccupied and uncultivated between 1788 and 1914, although other evidence suggests that it may not have been wholly abandoned. Bellvue ceased agricultural operations between 1792 and 1908 according to the tax records. Presumably, the area belonging to Sieben A, which had been absorbed into the Mollendal/Sieben sugar plantation, suffered the same fate (Rigsarkivet 1728-1915).

Field surveys by the author around Fish Bay located litte evidence of terracing on surrounding slopes, which tends to confirm statistical data suggesting that this area experienced relatively limited agricultural development.

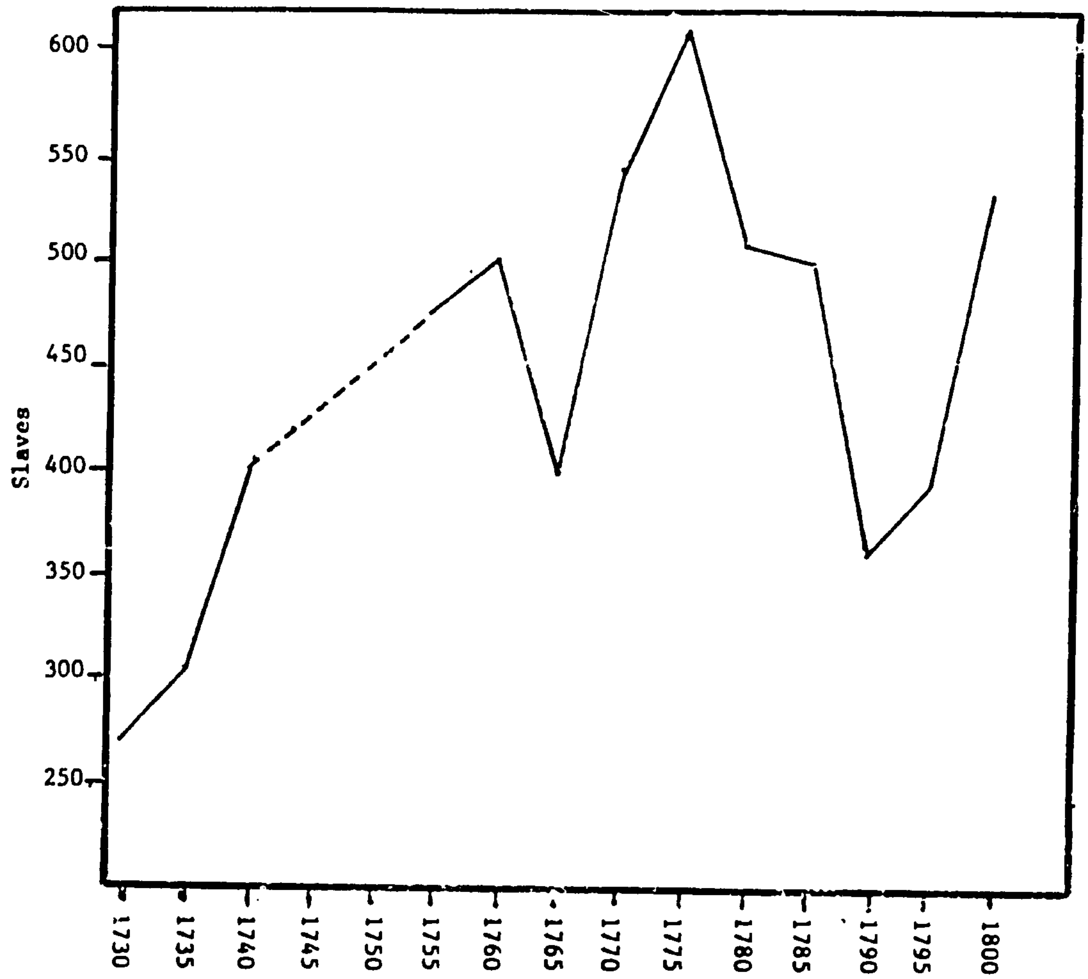


Figure 8. Fish Bay slave population trends, 1730-1800.

Figure 9. Fish Bay watershed in 1800 (Oxholm 1800).

The watershed slave population curve (Figure 8), which indicates the trend of agricultural activity, reflects an irregular development pattern during the eighteenth century, with highest population densities occurring between 1765 and 1780. A sharp decline took place between 1775 and 1790, followed by an upswing that pushed population and land exploitation up to previously high levels by 1800.

The nature of plantation land use and extent of land clearance in the Fish Bay watershed around 1800 can be rather precisely established from data presented in Table 11 and by examination of Oxholm's map (Figure 9).

TABLE 11. Land use on Fish Bay plantations, 1797 (Danish Acres)

Plantation	Cane Land	Other Crops	Pasture	Wood land	% Improved	Population	Livestock
Susanaberg/Fish Bay	100	25	200	175	65%	120	97
Beverhoudtsberg	90	10	84	41	82%	55	93
Adrian	150	30	170	0	100%	124	59
L'Esperance	156	25	25	19	92%	71	38
Herman Farm	150	40	110	0	100%	107	44
Sieben/Mollendal	80	60	150	261	53%	107	141
Bellvue	0	0	0	137	0%	0	0
Totals:	726	190	739	633	72%	584	472

Sources: Rigsarkivet 1728-1915; 1797

According to the data presented in Table 11, a total of 1655 acres, or 72% of watershed land, was improved in 1800. Nearly all of this improved land was located in the upland portion of the watershed. Two properties, Adrian and Herman Farm, were 100% improved, while almost all of L'Esperance, and 82% of Beverhoudtsberg had been cleared. Cropland accounted for 55% of the improved land, with pasture making up the remainder. Caneland comprised 72% of all cropland. The remaining cropland was planted in provisions.

Comparison with island-wide statistics of the period shows that the Fish Bay watershed, particularly its upland plateau, was one of the most extensively developed and intensively farmed areas on the island. Oxholm's map (Figure 9) confirms this impression. It shows a wide arc of cleared land stretching from Beverhoudtsberg northeastward to Herman Farm, and a somewhat narrower area of clearance between Herman Farm and the Sieben/Mollendal bluffs.

Conversely, almost the entire lower part of the watershed was wooded. There were only two thinly cleared areas in this section, both in Fish Bay valley. One was a narrow strip around the settlement site of plantation #8 (Fish Bay C) on the east side of the gut. The cleared area extended northward up the slope to the Mollendal settlement site. The other was associated with plantation #10, which was located on a small bluff near the southeastern base of Gift Hill.

It is likely, however, that a greater amount of the land around Fish Bay had once been cleared and occupied. Fish Bay D plantation was located somewhere around Owens Hill east of the Bay, while Fish Bay B was probably situated somewhere along Ditlef Point. Mollendal A may have occupied the narrow, north-south trending ridgeline just east of the plantation #8 settlement.

Data presented in Table 12 and charted in Figure 10, shows that agrarian land use fell off dramatically between 1797 and 1915. In the

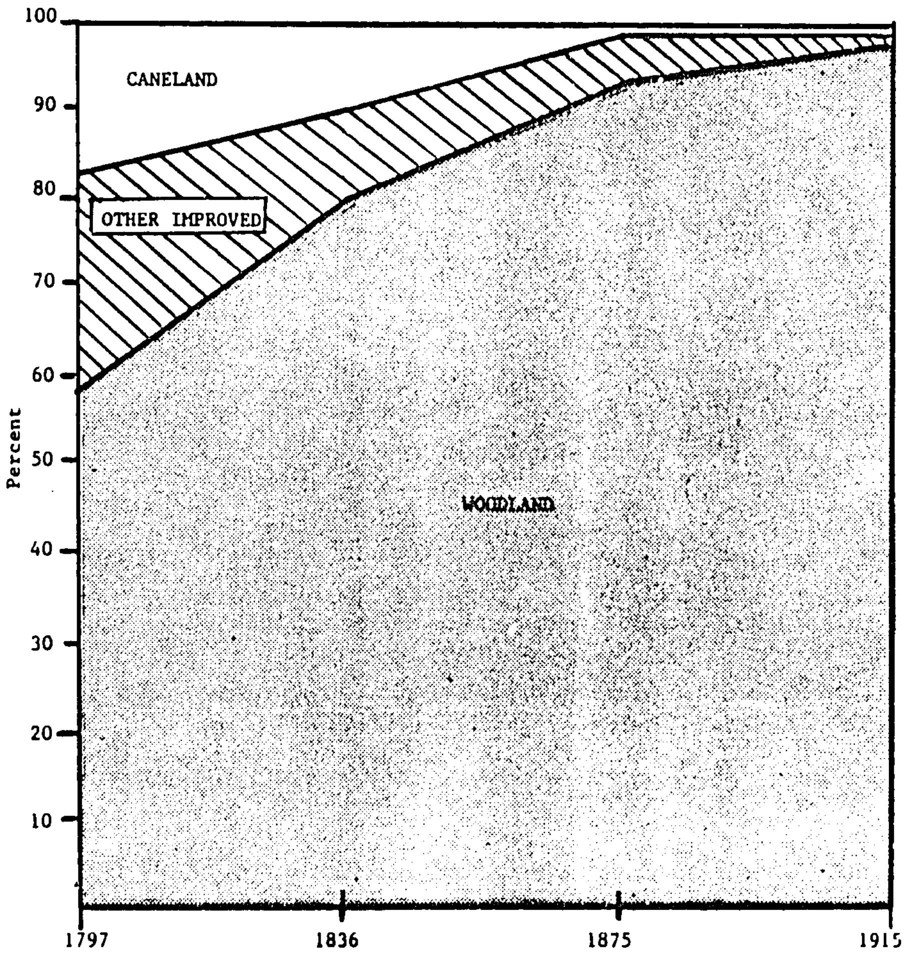


Figure 10. Land use trends in Fish Bay watershed, 1797-1915.

TABLE 12. Fish Bay plantation land use trends, 1797-1915

	1797	1836	1875	1915
Caneland				
Susanaberg	100	55	1	0
Beverhoudtsberg	90	30	0	0
Adrian	150	85	30	0
L'Esperance	156	0	0	0
Herman Farm	150	55	40	0
Sieben/Mollendal	80	0	0	0
Bellvue	0	0	0	0
Fish Bay	0	0	0	0
Total (Danish acres):	726	225	71	0
Other Improved Land				
Susanaberg	225[a]	50	37	70
Beverhoudtsberg	94	20	0	0
Adrian	200	40	44	0
L'Esperance	50	10	0	0
Herman Farm	150	40	33	0
Sieben/Mollendal	210	35	16	18
Bellvue	0	0	4	15
Fish Bay	-	0	0	3
Total (Danish acres):	929	195	134	106
Woodland				
Susanaberg	175[a]	195	262	230
Beverhoudtsberg	41	175	225	225
Adrian	0	100	151	225
L'Esperance	19	215	225	225
Herman Farm	0	205	227	300
Sieben/Mollendal	261	365	384	382
Bellvue	137	150	146	135
Fish Bay	-	350	350	347
Total (Danish acres):	633	1755	1970	2069
Population				
Susanaberg	120[a]	93	15	10 (1911)
Beverhoudtsberg	55	43	0	0 (1911)
Adrian	124	96	42	11 (1911)
L'Esperance	71	13	0	0 (1911)
Herman Farm	107	100	39 (1874)	0 (1911)
Sieben/Mollendahl	107	18	9	26 (1911)
Bellvue	0	0	6	18 (1911)
Fish Bay	-	0	0	0 (1911)
Total:	584	363	111	65 (1911)

Source: Rigsarkivet 1728-1915; 1797. [a] includes Fish Bay

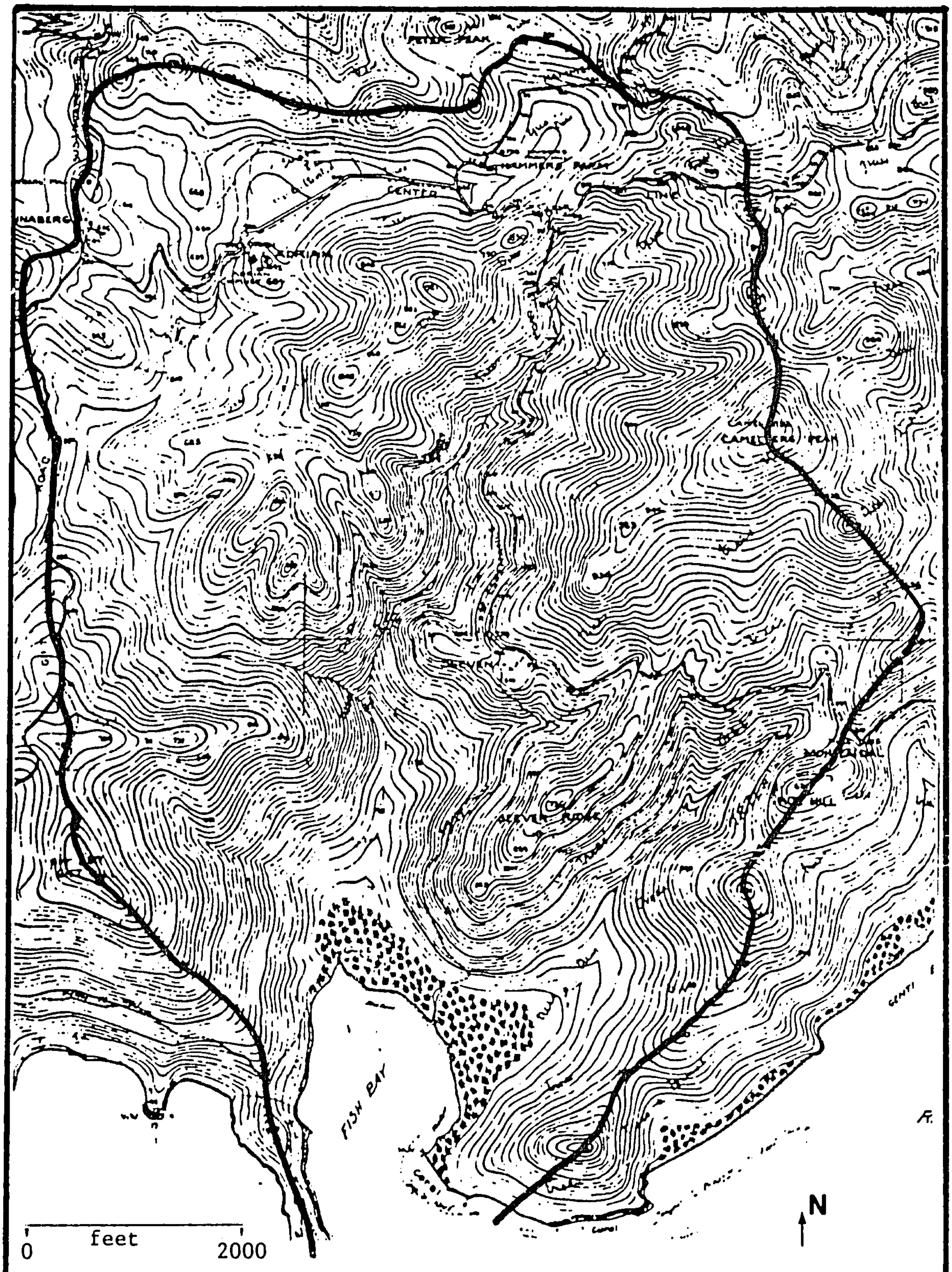


Figure 11. Fish Bay watershed in 1919 (USCGS 1919).

latter year only 5% of the watershed was still improved. During this period sugar production ceased altogether, while other kinds of agricultural pursuits contracted sharply. Population density plunged from 159 to 18 persons per square mile.

In 1808 the owner of Sieben/Mollendal discontinued cane cultivation in favor of stock farming. L'Esperance, which had the most caneland in 1797, abandoned the crop in 1830. Other plantations stuck with sugar until the end of the century. Beverhoudtsberg stopped production and was permanently abandoned in 1872. Susanaberg cultivated cane until 1879, but only in small amounts after the hurricane of 1867. Herman Farm and Adrian produced their last crop in 1896.

As the sugar industry atrophied, watershed planters turned to provision farming, fruit growing and livestock raising as a source of income. Louis Delinois, a St. Thomas merchant who owned all the properties in the upper watershed between 1883 and 1919, experimented with a variety of commercial crops, including coffee, cocoa, cotton, and fruits (guavas and mangoes). But his efforts to find an alternative cash crop proved unavailing (Tyson 1984). Stock raising seems to have been only moderately successful and herds tended to be small. In 1875, for example, the watershed supported a total of just 66 cattle, 120 sheep and 8 goats, 90% of which were pastured on Susanaberg, Adrian and Herman Farm (Rigsarkivet 1728-1915).

By 1915 the watershed contained only 106 improved acres, nearly all grass pasture. The remaining landscape had reverted to woodland and bush (Figure 11). Susanaberg, which functioned largely as a stock farm, was the only operational upland plantation, and 60% of its improved land was actually at Denis Bay. It did, however, have a small cultivation patch at its settlement site (Figure 11). Herman Farm had been shut down. Adrian was also uncultivated, but inhabited by 11 persons.

Smallholders rather than planters were responsible for the little agriculture that survived within the watershed during the last decades of Danish sovereignty. Only a handful of peasant cultivators managed to secure watershed land. All but two of these subsistence farmers were located on Sieben/Mollendal, whose owners parcelled out 49 acres between 1879 and 1913. By 1915 a total of 26 people lived on 11 smallholdings (ranging from 2 to 9 acres) at Sieben/Mollendal. Collectively, they had 18 improved acres, on which they grew fruit and ground provisions (Rigsarkivet 1728-1915).

The two other peasant farmers in the watershed owned and operated plots of land at Grunwald, a 25 acre parcel that had been separated from Bellvue in 1871. Collectively they kept between 3 and 12 acres in use up to 1915. In 1911 a total of 18 persons lived on Grunwald, and it is likely that this small community was responsible for the improved acreage at Bellvue and Fish Bay in 1915.

Little information could be found respecting land use trends in the Fish Bay watershed after St. John passed under American rule. A modest upswing in agricultural activity seems to have occurred between 1917 and 1930. In the latter year a total of 65 people lived in the watershed (Shaw 1940), while agricultural census returns (U.S. Bureau of the Census 1930) showed over 200 acres in improved land.

Adrian had 46 improved acres. The 25 people who lived there raised some goats and hogs and grew small amounts of cocoa, coconuts and fruit (limes, bananas, mangoes, guavas, soursop). Ten people lived on Susanaberg. This property was leased by Neptune Richards, who raised ground provisions and grazed a variety of livestock on 69 improved acres. There were 5 acres of improved land on Grunwald, where peasant cultivators grazed 10 head of cattle and harvested ground provisions and fruit (mangoes and sugar apples).

In 1930 agricultural land use was greatest on Sieben/Mollendal. Here Julius Sprauve, who leased the main plantation, maintained 82 improved acres, on which he raised provisions (beans, sweet potatoes, tanyas, yams), pastured 10 head of cattle and harvested 250 banana and 64 mango trees. Three peasant farmers also had an additional 9 acres in unpecified use.

No returns were submitted for Beverhoudtsberg, L'Esperance, Bellvue and Herman Farm, indicating that they were uncultivated. Fish Bay also seems to have been unoccupied and unimproved, although a small herd of 22 cattle grazed there in 1934 (NARS 1934).

This small-scale agricultural revival seems to have sustained itself through World War II. It is documented that during the 1940's Neptune Richards maintained his modest operation at Susanaberg, while Corey Bishop, an American entrepreneur, ran a sizable truck farm at Herman Farm (Johnson 1950). Aerial photographs of 1947 (U. S. Navy 1947) show an irregular, but broad, band of clearance along Centerline Road between Susanaberg and Herman Farm. There were also cleared patches along the southern slope of Peter Peak and at Sieben/Mollendal.

Nonetheless, agricultural land use occupied a relatively small area in 1947. Aerial photographs show over 90% of the watershed as sylvan. Of this vegetation, roughly 75% appears to be scrub, indicating intensive prior land use, while only 25%, located primarily in the southern and eastern sections (land belonging to Fish Bay, Sieben/Mollendal and L'Esperance), could be classified as forested.

The same configuration of clearance and vegetation is depicted on aerial photographs of 1954 (U. S. Geological Survey 1954) and the USGS topograhic map of 1958 (U. S. Geological Survey 1958), although the aerials do show some expansion of the forested area. Residential usage was limited to just eight buildings, according to the 1958 map.

LAND USE IN HAWKSNEST BAY

Geographical Setting

The Hawksnest Bay watershed, located on the north coast of St. John (Figure 1), drains 233 acres (Hubbard, et al. 1987). It is defined on the east and west by two mountain spurs that extend northward from St. John's central mountain ridgeline before culminating in headlands on either side of Hawksnest Bay. The western spur stretches for slightly more than a mile from Margaret Hill (840') to Hawksnest Point. The shorter eastern spur runs from the ridgeline near Susanaberg plantation ruins to an unnamed headland separating Hawksnest and Denis bays. The southern boundary is formed by the central mountain ridgeline, 600 to 700 feet above the Bay. The watershed is traversed by two small drainage guts with intermittent flows. Slopes are steep, and Cramer variety soils predominate (Rivera 1970).

Prehistoric Land Use

One of the largest prehistoric settlement sites on the northside of St. John is located at Hawksnest Point (Sleight 1962). This site, which was badly disturbed by resort development in the 1960's, supported a relatively large Indian population around 800 A.D. Aboriginal exploitation of land and marine resources in the area must have been intense. However, horticulture was undoubtedly concentrated on the flat, fertile land around Caneel Bay, rather than on steep watershed slopes. No evidence of Indian occupation has been found in the southern or western portions of the watershed.

Historic Land Use

Land use during the historic era is difficult to reconstruct precisely because the watershed falls within the boundaries of two plantations - Susanaberg and Caneel Bay - whose main agricultural areas were located outside of the watershed.

Field systems associated with Caneel Bay plantation were concentrated in the flatland directly behind Caneel Bay. However, as shown by Oxholm's map of 1800 (Figure 9), they did extend to the top of the Hawksnest Point ridgeline. Oxholm also shows one section of the plantation's settlement complex on this ridgeline, as well as a road running from Hawksnest Point up to Margaret Hill. Overall, however, operations of this plantation probably had a negligible impact on the Hawksnest Bay watershed, hence they have not been considered in this study.

Most of the Hawksnest Bay drainage area falls within the historical boundaries of Susanaberg plantation. Data respecting land use and population density on Susanaberg has been included in the section dealing with the Fish Bay watershed because the main Susanaberg settlement complex and its best agricultural land was located in the central upland plateau.

However, as shown by Oxholm's map of 1800 (Figure 9), Susanaberg's field systems also extended downslope through the Hawksnest Bay watershed to an associated settlement complex at Denis Bay, which was linked to it by a serrated trail. A road, running along the main drainage gut through the middle of the watershed, connected Susanaberg and other upland plantations with Hawksnest Bay, where sugar could be conveniently transported aboard securely anchored sailing ships.

The Denis Bay plantation was probably always associated with Susanaberg. Both were laid out in 1721, and, although they had independent settlement sites, they were being operated by members of the same family in 1728 (Table 9). Between 1740 and 1754 they were consolidated under the same ownership, and remained together until 1877, when Denis Bay was split off with 75 acres (Rigsarkivet 1728-1915).

Plantation agriculture at Susanaberg/Denis Bay clearly had a major impact on the watershed environment. Both plantations were cultivating sugarcane by 1729, and continued to do so into the second half of the nineteenth century (Rigsarkivet 1728-1915). An inventory of 1844 showed the entire property as improved, with 125 acres in canes, 40 acres in provisions and the rest pasture (Rigsarkivet 1832-1845). Field surveys by the author found evidence of extensive terracing on the watershed's eastern slopes. Indeed, human activity around Hawksnest Bay had become so intense by 1765 that the turtles the bay had been named after no longer nested there (Marfeldt 1765). Thus, it can be assumed that the level of land clearance shown by Oxholm in 1800 (Figure 9) characterized the watershed for much of the eighteenth and early nineteenth centuries.

By the 1840's, and probably earlier, agricultural activities and population were being concentrated around Denis Bay. Inventories of 1844 and 1846 show more caneland and pasture at Denis Bay than at Susanaberg. Denis Bay had the only slave village, as well as the only operative windmill and sugar factory (Rigsarkivet 1832-1845).

Agricultural activity and population pressure on Susanaberg/Denis Bay began to diminish after 1850. Cane cultivation ceased around 1880. But, the owners continued to maintain some pasture for livestock until the early part of the twentieth century. Throughout the nineteenth century Susanaberg/Denis Bay supported relatively large herds of cattle and sheep. In 1850, for example, 101 sheep and 34 cattle grazed the property. In 1873 there were 31 cattle and 60 sheep (Rigsarkivet 1728-1915).

A modest agricultural revival began on Denis Bay after it was sold to J. E. Lindqvist in 1905. Lindqvist not only raised cattle and maintained a guest house (McGuire 1926), but planted some 2000 pineapples,

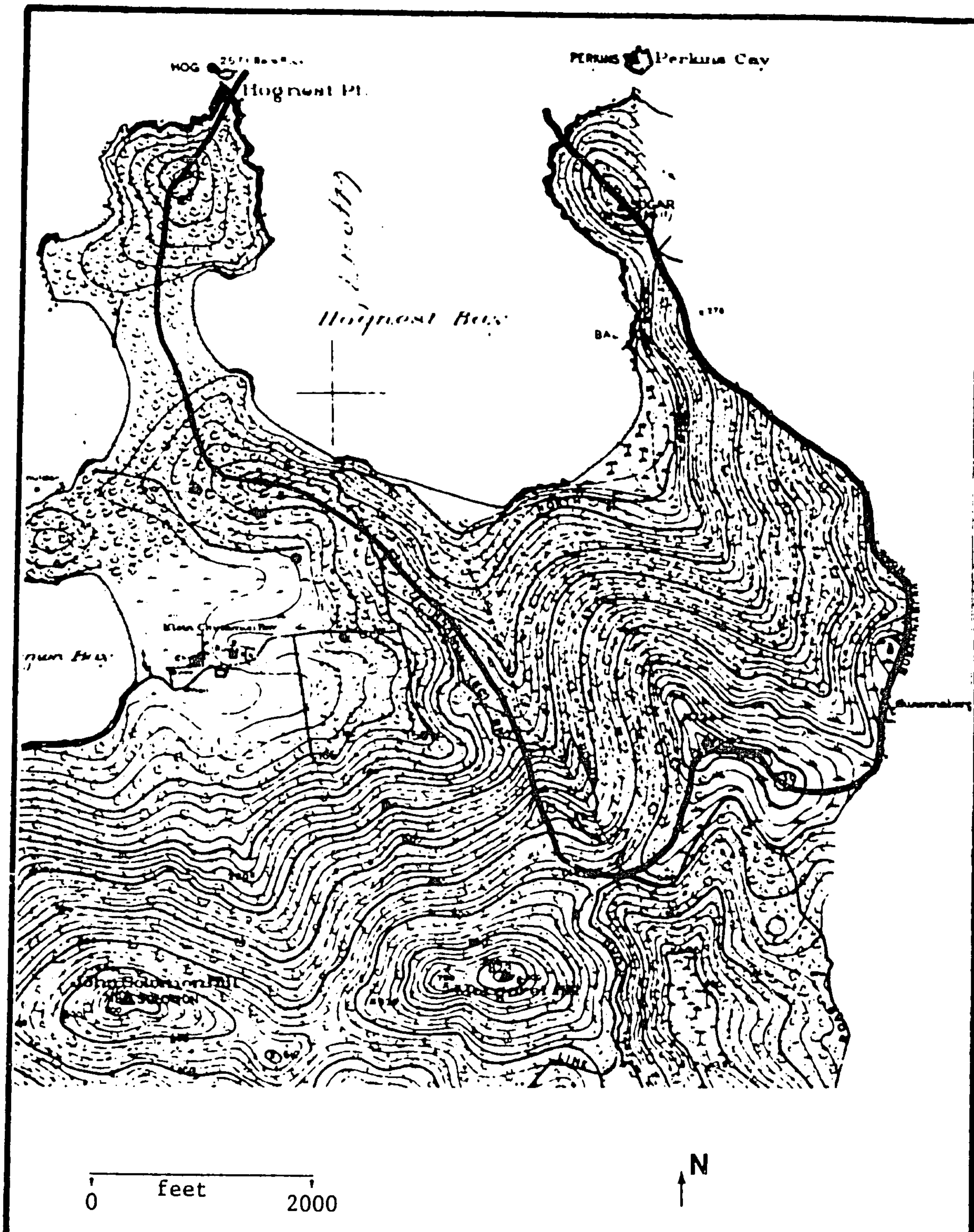


Figure 12. Hawksnest Bay watershed in 1919 (USCGS 1919).

1000 banana trees and 500 coconut palms. He also tried growing cotton and cocoa among the pineapples and beneath existing natural vegetation (Borgesen 1906).

Despite these undertakings, the contraction of overall agricultural activity on Susanaberg/Denis Bay after 1850 probably resulted in the reforestation of much of the watershed. Seventy-seven percent of the total acreage was in bush in 1915 (Table 12). The 1919 USG&GS fieldmap (Figure 12) shows the slopes covered with trees. Even the old road between Susanaberg and Hawksnest Bay had disappeared into the vegetation. The fieldmap also shows Lindqvist's cultivated land around Denis Bay lying outside the watershed.

While agricultural operations continued on both Susanaberg and Denis Bay at a considerably reduced scale into the 1940's, according to local informants and aerial photographs, they did not extend into the watershed. The 1947 aerials (U. S. Navy 1947) show that forested woodland prevailed almost everywhere, except for a small strip of clearance along the upper ridgeline near the Susanaberg settlement.

Aerial photographs of 1954 (U. S. Geological Survey 1954) and the 1958 topographical map (U. S. Geological Survey 1958) show the watershed entirely vegetated, except for a small area around the recently built Caneel Bay catchment basin. Residential usage was confined to two houses on the Caneel Bay ridgeline, and two others just behind the beach.

SUMMARY

Land use within the Reef Bay, Fish Bay and Hawksnest Bay watersheds has been associated almost exclusively with plantation agriculture and settlement that commenced with European occupation in 1718. Aboriginal land use seems to have been limited in these study areas.

The plantations spread throughout the watersheds between 1718 and 1740, resulting in the loss of most, if not all, of their natural vegetation. Extensive deforestation during this pioneer period induced soil erosion, sedimentation and changes in water quality and quantity. However, the slow pace of plantation development and associated vegetation removal facilitated the persistence of native species and probably moderated runoff.

Plantation operations and population densities in all watersheds were most intense in the second half of the eighteenth century, peaking between 1755 and 1780, but continuing at relatively high levels until about 1820. During this period approximately one-half of total watershed acreage was being intensively utilized for agricultural purposes. Much of the remainder was subject to periodic exploitation.

Extensive terracing was necessary to support this level of agricultural activity on steep watershed slopes. Field surveys conducted by the author found evidence that terraces extended from valley floors to the uppermost ridgelines in the Reef Bay and Hawksnest watersheds. Some terracing also occurred in the Fish Bay watershed, primarily in the uplands. There is also evidence in all three watersheds that watercourses were being systematically managed through damming and channeling. Terracing, watercourse controls and other plantation management strategies, mitigated soil and water runoff associated with land clearance and intensive land use.

Plantation agriculture contracted steadily in all three watersheds during the nineteenth century, leading to their progressive reforestation. This process accelerated after 1848 due to population decline and the demise of sugar production. By 1900 ninety-five percent of all watershed acreage was classified as woodland. Thereafter, agricultural land use never exceeded five percent of the total. Abandonment of plantation lands, however, also produced initial increases in erosion and sedimentation due to the breakdown of the terrace system and slow succession rates on severely cut over and degraded areas.

Post-emancipation subsistence farming had limited impact on the watersheds. Relatively few peasant smallholders managed to gain a foothold. Swidden farming and charcoal burning appear to have been confined to small areas along Bordeaux Mountain ridge and on Bellvue, Sieben/Mollendahl and Rustenburg plantation grounds.

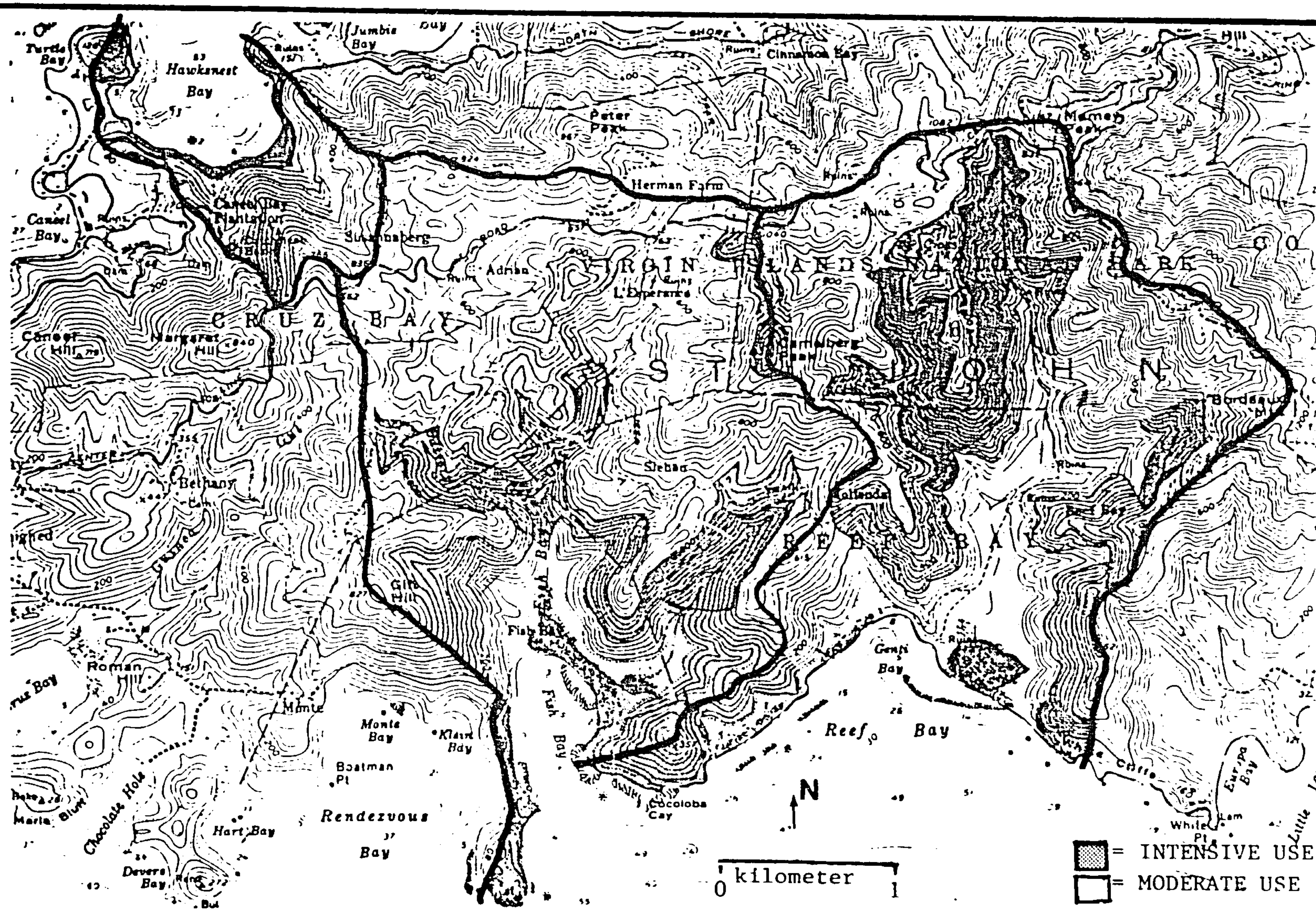


Figure 13. Estimated land use intensities in watershed study areas, 1718-1950.

Between 1718 and 1950 plantation land use activities were most pronounced in the upland plateau region between Beverhoudtsberg and Rustenburg plantations, in the Reef Bay valley between Little Reef Bay and Hope/Misgunst plantations and on the eastern slopes above Hawksnest Bay. Here extensive vegetation removal occurred. Moderately effected areas were the steep, rocky slopes and ravines located in the lower part of the Fish Bay watershed, the rugged middle section and precipitous northeast corner of Reef Bay watershed and the western portion of Hawksnest Bay watershed. Mangrove stands in Reef and Fish Bays, rocky headlands on the western sides of Hawksnest and Fish Bays, and all shorelines, also experienced limited human impacts.

Figure 13 presents an estimate of areal land use intensities within the three watersheds during the historic era (1718-1950), based on analysis of statistical data in the land tax records, soil types, historical documentation and maps. The area of most "intensive use" (white) was depicted as cleared on the Oxholm map of 1800. Much of it continued in use until after 1850. Overall, this zone experienced almost continuous cultivation for about 150 years. The "moderate use" area (lightly shaded) was shown as woodland by Oxholm, but can be documented or reliably estimated as having been cleared either before or after his map. The "limited use" area (dark shading) designates land where it is possible that little or no direct human modifications occurred.

It is unlikely, however, that the forest cover currently found in the "limited use" area contains any relics of the original climax forest, or even eighteenth century secondary growth. The historical record strongly suggests that most, if not all, indigenous vegetation was removed for fuel, lumber or land needs of the colonial population. What escaped the attention of man, undoubtedly fell victim to natural disruptions - periodic fires, droughts and, above all, hurricanes.

Though there can be little doubt that the present distribution and composition of watershed vegetation has been greatly influenced by past human environmental manipulations, the effect of pre-1950 cultural activity on watershed sedimentation discharge may have been far less profound.

Analysis of prehistoric and historic evidence (Table 13) suggests that the overall impact of human activity on sedimentation rates within the watersheds has been variable during the past two millennia, with significant stresses confined to relatively brief periods, and overall effects being relatively mild. This inference from historical documentation gains substantiation from recent studies of sedimentation impacts on watershed salt ponds (Nichols 1987) and reef systems (Hubbard, et al. 1987) that found little measurable evidence of man-induced impacts during the historic era.

TABLE 13. Estimated impact by human activities on sedimentation in Fish Bay, Reef Bay and Hawksnest Bay watersheds, A.D. 100 - 1950

Era	Impact	Primary casual factors
A.D. 100 - 1200	Low	Limited occupation levels
1200 - 1717	Non-Existent	No human occupation
1718 - 1750	Heavy to moderate	Land clearance for plantation development
1750 - 1850	Moderate to low	Intensive monoculture; mitigation by plantation management strategies
1850 - 1900	Moderate to low	Reforestation; breakdown of terrace system and slow succession process
1900 - 1950	Low	Reforestation

While man's role in shaping past and present watershed ecosystems cannot be denied, care must be taken not to overestimate the human imprint. On St. John the plantation system certainly did not overwhlem and transform the landscape to the same degree it did on more amenable Caribbean islands, such as St. Croix. Rather, due to chronic shortages of capital, manpower and technology, it made many accomodations with, and adaptions to, constraining environmental conditions. And, to a considerable extent, St. John planters and peasants strove to mitigate adverse environmental impacts in order to sustain the productive capabilities of the limited resources available to them.

Conversely, strong evidence exists that periodic natural disruptions, particularly hurricanes, were as destructive to terrestrial and marine ecosystems as man during the historic era. Photographic evidence showing the virtual annihilation of the re-emergent St. John forest by the severe hurricane of 1916 makes it clear that the current St. John wilderness is probably as much a product of this violent storm, and, to a lesser extent, that of 1924 as of two centuries of prior land use activites. Moreover, in addition to their devasting effect on vegetation cover, recurrent hurricanes (at least 40 struck St. John between 1718 and 1950), generate massive sedimentation discharges, and their associated ground seas can wipe out entire coral reef systems, as appears to have happened in Hawksnest Bay in 1916 (Hubbard, et al. 1987).

Although man's long-term impact on the landscape might sometimes pale in comparison with the destruction wrought by a single cataclsymic event, it must also be borne in mind that extensive human environmental re-arrangements can enhance storm destruction and significantly effect the inherent ability of tropical ecosystems to adapt to and recover from such disasters.

In sum, the conclusion remains inescapable that man and nature, in tandem, have brought St. John to its current state of development. Too much emphasis on one dimension or the other can only distort our understanding of the past and undermine our ability to shape a reasonable future. St. John is neither a pristine wilderness nor a ravaged victim of human over-exploitation. To imagine that it is either would be a case of historical ignorance. To try to manage it into one or the other would be equally misguided.

Despite some recent excesses, the essence of the place resides in the precarious balance achieved there by the complex interaction of man and nature - from man's creative adaptations to the insular environment and nature's adjustments to human endeavor. Understanding, maintaining and celebrating that delicate equilibrium, that mutual accomplishment, ought to be the focal point of the Virgin Islands National Park, as well as the St. John Biosphere Reserve.

LITERATURE CITED

Barrett, Ward
1965 Caribbean Sugar-Production Standards in the Seventeenth and Eighteenth Centuries. In John Parker, ed., MERCHANTS AND SCHOLARS. Minneapolis, Minnesota.

Borgesen, F.
1906 Indtryk fra en Rejse til Vestindien i Vinteren 1905-1906. ATLANTEN, I:534-535. Copenhagen, Denmark.

Bradstreet, Theodore
1975 Ceramic Culture Site Location Parameters of the Virgin Islands. JOURNAL OF THE THE VIRGIN ISLANDS ARCHAEOLOGICAL SOCIETY, 2:5-11. Frederiksted, St. Croix, U.S.V.I.

Bullen, Ripley P.
1962 CERAMIC PERIODS OF ST. THOMAS AND ST. JOHN ISLANDS, VIRGIN ISLANDS. William L. Bryant Foundation of American Studies Report No. 4. Tallahassee, Florida.

Figueredo, Alfredo E.
1978 The Virgin Islands as an Historical Frontier Between the Tainos and the Caribs. REVISTA/REVIEW INTERAMERICANA, 3:393-399. San Juan, Puerto Rico.

1982 Agricultural Systems of the Aborigines of the West Indies. 12th ANNUAL AGRICULTURAL FOOD FAIR OF THE VIRGIN ISLAND. St. Croix, U.S.V.I.

1986 Personal Communication, May 20th.

Hatch, Charles E. Jr.
1971 VIRGIN ISLANDS NATIONAL PARK, ST. JOHN ("The Quiet Island"), WITH SPECIAL REFERENCE TO ANNABERG ESTATE, CINNAMON BAY ESTATE. National Park Service. Washington, D. C.

Hubbard, Dennis, Stump J. and Carter B.
1987 SEDIMENTATION AND REEF DEVELOPMENT IN HAWKSNEST, FISH AND REEF BAYS, ST. JOHN, U. S. VIRGIN ISLANDS. Virgin Islands Resource Management Cooperative Technical Report #21. St. Thomas, U.S.V.I.

Johnson, Clarence L.
1950 ST. JOHN AND ST. THOMAS, VIRGIN ISLANDS OF THE UNTIED STATES. National Park Service. Washington, D. C.

Johnston, Barbara R.
1981 A SURVEY OF THE PREHISTORIC ARCHAEOLOGICAL SITES OF ST. JOHN, U.S.V.I. Virgin Islands Planning Office. St. Thomas, U.S.V.I.

Johnston, Barbara R. and Emily R. Lunberg
1983 Archaeological Survey of the United States Virgin Islands: A Preliminary Report. Paper presented to THE TENTH INTERNATIONAL CONGRESS FOR THE STUDY OF PRECOLUMBIAN CULTURES OF THE LESSER ANTILLES. Fort-de-France, Martinique, 25-30 July.

Koester, Stephen
1986 SOCIOECONOMIC AND CULTURAL ROLE OF FISHING AND SHELLFISHING IN THE VIRGIN ISLANDS BIOSPHERE RESERVE. Virgin Islands Resource Management Cooperative Technical Report #12. St. Thomas.

Larsen, Leif Calundann
1986 THE DANISH COLONIZATION OF ST. JOHN 1718-1733. Virgin Islands Resource Management Cooperative. St. Thomas, U.S.V.I.

Marfeldt, Christian
c.1765 THE BAYS ON ST. JOHN. Translated by Frederik Gjessing from the original in the Westergaard Transcripts, Library of Congress. Washington, D. C.

n. d. Samalinger. Vol. 4. Generaltoldkammeret Arkiver. Rigsarkivet. Copenhagen, Denmark.

McGuire, J. W.
1926 GEOGRAPHIC DICTIONARY OF THE VIRGIN ISLANDS OF THE UNITED STATES. Department of Commerce, U. S. Coastal and Geodetic Survey Special Publication #103. Washington, D. C.

NARS, (National Archives and Records Service), Washington, D. C.
1913 E. W. Marsh to Government, 21 Feb. 1913. Record Group #55, Box 1201.

1933 An Investigation to Determine the Immediate Need for Food, Clothing, or Steady Employment of People Living in the Coral Bay and Bordeaux Mountain Sections of St. John. Enclosed in Morris N. Nichols to Boyd J. Brown, June 15, 1933. Record Group #56, General Files 1932-1934.

1934 List of Cattle in Saint John. Record Group #56, General Files 1932-1934.

Nichols, Maynard
1987 MAN'S LONG-TERM IMPACT ON SEDIMENTATION: EVIDENCE FROM SALT POND DEPOSITS. Virgin Islands Resource Management Cooperative Technical Report #23. St. Thomas, U.S.V.I.

Olwig, Karen Fog
1986 CULTURAL ADAPTATION & RESISTANCE ON ST. JOHN. THREE CENTURIES OF AFRO-CARIBBEAN LIFE. Gainsville, Florida.

Oxholm, Peter L.
1780 Report on the Military Structures of St. John to the Royal Westindian Chamber, 30 August 1780. English translation by Per Ydmark of original in Rigsarkivet, Copenhagen, Denmark.

1800 CHARTE OVER DEN DANSK OE ST. JAN I AMERICA. Copenhagen.

Prokopetz, A. Wayne and C. Hamilton
1977 SURVEY AND ASSESSMENT OF THE PREHISTORIC ARCHAEOLOGICAL SITES IN VIRGIN ISLANDS NATIONAL PARK, ST. JOHN, U.S. VIRGIN ISLANDS. Southeast Archaeological Center, Tallahassee, Fla.

Public Record Office, London
1717 Governor Walter Hamilton to Lords of Trade and Plantations, 7 October 1717 in Colonial Office, Leeward Islands, 152/12.

Pickwood, Miss A.
1986 Interview with George Tyson. June 10th. St. Thomas, U.S.V.I.

Reeves, Roy
1987 Personal communication, February 25th.

Rigsarkivet, Copenhagen, Denmark
1728-1915 St. Thomas-St. John Landlister and Matriculs.

1763-1775 Registrerings -og vurderingsprotokoller. Landfogeden pa St. Jan, #126. Vestindiske Lokalarkiver.

1765-1786 Skylddokumenter vedk. de hollandske Fordringer paa Vestindien. Diverse Dokumenter, Den vestindiske Gjaelds Likvidations Direktion 1786-1816. Finansarkiverne.

1775-1796 St. Jan Skifteprotokoller. Landfogeden pa St. Jan [unnumbered]. Vestindiske Lokalarkiver.

1786-1816 Taxationet over Planternes II. Den vestindiske Gjaelds Likvidations Direktion 1786-1816. Finansarkiverne.

1797 St. John Plantation Census. Diverse uordnede sager 18.-19. arh (bl. a. skattesager or negerlister ca. 1770-1818). Vestindiske Lokalarkiver.

1804a St. John Plantation Census Returns. St. Croix Skatte-Lister 1804. Vestindiske Lokalarkiver.

1804b St. John Plantation Census 1804. Dokumenter vedr. Slavenhandelkommissionen, 1783-1806. Generaltoldkammeret Arkiver.

1832-1845 Landretssager. Landfogeden pa St. Jan, #85. Vestindiske Lokalarkiver.

1835-1911 Folketaellingslisterne for St. Jan: 1835, 1841, 1846, 1850, 1870, 1880, 1901, 1911.

Rivera, Luis H., et. al.
1970 SOIL SURVEY OF THE VIRGIN ISLANDS OF THE UNITED STATES. U. S. Department of Agriculture. Washington, D. C.

Shaw, Earl
1940 The Virgin Islands of the United States. In William H. Haas, ed., THE AMERICAN EMPIRE: A STUDY IN THE OUTLYING TERRITORIES OF THE UNITED STATES. Chicago, Illinois.

Sheridan, Richard
1973 SUGAR AND SLAVERY: AN ECONOMIC HISTORY OF THE BRITISH WEST INDIES 1623-1775. Baltimore, Maryland.

Sleight, Frederick W.
1962 ARCHAEOLOGICAL RECONNAISSANCE OF THE ISLAND OF ST. JOHN, UNITED STATES VIRGIN ISLANDS. William L. Bryant Foundation of American Studies Report No. 3. Tallahassee, Fla.

Swainson, O. W.
1919 Descriptive Report, St. John, Central Section. Department of Commerce. U.S. Coast and Geodetic Survey. Mss.

Tyson, George F. Jr.
1984 A HISTORY OF LAND USE ON ST. JOHN, 1718-1950 (Preliminary Report). Virgin Islands National Park. St. Thomas, U.S.V.I.

U. S. Bureau of the Census, Washington, D. C.
1930 Agricultural Census Returns, St. John, U.S. Virgin Islands.

U. S. Coast and Geodetic Survey, Washington, D. C.
1919 Fieldmap of St. John, Central Part. Register No. 3772. Mss.

U. S. Geological Survey, Department of the Interior, Washington, D. C.
1954 Aerial Photographs of the Virgin Islands.

1958 WESTERN ST. JOHN, V. I. Topographic Map.

U. S. Navy, Photographic Division, Washington, D. C.
1947 Aerial Photographs of the Virgin Islands.

Westergaard, Waldemar
1917 THE DANISH WEST INDIES UNDER COMPANY RULE. New York, N. Y.

Y-N-A134-589-A

VIRGIN ISLANDS RESOURCE MANAGEMENT COOPERATIVE

BIOSPHERE RESERVE
RESEARCH REPORT NO.20

A GENERAL REVIEW OF SEDIMENTATION AS IT RELATES TO ENVIRONMENTAL STRESS IN THE VIRGIN ISLANDS BIOSPHERE RESERVE AND THE EASTERN CARIBBEAN IN GENERAL

Dennis K. Hubbard
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

. 55

XN-ABH-589-A

A GENERAL REVIEW OF SEDIMENTATION AS IT RELATES TO ENVIRONMENTAL STRESS IN THE VIRGIN ISLANDS BIOSPHERE RESERVE AND THE EASTERN CARIBBEAN IN GENERAL

1987

BIOSPHERE RESERVE REPORT NO. 20

DENNIS K. HUBBARD
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)

56

ABSTRACT

This report discusses the impacts of sedimentation on tropical marine environments. Because of the greater susceptibility of reefs, the majority of the discussion is aimed at this specific environment. Included are:

1. A review of the general types of sediment stress that occur in marine systems.

2. A discussion of the critical parameters that should be measured in any study of sediment stress.

3. A discussion of sources of sediment stress in the Caribbean, including examples from within the V.I. Biosphere Reserve, the U. S. Virgin Islands and the eastern Caribbean.

4. A more specific treatment of area-wide problems, along with strategies that exist or should exist to cope with them.

This document is not meant to be an exhaustive review of the subject. Rather, it is intended to highlight the problems, provide some reasonable management guidelines, and serve as a starting point for developing future VIRMC projects dealing with this important topic. A synthesis such as this will never totally satisfy the needs of all individuals. Hopefully it can be a useful reference tool for those interested in pursuing the problem further.

TABLE OF CONTENTS

LIST OF TABLES

INTRODUCTION

Background

This is a final report to the Virgin Islands Resource Management Cooperative (VIRMC) outlining a number of topics related to the impacts of sedimentation within the V. I. Biosphere Reserve (VIBR). Specifically, the tasks initially outlined include:

1) A review of the literature on the impacts of sedimentation on tropical marine ecosystems ;

2) A review and evaluation of USVI and Federal legislation, policy and programs to control sedimentation in the USVI ;

3) A discussion of the general causes of sedimentation and its impacts within the V.I. Biosphere Reserve, the U. S. Virgin Islands and the eastern Caribbean ;

4) Recommendations on specific watershed management tools that might be useful within and around the V.I. Biosphere Reserve ;

5) A prioritized list of future research projects that would address site-specific problems within the VIBR.

This report is divided into two main sections. The first deals directly with sedimentation as it impacts marine systems (i.e. items 1 and 3). The primary focus will be on the coral reef system for two reasons. First, it is probably the most sensitive and least understood of the nearshore tropical marine ecosystems (mangroves, seagrass beds and reefs). Second, the focus of the management strategy within the VIBR with respect to sedimentation is likely to center primarily around reefs.

The second section specifically discusses the state of present protection measures with respect to sedimentation. The focus is on present strategies to stem sedimentation (item 2), as well as potential management approaches that might be useful to provide additional protection (item 4). Consistent with the embryonic state of our knowledge, the final recommendations must be somewhat general and cannot be imposed on every site-specific problem with equal vigor. Nevertheless, it is hoped that they will provide a useful framework from which to build a rational management plan within the VIBR.

The following discussions are not intended to exhaust the subject of sedimentation in the nearshore tropical system. Nor do they purport to reference all the critical papers on the subject. The complexity of the process and the poor level of understanding largely preclude this possibility. Furthermore, the background of the author, and thus the interpretations of the available literature; must reflect a physical bias toward the subject. The primary goal of this report is to help the reader appreciate the state of our knowledge and the problems upon which we must focus if we are to understand these complex processes.

Statement of the Problem

The literature dealing with sedimentation in the marine environment is certainly extensive. However, despite the great number of papers dealing with the subject, our understanding of its impacts is still in its infancy. Central to the problem are two things: 1) the lack of baseline data before sedimentation events, and 2) the lack of long-term field measurements relating increasing levels of sedimentation to metabolic processes within individual organisms.

As an example of the latter problem, several short-term or laboratory studies (e.g. Thompson, undated; Rogers, 1983) have demonstrated a surprising tolerance on the part of certain corals to short-term high doses of sediment. Yet, the literature is replete with what amounts to post-mortem autopsies of reefs destroyed by sedimentation during and after dredging in nearby environments. At the crux of this problem are the differences between high doses of sediment over a short period (acute stress) vs. much lower doses on a continuous basis (chronic stress). This is compounded by the general lack of baseline data on the condition of various marine areas prior to stress and subsequent degradation.

This problem surrounds our ignorance of the specific metabolic processes that occur within potentially affected organisms as levels of stress progressively increase. For example, a storm will have a greater impact on a marine environment that is already stressed by background sedimentation than one which occurs in pristine conditions. Before we can understand these cumulative effects, however, we must come to grips with the organism-level response to individual stresses.

Our attempts to model nearshore marine systems tell an unfortunate tale of confusion. Aller and Dodge (1974) and Dodge, et al. (1974) studied sedimentation in Discovery Bay, Jamaica. They concluded that the small size of the coral heads was an adaptation to sediment stress whereby smaller colonies would have a shorter distance to move sediment and clear the colony. Thus larger heads would eventually die, leaving the size distribution they observed. In contrast, Maragos (1974 a, b) interpreted the presence of all larger heads as a reflection of the same sediment stress. His logic centered around the inability of coral larvae to successfully recruit under conditions of high sediment load. Thus, the only corals that remain are those that recruited successfully prior to the existing conditions of high turbidity.

The above example typifies the problems in dealing quantitatively with the topic of sediment stress. Either one set of researchers is wrong about the controls of sedimentation, or else the controls in the two areas of study are somehow different from one another. In either case, extreme confidence in our quantitative understanding of the problem is probably not warranted. Attempts to model the interactions of tropical marine systems (e.g. Berwick and Chamberlin, 1985) have raised some "interesting" possibilities, but unfortunately will do little to understand the complex nature of the problem until realistic input data for such models are available.

In this respect, we are really back at the beginning. We certainly understand that sedimentation is (generally) detrimental to marine systems at some level. The problem centers around determining at what level that will occur, and how that might be incorporated into a rational management scheme that allows human entry into such fragile areas. Certainly mangroves are less susceptible to siltation than reefs; in fact, mangrove systems thrive under some conditions of high sedimentation in the absence of associated pollutants (e.g. heavy metals). Seagrasses, while more susceptible to sedimentation than mangrove complexes, can still tolerate a wide range of turbidity and sedimentation compared to coral reefs. As coral reefs are probably the best-represented of the major nearshore systems in the VIBR, and are profoundly affected by sediments at all levels, they become the most problematic in terms of management.

This report will first look at the types of impacts typically occurring during sedimentation events. While seagrasses and mangroves are considered (although briefly), the main focus is on coral reefs. The impacts on mangrove and seagrass systems are more related to direct removal (i.e. dredging, deforestation) than to indirect sedimentation. Thus, the management strategy becomes less dependant on understanding a complex cause-and-effect relationship and more one of strict preservation. Coral reefs, in contrast, are potentially affected by any marine or upland activity. They therefore become the most problematic from a management standpoint, and are the primary focus of this report.

The following section attempts to generally summarize the impacts of sedimentation on reefs. The discussion concentrates on scleractinean corals for three main reasons. First, they appear to be the most intolerant species present on the reef, and therefore represent the most critical problem in developing a management strategy. Second, the experience of the author is more broadly based with respect to scleractinean corals. And, finally, the available literature relating sedimentation to distributions of other organisms is limited and inconclusive.

61

With respect to the latter point, it probably is safe to say that octocorals, sponges, crinoids and a host of other organisms are more tolerant of (and in some instances thrive on) sedimentation. While it is not intended to ignore the importance of these organisms on modern reefs, their usefulness in the context of this discussion is more related to identifying conditions less favorable to stony coral growth. Thus, their occurrence is more useful in establishing ambient conditions. With respect to management, they become less problematic (although not wholly unimportant) from the standpoint of preserving water quality.

TYPES OF SEDIMENT IMPACTS

Increased sedimentation can adversely impact coral reefs in a variety of ways. These include:

1) smothering of the coral by settling;
2) reducing incident light by turbidity;
3) scouring of the coral by bedload transport of primarily sand;
4) inhibiting recruitment by juvenile corals.

Smothering

Of all the potential impacts, smothering is probably the easiest for a layperson to visualize. Dredging next to a reef suspends sediment and that material is moved in the prevailing currents until it settles on the nearby reefs. Certainly much of the damage documented from past dredging projects (Nichols, et al., 1972; Johannes, 1975; Dodge and Vaisnys, 1977; Bak, 1978; Taylor and Saloman, 1978) is related to the direct impact of sediments smothering reef organisms. Loya (1976) cited similar references to sediment damage in Australia (Fairbridge and Teichert, 1948), Johnston Island (Brock, et al, 1966), Hawaii (Johannes, 1975; Maragos, 1972), Puerto Rico (Kaye, 1959) and the Virgin Islands (van Eepoel and Grigg, 1970). Impacts due to increased runoff from the land have been discussed along the west coast of Puerto Rico by Morelock, et al. (1983). On Algarrobo Reef off Mayaguez, coral cover is presently below 2%, and is dominated by *Porites asteroides* and *Montastrea cavernosa*. At nearby Escollo Rodriguez Reef, increased runoff over recent decades has deposited up to 1 m of fine silt on the backreef and eliminated all coral cover.

Even those corals that successfully cope with elevated levels of sedimentation must pay a price in the removal of that material. Energy must be expended in mucus production, polyp expansion, or whatever sediment-clearing strategy an individual organism might employ. Different corals deal with sediment in different ways. Some depend almost solely upon external physical energy (e.g. waves and currents) to remove sediment and, therefore, are severely limited in the environments they can

62

occupy. Some (e.g. Madracis mirabilis) move sediment by ciliary action, while others rely on polyp expansion or mucus generation. Madracis mirabilis appears to remove sand by tentacular action while muddy sediments are moved by active cilia (Bak and Elgershuizen, 1976). Thus, the state of this particular coral affects its ability to remove sediments of varying sizes. When the tentacles are extended, the colony will be more effective at removing larger particles. During retraction, increased ciliary action will facilitate mud removal, but will impede sand rejection.

The ability of the reef to clear sediment has been difficult to quantify. Rogers (1977; 1983) demonstrated the ability of Diploria strigosa and D. clivosa to tolerate single, coarse sediment doses of 800 mg/sq cm and daily doses of 200 mg/sq cm for a period of 45 days. Acropora cervicornis also showed remarkable tolerance to short-term sediment loading. Thompson (undated) demonstrated a high tolerance of Porites to both carbonate sand and certain types of drilling mud. In contrast, Acropora palmata colonies died after single doses of 200 mg/sq cm (Rogers, 1983), and are likely susceptible to damage at much lower levels of stress. Bak (1978) felt that the platy form of Porites asteroides often found at depth on many Caribbean reefs was almost totally incapable of clearing sediment settling on its surface.

Montastrea annularis, probably the most important frame-builder in Caribbean scleractinian reefs has exhibited a wide range of tolerance in different studies. Lasker (1980) reported an ability to remove up to 16 mg/sq cm-day of deposited sediment. In contrast, Dodge, et al. (1974) inferred a reduction in coral growth related to sedimentation (their "resuspension") rates as small as 1.1 mg/sq cm-day. In this latter study, however, it was not demonstrated that the sedimentation levels measured during the 8 days of their investigation were those necessarily responsible for the long-term growth rates measured in their coral samples.

The impact of sedimentation on colony size is not well understood, and cannot be considered as much beyond speculation at this time. Dodge and Vaisnys (1977) felt that older colonies are more susceptible to sedimentation than younger colonies as they have to move sediment a greater distance to effect removal. Hubbard, et al. (1985) documented a gradual decrease over time of the growth rate of 100+ year-old Montastrea annularis colonies in Reef and Fish Bays on St. John. While they attributed the trend to subtle changes in runoff as the hillsides reforested, this decrease in growth rate may reflect a response similar to that described by Dodge and Vaisnys (1977). Maragos (1974a, b), however, described an opposite effect, whereby coral recruitment is inhibited by sedimentation. Therefore, older and larger corals formed prior to sedimentation will dominate on stressed reefs. There is probably at least some merit to both hypotheses which together point out the complexity of the problem.

Corals have evolved a complex set of strategies to deal with increasing sediment stress. These can be important at the level of the individual organism or the whole colony. At the organism level, Hubbard and Pocock (1972) related the sediment tolerance of individual corals to overall colony morphology, calyx structure and age of the coral. They felt that the more effective corals would have a greater number of more complex septa (related to the structural integrity of the skeleton/organism pair), higher calical relief (i.e. the polyps are elevated above the surrounding skeleton), V- or U-shaped calical floors and a lighter skeleton. Bak and Elgershuizen (1976) felt that long meandroid colonies (e.g. Diploria strigosa, Manicina aureolata, Colpophyllia natans) would be better at clearing sediment than those with short, reticulate valleys (e.g. Agaricia agaricites).

Colony shape and orientation are also important in determining the ability to shed sediment. Using Agaricia agaricites, Bak and Elgershuizen (1976) found that the ability of the colony to clear sediment could be progressively increased by tilting the coral away from the horizontal. This in fact appears to be the strategy by which otherwise sensitive species deal with sedimentation at depth. In Montastrea annularis, they showed that hemispherical colonies could remove sediment in a fraction of the time required by flatter morphs of the same coral. Also, hemispherical colonies were more effective at removing sand, while flatter colonies had an easier time with mud-sized sediment. Whether this is a long-term adaptation to the smaller sediment sizes introduced onto deeper-water corals (i.e. quieter energy) cannot be said with certainty, but is a tempting hypothesis.

