ISLAND RESOURCES
FOUNDATION
1718 P STREET, N.W., SUITE T-4
WASHINGTON, DC 20036
(202) 265-9712

CIRCULATION, WATER QUALITY AND ENVIRONMENTAL RESOURCES OF PERSERVERANCE BAY, ST. THOMAS

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DEPARTMENT OF CONSERVATION AND CULTURAL AFFAIRS

DIVISION OF NATURAL RESOURCES MANAGEMENT

GOVERNMENT OF THE U.S. VIRGIN ISLANDS

CIRCULATION, WATER QUALITY AND ENVIRONMENTAL RESOURCES OF PERSERVERANCE BAY, ST. THOMAS

by

Maynard Nichols and Edward Towle

with

David Grigg, Robert Huggett, David Olsen,

Galen Thompson and Richard Trotman

Submitted by:

Island Resources Foundation
Box 4187, St. Thomas
U.S. Virgin Islands

Dr. Edward L. Towle, Director

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ABSTRACT

The rocky shores, beaches, reefs, salt ponds, and grass beds of Perserverance Bay, St. Thomas are a natural resource of exceptional value. The bay is not only valuable, but it is vulnerable to the impact of a near-by runway extension and to future development of the watershed. Already the bay is partly soured; turbidity threatens reefs and grass beds, trash and debris accumulate on the beaches and mangroves are dying. This report provides a scientific background for improving the environment and suggests management practices leading to the best achievable condition.

Ocean waves are the most important source of energy affecting nearshore zones whereas tidal currents are most important in offshore reaches. Waves are dissipated by refraction on shoals and by reflection off rock cliffs. Southeasterly waves induce a longshore current that moves sediment in a turbid plume 1500 meters long from Brewers Bay into Perserverance Bay where it disperses and deposits. A convergence of longshore currents in the west bay head traps oil and floating debris.

Currents display a distinct periodicity and reversing character induced by the tides. Superimposed on the back and forth movement of the tide is a weak semi-permanent current presumably driven by density differences and supported by the wind. The resultant current pattern consists of a counterclockwise spin around the bay with an indraft on the east side and an outflow on the west side. Its result is to drive cool salty water into the eastern bay along the bottom and in turn, to diminish the oxygen content. Its further effect is to exchange bay water with the sea and to mix it into a single water mass with relatively uniform temperature and salinity. As a result of the clockwise circulation, currents in the central bay are attenuated, and thus provide a sink for fine sediment and potential pollutants.

Water quality is excellent for temperature, salinity, pH and dissolved oxygen but turbidity increases near the bottom owing to resuspension of mucus and sediment by waves and currents. Toxic metals and nutrients in bay sediments are normal despite scattered debris. However, salt pond sediments are enriched with copper and lead; total nitrogen content is exceptional (5300 ppm).

Nearshore and fringing platform reefs of the central and eastern bays are suffering most attrition presumably caused by excess turbidity. There is no recolonization of dead reefs. By contrast, coral reefs of the western bay and around headlands are relatively healthy. However, such reefs as well as adjacent grass beds, which are a significant natural and recreational resource for Virgin Islands, may suffer serious damage unless a concerted effort is made to eliminate additional sediment loads created by watershed development or airport construction.

CIRCULATION, WATER QUALITY AND ENVIRONMENTAL RESOURCES OF PERSERVERANCE BAY, ST. THOMAS

1. Introduction

Along the south coast of St. Thomas, not far from the municipal airport, is an attractive bay edged by rocky shores and a sand beach. Perserverance Bay is a resource unit of exceptional natural value. Its reefs and grass beds support a productive array of fish and benthic biota. Its configuration is a natural buffer against northeasterly trade winds and waves. Its water depth provides protected anchorage for deep draft vessels. The bay is filled with scenic contrasts, jutting headlands interspersed with pocket beaches, salt ponds and panoramic ridgelines. Beneath the water surface there are reef vistas filled with mystery and excitement that provide Virgin Islanders with recreational and educational opportunities. Although these natural units are of exceptional value, they are little understood or appreciated.

The bay is not only valuable but it is vulnerable. Lying as it does close to a busy airport, its circulatory vigor and productive ecology are threatened by construction of a runway extension. When trash was dumped onto the shore near the present runway in former years, it often drifted westward and accumulated in Perserverance Bay, an excursion of 2400 meters (1.4 miles). With little concern for fine sediment dispersal, the floor of Brewers Bay was stripped of grass beds in 1970 to dredge underlying sand. The dredging operation created a turbid plume extending 1200 meters (0.72 miles) westward into Perserverance Bay. Even today, after seven years of wave washing, fine sediment is intermittently released from former dredged material and dispersed from Brewers Bay into Perserverance Bay.

Another problem is the mosquitoes and flies that breed in the stagnant salt ponds. Reportedly they make living on contiguous hillsides uncomfortable but drainage of the ponds could eliminate their function as a sediment trap and threaten the reefs with excess turbidity. Surrounded by steep slopes conducive to rapid runoff and sediment discharge, the bay is particularly susceptible to prospective impacts of development in its watershed. As slopes are bulldozed for roads and residential sites, and as pressures mount for more facilities in the watershed, additional stresses will be placed on the bay. If uncontrolled more problems will be created and at the same time the bay's most useful environmental resources will be destroyed.

2. Study Objectives

The task now is to keep the bay healthy, to maintain the bay in its natural or best achievable condition. If the bay is to be attractive and useful, it must be understood so that impending problems of airport construction and watershed development can be anticipated and managed.

This study aims to provide basic scientific data for improving the environment. It suggests a framework for management practices leading to the best achievable condition and aims to find alternatives for proper use of environmental resources. The specific objectives of this study are:

- To determine the present condition of the bay, its circulation, water quality, biota and environmental resources.
- To ascertain what changes take place in the bay from winter to summer under contrasting low and high energy conditions of wind and waves.
- To determine how the circulation and water quality of Perserverance Bay is linked to corresponding elements in adjacent Brewer Bay.
- To analyze environmental processes and delineate areas suceptible to impacts; determine what natural features present opportunities for development or deserve protection.

3. Scope

This study embraces Perserverance Bay proper from the shoreline mainly to the 18-meter depth curve. It includes the water, shore, sediment bed and reefs. Since the bay is open to the sea and adjacent bays, contiguous waters of Brewers Bay and offshore waters are considered to evaluate water quality and circulation. Because the bay is linked to its watershed during times of runoff, the drainage basin and adjacent salt ponds are also taken into account.

Although different features of the bay and watershed are studied separately, it is recognized that all the features are part of an ecosystem. Each environmental component acts together as an ecologic unit. No single part of the system operates independently. To understand the bay environment means understanding not only the units but the interaction between units.

No natural ecosystem is static. It is continually changing in response to wind, tide, waves and solar radiation, and long-term changes. With time the field observations were planned to embrace measurements in two consecutive seasons, winter and summer 1977, at contrasting conditions of low and high energy.

The data obtained in this study were acquired before major impacts and irreversible changes. As such they provide baseline information against which future changes can be assessed. Indirectly, they contribute to long-term monitoring of Virgin Island bays. The data add to regional inventories of island environments useful for long-range planning and management.

4. Previous Studies

Previous scientific knowledge of the bay environment is limited. The shoreline and water depths were first charted in detail by the U.S. Coast and Geodetic Survey in 1924-1926 (smooth sheet 4651a). The bay was charted again in 1972 by the National Ocean Survey (smooth sheet 9272). The distribution of water quality parameters was first obtained from 11 stations in 6 surveys during July and August 1970 (CRI unpublished file data). Since December 1975, water quality of the bay has been monitored by the Division of Natural Resources Management as part of an island-wide water quality monitoring program. An environmental assessment of proposed airport construction in 1974 provided reconnaissance charts of communities on the bay floor based on aerial photography alone. Despite the wealth of aerial photographic coverage by different federal agencies since 1947, no other efforts have been made to extract information concerning the bay environment. An oceanographic engineering study for the proposed runway extension to Truman Airport in 1976-1977 provided new information on waves and currents in waters contiguous to Perserverance Bay (Tetra Tech, 1977).

5. Methods and Procedures

Station Locations. Fixed anchor stations and "dip" stations for vertical profiles were located to cover the bay at about 300 meter intervals from the shoreline to the 20 meter depth curve (Figure 1). This network provided measurements in sections transverse to the coastline and the predominate direction of flow. Additionally, several stations were sited around the headland at Black Point and in central Brewers Bay for comparitive measurements (Figure 1). One station was located offshore from Brewers Bay near the seaward end of the proposed runway extension, a site where flow characteristics may be expected to change substantially.

Sediment samples were collected in conjunction with benthic biological observations at about 100 meter intervals along seven transects laid out more or less transverse to shore. The transects cross a range of different sediment types in water depths from mean low water to 18 meters (Figure 2).

Borings and probes were sited across the salt ponds on transects approximately 100 meters apart (Figure 1). The probes of sediment thickness were made at 30 meter intervals. Because of the difficulty in penetrating sand, most borings were made in soft peat or fine-grained sediment.

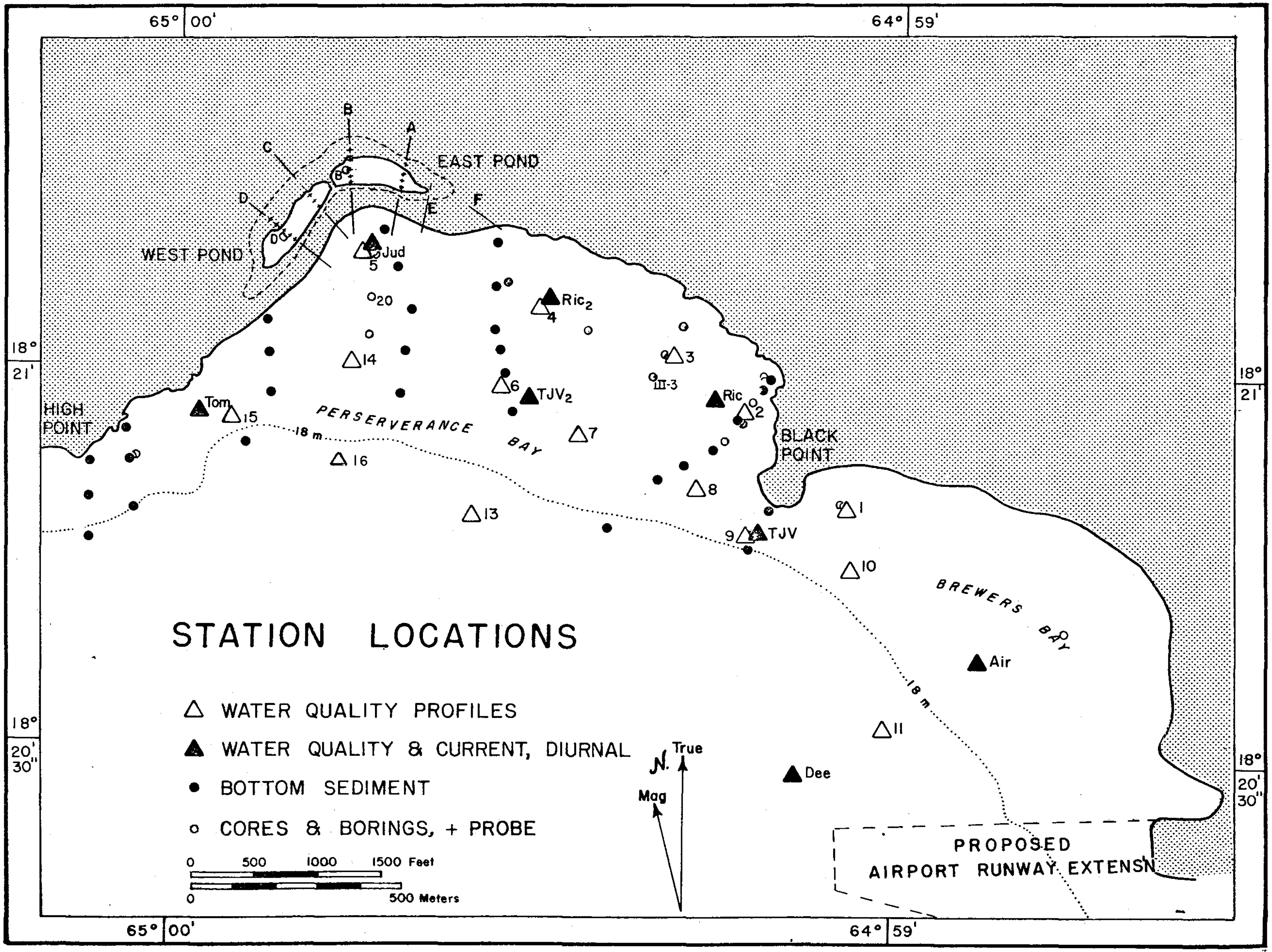


Figure 1. Location of sampling and observation stations in Perserverance Bay, January, 1977 and July-August, 1977.

Instrumentation and Procedures for Water and Sediments. Water quality parameters were mainly measured *in situ* with instruments provided by the Virgin Islands Department of Conservation and Cultural Affairs.

Water temperature and dissolved oxygen concentrations were measured with an *in situ* probe of a YSI (Yellow Springs Instrument) oxygen meter, model 54A, equipped with a membrane covered polargraphic probe. The measurements were calibrated at each station by running a saturated water sample having the same temperature as the sample water. The ratio of these readings and the corresponding theoretical saturation value provided the oxygen concentration in mg per liter.

During the January 1977 survey, salinity, pH and temperature were measured with an *in situ* Marteck Unit. The conductivity probe was initially calibrated in the laboratory against standard sea water and the pH probe was buffered with a pH 7 solution. Chlorinity (salinity) was analyzed on water samples returned to the laboratory by silver nitrate titration. The water was standardized against standard sea water having a salinity of 34.5 ppt.

Turbidity of water samples returned to the laboratory was determined within 24 hours of collection with a Hack turbidometer, model 2100A standardized with Formazin suspensions. Suspended solids of fresh samples were analyzed gravimetrically using Millipore filters of 0.80 pore size. Transparency of the water was measured with a white-black Secchi disk, 30cm in diameter. Because the disk could not be used at night and often rested on the bottom, the number of disk readings is limited.

For surveys other than January 1977, the pH of water samples was run in the field using a Beckman pH meter, model 1009, buffered with a pH 7 solution.

Rates of gross production of organisms in suspension were determined by conventional light-dark bottles installed *in situ*. BOD bottles were set for 24 hours, both near the surface and near the bottom of each anchor station. Similarly, rates of gross production and respiration of the waters *en toto* were determined from diurnal oxygen curves using the graphical method of Odum and Hoskins (1958).

Dissolved reactive phosphorous concentrations were measured on all survey samples in the DCCA laboratory, using the ammonium molybdate and stannous chloride reduction method developed by Robinson and Thompson (1948).

Laboratory methods for toxic trace metals and organic pollutants in sediments are given in Appendix I.

Current speed was measured with a two-component electromagnetic current meter manufactured by Marsh-McBirney, Model 511. The sensor was installed in a frame and stabilized with 20 to 30 pounds of lead weight. Measurements consisted of five consecutive and simultaneous readings of both X and Y horizontal components. Current direction in the upper 10 meters of water was measured from dye streaks with a hand-held pelorus. At depths greater than 10m, direction was measured by sighting a pelorus on a tethered drogue released for a distance of 30 meters. Both direction and speed profiles were measured from a vessel stabilized with four anchors from the bow and stern.

To observe current paths around irregular shores like Black Point, free drifting "window shade" drogues were deployed at several depth intervals. They consisted of single vanes made of cloth attached to a wood block float and ballasted to a section of rebar following construction details given by Mundy (1975). Position of the drogues was determined every 30 to 60 minutes by bearings on known landmarks.

The speed and direction of littoral currents along the shore was measured by observing the drift of dye patches with a pelorus and stop watch. Concurrently, breaker heights and water depths were measured with a graduated rod and the angle of approach was measured with a pelorus.

Meteorological conditions affecting water quality and currents were observed concurrently with oceanographic measurements. Air temperature was measured in the shade with a stem thermometer; wind speed was measured with a hand-held Sims anemometer while wind direction and wave direction was observed with a hand-held pelorus and streamer, and wave height was estimated visually.

The top 3cm of surface sediment was collected by SCUBA divers with a 5cm diameter core tube. Gross texture of the sediments was determined visually with aid of a hand lens and grade scales. Samples were frozen for future analyses of sediment chemistry and mineralogy.

The thickness of loose sediment above a relatively firm base was determined in the salt ponds by probing with a 6 meter steel rebar rod. Besides indicating the maximum depth of refusal to penetration by hand, the probe resistance also indicated depths of relatively firm interlayers between the surface and firm base.

Borings were made in the salt ponds with a Davis peat sampler which retrieves sediment sections 30cm long and 3.8cm in diameter. By adding extensions to the core head, relatively undisturbed cores were obtained down to 4.6 meters depth.

Cores 7.6cm in diameter were obtained from the bay by SCUBA divers. A PVC pipe was driven into the bottom manually to depths of 20 to 70cm.

Benthic Biota Survey. The benthic sampling program was designed to accomplish several goals. The primary goal was to provide a current baseline of the status of the biota in Perserverance Bay. Two types of sampling programs were initiated. The first effort concentrated on characterizing and mapping the distribution of the various biotic communities. These communities were characterized with regards to their dominant biological components and the distribution charted from aerial photography and *in situ* mapping.

The second aspect of the sampling concentrated on the most significant structural element of the reefs, the Scleractinian or hard corals. Based on the mapping efforts' subjective statements regarding the health of the coral community, we emplaced a series of six transect lines. By utilizing a technique that allows for recensusing we measured not only the species abundances but the frequency of colonies showing signs of necrosis. Thus, we obtained a measure of the community well-being, and a measure of one of the possible causative indicators.

The final element of the biotic sampling program was based on an a posteriori prediction from analysis of the oceanographic data. These data predicted that certain areas of Perserverance Bay will enter drastically altered regimes of siltation and current flushing. We censused the benthic flora in these regions in order to obtain a baseline against which later changes could be measured.

Benthic biota were surveyed in two ways: (1) a broad-area descriptive survey to chart community types, to delineate community boundaries and to estimate the percent cover of major constituents; (2) a detailed quantitative analysis of five sites to determine the abundance and composition of major constituents.

For the broad-area survey SCUBA divers observed the biotic composition and percent cover along eight transects from shore to about the 18 meter depth curve (Figure 2). A 220 meter marked line was laid on the bottom between transect points. Ends of the line were positioned by pelorus bearings on nearby landmarks. Then divers swam along the line referring observations and sample collections to marks on the line and to depth readings. Positions of the stations in relation to landmarks are on file at the Island Resources Foundation.

At Stations B, C and E (Figure 2) which have sand bottoms, $0.25m^2$ patches of the biota were extracted to a depth of about 8cm. These were washed and sorted. The plant material was weighed wet (damp-dry), dried at 104°C, and weighed again to determine biomass proportions of each species. Invertebrate

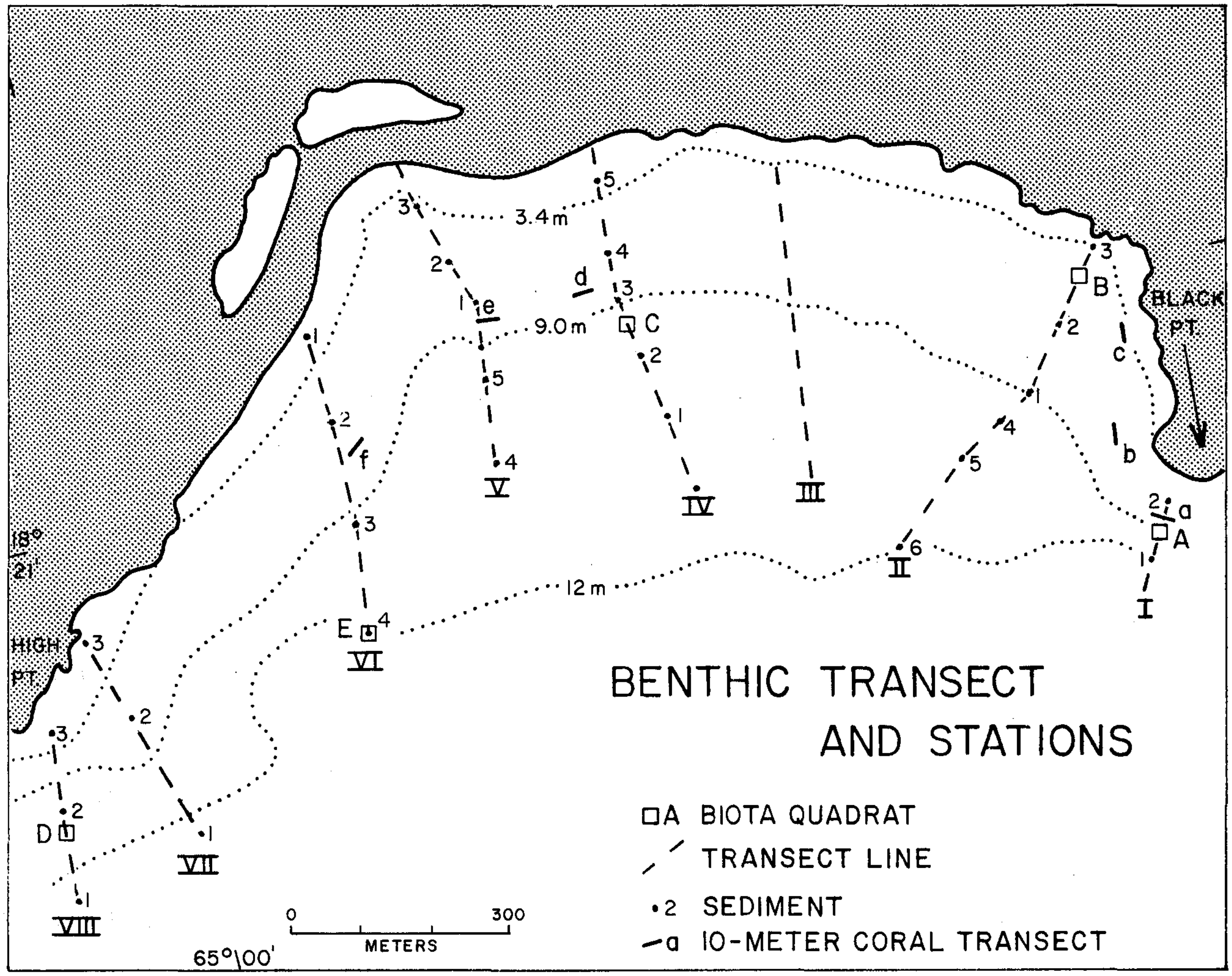


Figure 2. Location of benthic transects and sediment sample stations.

animals were sorted to major taxa and counted. On reef Stations (A and D) extractive sampling was not possible, and we were immediately aware that quantitative descriptions could not be made by visual observation. The resulting descriptive precision would allow general assessment of obvious, perhaps gross, changes in the future. In addition to these descriptive data, two series of monitoring stations were established at sites where it was felt that the impact of the airport would be greatest.