Shading

In addition to settling on benthic organisms, sediment can reduce the amount of light reaching the bottom at any given depth. Inasmuch as a substantial portion of the carbohydrates required by corals are produced by photosynthetic algae (zooxanthellae), this raises another potentially limiting problem for the coral reef. Similar impacts are likely important in seagrass beds.

Rogers (1977; 1979) clearly demonstrated the impacts of extreme shading on the corals of San Cristobal Reef in southwestern Puerto Rico. After 5 weeks of shading by black plastic, colonies of Acropora cervicornis showed significant bleaching of coral tissue and reductions in colony-extention rate. She proposed a relationship between polyp size and resistance to shading where corals with larger polyps would likely have a greater dependence on zooplankton and other in-water food sources. Corals with smaller polyps (A. cervicornis) were the first to show bleaching, followed by M. annularis (medium-size polyps) and two species of Diploria (largest polyps).

There are several excellent discussions of this problem in the literature. However, none of them establish quantitative limits above which reefs or other marine systems can be expected to suffer specific levels of damage. Cortes and Risk (1985) described a reef system at Cahuita, Costa Rica along which coral growth (and probably cover) has been gradually reduced due to increasing development pressure. They cite an increase in the amount of terrigenous sediment trapped within the coral skeletons over time as a response to growing agriculture and logging since the late 50's. Their data on coral growth, however, do not make a convincing correlation between runoff, reduced water quality and actual coral-growth rate.

Morelock, et al. (1979) described an environmental shift in the positions of reef zones within Guayanilla Canyon off the south coast of Puerto Rico. In the canyon, 18 m is the lower limit of coral growth, compared to 37 m along unstressed shelves. Furthermore, the corals within this zone were those typical of deeper-water environs in other areas, demonstrating an upward shift in depth zonation under conditions of higher turbidity (i.e. lower light). Dodge and Lang (1983) related a sudden drop in coral-growth rate in the Flower Gardens reef in the Gulf of Mexico with increased turbidity (and light reduction) during flooding of the Atchafalaya River. Rezak and Bright (1981) related it to submarine collapse of the underlying carbonate terrain , dropping the corals to a depth at which light level was significantly lower. In either case, the effect of lowered light levels remains a central control of the rate of coral growth.

Roy and Smith (1971) described an area on Fanning Island (Pacific Ocean) where reefs are surviving (31% cover) under conditions of high natural turbidity. In turbid areas (3.5 mg/l Total Suspended Solids - TSS) coral cover was reduced to 31% compared to 62% in less turbid areas (1.0 mg/l TSS). This was accompanied by a shift in the importance of ramose corals in turbid water (50%) compared to clear water (10%). Based on their observations, they placed light attenuation at the top of the list of impacts, followed by smothering and larval inhibition by burial. Once again, however, there is some question as to whether the conditions measured during the brief study period were in fact those responsible for the differences observed in the coral population. Nevertheless, changes in turbidity at some level emerge as important controls of reef development.

65

The critical question in this regard relates to the effects of specific levels of turbidity on various reefal organisms. Table 1 summarizes turbidity and sedimentation rates drawn from several literature sources. It appears that levels of TSS in the range of 1-2 mg/l can be considered as "normal" on most reef systems. Instances of reduced coral cover appear in areas where total suspended solids reach 3-5 mg/l over extended periods of time. Rogers (1982) did report storm-related turbidity levels of 10-30 mg/l on St. Thomas, however, with little environmental damage. Once again, these data together point to an ability for marine systems to tolerate significant short-term perturbations in water quality, while being relatively intolerant of much lower but chronic stresses.

Rogers (1979) reported reductions of light levels in 2 m of water to less than 65 microeinsteins/ sq m - sec. These conditions corresponded to TSS values of 9-16 mg/l. Decreasing of the TSS levels to 1.4 mg/l resulted in an order-of-magnitude increase in light level to 700 microeinsteins at the same depth. If these levels of TSS are reasonable indicators of reef responses to sediment stress, then minor shifts in the water quality of a reef system **over a long period of time** would appear to have a very profound impact on reef structure. Certainly this is not good news to those interested in protection of reefs from impending stress. What is yet to be established, however, is whether these levels of suspended solids are those responsible for the observed patterns of reef development. At a minimum, long-term measurements of water quality in these areas are needed. These would provide a more reasonable estimate of the present conditions associated with these environments. Even more useful would be historical data on water quality and reef character, but these kinds of information are essentially nonexistent.

Scouring and Inhibition of Recruitment

The impact of scouring on corals is more likely related to the occurrence of bedload (i.e. sandy) transport. Therefore, this is probably more important as a natural control in areas adjacent to sand-dominated systems. For example, reefs close to the beach are often characterized by corals sitting on pedestals that elevate the main colony from the prevailing traction carpet of shifting sediments. Likewise, the dominance of _A. palmata_ on many reef crests is likely a response to the energetic sand transport over the reef surface. By growing rapidly upward, this branching coral can quickly attain a position above the zone of periodic scour by shifting sands. There are other competitive strategies

(n

Table 1. Sedimentation data from several marine environments.

LOCATION	ZONE	TSS(mg/l)	SETTLING(mg/cm-da)
Costa Rica	outer crest	0.3-4.6	
	inner crest	1.4-18.8	
	lagoon	0.2-36.6	12.8-1180
	bay	2.8-54.0	
	rivers	1.4-6200	
Grand Cayman	general reef	0.1-2.4	
San Cristobal, PR	general reef	0.8	10.0 (1-21)
Guayanilla, PR	canyon	4.5-6.1	1.1-9.8
Punta Ventana, PR	canyon	3.5	2.3
Round Reef, Cstd, STX	backreef	1.3-1.5	
	forereef	2.1-3.4	
	east tip	2.0-3.4	
Long Reef, Cstd, STX	w. forereef	1.4-1.6	
	e. forereef	1.9-2.5	
	backreef	1.5-2.3	
Christiansted, STX	general		3-247
Limetree Bay, STX	general		
Florida Keys	general	3-5	
Discovery Bay, Jam.	general		0.5-1.1
Negro Bank, PR	e reef (steep)	11-17	3-5
	w reef (flat)	20	15
Fanning Is.	turbid lagoon	3.5	<1mm/yr
	clear lagoon	1.0	
	open ocean	0.3	
Discovery Bay, Jam.	backreef		0.5-1.1
Virgin Gorda, BVI	general	0.9-2.2	0.1-1.4
Brewers Bay, STT	grassbed		1.2

in this rapidly growing, branching morphology (e.g. shading), but growing out of the zone of sediment scour is probably an important factor in shallow reef areas.

Likewise, inhibition of larval recruitment can be important. The effects of this factor are very difficult to quantify, however. Morelock, et al. (1979) discussed the importance of substrate type in limiting larval recruitment. The gradual cover of the substrate by fine-grained sediment or algae limits the space available for settling. Roy and Smith (1971) cited the importance of sedimentation to larval recruitment on Fanning Island, but related it more to the decreased tolerance of the younger corals to sedimentation. Also, sedimentation increases (especially from terrestrial sources) are often accompanied by elevated levels of nutrient input. This favors colonization by fleshy algae, which further inhibit coral development.

WHAT ARE THE CRITICAL PARAMETERS?

Given that sedimentation can impact corals in many ways, the problem is reduced to determining how important each of these is in controlling reef development, and what the critical parameters that should be measured are. The following section will address two topics. First, the relative importance of the above limiting factors in a few example corals will be discussed to illustrate controls of sedimentation on coral type and zonation. Specific examples will be used to demonstrate the controls of bedload and suspended sediments on reef development in natural systems. Second, an attempt will be made to address the parameters related to sedimentation that can and should be quantified to eventually understand sedimentation as a control of reef development. Some guidelines concerning ways to measure these parameters and their general usefulness are offered .

Sedimentation Effects on Corals - a General Discussion

Of the four effects of sedimentation discussed above, siltation and light reduction are felt to be the most important. It is likely that the zonation seen on natural reefs, and therefore stressed reefs as well, is a response to both of these factors. Reduced light levels can vertically suppress zone boundaries (Morelock, et al., 1979; Adey and Burke, 1977). Hubbard, et al. (1985; in press) hypothesized that a gradual reduction in water clarity beginning 3-5,000 years ago has resulted in a progressive decrease in coral cover, diversity and reef accretion in Salt River submarine canyon on St. Croix. Likewise, sedimentation can reduce coral cover (Roy and Smith, 1971; Cortes and Risk, 1985) and slow the rate of coral growth (Dodge, et al., 1974; Rogers, 1982; Hubbard, in press; Hubbard, et al., 1985).

The success of *Acropora palmata* in the shallow reef zone is likely related to all the parameters discussed above (reduced shading, lower sedimentation levels and reduced scour), but sediment removed by wave action probably sits at the top of the list. Even low levels of sedimentation have a detrimental impact on this coral (Rogers, 1977). Changes in *Acropora* morphology appear to be some adjustment of the colony to offset the buoyant lifting forces generated by waves in the different reef zones (Shinn, 1966).

M. annularis appears to adapt morphologically to levels of sedimentation, while its growth rate is more a function of light level (Dustan, 1977; Hubbard and Scaturo, 1985). Bak and Elgershuizen (1976) showed that hemispherical colonies were more adept at removing sand found in shallower reef environments, while platier colonies occurring in deeper water were better adapted to removing finer particles. Hubbard, *et al.* (1985) cited the occurrence of knobbier forms of this coral in higher-stressed areas of Fish and Reef Bays on St. John as a possible adaptation to sediment loading.

Agaricia agaricites demonstrates a poor ability to clear sediment of any kind, and relies on a high angle with the substrate to clear sediment (Bak and Elgershuizen, 1976). This implies that smothering rather than light attenuation is more of a control in the distribution of this coral.

While excellent examples of sedimentary controls on reefs can be found in site-specific studies, stress on a given reef is generally the result of a combination of effects, and the relative role of each is difficult to quantify. Hubbard (in press) describes variations in reef development along the north coast of St. Croix where increases in the amount of sediment delivered from upwind shelves result in a progressive degradation of the reef cover. While bedload sedimentation is invoked as the primary control, accompanying changes in water quality are undoubtedly important as well. Adey, *et al.* (1977) cited increased sedimentation along the south shore of St. Croix 9,000 years ago as the cause of a a cessation of reef accretion, but is was not obvious how much of this was related to sedimentation as opposed to reduced light levels. A similar situation has recently been discovered along the shelf-edge reefs of La Parguera in southwestern Puerto Rico (Hubbard and Morelock, unpubl. data), where a present-day head-coral community veneers an *A. palmata* reef that stopped accreting, probably 4-5,000 years ago.

The complexity of the problem should not discourage future attempts to model sedimentary controls on modern reefs. In fact, isolation and manipulation of individual controls likely lies at the heart of solving the problem. It is important, however, that the researcher addressing sedimentation recognize the degree of complexity involved and not place too much emphasis on any one factor measured in a field situation. Given that word of caution, the next section attempts to list primary controls of sedimentation, and to suggest reasonable ways to measure them.

Important Parameters to Consider

The above sections have dealt with the general stresses induced by sediment loading and their impacts on reefs and reef organisms (primarily corals). This section addresses the parameters felt to be most important in understanding these impacts on reefs and other marine systems. At the outset, it should be stated that the factors listed below reflect the biases of the author, and may not be in agreement with the priorities of all researchers in the field.

Concentration of suspended solids - Certainly one of the the most important factors in dealing with sedimentation is the amount of sediment introduced into the water column. This parameter is important in determining both the attenuation of light in the water column and the potential for sedimentation as material settles over time. Total suspended solids (TSS) are typically determined by filtering large quantities of water through pre-washed and pre-weighed membranes (0.45 micron pore openings are the most common). Requirements for this procedure include a suitable filtering apparatus, an analytical balance, a clean drying oven and a controlled (i.e. temperature and humidity) room in which to weigh and manipulate samples. Controlled laboratory conditions and extremely careful procedures are required for this method; unless the minimal conditions listed above can be met, the data are nearly meaningless.

Recently, several optical methods have become available for **approximating** total suspended solids. These instruments measure some character of the suspended solids (i.e. reflectance, scatter, absorption) and report it in digital units. This methodology has several advantages, including precision and speed of data aquisition. Profiles of water character can be taken and used to map changes in the distribution of these parameters temporally and spatially. While of great value when used properly, all these methods share one serious disadvantage: they measure optical parameters affected by suspended particles, but do not actually measure the concentration of the particles themselves. Depending on the size, shape and composition of the suspended particles, optical measures can vary dramatically among samples of the same concentration of suspended solids.

Nevertheless, these methods can be valuable if two conditions are met. First, the researcher must establish the optical parameters that most likely affect the marine organisms of interest. Unfortunately there is little agreement as to which of the three parameters listed above is the most critical. Even then, the optical data are likely to relate only to impacts of shading and not of smothering. Second, the researcher must "calibrate" the instrumentation with the local sediments. Only by understanding the "signature" of the various components of the suspended particle spectrum can optical data be quantitatively related to values of total suspended solids. It must be further understood that these calibrations are site specific (i.e. optical calibrations from a reef/lagoon area in the open ocean cannot be used to translate optical data into TSS figures off of a river mouth where sediments have a different character).

Having said this, the author still feels that these optical methods may show the greatest promise for the future. But, they will be useful only after the above calibration procedures have been applied and only if the researcher remembers what he or she is measuring. Otherwise spatial and seasonal variations in the composition of suspended solids will likely lead to gross errors in subsequent interpretations.

At this point, a careful program of successive filtering for TSS concentration and composition as described below is the most reliable methodology. This coupled with calibrated optical methods, however, will greatly increase our ability to monitor spatial and temporal variations in suspended solids not logistically feasible using filtering alone.

Settling rate - Along with shading, direct sedimentation on benthic organisms plays the major role in limiting reef cover. At the simplest level, the absolute quantity of the material landing on the substrate is probably the most important parameter in determining the likelihood of damage due to smothering.

The most common method involves placing some sort of open container on or near the bottom and collecting material falling from the water column. While simple in concept, obtaining reliable measurements is in fact quite difficult. At the heart of the problem is designing a trap that will duplicate the amount of sediment that settles, is resuspended, and again settles on the adjacent bottom. A trap that is too wide at the mouth will allow scour within the trap to remove previously settled sediment more easily than it is resuspended from the adjacent substrate (undertrapping). Conversely, traps too narrow at their mouth relative to their vertical dimension artificially hold material within them while sediments on the adjacent bottom are resuspended and carried elsewhere (overtrapping). Gardner (1980a and b) evaluated a variety of trap designs, and concluded that a simple vertical-walled trap with a height-to-width ratio of 2.3 would most closely approximate settling conditions on the adjacent substrate. This value is based on both field and laboratory experiments. Baffles were recommended for areas where highly turbulent conditions might be expected (e.g. upper forereef).

\l\

Once a suitable trap design is chosen, the traps are placed in the field and allowed to collect sediments for some suitable period of time. Personal experience has shown that some interval less than a week is desirable unless conditions are highly uniform temporally. Traps are sealed in situ and returned to the lab. Filtering of the trap contents through pre-washed, pre-weighed filters provides a total weight of trapped material. Alternately the water can be evaporated from the container, but correcting for the salt content of the sediments and evaporated water becomes problematic unless very large quantities of sediment are trapped.

Origin of suspended and settled solids - Matter suspended in the water column can consist of inert sedimentary debris or more reactive organic material (e.g. plant and animal fragments, plankton). Each of these has a different impact on reef organisms, and the relative importance of each component must be identified. Organic matter is often beneficial to the marine system, whereas sediment almost always produces stress. There are several ways to differentiate between sediment and organic matter in the water column. The most common is dissociation of the organics by some method (chemical additives such as hydrogen peroxide; ashing of the organics at high temperatures) followed by filtration and reweighing. Equipment is identical to that listed above, with the addition of a muffle furnace for high-temperature ashing.

Character of the sediments - There are two critical parameters related to the suspended sediments. These are **size** and **composition**. Of the two, size is the most difficult to measure. In high concentrations, pipette analysis can be used to determine size distribution. The methodology is described in Folk (1974). This method is very time-consuming, however, and precision is achieved only under **very** carefully controlled conditions.

In lower concentrations, size distribution is extremely difficult and costly to determine. Coulter counters, originally designed for blood analyses, have been used effectively, but are expensive, and preparation is tedious. More recently, particle counters using a laser beam have become available, but like any optical instrument, must be "calibrated" against pipetting to give a reliable size distribution. Nevertheless, at a cost of around $18,000 they probably represent the easiest and least expensive means of determining size characteristics of suspended sediments in concentrations typically found on reefs.

This is obviously not an inexpensive venture. Unfortunately it probably lies at the heart of understanding the impacts of sedimentation on coral reefs and other marine systems. Our laboratory studies to date have used primarily coarse material (fine sand) to stress corals. Yet, much (if not most) of the

71

material reaching reefs from distant sources is comprised of silt and clay. In terms of predicting the dispersion of muddy sediments introduced into the marine environment, sediment size is critical as it determines the rate at which material will settle to the bottom. Thus, trends in water turbidity and settling are determined by this parameter along with local current patterns.

It is the author's opinion that understanding the control of sediment size **within the mud range** will prove to be the most critical step in ultimately unraveling the sediment-stress equations. Sediment size determines the nature of the stress (i.e. light attenuation vs. smothering), the likely mechanism by which the coral will expel sediment, and the likelihood that the sediment will carry adsorbed materials detrimental to the well-being of the reef (e.g. heavy metals).

The other element of sediment character is composition. At the most basic level, one must consider whether the sediment is carbonate (i.e. biological) or siliciclastic (i.e. likely from a terrestrial source). Within siliciclastic materials, the specific origin of the sediment, especially in the clay range, may have important implications to the adsorption of pollutants, heavy metals and nutrients. Observations by the author infer that corals can expel carbonate mud with greater ease than siliciclastic mud. While no concrete data can be provided to support this contention, the author feels that composition of the muddy sediment in the water column plays a role only slightly below that of size in determining stress levels.

Carbonate vs siliciclastic content can be determined by several methods. The most popular is digestion of the carbonate fraction in dilute (ca. 10%) hydrochloric acid. As in the case of organic digestion, the filter must be washed, redried and reweighed. The procedures for organic and carbonate contents must be done separately.

Composition of the siliciclastic fraction is typically done by X-ray diffraction. The equipment is available in most mainland geology departments, but is sufficiently specialized that it would not be readily available in the Virgin Islands. The U. S. Geological Survey likely operates an XRD unit in San Juan, Puerto Rico.

Light levels - One of the easiest measurements to make is that of light intensity. Numerous instruments are available to manually or remotely collect light data. Standard methods have been established to determine light intensity using a reasonably accurate, photographic light meter. More sophisticated units (e.g. Licor light probes) are commercially available within the price range of most local laboratories.

Light measurements taken through the water column can give a valuable picture of the effect of suspended materials. It is important that these data be taken on at least some sort of seasonal basis, as spot measurements taken at haphazardly chosen intervals can give a misleading picture. If a regular program of light measurements cannot be undertaken, certainly a careful collection of light data after extreme events (e.g. heavy seas, rains) can provide valuable information on the range of light conditions expected in the marine environment of interest.

Within the shallower water depths, data on light spectra may be useful. At greater depths, however, filtering of the red end of the spectrum results in somewhat uniform conditions. Spectral data may eventually prove to be more important than is implied here, but is is felt to carry a secondary importance to the more basic parameters discussed above.

Other factors - The above factors represent the primary parameters that can be measured or manipulated in an effort to understand the effects of sediment on marine organisms. In addition, there are several factors that, while still important, are not easily manipulated. They are nevertheless still important in affecting to what degree the above parameters might have an effect, and are worth mentioning.

Water depth plays an important role in determining the character of a marine system whether under natural or stressed conditions. Physical energy levels are progressively buffered with depth. On the positive side, short-term events such as hurricanes are less destructive in deeper water. On the negative side, however, lower energy levels limit the occurrence of organisms that rely heavily on water motion to clear sediment.

The primary importance of depth is related to light. With increasing water depth, both the intensity and the character of the light are modified. Absorption and scattering of light decreases the intensity and narrows the spectrum of the light reaching the bottom. In a natural system, the pattern of light intensity with depth in part controls the distribution of many reef organisms. Sediment introduced into the water column effectively reduces the amount of light reaching the bottom at any depth. On a large scale, the vertical compression and shallowing of faunal zones on the reef can result (Morelock, et al., 1979; Hubbard, et al., in press). On a local scale, the depths at which many marine organisms occur can predetermine the potential for impact due to sedimentation. In shallow marine systems (d<2m) moderate levels of sedimentation are somewhat benign from a standpoint of light limitation. Thus, impacts are limited to smothering and abrasion. In deeper water, however, many of the organisms are already at or near their lower threshold with respect to light. Thus, environmental damage can be done by reduced light even when sediment never directly contacts the substrate.

Current patterns are also important in determining the pathways over which sediment will travel. Whether related to dredging or runoff, sediment will typically have a direct effect (i.e. at the point of introduction) and an indirect impact at some "downstream" site. Critical parameters in predicting the patterns of sediment dispersal include:

1 - settling velocity of the suspended sediments
2 - current speed and direction
3 - diffusive and turbulent spreading of the sediment
4 - water depth over which the sediments are being spread
5 - the character of the bottom over which the plume is spreading and settling

Antecedent conditions play an important role in determining the potential impact of marine sedimentation. Certainly an already impacted area will be more susceptible to damage than one that is untouched by prior stresses. Thus, a critical management decision centers around whether an already stressed environment requires more protection because of its increased sensitivity or less protection because it is already in a degraded state. Often this must be a subjective decision.

Upland character is important in predicting the amount and type of sediment a marine system might presently be receiving. While not in the same general category as the parameters above, understanding the character of the watersheds and coastal areas adjacent to the marine environment is a key component of any rational management plan. This will be discussed in more detail in the following section.

PRIMARY SOURCES OF SEDIMENT STRESS

There are numerous ways in which reefs can be stressed by sediment. These include resuspension by boat traffic, hazardous spills, inadvertent dumping of sediment into the marine environment (e.g. open-ocean dumping), landfill and a host of others. The most common problems, however, are related to two general activities: marine dredging and upland development. While the importance of the other potential sources of stress should not be ignored, these latter two represent the most common assault on the marine environment, certainly in the Caribbean and likely on a worldwide basis. As they undoubtedly represent the primary problems from a standpoint of local resource management, the following discussions will focus on these two activities.

Dredging

Probably the most direct and easy to visualize impacts on the marine environment are related to dredging. Direct impacts are related to disruption (i.e. removal) of the marine habitat in the area of excavation. In addition, numerous downstream effects related principally to shading and smothering by suspended sediment take on equal importance.

The adverse effects of dredging on coral reefs and seagrass beds is well documented (Nichols, et al., 1972; Johannes, 1975; Dodge and Vaisnys, 1977; Bak, 1978; Taylor and Saloman, 1978; Penn, 1981). The immediate impact on the environment is obvious. A significant portion of the sea bed is disrupted. Downstream effects are more subtle and difficult to predict.

Although the area being disrupted is occasionally a reef (e.g. channel excavation), more typically it is open sediment or seagrass beds. Although seagrasses are more tolerant of sedimentation than reefs, they can be smothered given sufficient quantities of suspended sediments. The general importance of seagrass beds has been discussed extensively (for review, see Taylor and Saloman, 1968; Thayer, et al., 1985; Burrell and Schubel, 1977; McRoy and Helfferich, 1977, 1980). Removal of seagrass beds can impact stability of the substrate. Furthermore, the potential for seagrasses to act as sinks for heavy metals (Faraday and Churchill, 1979; Lyngby, et al., 1982) raises the likelihood of long-term toxic effects.

Once totally uprooted, seagrass beds will take over 5 years to recover even under ideal conditions. (Patriquin, 1975; Zieman, 1976; Thorhaug, 1981). While recovery can be accelerated by transplantation (Phillips, 1976; 1980), direct loss of seagrasses must be thought of as a long-term disturbance.

Downstream impacts on seagrass beds are harder to quantify and predict. Likewise, the major impact on adjacent mangrove systems are related to removal, and stands remaining after development (both natural and replanted) often appear to be coping with existing conditions. Since the 60's, the south coast of St. Croix has come under heavy pressure from industrial construction and operations. Despite high suspended-sediment levels over a protracted period of time, expansive seagrass beds still remain in the area between two major industrial complexes (VI Marine Advisors, 1984). No estimates of the primary productivity of that system have been made, nor have there been any studies of the indirect impacts on other marine organisms using those grassbeds. Nevertheless, they are existing at surprisingly high levels of stress from ambient sedimentation levels.

Generally the hardest hit, and therefore the areas of greatest potential concern, are the reefs. Sediment suspended by the dredge or poorly managed sediment-receiving areas on shore can move considerable distances from the initial point of introduction. How far the sediment will travel depends on a number of factors. These include:

1 - sediment size (settling velocity)
2 - current speed
3 - water depth
4 - importance of resuspension downstream

Once the dredging has ceased, the potential often remains for resuspension as the newly dredged area becomes a center for commercial navigation. The impacts due to this phenomenon are not trivial, and must be considered in terms of long-term environmental degradation.

Upland Development

Probably more important in the Caribbean are the impacts of upland development. Poor land management can result in a substantial increase in the sediment load delivered to the shore's edge. One factor that is often ignored and thus makes terrestrial impacts all the more dangerous is the cumulative impact of small projects that would be somewhat benign by themselves. As will be discussed below, a major problem in our present management and protective schemes is a system that is set up to evaluate primarily larger projects, while ignoring smaller ones that can collectively have a great impact.

To better understand the nature of the problem, it is instructive to first examine examples from Caribbean areas, and to then discuss some of the factors responsible for damage document in the literature. Morelock, et al. (1983) related dramatic increases in sedimentation off Mayaguez over recent years to urbanization, industrialization and cane agriculture in western Puerto Rico. Loya, (1976) described the effects of increased turbidity on the reefs south of Mayaguez, again a likely response to upland activities. Degraded reefs off Guayanilla on the south coast of Puerto Rico have had similar impacts due to nearshore development, dredging and ship traffic (Morelock, et al., 1979). On St. Croix, industrialization on the south shore has resulted in substantial loss of habitat (primarily seagrass and mangrove), and undoubtedly contributes in part to the poor water clarity along the southwest corner of the island. All three islands in the U.S. Virgin Islands have come under increasing pressure from upland development, and this problem is becoming progressively more acute on St. John, the least developed of the three.

The importance of this problem has been recognized at least to some extent by the National Park Service on St. John and the VIBR in that terrestrial sedimentation has been one focus of VIRMC studies over the past two years. The Park (and the VIBR) must coexist with adjacent development, and the impacts of these surrounding activities therefore take on paramount importance in the formulation of a workable management plan.

Central to minimizing the impacts of upland development on adjacent marine systems is understanding the factors that control runoff. An excellent review of the subject at a general level can be found in Gottfried (1985). Excellent references are made to worldwide importance of upland erosion (Crosson, 1983; Eckholm, 1976; Brown and Wolf, 1984), the importance of short intense rains typical of the Caribbean in affecting high rates of runoff (Suarez de Castro, 1950; Wolman and Miller, 1960; Hudson, 1971; Roose, 1977) and the effects of land use on runoff (Smith and Abruna, 1955; Wilson, 1972; Dunne, 1979; Veloz, et al., 1985).

Jordan (1972) described decreases in overland runoff in the U.S.V.I. over the past century, and related them to gradual reforestation of the island watersheds after the decline of the sugar cane industry on those islands. On St. John, excellent tax records compiled by Tyson (report in prep for VIRMC) show patterns of land use similar to those described on St. Croix by Jordon (1972). A likely conclusion would be that runoff in subsequent years showed a similar decline, thereby reducing stress levels on nearby reef systems. However, Hubbard, et al. (1985) were not able to relate this supposed decrease in sedimentation to any measurable change in the growth rates of Montastrea annularis sampled in Reef or Fish Bays on the south shore of the island. Short-term impacts on the growth rates of nearshore corals in Hawksnest Bay were found to correlate well with construction activity in the watershed, but no long-term effects could be found.

Crucial to the problem of managing upland development is understanding the effects of various land-use practices on sediment runoff, and to be able then to relate elevated sedimentation levels to specific levels of damage. Gottfried (1985) agreed with the contention of Dunne (1979) that land use is probably **the** primary control of runoff in tropical systems. Therefore, management of upland development takes on paramount importance in any management scheme. In this light, potential land-use problems and management solutions are discussed at the end of this report. At this point, however, some discussion of general controls of runoff are in order.

Controls of runoff - General guidelines for predicting the amount of fresh-water runoff (and therefore, sediment runoff) are provided in the Engineering Field Manual for Conservation Purposes (Kautz, 1975). The principal controls are:

1 - watershed area
2 - rainfall (volume and intensity)
3 - watershed slope
4 - soil conditions (i.e. is the soil wet or dry?)
5 - land use

Deitrich, et al. (1982) summarized the pathways through which water from precipitation might be cycled:

$$P = I + OF + AET + SM + GWS + GWR, \text{ where:}$$

P = precipitation
I = water intercepted by vegetation
OF = water flowing over the ground surface
AET = evapotranspiration
SM = soil moisture
GWS = potential for groundwater storage
GWR = underground runoff

A discussion of the importance of each of these parameters is beyond the scope of this discussion. However, some general comments on some of these factors is instructive. In the Virgin Islands, evapotranspiration is high, resulting in a significant loss of water back into the atmosphere during periods between rains. Thus, much of the water retained in the upland system is lost before it can be converted to potable water. This lies at the heart of our local water problem which often takes on crisis proportions. Typically, the potential for groundwater storage is moderate to small on all but the largest islands (e.g. the size of Puerto Rico). This is compounded even further during periods when antecedent soil moisture is high and most of the rainfall runs overland to the sea. As a result of these factors, modest olumes delivered in short but intense bursts on many small Caribbean islands do little to ameliorate the potable water problem while causing above-normal sedimentation damage.

GENERAL SEDIMENTATION PROBLEMS IN THE CARIBBEAN

The Caribbean islands (especially in the eastern Caribbean) share many common problems with respect to land use, water management and stress of nearshore and coastel areas. For a number of obvious reasons, development has and will continue to be concentrated along island shorelines. This development includes home construction, hotels, condominiums, port development and industrialization, to name a few. Each of these types of development carries with it a peculiar set of stresses, but they all share the common impact of increased sedimentation. In the case of land-based development, initial sedimentation is generally related to increased runoff as sites are cleared for construction. Later on, lower levels of chronic sedimentation related to permanent modifications of upland drainage pathways become more important. In the marine environment, stress is generally related to habitat disruption during dredging and filling operations, spreading of suspended solids away from the project site, disruption of previously existing flow patterns in the area and resuspension of sediments by continual operation of the new facility. This section focuses on problems occurring within the U.S. Virgin Islands and the VIBR, but it should be understood that most of the problems discussed below occur throughout the region.

Land-Based Development

There are numerous and recent examples of problems with upland development in the Virgin Islands. As recently as the spring of 1986, 30 acres of land were cleared for development of a resort hotel in Davis Bay on the island of St. Croix. Despite efforts to maintain construction-related runoff, sediment plumes have been seen after even moderate (ca. 1 inch) rains. Much of the upland drainage from the adjacent 400 acres has been diverted into a single watercourse, and the effect of this modification will have to await the passage of time. It is certain, however, that if sedimentation becomes a chronic problem in this area that the *Acropora palmata* formations to the west (i.e. downcurrent) of the project will suffer, as they are very intolerant of sedimentation (Rogers, 1983).

Hotel construction is on the rise on both St. Thomas and St. John. At the Virgin Grand Hotel on St. Thomas, major modifications to the upland watershed could have adverse impacts on nearshore coastal waters in the future. On St. John, hotel construction in Great Cruz Bay has opened a substantial hillside to erosion with few apparent erosion-control measures. The area was already modified in the past by dredging, but increased runoff will undoubtedy have an effect nonetheless.

During October, 1980, ground was broken for the construction of a hospital at the head of Hawksnest Bay on St. John. Studies of the corals in the bay fronting the watershed showed a significant decrease in the coral-growth rates after post-construction rains in 1981 and 1983 (Hubbard, *et al.*, 1985). Prior to construction, more severe rainstorms had produced no such effects. Fortunately, the impact of construction was short-lived, and the significant amount of vegetative cover separating the construction from the ocean somewhat buffered sedimentation impacts. A gradual increase in water quality and coral-growth rate followed cessation of construction and gradual restabilization of at least part of the upland watershed. Were the construction closer to the beach, however, or were it part of a longer-term project, it is likely that the damage would have been considerably more severe.

In the British Virgin Islands, development appears to be progressing not out of any need for employment, but rather in response to a growing government need to financially support its infrastructure. Thus, management is driven by other criteria and is somewhat more complicated. Development around Roadtown Harbor has progressed with no apparent plan, and little evidence of traditional West Indian architecture is readily discerned in new construction. The proliferation of small homesites, roads to serve them, dredging in the harbor and hotel construction are all proceeding at a very rapid pace. On Peter Island, a proposed 18-hole golf course could profoundly alter present runoff patterns and have far-reaching impacts on the nearshore reefs.

Another significant component of shore-based development is industrialization. Morelock, et al. (1979) cited this as part of the reason for increased sedimentation on the west coast of Puerto Rico. On the south shore of St. Croix, the South Shore Industrial Complex was developed starting in the 60s, and continues today. Contained in the complex are two refineries (Hess and VIRCO) and a major alumina processing plant (formerly Harvey Aluminum and now Martin Marietta). Over a 10 year period, many acres of mangrove were either dredged, filled or indirectly disrupted as part of the project. A declining economy and a need for local jobs were cited as a rationale for sacrificing the largest mangrove complex in the Virgin Islands. Ironically, Martin Marietta is now closed, Hess Oil has drastically cut back its work force and the recognition that tourist dollars and not heavy industry are now needed to solve all our financial woes represents the basis for the latest onslaught on the marine system - hotel and condominium construction.

The negative impacts of industrialization are shared by many members of the Caribbean community. Refineries and oil-handling facilities are located on St. Croix, Puerto Rico, Trinidad, St. Lucia and Barbados (ECNAMP, 1980). Tourism is on the rise throughout the Caribbean, and will likely accelerate in light of a strengthening U.S. economy and a rise in world-wide terrorism. Accelerated development raises the liklihood of poor planning in the face of a rapid influx of tourists and dollars.

Another Caribbean-wide sedimentation problem is agriculture. Traditionally sugar cane has been a major crop throughout the Caribbean, and presumably nearshore marine environments have suffered in the past. The fact that Hubbard, et al. (1985) were unable to relate land-use practices on St. John to long-term changes in the growth rates of Montastrea annularis raises some concern over our ability to detect sediment stress in the absence of adequate baseline data. This method has been very useful in

91

other areas, but either adaptation of local colonies to stress or some other factor (perhaps an absence of stress) have resulted in a relatively stable population of this one coral species on St. John over time.

On some Caribbean islands, sugar cane cultivation continues today (e.g. St. Kitts, Barbados, Antigua; ECNAMP, 1980). Elsewhere (St. Lucia, Guadalupe), large-scale agriculture is based on other crops (mostly bananas and coconuts). On Dominique agriculture exists at a subsistence level, but the cumulative impact of individual farmers can still be substantial.

A major problem on St. Croix and many Caribbean islands centers around clearing large hillsides of brush and forest to encourage grass. The plots are cleared just prior to the rainy season to ensure an adequate water supply for the new vegetation. Unfortunately the flashy rains typically result in wholesale slope erosion, loss of valuable topsoil and the introduction of large volumes of sediment into the marine environment. In 1977, a large rainstorm deposited a soil delta 60 ft out into Teague Bay on the north shore of St. Croix. Direct smothering and subsequent degradation of water quality due to resuspension likely caused significant damage to the bay ecology. At Salt River, to the west, a similar event flushed large quantities of suspended sediments into the bay and onto steep reef environments beyond. Visibility was reduced to less than 2 m for a period of several months, resulting in an estimated 20% reduction in live coral cover. Little was apparently learned from this episode as recent agricultural clearing near the base of the watershed and plans for marina development threaten further damage. Further evidence of indifference to this problem lies in the exemption granted to agriculture under the Coastal Zone Management Act of 1978. Under this mandate, all activity within the coastal zone, **except agriculture**, must come under the scrutiny of the organization created by the Act.

Port Development

Other than general upland construction, the most widely shared environmental pressures in the Caribbean probably come from port development. In an island community that has traditionally depended upon the water for transportation, commerce and communication, opening of further marine-based connections continues to dominate our thinking. Except now, instead of small-scale down-island commerce, we are facing tanker traffic and cruise liners of ever-increasing size.

Port development shares all the impacts of upland construction. Unique to port development, however, are:

1 - habitat loss due to dredging and filling
2 - long-term degradation of water quality due to resuspension

3 - potential pollution from spills and discharges

Between 1966 and 1972 over 0.5 million cubic yards of sediment were removed from Christiansted Harbor (V.I. Marine Advisors, 1983). Justifications included creation and maintenance of navigable channels, creation of new fastland, beach nourishment and excavation of construction aggregate. Many of the present harbor-erosion problems are related to construction of condominiums on land created during that time. In the western harbor, one complex presently sits 25 m seaward of the natural shoreline that existed prior to shoreline filling. The occupants are committed to a long-term program of beach nourishment to protect their investment. Next door, a costly seawall was built to stem runaway erosion related to the same problem.

It is difficult to assess the impact of all this activity on the marine environment as little or no baseline data exist. Eastern Long Reef and Round Reef certainly support a sparser cover than do other areas to the east and west. Relating this to specific events or to sedimentation in general is difficult in the face of nonexistent data prior to development. Similarly, on the south coast of the island, water quality is typically poor near and downcurrent of the South Shore Industrial Complex (SSIC). While turbidity levels are demonstrably higher than those upcurrent, there are several lines of evidence that construction is only in part responsible for the dirty water in the area. First, turbidity levels are typically elevated in the same area on aerial photographs prior to construction. Second, the southwest corners of tradewind islands typically exhibit a similar pattern in the absence of a readily identifiable development source. And finally, the presence of Sandy Point downstream of the development infers a persistent flow of sediment into this area over a very long span of time. The SSIC has likely protracted the turbidity problem along St. Croix's south shore, but the problem is in determining to what degree that has occurred and how the benthic population has changed as a result.

On St. Thomas, Charlotte Amalie harbor is coming under increasing development pressure. Expansion of port facilities in the western harbor continue as vessel traffic becomes progressively heavier. Recent dredging to accommodate the S.S. Norway increased the maximum harbor depth. Port development on this scale has a host of other problems including pollution, navigation conflicts, cross uses of the harbor and increasing density of moored and transient vessels. Sediment damage due to port creation and maintenance is difficult to assess as little or no data exist upon which to make an evaluation.

On St. John, Cruz Bay is falling under increased pressure to accommodate more vessel traffic. Present users include the National Park Service, small charter operators, local boaters, various ferries and commercial freight carriers, small cruise ships and the V.I. Seaplane Shuttle. Congestion in the harbor has necessitated plans to move part of the port operation to other sites, primary among them a small pond to the south. In addition to the lost sediment-retention function of the pond, the potential of sediment damage during dredging looms as a major possibility.

In the British Virgin Islands, increased boating traffic and construction is raising the need for larger harbors and the location of suitable sources of construction material. A large dredging project is presently underway in Roadtown harbor. Plans are being evaluated to select dredging sites on the eastern end of the island for extraction of construction aggregate.

Similar activities are occurring throughout the eastern Caribbean. Port operations in Guadalupe, St. Lucia and Trinidad all rely on dredging to maintain navigable ports. These activities undoubtedly continue on a smaller scale throughout the islands, largely without any real regard for damage to the marine environment. More examples could be given, but the basic story would remain the same. Expansion of ports and shore-based facilities continues throughout the eastern Caribbean to meet the demands of a spreading technological and tourism base. These projects are done largely without adequate baseline data upon which to predict effect or measure impact. These problems are not limited, however, to poor third-world countries who lack the technology or the money to properly address the problem. Many of the best available examples available of unecessary environmental damage occur within the U. S. Virgin Islands, and the local government has apparently learned little from past lessons.

The remainder of this report will focus on identifying elements of the problem that can be addressed at the local level. Primary development problems are listed, and possible solutions are suggested. Hopefully, some of these strategies will prove viable at least within the VIBR, and eventually in the Virgin Islands and the eastern Caribbean.

SPECIFIC PROBLEMS AND STRATEGIES

Problems

Examples of the general kinds of problems that occur in the Caribbean region have been discussed above. Also, the types of concerns that need to be addressed in studying the impacts of sedimentation in the marine environment have been elucidated. This section provides a more specific list of the main problems that exist specifically within the VIBR, but also within the greater Caribbean as well. A discussion of management strategies follows. Finally, a brief list of possible projects that might advance our knowledge of sedimentation effects is proposed.

Slope clearing - This represents one of the most significant problems facing the U.S. Virgin Islands today. Upland contruction sites are typically cleared with little or no regard for impacts of runoff. In the rare instances where sedimentation control measures are required by government agencies, they consist of a short-term sediment fence, temporary berms or similar structures. These measures are generally ineffective, poorly monitored, and do nothing to stem the longer-term erosion problems once the temporary structures have been removed and the development goes into operation. The clinic on St. John stands as our best documented example of this problem. Short-term degradation was documented (Hubbard, et al., 1985) and was minimized only by the short duration of the project and the remaining heavy vegetation in the lower watershed. Larger construction projects can often clear entire watersheds, and the potential for impact is much greater.

Agricultural clearing - Similar in impact to construction-related clearing is agricultural development. Two additional problems typically make this an even greater problem. First, clearing is often done just prior to the rainy season, thus maximizing the potential for sediment runoff. Second, this activity falls outside the control of Coastal Zone Management (CZM) and many other agencies created to stem erosion.

Building in watercourses - With the shortage of available building sites and the steep slopes that dominate most eastern Caribbean islands, many homesites and commercial developments are placed in the central valleys to watersheds. Structures placed along the sides of the valley add to the water and sediment load within the central gut. Those directly within the gut reduce the ability of the streambed to retain water and sediment. This can have significant impacts both within the watershed (increasing runoff to lower properties) and in the marine environment beyond (increased sediment load).

Road construction - Generally associated with any sort of development is the creation of roads and accessways. On steep slopes typical of Caribbean islands, these scars along hillsides not only serve as sites of erosion but can also provide channels to facilitate the carrying of eroded sediment to the ocean.

Infilling of coastal ponds - Over the past few decades, there has been a gradual reduction in the number of coastal ponds. Reasons include insect control, creation of fastland, and the ease with which such areas can be converted to level building sites. Underlying all these is a general disregard for the valuable functions that these ponds provide. In addition to their direct and varied ecological functions, these ponds typically serve as sediment sinks and settling basins. Typically these ponds formed at the entrances to embayments during the most recent rise of worldwide sea level. Since their formation, these ponds have been gradually filling with sediment derived from the erosion of associated upland watersheds. Because sediment is trapped in the ponds, the nearshore environments are buffered from the deleterious impacts of intense rains. With the elimination of the ponds, runoff and sediment are permitted to drain directly into the ocean.

Coastal and flood-plain clearing - Like the coastal ponds discussed above, low-lying areas serve to buffer the marine environment from upland runoff. Although the trapping function of coastal flood plains is more diffuse than that of coastal ponds, vegetative cover still serves to slow down water flow and thus retard the introduction of sediment into the ocean. Clearing of these low-lying areas minimizes or eliminates their sediment-trapping ability. In fact, drainage plans usually incorporate some means of improving the runoff potential of these areas (see discussion of channelization below).

Clearing of mangroves - Mangroves serve a number of valuable environmental functions that are sufficient reasons to justify their preservation. With respect to sedimentation, they serve two important functions. First, they stabilize the shoreline and prevent erosion. Inasmuch as they are typically associated with muddy shorelines, this translates into lower quantities of fine-grained sediment being introduced into the adjacent bay. With respect to upland runoff, they again trap sediment and thus reduce the amount of suspended load reaching seaward environs. The root structures break up flow and slow down the water coming from adjacent land areas. This results in localized sedimentation, lowering turbidity on the open shelf in the short run and creating protected areas which will further retard runoff down the line.

Building on filled submerged lands - With the shortage of flat land along the island shores, dredged material is often used to artificially extend the present shoreline. This material is often incapable of supporting the subsequent structures built in the area, causing costly engineering problems. Equally important is the greatly increased possibility of erosion and the subsequent need for coastal defense structures. The inherent instability of these areas often results in increased sedimentation offshore.

Opening of coastal ponds for marinas - If coastal ponds are tempting as future building sites, they are even more in demand as potential marinas. The already existing water body reduces the amount of dredging needed, and the cost of the project is lowered accordingly. As in the case of filling, the trapping function of the pond is compromised. Although the loss of function is not as complete as in a filled pond (i.e. the marina will still trap some sediment), the opening to the ocean still raises the potential for the movement of sediment into the ocean beyond, especially during periods of heavy rains. Fine-grained sediments trapped in the marina can necessitate maintenance dredging at a later date and can be resuspended by powerboat activity within the marina.

<u>Channelization of water guts in lowland areas</u> - One of the secondary problems of coastal development is the need to prevent flooding of low-lying areas. Typically sediment control plans amount to nothing more than effectively routing runoff around or through a particular area in some manner that minimizes upland flooding. While this is an understandable goal from a development standpoint, it increases the intensity of coastal sedimentation. A recent CZM permit on St. Croix included a condition wherein the developer would help to channelize runoff from adjacent properties. By eliminating periodic flooding in the surrounding neighborhood, the developer is providing an apparent service to the community. Unfortunately, the flooding of surrounding lowlands had prevented sedimentation in Christiansted harbor by ponding water long enough for some sediment to settle in the ephemeral pond created by the rains. The desire to protect personal property is understandable, but the impact on marine sedimentation occurs nonetheless.

<u>Harbor dredging</u> - Harbor dredging has been discussed in detail earlier in this report. Direct impacts are related primarily to habitat removal. Indirect effects include downcurrent sedimentation, habitat degradation and long-term resuspension due to vessel traffic. In areas where seagrasses are removed, sediments may become unstable even in the absence of traffic. In areas where reef is removed, the exposure to increased wave action can likewise result in increased sediment suspension and shore erosion.

<u>Seagrass removal</u> - The primary physical function of seagrasses is to stabilize the substrate. In experiments in Teague Bay on St. Croix, the removal of <u>Syringodium</u> from a small area of the lagoon allowed sediment that had been stable in currents over 1 m/ sec to be moved by currents of only 20-30 cm/sec (Hubbard, unpubl. data). Removal of seagrass on a large scale can result in a significant reduction in water quality as the fine-grained sediments are gradually winnowed from the newly exposed substrate. Eventually water clarity improves, but migration of the margins of the excavated area, especially in the presence of wave action, can cause the problem to migrate over time, greatly extending the impact of the initial removal both spatially and temporally.

Coastal defense structures - The main problem with structures placed in the marine environment is that they change the prevailing flow patterns in their vicinity. Scour around the edges of seawalls, jetties and the like can suspend sediment and cause localized erosion. This is a problem particularly at the ends of poorly planned seawalls. The most significant impact, however, is in wave reflection. Walls placed along the beach cause waves to be reflected seaward, much like a ball off a billiard cushion. Sediment suspended by the incoming wave is moved seaward by the reflected wave, and erosion results in front of the wall. This sediment is moved seaward and onto whatever might be in the immediate offshore zone. While small in comparison to problems discussed above, sedimentation related to wave suspension combined with the potential for disruption during construction do represent potential problems that will increase as shore development becomes more prevalent in the islands.

Clearing of upland vegetation - Most of the above activities in some way remove vegetation, and increased erosion typically results. In some instances, however, vegetation removal is not part of a larger construction project, but rather is done solely for the purpose of improving visual or physical access to the beach. The removal of dune grass in the mainland U.S. is a prime example. Locally it is more common for homeowners or developers to remove grass and shrubs to create more open sand, or to remove trees because they block their view. This problem is more related to ignorance, and is therefore more difficult to control. Nevertheless, the increased mobility of the underlying material results in beach erosion and the introduction of potentially large quantities of sediment into the surf zone. The future need for artificial protective structures adds to the problem.

Cumulative impacts of homesite development - Worth considering is the relative importance of single, large development projects vs. several smaller homesites. This is a hard subject with which to deal quantitatively, as homesite development can be so variable. Nevertheless, some thought needs to be given as to whether several homesites developed with virtually no sediment-retention measures can actually cause more damage than a larger project which has been forced to implement at least a poorly-conceived sedimentation control plan.

The primary potential for damage is the confidence that small projects will have small impacts. This is not always the case. A single homesite in western Reef Bay has had a substantial impact on slope stability in the immediate area. The actual impact on the adjacent marine environment has not yet been quantified, but considerable concern has been raised within the Park Service. As pressure increases on areas like St. John, homesite development could potentially play a role exceeding that of larger development.

Management Strategies

Typically there are two approaches to mananagement. One involves education, and the other regulation. Education simply consists of making people aware of the problems so they are more sensitive to them in the future. Unfortunately, due to the advanced stages of the problem and the small likelihood that developers will be in a frame of mind to be "educated" in the short term, regulation emerges as the primary tool of the manager. Past history has shown that with development, education usually emerges from regulation if only in the sense that the developers (large and small) "learn" what they can and cannot get away with. Certainly Coastal Zone Management in the Virgin Islands has brought to the forefront many of the environmental issues that concern us today. The presence of legislation and regulation at least forces the developer to listen, and hopefully to learn.

Because of the above problems with direct education, the remainder of this section will deal with legislative and regulatory approaches to management within the VIBR and the Virgin Islands in general. Inasmuch as most of the problems common in the area are related to physical and biological elements of the region, most of the strategies discussed below should be useful in the eastern Caribbean as well. What will differ from island to island is not the strategies that would be useful in a particular case, but rather the cultural elements of the situation that make one strategy or another more appropriate in each instance. The first section addresses legislative and regulatory options presently open to the territories. The final discussion suggests additional approaches that might be considered. General guidelines for the kinds of areas that should and should not be developed are suggested.

Existing regulations and laws - A number of local laws exist that can be used to affect marine protection. A paperback volume available from the Department of Conservation and Cultural Affairs (**Environmental Laws and Regulations of the Virgin Islands**) outlines these, and provides summaries of their applications. As these are already available in summary form, only the general areas of protection will be listed here.

Title 12, Chapter 3 provides protection for trees and other vegetation adjacent to watercourses. Under these regulations vegetation cannot be removed from any area within 30 ft of the center of the watercourse or 25 ft from its edge, whichever is greater. The problem with this law is likely to be inconsistent enforcement.

Title 12, Chapter 5 contains a number of regulations pertaining generally to water quality. The most applicable portion relates to the issuance of a water quality certificate prior to the granting of other related permits (e.g. Coastal Zone Management permit). Standards for water quality have been established, and any probability that a project will compromise these standards theoretically results in a denial of a certificate, and therefore, a subsequent permit. Included in these standards are minimum allowable quantities of turbidity. Degradation from upland runoff is supposedly considered in this regard. Unfortunately, color and turbidity standards are set in terms of optical measures, and these will suffer from all the problems discussed in an earlier section (i.e. the necessary calibration standards are not yet available). Nevertheless, there is a set of regulations within which the impacts of upland sedimentation can be argued. This represents one area where VIRMC could make a significant contribution.

The most locally significant piece of legislation presently in existance is the Virgin Islands Coastal Zone Management Act of 1978. This act created an organization to evaluate development within the coastal zone and a procedure to initiate that evaluation. It consists of citizen commissions on each island and a CZM Office which coordinates the activities of all the commissioners. The Office of Coastal Zone Management falls within the Department of Conservation and Cultural Affairs.

Like any organization of this type, CZM has been fraught with problems ranging from understaffing to political pressure from above. Nevertheless, it remains as the strongest support for citizen input to local development yet available. The pros and cons of this organization can and have been argued on many fronts. To repeat these arguments here would be of little purpose. Two major problems with the concept of the legislation, however, bear heavily on the problem of upland runoff and are worth mentioning. First, agriculture has been specifically exempted from the process, presumably based on some perceived tradition. As wholesale clearing of upland areas undoubtedly constitutes a major problem in the V.I., removal of this activity from regulation severely compromises the ability of CZM to protect adjacent marine waters.

The second, and perhaps larger, problem is the two-tier system built into the legislation out of deference to the role of Public Works in the prior permitting process. Under this scheme, the island is divided into a first tier near the water and a second tier above. Permits in the first tier are issued by CZM. Permits in the second tier are within the realm of Public Works. In some instances, the boundary between the two is a reasonable physiographic feature (e.g. a ridgeline), but altogether too often it is simply a road or similar cultural structure. The problem with this is two-fold. First, the often arbitrary boundaries can place critical coastal areas in the second tier, where permits are **much** easier to obtain. Second, with the small size of the three islands and the steep slopes, there are virtually no areas that do not potentially exert great control on the coastal zones of the Virgin Islands. A proviso does exist in the Bill whereby CZM can ask to have input in upland projects that might directly impact the marine environment, even though they are in the second tier. However, if this inclusion were taken seriously, few upland projects would escape the careful scrutiny of the Office of CZM.

In the late 70s, the V. I. Sedimentation Control Plan was introduced. The most significant contribution of this program was a series of maps that provided information on watershed areas, peak discharges and other critical design factors related to upland development. While useful from a design standpoint, this data set provides little or no guidance on the volumes of sediment potentially eroded from these areas, nor are variations in land use incorporated into the runoff estimates. Given opinions by several researchers (e.g. Jordan, 1972; Dunne, 1979) that land use probably plays the primary role in controlling runoff volumes, the absence of this factor in the predictions made by the maps is reason for some skepticism. Nevertheless, these maps do provide a starting point.

Future strategies - Certainly there is tremendous room for improving the present levels of environmental protection. The problems of competition between the local needs for economic improvement and environmental preservation are numerous, and will not be discussed here. Nevertheless, there are several specific management recommendations that have merit and could be immediately integrated into the management of the Biosphere Reserve. Most of these have wider applicability to the eastern Caribben as well.

There are several practices that should be either prohibited or discouraged. These include:

1 - development in major water courses
2 - development in watersheds that empty into low-energy embayments that will have problems dissipating sediments introduced during heavy rains.
3 - any dredging within the Biosphere Reserve boundaries
4 - any removal of seagrasses or mangroves
5 - any filling of coastal ponds
6 - any large-scale clearing

In areas where development must occur, certain guidelines must be provided for the developer. These include:

1 - The establishment of a sedimentation control plan. This should include identification of marine areas sensitive to sedimentation as well as a thorough discussion of present and proposed water and sediment flow to the ocean. Reasonable measures to guard against runoff during and after construction (i.e. sediment fences, berms, settling ponds, silt curtains during dredging, etc.) should be included and described in detail. It is critical that this plan not be a water management plan whose main objective is to facilitate the passage of water over the property. In fact, the goal of such a plan should be to retard runoff until it can soak into the ground or sediment can settle out of suspension. This is typically counter to the economic interests of any developer.

2 - The encouragement of sequenced development. Recently, 30 acres of watershed were cleared for hotel development in Davis Bay on St. Croix. Unusual seasonal rains broke through sediment-retention fences and introduced sediment onto the adjacent shelf. The developer's answer to allegations was that no project that clears this kind of acreage can effectively stop this kind of runoff. This is probably true, and the lesson learned should be to develop areas in pieces, allowing revegetation of one section before another is cleared.

3 - The planning and implementation of monitoring schemes. Any project has a potential for environmental damage. If that damage is perceived to be high, then some sort of monitoring plan should be implemented. This approach serves three purposes. First, it hopefully can identify areas of stress before permanent environmental damage is done. Second, it establishes a baseline against which environmental damage can be measured. The possibility of quantifying damage (and legal responsibility) may raise the level of consciousness within the development community and finally, the observations of environmental change in response to specific levels of stress provide data upon which to base future project evaluations.

4 - The provision of economic incentives for the developer to protect the environment. A simple example of this would be to require a developer to deposit an amount of money into an escrow account equal to 10% of the anticipated project costs. This money would serve as a sort of damage deposit which would be used to offset environmental damage due to violations of the project permit conditions. If the project is nearly completed as planned without damage, then this money would be applied to the final 10% of the project costs. If the developer stays within the restrictions of his original agreement, then there is no monetary loss. If there is significant environmental damage or the developer pulls out of the project, then the money can be put toward environmental restoration. This example would probably be impossible to implement in the local V.I. climate of development panic, but it might work elsewhere in the eastern Caribbean or

certainly within park or preserve boundaries where development is more easily controlled. For this plan to work, the Park Service (or whoever operates as manager) must fall under the same restrictions and penalties.

Future Goals and Objectives

Future efforts of VIRMC should center around two elements. The first is providing baseline data in areas likely to come under stress. The second relates to establishing some level of understanding about how individual organisms and systems respond to different stress levels.

The choice of baseline areas must be based on likely future environmental pressures, and primary study sites must necessarily center around those areas that are slated for change. The importance of "control areas" (i.e. those areas that will remain natural as a frame of reference) must be recognized, but this should not be used as an excuse to concentrate on untouched, and therefore, more scientifically interesting areas.

Understanding environmental change will ultimately center around studies of the interactions of the stress components with the elements of each marine system. It is at this level that our greatest efforts should be concentrated. It is fine to understand currents, or to trace sediment transport, or to quantify patterns of runoff in some number of watersheds as has already been done on St. John. All of these are important factors but will not answer the critical questions about levels of stress and their associated impacts. If we are ever to understand stress responses of marine systems, we must first assess where impact is presently taking place or is likely to occur in the future. After that, we need to formulate a list of parameters that are most likely to affect change. Only after completing all these preliminary tasks, we must compile a plan to measure these parameters and the responses of the marine environment that result. VIRMC has passed through a necessary first stage of baseline data gathering. It has attempted on a localized basis to establish stresses and impacts. Now is the time to move on to understanding the basic elements that cause change in the ocean.

In some respects, VIRMC has approached the problem from a direction opposite to that described above. Rather than addressing the levels of change, a much greater emphasis has been placed on establishing the magnitude of "potential" stresses (e.g. historical analysis of land use; studies of watershed character) and management. Less emphasis has been placed on determining where and how much actual impact is and has been occurring. This approach has assumed (occasionally in error) that impact is everywhere and measurable.

While erring from the basic plan discussed above, these early studies were probably necessary. They represented a logical starting point considering the almost total lack of background data on the biosphere reserve. But, it is time now to move on.

With respect to sediment stress, a number of studies would be useful. Most of these center around characterizing the nature of sediments being introduced into marine systems and their impacts on individual corals. For purposes of illustration, one large-scale experiment will be described, keeping in mind that the proposed future research objectives will likely have to consist of pieces of this project conducted by a variety of individuals.

The experiment would consist of both field and laboratory studies of corals responding to varying loads of widely differing sediments. Field experiments would include subjecting marine organisms to sediment varying in amount, size and composition. These experiments would be similar to those of Rogers (1977), with the addition of a better characterization of the sediments being used. Lethal effects could be determined by simply observing the corals. Sub-lethal effects would involve respiration chambers that are now becoming commercially available. Laboratory experiments would follow a parallel line, except they would allow more carefully monitored sediment applications and perhaps a continuous level of stress more closely approximating natural conditions.

At the same time, a parallel monitoring plan should be implemented in the field. Reefs near major water guts should be quantitatively surveyed and a set of basic measurements established. A protocol should be developed for sampling that can be followed by a team of observers on short notice. The following is a partial list of tasks.

1. Baseline survey of selected study reefs near watershed centers (e.g. Hawksnest, inner Fish Bay; this has already been done on a limited basis). These surveys should identify specific quadrats or transects that can be **precisely** reoccupied. Permanent markers should be established such that specific areas on the reef (e.g. individual corals) can be relocated. The level of accuracy on such a survey would necessarily be much greater than what has been attempted to date.

2. Selection of the primary channel(s) out of the water course. At these sites, cross section and flow velocity should be measured on an hourly basis during rain storms. Water samples should be taken for characterization of TSS and sediment character as described in an earlier section.

3. Sampling of marine waters near water guts and in the bay during rains. Surface, mid-water and near-botton (1 m) samples should be taken hourly at each site. Sample sites should be placed on a regular grid. The size of the grid would depend on a) the size of the sediment plume and b) the extent of potentially impacted marine systems in the bay.

4. Sampling of settling sediments. Traps as described above should be retrieved on at least a daily basis. Trapped sediments should be weighed and their size distribution should be determined.

5. Permanent quadrats/transects should be examined regularly to detect sub-lethal effects of sedimentation. Field chamber experiments could be used in conjunction, especially to quantify shading effects. The logistics of this are substantial, however.

6. Once enough successful field monitoring programs have been completed, the conditions measured in the field could be duplicated in the lab. By increasing either the sediment doses or the duration of exposure, conditions beyond those measured in the field could be examined.

While the above approach has been described for upland runoff, a similar regimen could be applied to in-water projects such as dredging. For this type of approach to yield usable data, a significant long-term commitment must be made to specific field sites. Gathering of baseline data is an important first step. Unless we start to examine responses of marine organisms, however, our research efforts will never advance beyond documenting what is lost or destroyed, and our ability to predict damage will never be realized.

LITERATURE CITED

Adey, W. and Burke, R., 1977. Lesser Antillean bioherms - geologic control of development, in: Frost, S., Weiss, M. and Saunders, J. (eds). Reefs and related carbonates - ecology and sedimentology. AAPG Studies in Geology No. 4: 67-81.

Adey, W. Macintyre, I., Stuckenwrath, R. and Dill., R., 1977. Relict barrier reef system off St. Croix: its implications with respect to late Cenezoic coral reef development in the western Atlantic. Proc. 3rd Intl. Coral Reef Symp. 2: 15-23.

Aller, R. and Dodge, R., 1974. Animal-sediment relationships in a tropical lagoon, Discovery Bay, Jamaica. J. Mar. Res. 32: 209-232.

Bak, R.,1978. Lethal and sublethal effects of dredging on reef corals. Mar. Poll. Bull. 9: 14-16.

Bak, R. and Elgershuizen, J., 1976, Patterns of oil-sediment rejection in corals. Mar. Bio. 37: 105-113.

Berwick, N. and Chamberlin, R. 1985, Systems analysis for integrating tropical coastal resources with watershed use. Proc. 5th Intl. Coral Reef Symp., Papeete, Tahiti.

Brock, V., Van Heukelem, W. and Helfrich, P., 1966. An ecological reconnaissance of Johnston Island and the effects of dredging. Tech. Rpt. Hawaiian Inst. Mar. Bio. No. 11, 56 p.

Brown, L. and Wolf, E., 1984. Soil erosion: quiet crisis in the world economy. Worldwatch Paper 60.

Burrell, D. and Schubel, J., 1977. Seagrass ecosystem oceanography, in: McRoy, CC. a,d Helfferich, C (eds). Seagrass ecosystems: a scientific perspective, Marcel Dekker, N.Y.: 195-232.

Cortes, J. and Risk, M., 1985. A reef under siltation stress: Cahuita, Costa Rica. Bull. Mar. Sci., 36: 339-356.

Crosson, P., 1983. New perspectives on soil erosion in the United States, Mimeo.

Deitrich, W., Windsor, D. and Dunne, T., 1982. Geology, climate and hydrology of Barro Colorado Island. in: Leigh, E., Rand, A. and Windsor, D. (eds). The ecology of a tropical forest. Seasonal rhythms and long-term changes. Smithsonian Inst. Press, Washington, D.C.

Dodge, R., Aller, R. and Thompson, J., 1974. Coral growth related to resuspension of bottom sediments. Nature 247:574-577.

Dodge, R. and Lang, J., 1983. Environmental correlates of hermatypic coral (Montastrea annularis) growth on the east Flower Garden Bank, Northwest Gulf of Mexico. Limnol. and Oceanog. 28: 228-240.

Dodge, R. and Vaisnys, J., 1977. Coral populations and growth patterns: responses to sedimentation and turbidity associated with dredging. J. Mar. Res. 35: 715-730.

Dunne, T., 1979. Sediment yield and land use in tropical catchments. J. Hydrol. 42: 281-300.

Dustan, P., 1977. Growth and form in the reef-building coral Montastrea annularis. Mar. Biol. 33:101-107.

Eckholm, E., 1976. Losing ground: environmental stress and world food prospects. W.W. Norton, New York.

ECNAMP, 1980, Survey of conservation principles in the Lesser Antilles.

Fairbridge, R. and Teichert, C., 1948. The low isles of the Great Barrier Reef, a new analysis. Geogrl. J. 3: 67-88.

Faraday, W. and Churchill, A., 1979. Uptake of cadmium by the eelgrass Zostera marina. Mar. Biol. 53: 293-298.

Folk, R., 1974. Petrology of sedimentary rocks. Hemphill Publ. Co., Austin, TX, 182 p.

Gardner, W., 1980a. Field assessment of sediment traps. J. Mar. Res. 38: 41-52.

Gardner, W., 1980b. Sediment trap dynamics and calibration: a laboratory evaluation. J. Mar. Res. 38: 17-39.

Gottfried, R., 1985. Tropical storms and the problem of erosion in Puerto Rico. preprint from Intl. Symp. on the Sustainable Development of Natural Resources in the Third World, Columbus, Ohio.

Hubbard, D., in press, Sedimentation as a control of reef development: St. Croix, U.S.V.I. Coral Reefs.

Hubbard, D. Burke, R. and Gill, I., 1985. Accretion in shelf-edge reefs, St. Croix, USVI. in: Deep-water carbonates, SEPM Core Workshop No. 6: 491-527.

Hubbard, D., Burke, R. and Gill, I., in press. Styles of reef accretion along a steep, shelf-edge reef, Salt River submarine canyon, St. Croix, USVI. J. Sedim. Petrol.

Hubbard, D. and Scaturo, D., 1985. Growth rates of seven species of scleractinean corals. Bull. Mar. Sci. 36:325-338.

Hubbard, J.A.E.B. and Pocock, Y., 1972. Sediment rejection by recent scleractinian corals: a key to paleoenvironmental reconstruction. Geol. Rundschau 61: 598-626.

Hudson, N.,1971. Soil conservation. Cornell Univ. Press, Ithaca, NY.

Johannes, R., 1975. Pollution and degradation of coral reef communities, in: Wood, R. and Johannes, R. (eds). Tropical marine pollution, Elsevier Scientific Publishing Co.: 13-51.

Jordan, D., 1972, Land-use effect on the water regimen of the U.S. Virgin Islands: U.S. Geol. Survey Prof. Paper 800-D: D211-D216.

Kautz, R., 1975. Engineering field manual for conservation purposes.

Kaye, C., 1959. Shoreline features and Quaternary shoreline changes, Puerto Rico. U.S. Geol. Survey Prof. Paper No. 317-B, 140 p.

Lasker, H., 1980. Sediment rejection by reef corals: the roles of behavior and morphology in Montastrea cavernosa (Linnaeus). J. Exp. Mar. Biol. Ecol. 47: 77-87.

Loya, Y., 1976. Effects of water turbidity and sedimentation on the community structure of Puerto Rican reefs. Bull. Mar. Sci. 26: 450-466.

Lyngby, J., Brix, H. and Schierup, 1982. Absorption and translocation of zinc in eel grass (Zostera marina L.). J. Exp. Mar. Biol. Ecol. 58: 259-270.

Maragos, J., 1972. The study of the ecology of Hawaiian coral reefs. PhD diss. Univ. of Hawaii, 290 p.

Maragos, J., 1974a. Reef corals of Fanning Island. Pac. Sci. 28: 247-255.

Maragos, J., 1974b. Coral communities of a seaward reef slope, Fanning Island. Pac. Sci. 28: 257-278.

McRoy, C. and Helfferich, C., 1977. Seagrass ecosyatems: a scientific prospective. Marcel Dekker, N.Y. 314 p.

Morelock, J., Boulon, K. and Galler, G., 1979. Sediment stress and coral reefs. in: Lopez, J. (ed), Proc. Symp. on Energy and Industry in the Marine Environment in Guayanilla Bay. U. Puerto Rico, p. 46-58.

Morelock, J., Grove, K. and Hernandez, M., 1983. Oceanography and patterns of shelf sediments, Mayaguez, Puerto Rico. J. Sedim. Petrol. 53:371-381.

Nichols, et al., 1972. Environment, water and sediments of Christiansted Harbor, St. Croix. Water Poll. Rpt. No. 16, Carib. Res. Inst., CVI.

Patriquin, D., 1975. "Migration" of blowouts in seagrass beds at Barbados and Carriacou, West Indies, and its ecological and geological implications. Aquat. Bot. 1: 163-189.

Penn, N., 1981. The environmental consequences and management of coral sand dredging from seagrass beds in the Suva region, Fiji Islands. Bull. Mar. Sci. 31: 814.

Phillips, R., 1976. Preliminary observations on transplanting and a phenological index of seagrasses. Aquat. Bot. 2: 93-101.

Phillips, R. 1980. Transplanting methods. in: McRoy, CC. a,d Helfferich, C (eds). Seagrass ecosystems: a scientific perspective, Marcel Dekker, N.Y.: 41-56.

Rezak, R. and Bright, T., 1981. Seafloor instability at east Flower Gardens Bank, northwest Gulf of Mexico. Geo-Mar. Lett. 1: 97-103.

Rogers, C., 1977. The response of a coral reef to sedimentation. Unpubl. PhD diss., Dept. of Botany, Univ. of Fla.

Rogers, C., 1979. The effect of shading on coral reef structure and function. J. exp. mar. Biol. Ecol. 41:269-288.

Rogers, C., 1979. The productivity of San Cristobal Reef, Puerto Rico. Limnol. and Oceanog. 24: 342-349.

Rogers, C., 1982. The marine environments of Brewers Bay, Perseverance Bay, Flat Cay and Saba Island, St. Thomas, U.S.V.I. with emphasis on coral reefs and seagrass beds, November 1978 - July 1981. Div. Nat. Res. Mgmt., Dept. Cons. and Cult. Affairs. V.I. Govt. 181 p.

Rogers, C., 1983. Sublethal and lethal effects of sediments applied to common Caribbean reef corals in the field. Mar. Poll. Bull. 14: 378-382.

Rogers, C., Fitz, C., and Gilnack, M., 1982. Coral reefs, mangroves, and seagrass beds of northern Virgin Gorda, British Virgin Islands, Report to ECNAMP and BVI Government, 45 p.

Roose, E., 1977. Use of the universal soil-loss equation to predict erosion in West Africa, <u>in:</u> Soil erosion: prediction and control. Spec. Pub. 21, Soil Cons. Soc. Amer.

Roy, K. and Smith, S., 1971. Sedimentation and coral reef development in turbid water: Fanning Lagoon: Pac. Sci. 25: 234-248.

Shinn, E., 1966, Spur and groove formation on the Florida reef tract. J. Sedim. Petrol. 33: 291-304.

Smith, R. and Abruna, F., 1955. Soil and water conservation research in Puerto Rico, 1938 to 1947. U. Puerto Rico Agric. Res. Sta. Bull 124.

Suarez de Castro, F., 1950. Relaciones entre las lluvias y la erosion. Agric. Trop (Bogota) 6: 45-47.

99

Taylor, J. and Saloman, 1978, Some effects of hydraulic dredging and coastal development in Boca Clega Bay, Florida. Fish. Bull. 67: 213-241.

Thayer, G., Wolfe, D. and Williams, R., 1985. The impact of man on seagrass systems. Am. Sci. 63: 289-296.

Thompson, J., undated, Effects of drilling mud on seven species of reef-building corals as measured in field and laboratory. Final Rpt. to USCS, Texas A and M University, Bept. of Oceanography, 55 p.

Thorhaug, A., 1981. Management of tropical ecosystems: seagrass biology and pollution effects. Bull. Mar. Sci. 31: 811.

van Eepoel, R. and Grigg, D., 1970. Effects of dredging at Great Cruz Bay, St. John. Water Poll. Rpt. No. 5, Carib. Res. Inst., CVI.

Veloz, J, Southgate, D., Hitzhusen, F. and MacGregor, R., 1985. The economics of erosion control in a subtropical watershed: a Dominican case. Land Economics 61: 145-155.

VI Marine Advisors, 1983, Environmental impact of proposed cruise port development in Christiansted harbor, St. Croix, USVI, in: deJongh and Associates (ed). Christiansted cruise ship facility master plan and feasibility study. Report to VI Port Authority.

VI Marine Advisors, 1984, Environmental impact of proposed port development, Third Port, St. Croix, USVI, in: Prince-TAMS, Environmental assessment report for the Third Port Project. Report to VI Coastal Zone Management Office.

Wilson, L., 1972. Seasonal sediment yield patterns of United States rivers. Water Res. Research 8: 1470-79.

Wolman, M. and Miller, J., 1960, Magnitude and frequency of forces in geomorphic processes. J. Geol. 68: 54-74.

Zieman, J.,1976. The ecological effects of physical damage from motor boats on turtle grass beds in southern Florida. Aquat. Bot. 2: 127-139.

107

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

10

XN-ABH-589-B

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

1987

BIOSPHERE RESERVE REPORT NO. 21

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)

102

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.

TABLE OF CONTENTS

LIST OF FIGURES

101

LIST OF TABLES

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.

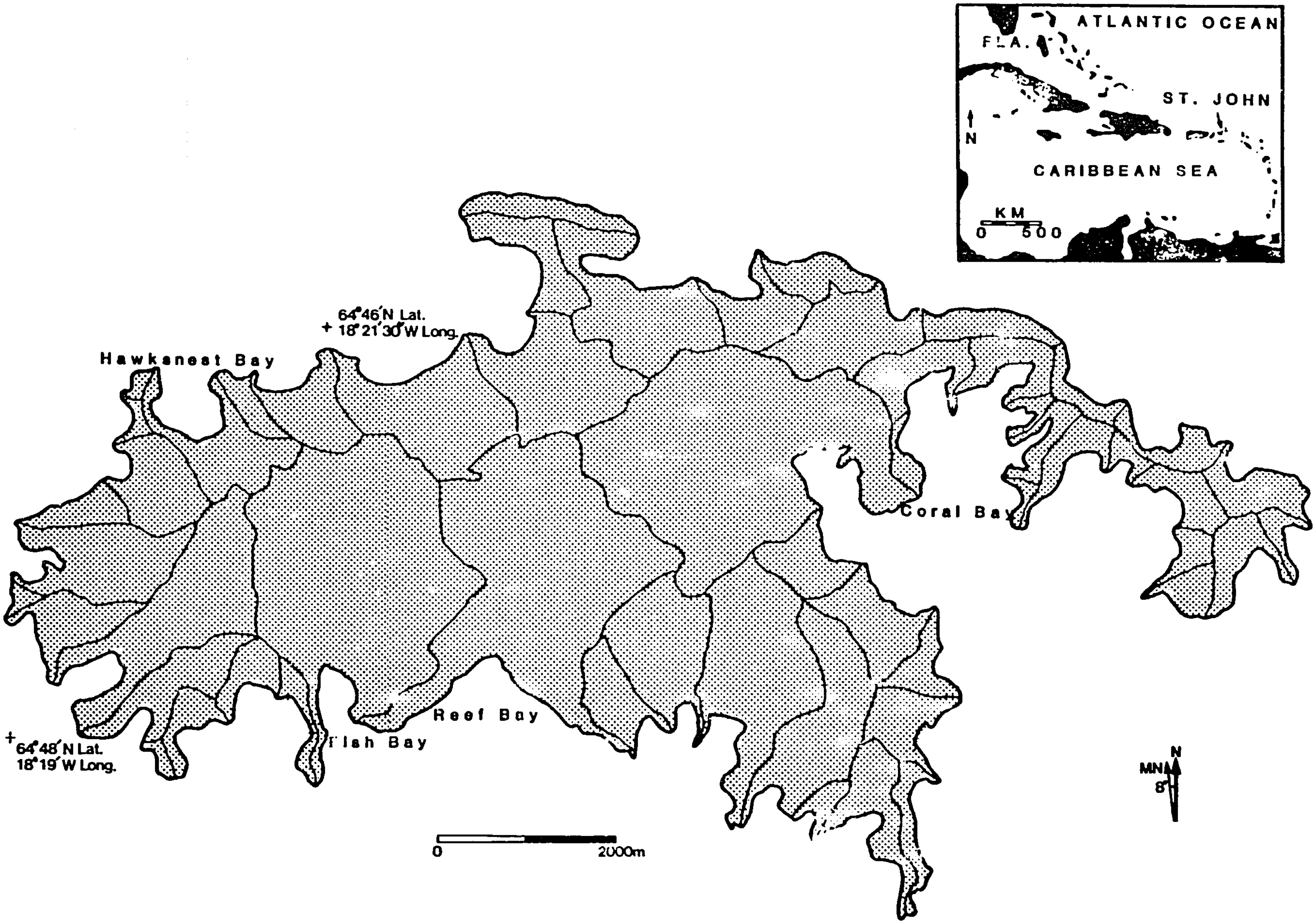


Figure 1. Map showing location of St. John and bays discussed in text.

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.

\\\(

PEAK RATES OF DISCHARGE FOR SMALL WATERSHEDS
TYPE II STORM DISTRIBUTION

SLOPES - STEEP
CURVE NUMBER - 80

24 HOUR RAINFALL FROM US WB TP-40

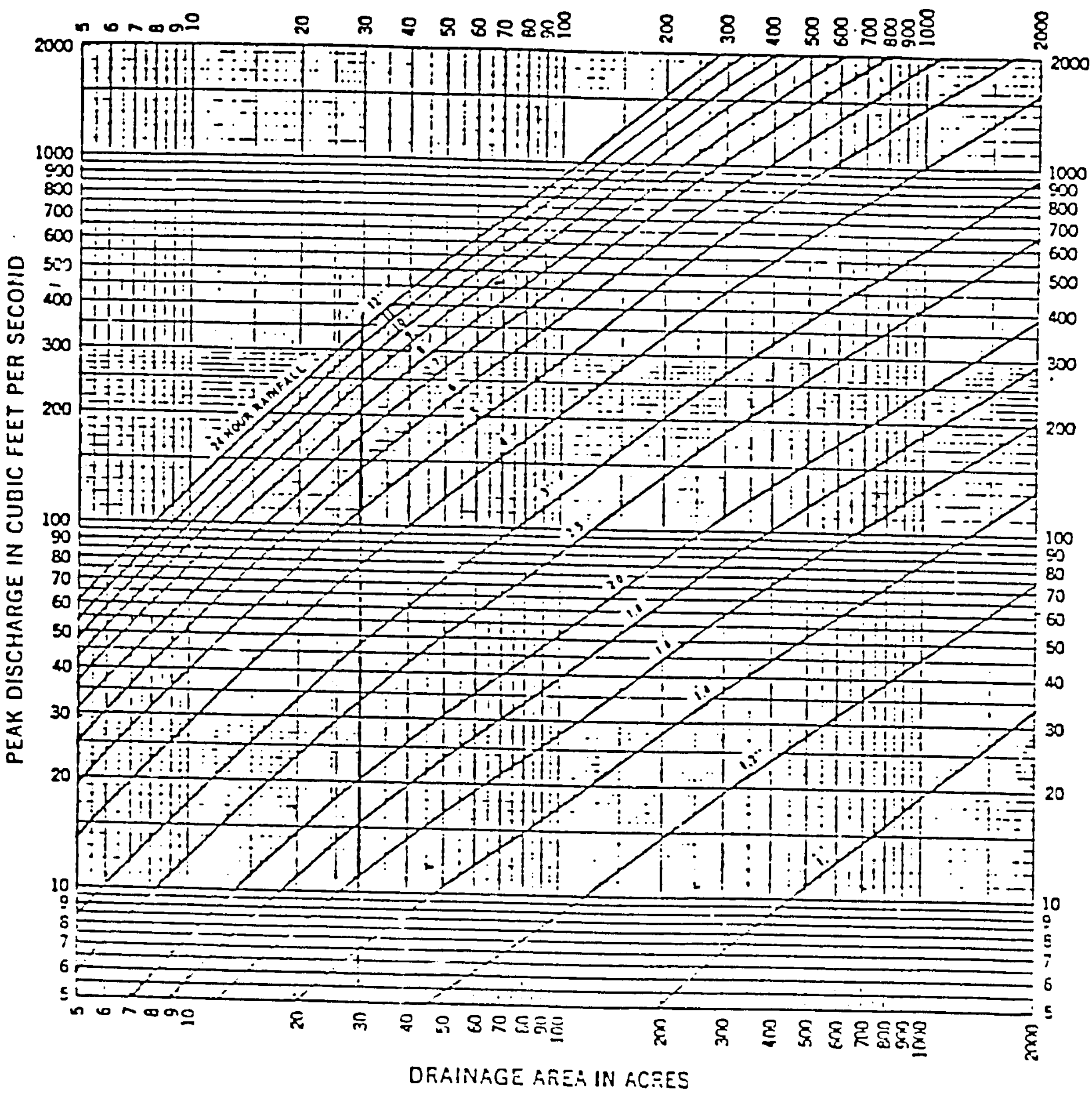


Figure 2. Nomogram used in calculation of peak discharge rates for watersheds with an average CN of 80.

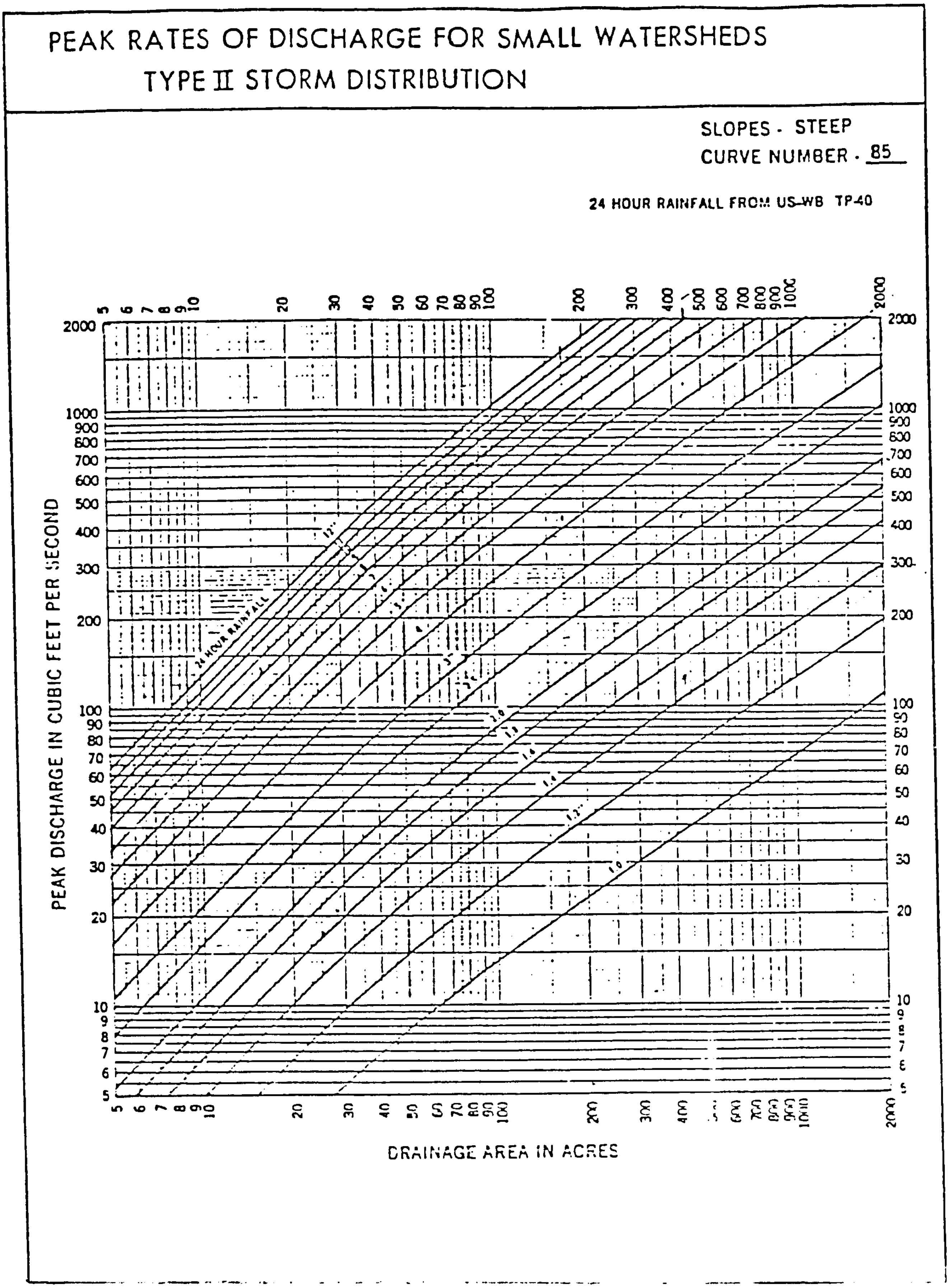


Figure 3. Nomogram used in calculations of peak discharge rates for watersheds with an average CN of 85. This nomogram was used for all calculations.

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	51-500	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	51-500	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	51-500	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.

124

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.

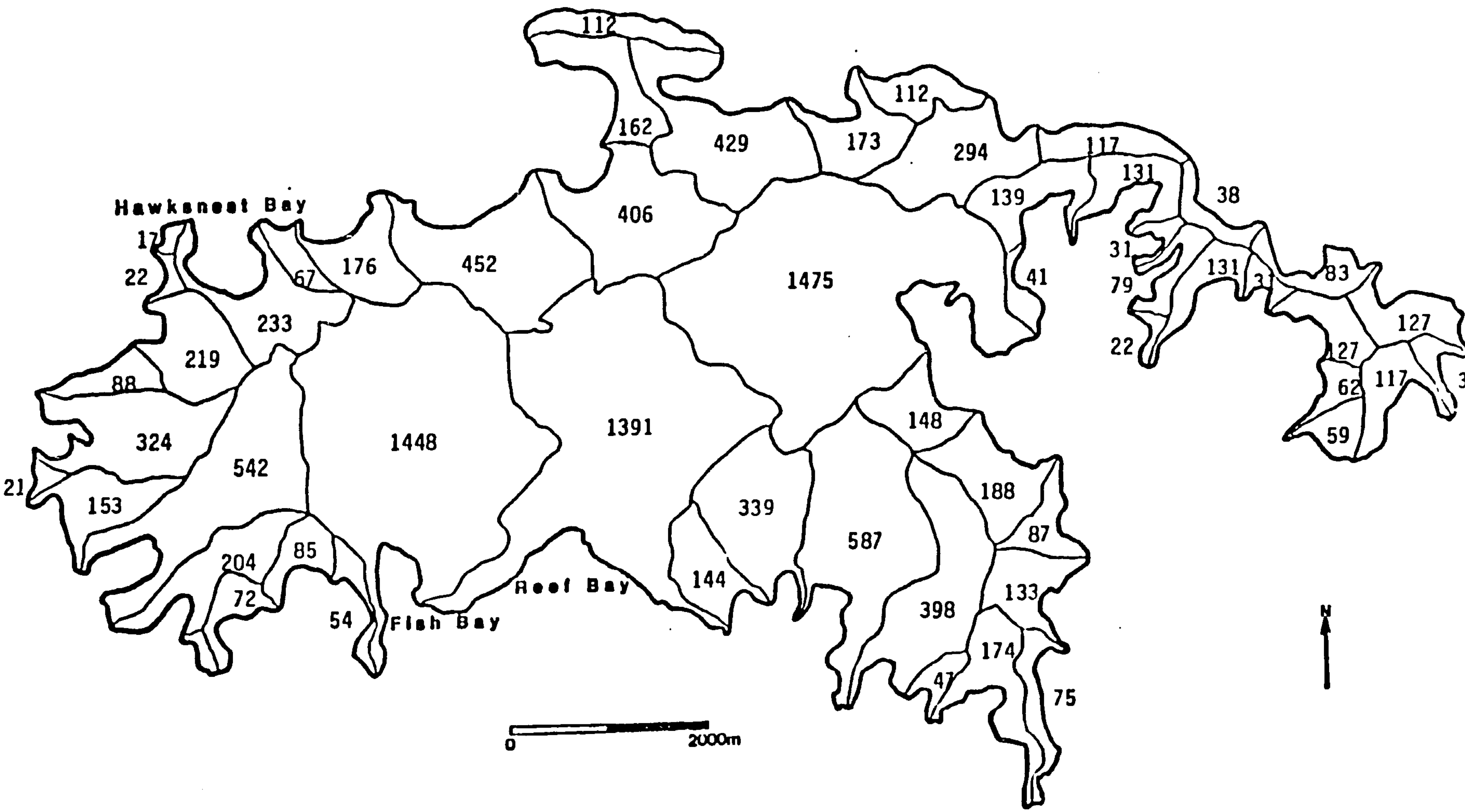


Figure 4. Map of St. John showing watershed areas in acres.

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	33	28
Haulover South	31	24
Hawksnest Bay	233	27
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
Mora 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

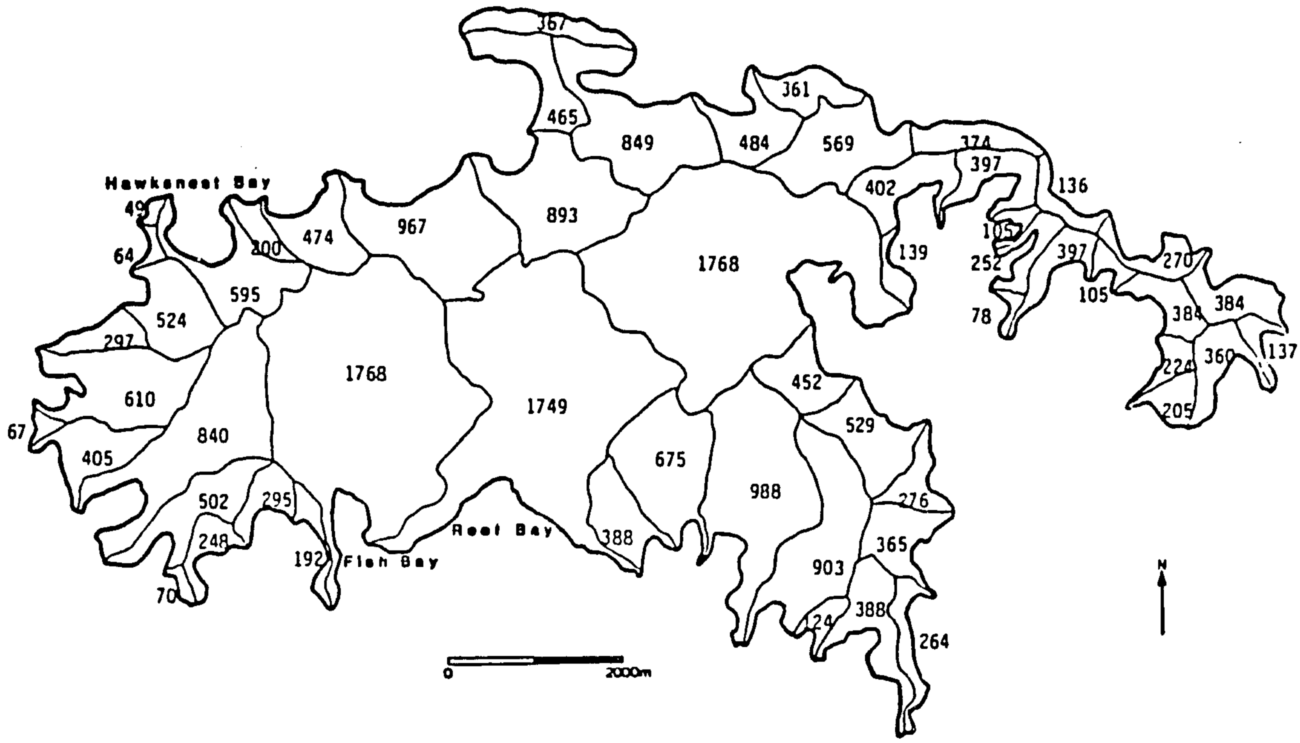


Figure 5. Peak discharge rates expressed in cfs for St. John watersheds during a 2-yr frequency storm (3.9"/24 hrs.).

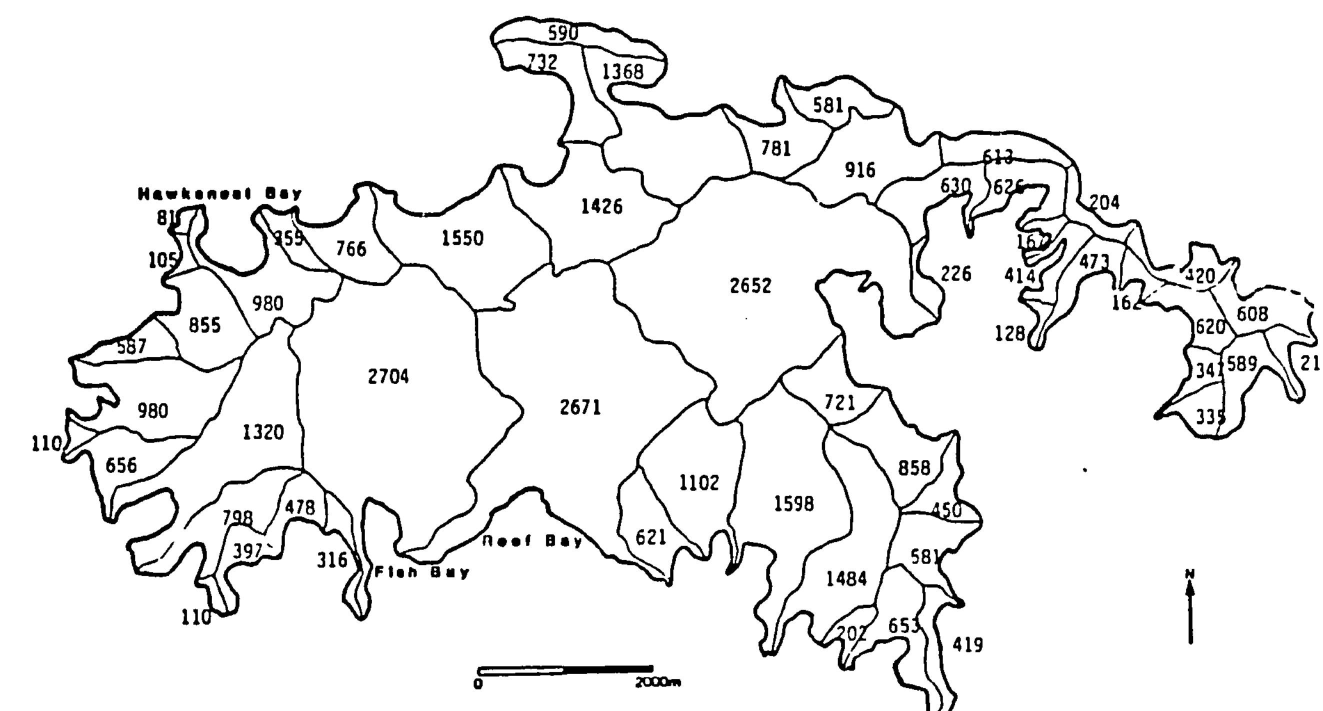


Figure 6. Peak discharge rates expressed in cfs for St. John watersheds during a 5-yr frequency storm (5.5"/24 hrs.).

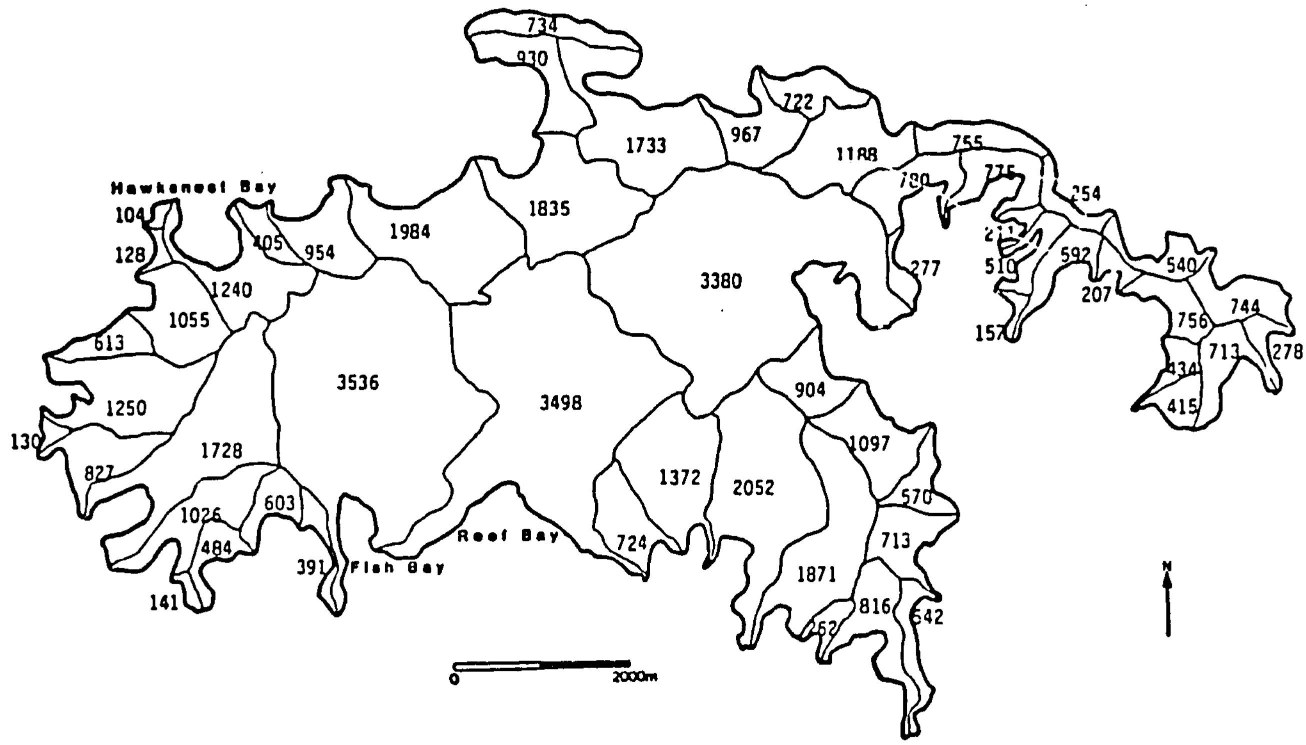


Figure 7. Peak discharge rates expressed in cfs for St. John watersheds during a 10-yr frequency storm (6.6"/24 hrs.).

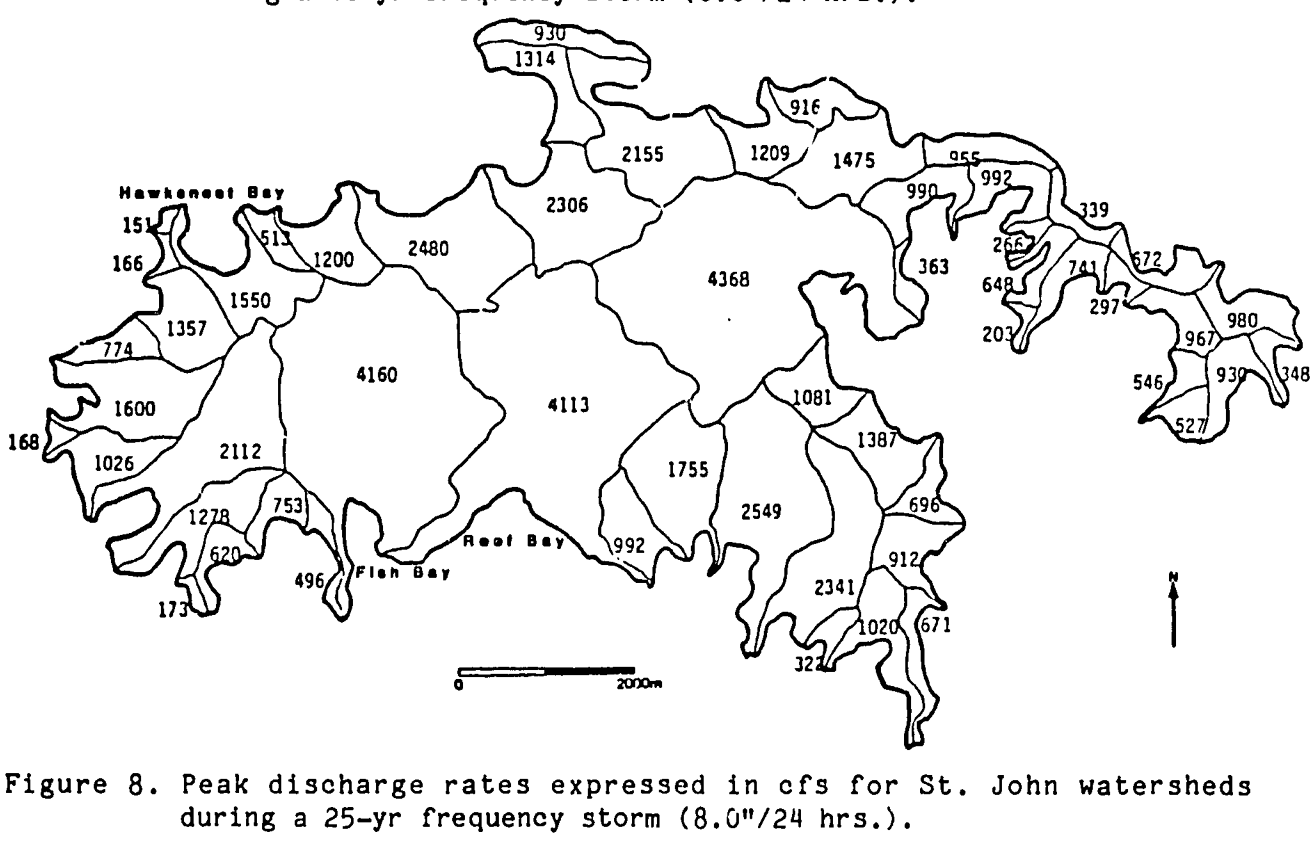


Figure 8. Peak discharge rates expressed in cfs for St. John watersheds during a 25-yr frequency storm (8.0"/24 hrs.).

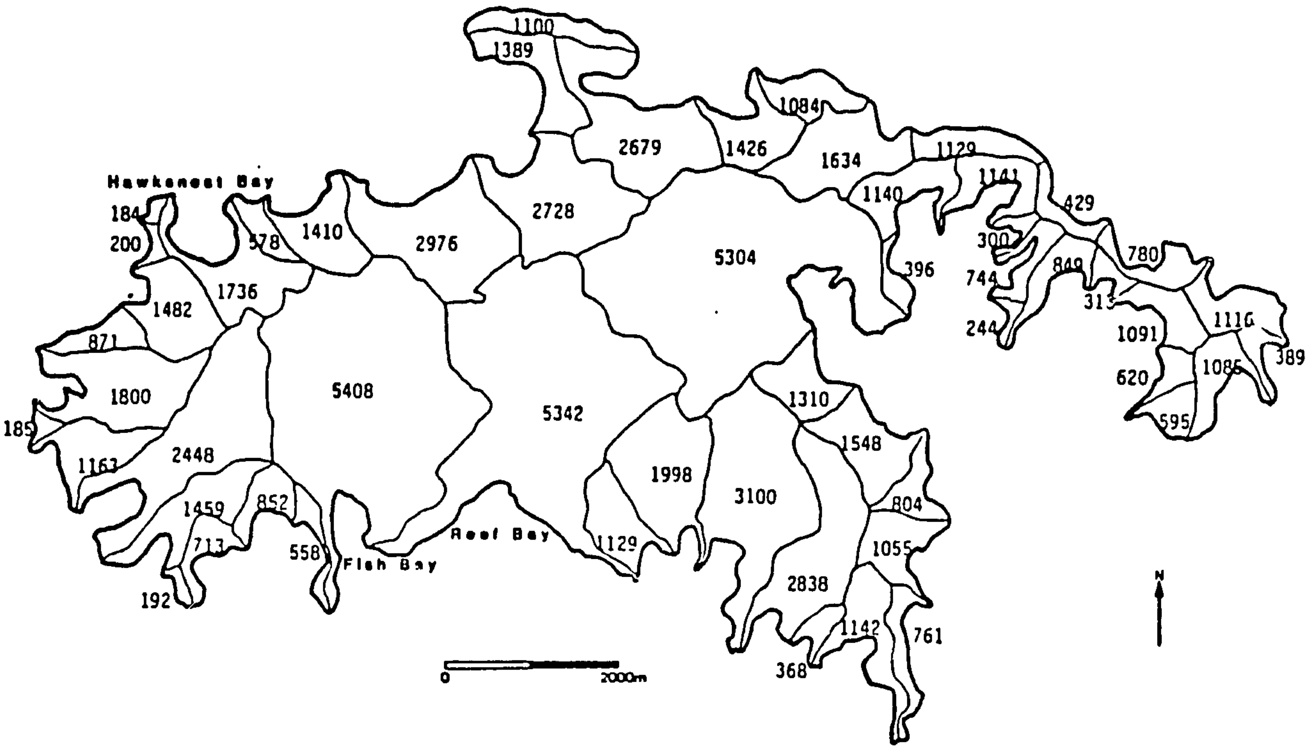


Figure 9. Peak discharge rates expressed in cfs for St. John watersheds during a 50-yr frequency storm (9.2"/24 hrs.).

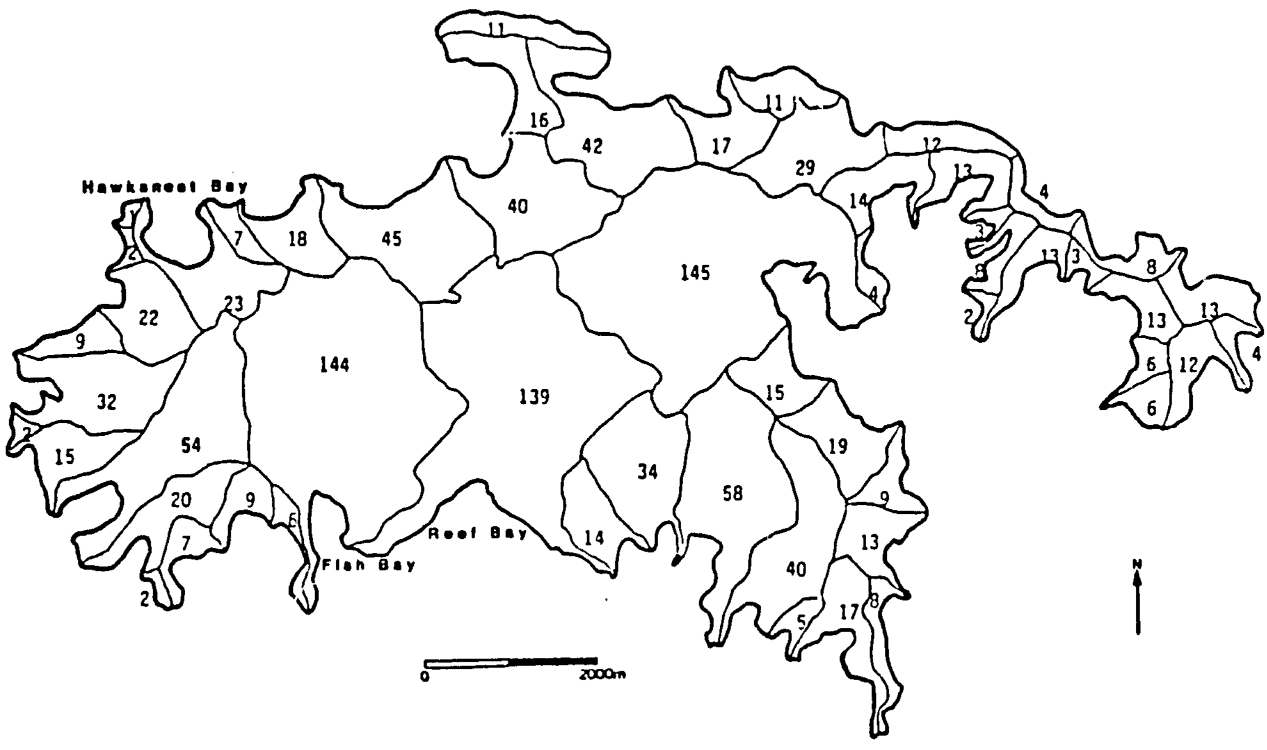


Figure 10. Average runoff volumes expressed in cfs for St. John watersheds during a 2-yr frequency storm (3.9"/24 hrs.).

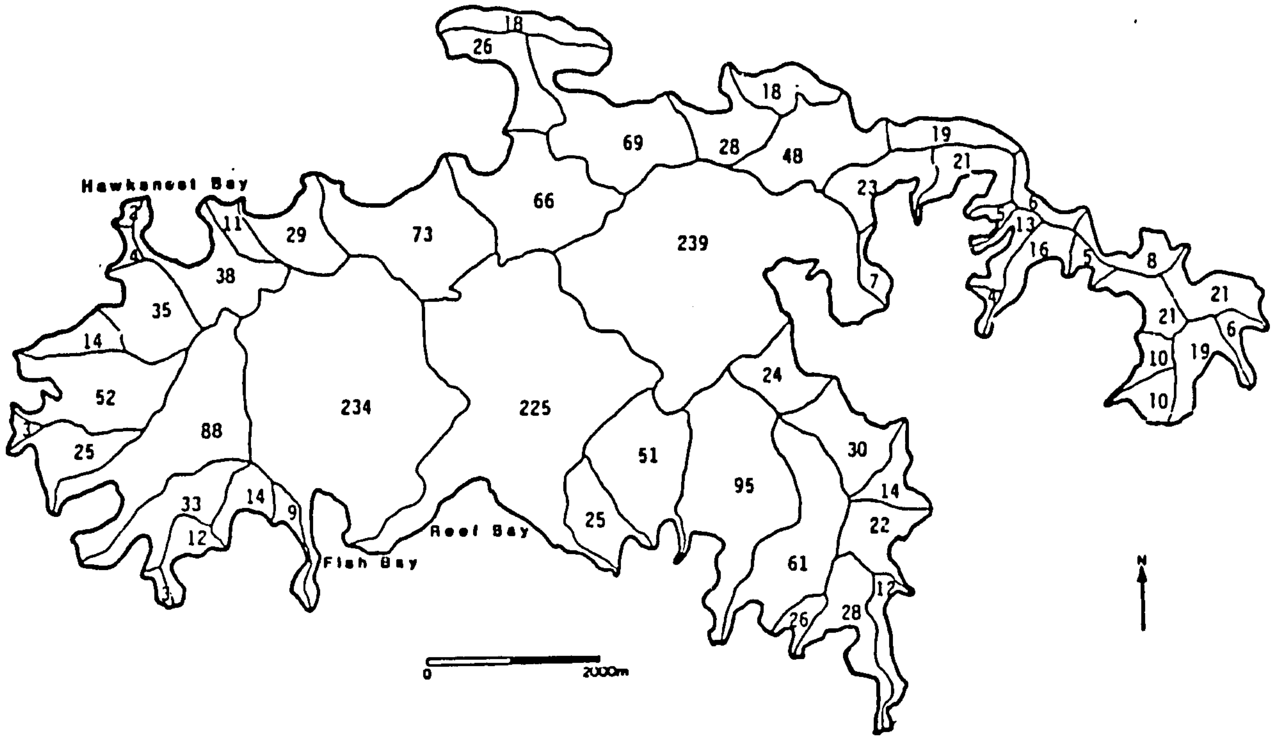


Figure 11. Average runoff volumes expressed in cfs for St. John watersheds during a 5-yr frequency storm (5.5"/24 hrs.).

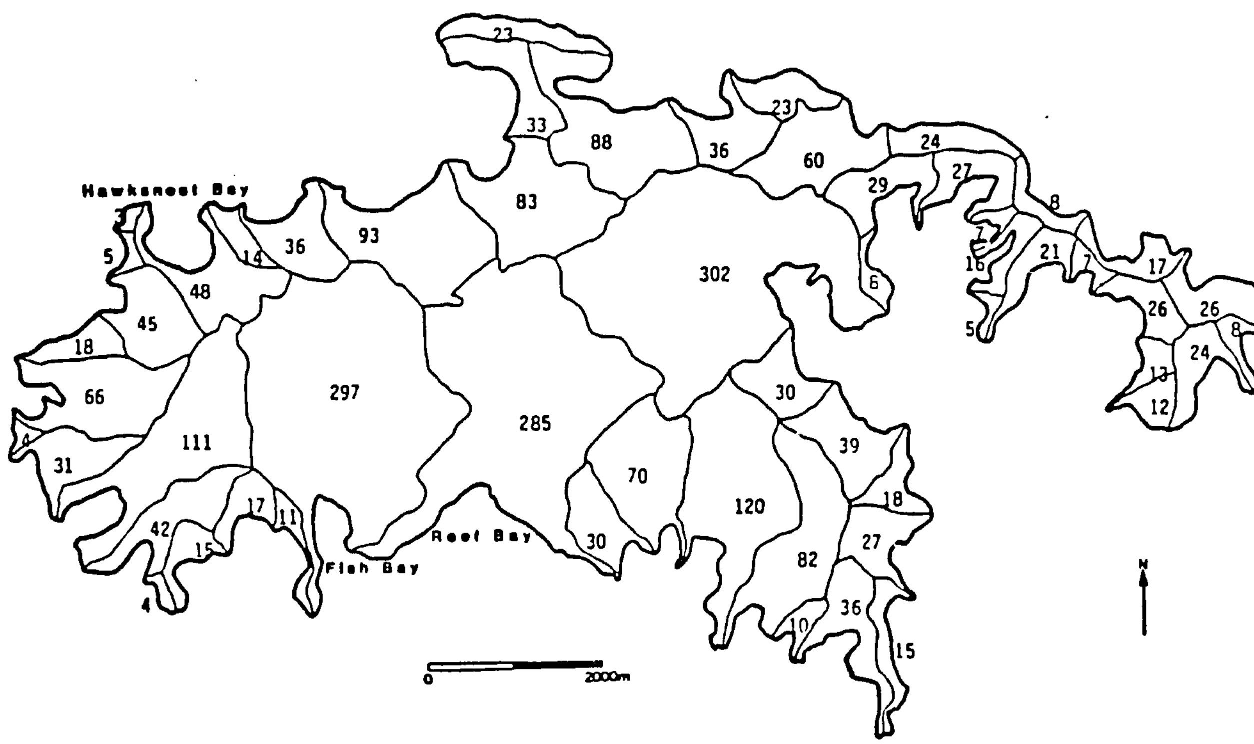


Figure 12. Average runoff volumes expressed in cfs for St. John watersheds during a 10-yr frequency storm (6.6"/24 hrs.).

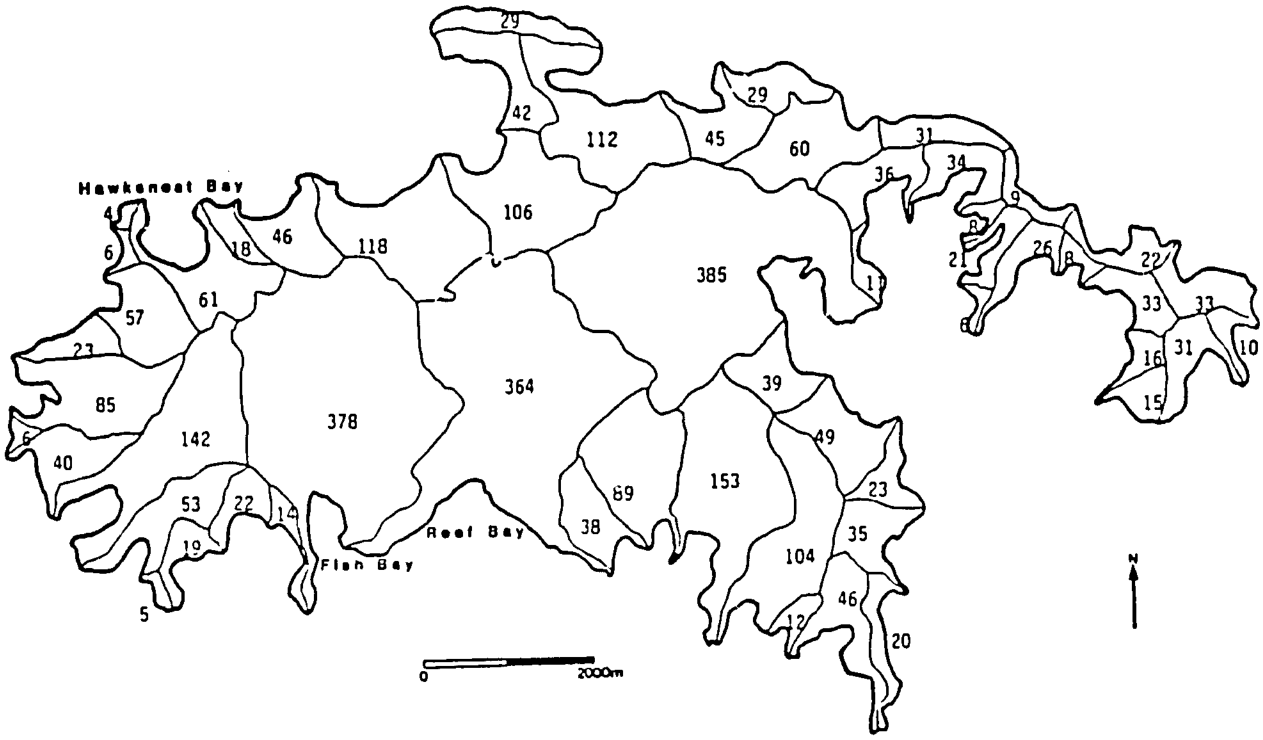


Figure 13. Average runoff volumes expressed in cfs for St.John watersheds during a 25-yr frequency storm (8.0"/24 hrs.).

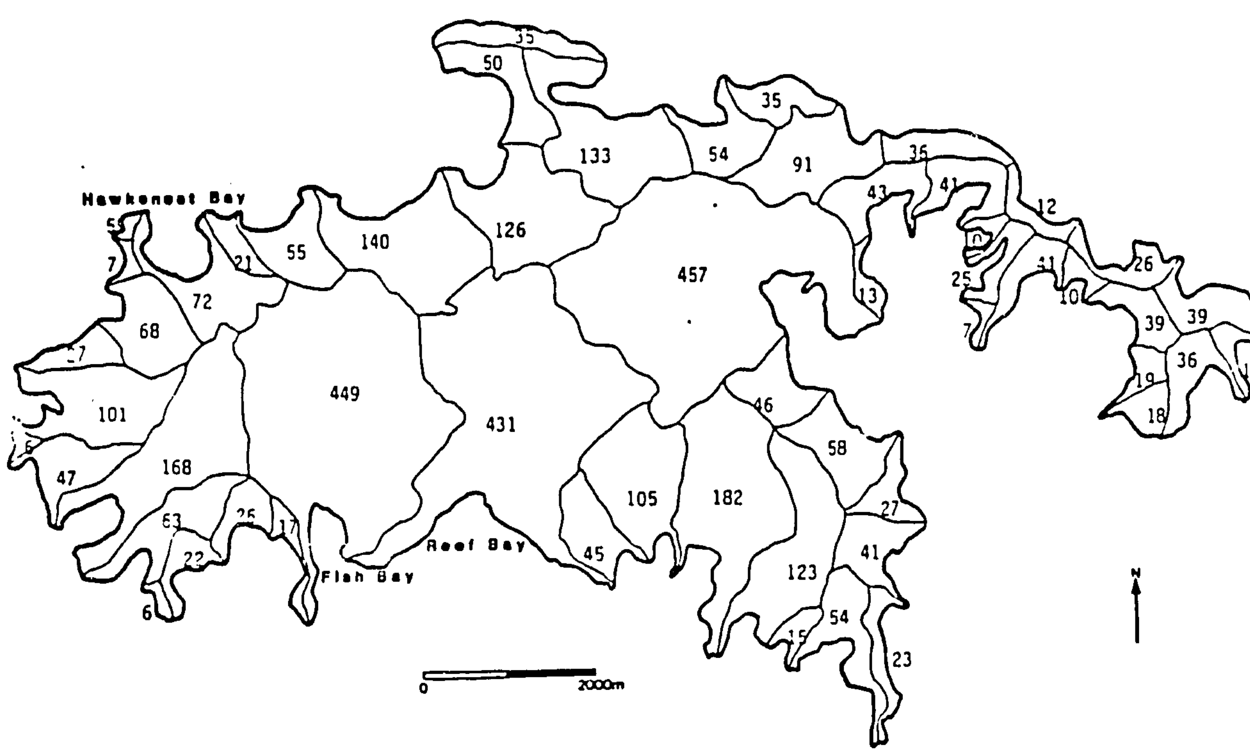


Figure 14. Average runoff volumes expressed in cfs for St. John watersheds during a 50-yr frequency storm (9.2"/24 hrs.).

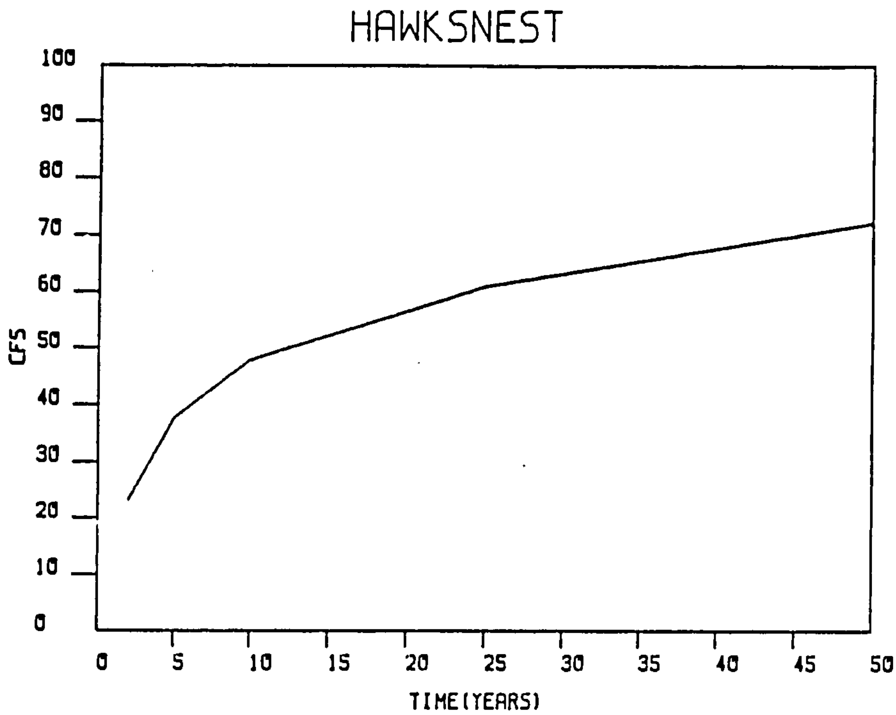


Figure 15. Average runoff volume expressed in cfs for Hawksnest Bay for different intensity storms. Note the consistent decrease in the slope of the curve with increasing storm intensity.

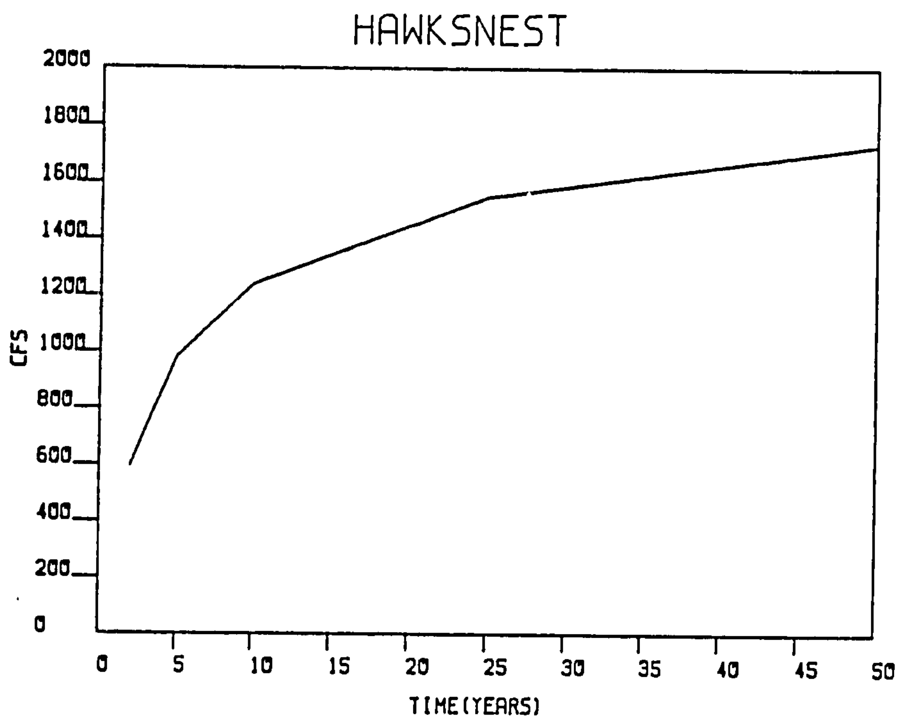


Figure 16. Peak discharge rate expressed in cfs for Hawksnest Bay for different intensity storms. Note the consistent decrease in the slope of the curve with increasing storm intensity.

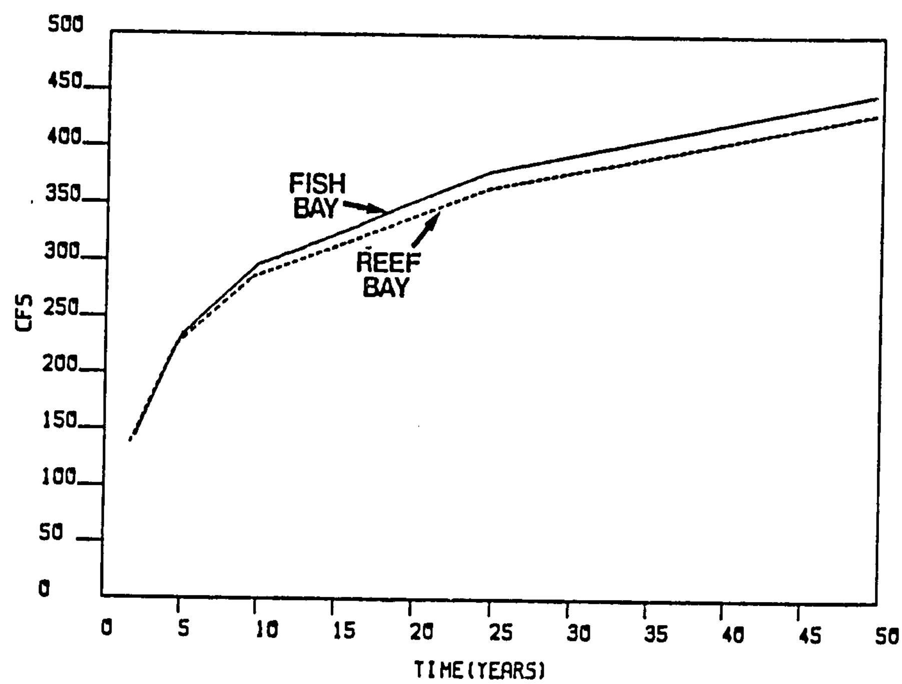


Figure 17. Average runoff volumes expressed in cfs for Fish and Reef Bays for different intensity storms. Note the consistent decrease in the slope of the curve with increasing storm intensity.