Since hard corals are the structural basis for reef construction, we established six ten-meter transects (Figure 2) after the method of Loya (1969) where a line is stretched along the bottom. In this case, we stretched the line parallel to the shoreline at the top of the reef face.

The transect method was chosen for two reasons. First, the ten-meter transect sampled 87% of the species that we observed in the area and is, therefore, considered to be an adequate sample of the greater community. The second reason is that although we left the transect lines in place, experience has shown that permanent marking on the sea floor is chancy, at best. If attempts to re-survey these sites cannot find the actual lines, then a new line, emplaced at the top of the reef edge in nearly the same locale, can be expected to give similar results, and differences can be interpreted as being indicative of community changes. An additional reason is that the technique gives information on the coverage by live corals, necrotic colonies, and the abundance of individual species.

In the course of doing the transects, coral abundance was measured for every species that occurred directly under or over a line. These intercepts can be analyzed for simple abundances or for more complex diversity statistics after the method of Pielou (1966). The Shannon-Weaver diversity statistic (Hs) was calculated, using the equation:

$$Hs \cdot \sum_{i=1}^{N} Pi \ln (pi)$$

Where Pi = the proportion of the i^{th} species in the collection. The Hs figure for the total collection was calculated by totaling the results of all 61 meters for each species. Limitations in computing capability restricted analysis somewhat, but the data have been preserved for later analysis. All data and specimens are on file at Island Resources Foundation.

In addition to coral intercept values, we also recorded whether or not each colony showed areas of necrosis. These necrotic areas may well indicate the underlying causes for later changes in abundance since Antonius (1972) has shown that the blue green algae <u>Oscillatoria submembranacea</u> frequently attacks and digests corals whose condition is weakened. Kohleminen (1973) has shown that sediment cleaning abilities of hard corals vary significantly from species to species. The energy expenditure of cleaning is certainly significant, particularly in view of the fact that the expenditure is necessitated by conditions which concurrently reduce incident radiation and concomitant anabolic feeding activities. The result of increased sedimentation is that the coral is expending increased energy for cleaning while receiving less light for photosynthesis and food production. Therefore, it becomes more susceptible to pathological agents and suffers greater mortality. Sedimentation also reduces population input through decreasing space available for settlement by coral planulae. The presence of corals in such an area becomes one of survival of the existing populations and selection of species with more efficient cleaning abilities and photosynthetic capabilities. Ecologically selective forces shift from biological competition for space to physical limitation from environmental factors.

Observational Period and Data Acquired. Field observations were concentrated during two periods: (1) an 18 day period, December 28, 1976 to January 15, 1977, a period of light wind and low waves; (2) a 14 day period, July 23, 1977 to August 5, 1977, a period of moderate to high wind and moderate waves. Most current measurements at anchor stations were made during spring range of the tide in each period. Altogether the field observations resulted in 7 anchor stations occupied twice over a 25-hour period for water quality and current measurements, 13 "dip" stations occupied twice for vertical profiles of water quality, 6 stations sampled twice for productivity measurements, 5 stations for deep borings, 12 for probes, 9 for shallow cores, 5 for benthic quadrats occupied twice, 2600 meters of track line for broad-area benthic observations and 6 ten-meter transects for special observations of hard coral reefs.

6. Description of the Bay

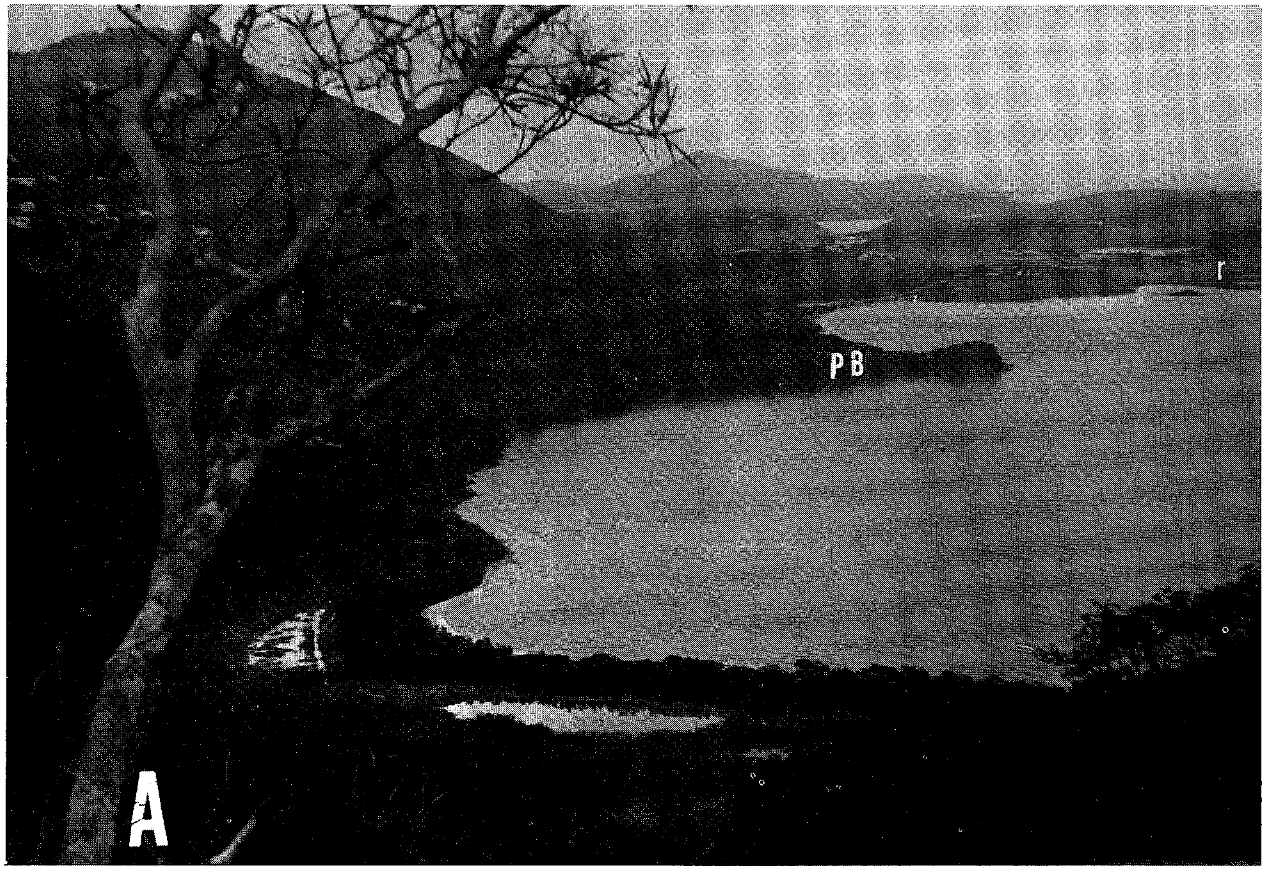
Of the five bays along the southwest coast of St. Thomas, Perserverance Bay is the largest. It covers a broad arcuate-shaped area of 0.70 sq. kms (0.27 sq. miles). It is 1.38 km (0.81 miles) long along a chord connecting its terminal promotories, and it is 0.48 km (0.29 miles) wide inside the 18 m (60-foot) depth curve.

The bay is not an enclosed lagoon or estuary but a lunate embayment open on the southwest to Southwest Roads and the Caribbean Sea. The bay lies between two protruding rocky headlands, High Point to the west and Black Point to the east, (Figure 3A). The eastern part of the Bay is backed by steep slopes rising up to 411 m (1370 feet) at Hawk Hill. Most of the slopes exceed 30 percent and are covered with dry forest vegetation. They intersect the bay as rocky cliffs 5 to 10 m (15 to 30 feet) high. By contrast the western part of the bay is backed by a lowland containing salt ponds and mangroves, while farther landward alluvial slopes rise steeply to more than 120 m (400 feet) at Bonne Esperance and Fortuna Hill.

On first sight, Perserverance Bay seems so little changed that it is possible to recapture a feeling of the primitive bay. However, detailed observations reveal that the Bay is far from pristine. The beach is strewn with bottles, tar and flotable debris (Figure 3B); while the nearshore bottom off the beach is covered with old tires, boilers, bottles and debris in addition to two sunken hulls. The salt ponds are crossed by a low causeway and shallow drainage way across East Pond, and the barrier ridge is partly channeled with shallow excavations. Ruins of a former

3A. General view of Perserverance Bay looking east toward Black Pt. (BP) and the airport runway (r). Hawk Hill lies to the left. Salt ponds, foreground, are rich in wildlife. They are threatened by impacts of development on steep slopes of the watershed.

3B. Beach at the western head of Perserverance Bay is strewn with trash and debris distributed from passing ships and formerly from a municipal dump near the airport. The littoral current which converges along the shore is a virtual trap for floating debris.


PB
r
A


B

plantation are found landward of West Pond. Thus, marks of human activity which have soured the environment, are scattered throughout the Bay. The extent of damage remains to be determined.

Since the bay shoreline assumes an irregular form in plan view, it is necessary to describe its geometry by a set of mathematical parameters. This allows comparison with other bays and provides quantitative data for calculating flushing and water movement.

Figure 4 gives the geometric terms and layout for describing the geometry following the scheme of Wright, et al, 1973. Given the chord length, lc, across the bay between terminal headlands, and the length of a biscector Pb, then assuming a circular form for the bay the radius of curvature can be calculated from the relation:

$$R = (P^2 + (lc/2)^2) / 2 Pb$$

and the angle, Yb made by the embayment arc is then

$$Yb = 2 \sin^{-1} (lc/2R)$$

The area, A, contained between the circular embayment arc and the chord is:

$$A = R^2 (Yb - \sin Yb) / 2$$

where Yb is expressed in radians. The length, S, of the predicted shoreline arc is calculated from:

$$S = RYb$$

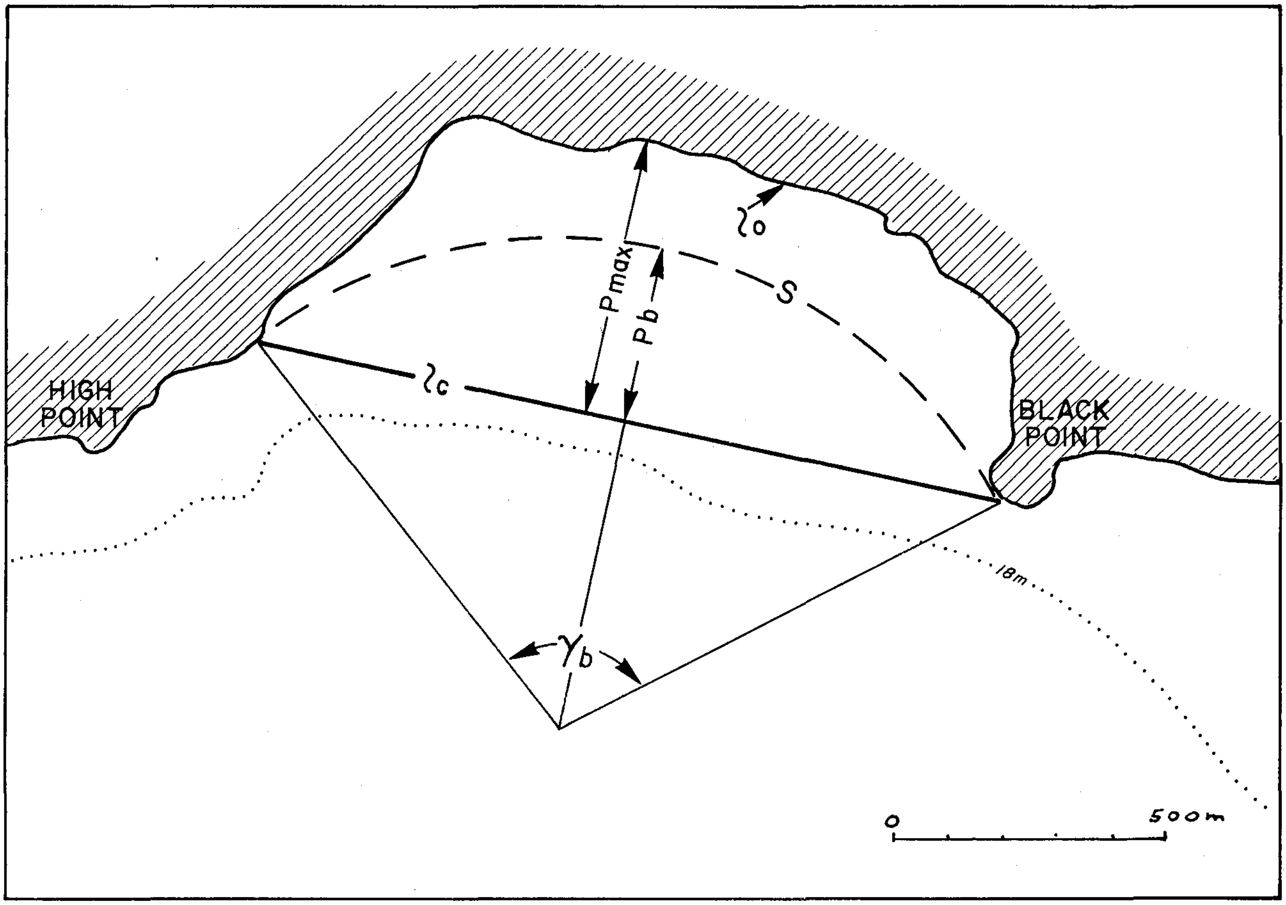


Figure 4. Definition of bay geometry; for explanation, see text.

The degree to which the predicted circular length, S, and the observed shoreline length, lo, conform is indexed by the ratio of S/l. And the asymmetry of the embayment may also be described in terms of the ratio Pb/Pmax where Pmax is the maximum observed distance from the chord to the bay shoreline. Table 1 summarizes geographic and bathymetric dimensions of the bay.

TABLE 1

SUMMARY OF GEOGRAPHIC AND BATHYMETRIC DIMENSIONS FOR PERSERVERANCE BAY

Parameter	Magnitude	
Length (lc)	1380 m	1504 Yards
Width (Pmax)	518 m	564 Yards
Area, MLW to 18 m Depth Curve	703,000m^2	843,600 Yards^2
Volume Below MLW	6.5$^{10^6}$m^3	8.51$^{10^6}$ Yards^3
Mean Depth	9.2 m	30.2 Feet
Mean Tide Range	0.27 m	88 Feet
Tidal Prism	189,810m^3	248,651 Yards^3
Shoreline Length (10)	1980 m	6494 Yards
Radius of Curvature (R)	910 m	2925 Yards
Arc Angle (Yb)	101°	1.75 Radians
Predicted Shoreline Arc (S)	1592 m	5222 Yards
Length Ratio	1.24	
Asymmetry Ratio	1.56	
Drainage Basin Area	1.63km^2	0.63 Sq. Miles
Hawk Hill Sub-Basin	0.29km^2	0.11 Sq. Miles
Fortuna Hill Sub-Basin	0.54km^2	0.21 Sq. Miles
Bonne Esperance Sub-Basin West	0.39km^2	0.15 Sq. Miles
Bonne Esperance Sub-Basin East	0.41km^2	0.16 Sq. Miles

The bay develops its varied character from the effects of geological structure, rock types and the action of marine processes. The headlands, Black Point and High Point are composed of very hard rock that resists wave erosion despite substantial wave exposure. Cliffs along the eastern part of the bay, which are more sheltered than in the western bay, consist of a plunging type. They show little affect of wave erosion except locally where secondary headlands protrude farther seaward than intervening shores. These cliffs plunge downward to the 3.6m (12 foot) depth curve without a break in slope or platform. This suggests they have been submerged by sea level rise relatively rapidly; that is, faster than waves could erode the cliffs.

Cliffs and the rocky shore along the western bay near High Point lie behind a shallow submerged platform about 1.5m (4.9 feet) deep. This coast is exposed to powerful wave attack from the east. The platform, which is veneered with loose rubble, is a product of long-continued wave erosion and recession of the shore. Sand and cobble beaches in more sheltered parts of the western bay are mainly built of coral debris derived mainly from erosion of offshore reefs rather than from erosion of cliffs.

Aerial Photo Evaluation

From an eye-in-the-sky of an aerial camera having a 15cm (6 inch) focal length, many environmental features are discernable that cannot be seen on the ground. Such features include turbid plumes, submerged vegetation boundaries and wave refraction which are not represented on charts and maps. When aerial photographs

Figure 5, next page. Aerial photograph of Perserverance Bay and its drainage basin taken by NOS, Nov. 15, 1976. For description, see text.

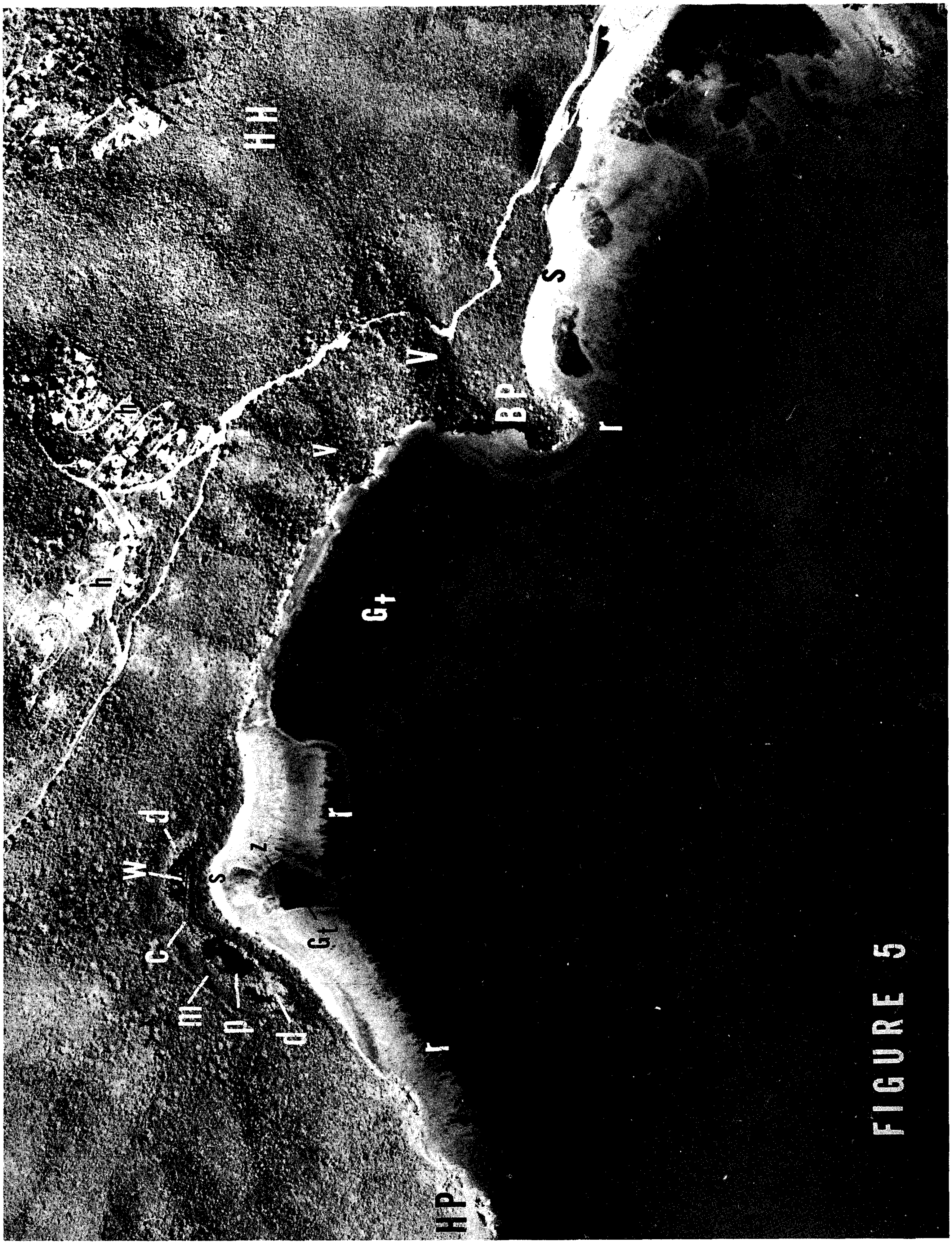


FIGURE 5

taken at different dates are compared, they reveal changes in environmental features such as shifts in benthic plant or mangrove communities and shoreline changes. Table 2 lists aerial photographic coverage of the bay examined in this study.