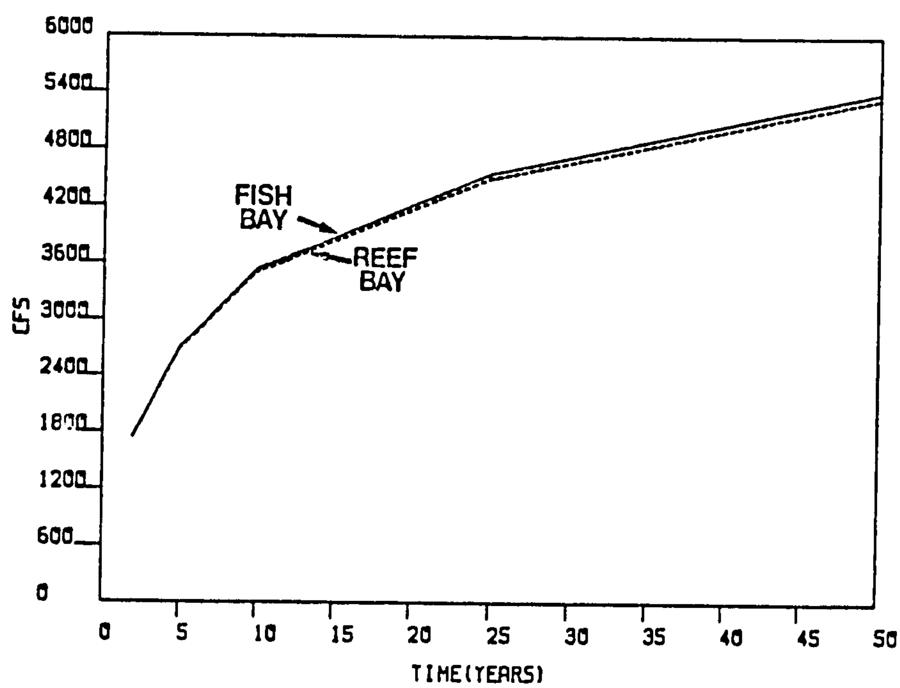


Figure 18. Peak discharge rates expressed in cfs for Fish and Reef Bays for different intensity storms. Note the consistent decrease in the slope of the curve with increasing storm intensity.

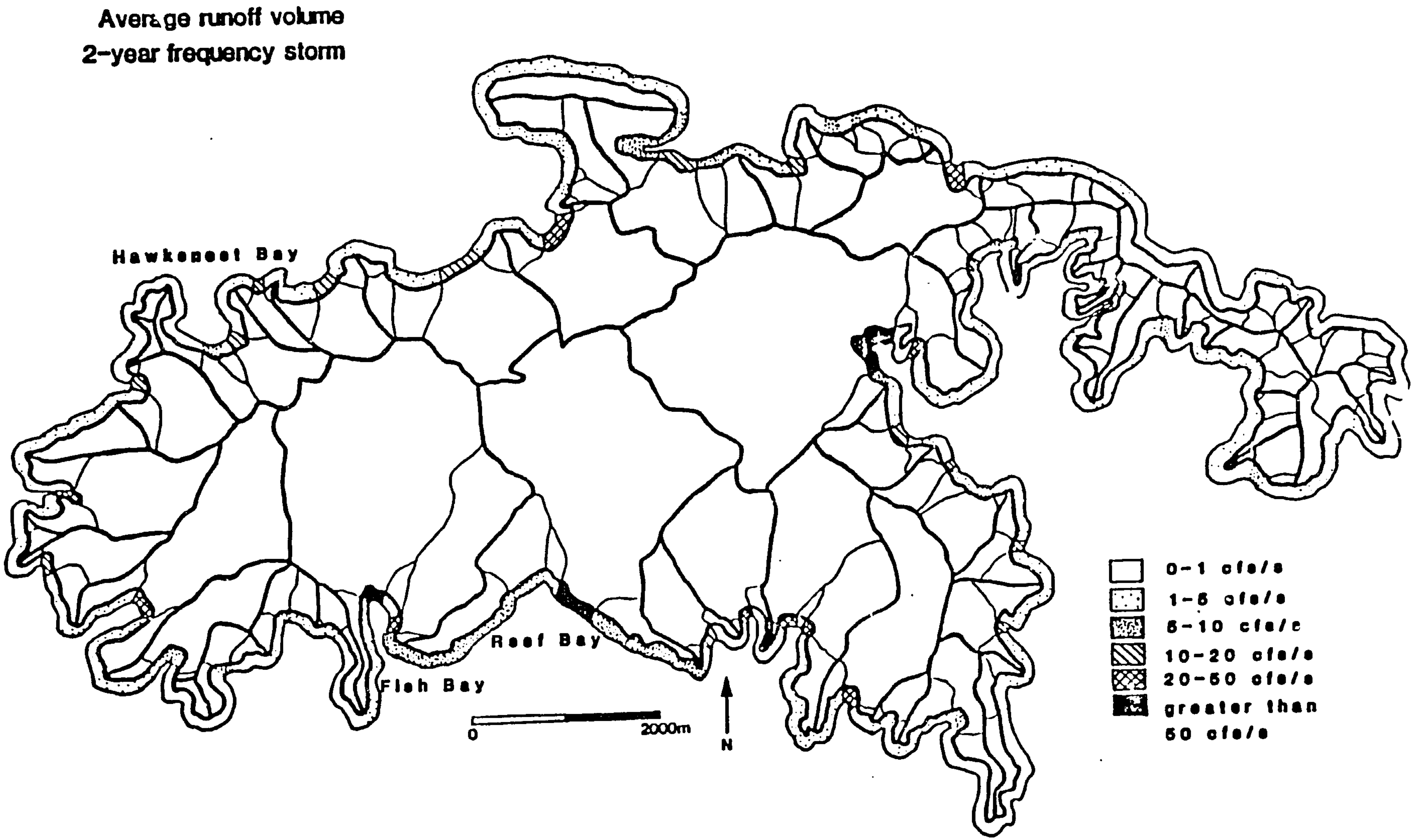


Figure 19. Map of St. John showing average runoff volume for shoreline segments for a 2-yr frequency storm. Dark symbols indicate high runoff values.

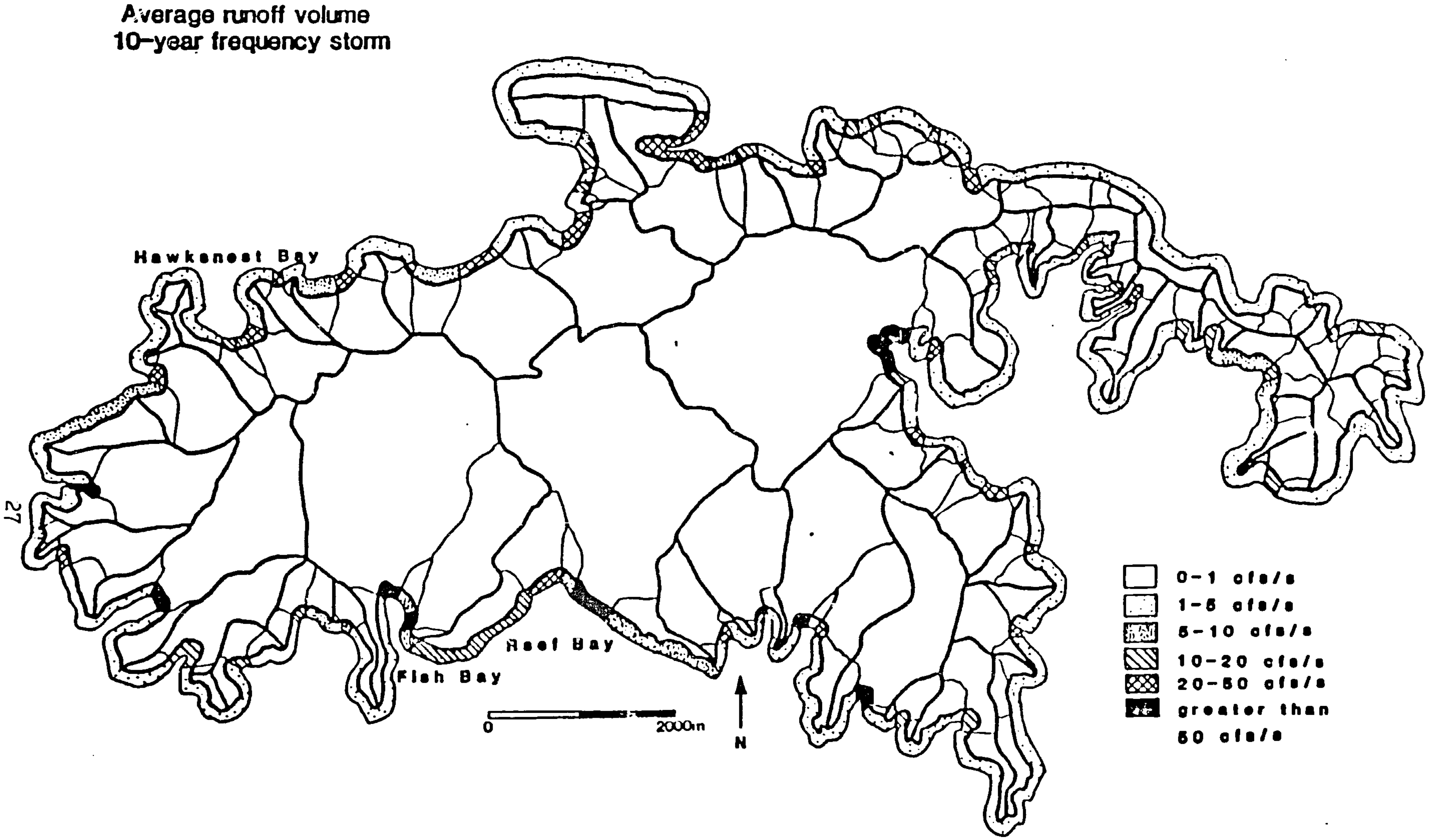


Figure 20. Map of St. John showing average runoff volume for shoreline segments for a 10-yr frequency storm. Dark symbols indicate high runoff values. The pattern of high-intensity runoff is significantly different than that shown for the 2-yr storm (Fig. 19), but is similar to that of more severe storms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

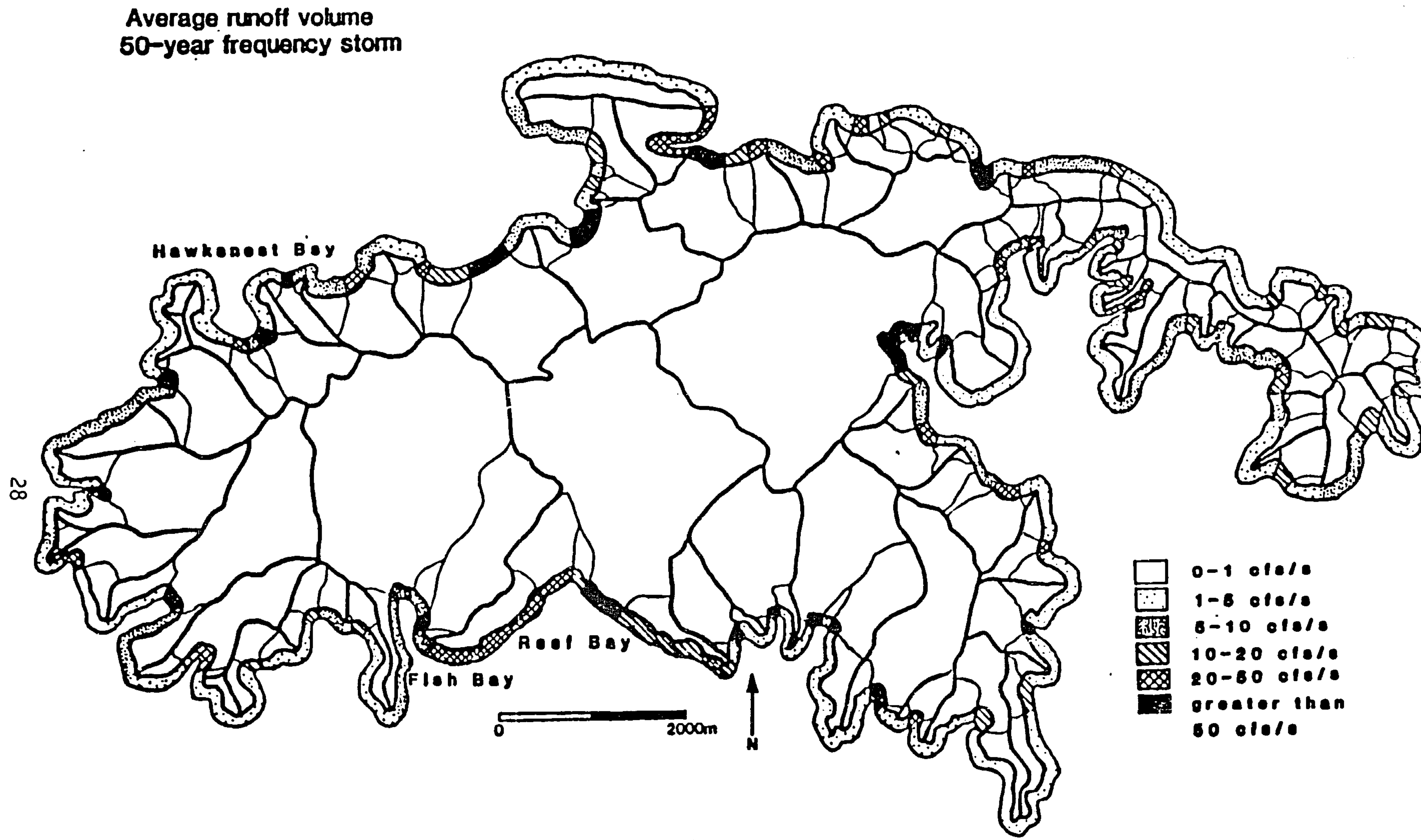


Figure 21. Map of St. John showing average runoff volume for shoreline segments for a 50-yr frequency storm. Dark symbols indicate high runoff values. Note the similarity to the pattern seen for less severe, 10-yr storms (Fig. 20).

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

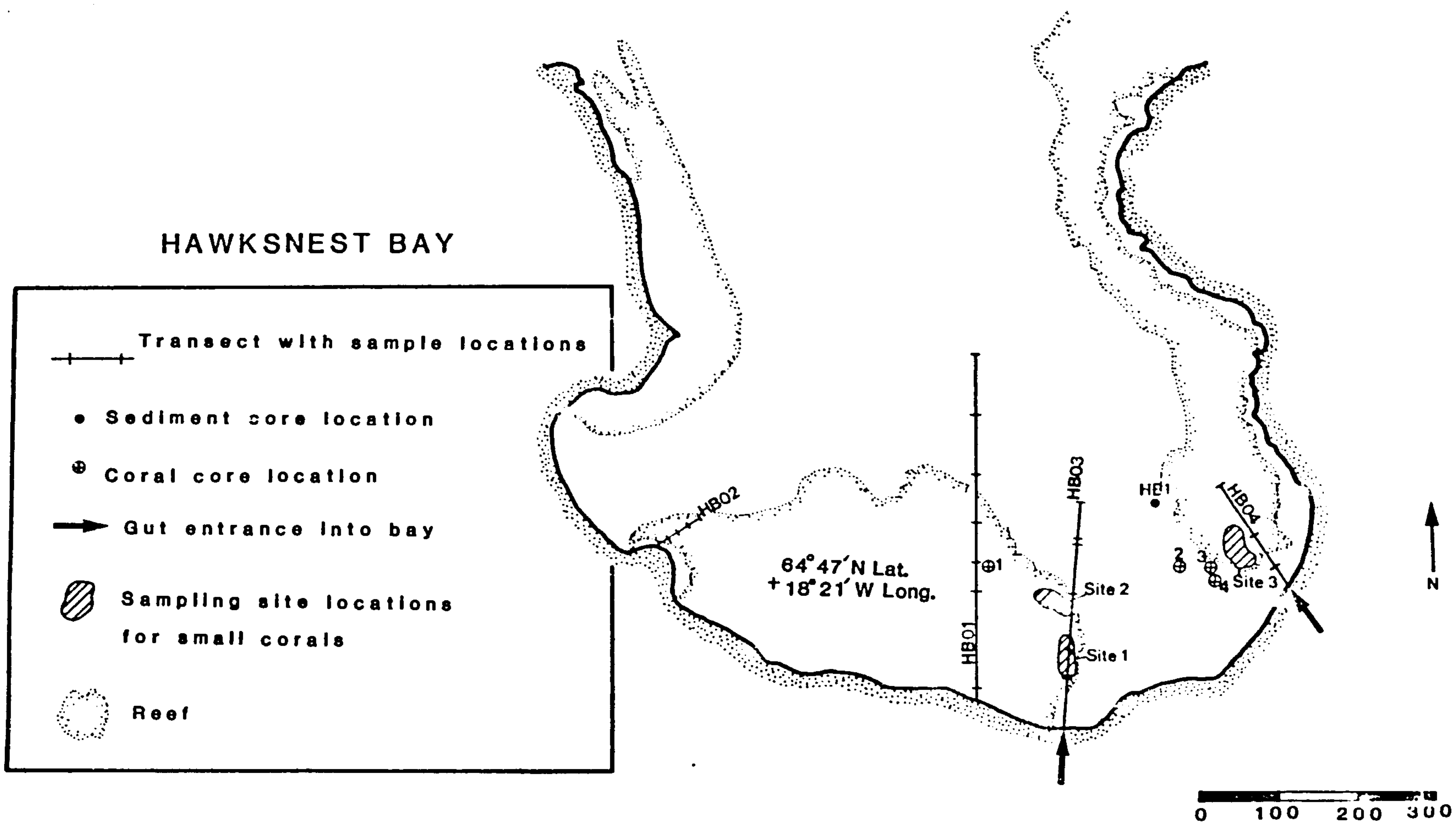


Figure 22. Base map of Hawksnest Bay. Locations of transects, sediment samples and coral cores are shown. Arrows delineate entrances of major guts into the bay.

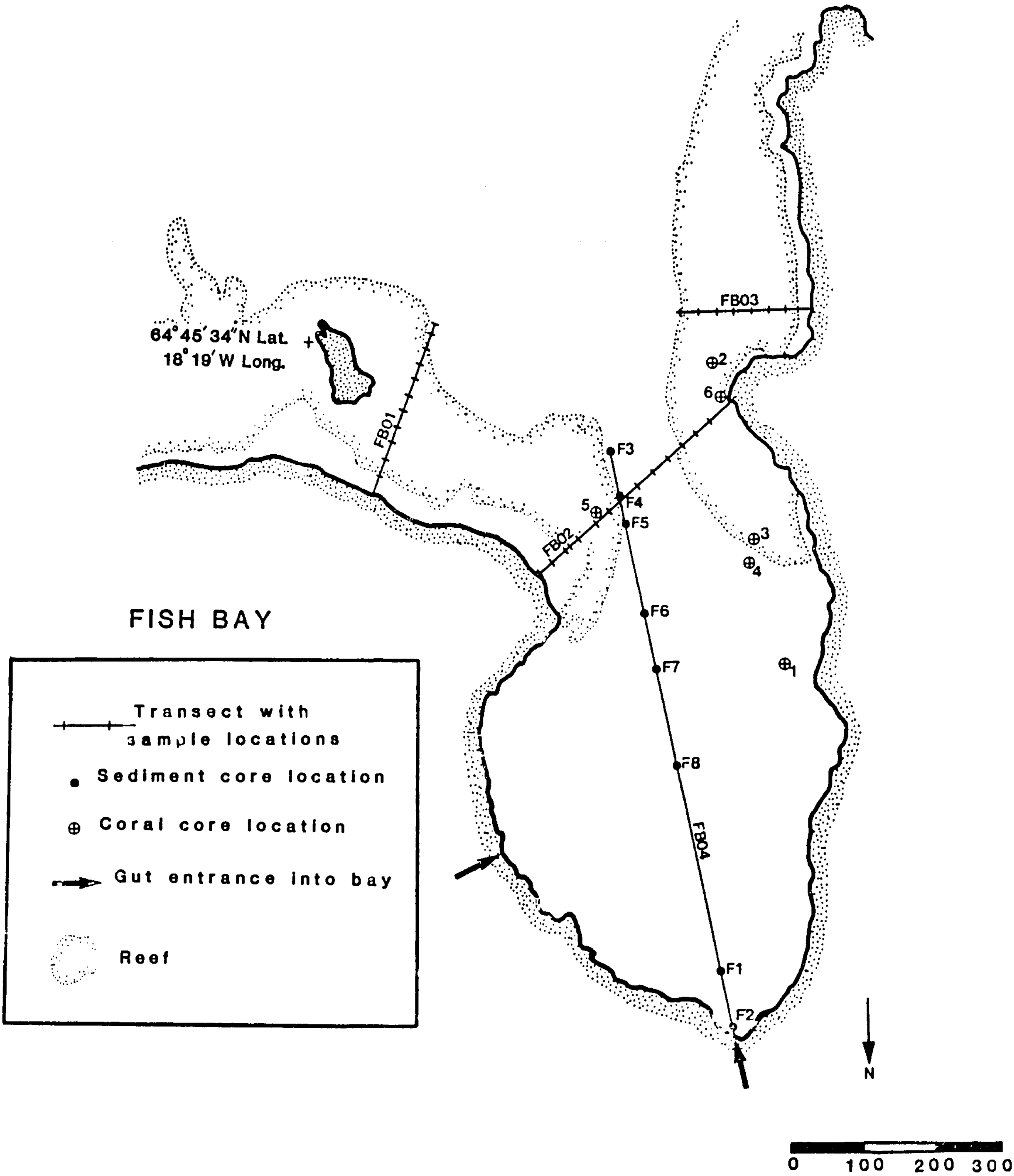


Figure 23. Base map of Fish Bay. Locations of transects, sediment samples and coral cores are shown. Arrows delineate entrances of major guts into the bay.

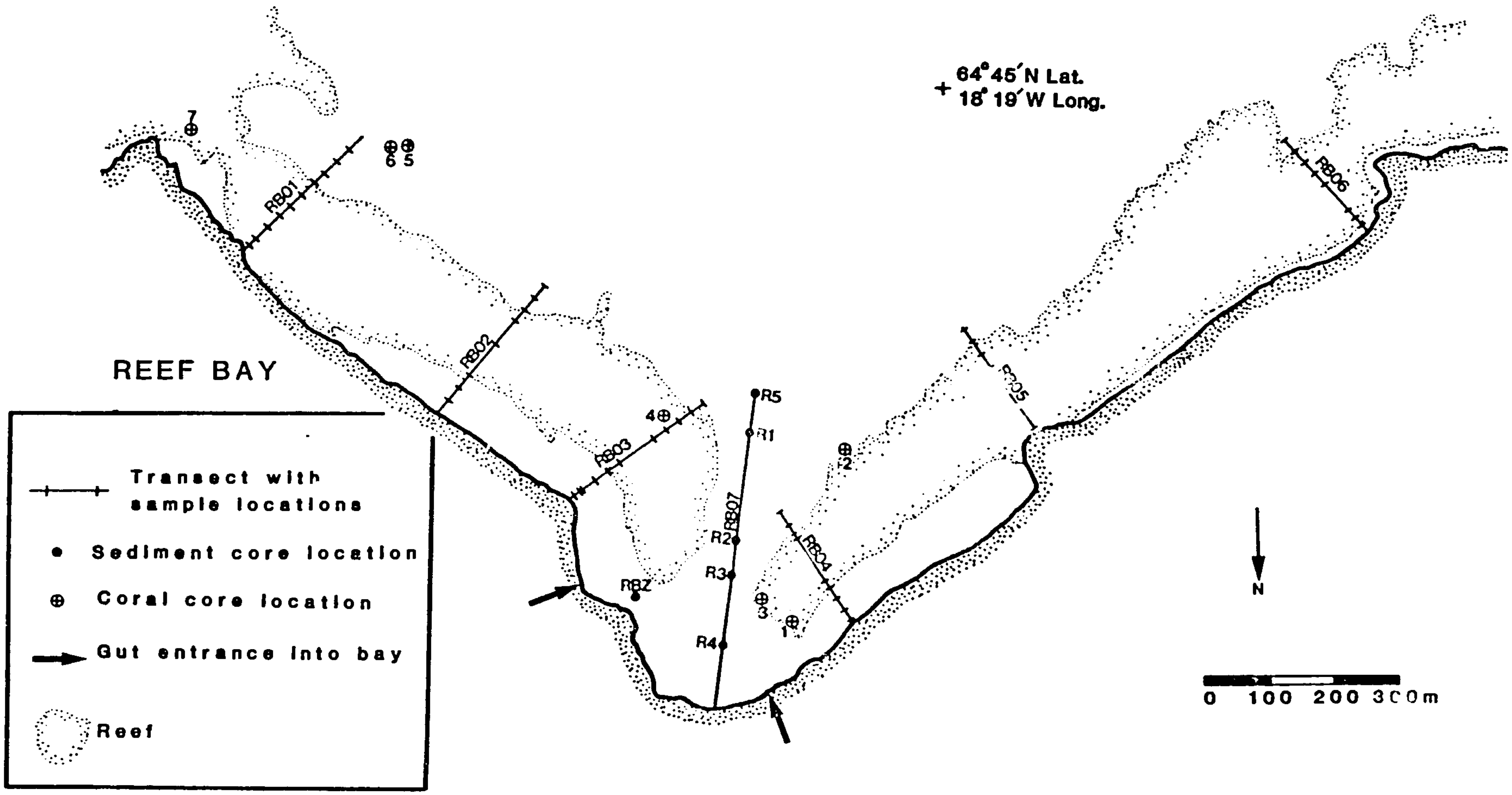


Figure 24. Base map of Fish Bay. Locations of transects, sediment samples and coral cores are shown. Arrows delineate entrances of major guts into the bay.

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.

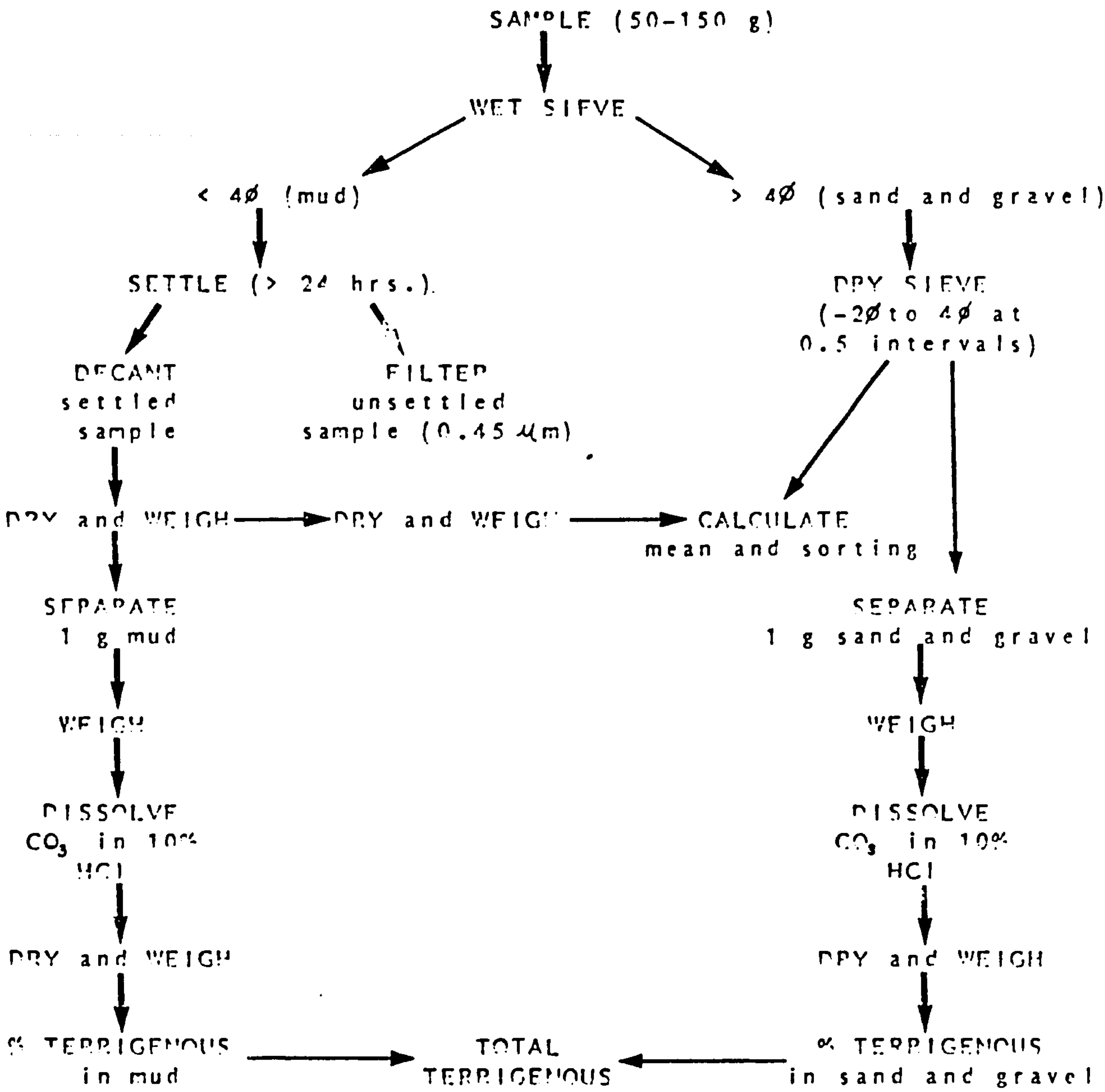
Hawksnest Bay (Figs. 25-30)

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.



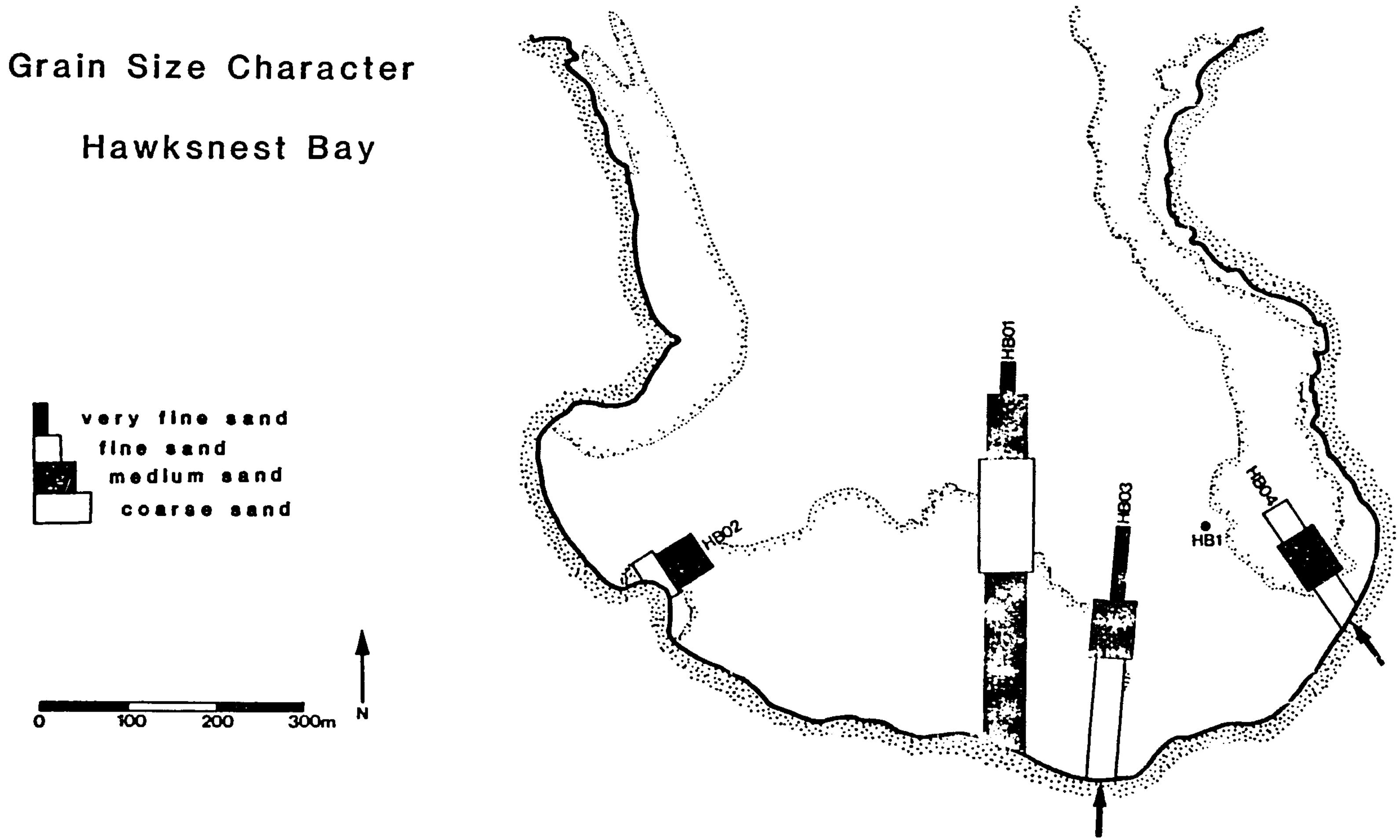


Figure 25. Map of Hawksnest Bay showing grain-size characteristics of surface sediments along each transect.

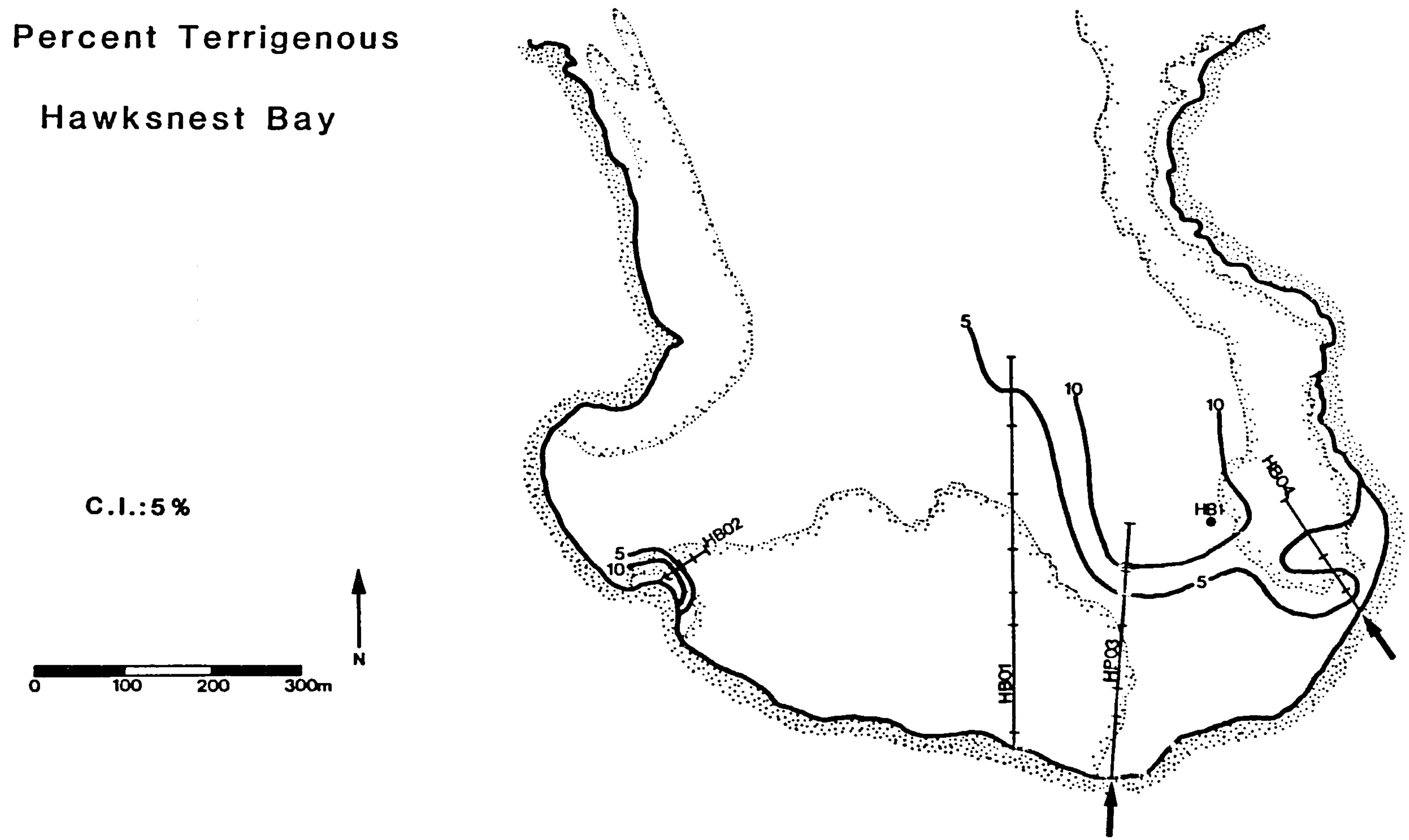


Figure 26. Map of Hawksnest Bay showing the percentages of terrigenous material in the surface sediments.

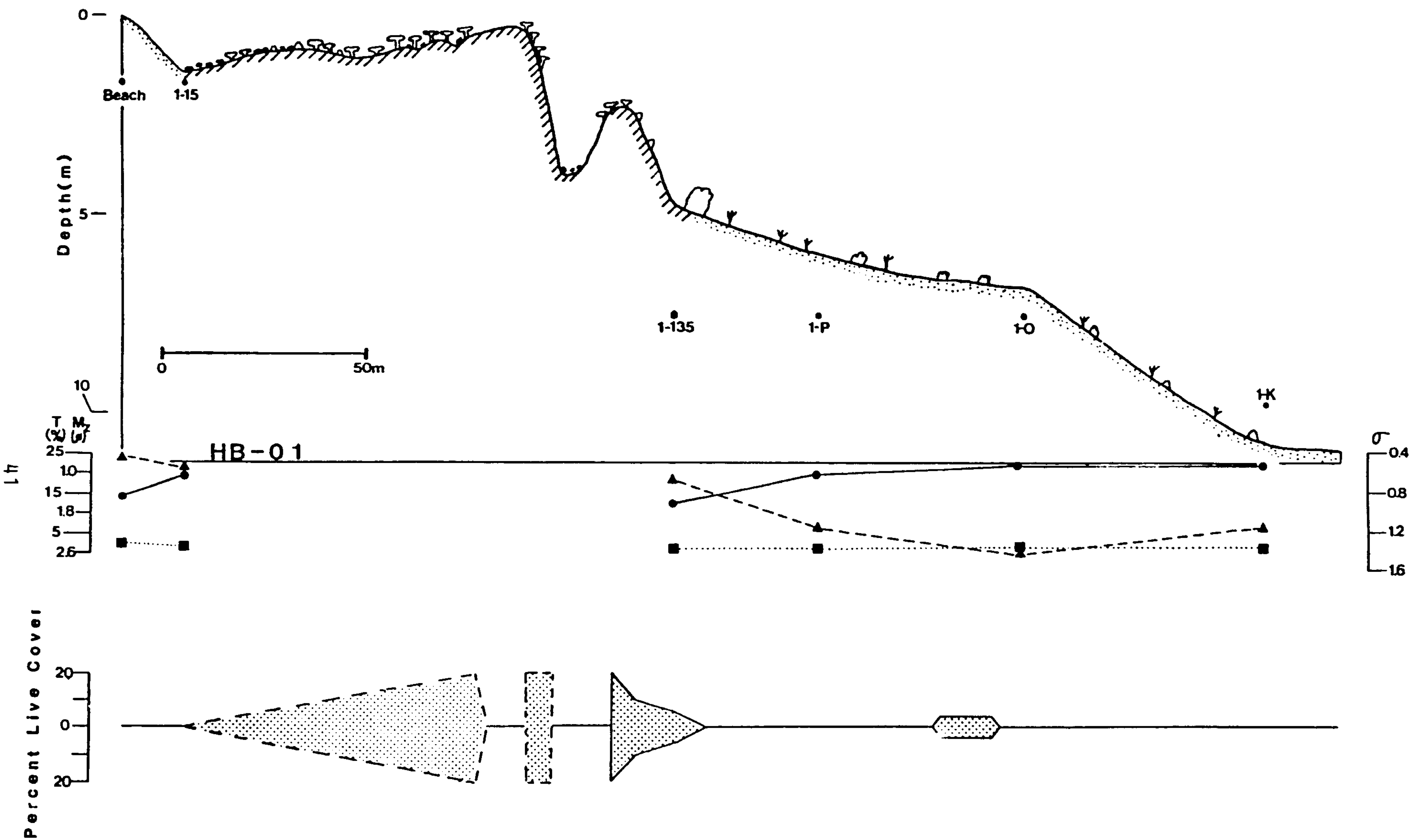


Figure 27. Hawksnest Bay profile HB-01. A key to profile symbols is included in Figure 28.

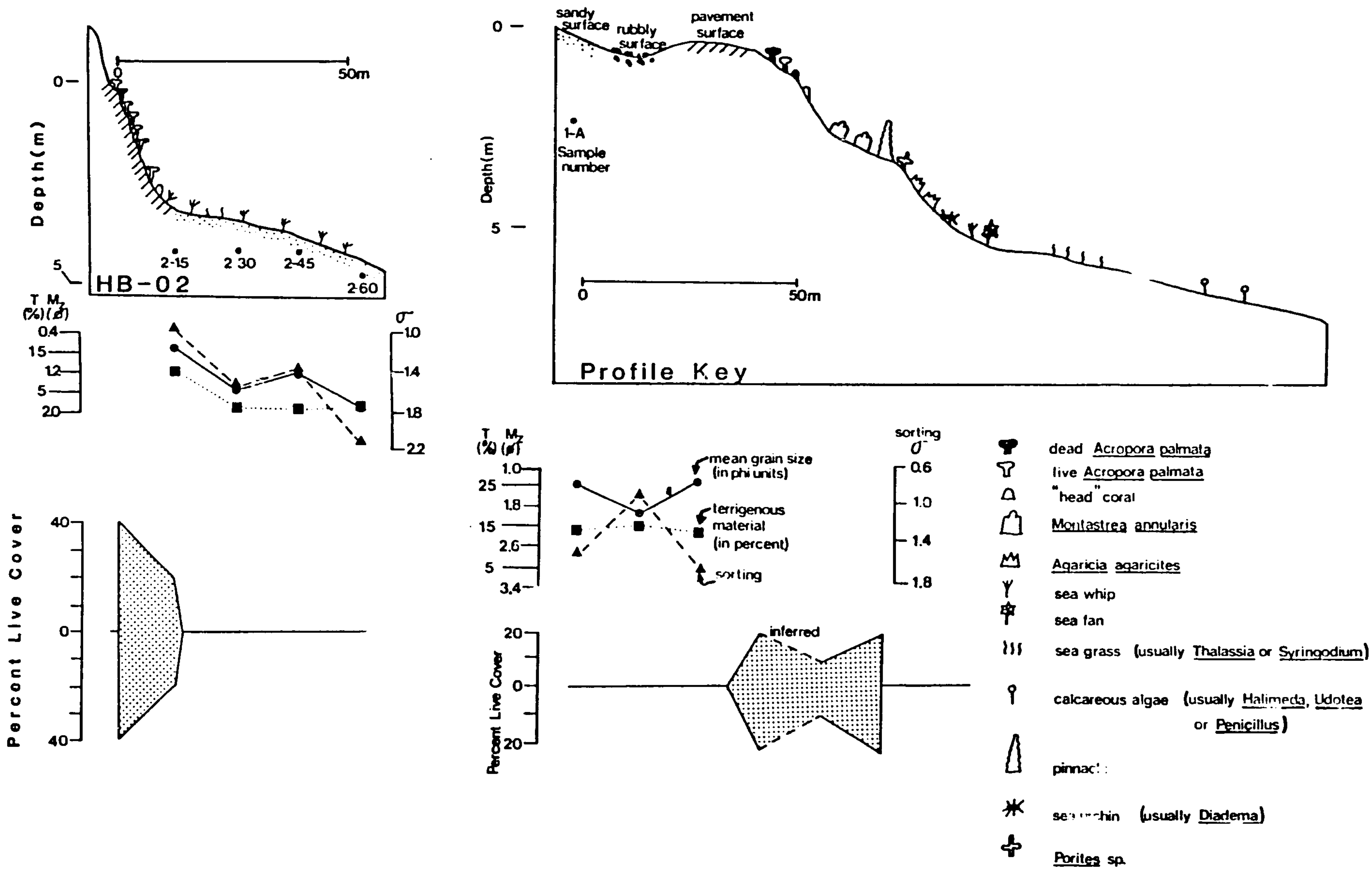


Figure 28. Hawksnest Bay profile HB-02 (left). The symbols shown in the key (right) are consistent on all profiles in this report.

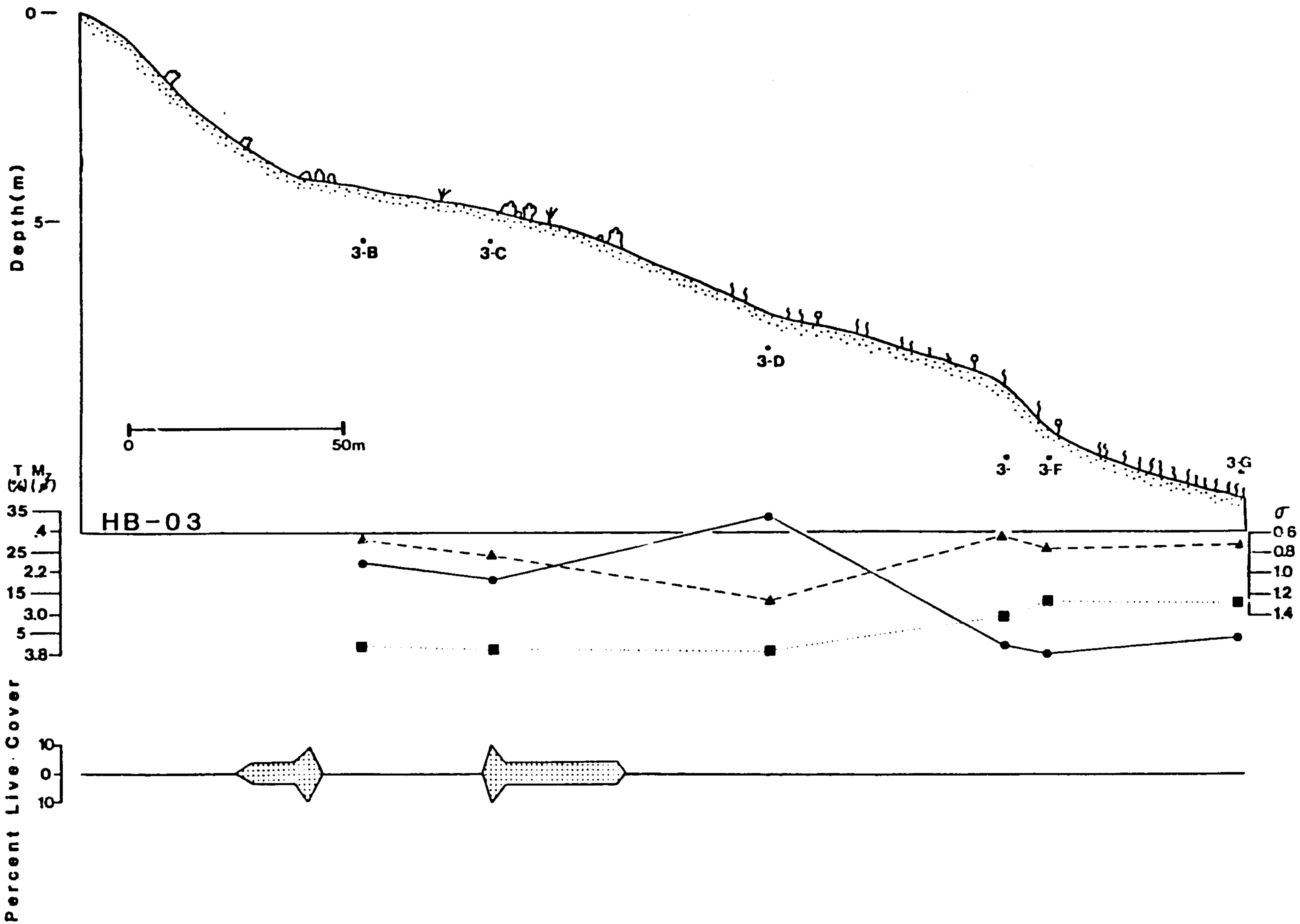


Figure 29. Hawksnest Bay profile HB-03. A key to profile symbols is included in Figure 28.

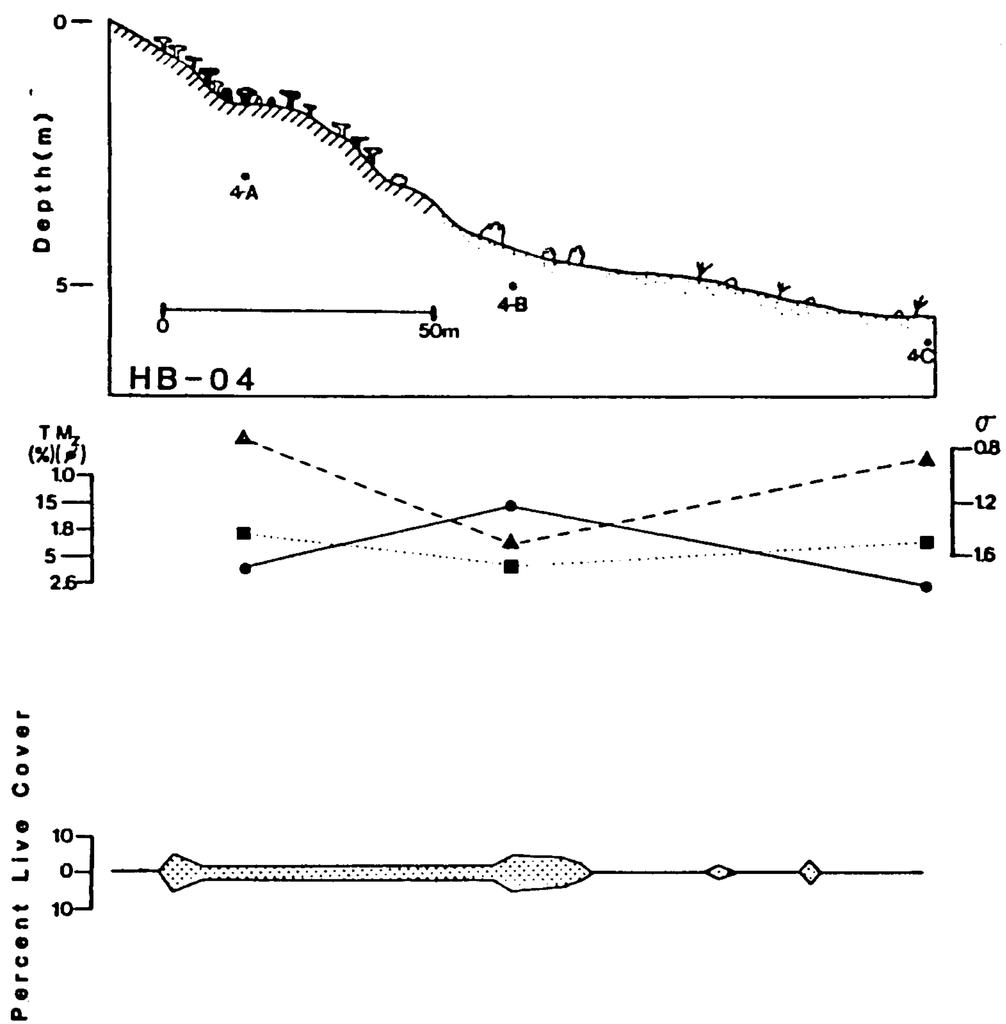


Figure 30. Hawksnest Bay profile HB-04. A key to profile symbols is included in Figure 28.

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

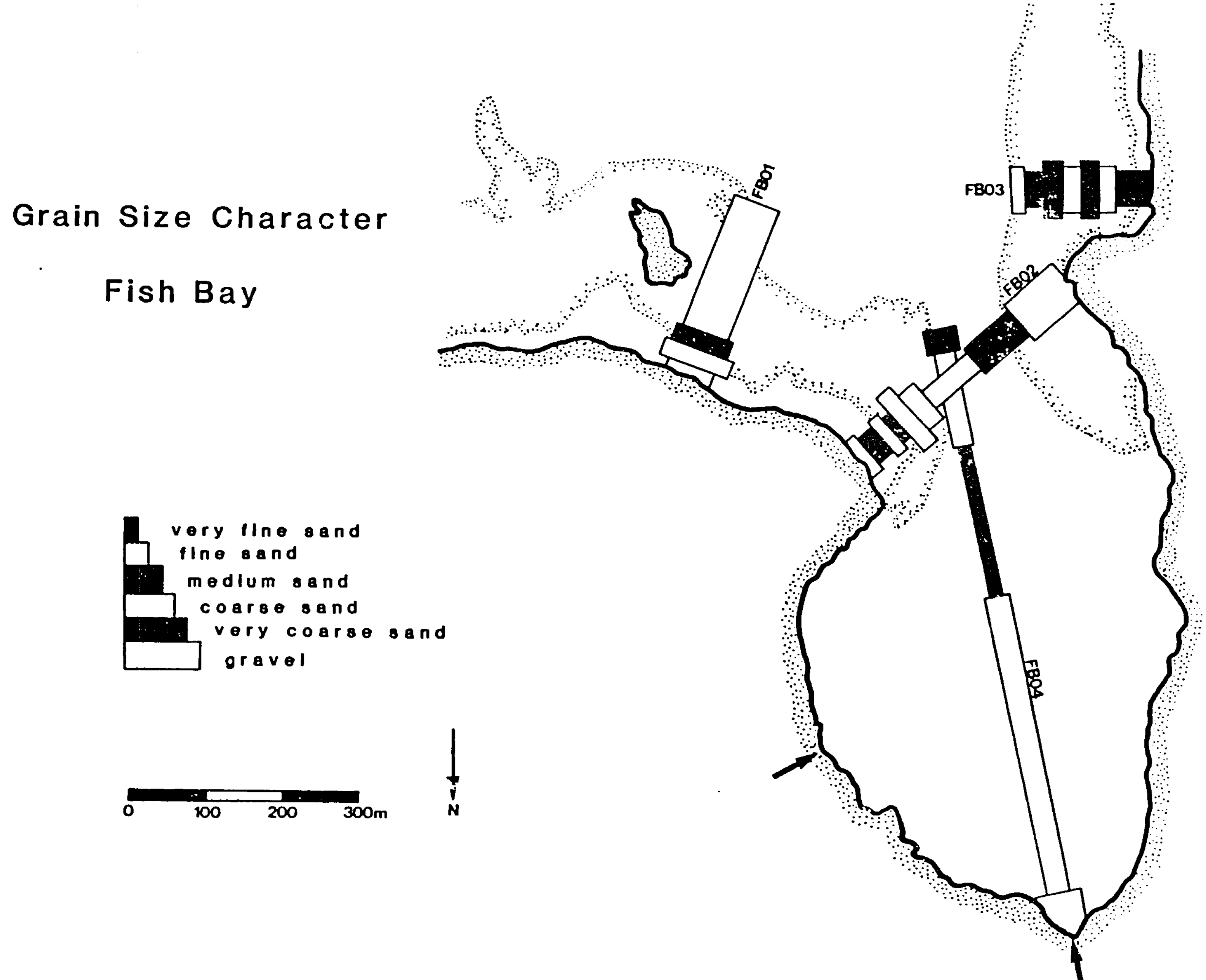


Figure 31. Map of Fish Bay showing grain-size characteristics of surface sediments along each transect.

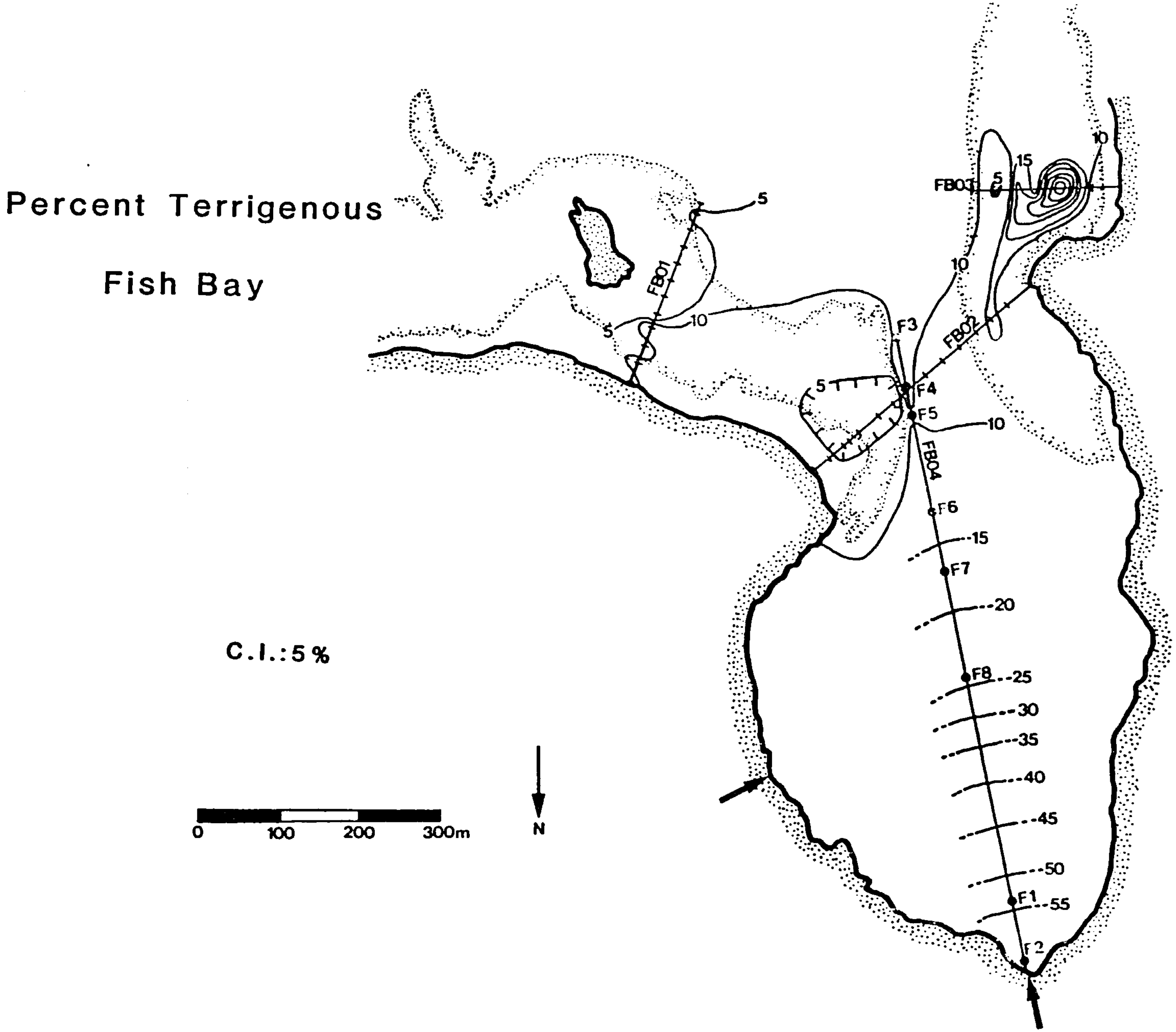


Figure 32. Map of Fish Bay showing the percentages of terrigenous material in the surface sediments.

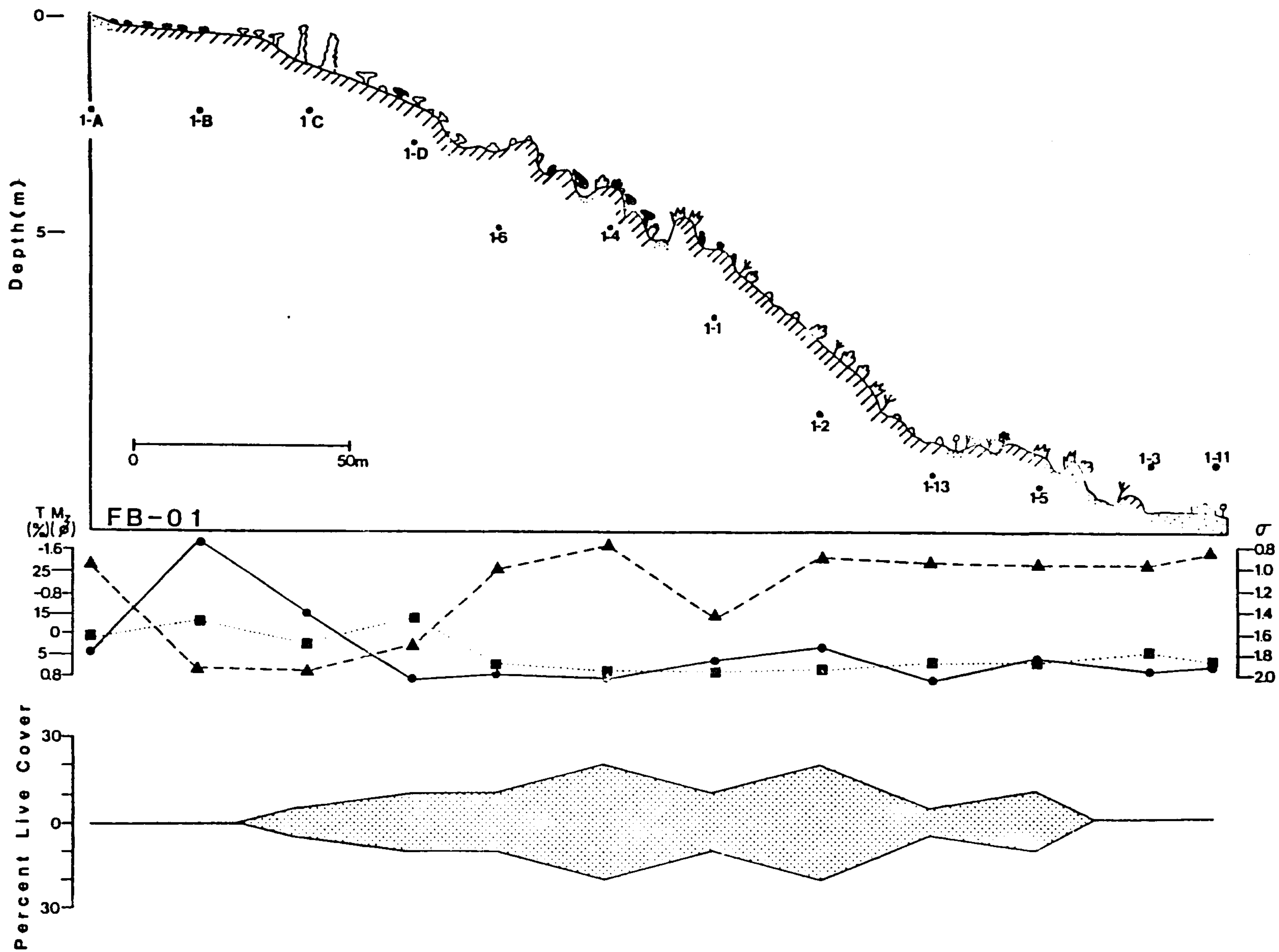


Figure 33. Fish Bay profile FB-01. A symbol key is included in Figure 28.