TABLE 2

AERIAL PHOTOGRAPHIC COVERAGE OF PERSERVERANCE BAY AND VICINITY

SOURCE	DATE	SCALE	TYPE
National Ocean Survey	November, 1971	1:30,000	Color
Soil Conservation Service	February, 1971	1:20,000	B & W*
National Ocean Survey	March, 1965	1:15,000	B & W
National Ocean Survey	February, 1964	1:24,000	B & W
National Ocean Survey	November, 1958	1:10,000	Color
U.S. Geological Survey	January, 1954	1:30,000	B & W
U.S. Navy	March, 1947	1:30,000	B & W

*B&W is black and white

A black and white reproduction of a color aerial photo taken at 4.5 km (15,000 feet) altitude on November 15, 1971, the most recent coverage of the bay, is shown in Figure 5. The most conspicuous tonal contrast is the change between light-toned areas, representing beach sand or nearshore coral rubble (S) and the dark-toned areas representing vegetation cover either on land or submerged beneath the water (Gt). Important natural features are: Black Point (BP) a rocky headland that separates Perserverance Bay from Brewers Bay; High Point (HP) a rocky promontory; salt ponds (P) marked by black patches surrounded by dense stands of mangroves (M), dark-toned; dead mangroves (d) marked by light-toned zones between the dense mangroves (M) and the ponds (P). Stream valleys (V) which drain the slopes of Hawk Hill (HH) are discerned by shadows on northwest slopes of the valleys.

Features of the bay floor are displayed to a depth of about 12m (40 feet). The broad dark-toned area (Gt) is benthic grass, mainly Thalassia. Fringing reefs are represented by ragged dark-toned and elongate patches (r). Most of the reefs are bordered on seaward margins by narrow light-toned zones of sand. Different bottom types and benthic communities discerned from the photograph are displayed in Figure 24.

The most conspicuous cultural features are the roads and houses (h) that cluster upper slopes of the drainage basin, near Bonne Esperance and Fortuna Hill (not displayed). Close inspection of the salt pond area reveals a causeway between the ponds (c) and a former drainage ditch across East Pond (w). Landward, ruins of a former plantation are nearly hidden by trees near (x). Submerged debris off the beach is visible near point (z).

Bathymetry

Depth contours of the bay which were drawn on a recent unpublished NOS smooth sheet (H-9272) define the geometry of the bay floor (Figure 6). The eastern sector has steep sides and relatively deep water close to shore. For example, the 3.6 m (12 foot) contour is less than 30 m from shore. In the western sector, the 3.6 m contour delineates a gently seaward sloping

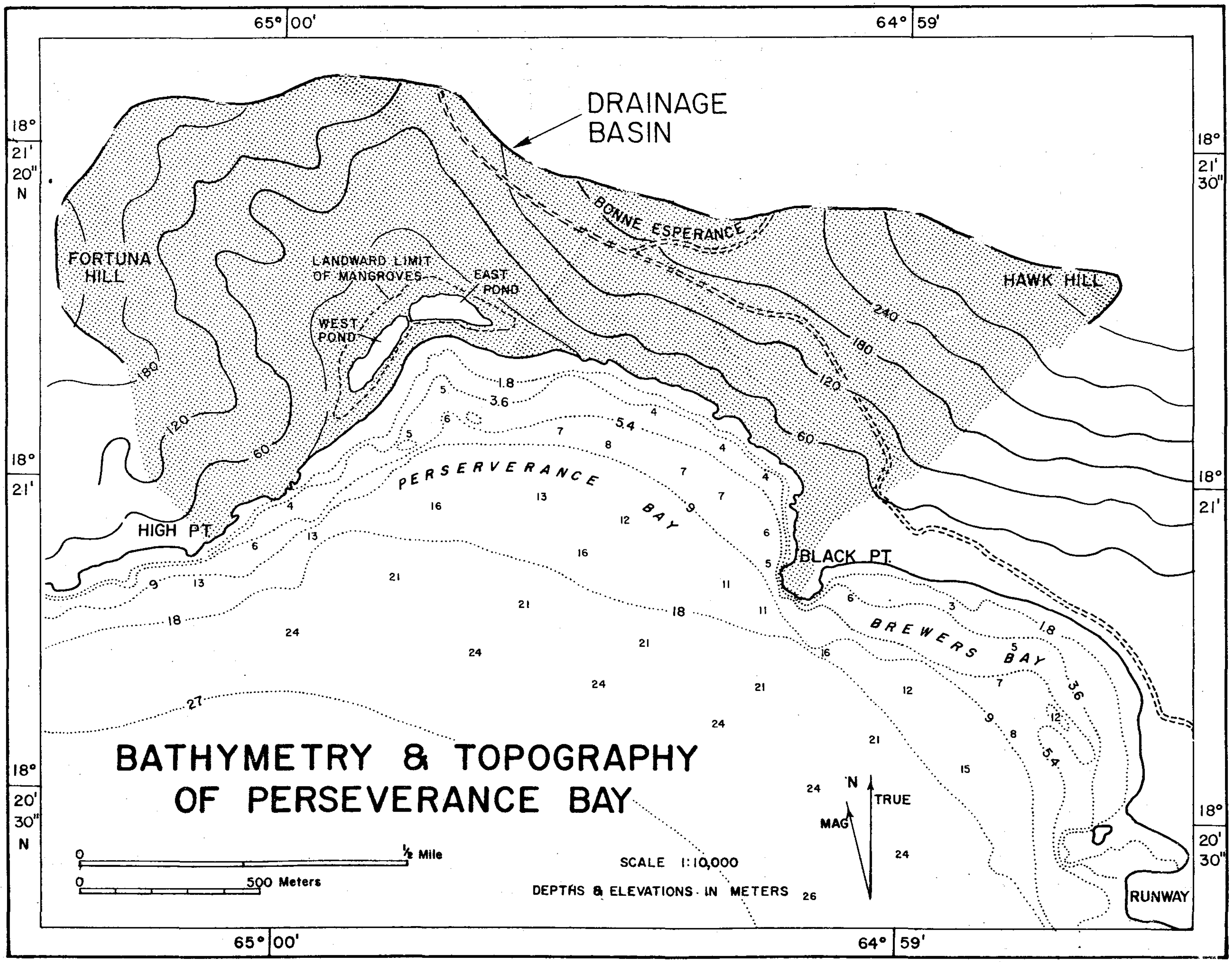


Figure 6. Bathymetry, topography and drainage basin of Perserverance Bay. From NOS Soundings, 1972-1973.

platform which veneered with coral rubble. This feature extends approximately 90m offshore. Continuity of the platform along the shore and along contiguous reefs is broken by a trough with depths from 1.2m nearshore to 9m. The trough probably follows the drainage of a former stream channel cut at lower sea level. Seaward parts of the bay floor, between 9m and 30m deep, slope gently seaward at about 1m per 55m (1 foot per 55 feet). The smooth lunate-shaped floor is interrupted by near-vertical walls 95m southeast of Black Point and also 45m south of High Point. These features most likely are former cliffs cut at a time when sea level was lower, by about 16m, and stood at nearly the same level, for a long time.

The salt ponds fill shallow pan-like basins. The West Pond is flat-floored for a width of 87m (291 feet) while the East Pond is dissected for a width of 42m (140 feet) (Figure 8A). The central floor of East Pond is dissected by a shallow channel about 12cm below the average level of the pond floor. Presumably this is a former drainage channel leading to the bay at the extreme east end of the barrier ridge. The channel appears on 1947 aerial photography and therefore is at least 30 years old. Water depths in the ponds vary with the amount of precipitation and evaporation. During the study period, January-October 1977, depths in East Pond ranged 0 to 43 cm while in West Pond they ranged 2 to 55 cm.

Banks of the ponds are relatively steep seaward along the beach ridge whereas landward they merge gradually with low alluvial slopes. The beach ridge rises 2.9m (9.2 feet) seaward of East Pond while it rises 1.9m (6.2 feet) seaward of West Pond (Figure 7). The lowest part of the ridge, a possible drainage-way for release of extreme flood water, lies at the extreme east end of East Pond.

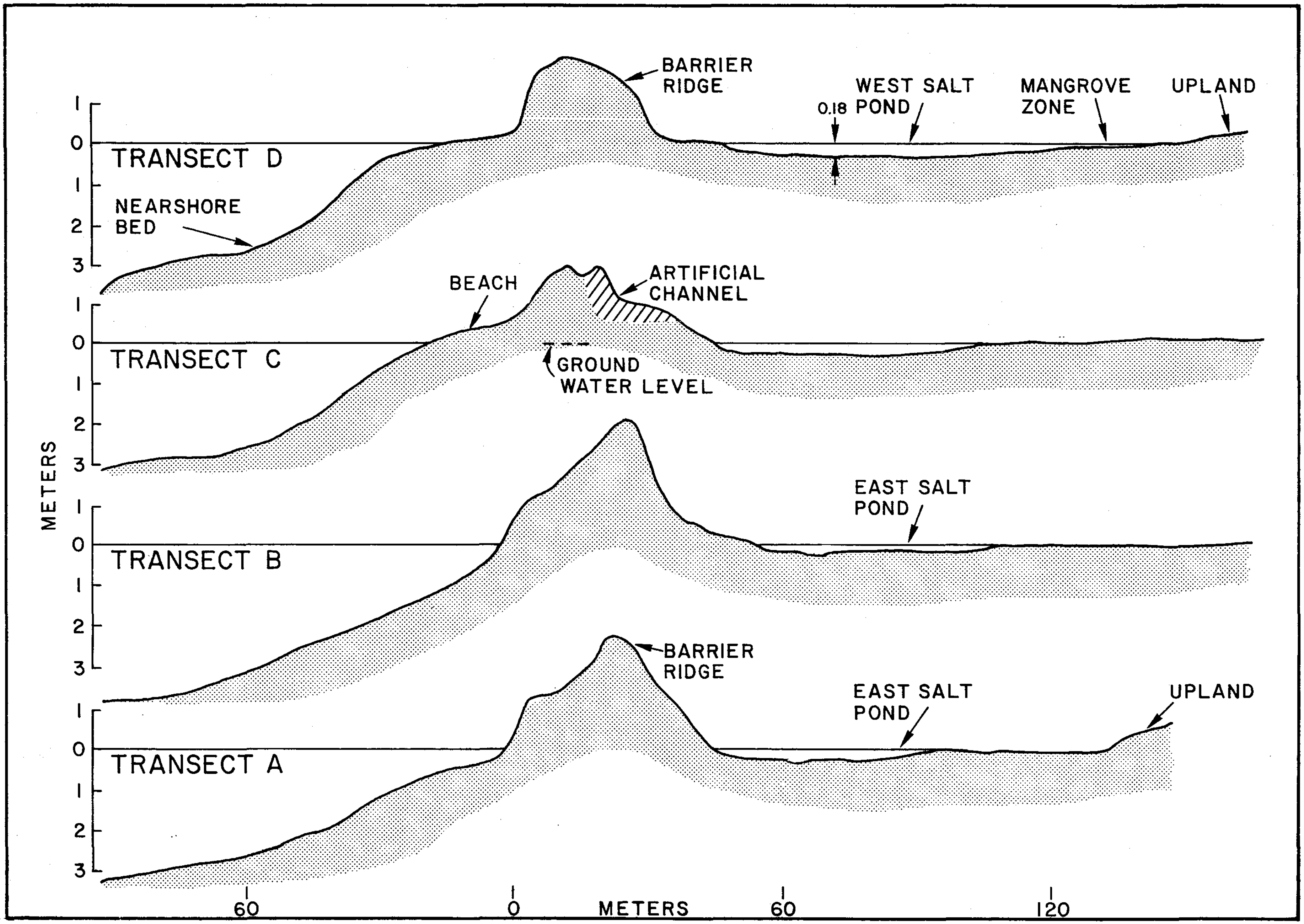


Figure 7. Topographic profiles across the nearshore bed, barrier ridge and salt ponds. For transect location, see Figure 1.

The bed of this channel lies 1.6m (5.5 feet) above mean low water; it is filled with boulders from the adjacent slope and with trees and brush about 30-40 years old (Figure 8B). A formerly excavated drainage way cuts through the central ridge to a depth of 1.5m but it is now back-filled to about 0.6m above tide level. Elsewhere the ridge is unbroken and effectively isolates the ponds from the bay up to an elevation of 1.6m (5.5 feet) above mean low water (Figure 7).

Watershed and Pond Drainage

The watershed which surrounds the bay landward (Figure 6), is a source of freshwater runoff and upland sediment during times of heavy rainfall. Therefore, a change in watershed topography and vegetation cover may affect natural functions in the salt ponds as well as in the bay itself.

Perserverance Bay is backed by a drainage basin of 1.63km^2 (0.63 sq. mi.). Runoff from the steep sloping eastern sector drains directly into the bay. The largest sub-basin in this sector leads into the east head of the bay through a gut (Figure 8C). Upper slopes of the eastern sector have been cut by roads, and a few residences have been established in the vicinity of Bonne Esperance. Runoff from the western sector drains mainly into the salt ponds. Each salt pond is backed by basins of nearly equal drainage area (Table 1).

The drainage basin receives about 110cm (45 inches) of rainfall annually. As much as 15cm (6 inches) has been recorded from a single storm. The upper parts of the Hawk Hill drainage basin receives the highest amount of rainfall on St. Thomas, 125-

Figure 8A. Floor of East Pond during the dry season, March, 1977, showing shallow drainage channel leading to right (d). Note dead red mangroves.

Figure 8B. Former drainage channel leading from East Pond to the bay through brush at extreme east end of ponds. Floor of channel lies 1.6 m (5.5 feet) above mean low water and carries water only during extreme floods from the land or storm tides from the bay.

Figure 8C. Zone of dead red and black mangroves along edge of West Pond. Mangroves suffer from sedimentation of the pond floor and resulting high salinity during periods of drought, March, 1977, a time of very low water in the ponds.


d
A


B

137cm (50-55 inches) on the average per year. The amount of rainfall that produces runoff is unknown. However, it is probably higher per unit area than elsewhere on St. Thomas because the rainfall is relatively high and the drainage slopes are relatively steep, largely more than 30 percent. Nonetheless, the stream channels and guts are dry most of the year and mainly carry intermittent storm runoff.

Future development of the upper drainage basin in the vicinity of Fortuna Hill and Bonne Esperance will increase the potential for flash flooding into the bay and salt ponds. By constructing roadways, parking lots, residential sites and by lining stream beds with concrete, the natural absorptive capacity of the soil and vegetation will be destroyed. A change in the drainage pattern can alter both the rate and quality of runoff. Flood water from torrential rains charged with sediment can be delivered to the bay quickly. Without vegetation cover or infiltration into the soil as ground water, natural purification of runoff will be reduced.

The ponds act as natural catchments and, in turn, they buffer the bay and its reefs against extreme freshwater inflow. This is evidenced partly by the fact that reefs are absent in the eastern bay whereas they are well developed in the western bay which is backed by salt ponds. For another part, the western bay receives more wave energy than the eastern bay, a factor also essential to reef growth (Fig. 10B).

A line of levels run across the ridge from the pond surface to the bay surface revealed that the pond surface in January 1977 was essentially at the same level as the bay when the bay surface was close to predicted half-tide level (Figure 7). Likewise, the level of ground water measured in a pit dug into the ridge on Transect C was close to that of the pond and bay surface. The groundwater level was only 5cm (0.17 feet) higher in the ridge than in the pond. A 2-liter injection of Rhodamine B dye into the ground water was retained in the ridge for more than six months. Water levels in the ponds are essentially constant for at least four days; there is no rise and fall caused by bay tides. These observations suggest the ridge is relatively impervious to direct exchange and percolation of water between the bay and the pond. Because the salinity of ground water in the ridge (33.19%) is less than average bay water (35.5%) and less than pond water (42.58%), infiltration of rainfall must freshen upper parts of the groundwater table in the ridge. Short term or seasonal changes in water level of the ponds are mainly due to precipitation and runoff. It seems likely that level of the ponds relates to level of the bay over the long-term with geologic submergence of the region.

7. Geologic Conditions

The bay system operates within the confines of a basin which is determined by geologic conditions. These conditions determine the general shape, size and shore characteristics of the bay. In turn, they are modified by currents, waves and vegetation and thus acquire different aspects from place to place.

The rocky headlands, cliffs and steep slopes of Perserverance Bay are supported by volcanic tuffs and breccia of the Louisenhoj Formation. These rocks have been extensively folded, faulted and partly buried by recent alluvium. The alluvial deposits, brown silt, clay, fine sand and gravel beds, fill the lowland landward of the salt ponds to a probable depth of 5 to 12 meters. Alluvium extends beneath the landward margins of the ponds (Figure 9), and alluvial silt provides near-surface fill over mangrove peat in a relationship that indicates progressive infilling of ponds. Deposits beneath central parts of the ponds mainly consist of homogeneous gray clay with varying amounts of organic matter for a thickness of 210cm. Reddish brown mangrove peat underlies the gray clay at 240 to 330cms. At greater depth, 330 to 460cm the pond and mangrove deposits are underpinned with firm shell beds and silt indicative of a former lagoon. The barrier ridge is topped by coarse sand and cobble while at depths of 0.5 to 1.0 m sediments are predominately sand with cobbles and gravel. The bed of sand on the beach is relatively thin, less than 1.0 m thick in most places. The relationships between the alluvium, pond, peat, lagoon and barrier deposits are schematized in Figure 9.

The basins occupied by the salt ponds began to form more than 4,000 years ago when the coast was downfaulted and cut by streams during lowered sea level. When sea level rose to the 5.5m depth, lowlands of the present pond area were inundated. As waves attacked the shore and nearshore bed they formed a barrier spit across the submerged alluvial lowland and thus formed a shallow lagoon. With rise of the sea level after 4,000 years B.P. (before the present), the barrier built upward and isolated the lagoon. Thus, the lagoon was transformed into a salt pond. It had a clayey floor and was fringed with red mangrove stands. With continued rise of sea level and submergence of the area, the mangroves grew upward and transgressed landward over lower parts of the alluvial plain. At the same time mangroves grew upward as the barrier built upward and moved slowly landward. Evidently, direct tidal exchange with the bay was not essential for mangrove growth. However, salt content could have been kept low by frequent runoff and percolation of seawater through the barrier.

During late stages of pond infilling, in the last 200 years, sedimentation from the land slightly exceeded the long term rate of submergence. Elevation of landward pond margins became too high and saline for mangrove growth. Therefore, the mangrove stands regressed pondward and alluvium buried former mangrove peat (Figure 9). With a slow sea level rise in recent years, about 12cm (4.8 inches) per century, sediments from the land continue to build the pond floor upward and to reduce the pond area.

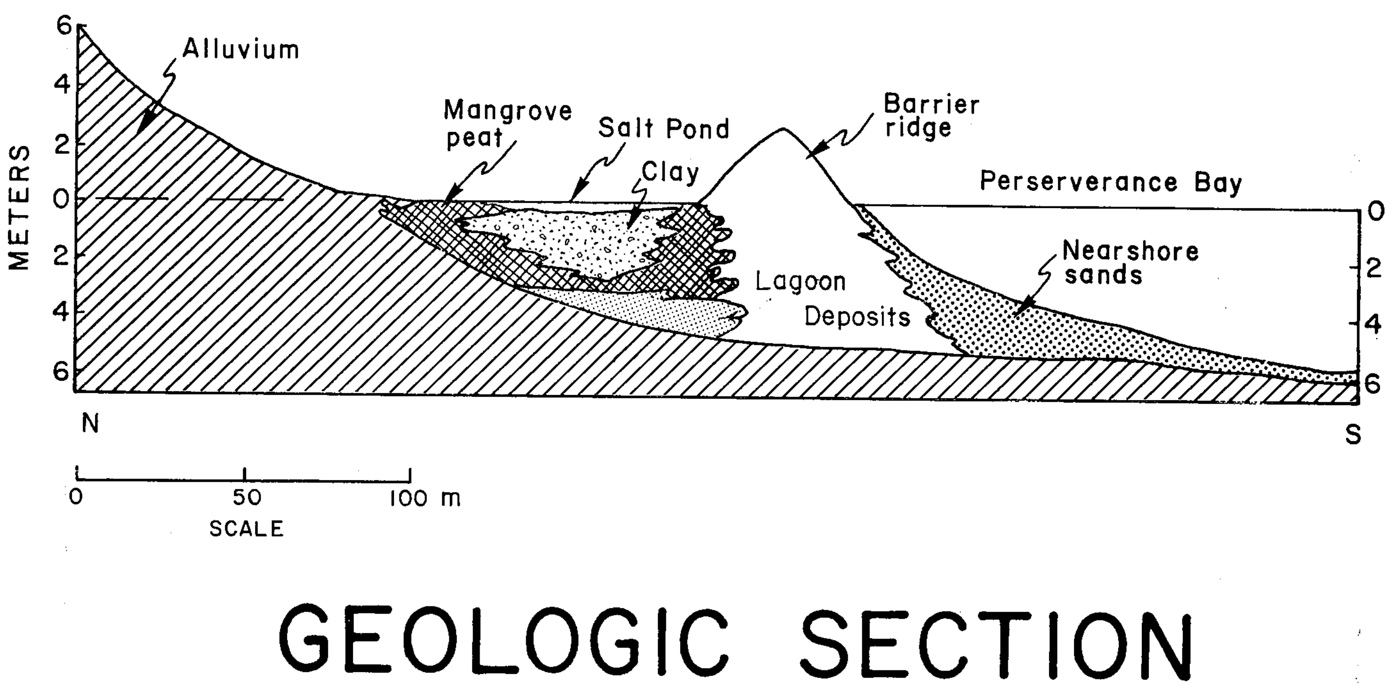


Figure 9. Schematic geologic section based on borings and probes showing relationships between principal sedimentary units.

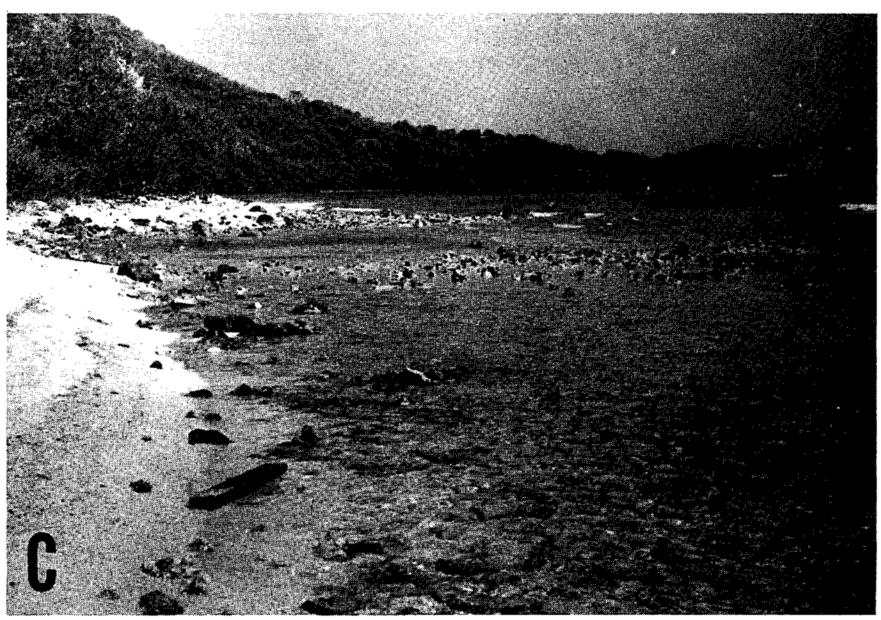
Figure 10A. Aerial view of Black Point, a headland that shelters eastern reaches of the bay, left. Gut (g) is the main route of freshwater runoff and sediment discharge into this sector of bay. Faint plume of turbid water extends from Brewers Bay, off Black Point, dotted line, and into Perserverance Bay where it spreads out.

Figure 10B. Aerial view of main beach and western head of Perserverance Bay, October 9, 1977. Littoral drift which is driven from breaker zones on shoals (s) converges off the beach and partly flows seaward through a trough (t). The salt ponds (p) behind the shore act as natural catchments for silt and buffer the bay and its reefs against extreme runoff and sediment discharge from the land.

Figure 10C. Nearshore platform covered with coral debris near the west bay head. Waves breaking on this platform drive a littoral current into the bay head.


A


s
t
s
B

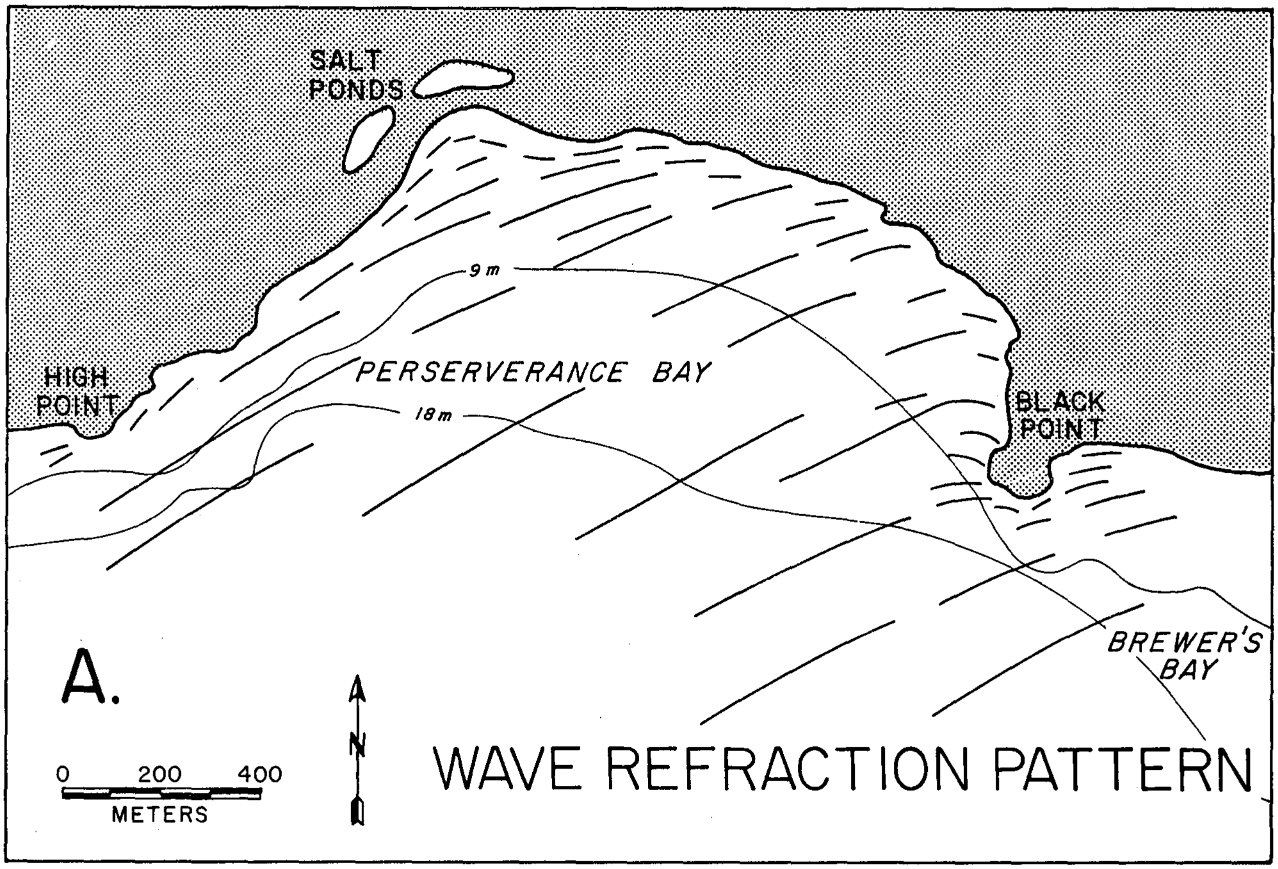

C

8. Environmental Conditions

Waves. Of the different energy sources affecting the lagoon, wind, tide, and stream inflow, waves are the most important source of physical energy in nearshore reaches (0-10m depth) whereas tidal currents are the most important in offshore reaches (10-18m depth). Despite protection of the bay from predominate trade wind waves, the bay receives local waves from the east and southeast by refraction around shoals off Red Point and Porpoise Rocks, off Water Island. Besides these wind waves, the bay receives direct swells and wave "chop" from the southeast, mainly from September through November. At times of hurricanes and tropical storms the southeast and southwest are the predominate directions. In winter, December through March, when infrequent northern swells pound the north coast, waves are refracted around the west end of St. Thomas and attack Perserverance Bay from the west. However, the most common waves are those approaching from the east and southeast. Typically they have a deep water height of 0.5 to 0.8m, a period of 8-12 seconds and a length of 8 to 18 meters.

As waves and swell enter Perserverance Bay they "feel" bottom on approaching shoal water where depth is in the range 4 to 9 meters. Wave crests tend to bend into gently-curved patterns with crests more-or-less parallel to the bottom contours. Because the bay is relatively deep and steep sided, most refraction of normal waves takes place in a narrow zone less than 50 meters from shore (Figure 11). Around High Point easterly waves approach head-on and break parallel to shore resulting in substantial reflection of wave energy from the rock cliffs. A reflection clapotis or "chop" is recorded on aerial photographs for more than 800 meters offshore from High Point. Elsewhere, waves break at an acute angle while along the west side of Black Point they run transverse to shore (Figure 11). Northern swells that refract around the western end of the island approach Perserverance Bay from the west for short periods during December through March. Because these waves have a long wave length (60-180m) and a high angle of approach they must have a significant impact on the floor and shores of the bay. Figure 11 shows the refraction pattern of northern swells traced from U.S.G.S. 1954 aerial photos.

Although direct measurements of storm waves and hurricane surge have not been made, effects of such waves are recorded by sedimentary features. Erosion of the bay floor is evidenced by an extensive zone of "blowouts" and scour channels in grass beds appearing on NOS aerial photos dated 1958. The zone runs along inner reaches of the central bay and extends seaward 160 meters to a water depth of 6m. Another feature is the occurrence of wave worn cobbles atop cliff ledges more than 6 meters (19 feet) above the cliff foot. Presumably these were emplaced by storm waves. Additionally, the barrier ridge across the salt pond is built of wave worn cobbles entending from the beach landward to the pond edge more than 60m (182 feet) and upward to heights of 1.9 to 3.0m (6.1 to 9.6 feet). According to the Corps of Engineers (1975) hurricanes, which have a frequency on the average of once in 33 years, raise water levels in the area from 1.5-3.6m (5 to 12 feet).



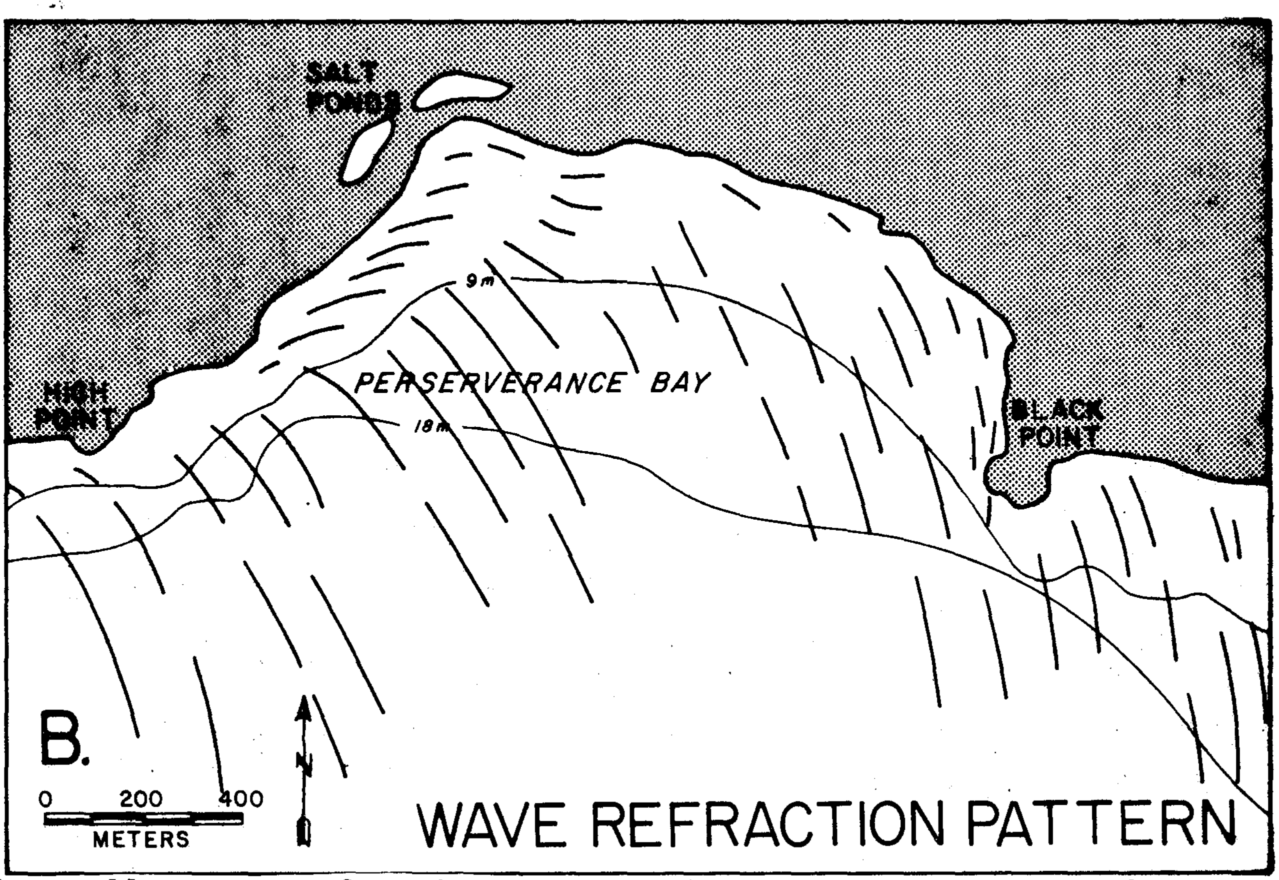


Figure 11. Wave refraction patterns in Perserverance Bay: A. normal pattern with wave approach from the southeast; B. pattern with wave approach from the west driven by northers. Lines represent direction of crests.

Waves of such heights (> 6 feet) would flood the salt ponds and adjacent lowlands.

Currents and Circulation

Currents in the bay display different modes determined by environmental driving forces, the wind, waves, tide and semi-permanent flow. At times of high runoff from the land, density gradients and bouyancy effects may assume a short-term role along inner reaches. Because the bay has an irregular shore configuration and bottom geometry, these elements influence the flow field and must be taken into account. Therefore, the current speed and direction at any single time and place is the resultant of components derived from the geometry or from different driving forces. Prominent modes of current recognized in the bay proper are illustrated by schematic vector diagrams of Figure 13.

Littoral Currents. Since refraction of waves is often incomplete, waves break at an acute angle to the shore. They run up at an angle to the beach or nearshore shoals and create a longshore current running parallel to the shore. Where a supply of sand is available, such currents move the sand alongshore.

Figure 12 shows the direction of littoral currents observed in Perserverance Bay, January 4-11, 1977 a time when waves were relatively low and breaker heights alongshore ranged 10 to 40cm (0.3 to 1.2 feet). The littoral currents were quite slow, mainly less than 8cm per sec but during moderate breaker heights in August 1977, speeds reached 78cm per sec. Although deep water waves approached from the southeast at 148 to 196°, such as shown in Figure 11A, littoral current directions were quite variable, depending on the local shoreline configuration. The littoral current does not persist for a great distance. Instead, it is fragmented into cells with local zones of convergence or diffusion. The currents often run seaward off secondary headlands.

The largest convergence zone is at the west bay head near the main beach. In this area, waves are refracted onto local shoals to each side of the beach, and thus build up a hydraulic head of water which drives a littoral current inward toward the bay head. The resulting convergence of flow is a virtual trap for oil or floating debris. At times of high waves, the debris is driven onto the beach where it is stranded (Figures 3B, 10B).

A large scale littoral current flows from Brewers Bay into Perserverance Bay during times of moderate to high waves and swell from the east and southeast. As waves attack the nearshore bottom and beach of central and western Brewers Bay they stir up fine sediment. This is transported by the littoral current around Black Point where it either circuits around in the flood gyral west of Black Point or spreads out into central Perserverance Bay (Figure 10A). Large turbid plumes reportedly developed along this route during dredging of Brewers Bay in 1970 and have been observed intermittenly since that time. Undoubtedly, some fine sediment is derived from erosion of the artificial fill along Brewers Bay beach. At times of flooding from the land, landborne fine sediment also may contribute to the turbid plume. None-the-less, the plume is not entirely due to dredge and fill as

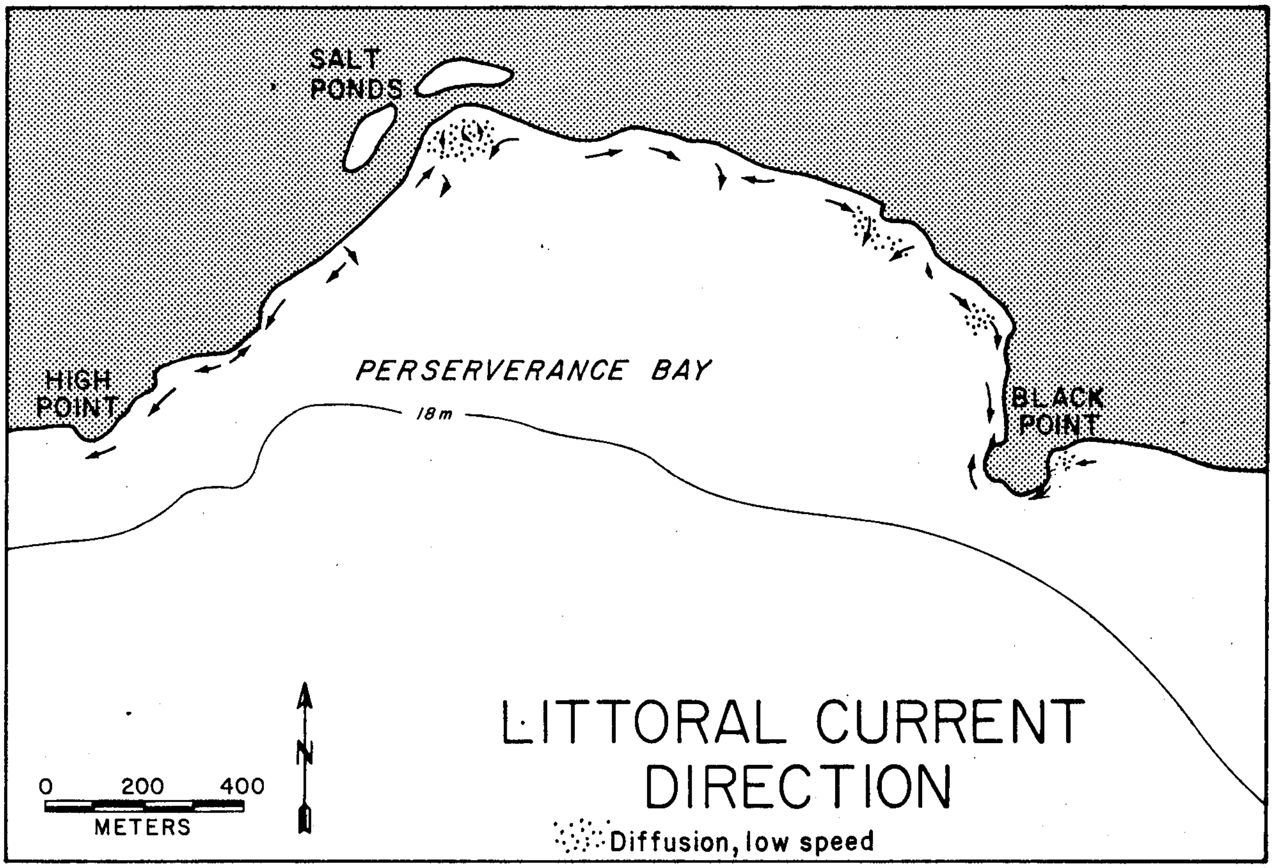


Figure 12. Pattern of littoral current in the breaker zone along shores of Perserverance Bay under relatively low waves, January, 1977.

it is displayed on 1947 aerial photos prior to disturbance of the area. Prominent modes of current recognized in the bay proper are illustrated by schematic vector diagrams in Figure 13.