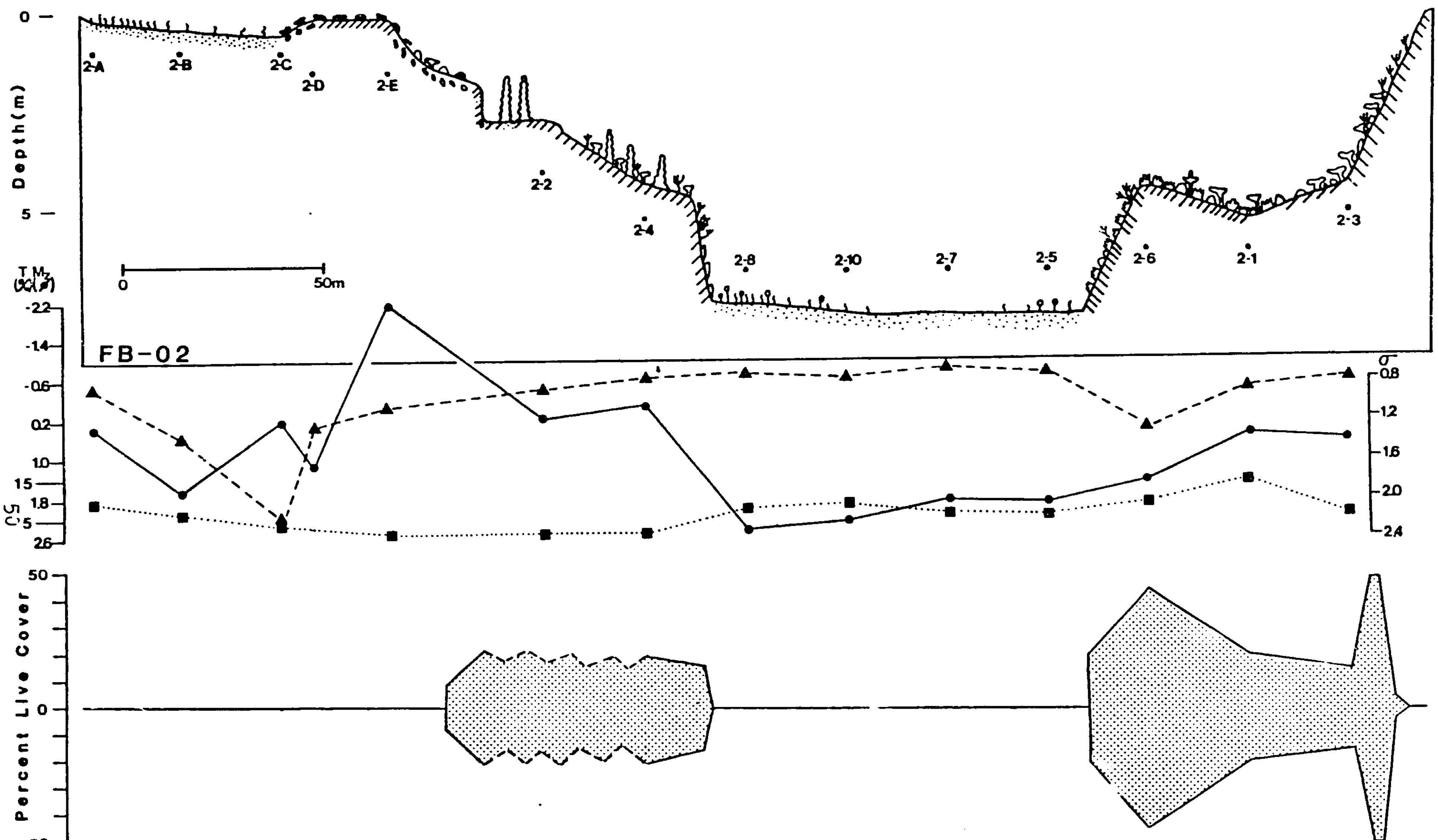


Figure 34. Fish Bay profile FB-02. A symbol key is included in Figure 28.

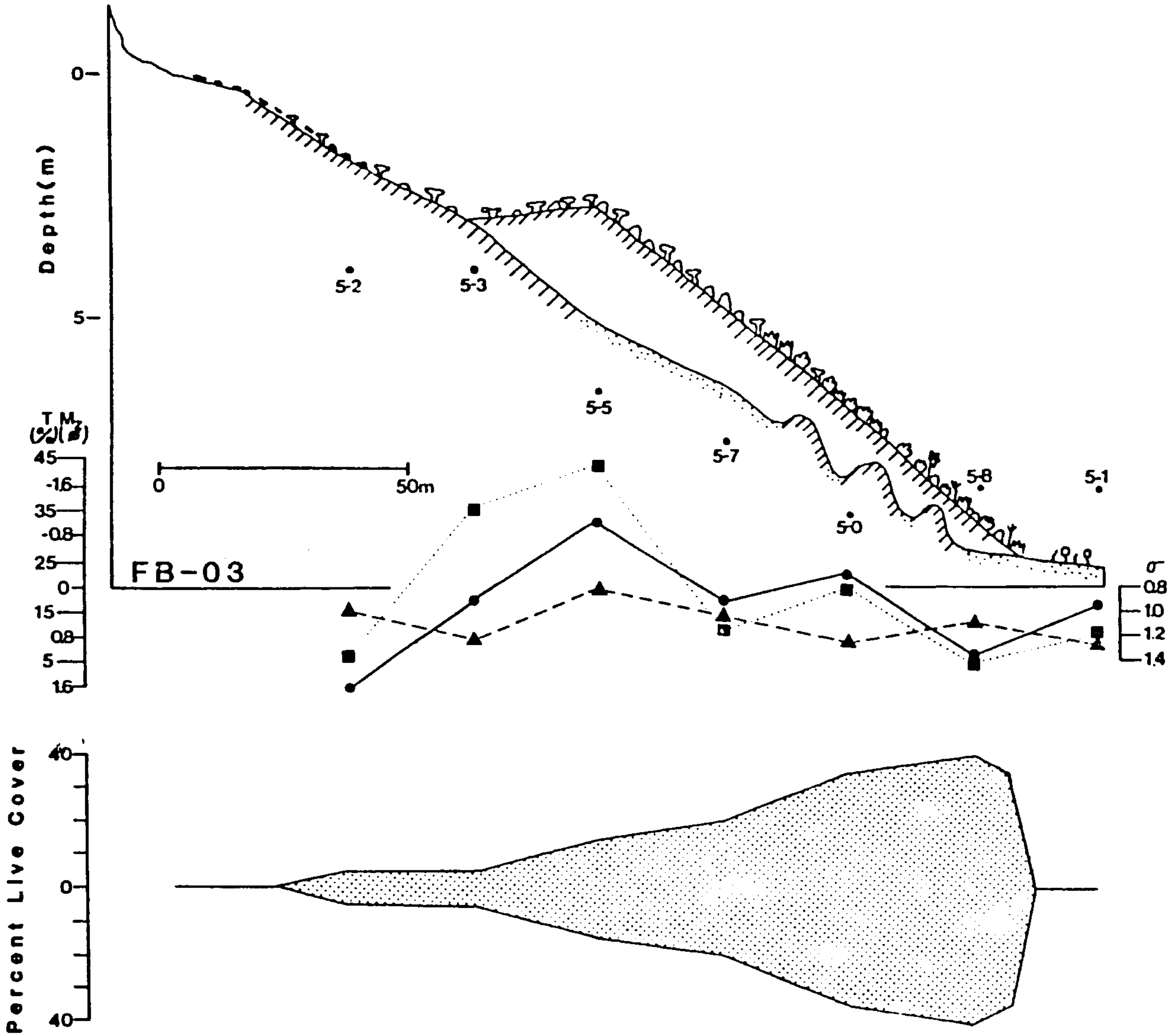


Figure 35. Fish Bay profile FB-03. A symbol key is included in Figure 28.

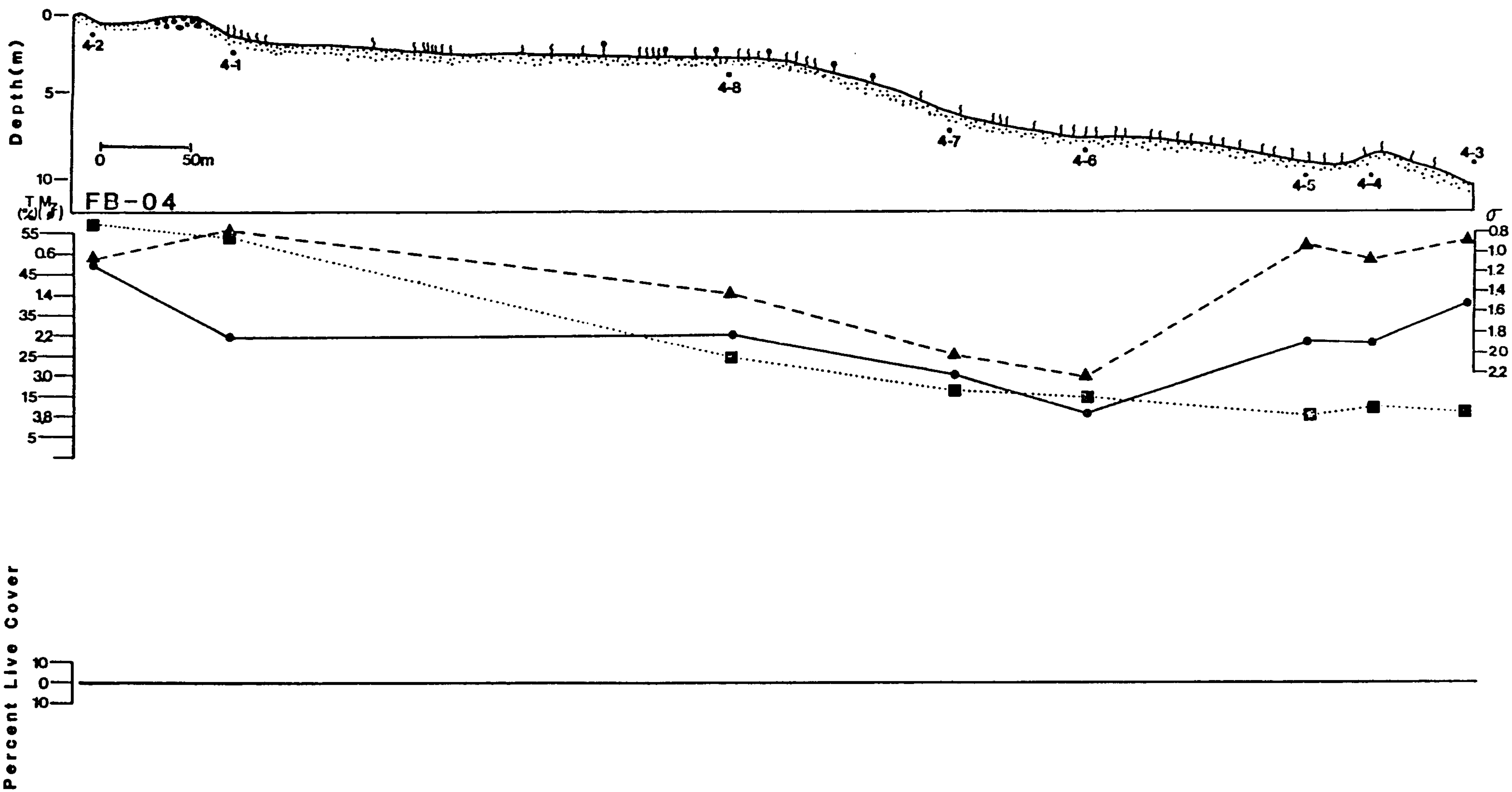


Figure 36. Fish Bay profile FB-04. A symbol key is included in Figure 28.

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.

<u>Reefs</u> - 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.

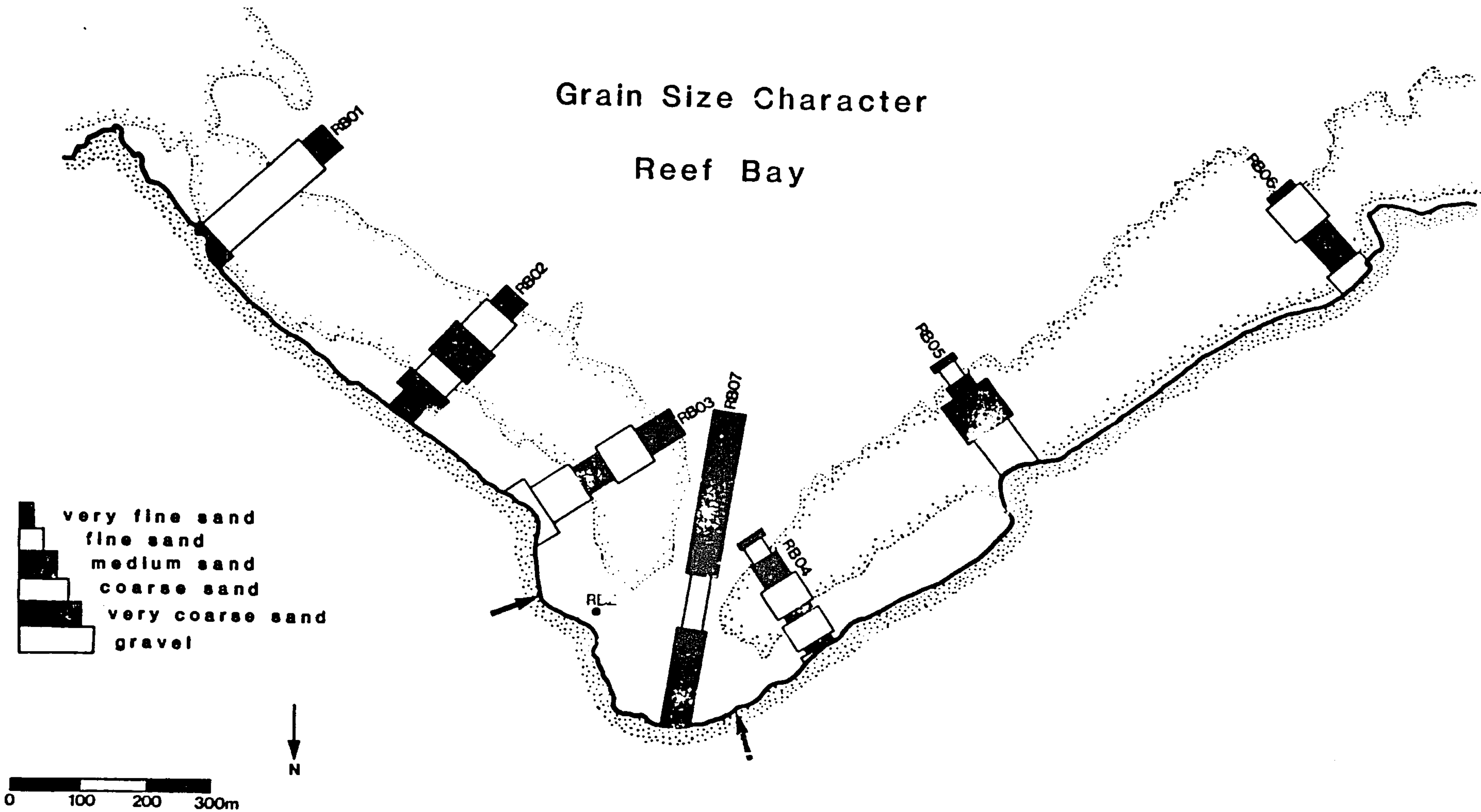


Figure 37. Map of Reef Bay showing grain-size characteristicsofsurface sediments along each transect.

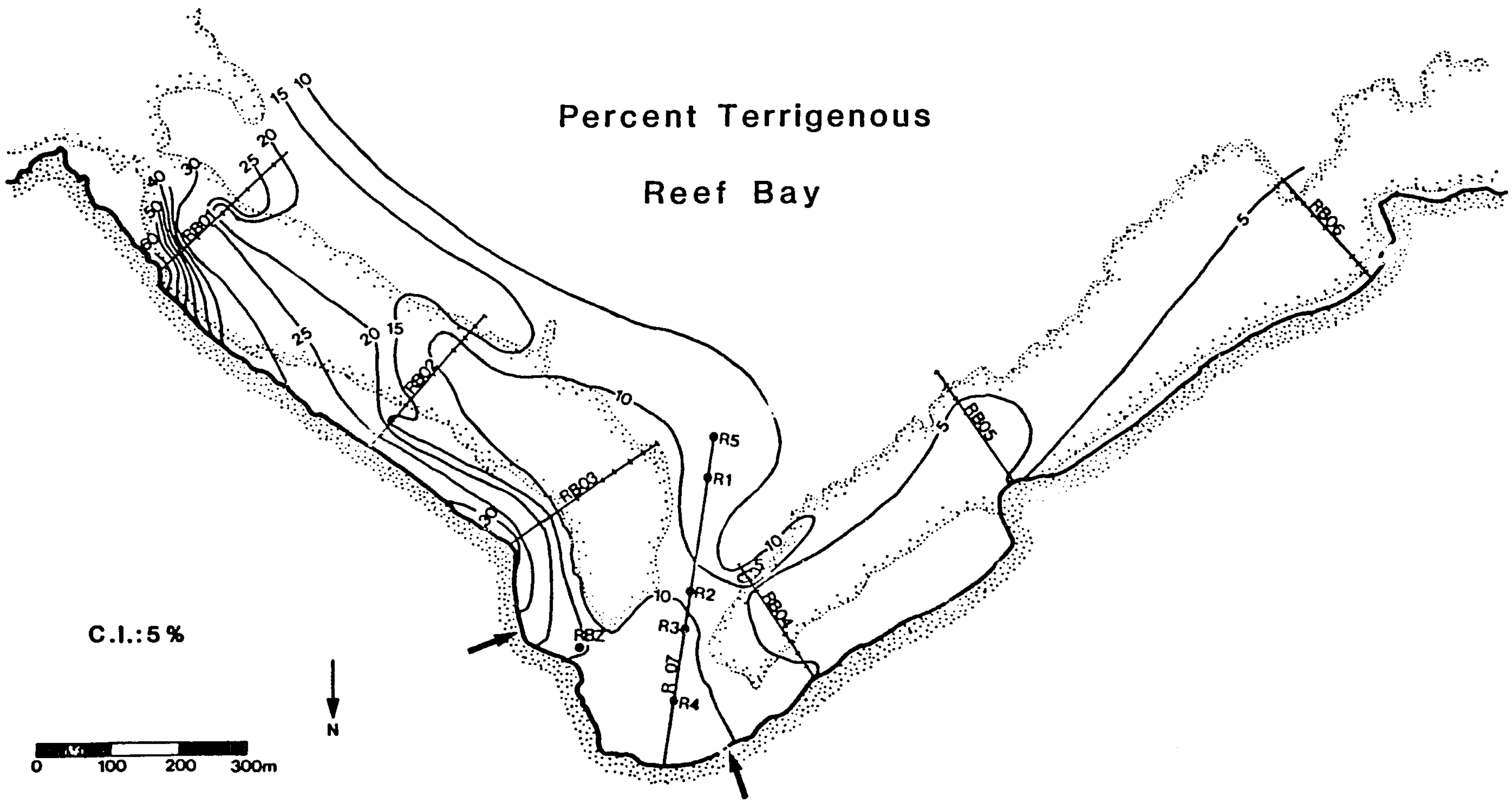


Figure 38. Map of Reef Bay showing the percentages of terrigenous material in the surface sediments.

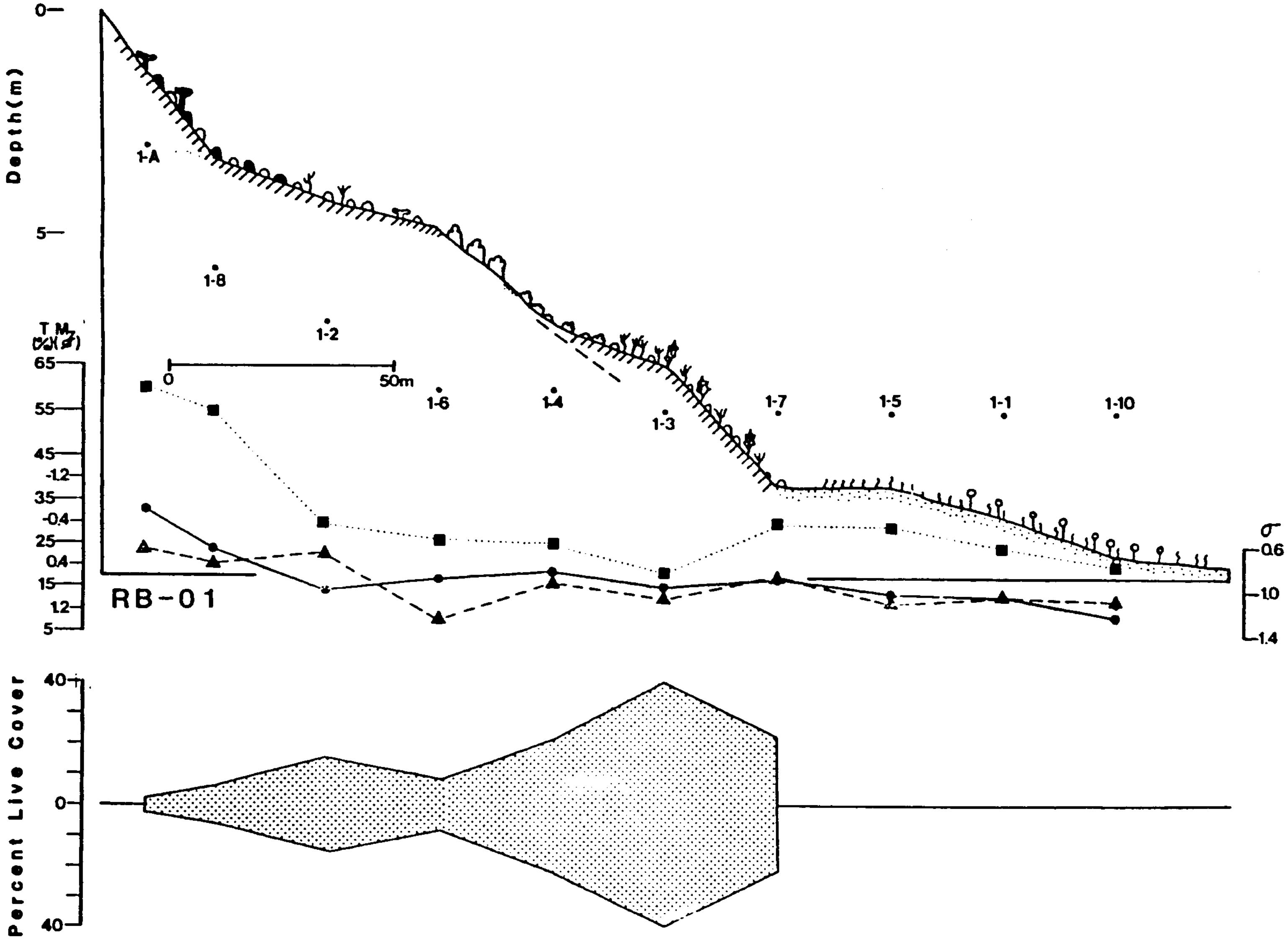


Figure 39. Reef Bay profile RB-01. A symbol key is included in Figure 28.

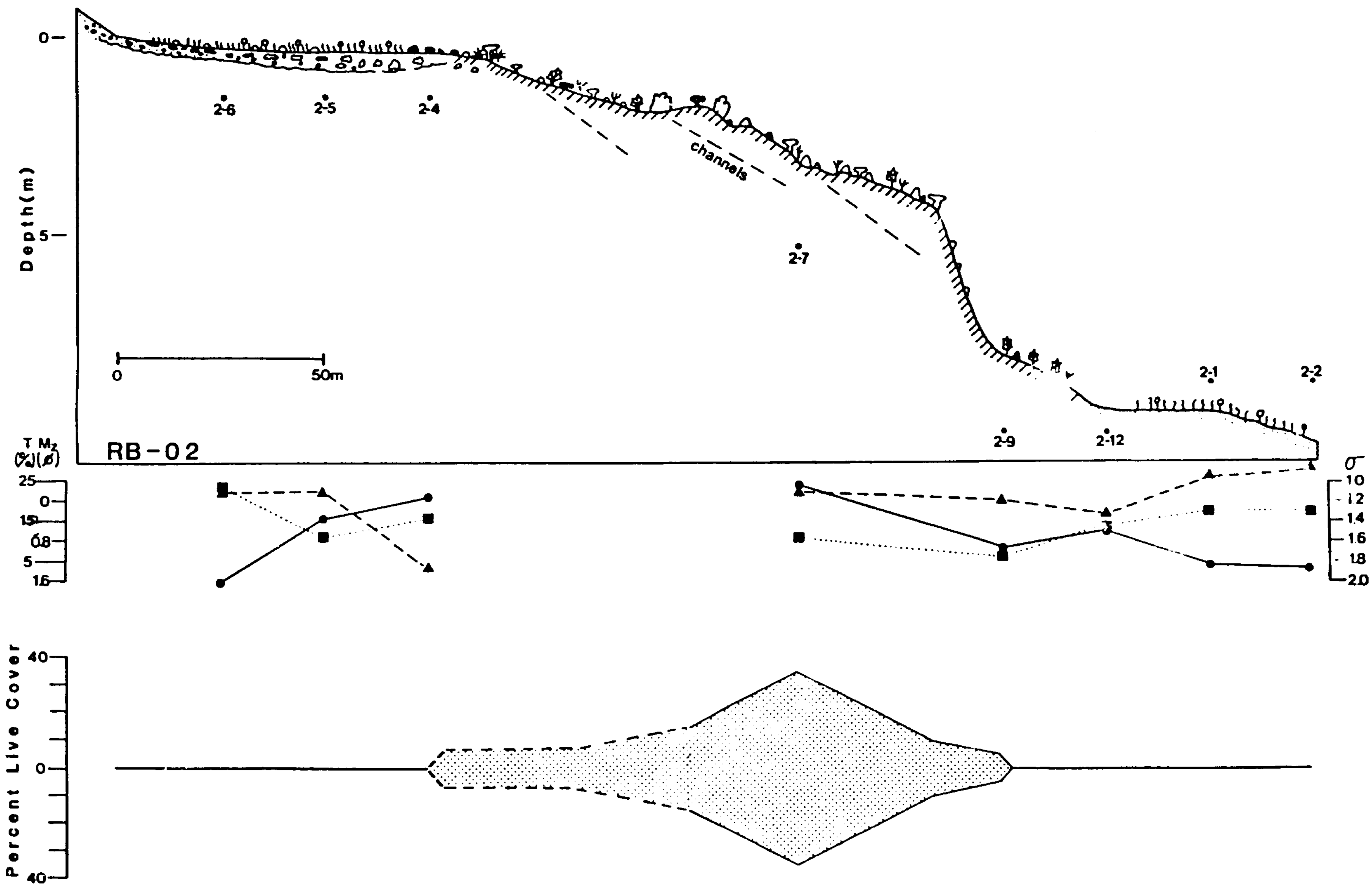


Figure 40. Reef Bay profile RB-02. A symbol key is included in Figure 28.

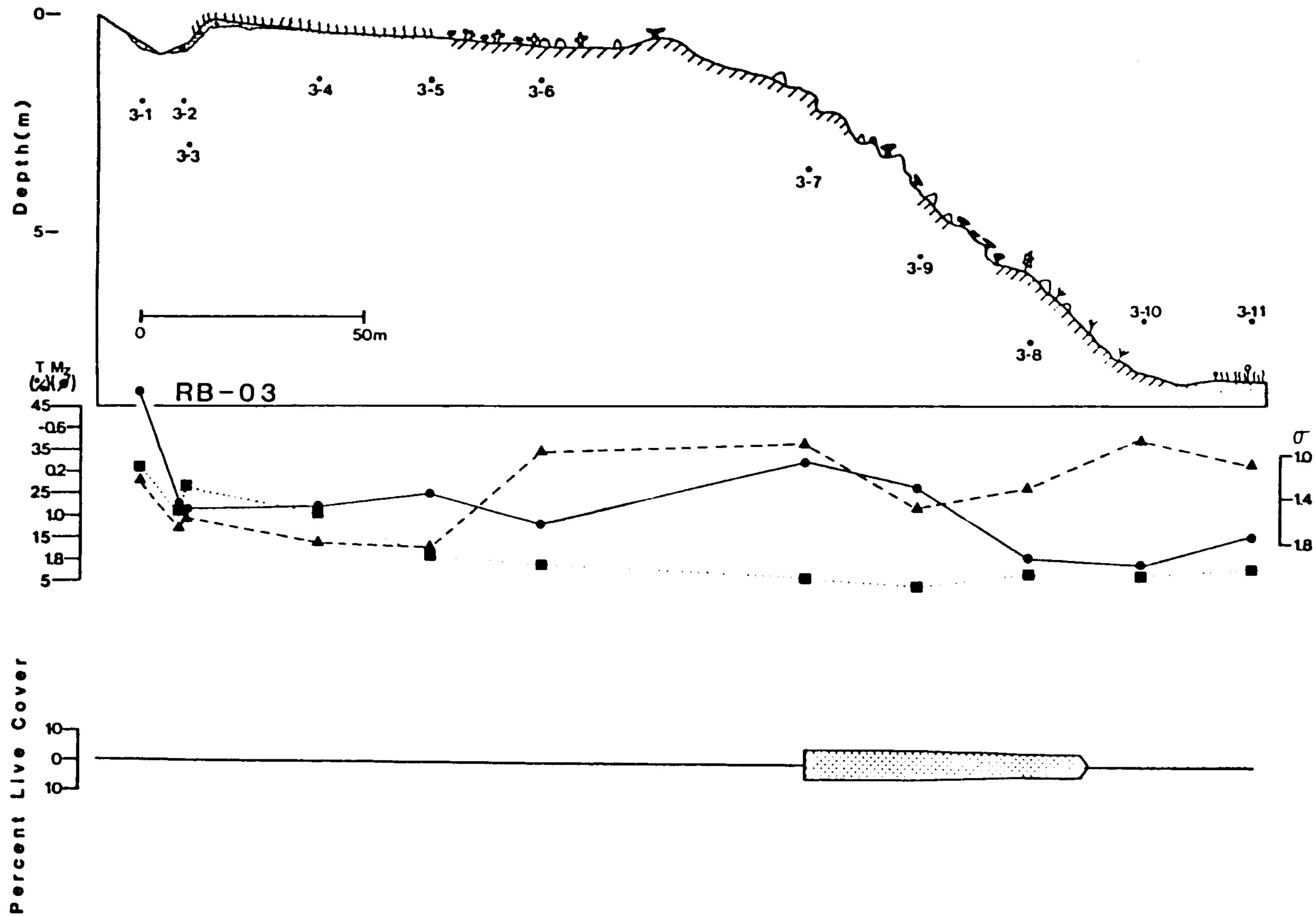


Figure 41. Reef Bay profile RB-03. A symbol key is included in Figure 28.

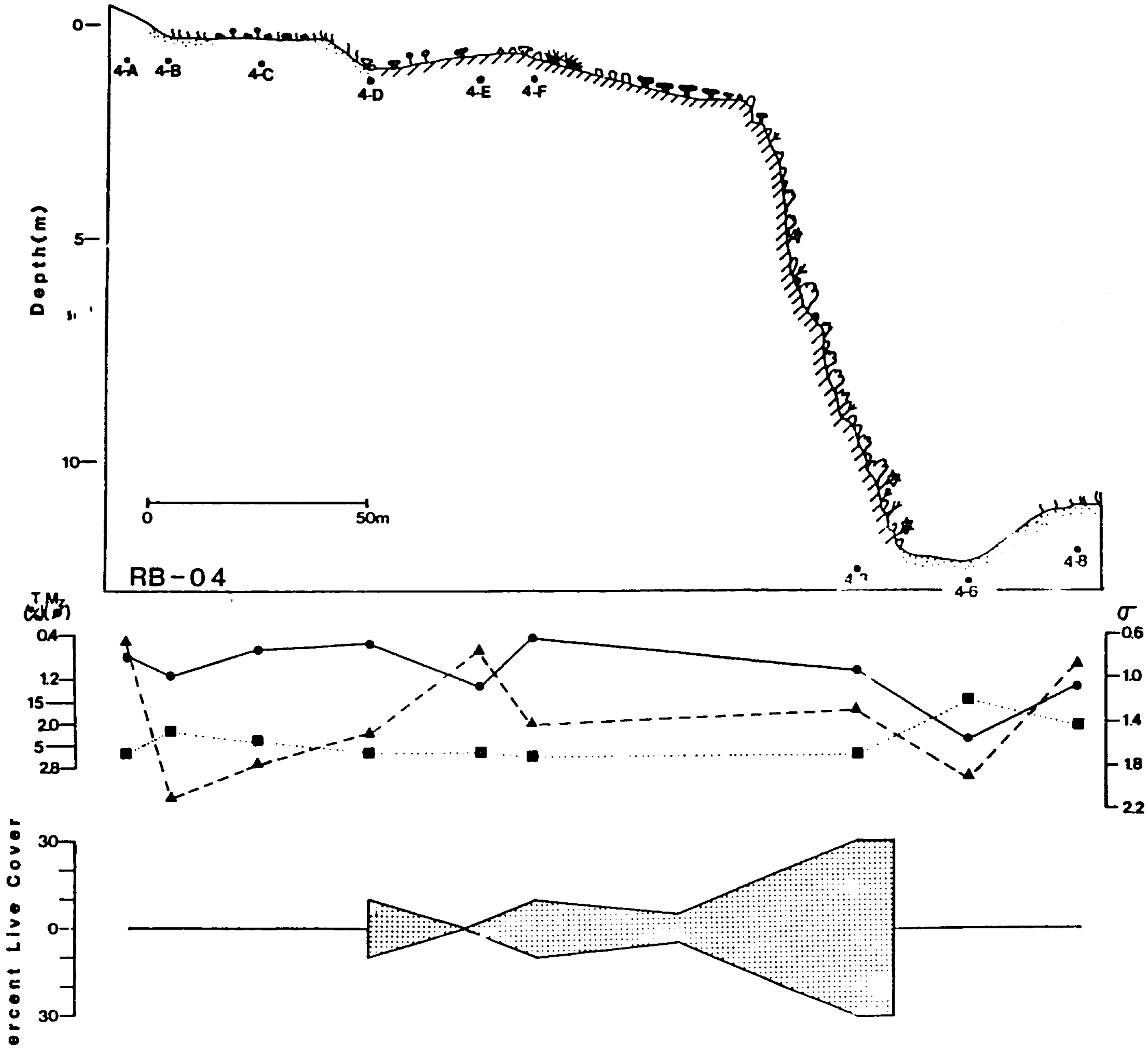


Figure 42. Reef Bay profile RB-04. A symbol key is included in Figure 28.

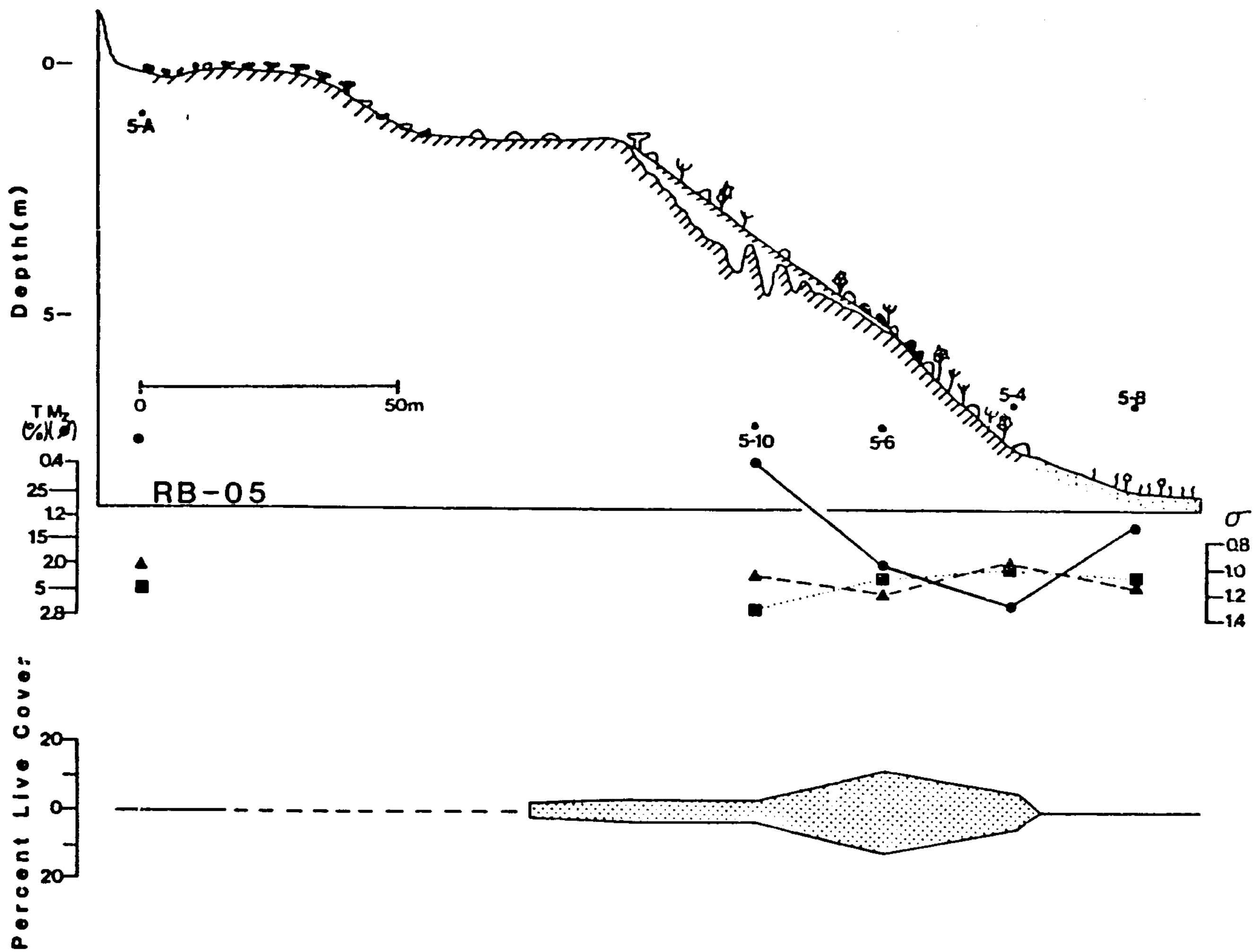


Figure 43. Reef Bay profile RB-05. A symbol key is included in Figure 28.

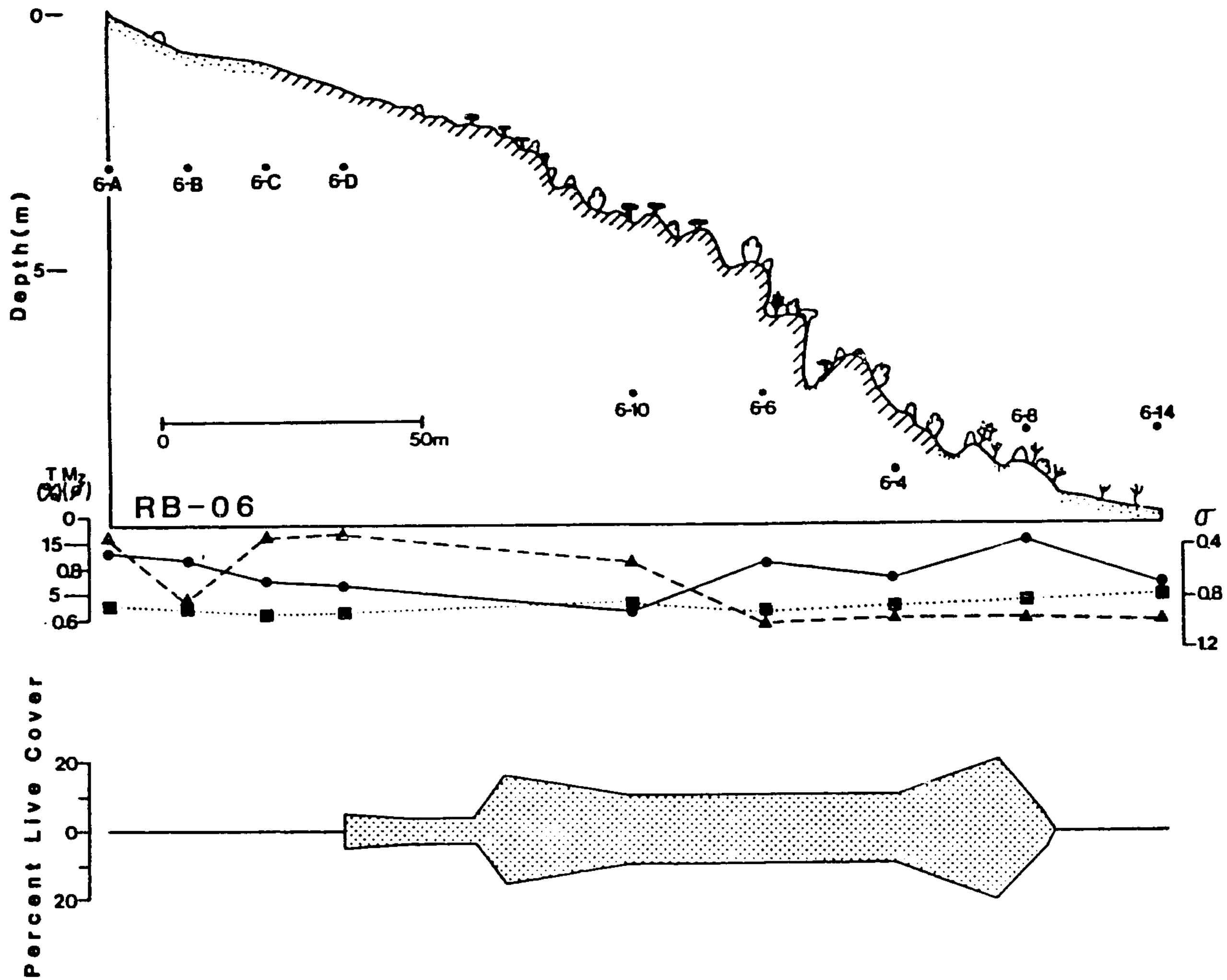


Figure 44. Reef Bay profile RB-06. A symbol key is included in Figure 28.

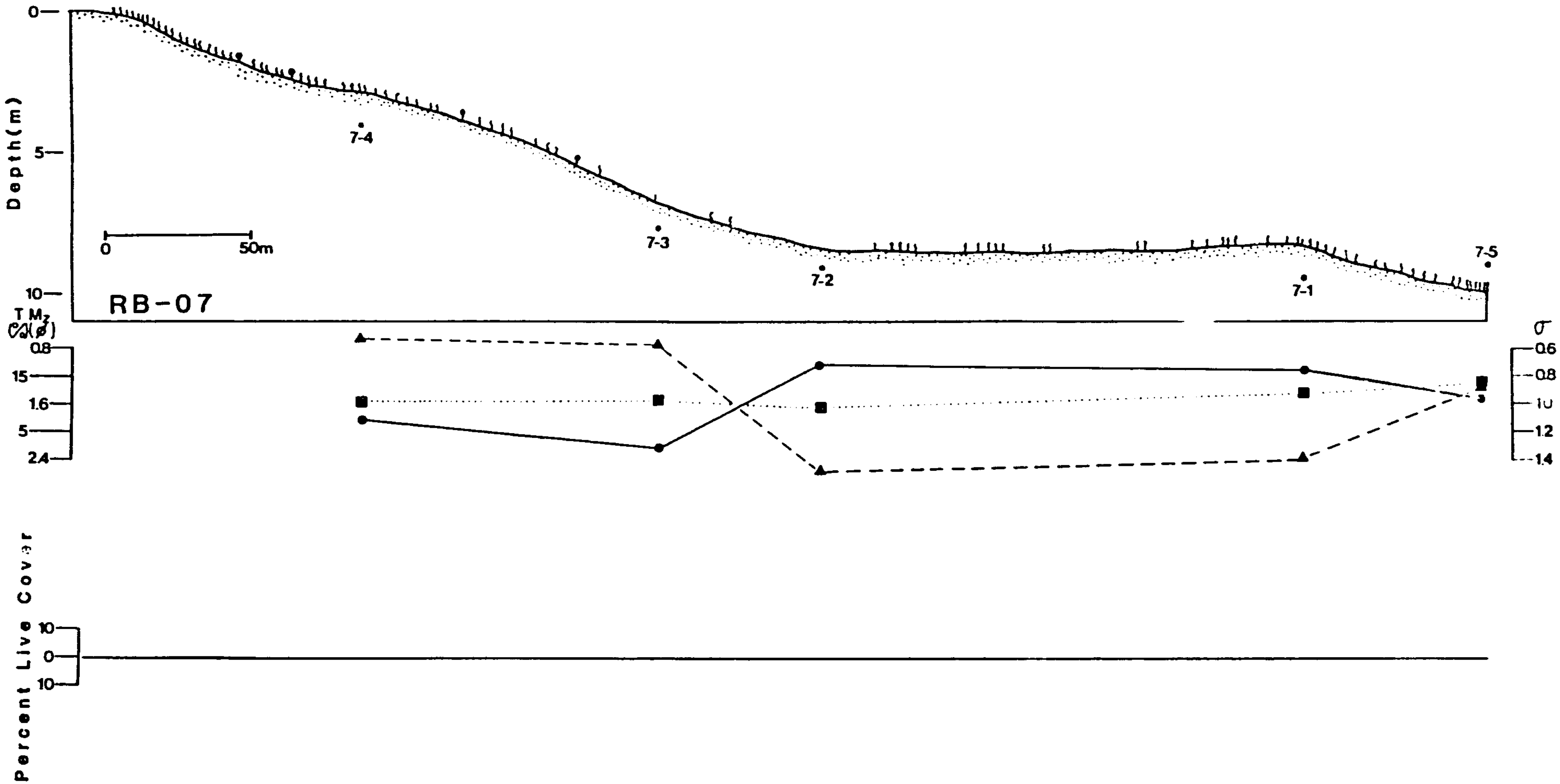


Figure 45. Reef Bay profile RB-07. A symbol key is included in Figure 28.

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.

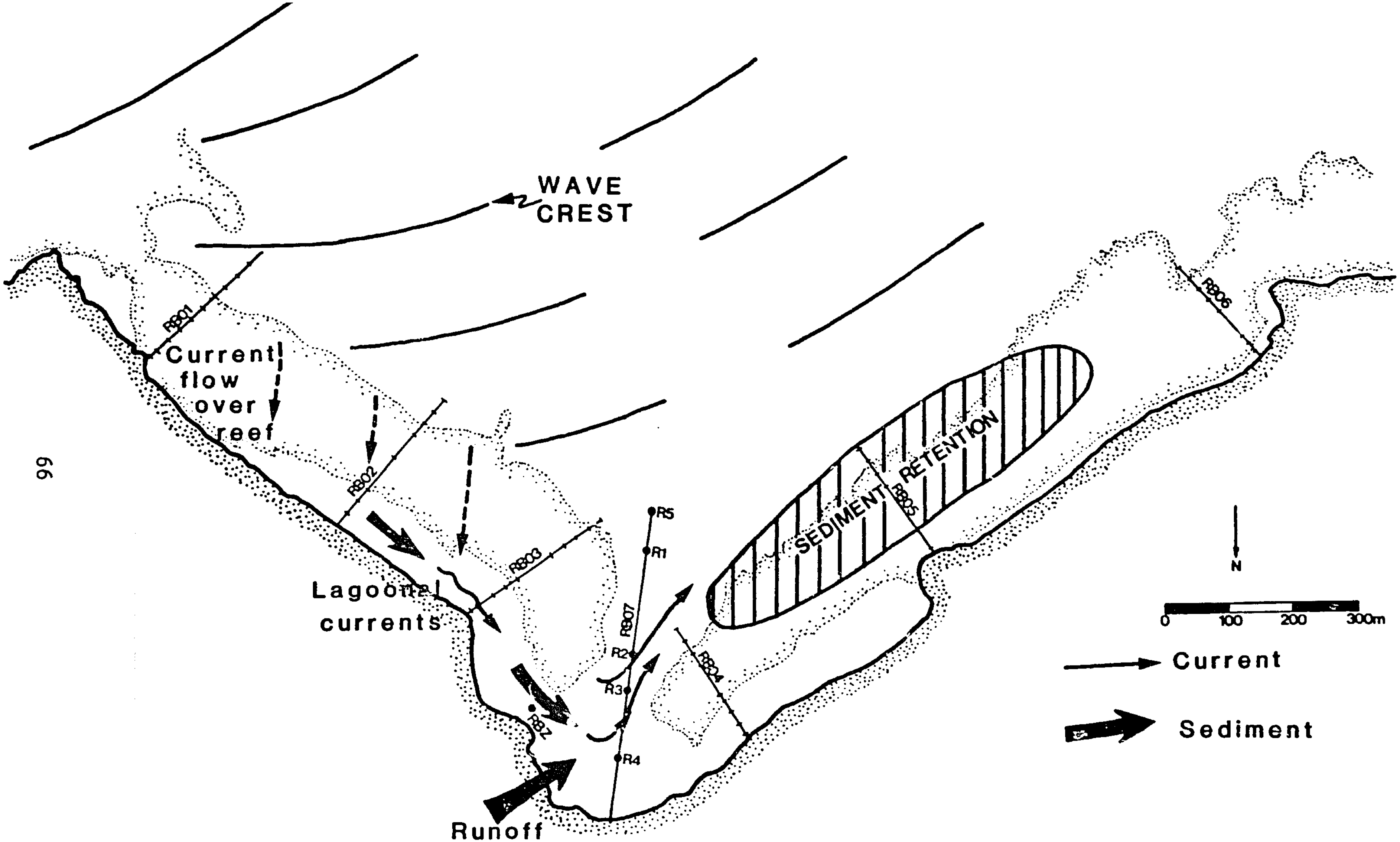


Figure 46. Generalized circulation within Reef Bay. To the east, wind and wave-driven currents carry turbid lagoonal waters toward the bay head. This sediment, along with that derived from runoff, flows toward the western reef face where it is confined by incoming waves. This flow pattern likely accounts 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,

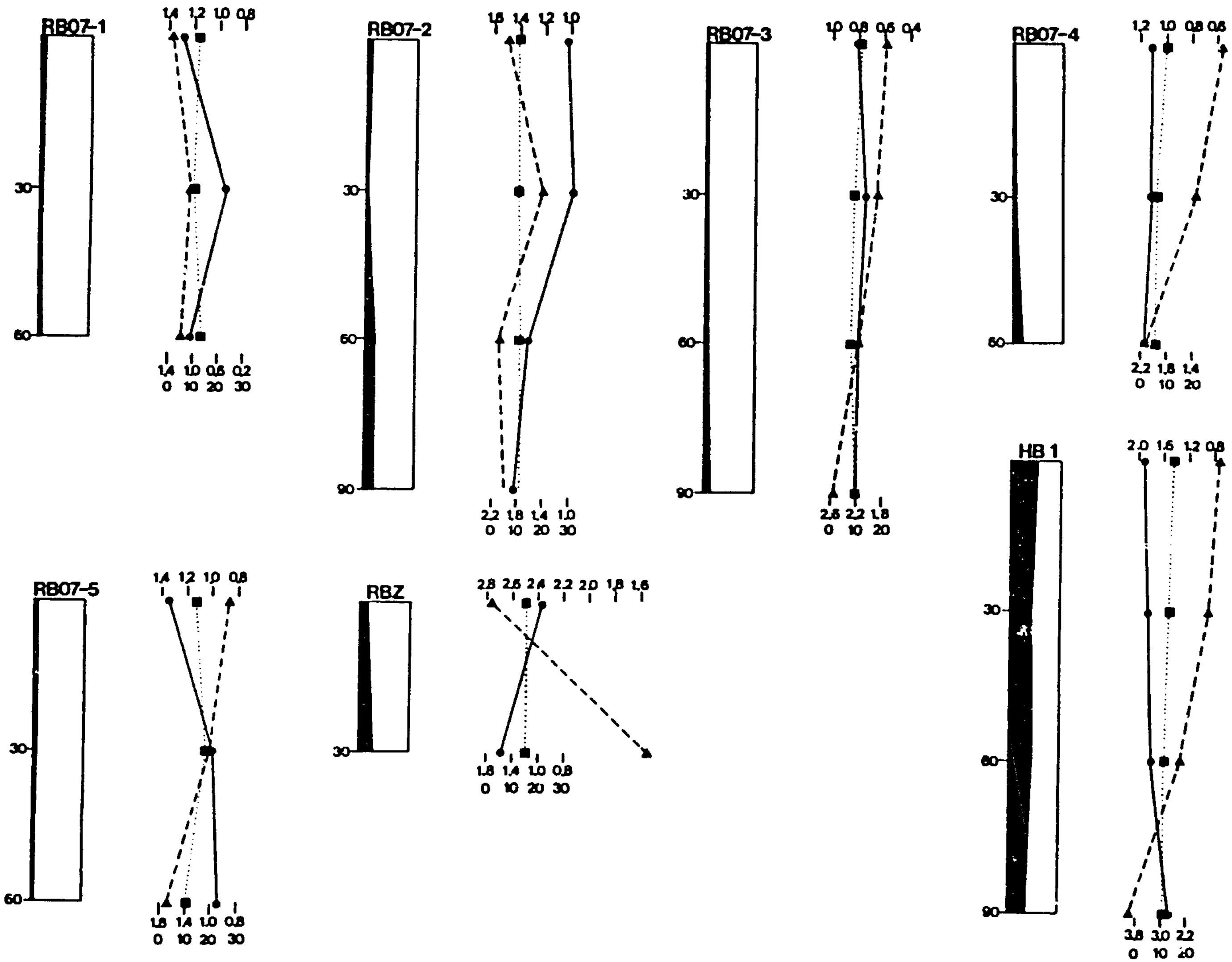


Figure 47. Sediment cores from Reef and Hawksnest Bays. See Figure 48b for key to symbols for core logs.

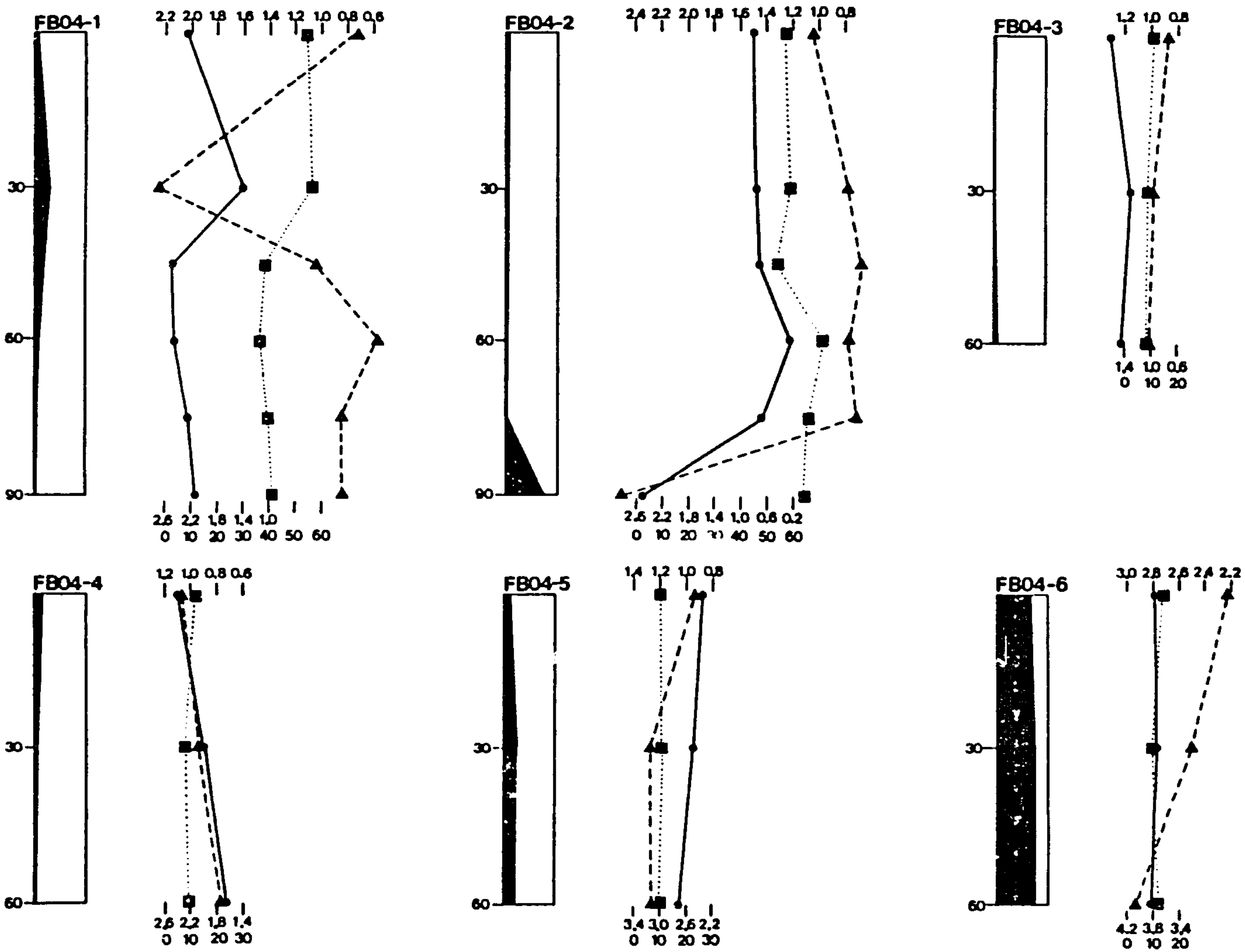


Figure 48a. Sediment cores from Fish Bay. See Figure 48b for key to symbols for core logs.

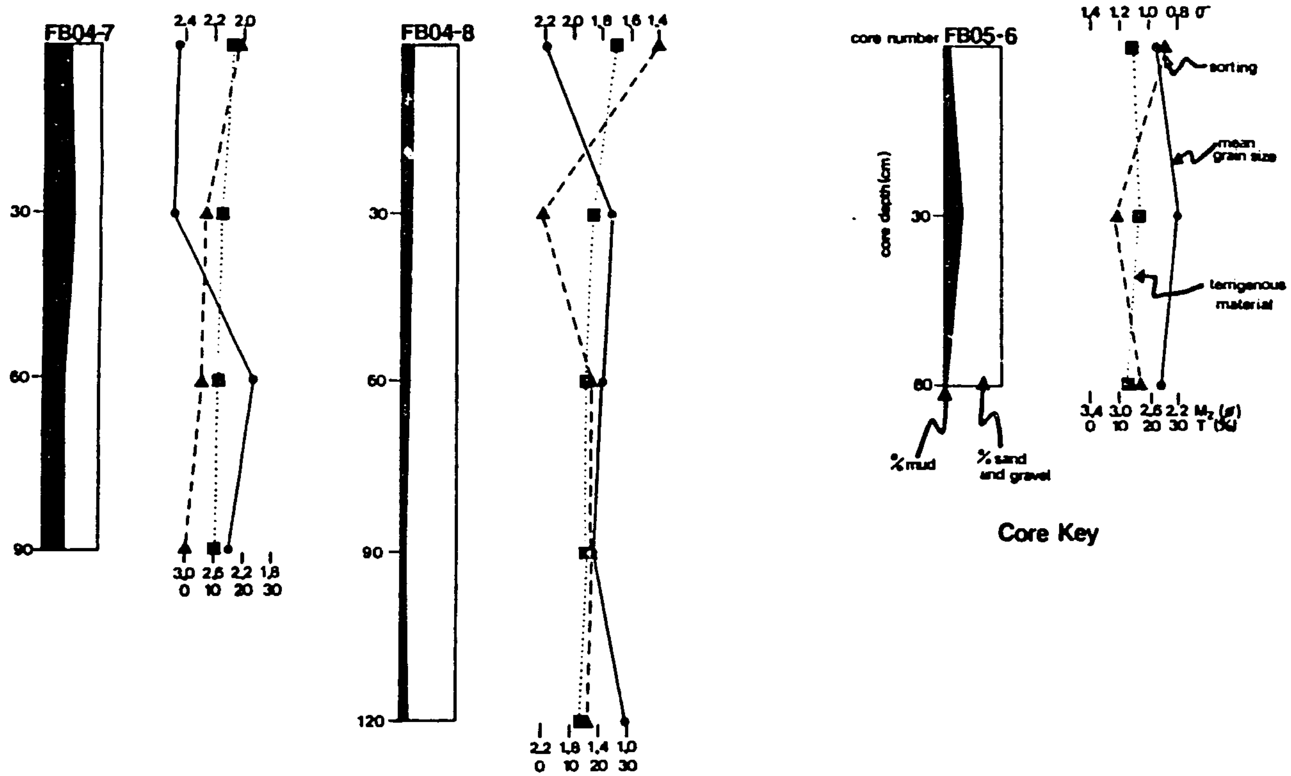
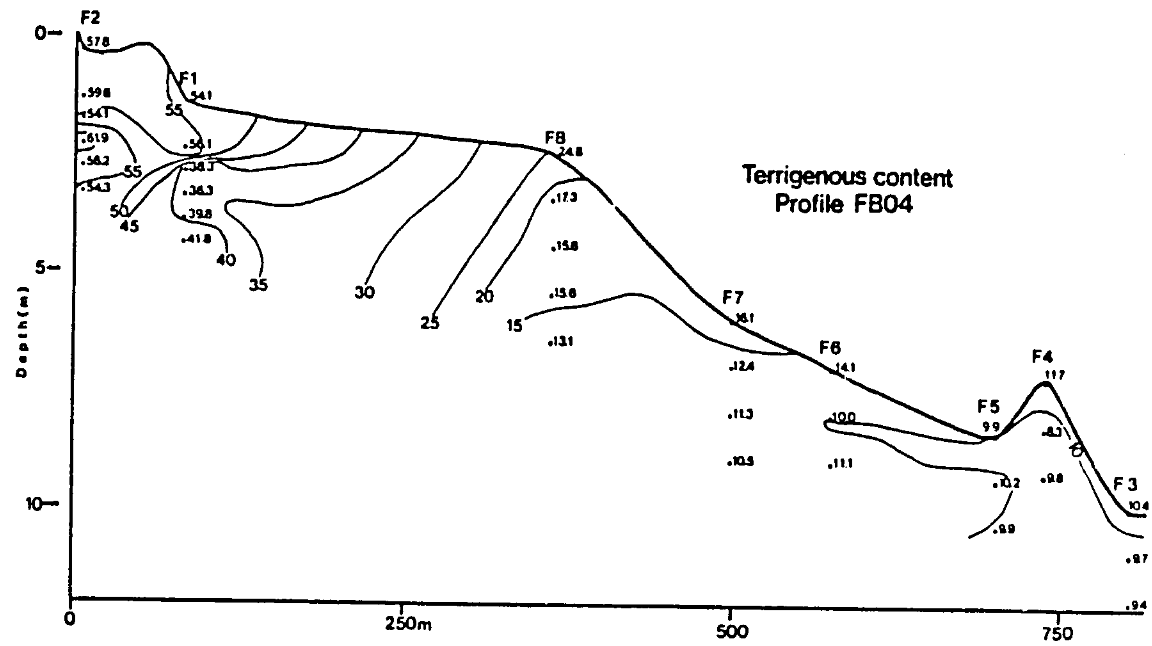


Figure 48b. Sediment cores from Fish Bay (continued) on left. A key to symbols in Figures 47 and 48a is located on the right.