Reversing Tidal Currents. These currents are recognized by their periodic reversals in direction and changes in speed that relate to rise and fall in tidal height (Fig. 13A). The flood current is one that sets to the west which is the supposed direction of propagation of the oceanic tide wave. The ebb current is one that sets to the east. The change from flood to ebb produces a period of slack water during which the speed

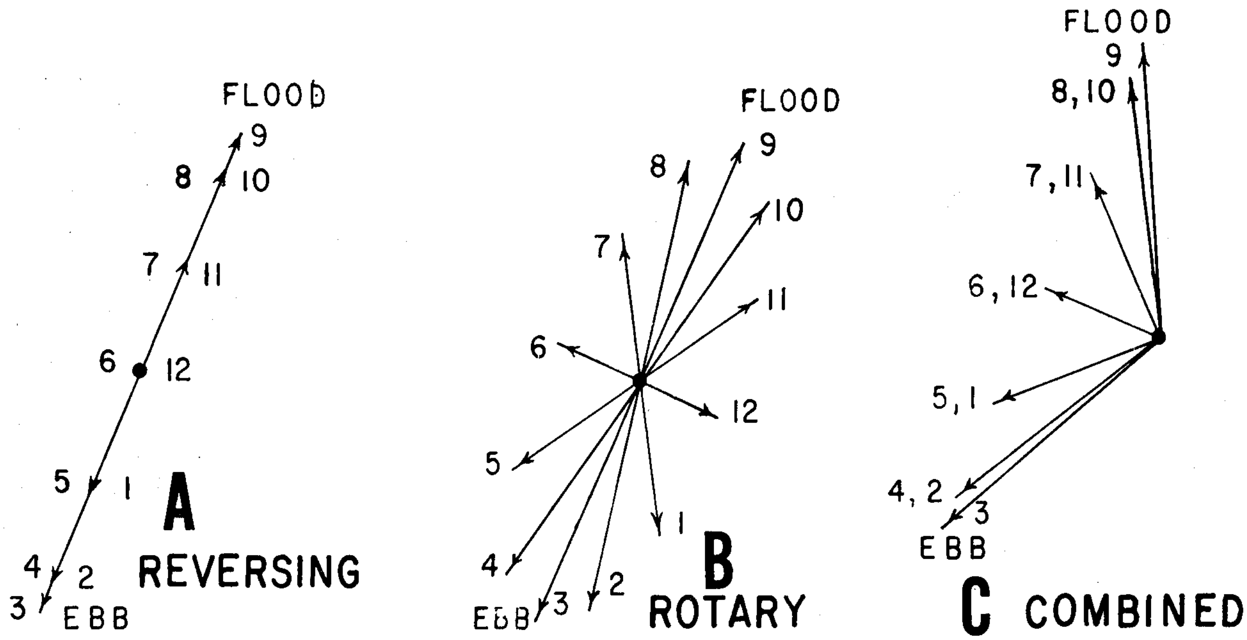


Figure 13. Schematic vector current diagrams of different current modes recognized in St. Thomas water; A. reversing tidal current; B. rotary tidal current; and C. combined reversing tidal current with shore geometry or semi-permanent flow from the right.

is nearly zero. It is the periodicity of the tidal current that distinguishes it from other kinds of currents.

The most prominent reversing currents were observed at station TJV off Black Point in January, 1977 (Fig. 14). Not only do the currents reverse in direction but they reverse periodically, about every 6 hours. Figure 16 provides greater detail on the periodic tidal character at this station. Maximum ebb (easterly) current speeds occur near the beginning of the prominate fall in the tide, i.e., before low water. By contrast, maximum flood (westerly) speeds occur at low water or near the beginning of the prominate rise in the tide. It appears that the current tends to anticipate a large fall or rise. The greater the fall or rise, the stronger the maximum current.

These characteristics are in accord with a progressive tidal wave in the open ocean where the maximum current velocities in the direction of propagation tend to occur at high and low tides. Evidently, ocean tides reaching Perserverance Bay are not modified to any degree. Nearly all the current measurements, except inshore stations JUD and RIC, display a partial reversing trend. This trend is remarkable considering the small tide range, small size of the islands in relation to the tidal wave length, and great water depth surrounding the islands. None-the-less, the range of directions varies a great deal and suggests other forces are active.

Rotary Tidal Currents. These are recognized by a continual change in direction with time. As shown in Figure 13C during a period of 12 or 24 hours, a purely rotary current shifts completely around the compass and defines an ellipse. There is no slack water.

Only a few of the observations exhibit rotary trends, namely stations JUD, RIC, and RIC_2 of January, 1977 and DEE and TJV of July-August, 1977. Most of the rotation occurs only at times of weak current such as around long slack waters. Rotation is incomplete; no complete or distorted ellipses are evident.

Semi-Permanent or Non-Tidal Currents. These currents consist of uni-directional flow created by the wind or by ocean currents of the north equatorial current which is westward along St. Thomas. Speeds of ocean currents vary 20 to 30 cm per second (0.4 to 0.6 knots). Such a flow, superimposed on the tidal currents, was recorded by NOS at a station 2 km south of Saba Island. At times, ocean currents may impinge on

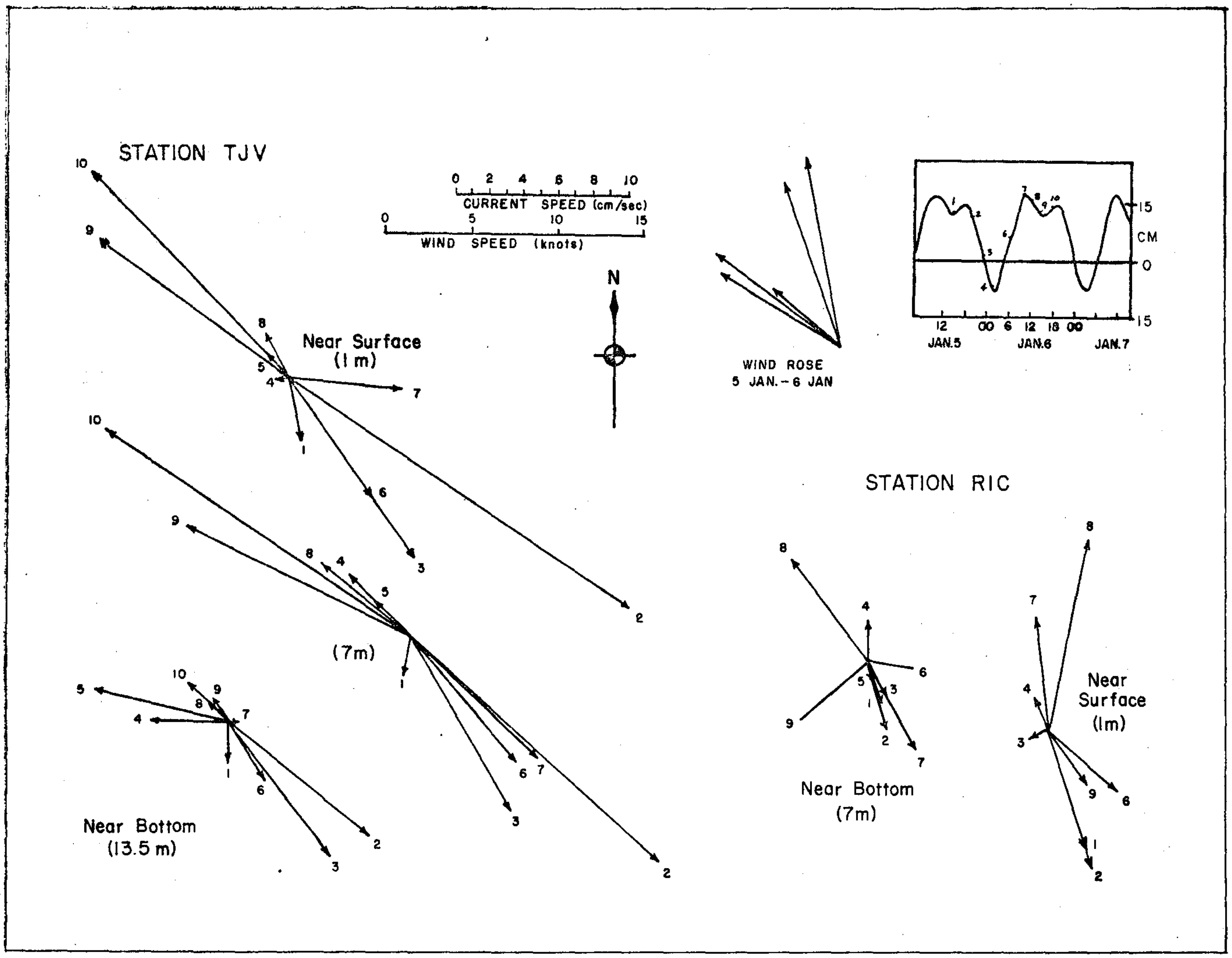


Figure 14. Vector current diagrams for anchor stations TJV and RIC, January, 1977.

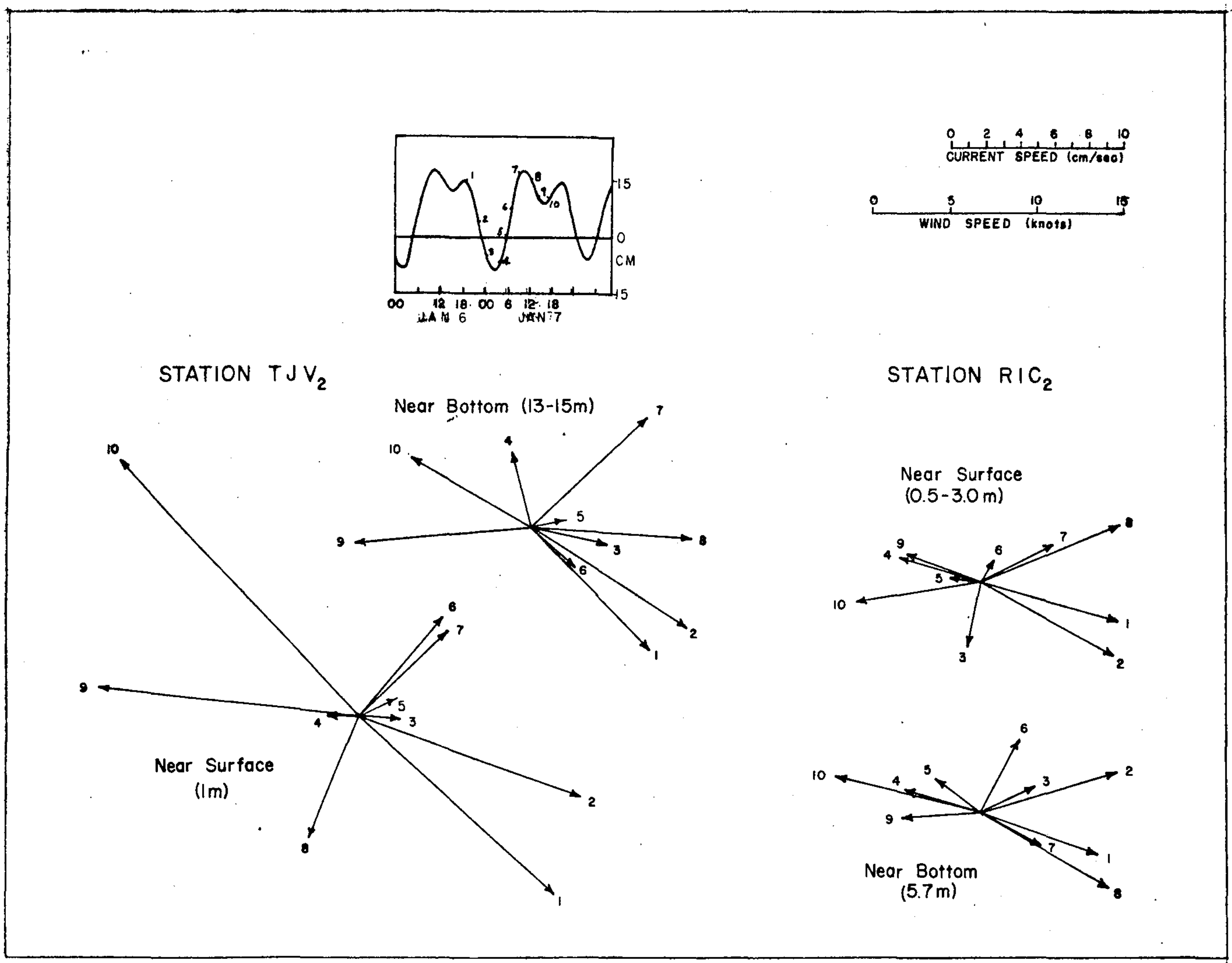


Figure 15. Vector current diagrams for anchor stations TJV_2 and RIC_2, January, 1977.

Southwest Roads, either through passages between Saba Island, Flat Cays, and Red Point, or as eddies that migrate into Southwest Roads from the southwest. Because of the seaward projecting bed geometry southwest of Water Island, and the restrictive cays and islands, it seems probable that the ocean current is diverted seaward off Southwest Roads rather than intruded into the area.

Wind-driven currents, which result from direct wind drag over the bay, consist of a downwind flow, westerly, in near-surface water or a flow to the right of the wind, northwesterly, below the surface. Since wind is normally greater during the day, reaching a peak in early afternoon than at night, strength of these currents often exhibits a dirunal change.

The combination of a semi-permanent current and a reversing tidal current creates a resultant current which changes direction, within a certain range of directions, without quite reversing as shown in Figure 13C. A similar trend is produced by a combination of semi-permanent current on a rotary tidal current whereby the vectors describe an asymmetrical ellipse with respect to the point of origin.

Nearly all the current observations exhibit the influence of semi-permanent flow superimposed on reversing or rotary tidal currents. However, directions of the flow are quite variable. At station RIC_2, July 28-29, 1977, the current at all depths is landward (northerly), whereas at station JUD, July 30-31, 1977, the current at all depths is seaward (southerly). Elsewhere, i.e., stations TJV, AIR, TOM, July-August, 1977 (Figs. 16, 17, 18) the current vectors cluster in two directions with the larger cluster indicating the predominate current. Near-surface currents at station TJV_2 (Fig. 19) and DEE, January, 1977 are influenced by wind drag relative to currents at greater depth. The wind acted to strengthen flood currents and dampen ebb currents. At other stations the chief effect of the wind is to increase the range of directions in the near-surface current vectors.

Shoreline and Bottom Geometry Effects. The interaction of geometry with tidal currents and semi-permanent currents results in components of flow that distort patterns in various ways. The effects of headland geometry are evident in vector diagrams for stations TJV and RIC, Figures 14 and 15. Whereas currents at TJV are distinctly reversing with an offshore resultant at mid-depth, currents at RIC are partly rotary with a southerly resultant at mid-depth. The effect of the headland is three fold: (1) the flood tide surface flow diverges west of the point and turns landward into a clockwise gyral on the west side of Black Point (Fig. 20B). No such eddy is formed on the ebb tide at this location. Instead, eastward (ebb) flow through the main bay converges with inshore ebb flow (Fig. 20A). (2) The headland intensifies the reversing character of the tidal current and at times redirects the current seaward.

Figures 20A and 20B show the general pattern of circulation when the current is at maximum strength. This is based on a composite of anchor station data and gives only

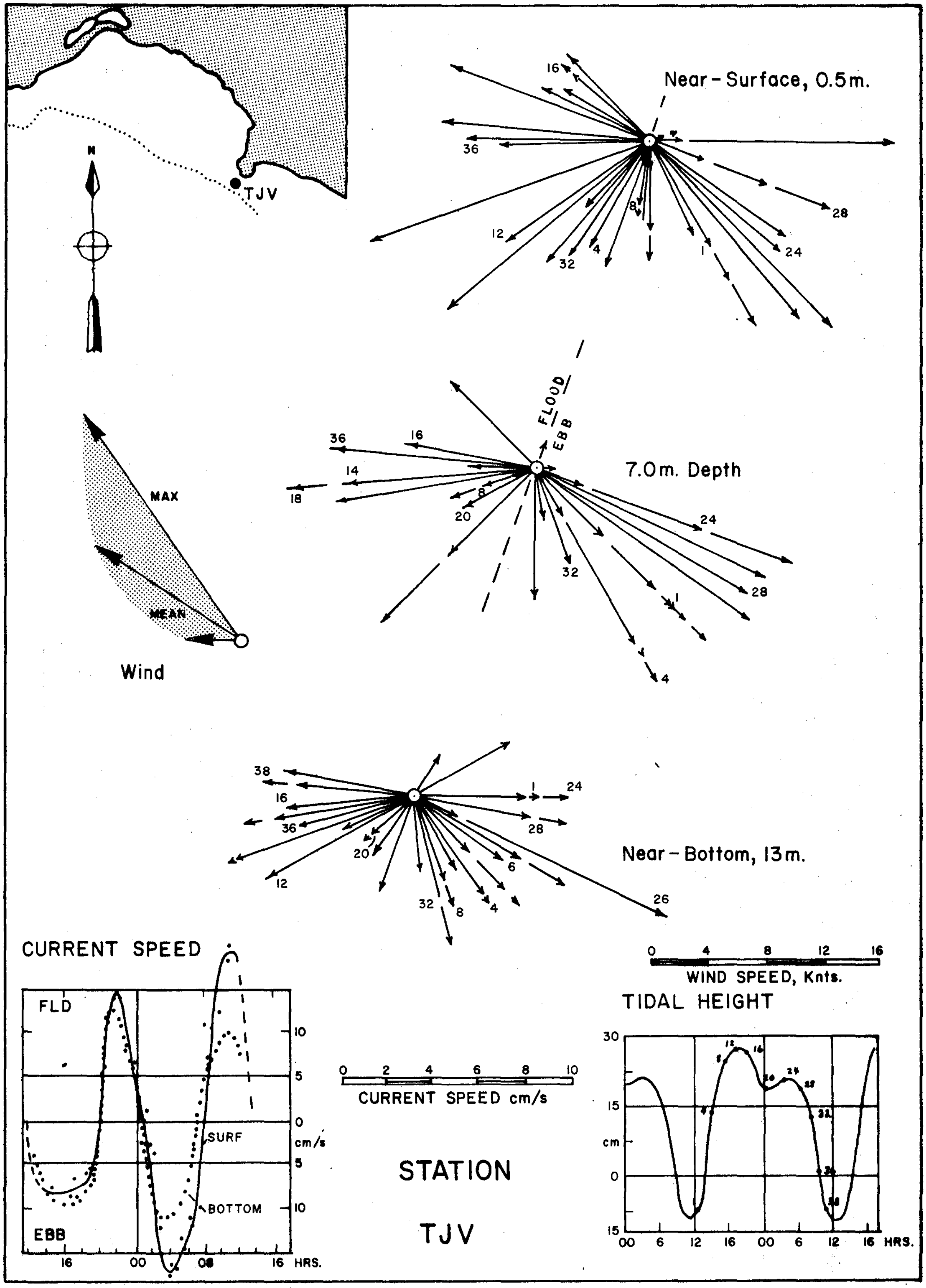


Figure 16. Vector current diagrams for three depths at anchor station TJV, July 26-27, 1977.

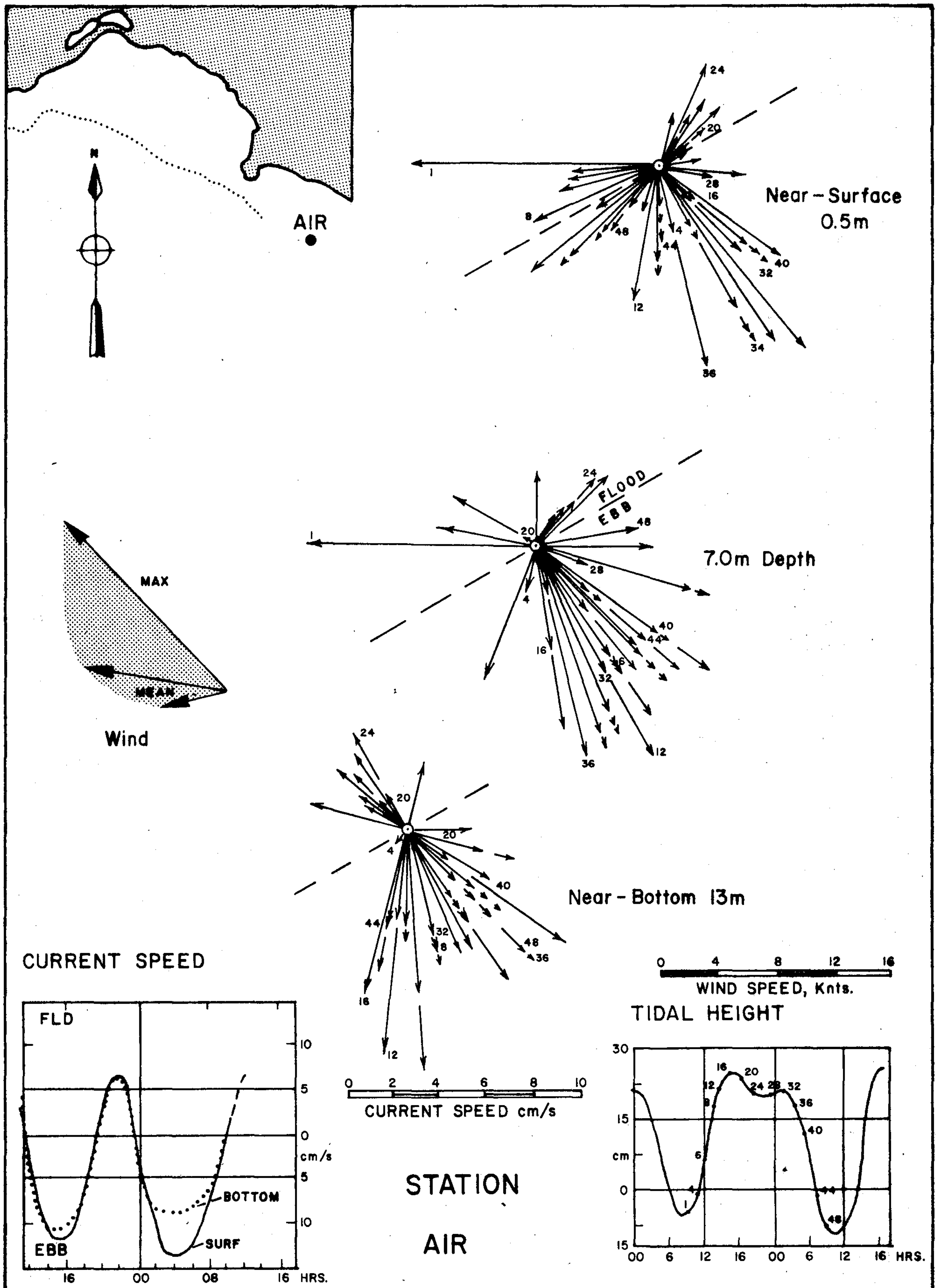


Figure 17. Vector current diagrams for three depths at anchor station AIR, July 25-26, 1977.