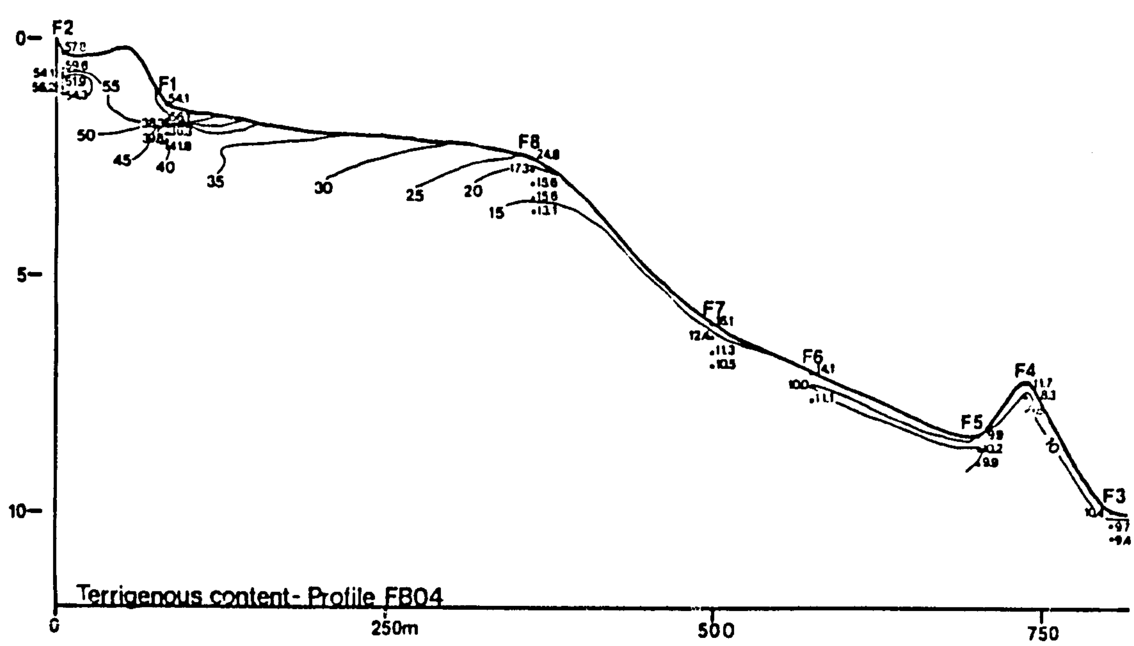


C.I.: 5%

Vertical exaggeration (profile): 35x

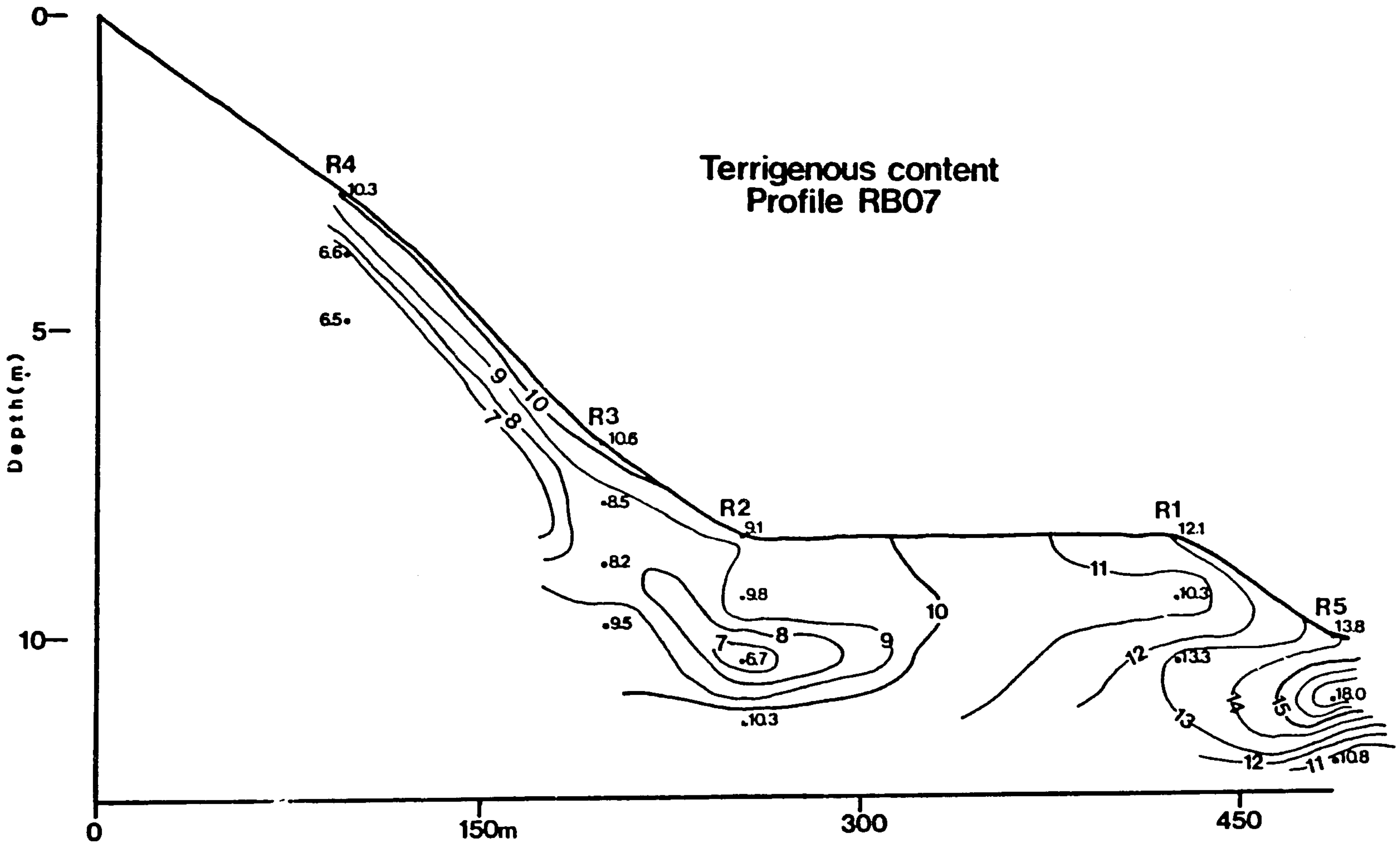
Vertical exaggeration(cores): 116.7x

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

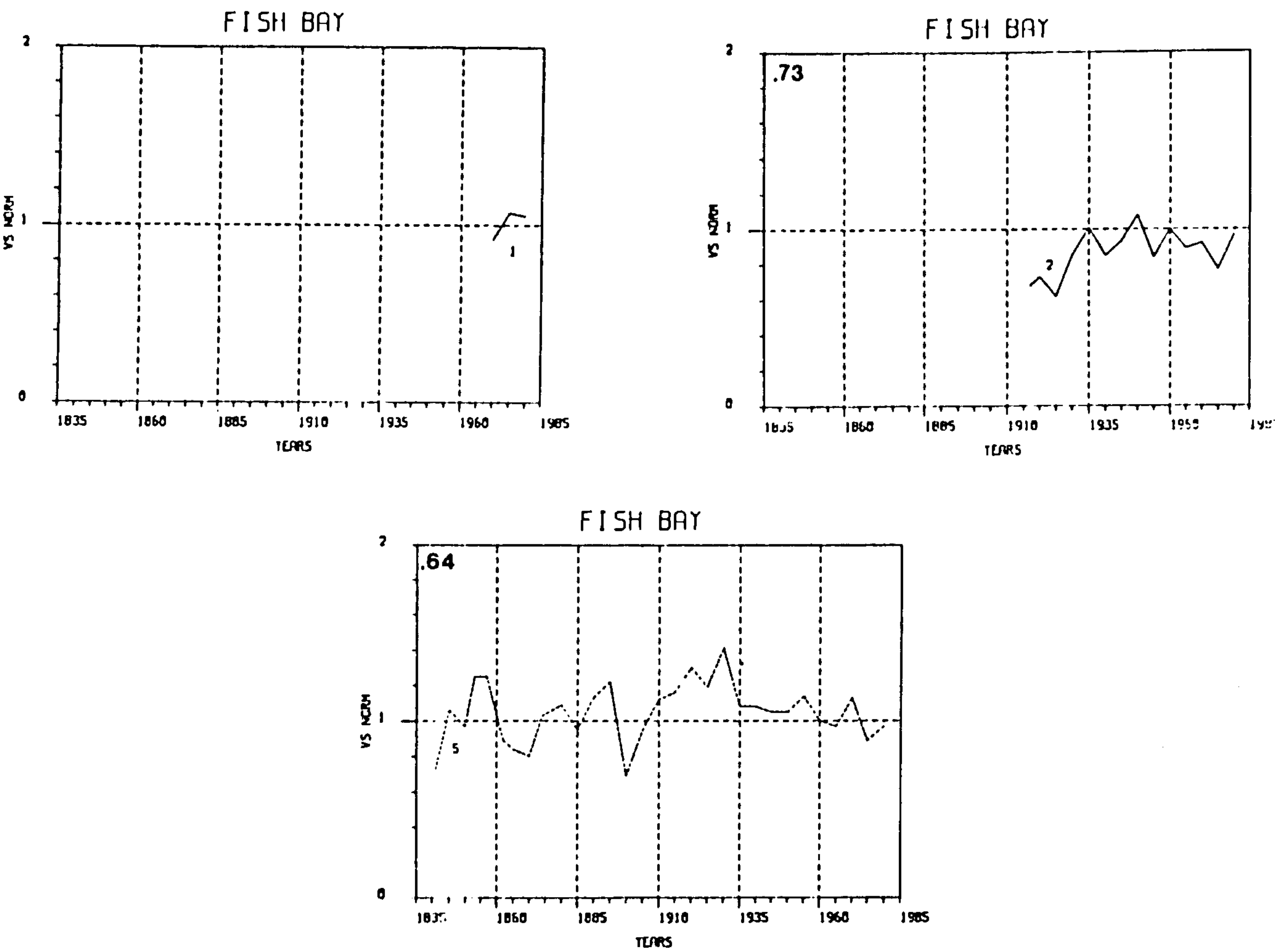


Figure 52. 5-year average growth rate for cores from Fish Bay. All values have been normalized to remove variability between corals due primarily to depth of occurrence. To obtain actual growth rates, multiply values derived from the graph by the number in the upper left-hand corner.

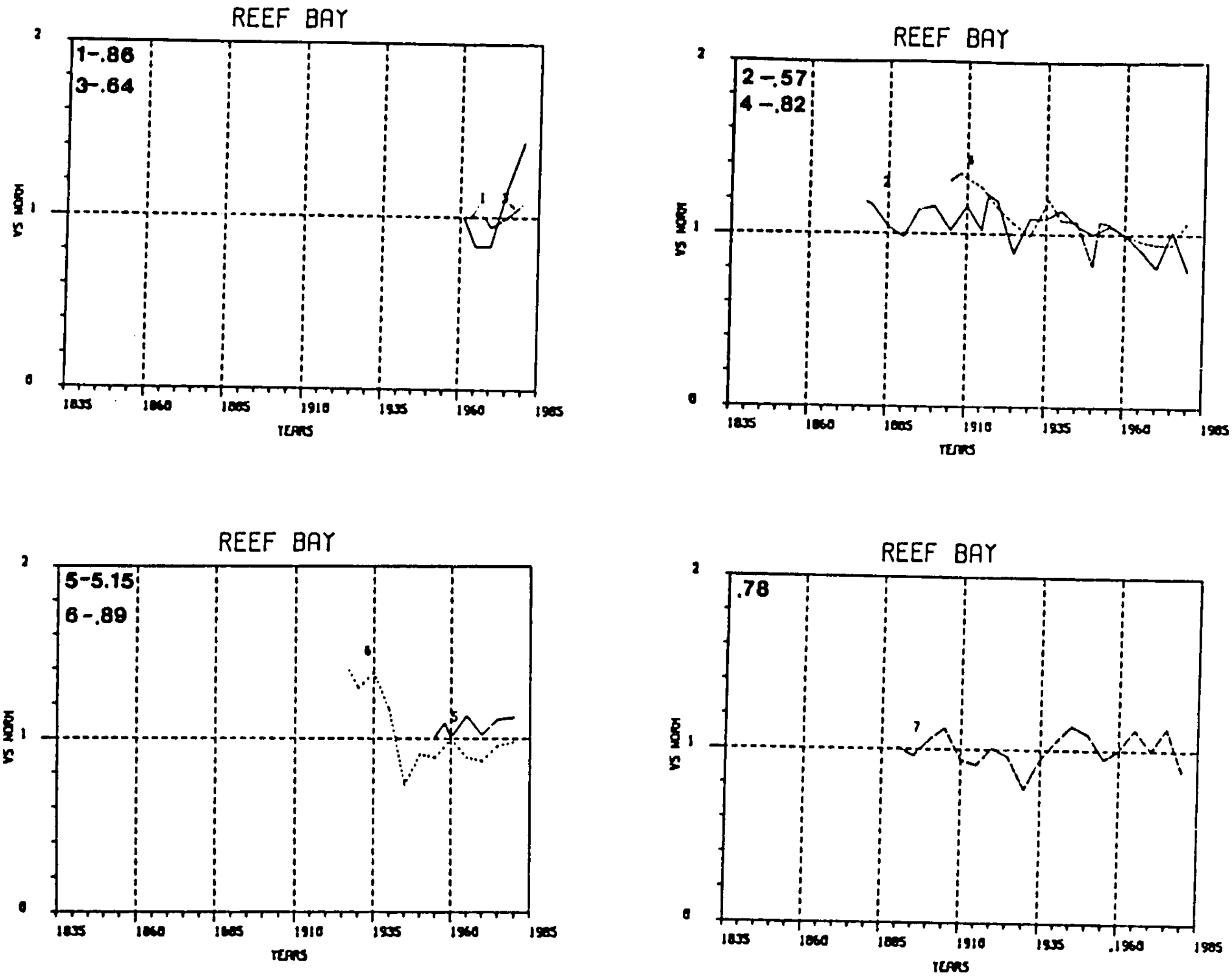


Figure 53. 5-year average growth rate for cores from Reef Bay. All values have been normalized to remove variability between corals due primarily to depth of occurrence. To obtain actual growth rates, multiply values derived from the graph by the number in the upper left-hand corner.

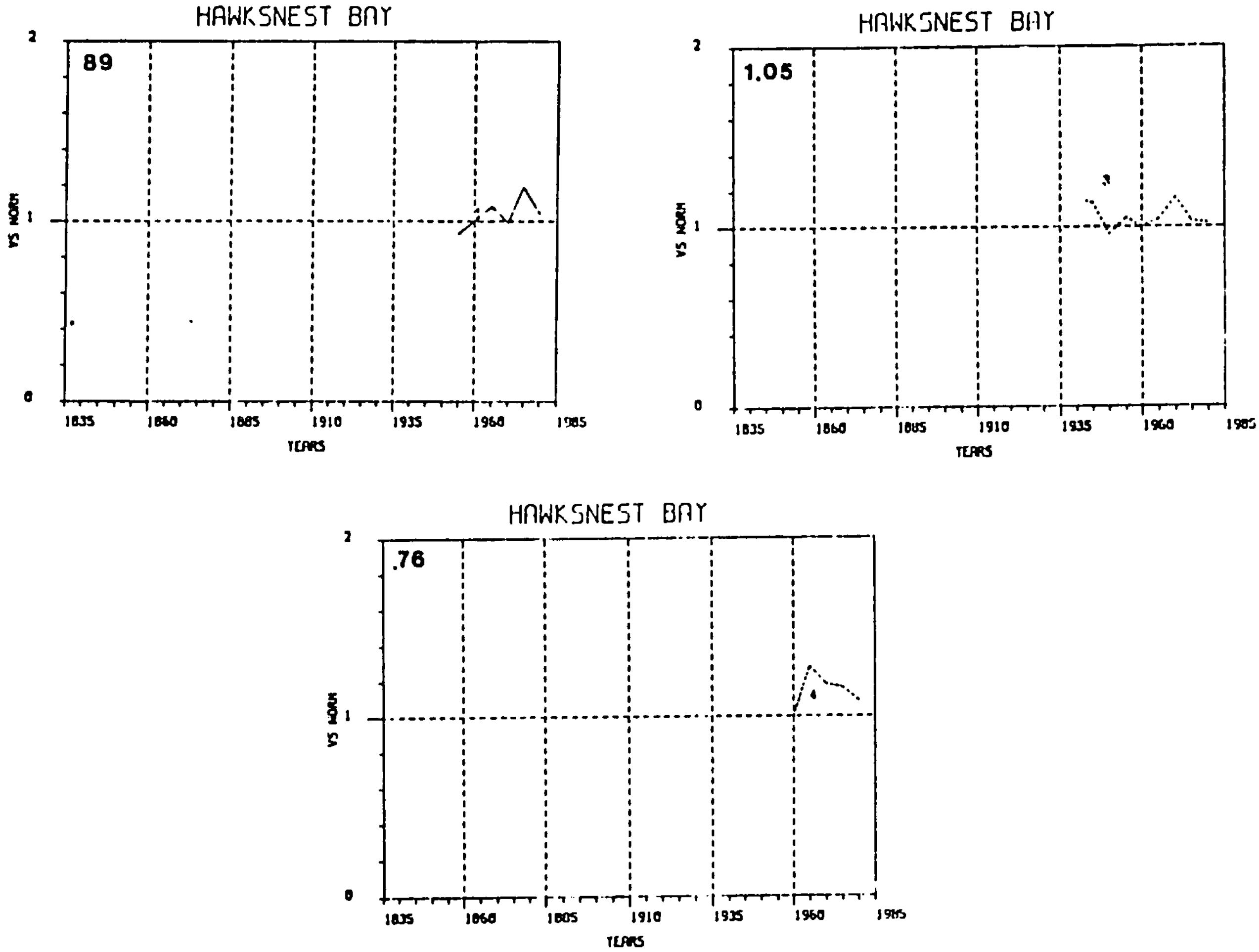


Figure 54. 5-year average growth rate for cores from Hawksnest Bay. All values have been normalized to remove variability between corals due primarily to depth of occurrence. To obtain actual growth rates, multiply values derived from the graph by the number in the upper left-hand corner.

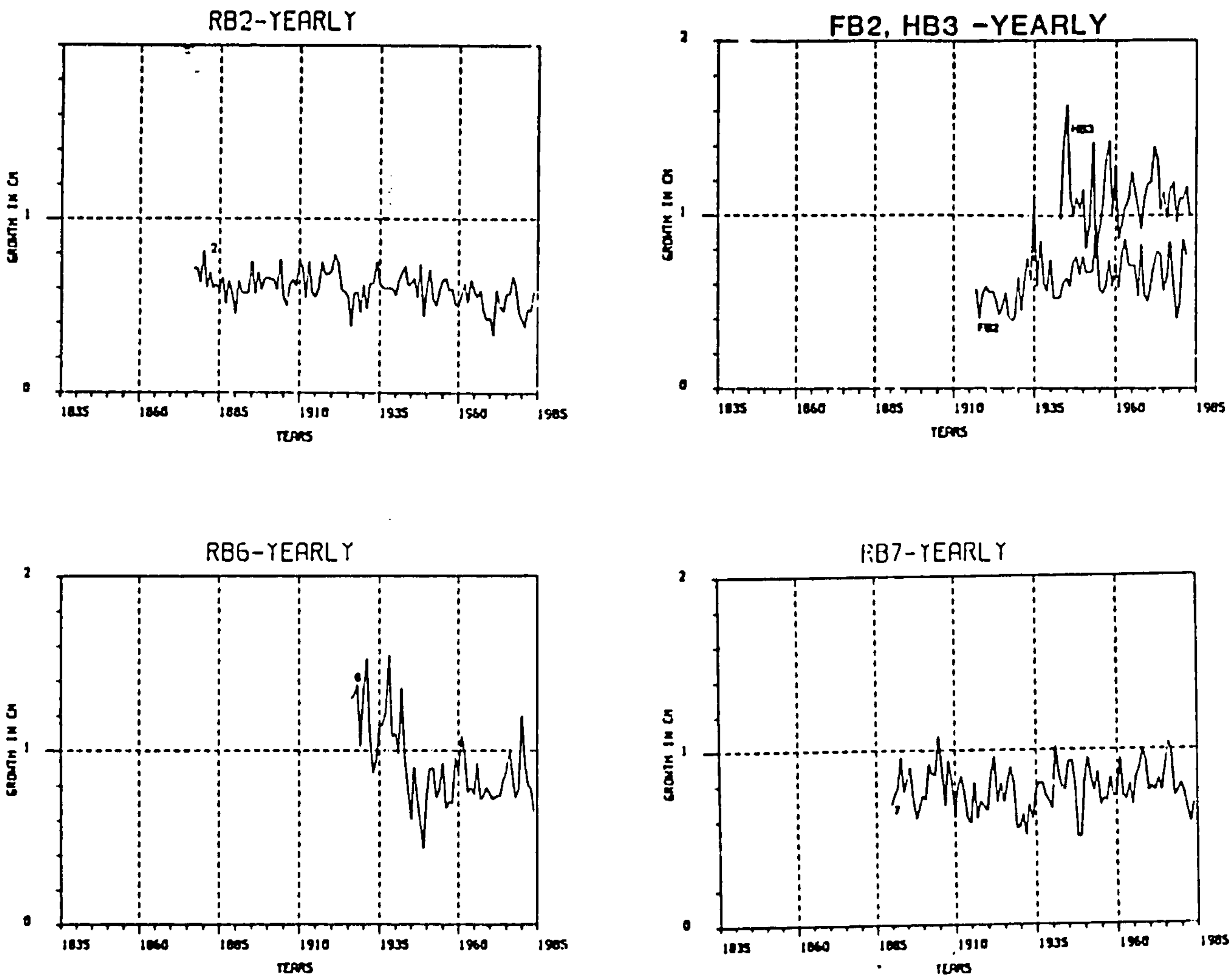


Figure 55. Annual plots of growth rates for selected corals from the three bays.

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).

Results (cores) - Fifteen *Montastrea annularis* 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.

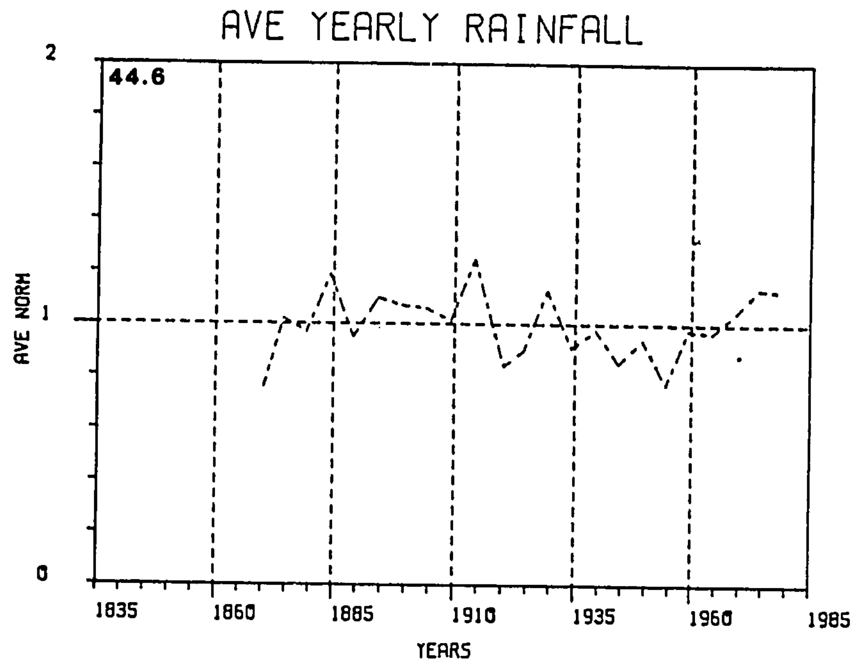


Figure 56. Average yearly rainfall for St. John. Each point is a 5-year average of data provided by the National Park Service on St. John. Data are normalized in the same fashion as for coral growth. To obtain actual rainfall, multiply values derived from the graph by the number in the upper left-hand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

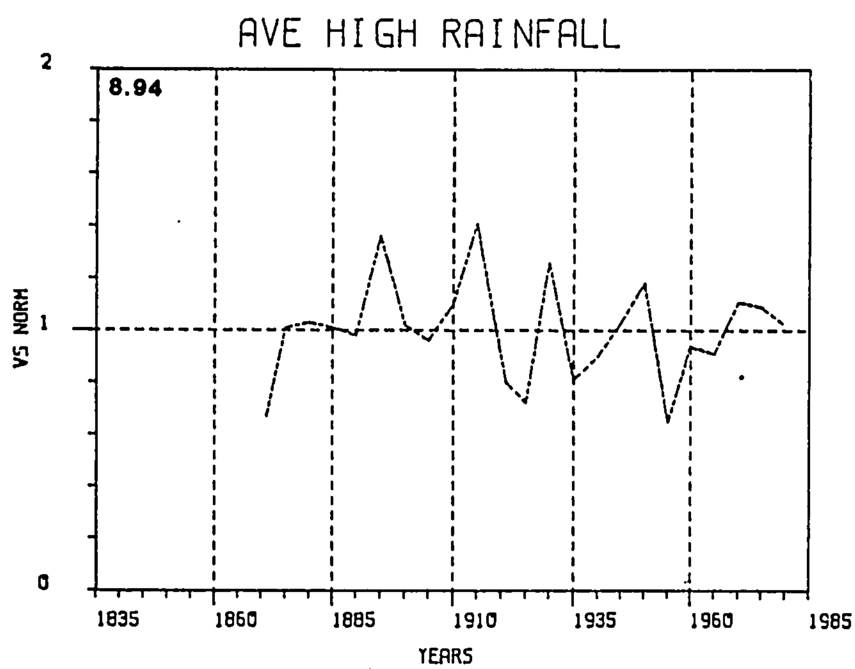


Figure 57. Maximum yearly rainfall for St. John. The maximum monthly rainfall was averaged over five-year periods. Data are normalized in the same fashion as for coral growth. To obtain actual rainfall, multiply values derived from the graph by the number in the upper left-hand corner. Data provided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

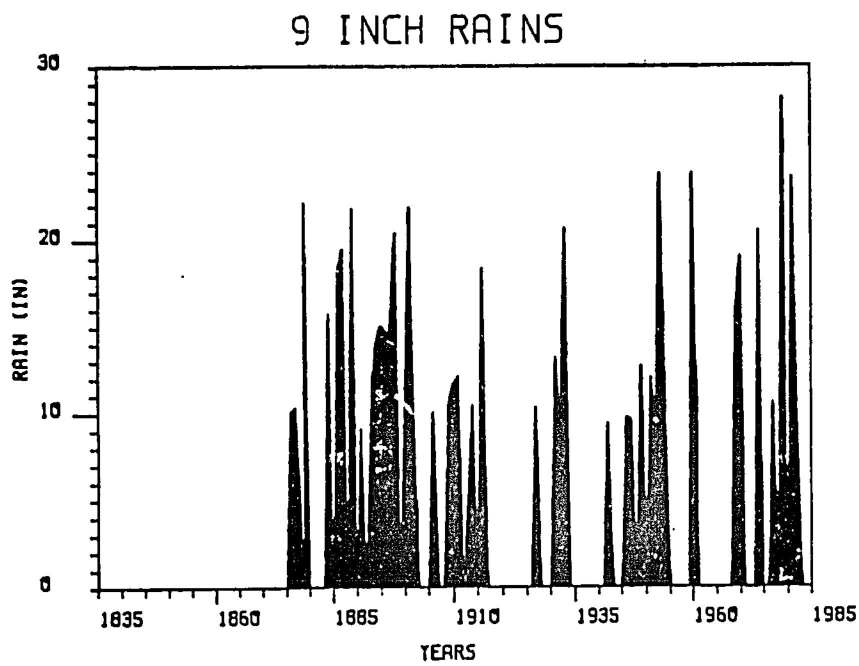


Figure 58. Graph displaying amount of annual 9" rainfall. The value reported is the sum of all monthly rains equal to or exceeding 9".

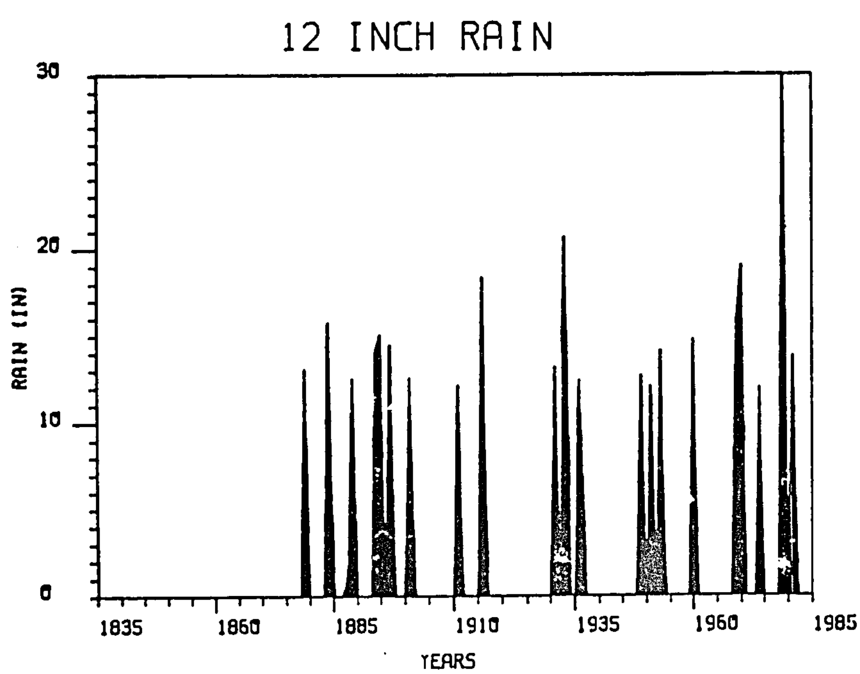


Figure 59. Graph displaying amount of annual 12" rainfall. The value reported is the sum of all monthly rains equal to or exceeding 12".

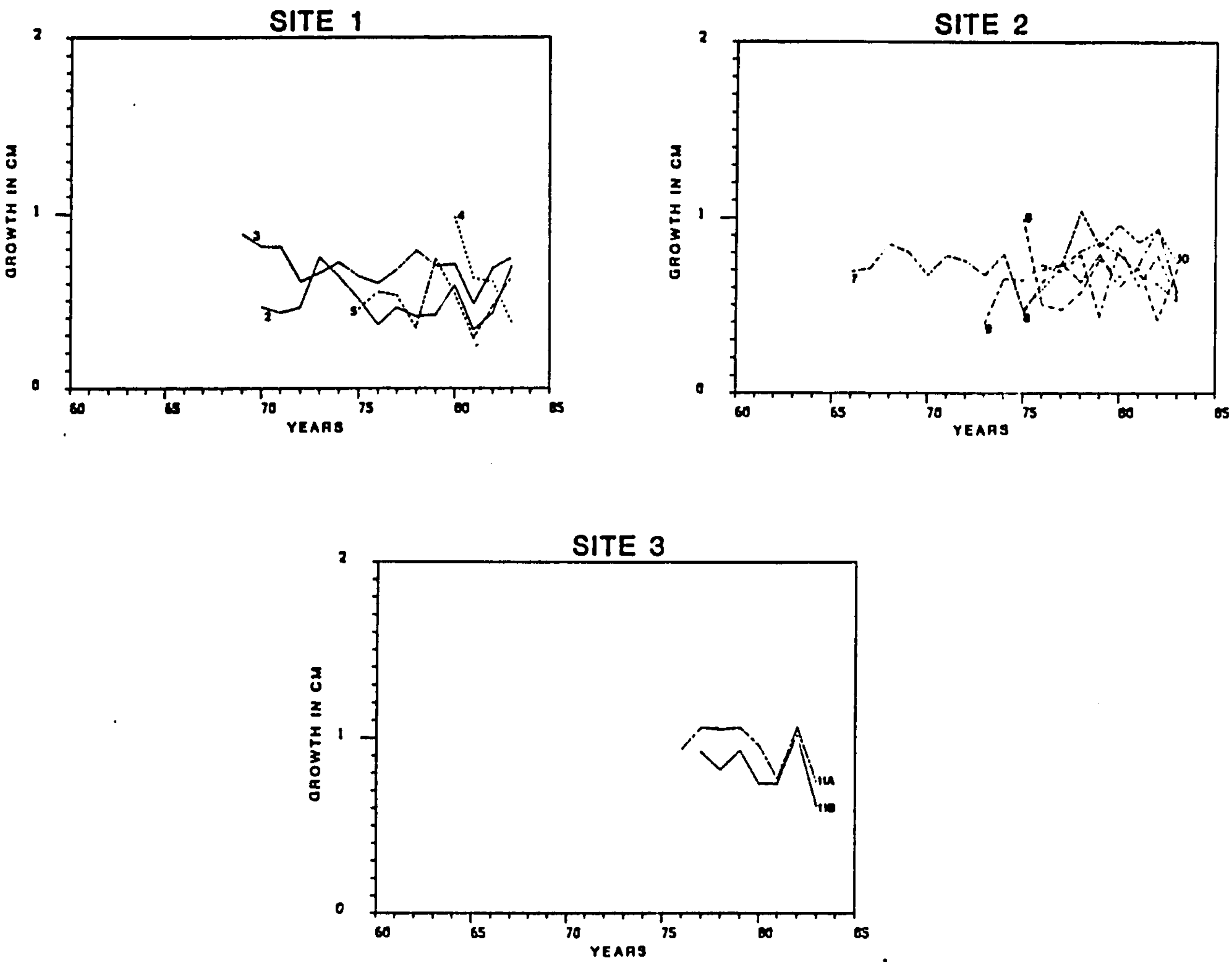


Figure 60. Annual growth rates for small coral heads collected from three sample sites in Hawksnest Bay (for sample-site locations, see Figure 22).

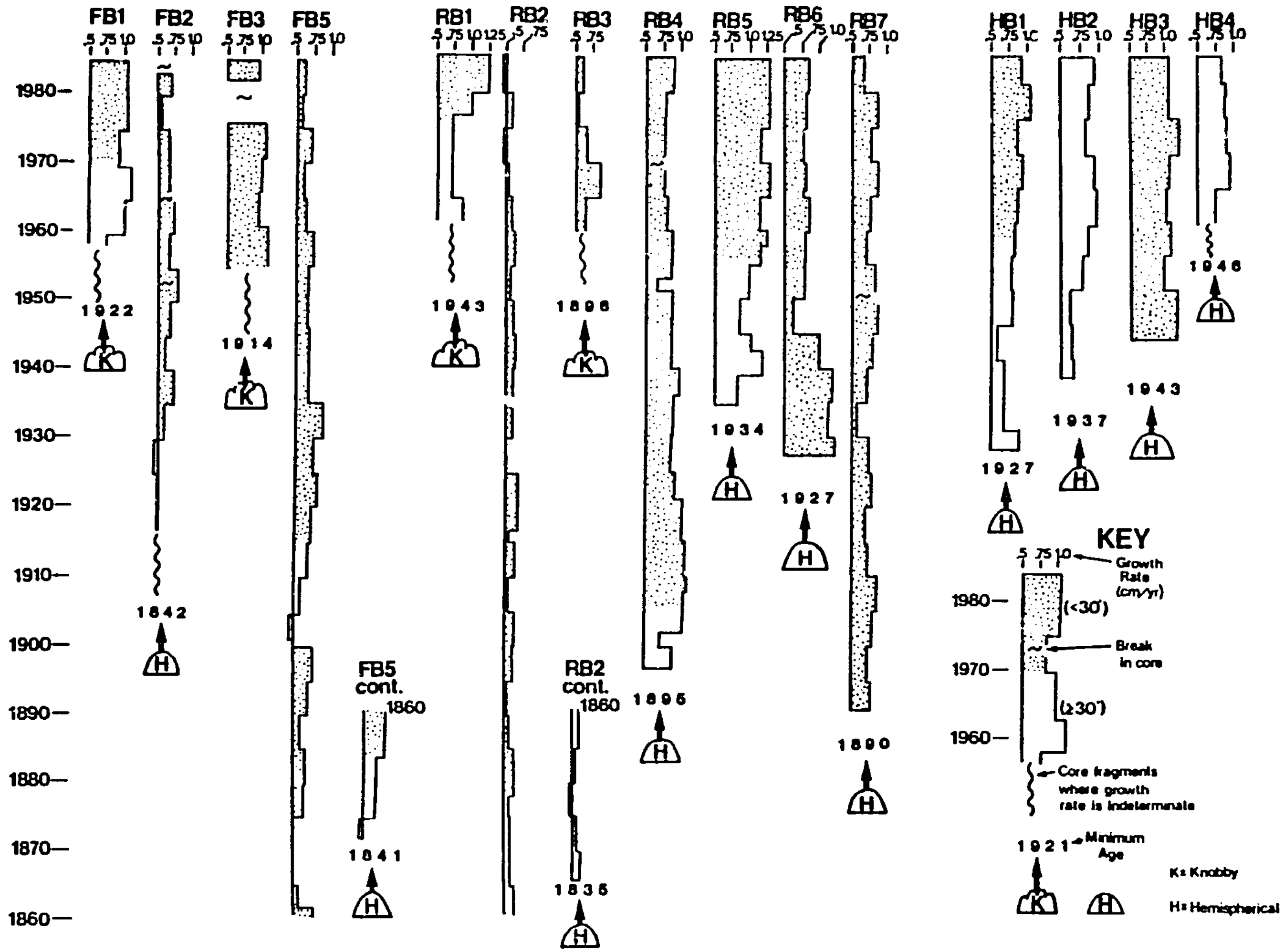


Figure 61. Summary of annual growth data from coral cores in the three bays on St. John. Within 5-year periods, growth rates are grouped in intervals between 0-0.5, 0.5-0.75, 0.75-1.0 and >1.0 cm/yr. Variations in the direction of coral growth relative to the axis of the core are shown by the solid white 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.

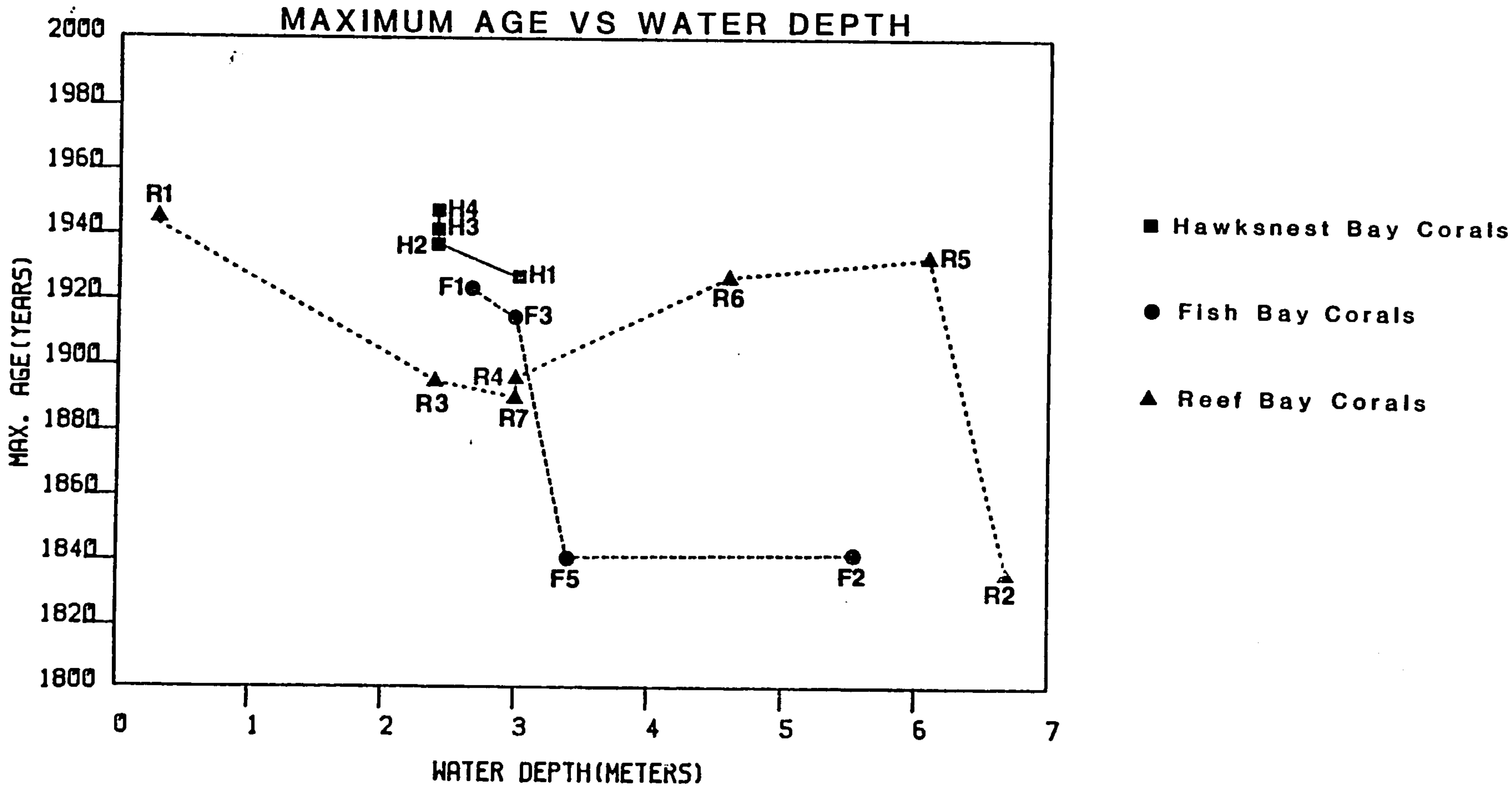


Figure 62. Graph of maximum coral age versus water depth in the St. John cores. Note the trend toward increasing age with depth (and away from sources of runoff).

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.

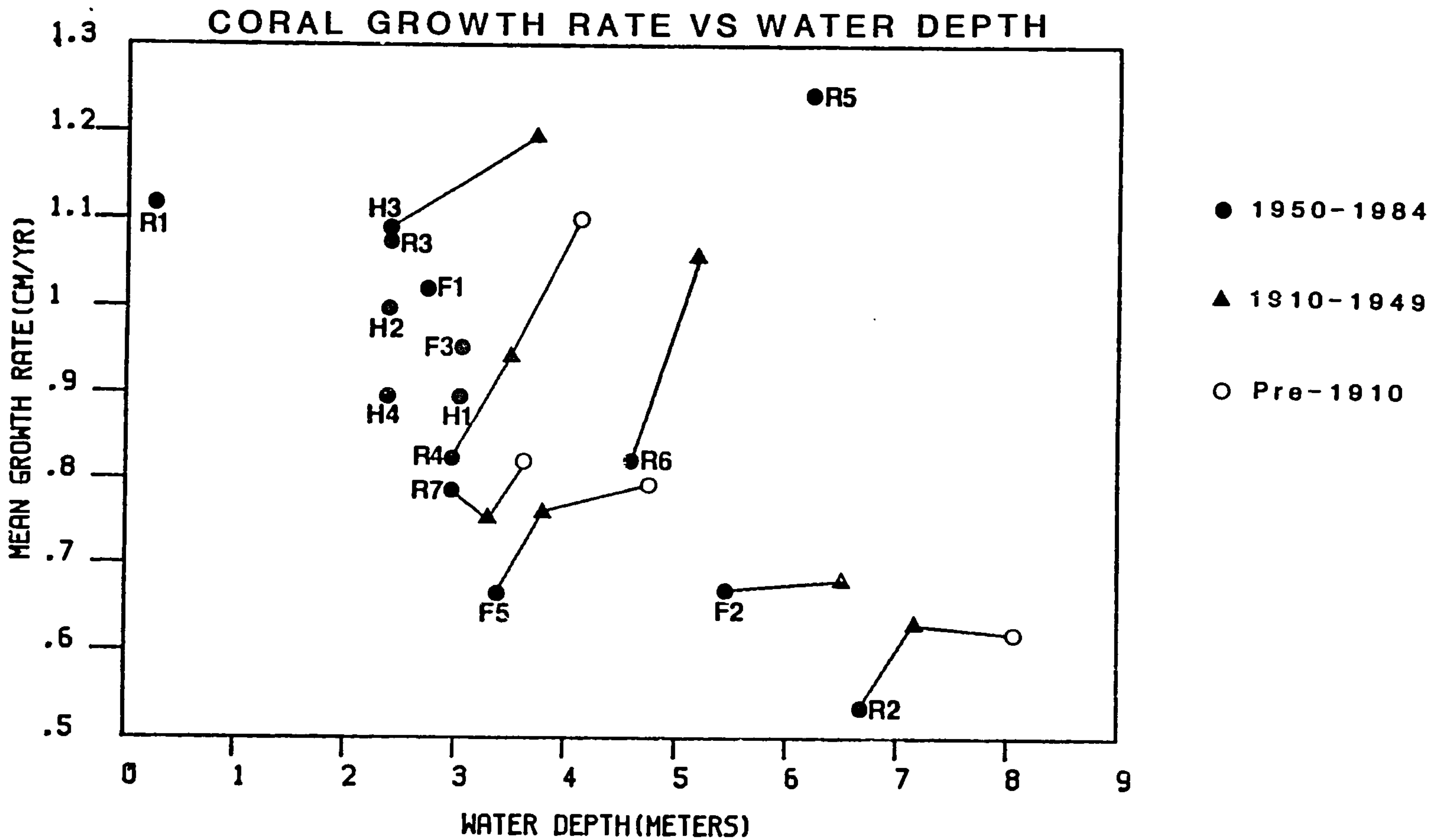


Figure 63. Graph of coral-growth rate vs. depth in the St. John cores. The dashed line describes the range of growth rates for corals from simlar depths at Cane Bay on St. Croix (Hubbard and Scaturo, 1985). Changes in average-growth rate during the three development periods are also shown.

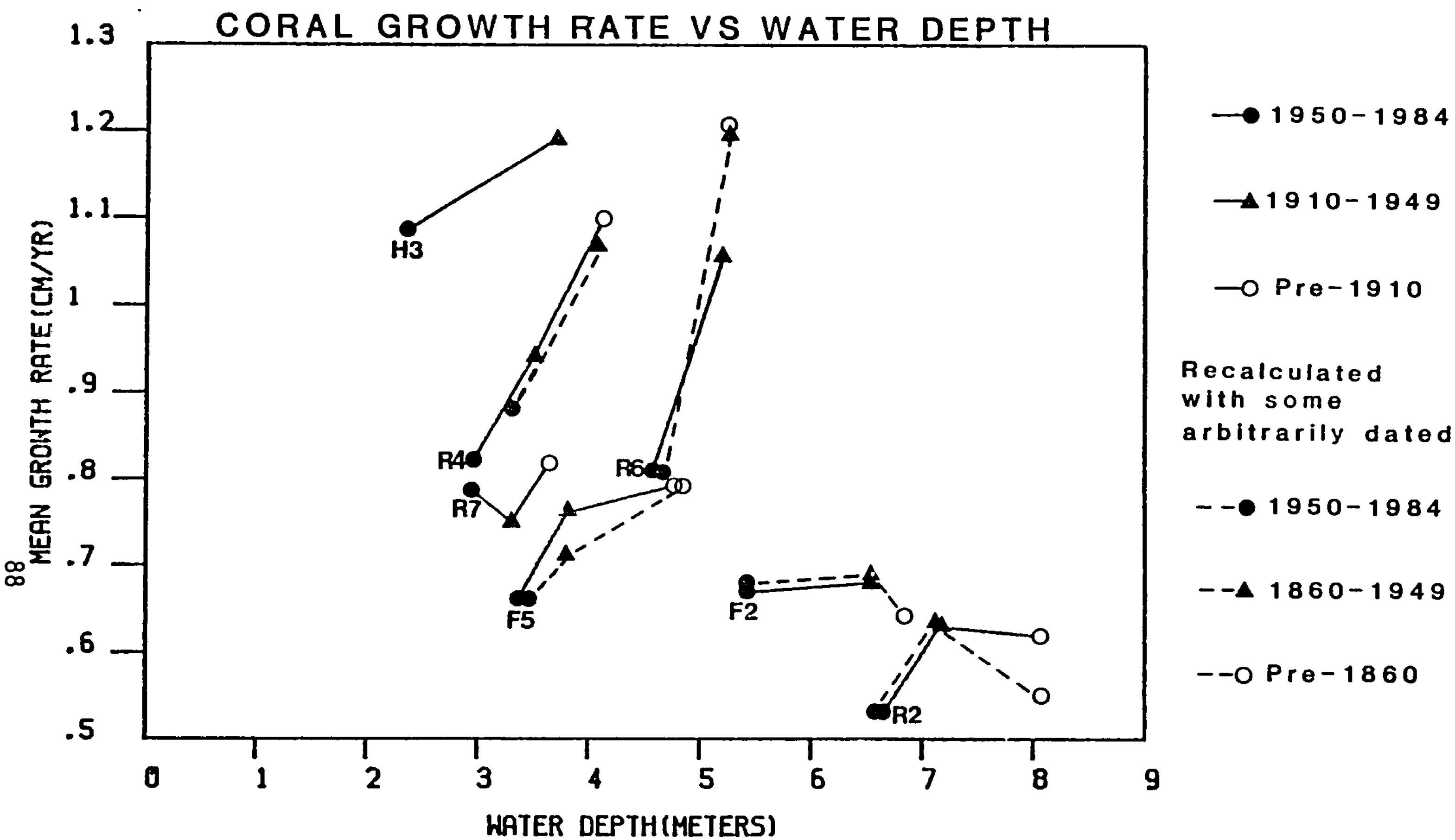


Figure 64. Graph of coral-growth rate vs. depth in the St. John cores. Points connected by solid lines are taken from Figure 63. Points connected by a dashed line are those based on different boundaries between the three development periods. Note that despite changed temporal boundaries, the trends remain 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, <u>at the present level of development.</u>

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 devel'ment 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 quantitative 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 near the organisms 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.

REFERENCES CITED

Beets, J., Lewand, L. and Zullo, E. S. 1985. Marine community descriptions and maps of bays within the Virgin Islands National Park/Biosphere Reserve. Biosphere Reserve Research Report No. 2. U. S. Dept. Interior National Park Service.

Dodge, R. and Vaisnys, J., 1977. Coral populations and growth patterns: responses to sedimentation and turbidity associated with dredging. J. Mar. Res. 35: 715-730.

Dustan, P., 1977. Growth and form in the reef-building coral Montastrea annularis. Mar. Biol. 33: 101-107.

Falk, R., 1974. Petrology of sedimentary rocks. Hemphill Publ. Co., Austin, TX, 182p.

Gladfelter, E. H., Monahan, R. K. and Gladfelter, W. B., 1978. Growth rates of five reef-building corals in the northeastern Caribbean. Bull. Mar. Sci. 28: 728-734.

Hubbard, D. K., Burke, R. B. and Gill, I.P. in press. Styles of reef accretion along a steep, shelf-edge reef, St. Croix, U. S. Virgin Islands. J. Sedim. Petrol. 56.

Hubbard, D. K. and Scaturo, D., 1985. Growth rates of seven species of scleractinean corals from Cane Bay and Salt River, St. Croix, USVI, Bull. Mar. Sci. 36: 325-338.

Hudson, J. H., Shinn, E.A., Halley, R. B., and Lidz, B., 1976. Sclerochronology:: a tool for interpreting past environments. Geology 4: 361-364.

Kantz, E., 1975. Engineering Field Manual for Conservation Purposes. Full citation unavailable, Xerox copy available from McComb Engineering, Sub Base, St. Thomas, USVI 00802.

Knutson, E. R., Buddemeier, R. W. and Smith, S. V., 1972. Coral chronometers: seasonal growth bands in coral reefs. Science. 177:270-272.

Macintyre, I. G., 1975. A diver operated hydraulic drill for coring submerged substrates. Atoll Res. Bull. 185: 720-738.

Runcorn, S. K., 1967. Corals and the history of the earth's rotations. Sea Frontiers. 13: 4-12.

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 = 2.832×10^{-2} m^3/sec

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

VIRGIN ISLANDS RESOURCE MANAGEMENT COOPERATIVE

BIOSPHERE RESERVE
RESEARCH REPORT NO.22

A BASIS FOR LONG-TERM MONITORING OF FISH AND SHELLFISH SPECIES IN THE VIRGIN ISLANDS NATIONAL PARK

Ralf H. Boulon, Jr.
V.I. Division of Fish and Wildlife
Department of Planning and Natural Resources
St. Thomas, U.S. Virgin Islands

U.S. MAN AND THE BIOSPHERE PROGRAM

Virgin Islands National Park

August, 1987

XN-ABC-589-C

A BASIS FOR LONG-TERM MONITORING OF FISH AND SHELLFISH SPECIES IN THE VIRGIN ISLANDS NATIONAL PARK

1987

BIOSPHERE RESERVE REPORT NO. 22

RALF H. BOULON, JR.
V.I. DIVISION OF FISH AND WILDLIFE
DEPARTMENT OF PLANNING AND NATURAL RESOURCES
ST. THOMAS, 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

A long-term monitoring program was initiated for fish and invertebrate species of commercial importance within the Virgin Islands National Park/Biosphere Reserve. Additionally, generally surveys were made for lobsters and conch. Hopefully, the data obtained will begin to fulfill the need for quantitative baseline data to assess and manage these resources adequately.

A one-year study indicates that; 1) some species of reef fish may have seasonal trends in numbers; 2) the inshore spiny lobster (Panulirus argus) population shows summer and winter peaks at Fish Bay but not Reef Bay, where numbers are very low; 3) conch (Strombus gigas) show a definite seasonal trend in deeper water with low numbers during the summer reproductive season; 4) whelk (Cittarium pica) at one study site show a large annual cohort of juveniles decreasing in abundance with increasing size. Few adults are present due to natural mortality. General surveys for conch and lobster demonstrate that the populations are of low abundance and highly dispersed.

These data will be useful to assess population trends in the absence or presence of management actions on the species or species groups. Recommendations for monitoring methodologies and management actions are discussed.

Acknowledgements

I would like to acknowledge and extend my deep appreciation to University of the Virgin Islands students, Lauren Patterson and Sue Johnson, and National Park Service technicians, Vonnie Zullo and John Blount, for their very valuable assistance in the field. Special thanks to Jim Beets of the University of Georgia for his discussions on this study, his help in the field, and his analysis of the data. Statistical analyses of the data were completed using STATPRO on an Apple computer and SYSTAT on an IBM PC.

Table of Contents

221

List of Tables

List of Figures

Introduction

Fish and marine invertebrates in the Virgin Islands are being affected by a number of stresses. Foremost of these is the heavy fishing pressure exerted on most species. With a limited shelf area of approximately 160,000 hectares (St. Thomas and St. John) and a total of 255 registered commercial fishermen (St. Thomas and St. John) for 1984-85 (Clavijo, et al., 1986), not to mention an unknown number of recreational fishermen and sport divers, the reef fish, lobsters, conch and whelk are being harvested at a rate exceeding replacement. As a result the stocks are declining at an alarming rate (Caribbean Fisheries Management Council (CFMC), 1985), a fact corroborated by fishery landings data as well as by fishermen. Other stresses include effects of development (sedimentation, increased runoff, potential toxic pollutants) and habitat degradation through anchor and boat damage and large numbers of visitors utilizing and affecting the marine ecosystems.

As it is very difficult to estimate accurately the total potential fishery yield of tropical insular shelf marine environments, many fisheries have been overexploited both biologically and economically before the condition is realized. Management is, therefore, a necessary tool in mitigating adverse conditions in a fishery. A prerequisite to developing management plans is to have information on the status of the fishery unit in question. The Caribbean Fishery Management Council (1985) lists as its number one problem the insufficiency of data needed for long-range management. This need can be satisfied by obtaining these data through research and surveys. With this information, management actions can be formulated to restore and maintain adult stocks at levels that ensure adequate spawning and recruitment required to maintain the population. This is accomplished through the promulgation of laws which prevent the harvest of individuals of species of high value by enforcement of minimum size restrictions and/or closed seasons. Monitoring the effects of a management action is essential in order to determine the success of the action and to assess the need for modification of regulations.

While stresses due to adverse fishery conditions can be mitigated (although not without upsetting the segment of the population involved in the fishery), it is harder to control and mitigate the more subtle stresses of development. This is an area where control of continuing development is probably impossible and mitigation would be extremely costly. Our goal must be to measure the effects and work for establishment of restrictions on development in productive areas.

The main objective of this study was to select areas within the National Park for long-term monitoring of fish and marine invertebrates. Reef fish, lobster, conch, and whelk were selected as high value species to be monitored in bays associated with disturbed and undisturbed watersheds. The data to be collected are to be used as baseline data for formulating and monitoring recommended management actions. Monitoring methodologies were developed which could be easily used and taught to non-scientists yet yield accurate results. These methods could be used throughout the Caribbean to produce comparable data bases in areas with little technology or resources.

Reef fish

Methodology

Three main watershed areas have been selected within the National Park for long-term study. These include Reef Bay (a completely protected watershed), Fish Bay (a watershed under development), and Hawksnest Bay (potentially impacted by construction of the St. John Clinic and future development) (Figure 1). Therefore, these bays were selected for long-term reef fish monitoring. Primary reef fish habitats were selected for monitoring within each bay based on previous designation of fishery habitats (Boulon, 1985a).

Species of fish were selected for study on the basis of their importance in the local commercial fisheries (Table 1). Any species taken as a food fish by any means were considered. Nearly all species selected for this project are considered in the Fishery Management Plan for the Shallow-Water reef fish Fishery of Puerto Rico and the U.S. Virgin Islands (CFMC, 1985). The species considered in the Fishery Management Plan were selected out of approximately 180 species which are landed and used in quantity throughout the Caribbean.

A census was taken of fish species of commercial importance present in the selected habitat within each of these bays using a random point, visual census technique (Bohnsack and Bannerot, 1983). Census locations were selected on a random basis within a habitat. The attempt was to locate oneself in a site characteristic of the selected habitat. It is important to avoid mixing the habitats (e.g. lower forereef and sand) within a single census radius. At each census location, the observer would begin by facing in one particular direction and during a five-minute period, rotate clockwise 360°, sampling all fish within an eight meter radius cylinder surrounding the observer. Due to good water clarity, an 8m radius could be used in all study sites. As the observer rotated through the census, the number of individuals observed for each species was recorded on mylar over a preprinted form. The preprinted form saves time in writing down the species' name. After using this form a few times, the location of a species' name is easily remembered. Use of the preprinted form did not appear to produce a bias (Bohnsack and Bannerot, 1983) since the form is only looked at to write down fish just observed and does not cause the observer to select fish to look for. This method proved more reliable in our study. The chance of counting an individual twice was greatly reduced by strictly adhering to the 360° census with no overlap and avoidance of recounting in subsequent censuses obvious

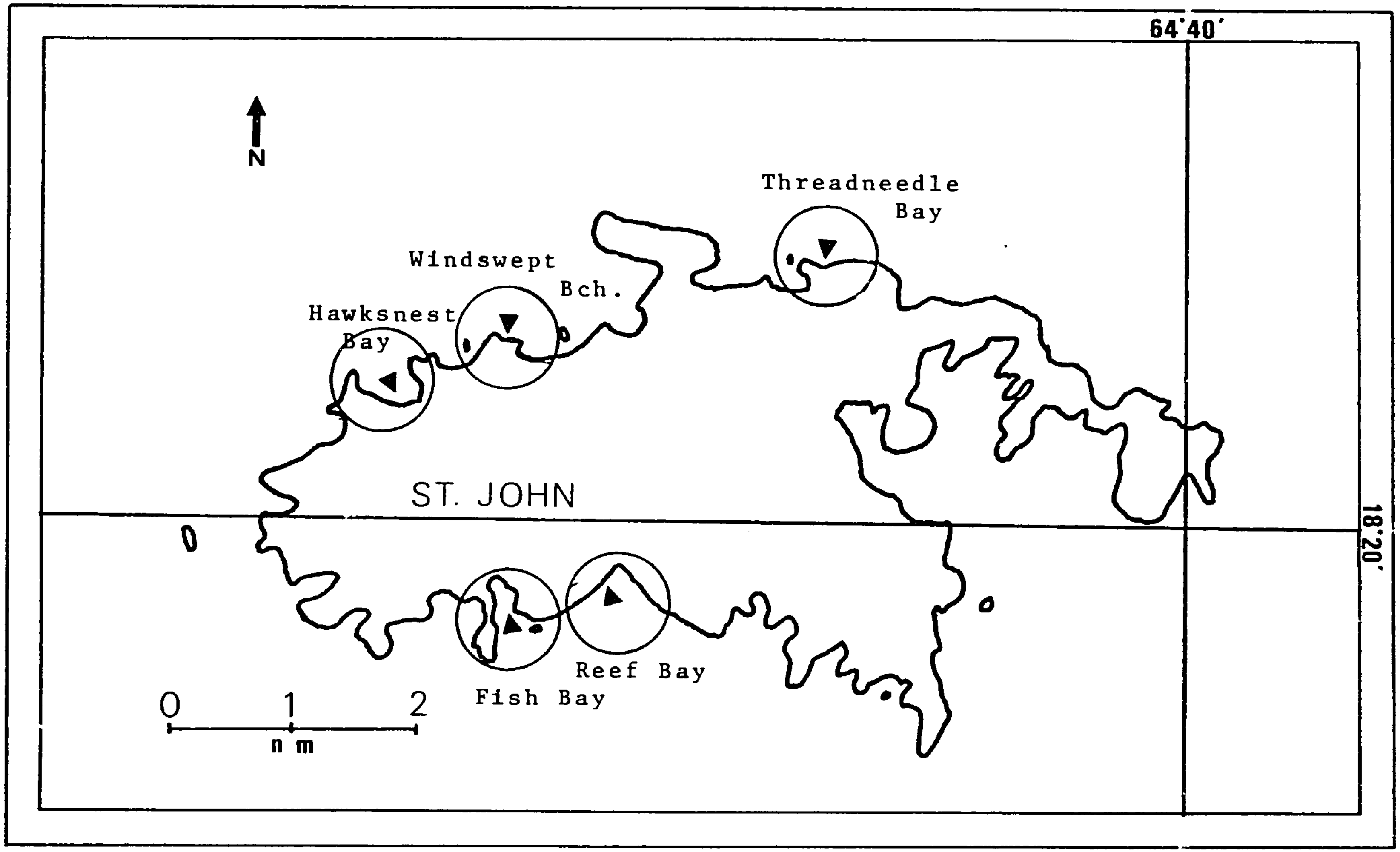


Figure 1. Map of St. John, USVI, showing location of study sites.