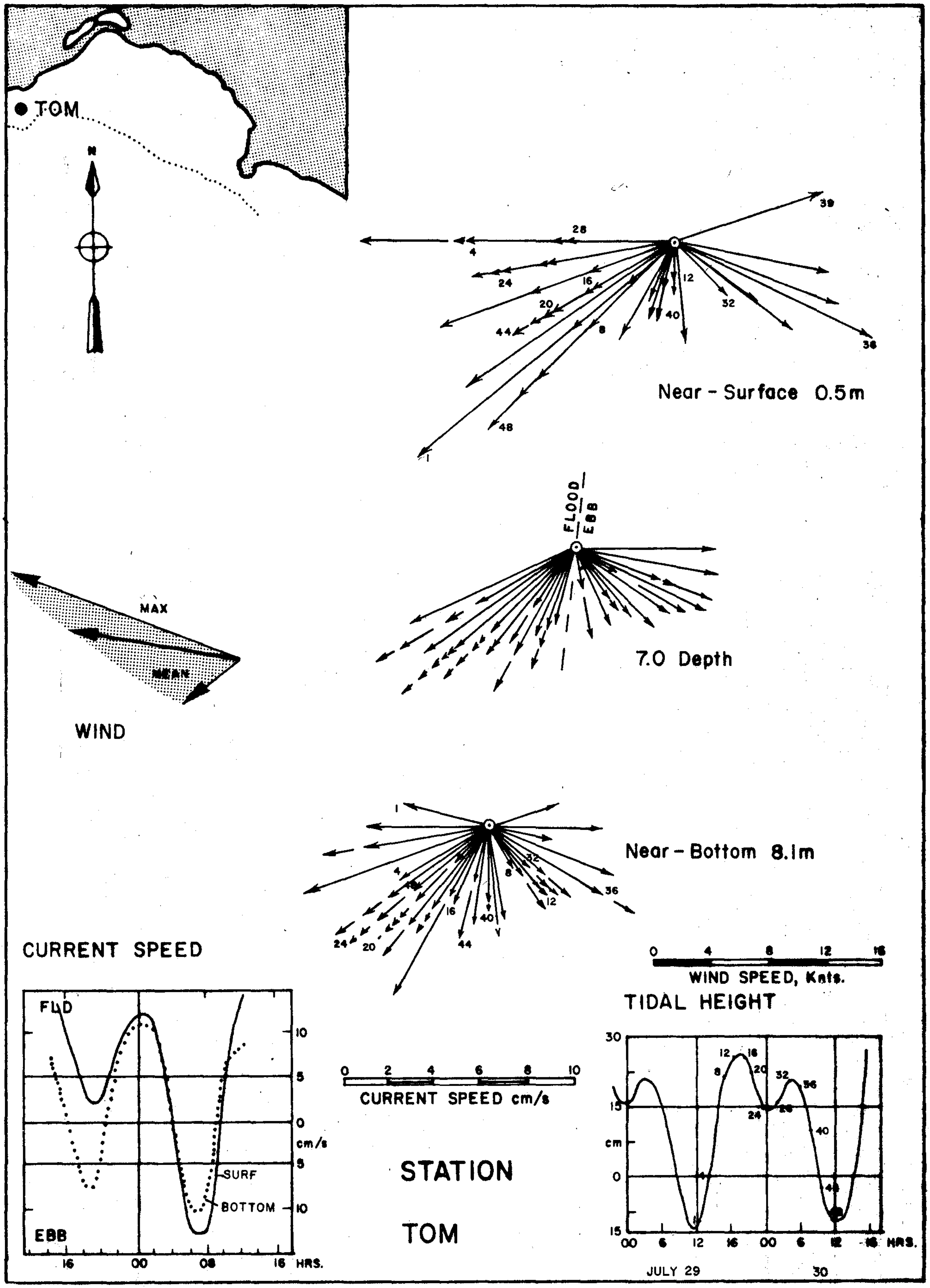


Figure 18. Vector current diagrams for three depths at anchor station TOM, July 29-30, 1977.

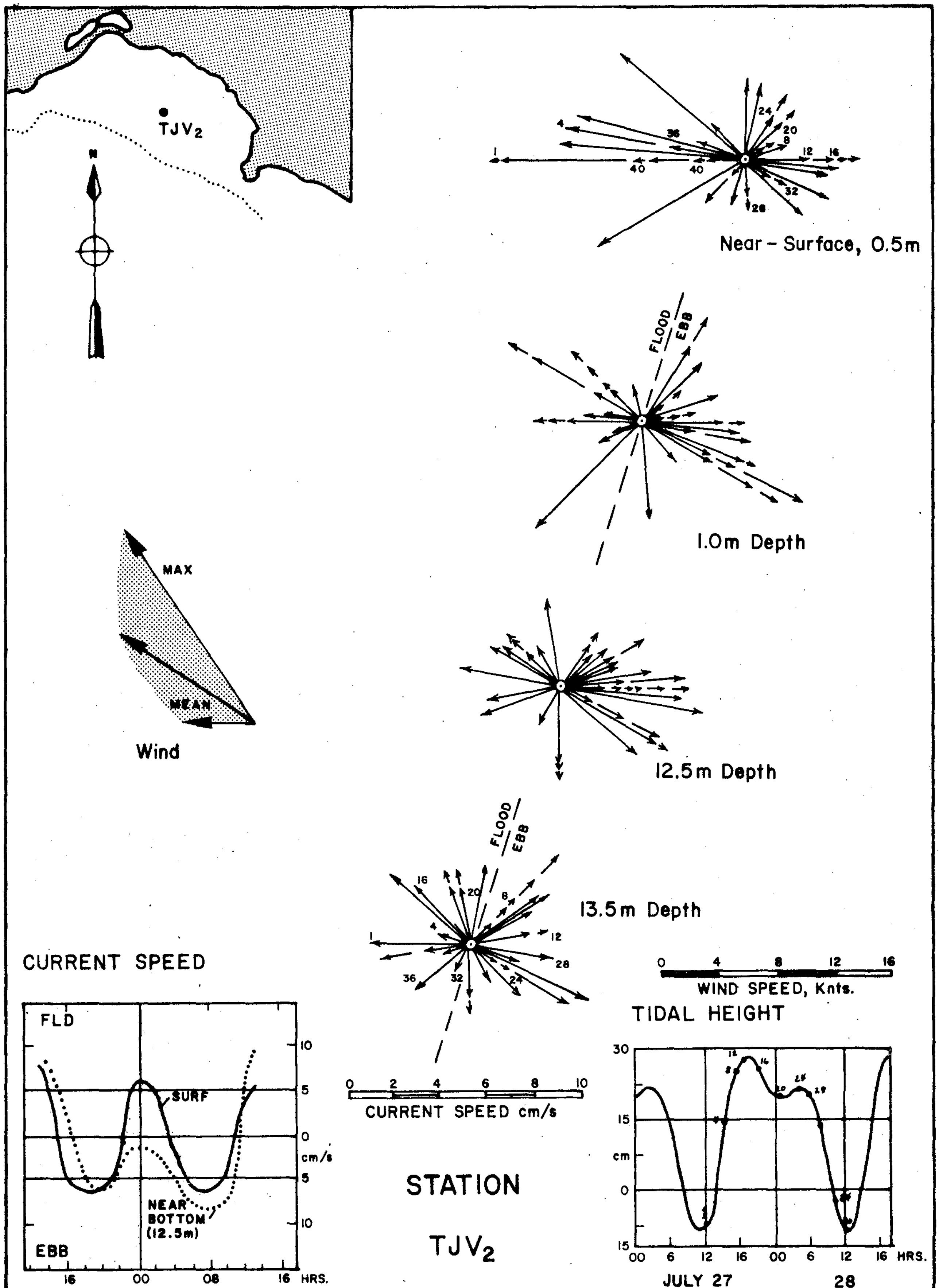


Figure 19. Vector current diagrams for three depths at anchor station TJV_2, July 27-28, 1977.

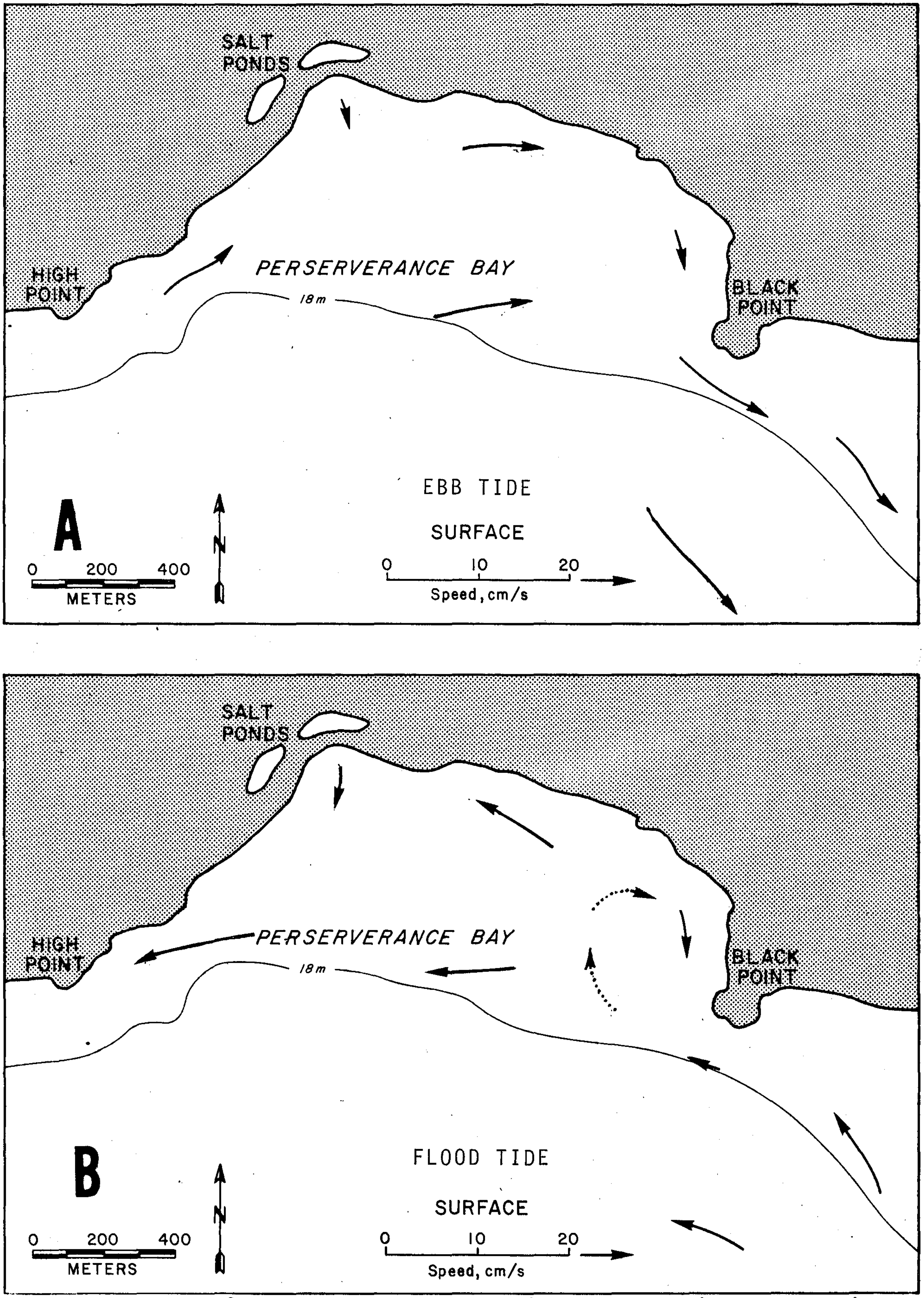


Figure 20. Surface current pattern when current is near maximum strength; A. during an ebb tide (easterly); and B. during a flood tide (westerly), July-August, 1977.

the prevailing current at maximum strength. Undoubtedly, there are many transient eddies whose positions are unpredictable from time to time. The charts are not strictly synoptic inasmuch as the tide phases vary from place to place throughout the bay. The currents are stronger off the headlands than in the east and west bay heads. Although currents are relatively weak in the bay heads, especially the east bay head that is protected from winds and waves, it remains to determine the resultant flow, over two semi-diurnal tidal cycles that affects flushing and transport capacity.

Resultant Current and Bay-Wide Circulation. When the vector resultant is computed for each measurement point at each station, a distinctive circulation pattern is revealed. As shown in Figures 21A and 21B, the strongest resultant current occurs near High Point (station TOM) where the predominate flood and semi-permanent flow combine to create rapid westward flow. This is a zone of rapid transport where sediment, floating debris, etc. are flushed out of the bay. By contrast, the weakest resultant current occurs in the central bay (station TJV_2) where there is a slight westward drift near the surface and a slight landward drift near the bottom. This defines a virtual null zone where transport over many tidal cycles is nearly zero. Thus pollutants, debris, and sediment may be expected to accumulate in this zone. The occurrence of very fine sediment in the central bay tends to verify the circulatory pattern.

Off Black Point the resultant currents are directed south to southeast near the bottom and near the surface despite exposure to easterly winds. These currents are also opposed to the littoral drift which is directed westward alongshore.

When the vertical distribution of resultant July-August currents is examined (Table 4), most stations display an orderly counterclockwise rotation with depth. Current speed near the bottom is often less than at one meter above the bottom or at mid-depth. This trend suggests net non-tidal currents are attentuated and redirected by the frictional effect of bottom geometry and hydraulic roughness that interacts with density differences.

Figures 21A and 21B display the basic pattern of circulation, based on quasi-synoptic resultant currents derived from measurements at 8 anchor stations occupied over two semi-diurnal tides during a 7 day period in July-August, 1977. The basic pattern of circulation in the bay consists of a counter-clockwise spin with an indraft along the eastern side and an outflow along the western side. Its result is to drive cool salty water into the eastern bay along the bottom and in turn, to diminish the oxygen content. Its further effect is to exchange bay water with the sea and to mix it into a single water mass with relatively uniform temperature and salinity. As a result of the clockwise circulation, central bay water is relatively inactive and thus provides a sink for fine sediment and potential pollutants.

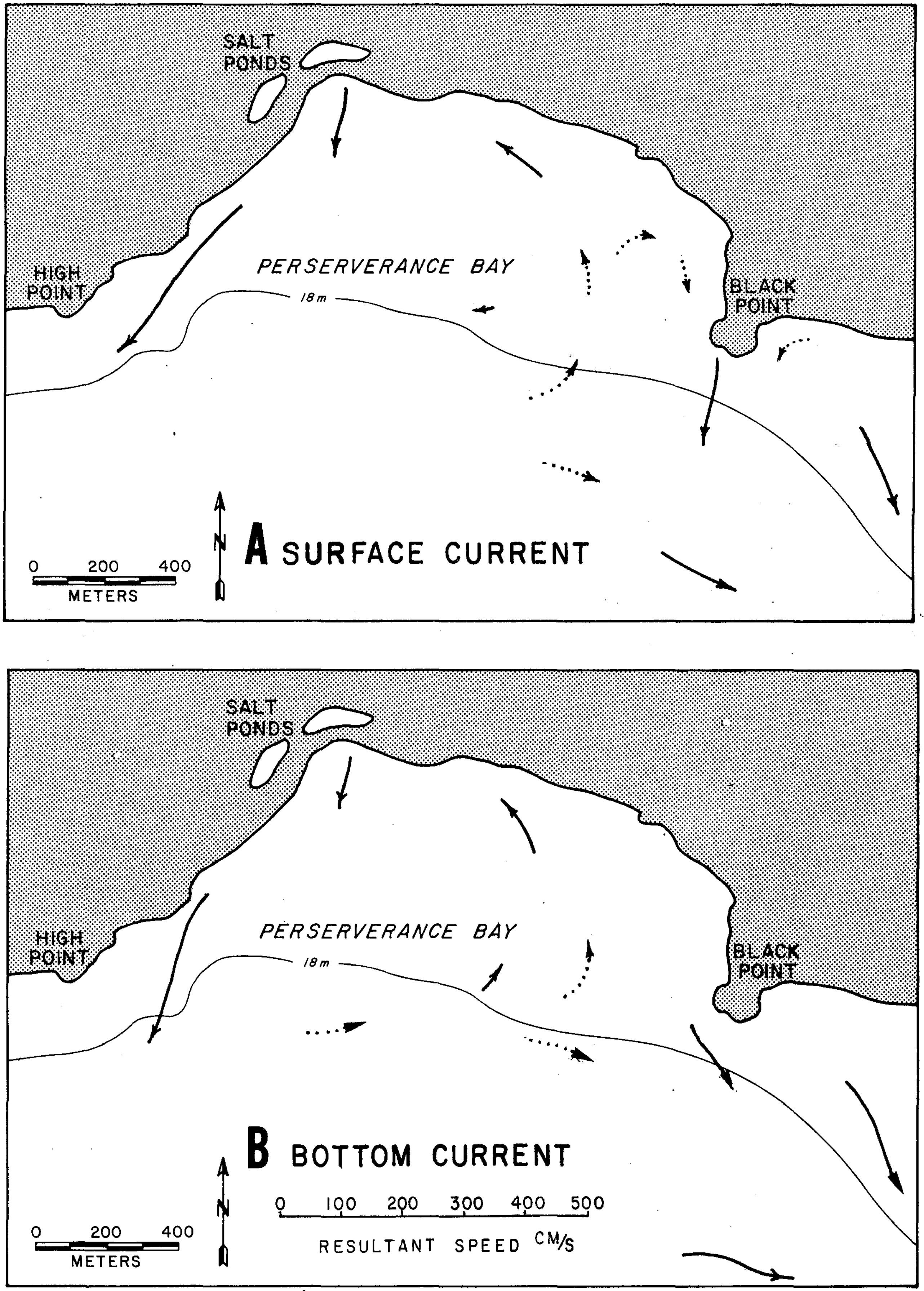


Figure 21. Resultant current pattern based on anchor station measurements, July-August, 1977. Arrow length represents magnitude of resultant current over 25 hours. A. near-surface current; and B. near-bottom current. Inferred current, dotted arrow.

Table 3. Summary of anchor station current data for Perserverance Bay and vicinity, January 5-11, 1977. Includes vector resultant and average speed and direction.

STATION	DEPTH, m	VECTOR SPEED,* cm/s	RESULTANT DIRECTION, mag.	AVERAGE CURRENT SPEED, cm/s FLOOD	EBB
AIR	0.5	8.5	87	6.0	7.5
	7.0	12.3	91	5.4	5.4
	13.0	16.3	76	4.2	5.8
TJV	0.5	17.3	129	7.1	10.9
	7.0	17.4	207	9.9	10.7
	13.5	14.8	282	3.7	5.3
DEE	0.5	9.9	329	6.8	3.1
	7.0	12.9	106	-	-
	13.0	24.2	118	6.9	9.0
	26.0	23.4	88	7.6	7.7
TJV_2	0.5	5.8	26	12.2	8.8
	7.0	27.5	26	10.6	8.7
	9.0	22.1	75	-	-
	13.5	20.9	112	7.4	7.6
RIC_2	0.5	18.2	52	4.8	6.7
	3.0	9.9	359	-	-
	5.5	13.4	74	4.8	6.3
JUD	0.5	21.1	258	4.4	2.8
	4.0	17.7	252	3.4	2.1
TOM	0.5	34.9	285	7.2	6.5
	4.0	21.2	245	-	-
	8.0	18.1	249	4.5	3.9
RIC	0.5	12.9	67	6.8	4.8
	4.0	19.9	147	-	-
	7.5	13.5	174	4.8	3.1

*Resultant of 12 measurements taken every two hours over a 25-hour period.

Table 4. Summary of anchor station current data for Perserverance Bay and vicinity, July 25-August 1, 1977. Includes vector resultant and average speed and direction.

STATION	DEPTH, m	VECTOR SPEED,* cm/s	RESULTANT DIRECTION, mag.	AVERAGE CURRENT SPEED, cm/s FLOOD	EBB**
AIR	0.5	183.8	165	6.2	7.5
	7.0	354.7	138	5.0	10.4
	13.0	237.4	162	4.9	8.2
TJV	0.5	169.5	198	10.4	8.3
	7.0	186.4	168	9.0	11.5
	13.0	137.5	158	8.9	8.5
DEE	0.5	174.1	120	8.1	8.8
	7.0	238.4	107	7.9	10.2
	12.5	271.7	108	7.2	10.4
	26.0	-	-	4.3	9.0
TJV_2	0.5	42.2	279	7.1	4.1
	7.0	42.8	80	4.9	5.6
	12.5	100.9	84	4.8	5.8
	13.5	54.6	50	4.6	4.5
RIC_2	0.5	116.3	320	4.94	5.74
	4.7	127.9	358	3.97	5.43
	5.7	107.8	346	4.04	4.17
JUD	0.5	146.6	196	3.6	-
	3.0	94.7	203	3.0	4.4
TOM	0.5	362.6	233	11.1	8.0
	7.0	310.9	210	10.0	7.1
	8.1	261.1	206	8.5	6.3

*Resultant of 48 measurements taken every 30 minutes over a 25-hour period.