TABLE 1. Commercially important species of fish observed at the long-term monitoring study sites. Common and scientific names taken from Robins, et al. (1980). Local common names from J.A. LaPlace (pers. comm.).

COMMON NAME	LATIN NAME
COASTAL PELAGIC FISH:	
cero mackerel	*Scomberomorus maculatus*
horse-eye jack	*Caranx latus*
bar-jack-carang	*C. ruber*
DEMERSAL FIN FISH:	
queen triggerfish - old wife	*Balistes vetula*
bluestriped grunt	*Haemulon sciurus*
white grunt	*H. plumieri*
french grunt	*H. flavolineatum*
tomtate	*H. aurolineatum*
smallmouth grunt	*H. chrysargyreum*
spanish grunt	*H. macrostomum*
striped grunt	*H. striatum*
sailor's choice	*H. parra*
juvenile grunts	*H.* spp.
margate	*H. album*
mutton snapper - virgin snapper	*Lutjanus analis*
dog snapper - dogtooth snapper	*L. jocu*
grey snapper	*L. griseus*
schoolmaster - mango snapper	*L. apodus*
yellowtail snapper	*Ocyurus chrysurus*
mahogany snapper - burn tail	*L. mahogoni*
lane snapper - pot snapper	*L. synagris*
queen & french angelfish - swede angel	*Pomacanthus* spp.
grey angel - flatfish	*P. arcuatus*
rock beauty - black and yellow swede	*Holocanthus tricolor*
red hind - hind	*Epinephelus guttatus*
rock hind	*E. adscensionis*
graysby - butter socks	*Petrometopon cruentatum*
coney - butter fish	*Cephalopholis fulva*
nassau grouper	*Ephinephelus striatus*
black grouper	*Myctoperca bonaci*
tiger grouper	*M. tigris*
porgies	Sparidae
surgeonfish	*Acanthurus* spp.

Table 1. (Continued)

Commercially important species of fish observed at the long-term monitoring study sites. Common and scientific names taken from Robins, et al. (1980). Local common names from J.A. LaPlace. (pers. comm.).

COMMON NAME	LATIN NAME
DEMERSAL FIN FISH: (continued)	
blue tang - blue doctor	*A. coeruleus*
yellow goatfish - queen mullet	*Mulloidichthys martinicus*
spotted goatfish	*Pseudupeneus maculatus*
spanish hogfish - spanish piper	*Bodianus rufus*
hogfish - eaglemouth	*Lachnolaimus maximus*
parrotfish - goutou	Scaridae
trunkfish - shellfish	Ostraciontadae
sea chubs	*Kyphosus* spp.
barracuda	*Sphyraena barracuda*
squirrelfish	Holocentridae
glasseye/bigeye - bleareyes	*Priacanthus* spp.
mojarra - sand diggers	Gerreidae

of species that tend to be very mobile (e.g. mutton snapper, barracuda).

At the end of a sample period, the minimum and maximum lengths for each species were recorded. Where a clear dichotomy in sizes was observed, this was noted. These lengths are estimates based on pre-study tests and extensive field experience in which estimates were made of objects at various distances from the observer and then measured to determine accuracy. When other observers were used, size estimates were examined for consistency with data collected by the author and discrepancies were discussed with the other observer.

Most species of fish occurred in low numbers during a census. Schools of fish are counted as they appear in the sample radius and if large, are counted in 10s, 100s or even 1000s.

Advantages of this method are numerous. It is simple, rapid, unbiased and precise. It is easily performed by anyone with a minimum of instruction and practice. It requires no complicated accessories such as cameras, transect lines, compasses, etc. As such, it is very applicable to developing countries where technology is not available for higher-tech methods requiring many accessories. It is easily performed either by snorkeling or using SCUBA (for depths greater than 4m). A stationary observer has a better chance of observing more cryptic or wary species which would otherwise avoid a moving diver. There are also species which are attracted to a moving diver, thus biasing the data. Additionally, due to the small area actually sampled in one census, the chances of crossing habitats within a census are greatly reduced. The only requirement of this method is an underwater watch and an ability to identify fish species using external morphological or visual characteristics. This is easily accomplished after several practice censuses with review and reference of a good identification guide (e.g. Randall, 1968; Chaplin, 1972; Stokes, 1980).

Several disadvantages of this direct sampling method must be acknowledged. Using this method, nocturnal and highly cryptic species tend to go undetected. Being a random point census technique, the effects of schooling, territoriality or preference for specific microhabitats (all of which can cause nonrandom distribution of fish populations) can affect abundance estimates. Also, juvenile fishes tend to be underrepresented. However, ensuring that censuses are performed in habitat "core areas" (Boulon, 1985a) will eliminate the significance of these problems.

A preliminary test was made of this method to determine number of censuses necessary to accurately describe an area in terms of species composition. Ten successive censuses were made in one location. The results indicate that approximately 80 percent of the resident, nonmigratory and non-cryptic species are observed in four censuses (Figure 2). Species added in subsequent censuses include migratory species such as mackerel

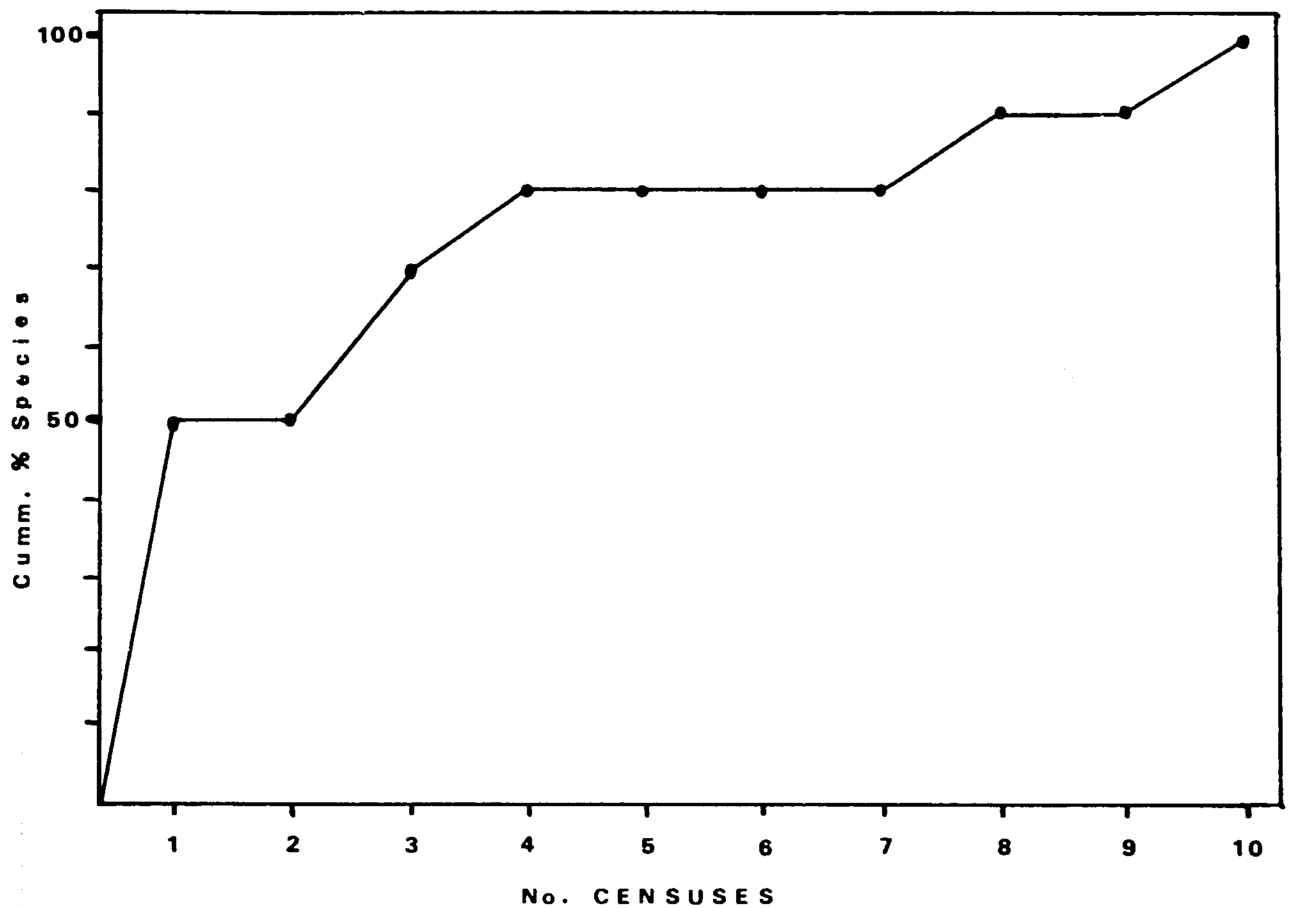


Figure 2. Cumulative percent species curve for ten repetitive fish censuses at one location in Fish Bay, St. John, USVI, on January 22, 1985.

(*Scomberomorus maculatus*) and cryptic species such as small coney (*Epinephelus fulvus*), whose behavior is to hide behind coral heads and peek out frequently unobserved. Based on this study and the size of most of the areas monitored, ten censuses per location per date was selected as an adequate sample size to yield a representative sample of the fish assemblage composition and abundance within that particular habitat. At certain selected locations the reef or habitat being sampled was smaller in size and fewer censuses were needed to adequately cover the area without overlap.

Hawksnest Bay

Hawksnest Bay, on the north shore of St. John (Figure 3) was chosen as a long-term monitoring site for two reasons. First, it is an area suspected of having been affected by sedimentation produced by the construction of the St. John Community Health Clinic in 1982 at the top of this watershed. Unstabilized sediment berms created by the excavation for the hospital have been steadily eroding since 1982 and may have raised the sediment load of the bay, decreasing visibility (light transmission) and taxing the sediment removal capabilities of benthic organisms. Changes in benthic communities would be reflected in long-term changes in reef fish assemblage composition and abundance. The second reason for selecting Hawksnest is that other long-term coral and sedimentation studies were initiated in the watershed and an integrated view is evolving. Three areas in the bay, representing two different habitat types, were selected for this study.

Shallow bay patch reef-SBpr

Located in the middle of Hawksnest Bay (Figure 3) this reef is approximately 75m long and 30m wide with the long axis oriented N_rth-South. It is characterized by having an east facing forereef which rises up from a 12m deep sand plain to about 9m. This forereef, with its vertical relief and moderate coral coverage, has the greatest abundance of fish on the reef. Behind this the reef is relatively flat with scattered corals, gorgonians, and sponges. The back of the reef (west side) is very sandy with sparse, scattered gorgonians,and few fish. The reef was characterized by monthly samples of five censuses along the forereef and five censuses along the middle portion of the reef.

Eleven monthly samples were made (Table 2) on this reef from March 1985 to February 1986. A total of 36 species of commercially important fish were observed on the reef during this period with a mean of 21.4 (sd=2.19) species seen on each sample date. A mean of 428 (sd=127) individual fish were seen on each sample date. Mean average fish size for the entire period was 5.8 (sd=0.6) inches. Of the 36 observed species, 20 species were present in eight (75%) or more samples and eight species were present in every sample.

No trends are evident for species abundance or average fish

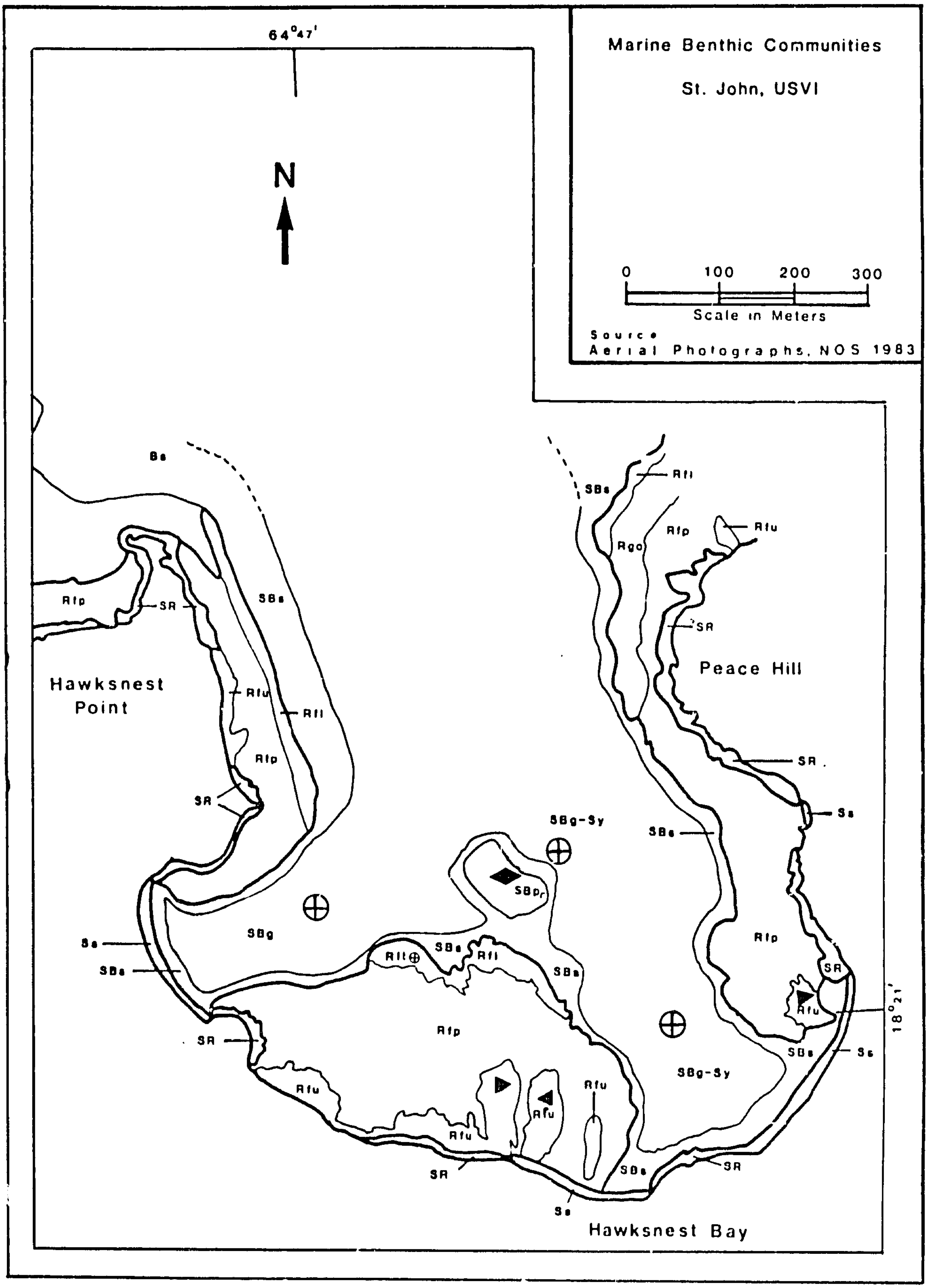


Figure 3. Hawksnest Bay, St. John, USVI, showing location of study areas for long-term monitoring of reeffish and lobster populations. ◀- fish study areas, ◆- lobster and fish study areas. ⊕- conch survey areas. See Table 3 for acronyms.

TABLE 2. Average number of fish per census per species for Hawksnest Bay Shallow Bay Patch Reef (SBpr) from March 1985 to February 1986. (Total # fish/# censuses).

Species	3/85	4/85	5/85	6/85	7/85	8/85	9/85	10/85	11/85	12/85	2/86
queen trigger-fish	.1		.1		.1						
bluestriped grunt			1.4		.6	1.6	.3			.2	.6
white grunt	.8	1.1	.1	.8		.7	.3		.3		.2
french grunt	1.2	1.2	.7	1.4	.9	1.1	1.2	.8	1.4	.9	1.5
tomtate	.1			.3	1.2	.1			.6		.1
small mouth grunt							.7	.5			
striped grunt								.6	.3	1.3	.5
juvenile grunt						2.0				2.5	
margate			.1								
mutton snapper	.3	.2		.2	.8		.3	.1	.3	.3	.2
dog snapper							.1				
yellowtail snapper	1.4	3.0	7.3	4.0	4.8	3.7	2.8	3.7	1.7	.9	1.6
mahogany snapper	.3	.4			2.2	1.3	1.1	.7	.5	.1	.2
lane snapper				1.3	.6	2.5	5.3	1.8	6.3	3.9	4.2
q. and fr. angelfish	.1	.1	.1		.3		.4	.2	.2	.2	.3
gray angelfish	.1	.2	.3	.1	.1	.1			.1	.1	
red hind	.2	.2	.7	.6	.5	.3	.5	.5	.5	.4	.3
rock hind			.2								

Table 2 (Continued)

Average number of fish per census per species for Hawksnest Bay Shallow Bay Patch Reef (SBpr) from March 1985 to February 1986. (Total # fish/# censuses).

Species	3/85	4/85	5/85	6/85	7/85	8/85	9/85	10/35	11/85	12/85	2/86
graysby			.1	.3	.2	.1	.1	.1	.2	.4	
coney	.4	.1			.2	.6	.2	.5	.1	.2	.2
nassau grouper		.2	.1	.3							
blue tang	2.3	5.1	4.9	5.9	7.4	4.8	7.1	2.4	4.7	1.8	5.7
surgeon-fish	1.4	1.8	1.4	1.0	3.7	1.4	1.0	.7	1.9	.3	.4
yellow goatfish		1.8	2.5	2.7	1.9	1.5	1.5	1.1	1.2	1.2	2.3
spotted goatfish	.7	.1	1.0	.3	.9	.6	.8	.2	.4	.1	.1
spanish hogfish			.1								
hogfish					.2						
porgies	.2	.4	.1	.2	1.2	.2	.4	.5	.1	.2	.1
parrot fish	27.7	18.3	14.0	10.6	43.5	33.8	18.9	20.5	15.3	12.1	24.0
trunk fish						.1			.2	.2	
barracuda	.1	.1	.2	.1						.1	
squirrel fish	.2		.2	.6	.4	.8	.6	.6	.4	.6	.5
glasseye/ bigeye										.2	
mojarra			.4	1.0	1.7		1.1	.1	3.4	2.9	1.7
mackerel		.6		.4					.4		
bar jack		.2			1.1	1.4	.3	.4	.7	1.0	.3
total # species	18	18	21	21	24	21	22	20	24	25	21

Table 2 (Continued)

Average number of fish per census per species for Hawksnest Bay Shallow Bay Patch Reef (SBpr) from March 1985 to February 1986. (Total # fish/# censuses).

Species	3/85	4/85	5/85	6/85	7/85	8/85	9/85	10/85	11/85	12/85	2/86
total # individuals	376	316	364	321	748	593	450	358	412	321	450
average size(in)	5.34	5.79	7.16	5.95	5.96	4.68	5.44	5.74	6.53	5.86	5.35

Table 3. Zone and subzone designations with acronyms.

A)	Shore Zone			S
	1)	Beach rock		Sb
	2)	Sand		Ss
	3)	Mangrove		Sm
B)	Subtidal Bedrock			SR
C)	Lagoon			L
	1)	Pavement		Lp
	2)	Seagrass bed		Lg
D)	Shallow Bay			SB
	1)	Sand		SBs
	2)	Pavement		SBp
	3)	Seagrass bed		SBg
	4)	Patch reef		SBpr
		a)	pavement	SBprp
	5)	Algae		SBa
E)	Reef (fringing and barrier)			R
	1)	Backreef		Rb
		a)	head coral/groto	Rbh/Rbg
		b)	pavement	Rbp
	2)	Reef crest		Rc
	3)	Fore reef		Rfu
		a)	upper (arborescent)	Rfu
		b)	lower (massive)	Rfl
		c)	pavement	Rfp
	4)	Sand		Rs
	5)	Gorgonian-dominated pavement		Rgo
	6)	Pavement		Rp
F)	Bank			B
	1)	Gorgonian-dominated pavement		Bgo
	2)	Pavement		Bp
	3)	Sand		Bs
	4)	Seagrass bed		Bg
	5)	Patch reef		Bpr
		a)	crest	Bprc
		b)	fore reef upper/lower	Bpru/Bprl
		c)	pavement	Bprp
		d)	gorgonian-dominated pavement	Bprgo
	6)	Algal plain		Ba

size during the study period. Total number of individuals may increase during the summer months (July to September). The primary contributors to this increase appear to be the herbivorous blue tang, surgeonfish and parrotfish. Other species show no clear seasonality in presence or numbers. This reef has a large number of foraging groups of juvenile (1 to 2 inch) parrotfish which some observers during this study may have overlooked. This may produce some of the fluctuations in numbers of parrotfish per census. (e.g. June, 1985).

During the study period, fish traps (2 to 3) were observed set on this reef. The potential impact of this fishing technique on a small, isolated reef is not fully understood. In order to quantify the impact it is necessary to have an intensive before and after census schedule and a total enumeration of species and numbers of fish harvested. It was noted from the census data in this study, that eighteen species of fish that are commonly caught in fish traps decreased slightly in numbers from before to after trapping. The small sample size does not enable any conclusive statements to be made regarding this observation.

Southern fringing patch reef-Rfu

Along the south side of Hawksnest Bay immediately off the public swimming beach are three patches of shallow water, upper-fore, fringing reef. The two larger, western reefs are primarily composed of *Acropora Palmata* with small amounts of other hard coral species. The two larger reefs were selected for the study due to their greater coral cover and 'healthier' nature. The smaller reef appears to be subjected to greater scouring action by winter swells and is generally more turbid making it difficult for visual censuses.

Eleven monthly samples were made (Table 4) on these reefs from March 1985 to February 1986. Five censuses were made on each reef each sample period which was felt to adequately cover each reef without any overlap of censuses. A total of 22 species of commercially important fish were observed on the reef during this period with a mean of 11.5 (sd=2.27) species seen on each sample date. A mean of 388 (sd=88.7) individual fish were seen on each sample date. Mean average fish size for the entire period was 4.56 (sd=.50) inches. Of the 22 observed species, seven species were present in every sample.

The only species showing evidence of a seasonal trend on these shallow patch reefs were yellow goatfish. During the months of September and October, large schools of juvenile yellow goatfish (3-5 inches long) were observed taking refuge in these reefs. As fast as they appeared, they disappeared and by November they were not in evidence. No seasonal trends are obvious for any other species either in numbers of individuals or size except for possibly sailor's choice and mahogany snapper which were only present during later summer and early fall. This reef has large numbers of juvenile herbivores, primarily parrotfish, blue tang and surgeonfish, which probably accounts for the smaller mean fish size for this reef compared to the SBpr.

TABLE 4. Average number of fish per census per species for Hawksnest Bay southern fringing patch reefs (Rfu) from March 1985 to February 1986. (Total # fish/# censuses).

Species	3/85	4/85	5/85	6/85	7/85	8/85	9/85	10/85	11/85	12/85	2/86
blue striped grunt	.1	.1	.2	.3	.3	.3		.3	.6	.2	.4
white grunt			.1								
french grunt	.7	.4	.7	.6	2.2	6.9	4.4	6.5	1.8	3.5	4.4
small mouth grunt								.2			
sailor's choice						.7	.1	.1			
yellowtail snapper	.1		.3	.4	.3	.1	.2	.3			
mahogany snapper					.8	.1	.1				
red hind		.2		.1			.1				.1
graysby				.1	.1			.1			
coney			.1					.2	.1	.1	
nassau grouper				.1							.1
blue tang	8.9	14.9	2.8	12.5	8.3	6.4	6.6	9.3	7.7	11.1	11.6
surgeon fish	4.3	3.7	5.2	8.5	7.5	5.5	5.5	5.6	4.9	8.8	7.5
yellow goatfish			.6		3.4	1.1	9.1	7.1	.2		.5
spotted goatfish		.1	.1	.4	.3		.2	.5	.2		
porgies							.1				
parrot fish	18.3	9.8	15.6	10.3	23.6	17.3	18.0	22.5	14.1	23.2	16.0
trunkfish	.1	.1	.1	.2				.1	.3		

Table 4 (Continued)

Average number of fish per census per species for Hawksnest Bay southern fringing patch reefs (Rfu) from March 1985 to February 1986. (Total # fish/# censuses).

Species	3/85	4/85	5/85	6/85	7/85	8/85	9/85	10/85	11/85	12/85	2/86
squirrel fish		.2	.1	.1	.1	.4	.4	.2	.2	.9	.2
mojarra			.5				.1	.2		.2	
mackerel	.8										
bar jack	1.0	.2	.2	4.0	.1		.3	.7		.3	.8
total # species	9	10	14	13	12	10	14	16	10	9	10
total # individuals	309	271	266	377	470	391	453	539	298	483	416
average size(in)	5.73	3.89	5.15	4.39	4.54	4.25	4.18	4.83	4.45	4.62	4.11

Eastern fringing patch reef-Rfu

Directly off the northeastern end of the privately owned beach in Hawksnest Bay is a small patch of shallow water, upper-fore, fringing reef. This reef is not as developed as the southern fringing reefs possibly due to lower energy levels and being near the major gut draining this watershed (Hubbard, et. al. 1986).

Eleven monthly samples were made (Table 5) on this reef from March 1985 to February 1986. Due to the size of this reef, four censuses were deemed adequate to sample the fish assemblage present there. A total of 19 species of commercially important fish were observed on the reef during this period with a mean of 11.6 (sd=1.07) species seen on each sample date. A mean of 363 (sd=140) individual fish were seen on each sample date. Mean average fish size for the entire period was 4.87 (sd=.57) inches. Of the 19 observed species, eight species were present in eight (75%) or more samples and five species were present in every sample.

The only species showing evidence of a seasonal trend on this reef were yellow goatfish and possibly tomtate. As with the southern patch reefs large schools of juvenile yellow goatfish (3-5 inches long) were observed taking refuge here during the months of September and October. As opposed to the southern reefs, however, a higher year-round background level of yellow goatfish exists on this reef. This large number of yellow goatfish is responsible for the peak in total number of individuals for these two months. Tomtate were only observed from May to September which may or may not be a seasonal trend. Fewer very small herbivores were observed on this reef which results in a slightly higher mean fish size than for the southern reefs.

TABLE 5. Average number of fish per census per species for Hawksnest Bay eastern fringing patch reef (Rfu) from March 1985 to February 1986. (Total # fish/# censuses).

Species	3/85	4/85	5/85	6/85	7/85	8/85	9/85	10/85	11/85	12/85	2/86
blue striped grunt		.3	.5	.3				.3			1.0
french grunt	39.5	51.5	40.3	50.8	50.8	25.8	38.5	65.3	42.3	39.5	29.3
tomtate			1.5	6.5		1.8	1.8				
small mouth grunt		.8			4.0			4.8	4.3	3.8	1.3
spanish grunt		.3			.3		.3				.3
school master	.3	.3	.3	.3							
yellowtail snapper	.3	1.0	1.8	2.0	.5	2.0	2.8	4.3	3.3	2.3	1.5
mahogany snapper			.5	2.8	.8	.5			.5	.8	.3
coney										.5	
blue tang	3.5	4.8	15.3	5.5	1.8	8.8	12.3	6.0	7.8	14.5	3.0
surgeon fish	2.8	5.5	3.3	2.0	5.0	1.8	7.8	2.0	4.3	10.0	3.8
yellow goatfish	1.3	4.3	6.5	4.0	5.0	10.8	64.3	65.0	7.3	4.5	
spotted goatfish	.3	.3		1.0		.3				.5	
parrot-fish	12.3	5.0	9.8	8.5	6.3	8.3	11.5	14.8	9.0	15.0	15.8
trunkfish	.3						.3		.5		.5
squirrel fish	.3	.5	1.8	1.8	1.8	1.0	1.8	1.3	.8	1.0	3.0

Table 5 (Continued)

Average number of fish per Census per species for Hawksnest Bay eastern fringing patch reef (Rfu) from March 1985 to February 1966. (Total # fish/# censuses).

Species	3/85	4/85	5/85	6/85	7/85	8/85	9/85	10/85	11/85	12/85	2/86
mojarra							.3			1.3	
sea chubs							2.5				
bar jack	2.5	.8	.5		1.0	.5	.8	12.5		2.5	.5
total # species	11	13	12	12	11	11	13	10	10	13	12
total # individuals	252	291	327	341	308	251	578	704	309	387	240
average size(in)	6.28	4.33	4.44	4.55	4.04	5.16	4.90	4.78	5.14	4.75	5.19

Reef Bay

Reef Bay, on the south shore of St. John (Figure 4), was chosen as a long-term monitoring site for two reasons. First, being a relatively protected watershed with no chance for development, it may act as an indicator of general marine "health". Secondly, like Hawksnest Bay, the combination of this study with other long-term research creates a more complete picture of the bay. An area that is being studied for changes in coral composition and abundance (Rogers and Zullo, 1986) was selected for the reef fish monitoring study.

The study area in Reef Bay is along the lower forereef portion of the western fringing reef. The reef at this site is very steep, going from the surface to 11m in depth with a slope averaging approximately 45 degrees. Several buttress-like formations in the study area have the greatest coral cover and the greatest numbers of fish. The study area includes the 50m stretch of reef described in Rogers and Zullo (1986) and an additional 50m of reef to the west of it. This 100m study area was characterized by monthly samples of 10 censuses each. Since there were some clumping of fish on the buttress-like formations, these were censused every month. Other censuses were randomly distributed through the study area.

Poor weather (waves, visibility) and logistical problems only enabled nine samples to be made (Table 6) at this site from February 1985 to January 1986. A total of 34 species of commercially important fish were observed in the study area during this period with a mean of 21.0 (sd=2.4) species seen on each sample date. A mean of 657 (sd=185) individual fish was seen on each sample date. Mean average fish size for the entire period was 5.82 (sd=.51) inches. Of the 34 observed species, sixteen species were present in seven (75%) or more samples and thirteen species were present in every sample.

The general fluctuation of number of individuals per species from sample to sample does not indicate any easily observable seasonal trends. The only possible exception to this is spotted goatfish which do show a peak in abundance for September with the majority of those seen being relatively small (4-5 inches). There is a peak in total numbers of individuals during the period of June to September. The major contributors to this are white grunt, juvenile grunt, mahogany snapper and blue tang, with different ones in different months being responsible for elevating the total number of individuals.

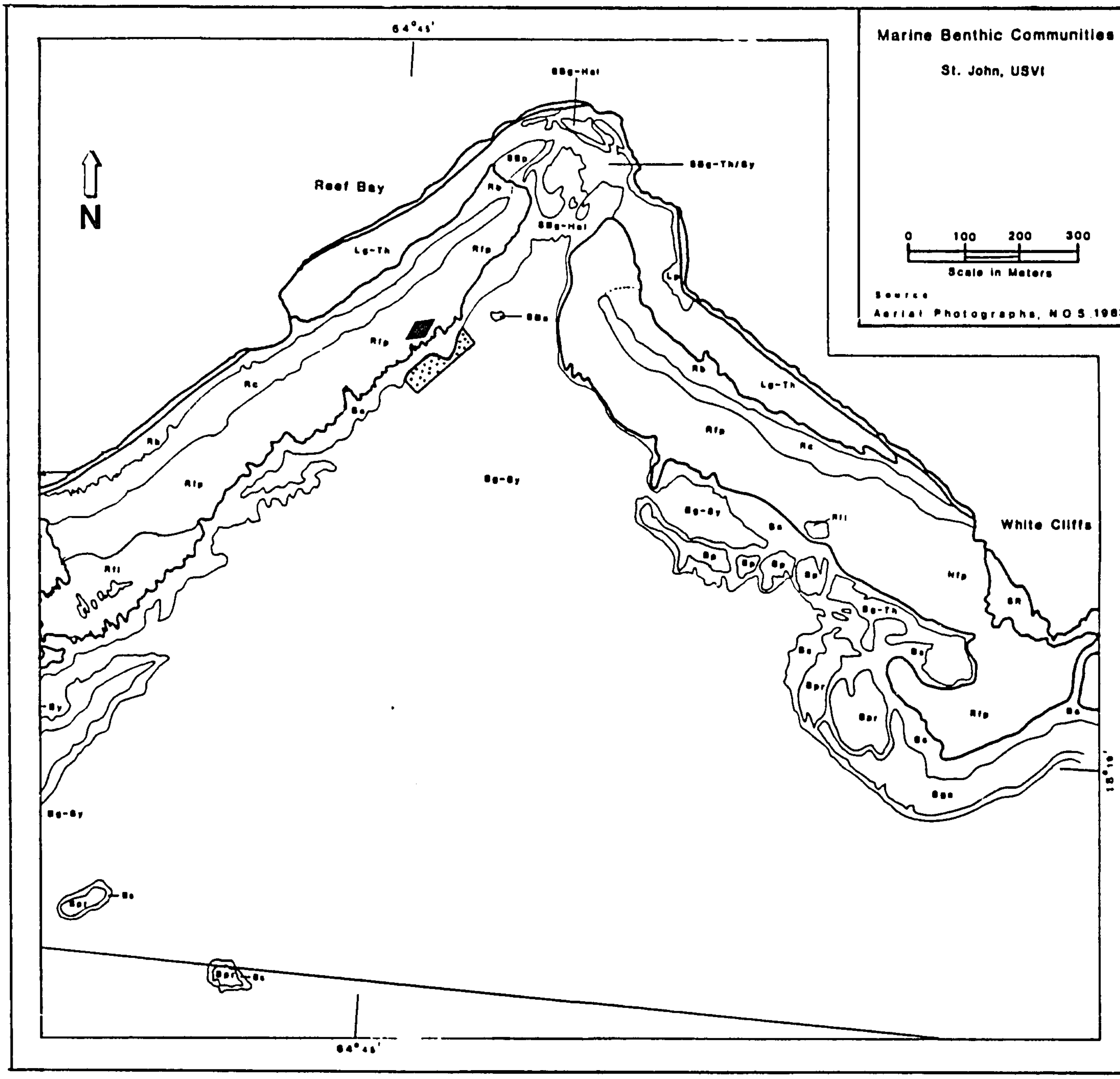


Figure 4. Reef Bay, St. John, USVI, showing location of study site for long-term monitoring of reef fish and lobster populations. ◆ - study area. [stippled box] - conch survey area. See Table 3 for acronyms.

TABLE 6. Average number of fish per census per species for Reef Bay lower fore reef (Rfl) from February 1985 to January 1986. (Total # fish/# censuses).

Species	2/85	4/85	6/85	7/85	8/85	9/85	10/85	12/85	1/85
queen triggerfish								.1	
blue striped grunt	2.8	2.4	3.3	2.0	3.3	3.3	3.8	2.0	1.2
white grunt	4.2	6.9	16.9	16.1	8.2	15.9	14.9	6.1	5.3
french grunt	4.8	9.1	11.2	8.2	6.4	13.1	7.3	3.9	5.0
tomtate	.2								
small mouth grunt		.6	.5			1.4			
spanish grunt	.2	.5	.5	.7	.2	.6	.2	.2	.2
juvenile grunts	2.8			16.7		6.0			
mutton snapper	.1	.3	.1						.1
dog snapper			.1	.1		.1			
gray snapper		.3							
lane snapper			.1						
school master	.9	.4	.7	.2	1.0	1.1	.6	.4	.4
yellowtail snapper	4.7	3.8	2.4	3.8	1.8	4.7	3.3	4.9	2.5
mahogany snapper	.2	2.8	9.2	8.3	2.1	1.0	1.3	5.3	3.8
q & fr angelfish	.1		.1		.1	.2	.1	.2	
gray angelfish	.2		.1	.2		.4			
red hind								.1	
coney			.2			.2	.1	.1	
nassau grouper						.1	.1		.1
black grouper						.1		.2	
tiger grouper		.1	.1			.1	.1	.1	.1
blue tang	4.2	12.9	30.2	11.7	22.7	11.5	7.6	11.1	16.9

Table 6 (Continued)

Average number of fish per census per species for Reef Bay lower forereef (Rf1) from February 1985 to January 1986. (Total # fish/# censuses).

Species	2/85	4/85	6/85	7/85	8/85	9/85	10/85	12/85	1/86
surgeon fish	1.8	6.5	4.6	9.1	11.6	5.4	2.1	4.0	4.1
yellow goatfish	1.4		1.7	3.0	2.5	2.5	3.9	.6	1.1
spotted goatfish	.2	.5	.6	.8	1.5	5.8	1.7	2.0	.5
spanish hogfish	.3	.5	.4	.1	.2	.6	.1	.2	
parrot fish	5.8	11.1	11.7	8.0	11.7	6.2	8.9	11.8	12.1
trunkfish	.1				.2			.1	
barracuda	.1	.3							
squirrel fish	.1	.5	1.1	.6	.8	1.6	1.0	1.2	.6
mojarra	.1	.1	.1	.3				.1	
mackerel		.1				.1		1.6	
bar jack	2.1	.4	1.1		.3	1.0	1.9	1.1	.2
total # species	22	21	22	20	17	25	19	24	19
total # individuals	344	475	964	826	750	815	596	586	555
average size(in)	6.89	5.81	5.77	5.42	6.01	5.01	5.38	6.22	5.86

Fish Bay

Fish Bay, on the south shore of St. John (Figure 5), was chosen as a long-term monitoring site for two major seasons. First, this is a large watershed which is still relatively pristine but is planned for major residential development (over 200 lots) in the lower part of the watershed. The middle part is owned by the National Park Service and The Nature Conservancy and the upper part is private with potential for additional development. There is therefore potential for major impact on the marine resources of this bay. Secondly, like Hawksnest and Reef Bays, the combination of this study with other long-term research creates a more complete picture of the bay. Two habitats were selected as being the major habitats of importance for reef fish. These include the lower forereef and backreef habitats. The mangroves along the coastline were surveyed for juvenile nursery potential but the extreme shallowness of the water (only a few inches at low tide) makes it unsuitable for fish to reside there. Only a very few fish were observed and those were in small hollows where the gut enters the bay. Visibility in these hollows is not much better than half a meter which makes any survey method nearly impossible.

Lower Forereef-Rf1

The lower forereef in Fish Bay is a series of spurs oriented northwest to southeast with sand between them (Figure 5). Maximum relief of the spurs is approximately 2m. The study area covers approximately 50 percent of the lower forereef habitat and is 11m in depth with a well developed and diverse coral community (Rogers and Zullo, 1986).

Ten monthly samples were made (Table 7) on this reef from January 1985 to January 1986. A total of 34 species of commercially important fish were observed on the reef during this period with a mean of 16.5 (sd=1.75) species seen on each sample date. A mean of 298 (sd=110) individual fish were seen on each sample date. Mean average fish size for the entire period was 5.49 (sd=.39) inches. Of the 34 observed species, 12 species were present in eight (75%) or more samples and five species were present in every sample. Eleven species were seen only once during the study period.

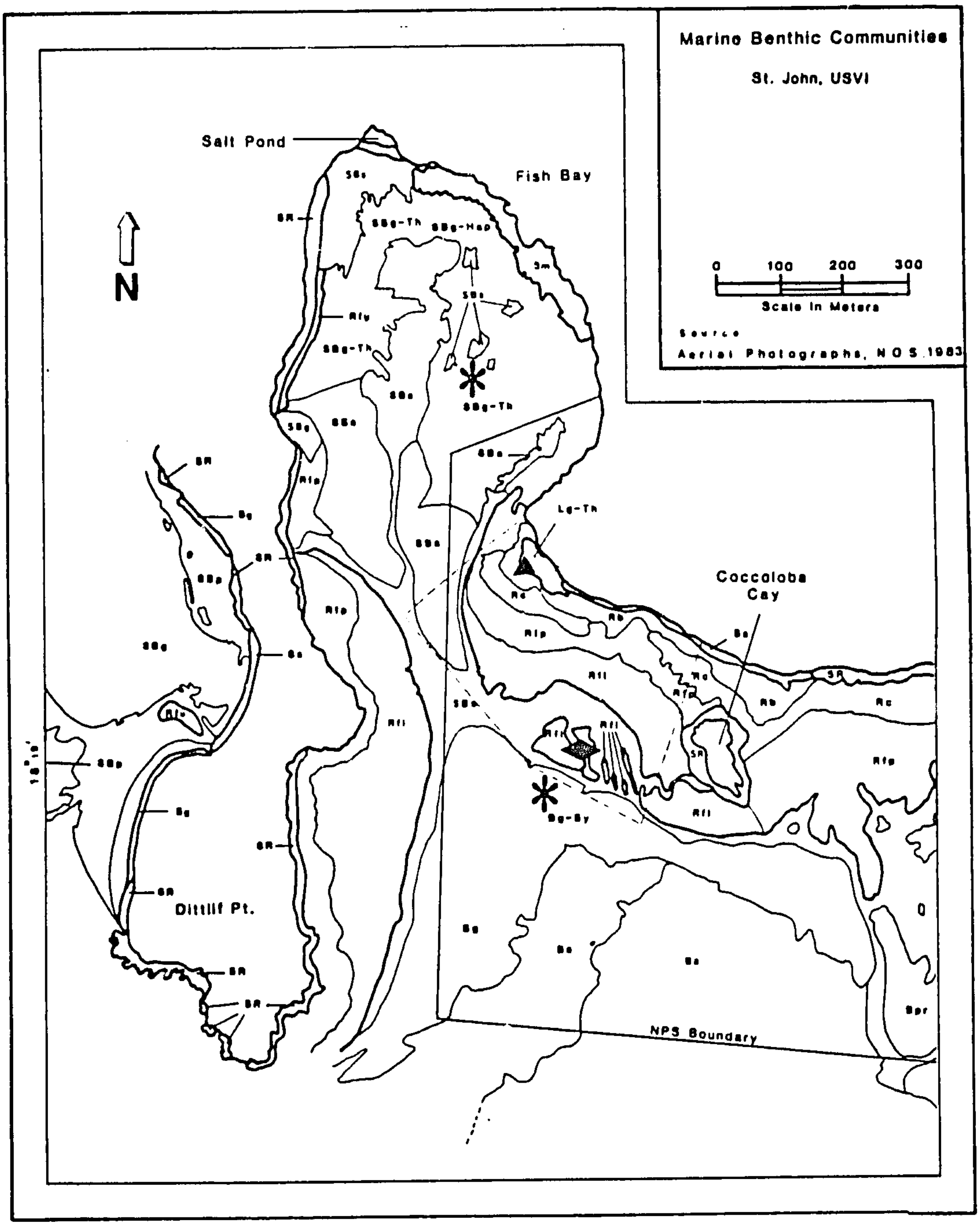


Figure 5. Fish Bay, St. John, USVI, showing location of study sites for long-term monitoring of reef fish , lobster and conch populations. ◄- fish study areas, ◆- fish and lobster study areas, ✱ - conch study areas. See Table 3 for acronyms.

TABLE 7. Average number of fish per census per species for Fish Bay lower forereef (Rf1) from January 1985 to January 1986. (Total # fish/# censuses).

Species	1/85	3/85	4/85	6/85	7/85	8/85	9/85	10/85	11/85	1/86
queen triggerfish				.1						
bluestriped grunt		.2		5.1	.3	.4	.4	.1	.5	.3
white grunt		2.0	4.4	1.5	.3	1.7	1.3	.8	.4	1.2
french grunt	1.4	.4	1.1	.7	1.7	1.7	1.5	1.9	2.0	.5
tomtate				5.5						
spanish grunt						.1				
margate	.1									
mutton snapper						.1				.1
schoolmaster	.1	.1	.3		.2	.5	.4	.4	.1	.3
yellowtail snapper	1.7	2.4	.8	1.5	1.2	.8	1.3	.9	1.0	.3
mahogany snapper				1.6	.2	.3	.3			
q & fr. angelfish								.1	.1	.1
rock beauty			.2			.1				
red hind	.1		.1	.1	.1			.1		
graysby			.3	.1	.1	.1				.1
coney		.1	.1	.2		.1	.3	.3	.2	
nassau grouper							.1			
black grouper							.1			
tiger grouper								.1		.2
blue tang	2.5	11.0	4.3	21.6	1.6	4.5	5.0	7.7	4.3	2.4
surgeonfish	3.0	7.5	4.6	8.2	3.3	4.1	6.3	5.6	4.6	5.1
yellow goatfish	1.5			.6	.2	.3	.2		.4	
spotted goatfish	.6	1.4	.2	.9	1.4	1.0	6.6	1.2	1.2	
spanish hogfish	.1	.4	.5	.3		.2	.3	.3	.1	.2
hogfish	.1									
porgies							.1		.2	
parrotfish	4.7	9.4	7.8	9.2	12.3	14.9	6.7	7.5	9.3	6.1
trunkfish					.1		.1		.2	
barracuda	.1									.1
squirrelfish	.3		.7	.5	.5	.3	.5	.4	.6	.3
mojarra					.1					
mackerel								.2		
bar jack	1.0	1.1	.2		.5	1.8	.8	.3	.8	.2
horseeye jack		.1								
total # species	15	13	15	17	17	19	19	17	17	16
total # individuals	173	361	256	577	242	330	324	279	260	175
average size (in)	6.32	4.91	5.91	5.48	5.76	5.36	5.46	5.11	5.31	5.29

The only species showing any evidence of a seasonal trend at this study site were spotted goatfish and possibly parrotfish. As with the Reef Bay site, spotted goatfish show a peak in September with many being relatively small (2-5 inches). Parrotfish do show a peak in July and August although this was not due to an increase in number of juveniles. Many species at this site occur infrequently and sporadically, providing no evidence for seasonality. Total number of species shows a peak in August and September but this is probably due to a coincident occurrence of some of the species normally having a sporadic or infrequent occurrence.

Backreef-Rb

On the east side of Fish Bay is a fringing reef (Figure 5). Periodic storms have created an emergent boulder ramparts composed primarily of old broken plates of _Acropora palmata_. This emergent reef crest has created a relatively protected, shallow backreef lagoon with colonies of _Montastrea annularis_, _Porites porites_ and areas of _Thalassia testudinum_. The submerged portions of the boulder ramparts contain numerous spaces to serve as refuge for fish.

Eleven monthly samples were made (Table 8) in this backreef lagoon from January 1985 to January 1986. Only two censuses were done each month as the primary fish habitat is very limited. A total of 18 species of commercially important fish were observed in this backreef during this period with mean of 11.4 (sd=1.3) species seen on each sample date. A mean of 116 (sd=13.3) individual fish were seen on each sample date. Mean average fish size for the entire period was 4.88 (sd=.24) inches. Of the 18 observed species, eight species were present in eight or more samples (75%) and seven species were present in every sample.

The most notable thing about this site is the large, resident school of schoolmaster snapper. Only two species show any observable indication of a seasonal trend in abundance. French grunt have a definite peak in September/October and squirrelfish appear to be most abundant in July to September. Although the average size for the schoolmaster seen was approximately 6.5 inches, the abundance of very small surgeonfish, tang and parrotfish depressed the mean average size.

General Conclusions

One year of monitoring the fish assemblages in six locations around St. John allowed for statistical analysis of differences in numbers of individuals and species among bays and among dates.

TABLE 8 Average number of fish per census per species for Fish Bay backreef (Rb) from January 1985 to January 1986. (Total # fish/# censuses).

Species	1/85	3/85	4/85	5/85	6/85	7/85	8/85	9/85	10/85	12/85	1/86
blue-striped grunt						1.5	1.0	2.0	2.5	1.5	2.0
french grunt	7.0	4.5	3.5	7.0	2.0	2.5	7.0	21.0	13.0	9.5	11.5
tomtate	2.0	1.5	1.5	1.5	1.5	1.0	2.0	1.5	2.0	4.0	1.0
small-mouth grunt										2.0	
school master	13.0	14.0	19.0	14.5	24.5	13.5	17.5	13.0	12.0	15.5	10.0
yellow-tail snapper	4.0	1.5	2.0	1.0	1.0	2.0	1.0	.5			
mahogany snapper	3.5	1.0		1.0		.5	.5				
blue tang	4.5	4.0	3.0	6.0	2.5	2.5	3.5	3.5	7.0	6.0	2.0
surgeon fish	7.5	10.0	14.5	6.0	11.5	19.0	10.0	13.0	8.0	9.0	12.0
yellow goatfish	5.5	1.5	3.5	1.0						.5	
spotted goatfish						.5	2.0	.5	.5		.5
porgies	.5										
parrotfish	4.0	10.0	13.0	9.5	12.0	8.5	10.5	13.0	6.0	8.0	10.0
trunkfish					.5			.5			.5
barracuda		.5		.5		1.5		.5	.5		
squirrel fish	.5	3.0	1.5	2.5	2.5	5.5	4.0	5.0	2.5	2.0	1.5
mojarra	.5			1.0			1.0	1.5	.5	1.5	.5

Table 8 (Continued)

Average number of fish per census per species for Fish Bay backreef (Rb) from January 1985 to February 1986. (Total # fish/# censuses).

Species	1/85	3/85	4/85	5/85	6/85	7/85	8/85	9/85	10/85	12/85	1/86
bar jack		.5				1.5					
total # species	12	12	9	12	9	13	12	13	11	11	11
total # individuals	105	104	123	103	116	120	118	151	109	119	103
average size (in)	5.31	4.76	4.69	4.96	4.73	5.35	4.95	4.63	4.91	4.72	4.66

Significant differences were demonstrated in number of individuals and species per census among study sites (Table 9). Reef Bay, with a total of 34 species observed, has the highest number of individuals (KRUSKAL-WALLIS, H=82.42, DF=2, P<.001) and species (KRUSKAL-WALLIS, H=48.92, DF=2, P<.001) for the three deeper water sites (Hawksnest SBpr, Reef Rfl, Fish Rfl). This is probably related to the high relief of the site providing more abundant shelter. In comparison, Fish Bay yielded the same number of species but demonstrated a very low mean number of individuals observed per sample date. This is probably due to the low vertical relief of the site.

Significant differences existed in number of individuals and species per census among sample dates for the three deep sites combined. Numbers of individuals differed significantly among dates (KRUSKAL-WALLIS, H=24.37, DF=11, P <.05) with larger means occurring from June to September. Number of species also differed significantly among dates (ANOVA, F=2.45, DF=11, P<.01) with no clear temporal pattern.

Total number of species differed between shallow and deep habitats with upper forereef and backreef areas having the lowest number of species and the lower forereef and shallow bay patch reef having the greatest (Table 9). This is consistent with the results obtained from a fishery habitat mapping study (Boulon, 1985a). The shallow bay patch reef had the greatest number of species and this is probably related to the nature of patch reefs to concentrate species from surrounding less productive or low relief areas which do not provide adequate shelter.

The only species demonstrating any evidence of a seasonal variation in numbers are yellow and spotted goatfish. The inshore upper forereef had a dramatic increase in schools of small yellow goatfish in September and October. The two lower forereef sites on the south shore had peaks in numbers of spotted goatfish in September. It appears that juvenile yellow goatfish aggregate in shallow water while juvenile spotted goatfish tend to stay in deeper water. No obvious variations are evident for other species. Small fluctuations which appeared to be differences were treated with caution for such fluctuations could be a product of observer biases (see Summary Conclusion).

With the observed differences among bays and dates during the period of this study, the data provides a base to measure long-term changes in the fish assemblages at these sites. Future samples of replicated censuses conducted during a defined period should provide information on stability or decline of the fish assemblages. At present there are no comparable studies for other areas in the United States Virgin Islands which would enable statements to be made regarding state of these populations (i.e. are we looking at primarily juvenile, heavily overfished populations, etc.?) Commercial biostatistical sampling data for the U.S.V.I. has never been

TABLE 9. Sample statistics for each of the long-term reef fish monitoring sites on St. John, USVI.

	Hawksnest Bay			Reef Bay	Fish Bay	
Statistic	SBpr	Southern Rfu	Eastern Rfu	Rfl	Rfl	Rb
Total No. Species	36	22	19	34	34	18
$\bar{X}$ Species/sample (sd)	21.4 (2.19)	11.5 (2.27)	11.6 (1.07)	21.0 (2.40)	16.5 (1.75)	11.4 (1.30
$\bar{X}$ Fish/sample (sd)	428 (127)	388 (89)	363 (140)	657 (185)	298 (110)	116 (13)

analyzed for size by species so comparisons cannot be made as to what is being taken out of the resource.

Lobster - *Panulirus argus* and *P. guttatus*

Methodology

The same three watersheds were selected for long-term lobster population monitoring for the same reasons as with reef fish. The method used for monitoring the populations was simply to delineate an area to be studied and then thoroughly canvass it on a monthly basis. All ledges, crevices, and holes were carefully examined and all spiny (*Panulirus argus*) and spotted (*P. guttatus*) lobsters were counted. For each lobster an estimate was made as to carapace size (measured from the ridge between the horns to the posterior edge of carapace). A flashlight was used to examine the tops and backs of the deeper caves. Spiny lobsters are usually easily seen because they generally are found on the floor of the caves. Spotted lobsters are more difficult to find because they seem to prefer the tops of the caves. Due also to their smaller size, it is very likely that their abundance is underestimated. Capture of the lobsters for determination of sex and reproductive state was not performed due to the potential for injury or trauma to the lobster.

Underwater maps were drawn of the study areas (Appendix Ia and Ib) and locations of lobster were marked on mylar overlays. By comparing monthly surveys as to size and location, some idea of residency can be determined.

Reef Bay

The lobster monitoring site at Reef Bay was located within the reef fish monitoring site (Figure 4). The study area was located on the seaward side of the fringing reef and includes the 50m coral monitoring site (Rogers and Zullo, 1986) (Appendix Ia) plus an additional 100m section of reef contiguous to and west of the 50m coral monitoring site. The study area is approximately 15m wide from the bottom of the reef at 11m to approximately 3m in depth. The total area monitored was approximately 2250m .

This site is exposed to the predominant wind and waves from the south and southeast and is frequently rough. Nine monthly samples were made at this site from April 1985 to February 1986 (Table 10). Numbers of spiny lobster found during this period ranged from zero to four per sample with all being less than 3.5 inches in carapace length and all being found in the 100m extended portion of the study area. No spiny lobster (*Panulirus argus*) were found on four of the sample dates. Numbers of spotted lobster (*P. guttatus*) found during this period ranged from zero to 10 per sampling date. Seventy-four percent (74%) of

TABLE 10. Numbers of spiny and spotted lobster by two size classes per sample date for two long-term monitoring sites, St. John, USVI. Dashes indicate no data available.

		1985									1986	
		Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb
Reef Bay	Spiny (>3.5")	0	0	0	0	0	0	0	-	0	-	0
	(<3.5")	0	0	0	2	1	4	2	-	1	-	0
	Spotted (>2")	0	0	1	0	2	2	7	-	6	-	5
	(<2")	0	1	0	1	0	0	0	-	4	-	2
Sea + conditions:		2	2	1	1	1	1	1	3	1	3	1
Visibility:		15'	15'	20'	30'	30'	30'	20'	-	30'	-	30'
Fish Bay	Spiny (>3.5")	0	0	0	3	5	2	1	-	1	2	3
	(<3.5")	2*	0	1	5	2	6	0	-	1	10	1
	Spotted (>2")	0	0	0	1	2	3	2	-	2	5	4
	(<2")	0	0	0	0	1	1	2	-	1	3	0
Sea + Conditions:		2	2	2	1	1	1	2	3	2	1	1
Visibility:		15'	20'	20	60	30'	40'	20'	-	20	30'	20'

\+ 1 - calm (waves <2')
2 - rough (waves 2'-4')
3 - very rough (waves >4')

* Both were molts

the spotted lobsters found had carapace sizes greater than or equal to two inches, a size chosen by the author as a possible size representing maturity as the size range observed was 1.5 to 3 inches. Only one sample contained no spotted lobsters.

During the study period, there appears to be some indication of seasonality of abundance for both species (Figure 6). Spiny lobsters were not seen for the first three months of the study. Their numbers increased to a peak in September and then decreased to zero again in February 1986. Spotted lobster showed a gradual increase in numbers from zero at the beginning of the study to a peak in December and then an apparent decrease after that. Caution should be exercised in interpretation of the observed trends due to the small sample size and the monthly gaps in the data set at the end of the study.

Fish Bay

The lobster monitoring site at Fish Bay was located within the reef fish monitoring site (Figure 5). The study area is located in the lower forereef spur system where many undercuts and coral overhangs occur along the interfaces between the spurs and the sand separating them. Due to the topography of this reef system (see Appendix Ib), the boundaries do not form a simple geometric shape resulting in difficult areal computation. A rough estimate of area within the boundaries is approximately 1600m .

Ten monthly samples were made at this site from April 1985 to February 1986 (Table 10). Numbers of spiny lobster found during this period ranged from zero to twelve per sample date with 40% being 3.5 inches or larger in carapace length. No live spiny lobsters were found on two occasions although two molts were found on one of these occasions. Numbers of spotted lobster found during this period ranged from zero to eight with 70% having carapace sizes greater than or equal to two inches. Three samples contained no spotted lobsters.

During the study period, there appears to be some indication of seasonality of abundance for both species of lobsters (Figure 6). For spiny lobsters there appear to be two peaks in abundance, one in the summer as was seen at Reef Bay, and another one in the winter, which was not observed at Reef Bay. Spotted lobsters show a seasonal trend very similar to that observed at Reef Bay. None were observed at the start of the study and numbers then increased to a peak in January and dropped off rapidly after that.

Hawknest Bay

The shallow bay patch reef in Hawksnest Bay was selected as a long-term monitoring site for lobster due to its location in the bay and the presence of suitable lobster habitat. The reef was surveyed monthly along its forereef side only as the rest of

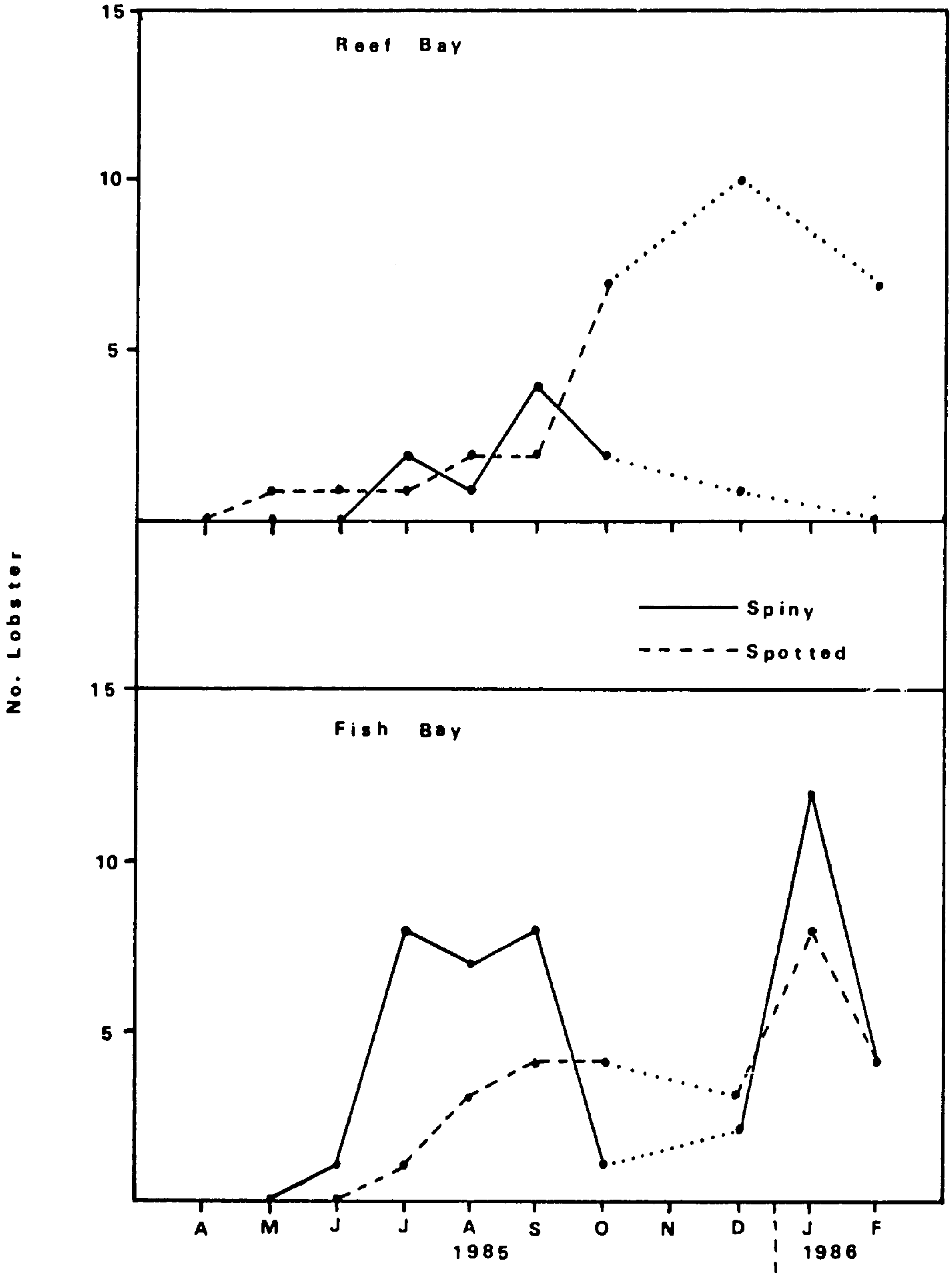


Figure 6. Numbers of spiny and spotted lobster per sample date for two long-term monitoring sites, St. John, USVI. Dotted lines indicate months where no sample was obtained.

the reef provides no significant habitat for lobsters. In all cases these surveys were conducted on the same date as fish censuses.

Eleven visits were made to this reef during the study period. Only one spiny lobster (carapace length approximately five inches) was observed on the reef (August '85). No spotted lobster was ever observed on the reef.

General Surveys

During the months of July and August 1985, nine additional sites around St. John were surveyed for lobster abundance (Figure 7). Sites were surveyed either using a measuring tape or by swimming an area and estimating the size. Minimum estimated area is indicated by a plus sign in Table 11 (e.g. 1000m +).

Spotted lobsters were very common in all general surveys carried out in Reef Bay. Many areas containing good lobster habitat (Ram Head, western Hawksnest Bay and Western Haulover Bay) were surprisingly depauperate of lobsters. No juvenile lobsters were observed in the mangroves in Hurricane Hole. Three of the spiny lobsters observed in Mary's Creek were beneath undercut portions of shallow *Thalassia* grass beds in the bay. All three were from 1.5 to 2 inches in total body length. Observations based on general surveys east and west of the long-term study site in Fish Bay demonstrated that the selected monitoring site was the optimum (or at least preferred) lobster habitat.

General Conclusions

Although there is some evidence of seasonal variations in abundance for both spiny and spotted lobster at Fish Bay and Reef Bay, another factor became evident during the study, which may influence the observed differences. Abundance of observed lobsters appears to be affected by sea conditions. Table 10 shows sea condition and visibility for each survey date. The presence of a swell or surge of sufficient magnitude to cause sediment suspension and movement causes visibility to decrease. The lower number of lobsters observed under these conditions may be due to lobsters becoming more difficult to observe or lobsters moving deep into caves or into deeper, more protected water. A combination of the first two possibilities seems more likely as movement into deeper water would not be a rapid process, would be very energy intensive, and could be necessary frequently depending on the frequency of swells.

Although no fishermen were observed at either of these sites during the study period, it is known that recreational fishermen (including sport divers) and some St. Thomas commercial fishermen do dive here and take lobster. Many people have mentioned that these areas are good lobstering spots which would indicate general knowledge. Interpretation of any results from these areas must therefore acknowledge the potential for harvest.

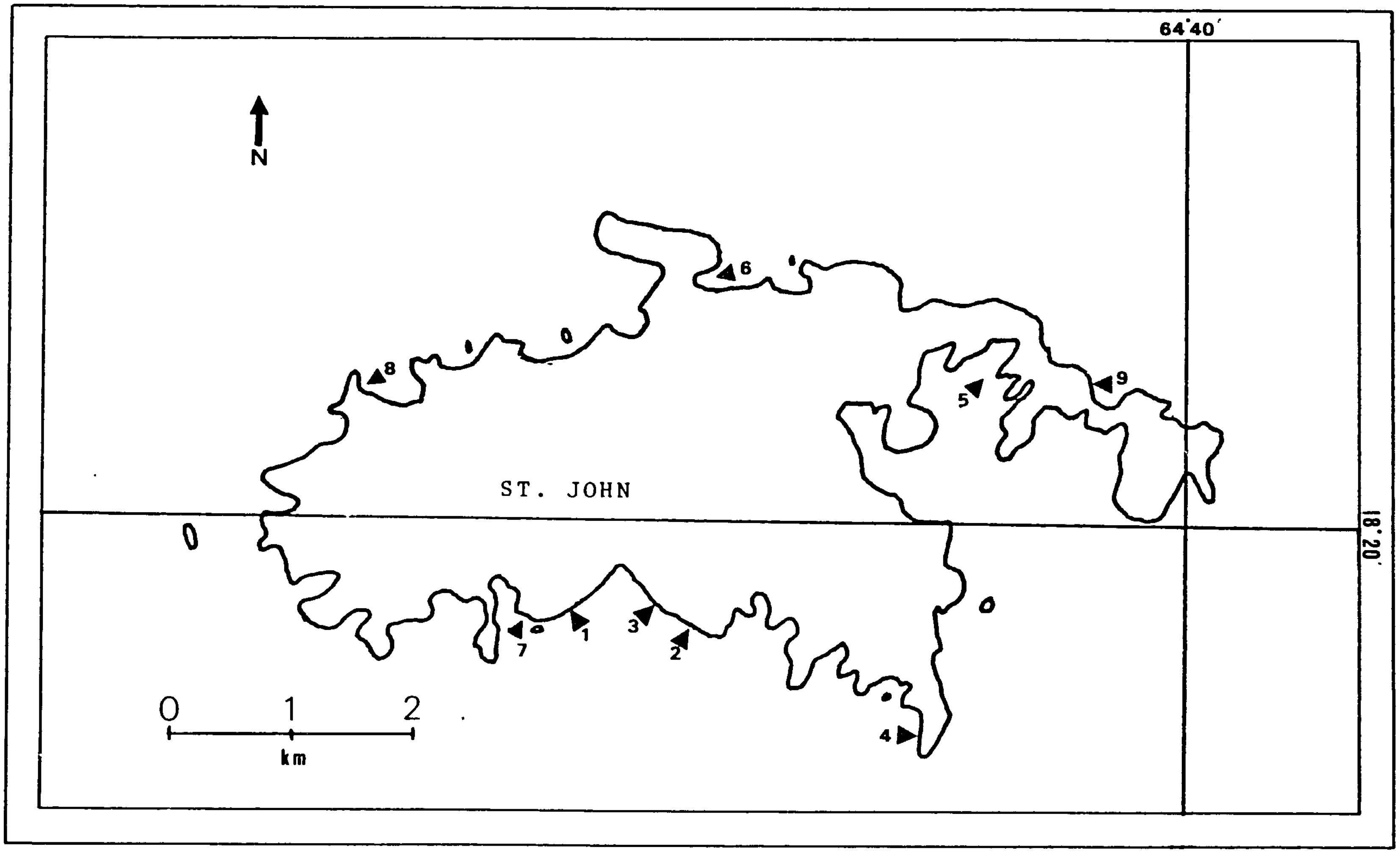


Figure 7. Location of general lobster surveys , St. John, USVI.
Refer to Table 11 for location names.

TABLE 11. Results of general lobster survey around St. John, USVI, during the summer of 1985. Refer to Figure 7 for locations.

Location	Date	Approximate area surveyed	Numbers by Carapace Size Spiny <3.5"	Spiny >3.5"	Spotted <2"	Spotted >2"
1. Western Reef Bay	7/1/85	300m^2	1	0	1	8
2. Eastern Reef Bay (White Cliffs)	7/1/85	1900m^2	0	1	0	3
3. Eastern Reef Bay (west of White Cliffs)	7/1/85	1900m^2	0	0	1	4
4. West Ram Head	7/12/85	500m^2	0	0	0	0
5. Hurricane Hole (Mangroves)	7/17/85	500m^2	0	0	0	0
6. Mary's Creek (mangroves/grass beds)	7/25/85	500m^2	4	0	0	0
7. Fish Bay (west & east of study area)	7/31/85	500m^2	0	1	2	0
8. Hawksnest Bay (western shore)	7/27/85	1000m^2	2	0	0	0
9. Haulover Bay	8/6/85	1000m^2	1	0	0	1

The three sites surveyed appear to have different potentials for lobster presence and abundance. The Hawksnest Bay site has the least potential due to limited habitat coupled with its location in a deep embayment (reduced circulation lowers recruitment and food supply). Although the largest lobster of the entire study was seen here, large lobsters may be very mobile and are probably transient.

Fish Bay appears to have the best lobster habitat of the three long-term monitoring sites. It has good water circulation, and many good refuges for lobster. This site had significantly more spiny lobster greater than 3.5 inches in carapace length than Reef Bay (Mann-Whitney U=76.5, P=.05). No significant differences were observed in total numbers of spiny lobster or spotted lobster among Fish and Reef Bays.

Spotted lobster may be more abundant than observed in this study. They are difficult to observe because they are usually on the roofs of caves and their smaller size allows them to be cryptically hidden in the smaller caves and crevices in a reef system. They are more cryptic than spiny lobsters. Fisherman generally do not take them since they are small and there is no market for them. These factors, combined with their total protection in park waters, probably makes them more abundant than spiny lobsters.

None of the spiny lobsters observed were long-term residents of one particular hole. In Fish Bay, where actual locations of lobster sightings were recorded, no single spiny lobster was observed for more than two months in the same hole. No single hole had spiny lobsters present in it for more than a three-month period. Spotted lobster appear to be more resident. Residency could only be documented with a tagging study.

Conch - *Strombus gigas*

Methodology

Five sites were originally selected for long-term monitoring of queen conch(*Strombus gigas*) populations. These include Reef Bay, Outer Fish Bay, Inner Fish Bay, Hawksnest Bay and the small bay east of Leinster Bay which will be referred to from now on as Threadneedle Bay (it is bounded by Leinster Point to the west and Threadneedle Point to the east) (Figure 1).

Visual swimming strip transects were used to estimate conch densities and determine abundance and adult to juvenile ratios. A one-hundred meter long, fiberglass tape measure, weighted at both ends, was laid out on the bottom. A diver then swam the transect line, counting all conch within 2m of each side of the line. Conch were recorded as adult or juvenile, based on the presence or absence, respectively, of a flared lip. Number of strip transects varied between sites, depending on size and nature of the site, but the same number of transects were made on each sample date at each site. SCUBA was used at deeper sites (>3m) or where visibility is such that repeated free diving would cause inaccuracies in the counting of conch.

Reef Bay

Seaward of the fringing reef along the west side of Reef Bay is a rather extensive seagrass bed (Figure 4). The grassbed is composed of sparse to moderate density *Syringodium filiforme* and appears to be good habitat for conch. However, this area was spot-checked a number of times during the entire study period and not a single queen conch (*Strombus gigas*) was observed. As queen conch tend to aggregate near the sand-grass interface, this was checked nearly every time fish surveys were completed at this study site. On several occasions forays were made up to 20m into the grassbed to determine if conch were present in the interior parts of the grassbed.

Hawksnest Bay

Hawksnest Bay has been reported to have large areas of dense seagrasses within the bay (Kumpf and Randall, 1971; E. Gibney, pers. comm.). Although these areas are still reported to exist, the density of seagrasses within these areas is reported to be low to moderate (Beets, et al., 1985) and very much reduced, presumably due to heavy anchoring in the area (E. Gibney, pers. comm.).

In both April and August of 1985 large portions of the bay were surveyed by swimming and towing. No conch except for a few West Indian fighting conch (*Strombus pugilis*) were observed. The grassbed to the east of the shallow bay patch reef was spot-checked several times during the entire study period in conjunction with fish surveys at this site. No queen conch were ever seen at this site.

Fish Bay

Inner Fish Bay

The inner part of Fish Bay is a shallow seagrass bed of moderate to dense *Thalassia testudinum* (Figure 5). This bay is reported to have had large populations of juvenile conch (no flared lip). Unfortunately, harvesting of these juvenile conch has severely diminished the numbers. Piles of empty juvenile shells in places along the shoreline yield evidence of the harvesting.

In the middle of the bay is a large mooring buoy that has been unused for at least two years. This mooring was used as the apex for two 100m long by four meter wide strip transects. These two transects yielded 800m^2 of area surveyed per sample date. Eleven monthly samples were made from March 1985 to February 1986 (Table 12). While numbers of both adult and juvenile conch were very low, there does appear to be a trend during the study period (Figure 6, top). Both adults and juveniles peaked in abundance in late Spring and then declined through the rest of the study period. Juveniles were more abundant than adults throughout the study period.

Outer Fish Bay

Seaward of the lower forereef described in previous sections there is a seagrass bed (11m deep) that is composed of moderate to dense Syringodium (Figure 5). This seagrass bed parallels the shoreline in this area and is at least 100m wide. Seaward, this grass bed grades into an algal plain. To the east, the grass bed extends around Cocoloba Cay and into Reef Bay. The grass bed to the east of Cocoloba Cay was surveyed in September 1985 and found to have a lower density of conch than the study area selected just seaward of the lower forereef in Fish Bay.

Four parallel 100m by four meter strip transects were traversed approximately 10m apart from each other on each sample date. The four transects were made in the same general location on each sample date. These yielded 1600m of area surveyed per sample date. Ten monthly samples were made from February 1985 to January 1986 (Table 12). Rough seas and poor visibility prevented missing samples from being taken. Throughout the study period, numbers of juvenile conch remained very low. Numbers of adult conch exhibited a very distinct seasonal variation with a peak in the winter and a low during the summer (Figure 8, middle). Summer is the reproductive season with numbers of conch observed copulating only in July and laying egg masses in August.

In general, conch in this grass bed were associated with the grass/sand "blowouts" in the grass bed. Conch were not extremely common in the interior dense seagrass areas, except for the last sample which also had the greatest number of conch observed during the study period. Numbers of adult milk conch (Strombus costatus) were observed in interior parts of the grass bed where a greater abundance of macroalgae occurs.

Threadneedle Bay

To the east of Leinster Bay on the north shore of St. John, there is a small shallow bay located between Leinster Point and Threadneedle Point (Figure 9). The seagrass bed parallels the shoreline and is bounded inshore by a fringing reef and offshore by sand grading into a deep water algal plain and rubble bottom. The seagrass bed is composed of moderate to dense Thalassia and is approximately 300m long and 30m wide. Two 100m strip transects were made at this site on each sample date. The transects were started at the approximate center of the grass bed

TABLE 12. Numbers of adult and Juvenile conch per sampling date for three long-term monitoring sites, St. John, USVI. Dashes indicate that no sample was taken.

Months	Inner Fish Bay ($800m^2$)			Outer Fish Bay ($1600m^2$)			Threadneedle Bay ($800m^2$)		
	*N/A	+N/J	D	N/A	N/J	D	N/A	N/J	D
Feb. (1985)	-	-	-	208	2	.13	0	1	.001
Mar.	0	0	.0	198	0	.12	0	0	0
Apr.	6	4	.01	127	3	.08	1	10	.01
May	-	-	-	-	-	-	8	26	.04
June	2	13	.02	102	5	.07	2	27	.04
July	3	5	.01	71	6	.05	4	11	.02
Aug.	1	3	.004	88	7	.06	0	10	.01
Sept.	0	3	.005	120	4	.08	0	3	.004
Oct.	0	5	.006	147	7	.10	1	21	.03
Nov.	0	2	.003	131	7	.09	1	22	.03
Dec.	0	2	.003	-	-	-	1	0	.001
Jan.	1	3	.005	282	1	.18	-	-	-
Feb.(1986)	0	2	.003	-	-	-	136	401+	.67
$\bar{X}$	1.18	3.82		147.4	4.2		12.8	14.3	
sd	1.88	3.37		64.3	2.62		38.86	12.9	

*N/A = Number of Adults
+N/J = Number of Juveniles
D = Density (Conch/m2)

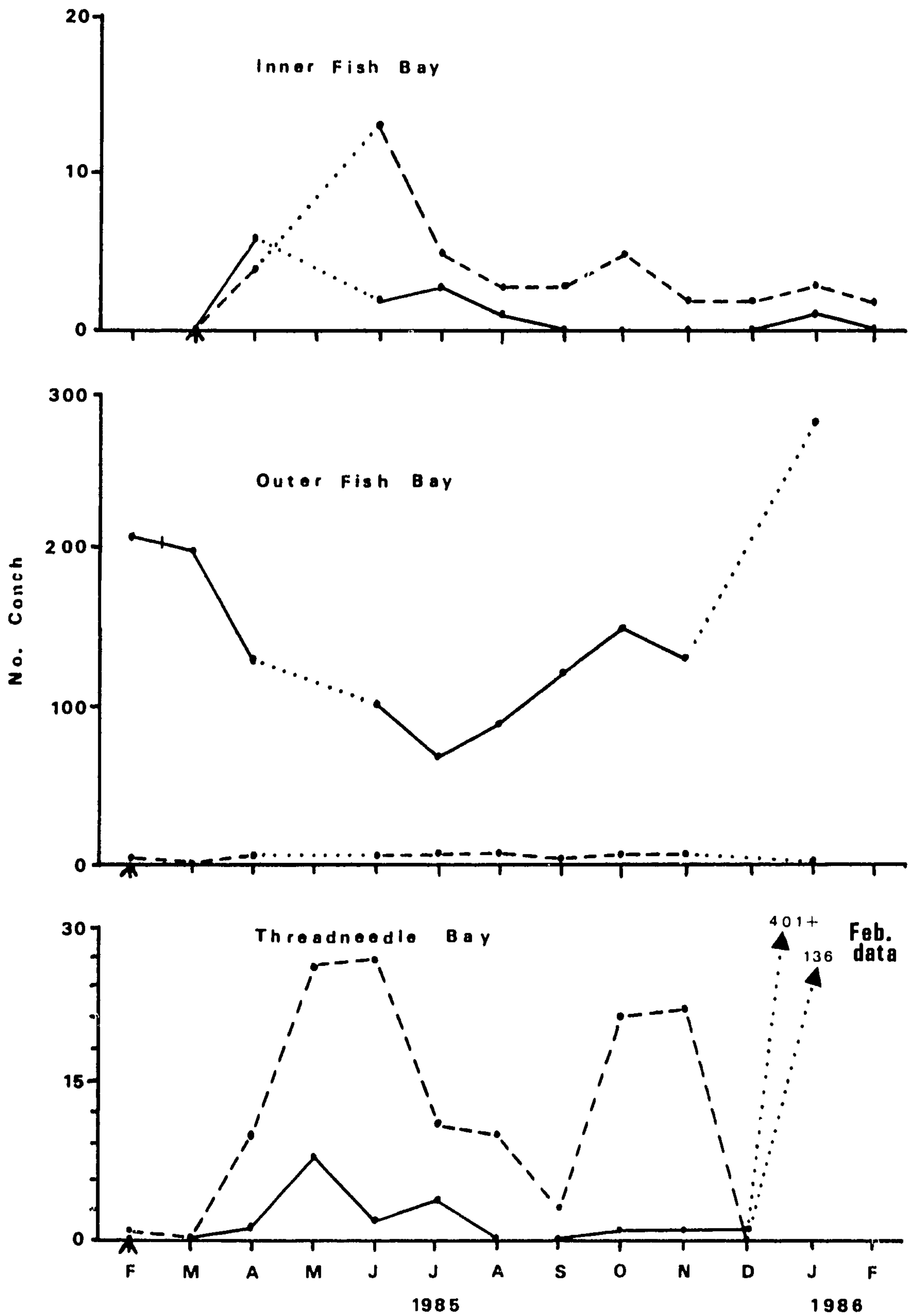


Figure 8. Numbers of adult and juvenile conch for three long-term monitoring sites on St. John, USVI. Arrow indicates date of first sample. Solid lines represent adults, dashed lines represent juveniles and dotted lines indicate months where no sample was obtained.

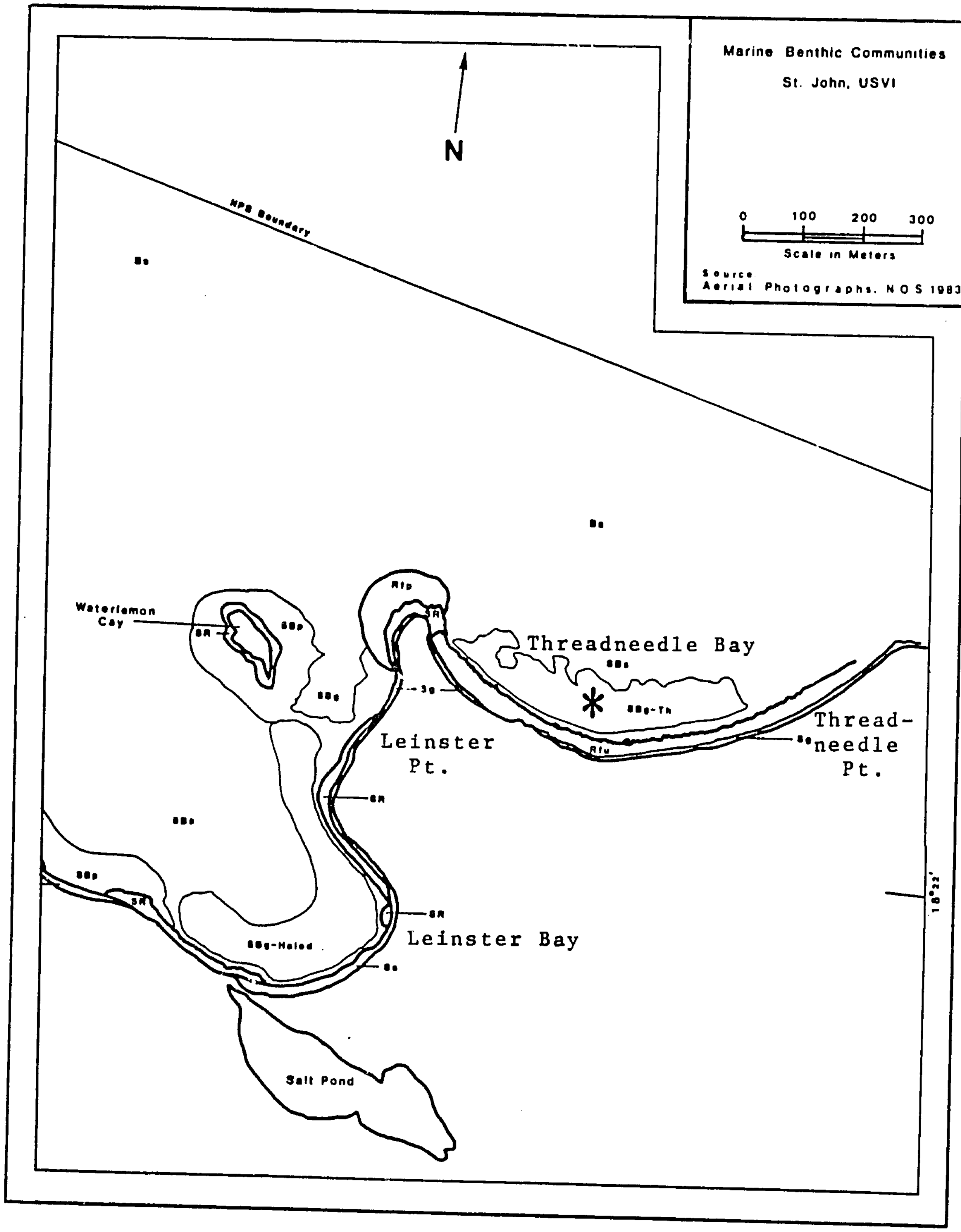


Figure 9. Threadneedle Bay, St. John, USVI, showing location of study site for long-term monitoring of conch population. * denotes study area. See Table 3 for acronyms.

241

and run 100m in each direction (east and west) approximately 10m in from the shoreward edge of the grass bed to yield $800m^2$ to area surveyed per sample.

Twelve monthly samples were obtained at this site during the period from February 1985 to February 1986 (Table 12). Few conch were actually observed in this bay during all but the last month of the study. The majority of conch cou.ted were juveniles. During the first eleven samples, numbers fluctuated considerably yielding no visible seasonal trends (Figure 8, bottom). There are two peaks which coincide roughly with the two peaks observed at the Inner Fish Bay site. Abundance of adult conch showed a similar pattern as well to the adult conch observed at the Inner Fish Bay site. On the last sample of the study period, however, the populations of both adult and juvenile conch increased tenfold. One hundred and thirty six adults were observed, of which over 90 percent were old, heavily eroded, thick-lipped "bullet" conch. The juveniles were mostly in the seven to twelve centimeter range and covered the bottom in large, dense patches.

General Surveys

General surveys for distribution of conch populations around St. John were conducted in two ways. The first was a repeat of a series of conch tows that were made in 1981 (Wood and Olsen, 1983). The second was a series of spot surveys in sites where conch habitat was known to exist or conch were known to have been found in the past.

Nine conch tows were made attempting to duplicate as closely as possible, through bearings and distances, the exact locations and lengths of tows made by Wood and Olsen (1983) (Figure 10). Tows were made using a diving sled (pictured in Kumpf and Randall, 1971) towed by a boat. The sled was manipulated by the diver in such a way that it was maintained close enough to the bottom so that all conch could be counted within a swath approximately four meters wide.

Numbers of conch observed in 1985 were not significantly different from numbers observed in 1981 (Mann-Whitney U Test, $U_{.05}=60.0$) (Table 13). In 1981 four of the nine tows had more conch than in 1985. All of these were within National Park boundaries. In 1985, two tows had more conch than in 1981. Both of these were outside National Park boundaries.

Fourteen sites were spot-checked for conch (Figure 10, Table 14). This consisted of selecting a site and having divers swim over it noting bottom type and numbers of conch observed. Approximate area of surveys was estimated. Few to no juveniles were observed at sites which can be considered good juvenile habitat (shallow, protected, with ample food resources) (sites 1, 2, 5, 6, 7, 10, 11, 12 and 13). Very few adults were observed at sites which can be considered adequate or good adult habitat (sites 2, 3, 4, 8, 9, 12 and 14). Many harvested conch were observed at several sites.

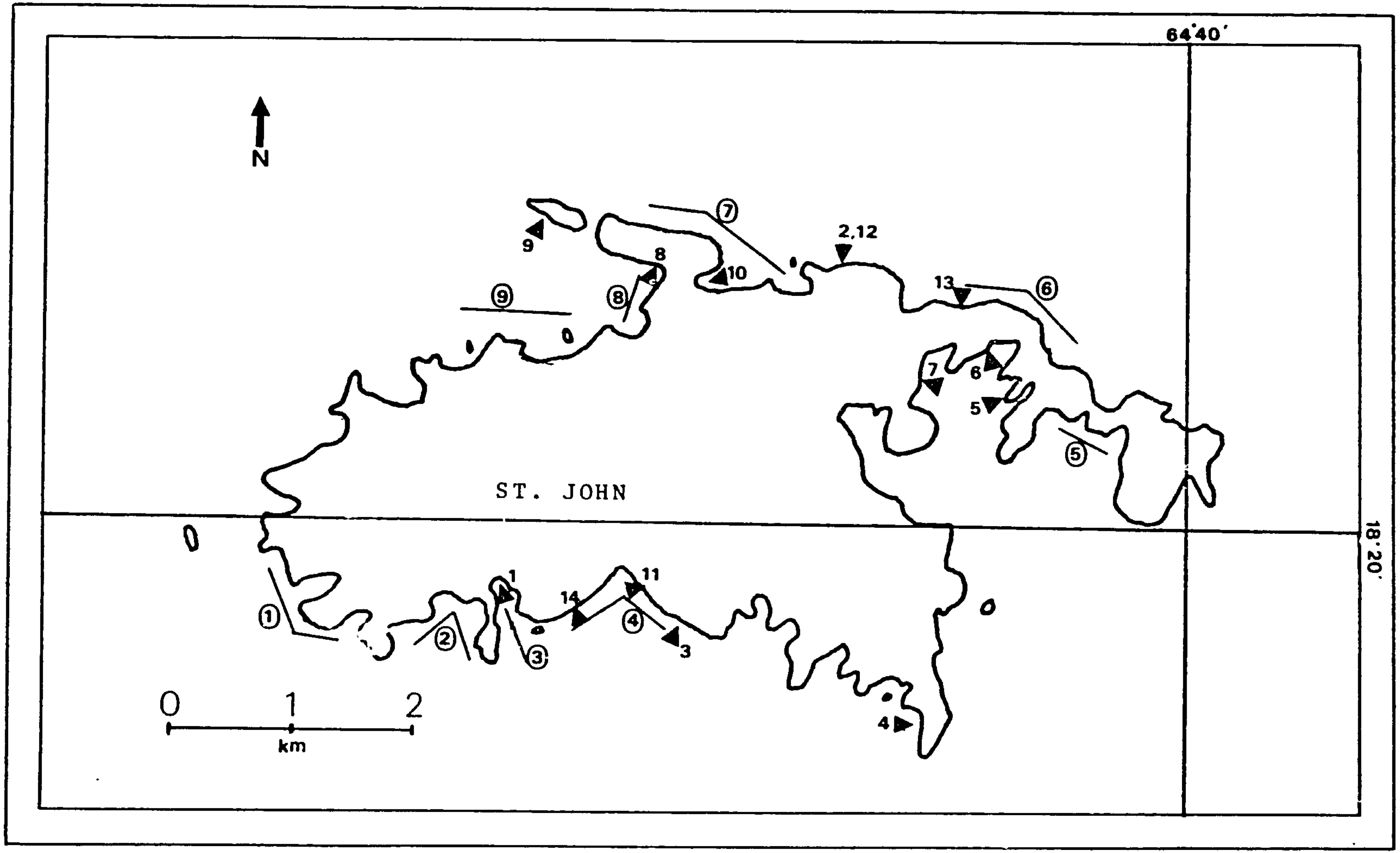


Figure 10. Location of conch tows and general surveys (◀), St. John, USVI. Refer to Tables 15 and 16 for location names. Circled numbers represent conch tows.

TABLE 13. Results of conch tows duplicating those made in 1981 by Wood and Olsen (1983). Refer to Figure 10 for locations. Numbers in parentheses are densities in conch per square meter.

Location	Date	Approximate Area Surveyed(m^2)	No.Conch	No.Conch in 1981
1. Turner Bay to Chocolate Hole	8/20/85	9000	34(.003)	25(.003)
2. Rendezvous Bay	8/20/85	7500	68(.009)	32(.004)
3. Fish Bay	8/20/85	3000	8(.003)	26(.009)
4. Reef Bay	8/21/85	12500	34(.003)	45(.004)
5. Round Bay	8/21/85	2500	-0-(0)	-0-(0)
6. West of Haulover Bay	8/7/85	9600	61(.006)	167(.017)
7. Leinster Bay/ Mary's Point	8/7/85	16500	59(.004)	128(.008)
8. Francis Bay	8/7/85	2100	-0-(0)	-0-(0)
9. Cinnamon Bay to Trunk Bay	8/7/85	9200	-0-(0)	-0-(0)

TABLE 14. Results of general conch surveys around St. John, USVI, during the summer of 1985. Refer to figure 10 for locations.

Location	Date	Approx. Area Surveyed	Numbers Observed	Bottom Type*
1. Inner Fish Bay	7/2/85	Inside long-term transect to shore	None	Dense Th
2. Bay E. of Leinster	7/2/85	Seaward of long-term study area	3 adults	Moderate Th
3. Eastern Reef Bay	7/12/85	3000m	1 adult	Moderate Th/Sy
4. West Ram Head	7/12/85	1000m	6 old adults	Sparse Sy
5. Otter Creek/ Water Creek	7/17/85	1000m +	None	Algae on sand
6. Borck Creek/ Popilleau Bay	7/17/85	1000m +	None	Moderate Th/Sy
7. Princess Bay	7/17/85	1000m +	61 harvested shells	Moderate Th
8. Francis Bay (Northside)	7/25/85	1000m +	None	Sparse Sy/Hal
9. Whistling Cay	7/25/85	500m +	None	Sparse Sy
10. Mary's Creek	7/25/85	1000m +	2 juveniles	Th and coral rubble
11. Reef Bay (Lg)	7/24/85	500m +	1 juvenile	Dense Th
12. Bay E. of Leinster	8/6/85	500m + (E. of L-T study area)	15 adults 5 juven-iles	Moderate Th/Sy
13. Bay E. of Brown Bay	8/7/85	1000m +	3 juveniles 50 harv-ested shells	Moderate Th/Sy

Table 14. (Continued)

Results of general conch surveys around St. John, USVI during the summer of 1985. Refer to Figure 10 for locations.

Location	Date	Approx. Area Surveyed	Numbers Observed	Bottom Type*
14. Western Reef Bay	9/3/85	$500m^{2+}$	Low density	Moderate Sy

* Th - Thalassia testudinum
Sy - Syringodium filiforme
Hal - Halodule wright

2k

General Conclusions

The five long-term monitoring sites provide information on variation in conch abundances among locations around St. John. Hawksnest Bay, reported by residents to once have had an unquantified abundance of conch, now appears to have none. This may be due to past heavy harvesting coupled with past and present habitat degradation, primarly due to heavy anchoring impacts on the seagrass beds. Reef Bay presents a perplexing situation in that the grassbed surveyed appears to be adequate habitat for queen conch and yet no conch were ever observed there.

Inner Fish Bay has adequate habitat for juvenile conch as evidenced by past observations (Boulon, 1985b). Present low numbers may be due to movement of the conch, harvest of the juveniles or inadequate recruitment. Piles of harvested juvenile shells on shore attest to the fact that harvest may occur there. Outer Fish Bay has the greatest abundance of conch observed anywhere in National Park waters. This area should probably be entirely closed to harvest of conch to protect it. A significant difference was observed among months for numbers of conch at this site (KRUSKAL-WALLIS, $H=20473$, $DF=9$, $P<.05$) with June to August having the lowest number of conch. The seasonal trend observed here in 1985 is very similar to the trend observed in the four samples taken between March and June 1984 (Boulon, 1985b). A comparison of the two sets of samples for that period shows a decline in numbers to lowest abundance in July 1985.

Observations on mating and egg laying during July and August suggests that a peak reproductive season exists. That this coincides with the low peak in numbers of inshore conch suggests that they may be migrating offshore into deeper water to mate and lay their eggs. This movement pattern would bring them into contact with other individuals in the population, provide greater protection from storm-induced sediment movement for the egg masses and/or enhance larval dispersal by ocean currents. This movement pattern is similar to that described by Hesse (1979) for the Bahamas but may occur somewhat earlier in the year. She described the offshore migration in September and October. Coulston, et. al. (1985) describe an offshore movement of conch during the period from November to March at Salt River, St. Croix, U.S.V.I. This observation differs from ours and demonstrates the variation that apparently exists among sites. Coulston, et. al. (1985) reports a reproductive period from March to November in shallow water (50 to 70 feet).

Threadneedle Bay does not appear to have a stable population of conch. The 1984 data showed evidence of rapid population changes going from 80% (165) adult and 20% (44) juvenile in one sample to 99% (253) juvenile and 1% (2) adult six weeks later (Boulon, 1985b). This year's data suggested that a low abundance of primarily juveniles inhabited the bay.

However, the last sample increased these numbers by tenfold. The older "bullet" conch observed in this sample may have moved inshore from deeper water (15-20m) populations known to exist immediately offshore of this site. The juveniles may be the year class from the 1984 reproductive season just becoming evident in the inshore habitat. Several investigators have estimated mean lengths for yearling conch to be from 7.6 to 10.8cm (Brownell, 1977; Berg, 1976). Prior to inshore movement and after settlement, these conch may have been dwelling offshore in the nearby deeper algal plain habitat, which may be advantageous in terms of growth and mortality (Appeldoorn and Ballantine, 1982). While a significant difference was observed among months at this site (KRUSKAL-WALLIS, H=18.709, DF=10, $P<.05$) no trends were evident.

Disregarding the final sample at Threadneedle Bay, the population fluctuations observed in this bay and in inner Fish Bay are somewhat similar. These patterns may reflect the background levels of conch and their fluctuations in shallow, inshore waters.

The results of the conch tows suggests that there has been no net difference in numbers of conch since 1981 in the deepwater areas. However, the comparison needs to be treated with caution due to possible differences in relocation of transects, observers, small sample size and differential harvest inshore and offshore.

In general it appears that the abundance of deeper water conch may be presently stable. This is probably due to lower fishing pressure in these less accessible areas. These individuals may be responsible for maintaining the inshore abundances. Shallow water individuals appear to be in trouble as evidenced by the quantity of available habitat and the paucity of conch inhabiting it. The continued harvest of subadult conch will lead to the gradual decline and eventual near extirpation of local populations.

Whelk - *Cittarium pica*

Methodology

The site selected for long-term monitoring of a whelk population within the Virgin Islands Biosphere Reserve is located along the north coast of St. John between Windswept Beach and Peter Bay (Figure 11). This section of coastline is bordered on its landward side by private property. The site was selected due to accessibility and known low levels of fishing pressure.

The site is composed of good whelk habitat varying from solid bedrock sheets extending down into the water to scattered boulders with occasional tide pools. Seaward of this site is a narrow fringing reef. Benthic filamentous algae appeared to be plentiful as a food resource for the whelks. The study area

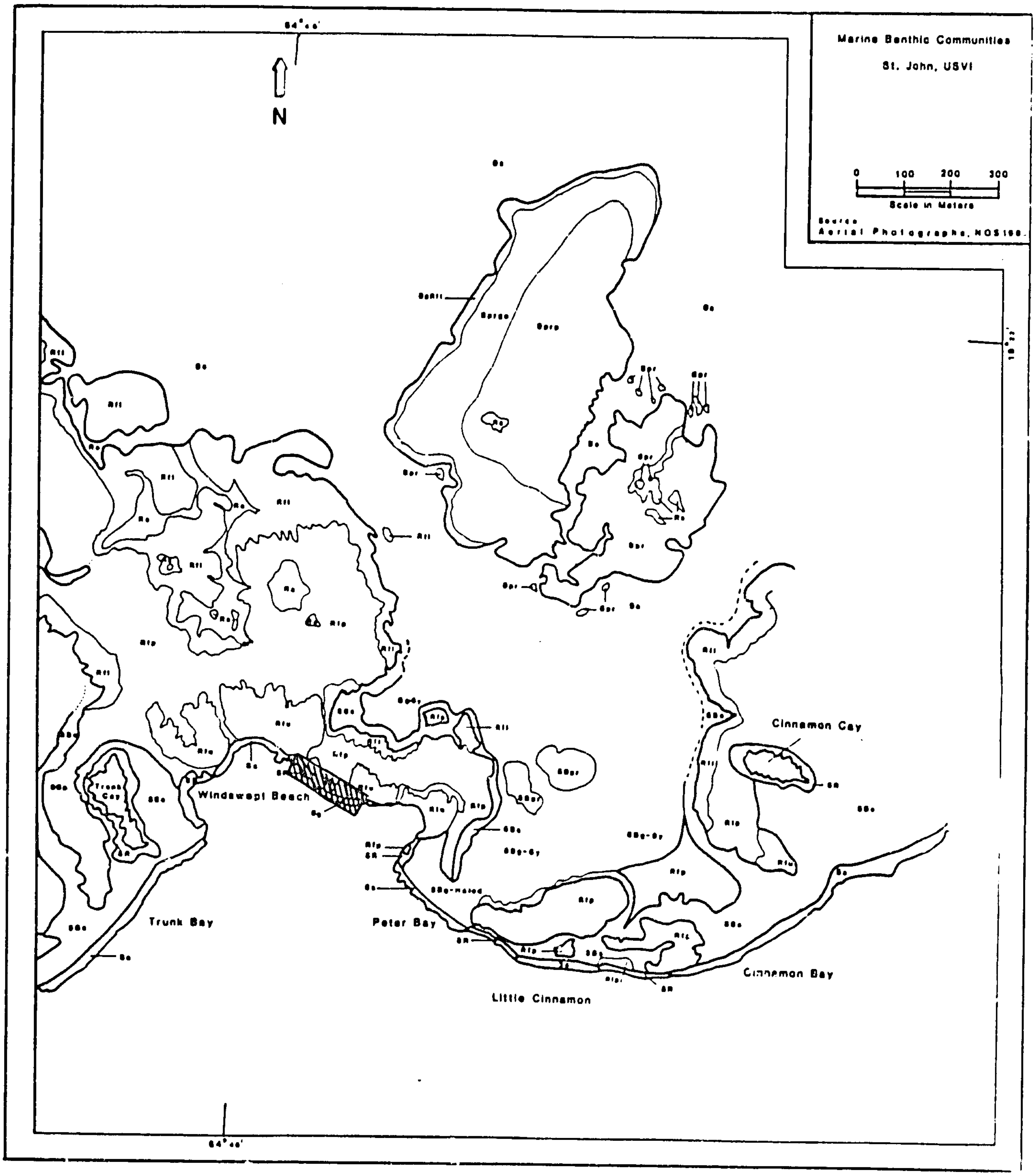


Figure 11. Windswept Beach, St. John, USVI, showing location of study site for long-term monitoring of whelk populations. [hatched box] denotes study area. See Table 3 for acronyms.

included approximately 100m of coastline.

Along this strip of coastline 10 randomly selected sampling sites were chosen. At each sampling site a one-meter wide strip transect was run perpendicular to the shoreline from above the high water mark to approximately one meter in depth seaward of the furthest offshore emergent boulders along the transect. All whelks were collected within this strip transect. Underwater portions of the transect were surveyed using mask and snorkle. After collection, all whelks were measured from tip of spire to distal edge of the lip and released at the capture site.

Results

Four quarterly samples were made during the study period with a mean of 33.5 (sd =6.28) whelks per strip transect (per meter of coastline) or a mean of 335 (sd =62.8) whelks per sample date (Table 15). There appears to be a greater number of whelks in the summer/early fall sampling than in the winter/spring samples. Although the number of whelks per sampling date varied, relative proportions of whelks in the larger size classes (greater than 2.5 cm) remained relatively stable for the study period (Table 15).

The greatest difference among samples occurred in the first four size classes (Figure 12). The first sample had the greatest number of whelks in the 0 to .49 cm size class. The second sample had the peak in the .50 to .99 cm size class. In the third sample the peak was in the .50 to 1.49 cm size classes and by the fourth sample the peak was in the 1.0 to 1.99 cm size classes.

Table 15. Numbers and relative abundance of whelk per size class on four sample dates at Windswept Beach, St. John, USVI. Density is expressed as number of whelk per meter of coastline.

Size Class (cm)			4/22/85	7/11/85	9/4/85	12/16/85
1.	0	- .499	84 (.36)	48 (.12)	13 (.04)	11 (.03)
2.	.5	- .999	43 (.18)	117 (.29)	104 (.29)	26 (.08)
3.	1.0	-1.499	39 (.17)	66 (.16)	98 (.27)	113 (.33)
4.	1.5	-1.999	21 (.09)	32 (.08)	32 (.09)	102 (.30)
5.	2.0	-2.499	13 (.06)	21 (.05)	19 (.05)	33 (.10)
6.	2.5	-2.999	7 (.03)	36 (.09)	20 (.06)	14 (.04)
7.	3.0	-3.499	5 (.02)	26 (.06)	18 (.05)	12 (.04)
8.	3.5	-3.999	4 (.02)	15 (.04)	14 (.04)	12 (.04)
9.	4.0	-4.499	4 (.02)	10 (.02)	6 (.02)	5 (.01)
10.	4.5	-4.999	3 (.01)	11 (.03)	8 (.02)	-0- (0)
11.	5.0	-5.499	1 (.004)	4 (.01)	4 (.01)	-0- (0)
12.	5.5	-5.999	-0- (0)	1 (.002)	1 (.003)	2 (.006)
13.	6.0	-6.499	-0- (0)	2 (.005)	1 (.003)	2 (.006)
14.	6.5	-6.999	1 (.004)	1 (.002)	1 (.003)	1 (.003)
15.	7.0	-7.499	-0- (0)	3 (.007)	2 (.006)	1 (.003)
16.	7.5	-7.999	-0- (0)	2 (.005)	4 (.01)	2 (.006)
17.	8.0	-8.499	2 (.008)	-0- (0)	-0- (0)	-0- (0)
18.	8.5	-8.999	4 (.02)	2 (.005)	2 (.006)	-0- (0)
19.	9.0	-9.499	3 (.01)	7 (.02)	4 (.01)	-0- (0)
20.	9.5	-9.999	-0- (0)	2 (.005)	3 (.008)	2 (.006)
21.	10.0	-10.499	1 (.004)	3 (.007)	2 (.006)	-0- (0)
22.	10.5	-10.999	-0- (0)	-0- (0)	-0- (0)	1 (.003)
23.	11.0	-11.499	1 (.004)	-0- (0)	1 (.003)	-0- (0)
24.	11.5	-11.999	-0- (0)	-0- (0)	-0- (0)	-0- (0)
Total			236	409	357	339
Density			23.6	40.9	35.7	33.9

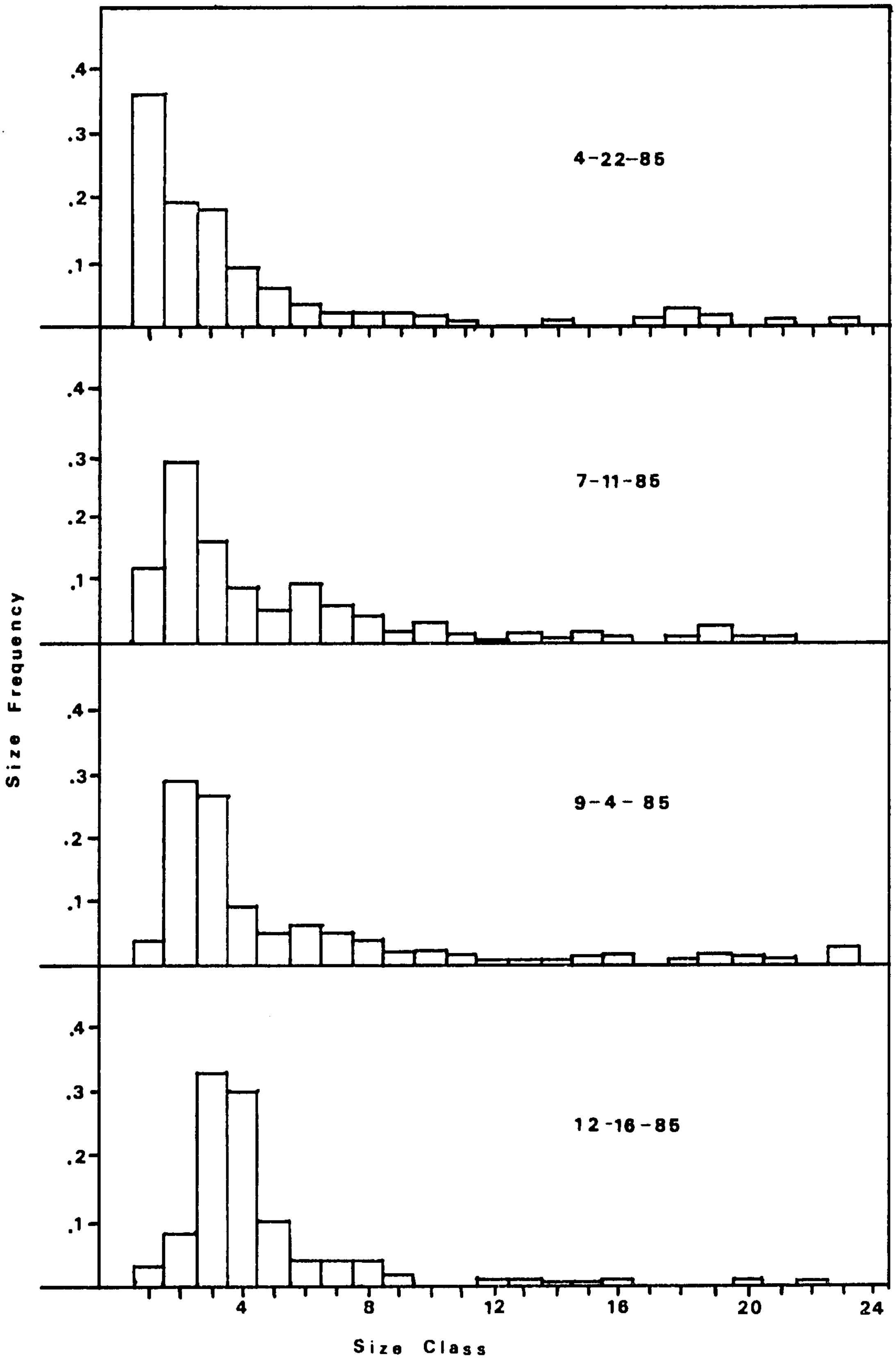


Figure 12. Size frequency of whelks collected at Windswept Beach, St. John, USVI, on four sampling occasions. X-axis numbers refer to size classes shown in Table 15.

General Conclusions

The data suggest a seasonal variation in numbers of whelks observed during the study period. A peak abundance in summer with lower numbers during the winter months may be a response to the increased frequency of high wave energy in the winter months. The whelk may move into more protected areas (deeper water or bays) or deeper into rock crevices where they are harder to observe.

The most interesting aspect of these data is the presence of a very visible annual cohort. The April sample reveals the presence of post-recruits and the December sample shows yearlings in the 1.0 cm to 1.99 cm size class. This agrees well with Randall's (1964) estimate of growth rates of 1.06 mm per month for whelk ranging in size from 1.5mm to 8.2mm. Additionally, the size class distribution for juvenile whelk under 1.0 cm in the present study agrees very closely with the distribution observed by Randall (1964) in Europa Bay, St. John in 1959 and 1960. Her data for April, 1960 demonstrates the peak numbers of juveniles in the 0 to .5 cm size class as does this study. Randall (1964) also demonstrated that recruitment occurred in January.

The majority of the individuals during the study were juveniles and subadults (<5cm). Most marine invertebrates have high reproductive output to compensate for the high mortality of larvae and juveniles. However, the middle range of adult size classes (5 to 8 cm) is represented by very low numbers. This is indicative of very high predation or mortality. Harvest mortality appears to be responsible for most mortality of adults in the Virgin Islands. There is a small number of large adults (>9cm) which has escaped predation by residing in the deeper portion of the transects. These large individuals may be responsible for the majority of the reproductive output in this area and for maintaining the present population.

Summary Conclusions

Management of a species or population depends on knowing the status of the species or population (present condition), where it is going (trends) and what is causing those trends (impacts). Management involves synthesizing this information and developing measures to mitigate negative impacts and reverse or stabilize downward trends. Obtaining this basic information involves development of a long-term monitoring technique which will best produce the necessary information for the species in question. The technique utilized depends on the size, mobility and general nature of the species as well as what information is being sought.

Frequency of monitoring on the time frame of the questions being asked. In general, where information on basic population size and fluctuations during one year is desired, monthly samples may be deemed adequate. The primary constraints on sampling frequency are financial resources and availability of qualified personnel. Some methods are very weather dependent and must be opportunistic in order to obtain adequate samples within the time frame of the study. Data produced over a single, one-year period will be useful for comparing to a similar unit of time in the future for determining long-term trends.

Monitoring Recommendations

When selecting or developing techniques for long-term monitoring of fish and invertebrate species, an attempt was made to use techniques that were simple, easily learned, relatively free from observer bias, did not require excessive equipment, and produced accurate quantitative data that could be used as a baseline data set for measuring changes in population levels or structure over a long period of time. The methods could easily be used in other Caribbean islands to produce comparable data sets. Although methods may be simple and easily taught, a basic recommendation is that, within any particular study, the same person(s) should conduct all the data collection to avoid individual observer bias.

The random point, visual census technique used for assessing fish populations is good in that it is simple, easy to learn and accurate. A potential problem with this method arises from using different observers during the course of a study. When using a number of different observers, the data decrease in reliability. Various inconsistencies or biases due to observer differences can produce a high within-sample variability which can mask among-sample variation and obscure subtle trends or differences. Some of the inconsistencies which have to be considered include:

1. Misidentification of species - can be corrected if data is reviewed with the observer immediately after collection,

2. Overlooking of juveniles of some species (parrotfish, surgeonfish) which lowers the number of individuals observed and increases average size estimates.

3. Over or underestimation of size - usually consistent for each observer, and,

4. Lack of care in recording information (sizes or numbers of individuals).

While the preliminary test of this method suggests that

80 percent of the species in an area are detected in the first four censuses (Figure 2), it is advisable to use at least ten censuses (for statistical reliability) within a habitat type unless the selected habitat is small and can be adequately covered with fewer censuses. Given the residence patterns of most reef fish species, monthly samples may be adequate to assess seasonal variation. The effects of fishing pressure (eg. fish traps on Hawksnest Bay SBpr) can also be detected with monthly samples, but more frequent sampling should yield more accurate analysis.

The canvass method for surveying lobsters in an area is extremely simple and avoids random sampling error. The important consideration is extreme dedication to searching all possible refugia for lobsters. A flashlight is very useful in detecting lobsters in deep caves. Additionally, it is essential to initially map out the area to be surveyed. This enables a complete canvass of an area without missing or overlapping segments, as well as documenting the location and movement of lobsters within an area. Unfortunately, reproductive state of the lobsters is difficult to detect in a dimly lit cave so reproductive seasonality is difficult to obtain. Lobsters do appear to be somewhat sensitive to surge and sediment suspension. The sediment clouds washing in and out of their caves may affect them. This needs to be accounted for in any lobster survey. Lastly, it is important to determine the area surveyed in order to estimate densities.

The strip transect methods used for conch and whelk are basic, simple and accurate. A possible improvement on the method might be to mark half transect widths (2m for conch, individuals who are on the edge of the strip transects) With conch, it is advisable to check all shells in which either movement or eyes protruding from the siphonal canal are not observed. With conch, if visibility is less than about 3m, the method is difficult and time consuming. The whelk survey method is impossible to conduct in high wave action. Wave wash makes it impossible to detect the very small (<1cm) whelk which live in the small crevices in the intertidal (pink) zone. Only under calm conditions is it possible to carefully go over all the rocks and crevices without being washed around and having foam obscure your vision. Selecting a more protected area for the study may not provide a representative sample as whelk tend to prefer higher energy points and coastlines.

Management Recommendations

It is a well-known fact that fishery landings have been seriously declining in Puerto Rico and the U.S. Virgin Islands both in terms of catch-per-unit-effort (CPUE) and in size of individuals (CFMC, 1985). In order to stabilize or reverse this trend before the fishery is entirely decimated, a number of very strict management actions will have to be developed and enforced. For the species or species groups monitored in this study, the following recommendations are made. These recommendations are made primarily for the National Park Service but with U.S.V.I. Government legislation could be extended to all Territorial waters:

A. Reef fish - All of the commercially important species of fish are declining in numbers and sizes from overfishing (CFMC, 1985). As long as individuals are caught before sexual maturity, replacement is not achieved and the stocks decline. Currently, federal regulations in the Exclusive Economic Zone (EEZ) establish a minimum size limit of eight inches for yellowtail snapper and 12 inches for nassau grouper with a one inch per year increase to 12 inches for yellowtail and 24 inches for nassau grouper. Additionally, a closed season is set for nassau grouper from January 1 to March 31 of each year, when reproduction takes place. However, without Territorial adoption and implementation of these regulations, enforcement is nearly impossible. Within the Park there are three proposed strategies: 1. Complete closure of fishery. No fishing with traps or nets within the Park, only handline fishing allowed. 2. Temporary closure, five year minimum. Open on a restricted basis (eg. only two traps per fishermen, no beach seines, limited amount of baitfish). 3. Rotating area closures - close north shore for three years, then south shore for three years. Restricted fishing when open (as in no. 2). The optimum strategy for recovery of the populations is complete closure. However, it may be more politically expedient to use a less drastic measure initially to demonstrate the potential for recovery. The National Park Service could serve as a model for this in the Caribbean.

B. Lobster - The current allowable take for lobsters in National Park waters is greater than the population can tolerate given the number of lobster observed in this study. Populations appear very limited, even in the best inshore habitats (Fish Bay). A bag limit of two lobster per person per day, with four people in a boat, could easily wipe out a good reef area which could take months to repopulate. The recommendation is to close lobsters to all harvest in Park waters. If, after a period of time, monitoring indicates a sizeable number of large individuals has reestablished itself, then a season could be opened or harvest restrictions relaxed. Spotted lobster are currently completely protected in Park waters. They will most likely never be a target species due to their size and the difficulty of catching them.

C. Conch. - Currently it appears that the most stable abundance of conch are those residing in the deeper algal plains on the shelf. These are somewhat protected by the depth at which they are found. Inshore numbers have been devastated. Continued harvesting of juveniles and subadults will result in a continued stock decline leading to local extirpation. The recommendation is to restrict all harvest of conch during the reproductive period (June to September), maintain the current bag limit (two per person per day) during open season and to restrict take to only those individuals having an eroding flared lip (sexually mature). This will prevent the harvest of juveniles and allow them to reach reproductive size. The open season could additionally be restricted to open areas within the Park if a rotating area closure system were initiated.

D. Whelk. - The whelk populations in the Virgin Islands appear extremely overharvested. Heavy fishing pressure coupled with the taking of smaller and smaller whelk, as the large ones become scarcer, has resulted in a small number of older, reproductively active adults in deeper water which are supplying recruits. The small individuals are harvested, probably before reaching sexual maturity. As the older whelks die off, recruitment will decline further until it is minimal and may result in local extirpation. The recommendation is to close immediately all park coastlines to the harvest of whelk until the population has recovered (minimum of five years). Once monitoring indicates that a sufficient population size exists to withstand limited harvest, a season may be reestablished retaining the current bag limit of two quarts of whelk (in the shell) per person per day. At this time a size limit should be implemented to stop the harvest of immature whelk. The smallest mature individuals found by Randall (1964) were 33.7mm (female) and 32.4mm (male) in length (tip of spire to distal edge of lip).

A safe size limit to ensure at least one reproductive season would be failure to pass through a 50.8 mm (2 inch) inside diameter ring. Only whelks failing to pass through could be retained. Not enough is known about the reproductive cycle of whelk to establish a closed reproductive season.

It is very clear to biologists that management strategies must be implemented if populations of marine fisheries species are to survive and if the commercial fisheries of the Virgin Islands are to continue on a viable basis. While fishermen are the first to tell you of the decline in fisheries, they are usually the most opposed to any management actions. As a precursor to implementation of any strategy, there must be a public forum to attempt to have the fishermen understand the need and biological basis for any action taken. They must also be made to feel that they are contributing to the management decisions. Following establishment of any management action, there must be a strong and consistent enforcement effort.

The data collected in this study will be very useful in determining the effect of any management action. In the event that several years transpire between this report and implementation of any management action, it is suggested that a monitoring program be reinitiated to establish current populations of the species or species group to be managed.

Literature Cited

Appeldoorn, R.S. and Ballantine, D.L., 1982. Field release of cultured queen conch in Puerto Rico: Implications for stock restoration. Proc., Gulf Carib. Fish. Inst., 35:89-98.

Beets, J., Lewand, L. and Small, E., 1985. Marine community descriptions and maps of bays within the Virgin Islands National Park/Biosphere Reserve. V.I.R.M.C. I.

Berg, C.J., Jr., 1976. Growth of the queen conch, _Strombus gigas_, with a discussion of the practicality of its mariculture. Mar. Biol., 34:191-199.

Bohnsack, J.A. and Bannerot, S.P., 1983. A random point census technique for visually assessing coral reef fishes. _In_: C.A. Barons and S.A. Bortone (Editors), The Visual Assessment of Fish Populations in the Southeastern United States: 1982 Workshop, South Carolina Sea Grant Consortium Tech. Report 1, SC-SG-TR-01-83, pp. 14-17.

Boulon, R.H., Jr., 1985a. Distribution and species composition of fishery habitats within the Virgin Islands Biosphere Reserve. Virgin Islands Resource Management Cooperative, Biosphere Reserve Research Report No. 8, 70 pp.

Boulon, R.H.,Jr., 1985b. Long-term monitoring for fishery resources of the Virgin Islands Biosphere Reserve. Virgin Islands Resource Management Cooperative, Biosphere Reserve Research Report No. 13, 32 pp.

Brownell, W.N., 1977. Reproduction, laboratory culture and growth of _Strombus gigas_, _S. costatus_, and _S. pugilis_.. in Los Roques, Venezuela. Bull. Mar. Sci., 27:668-680.

Caribbean Fishery Management Council, 1985. Fishery Management Plan Final Environmental Impact Statement and Draft Regulatory Impact Review for the Shallow-Water Reeffish Fishery of Puerto Rico and the U.S. Virgin Islands. Prepared under PL-94-265 (MFCMA), for NMFS, NOAA. 69 pp.

Chaplin, C.C.G., 1982. Fishwatchers Guide to West Atlantic Coral Reefs. Harrowood Books. Newton Square, Penn.

Clavijo, I.E., Tobias, W.T. and Jennings, C.A., 1987. State/Federal Cooperative Statistics Program, U.S. Virgin Islands. Annual Report to NMFS, Segment 3 - Project No. SF-22.

219

Coulston, M.L., Berey, R.W., Demsey, A.C. and Odum, P., 1985. Assessment of the queen conch (Strombus gigas) population and predation studies of hatchery-reared juveniles in Salt River Canyon, St. Croix, U.S.V.I. NOAA Hydrolab Quick Look Report, Mission 84-14. 10 pp.

Hesse, K.O., 1979. Movement and migration of the queen conch, Strombus gigas in the Turks and Caicos Islands. Bull. Mar. Sci., 29:303-311.

Hubbard, D.K., Stump, J.D. and Carter, B., 1986. Sedimentation and reef development in Hawksnest, Fish and Reef Bays, St. John, USVI. V.I. Biosphere Reserve Research Report No. 21. 99 pp.

Kumpf, H.E. and Randall, H.A., 1971. Charting the marine environments of St. John, U.S. Virgin Islands. Bull: Mar. Sci. Gulf Carib., 11(4):543-555.

Randall, H.A., 1964. A study of the growth and other aspects of the biology of the West Indian Topshell, Cittarium pica. Bull. Mar. Sci. Gulf and Carib., 14(3):424-443.

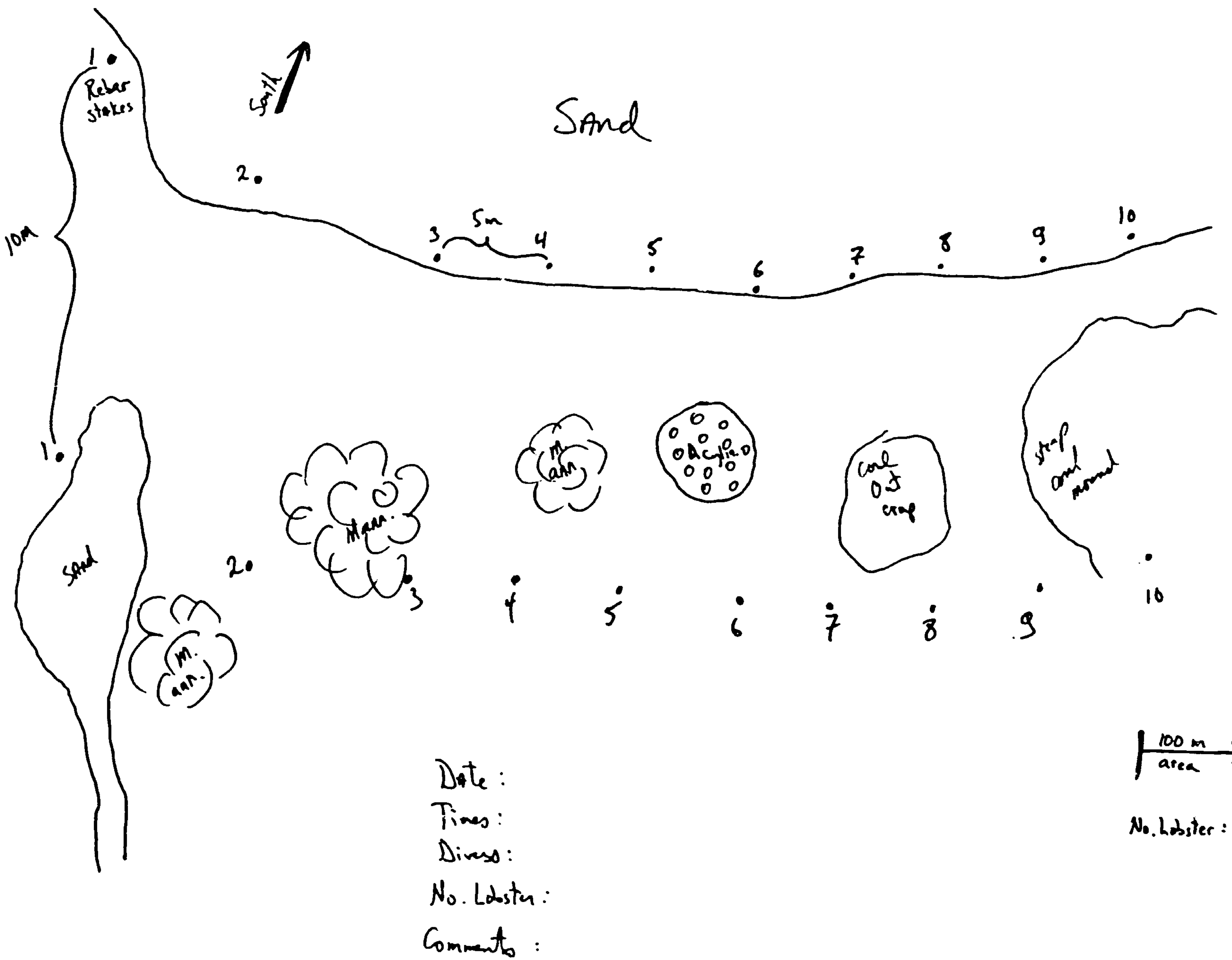
Randall, J.E., 1968. Caribbean Reef Fishes. T.F.H. Publications, New Jersey. 350 pp.

Robins, C.R., R.M. Bailey, C.E. Bond, J.R. Brooker, E.A. Lachner, R.N. Lea and W.B. Scott, 1980. A list of common and scientific names of fishes from the United States and Canada (Fourth Edition) American Fisheries Society, Spec. Publ. No. 12, 174 pp.

Rogers, C.S. and Zullo, E.S., 1986. Initiation of a long-term monitoring program for coral reefs in the Virgin Islands National Park. V.I. Biosphere Report No. 17. 33 pp.

Stokes, F.J., 1980. Handguide to the Coral Reef Fishes of the Caribbean and Adjacent Tropical Waters Including Florida, Bermuda, and the Bahamas. Lippincott and Crowell, Publishers, New York. 160 pp.

Wood, R.S. and Olsen, D.A., 1983. Application of biological knowledge to the management of the Virgin Islands conch fishery. Gulf Caribb. Fish. Inst., 35:112-121.



Appendix Ia. Reef Bay lobster study site diagram.

Appendix Ib. Fish Bay lobster study site diagram.