**Flood and ebb directions based on clustering of vectors into groups, e.g., as shown in Figures 16-19.

Discussion of Currents

The basic pattern is partly attributed to a decrease in water density, and resulting slope, above the nearshore bed through solar heating. For another part the pattern is created by drag of local easterly winds whereby warmer surface water is displaced downwind and toward the right-hand shore according to Ekman drift. Such a pattern is consistent with the generality of counterclockwise circulation in lakes and coastal seas (Emery and Csanady, 1973).

The resultant current representing the semi-permanent flow is clearly to the east at offshore stations, AIR and DEE, in the vicinity of the proposed runway extension. This trend was observed in both sets of observations, January and July-August, 1977. The easterly direction is opposite to the direction of the oceanic Equatorial Current or trade wind drift. It is also contrary to observations of a predominate westerly flow used by Tetra Tech (1977) to calibrate a circulation model of the area. An easterly surface current is also indicated by the accumulation of debris in Perserverance Bay presumably derived from the airport waste disposal area. Such varied results indicate that currents in the area are transient and may change direction with time over periods of weeks or months.

Water Quality. Water quality was excellent during the low to moderate energy conditions observed for temperature, salinity, dissolved oxygen and pH. The distribution of different water quality parameters is illustrated in isometric sections of Figures 22 and 23, and the measured values from "dip" stations and anchor stations are given separately on file data sheets.

Temperature distributions indicate bay water is nearly isothermal. A slight vertical gradient was detected at most stations in which near-bottom water at 13 m depth was cooler than surface water by 0.2°C. In January there was also a slight decrease of temperature with distance seaward; e.g., from 26.8°C in surface water of the west bay head (Station 4) to 26.6°C in the central bay (Station 13). Nearshore water west of Black Point was slightly cooler than nearshore water east of the point. Such a change may develop during flood tide as cool offshore water moves landward in an eddy or indraft west of the point, Figure 22A. Temperatures recorded in the bay were about 0.5°C lower than those normally recorded in south coast bays during July (Francois and Brown, 1975).

Bay water is isohaline. Salinity values during July-August vary within narrow limits throughout the bay, from 36.11 to 36.60 °/oo. Many vertical profiles display a slight salinity increase with depth whereby water below mid-depth is slightly saltier than water above mid-depth. Of note is a wedge of saline water west of Black Point, Stations 2, 8, Figure 22B. This is associated with cool water and reflects an indraft of saline ocean water into the bay. The salinity values recorded fall within the range of values reported for south coast bays during January and July (Francois and Brown, 1975).

Dissolved oxygen concentrations at dip stations vary from 6.38 mg/l in near-bottom water of the central bay (Station 13) to 7.69 mg/l in surface water of the western bay (Station 14) (Figure 22C). Near-surface water at Stations 2 and 8, west of

Black Point, has lower oxygen content than elsewhere, Figure 22C. The dirunal range recorded at anchor stations is very small, largely from 6.30 to 7.63 mg/l with a greater range in near-bottom water than in near-surface water. Corresponding percent oxygen saturation varies 97 to 117 percent over a dirunal cycle (Fig. 23A). Oxygen concentration at dip stations occupied at mid-day is generally 0.5 mg/l lower in near-bottom water than in near-surface water. As shown by stations TOM (Table 4A) and 13 (Fig. 22C), there is a marked reduction in oxygen content one meter above the bed.

The pH of bay water varies within narrow limits, mainly within the range pH 8.05 to 8.15 (Fig. 23B). Such values are very close to average seawater, pH 8.10. Diurnal values as low as pH 7.85 were obtained, but the upper limit did not exceed pH 8.34.

The distribution of turbidity is relatively uniform throughout the bay, Figure 23C. There is a slight vertical gradient whereby values are higher in near-bottom water than in near-surface water; e.g., 1.01 to 0.37 JTU at dip station 13. A marked increase often is observed one meter above the bed, a trend that suggests the bay floor is a source of turbid materials. Values in Brewers Bay, e.g., 0.56-0.79 JTU at Station 1, are slightly higher than those in Perserverance Bay, 0.34-0.44, Station 8, but overall, lateral and longitudinal gradients of turbidity are very weak. This trend probably reflects the lack of runoff and the low to moderate wave conditions during the observation periods.

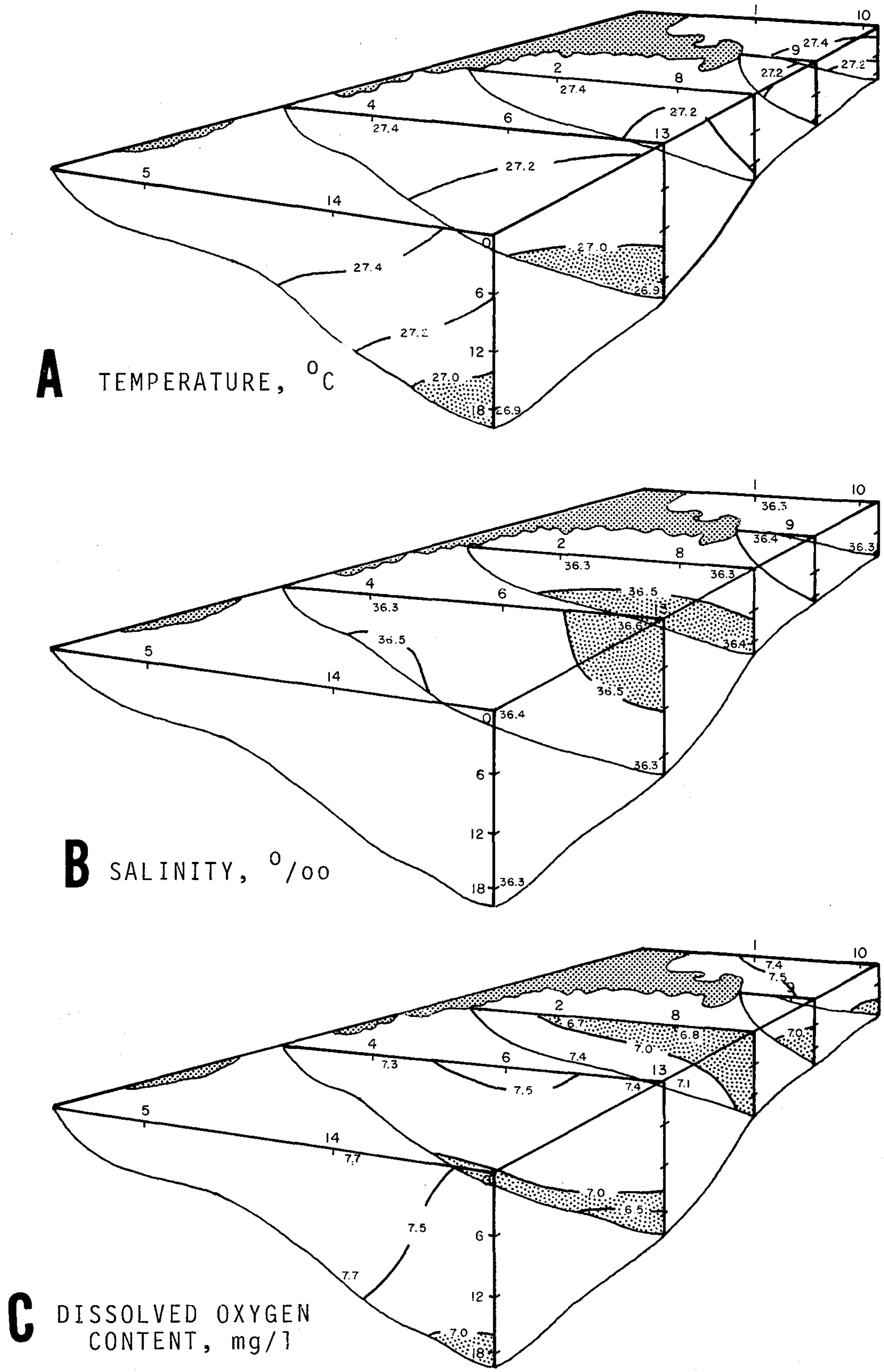


Figure 22. Distribution of water quality parameters, temperature, salinity and dissolved oxygen, in transects through "dip" stations and anchor stations, July-August, 1977.

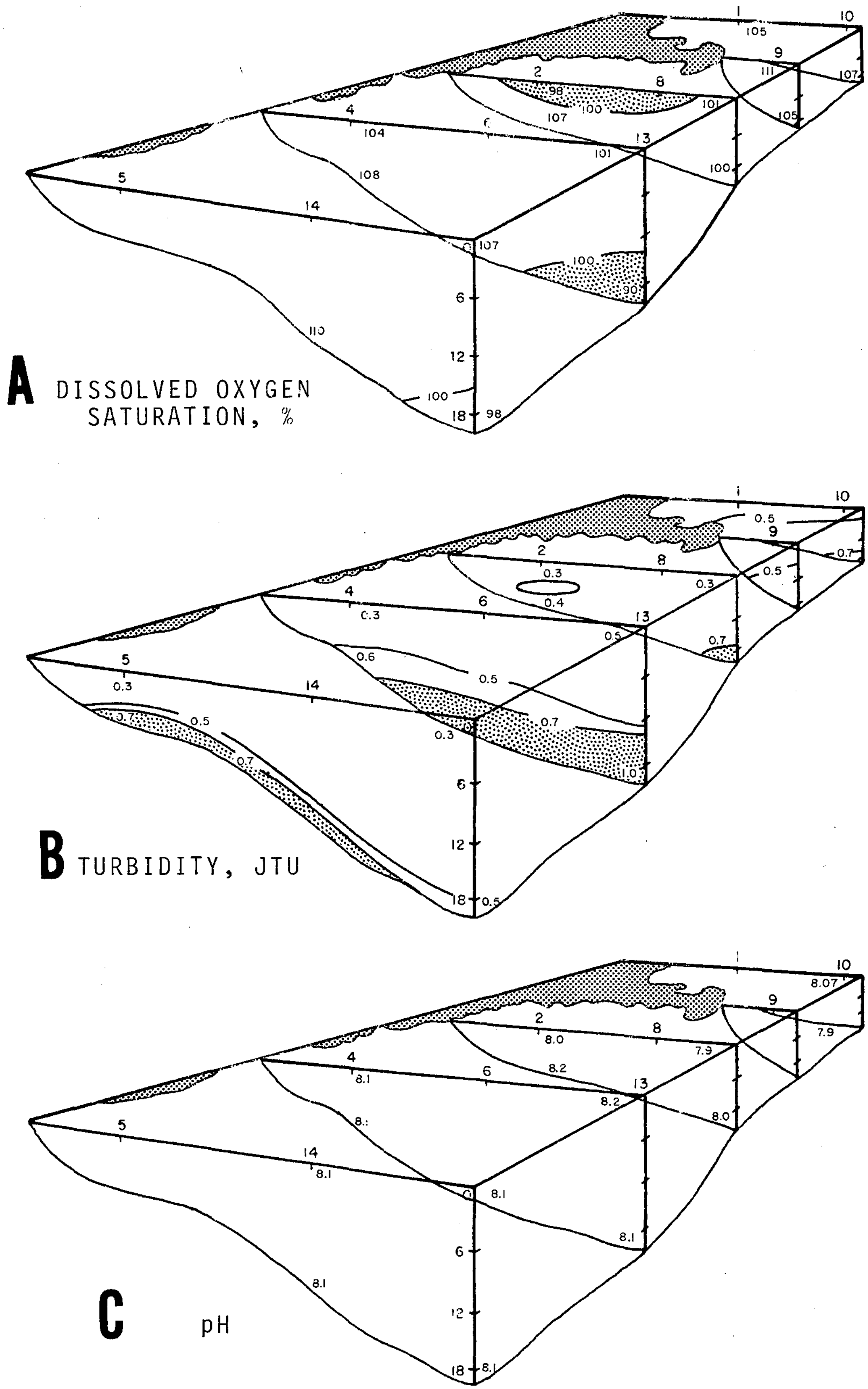


Figure 23. Distribution of water quality parameters, dissolved oxygen saturation, turbidity, and pH, in transects through "dip" stations and anchor stations, July-August, 1977.

Table 4a. Summary of water quality characteristics at anchor stations in Perserverance Bay, July 25-August 1, 1977. Mean values for a 25-hour diurnal period.

STATION	DEPTH, m	TEMP., ^oC	SALINITY $^o/oo$	DISSOLVED OXYGEN, mg/l	OXYGEN SATURATION, %	TURBIDITY JTU
TJV	0.5	27.1	36.17	7.27	111	0.60
	7.0	27.1	36.20	7.03	107	0.51
	13.0	27.1	36.24	6.88	105	0.51
TJV_2	0.5	27.2	36.34	7.63	117	0.57
	7.0	27.0	36.33	7.20	111	0.57
	12.5	--	--	7.15	104	0.75
	13.5	26.9	36.44	7.04	108	0.67
RIC_2	0.5	27.1	36.46	7.28	108	0.52
	4.7	--	--	7.21	110	0.52
	5.7	27.0	36.56	7.03	108	0.57
TOM	0.5	27.0	36.35	7.01	101	0.75
	7.0	--	--	7.16	108	0.62
	8.1	27.0	36.28	6.64	102	0.69
DEE	0.5	26.7	36.19	7.16	104	0.36
	7.0	26.8	36.18	6.40	98	0.43
	13.0	26.4	36.49	6.38	97	0.38
	25.0	26.5	36.48	6.48	99	0.90
AIR	0.5	27.2	36.25	7.31	113	0.35
	7.0	27.1	36.26	6.92	107	0.40
	13.0	27.1	36.11	6.62	102	0.32
JUD	0.5	--	--	--	--	0.70
	3.5	--	--	--	--	0.63

Total concentrations of suspended solids for January are less than 4.0 mg/l and they fall mainly within the range 1.8 to 2.9 mg/l. Differences from station to station and with depth are so small that no definite trend was evident.

Bottom Sediments. The bay is floored with a variety of sediments ranging from mud to cobbles. Distributions of exposed sand, cobble and rock are presented in the benthic biotic chart, Fig. 24, and corresponding profiles (Figures 25 and 26). The distributions generally follow an energy format with coarse-grained sediment along high energy western reaches affected by heavy wave action. By contrast, muddy sediment covers relatively low energy parts of the central bay and deep parts of the eastern bay below the 15 meter depth. Organic content indicated by loss on ignition is relatively low, less than 3 percent by weight throughout the bay, except in salt ponds where it reaches 43 percent. Carbonate content of bay sediments determined by acid digestion ranges from 16 to 95 percent. Relatively low percentages come from the eastern corner where carbonate, which is mainly produced in the bay, is diluted slightly by land-borne sediments that are discharged from Hawks Hill. Land-borne sediments, however, are limited to landward areas, less than 450 meters from shore, and 12 meters deep.

Sediment Chemistry

The concentration of potential toxic substances and chemical contaminates was analyzed on selected sediment samples from different parts of the bay and the salt ponds. The methods used to determine trace metals and nutrients are given in Appendix I. Resulting data are tabulated in Table 4b.

Content of volatile solids (Vs) and chemical oxygen demand is 5 to 10 times higher than normal in surface sediments of the salt ponds. This trend reflects accumulation of organic matter which ranges about 22 to 26 percent. Content of oil and grease in West Pond is higher than normal but its source is unknown. Total nitrogen in salt pond sediments reaches 5300 ppm. This exceptional content is mainly due to bird manure, however, much nitrogen is probably supplied from mangrove leaf detritus and soils of the watershed. Copper concentrations are 4 to 6 times higher in pond sediments than in the bay. And lead concentrations of pond sediments are more than twice normal. The mercury content in East Pond is substantial. Present day sources of metals in the area are unknown, but they may have been derived from a former plantation that once occupied lowlands landward of the ponds. Because the ponds are enclosed and lack exchange with the bay, fine sediment, organic matter and chemical constituents supplied to, or produced in the ponds, are readily retained.

Except for a high phosphorus value in the west bay head, Station 5, concentrations of constituents in bay sediments are normal despite scattered debris.

Table 4b. Concentrations of chemical constituents in sediments from Perserverance Bay and salt ponds, January, 1977. For locations, see Figure 1.

SAMPLE NO.	% TS	% VS	PPM TP	PPM TKN	PPM O&G	% COD	PPM Cd	PPM Cu	PPM Zn	PPM Pb	PPM Hg
III-3	63.9	5.67	41	760	340	1.3	1.7	8.0	17	27	<0.002
B	32.4	26.0	7	5300	310	5.6	1.8	46.0	30	46	0.056
D	33.7	21.6	23	5200	620	12.0	2.0	29.0	22	50	0.002
5	63.4	5.40	130	970	500	1.3	2.1	7.3	17	32	0.003
20	71.7	4.09	17	450	140	0.1	1.7	6.7	11	21	0.015

9. Biological Conditions

A biotopic map of Perservance Bay was traced from NOAA color airphoto transparency (National Ocean Survey, October 28, 1958) and verified by eight transect lines. Results were reduced to the airphoto scale and the biotic observations superimposed on the photographic distribution patterns. Profiles of each transect were also prepared and presented in Figures 25, 26.

Description of Benthic Communities

Photographic patterns reveal seven mappable units (Figure 24). Transect observations revealed that one of these, the large grass area in the eastern part of the bay, varies in the predominance of three species of grasses. *Thalassia testudinum* predominates over most of the area, *Syringodium filiforme* occurs locally at the margins of the grass bed, and *Diplanthera wrightii* is limited to the shallow nearshore edges of grass growth where wave action influences the bottom (the breaker zone). In areas of *Thalassia* and *Syringodium* vegetation there are scattered growths of the green siphonalean algae *Penicillus*, *Halimeda*, *Caulerpa*, *Udotea*, *Diplanthera* usually occurs alone. These variations within the grass bed are mapped as Gt, Gs and Gd, respectively (Figure 24).

Thalassia (Gt) predominates to 10-11 m depth with coverage of the bottom reaching 100 percent. *Syringodium* (Gs) and siphonalean algae contribute 10-20% of the vegetation mass. At depths less than 3 meters the green algae almost disappear except for a few *Penicillus* and more *Syringodium* is present. At

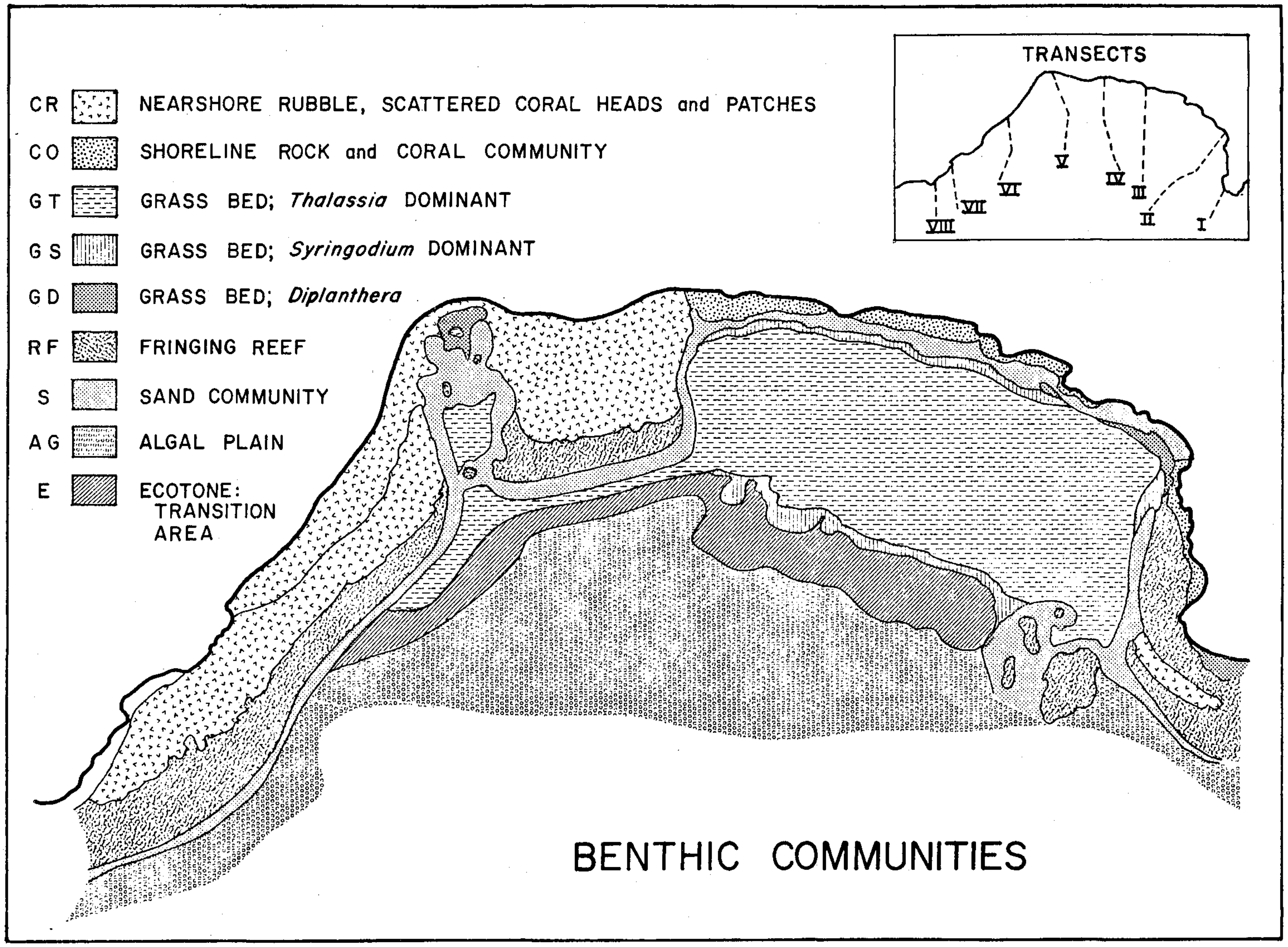


Figure 24. Distribution of benthic communities, January, 1977.

1.5-2 meter depth Thalassia is very sparse and the plants short. The very fine-bladed grass Diplanthera (Gd) is often the only plant in the breaker zone (Figures 25, 26). At the west margin of the grass bed Thalassia gives way to Syringodium and the green algae (Gs) in a patchy, ragged transition to the bare sand (S) "halo" zone (Figure 24) which separates the grass bed from the reef areas to the west. Only a few scattered siphonalean algae are common to the sand halos.

The major differences in quantitative biomass reflect the composition of in situ coverage. In the grass bed (Station B, Figure 25) Thalassia accounts for 85 percent of the vegetation by weight, Syringodium 5.6 percent and green algae 9.4 percent. There were a total of 51 individual animals representing more than 17 species (Table 7). On the patchy western edge of the grass bed (Station C, Figure 23) plant biomass was only 17 percent of that at Station B with only 18 percent being Thalassia, 2.6 percent Syringodium and 79 percent green algae (Table 8). The sand here is coarse with many gravel-sized pieces of coral. This accounts for the occurrence of encrusting coralline algae (two species) and the spherical green alga Valonia which all require rocky holdfasts. The coarse sediment and the thin vegetative cover also accounts for the reduction in numbers and diversity of animals - only 9 individuals of 5 species. It would be very informative to reassess this transitional fringe area periodically, particularly the relationship of sediment texture to biota.

There is a thin blanket of fine silt on plants in the grass bed, but there is no evidence that it is causing adverse

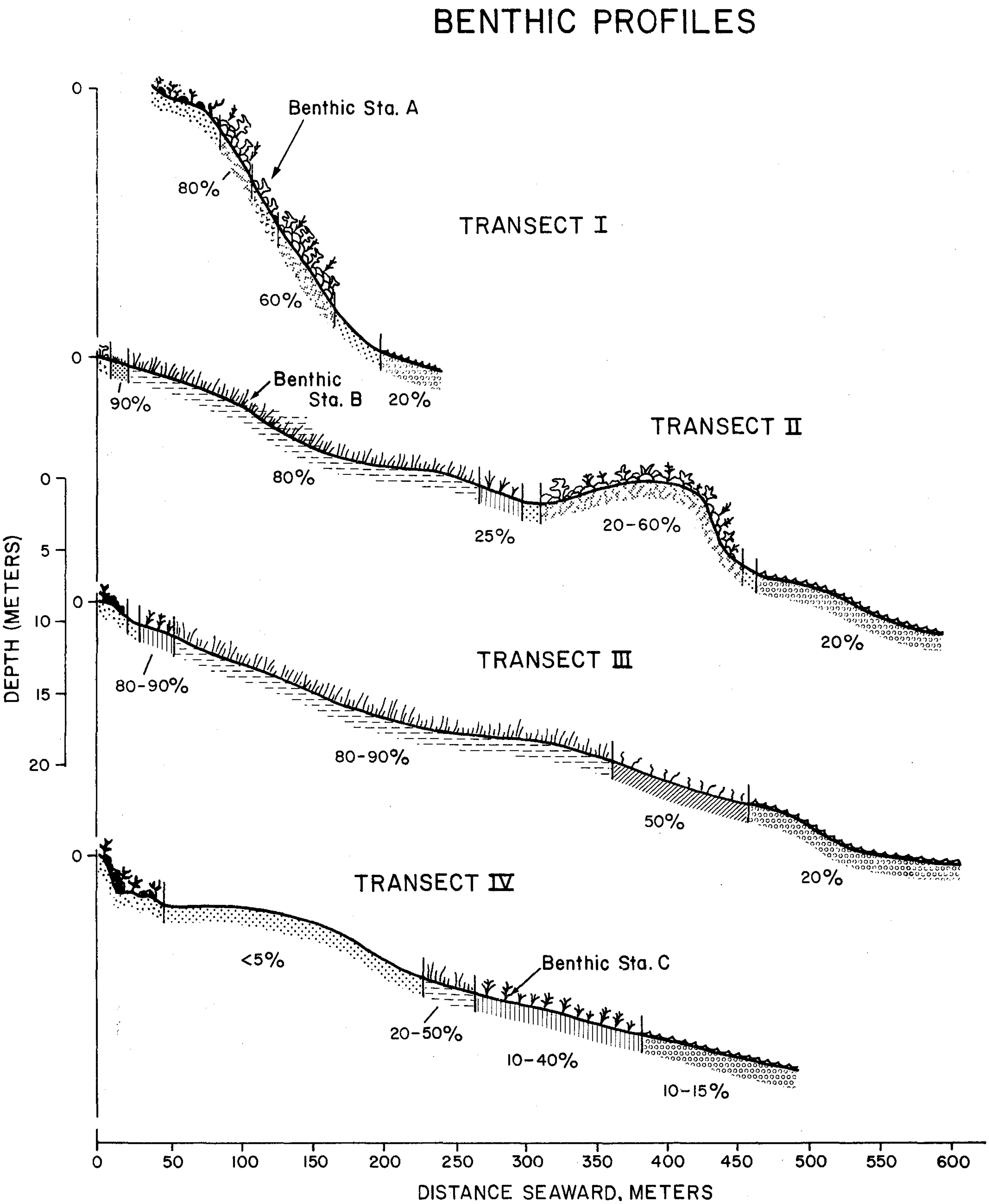


Figure 25. Distribution of benthic types and percent cover on Transect I thru IV. Percent represents bottom cover for plants and percent of live coral for reef areas. For symbols representing benthic types, see Figure 24.

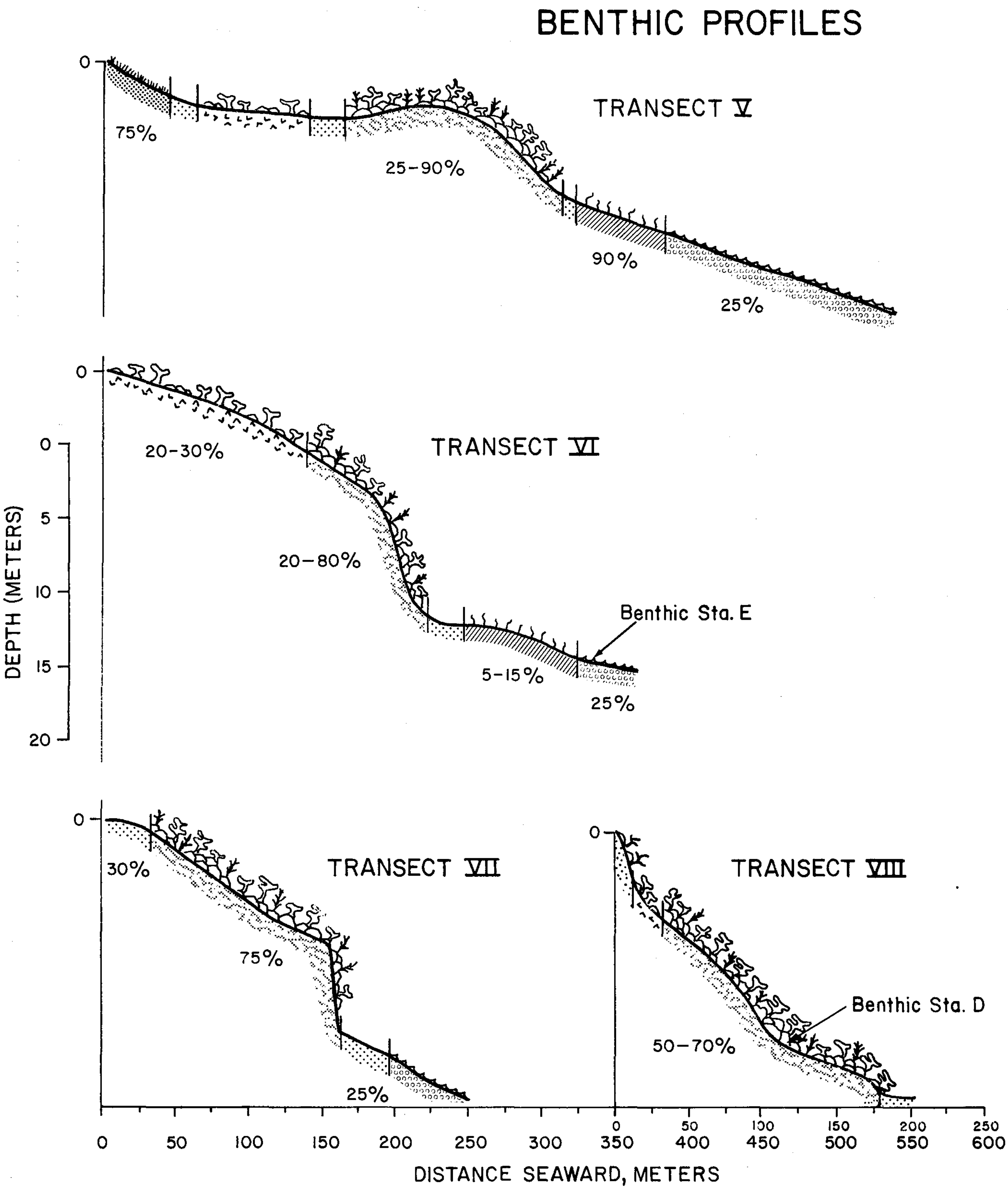


Figure 26. Distribution of benthic types and percent cover on Transect V thru VIII. Percent represents bottom cover for plants and percent of live coral for reef areas. For symbols representing benthic types, see Figure 24.

Table 5. Relative abundances (percent) of benthic plants in Perserverance Bay. Relative abundances are the averages of five .25 m^2 quadrats collected from the locations shown in Figure 2.

	Quadrats		Sites		
Species	A	B	C	D	E
Halophila baillonis	15			5.4	
Thallassia testudineum	0	64	66		56
Syringodium filiforme	0				18
Penicillus capitatus	0	2	5.8		7.6
Caulerpa mexicana	3	2			
Caulerpa cupressoides		3.5		10.8	
Schizothrix sp.	15			14	
Dictyota sp.	3	1	9.6	8	
Halimeda sp.		4	4.6		
Ceramiacea	2			8.6	
Udotea flabellum		3.5	6.6		
Udotea cyathiformes		0.5	2.4		
Sand	62%	19.5%	5%	60%	20%

effects. Except for variations in species composition and floral density as described, which is not unusual, the grass bed is judged to be healthy and productive.

Seaward of the grass bed, the area from about 10.5 to 14 meters depth represents an ecotone (E in Figure 26) wherein siphonalean algae predominate. Grasses are sparse or absent and Syringodium is more abundant than Thalassia. Density of coverage is at most 50 percent, decreasing with depth.

Farther seaward beyond the 15 meter depth, Thalassia and Syringodium are scarce; they are replaced by Halophila. Siphonales are the dominant plants, but total floral coverage is generally less than 25 percent. This deeper assemblage is called the "algal plain" (AP in Figure 24) and is apparently characteristic of most of the flat floor below 15 m - at least along the south coast from the harbor to Perseverance Bay where several studies (Coulbourn, et. al., 1973 , Virgin Islands Port Authority 1975, Insular Environments, 1975, 1977) have been done in recent years. Station E, near the shoreward edge of the algal plain (Figure 26, Trans. VI), is characterized by the absence of Thalassia and Syringodium, the presence of Halophila and predominance of green algae which account for 83 percent of the plant life. There were 15 animals of 8 species, primarily infaunal forms. Fighting conch (Strombus pugilis) and large hermit crabs (Petrochirus bahamensis) are commonly observed here. Sponges are the most common sessile animal on the surface, but like other organisms on the algal plain, they are scattered. Some of the more common species are listed in Tables 9-14.

Table 6. Summary of benthic community types and their characteristics.

Map Unit	Map Symbol	Characteristics and Depth Range	Predominate Species
Shoreline Rock & Coral	Co	Off high relief rocky shores. Primarily coral growth on boulders and exposed rock. 0-3 m. depth	*Millepora*, *Acropora*, *Palmata*, *Diploria*
Nearshore Rubble Scatter Coral Heads & Patches	Cr	Mostly off sandy shores on gently sloping bottom behind reefs. As intergrading bands with varying proportions of live and dead coral and rubble on sand. Also occurs as patches and troughs within reefs, 1-7 m. depth	*Diploria*, *Agaricia*, *Montastrea*, *Porites*
Fringing Reef	Rf	Projecting from headlands and parallel to beaches at distances up to 300 m. As 1 or 2 platforms of steep faces and more gentle back slopes. Interrupted by sand troughs and grass beds. 0-20 m. depth	*Acropora*, *Millepora*, *Diploria*, *Agaricia*, *Porites*, *Montastrea*, *Gorgonia*
Sand	S	As bands forming "halos" or meandering ribbons and troughs between coral and vegetation zones or as large area background of unit Cr. At reef bases may contain rubble. Depth varies. Live cover ca.5%	Occasional *Halimeda*, *Udotea*, *Penicillus*, *Caulerpa*, *Halophila*, and/or Sponges *Tedamia*, *Ircinia*, *Chondrilla*
Grass Beds	Gt	On gently sloping sand dense coverage (75-100%) Dominated by *Thalassia*. Depth varies 3-17 m.	*Thalassia*, *Halimeda*, *Udotea*, *Penicillus*, *Syringodium*

Table 6. (Continued)

Map Unit	Map Symbol	Characteristics and Depth Range	Predominate Species
Grass Beds (Continued)	Gs	Dominated by Syringodium Usually at margins of Gt. Depth Varies	Syringodium, Halimeda, Caulerpa, Udotea, Penicillus, Thalassia
	Gd	Almost exclusively Diplanthera in breaker zone. 3 m. depth	Diplanthera, occasional Syringodium
Ecotone	E	Transition zone; represented here primarily by change between grass bed and algal plain. 12-15 m. depth	Halimeda, Udotea, Caulerpa. Some Thalassia & Syringodium in upper reaches. Halophila in deeper parts.
Algal Plain	Ag	On relatively flat or gently sloping bottom with high pctg. of fine material in surface sediment. Large variety of organisms but coverage only about 25% below 15 m.	Halophila, Udotea, Halimeda, Caulerpa, Avranvillea, Strombus Pugilis, Bahamensis, Iotrocota, Ircinia, Chrondrilla, Haliclona, Microciona, Sabellid worms

Corals are the predominant organisms in three distinct zones (Figure 24) shoreline rock and coral (Co), nearshore rubble and coral (Cr) and the fringing reefs (Rf). Differences in these areas are due to the relative abundance of particular coral species, depth range, proportion of the bottom which is covered and the relative proportions of living to dead coral (Table 7). Along rocky shores and headlands to about 3 m. depth, coral growth is on large boulders or exposed bedrock (Co) and the predominate species are Acropora palmata, Diploria, and Millepora. Lesser amounts of several other corals were observed, primarily Agaricia and Montastrea. All appeared to be producing new growth and hardly any dead areas were observed.

Seaward of the sand and cobble beaches from depth of 1 to 7 meters, there is a zone of patchy, scattered coral and sand (Cr). This map type was also observed as occassional patches and troughs within the deeper fringing reefs (Rf). Generally, this zone occupies the back reef platform of the offshore reefs, but off the headlands where shoreline coral growth (Co) is almost continuous with the reef (Rf) the scattered coral zone (Cr) is very narrow or non-existent. Most of the material appearing in this zone on the aerial photograph is dead coral heads, coral rock and rubble. Most of the live coral is Diploria, Agaricia, Montastrea and Porites.

The offshore fringing reefs (Rf) fringe headlands at both ends of the bay (Figures 24,25) but for the most part, they parallel the shoreline at a distance of up to 300 meters. The reef is interrupted by the grass bed (Gt and Gs) in the eastern part

Table 7 . Summary of results of coral transects. Locations of transects are shown in Figure 2.

Transect	% Coverage total cm	Hs (nats)	Total # Species	Total % Necrotic Colonies
a	58.7%	2.3816	13	47.1%
b	41.5%	2.0315	13	20%
c	24.1%	1.8247	9	20%
d	59.7%	1.8571	8	14.5%
e	31.8%	1.5414	6	17%
f	48.8%	1.7912	9	4.8%
All Combined	44.1%	2.3033	21	20.1%

Table 8. Summary of the results of 6 transects (61 meters) showing scleractinian abundances.

	Total Colonies	Total Coverage (cm)	% Coverage by Species	% Necrotic Colonies
Diploria Labyrinthiformes	7	111	4.23	57.1
Diploria Stringosa	1	12	.45	0
Porites porites	52	390	14.87	13.4
Porites furcata	1	8	.31	0
Montastraea annularis	56	531	20.25	17.9
Porites astrepides	42	275	10.48	7.1
Siderastraea radians	31	451	17.20	51.6
Sid. siderea	11	75	2.86	18.2
Agaracia agaricites	69	287	10.94	8.6
A. sp.	2	9	.34	0
Millipora complanata	12	147	5.61	0
Dichocoenia stokesii	2	13	.49	50
Stephanocoenia Michelinia	2	28	1.09	0
Dendrogyra cylindrica	1	9	.34	0
Eusmilia fastigiata	7	44	1.68	42.8
Montastraea cavernosa	7	126	4.81	8.1
Dendrogyra cylindrica	1	9	.34	0
Mussa angulosa	-	-	-	0
Madracis sp.	4	87	3.31	100
Madracis decactis	8	2	.07	0
Favia Fragum	1	2	.07	0
Porites wicklundi	1	6	.23	0
	318	2622		

Total Necrotic = 20.12% Total Coverage = 42.9%

Species Diversity (Hs) = 2.3033 nats

of the bay and by a channel leading to the deeply indented center of the beach. This latter feature may be a remnant of an old opening to the ponds. The reefs slope steeply seaward, rising from 18 to 10 meters or less at the top. There is an impressive variety of living species, but Acropora palmata, Diploria, Montastrea, Porites, Meandrina, Agaricia and Gorgonia predominate on the seaward reef face. Signs of stress and attrition are evident everywhere in the shallower reef platforms and shoreward portions of all the reefs. However, shallower reef portions (less than 10 m) near headlands seem to be less affected.

Turbidity over the reefs is unusually high. This is due mostly to silt particles and mucus in suspension. Such a mucus-silt complex is believed to be created by the cleaning activity of coral polyps under stress of siltation. Broken coral rubble is plentiful shoreward of the central reef areas. Silt has accumulated on the surface of living and dead coral to the extent that a visible cloud can be stirred up by a wave of the hand. Necrotic patches within living colonies are numerous and contain small piles of silt. There is no widespread recolonization of dead coral rock and surprisingly few young colonies, considering the available area of hard substrate for attachment. These observations suggest that the reefs are under stress of siltation and are suffering a decline in productivity.

Sand (S) occurs as bands or meandering ribbons and troughs forming "halos" around reef areas and separating them from vegetation zones (Transects I, II, V, VII). Sand also floors zones of scattered coral and rubble (Cr) shoreward of reefs. Sand strips at the deep seaward base of reefs have a fine surface texture with a thin layer of silt and is usually inhabited by tube worms and burrowing mollusks. On the surface, there is usually scattered coverage of sponges and Halophila. In shallower water, sand is generally coarser with less evidence of tube worms, but surface vegetation is more varied. Usually Penicillus, Halimeda, Udotea are found, but not sponges. In all sand areas, plant coverage is about 5 percent of the bottom. Abrupt sand ribbons or halos between reef and plant areas are thought to be created by the browsing of fishes and sea urchins which live on the reef and forge at the edge of the plant beds. They may also be partly maintained by the scouring of localized currents.

Tables 9-15 summarize the results of the coral transects. Transect a was censused at the offshore edge of Black Point. It is interesting that coverage of live corals was high (53 percent) and percentage of necrotic colonies was also high. The results indicate that this community is in the process of degenerative change. We could predict decreases in live cover and possibly changes in abundances which will depress the species diversity value (2.3316 nats) in the future. Transect b was censused immediately to the west of Black Point; there is less evidence of siltation, high coverage (41.5 percent) by living corals and average diversity 2.0315 nats. Transect c at the northeastern corner of Perserverance Bay has great reduction in coverage (24.1 percent) reduced diversity (1.8247 nats) but average abundance of necrotic colonies (20 percent). It appears that this area has already undergone severe degradative changes in the coral fauna

Table 9 . Summary of hard coral transect results for transect a. The locations of the transects are shown in Figure 2.

SPECIES	Total Colonies	Total Coverage	% Coverage by Species	Total Necrotic Colonies
Diploria Labarinthiformes	2	17	2.9	100
Porites Porites	7	16	2.7	
Montastraea annularis	7	64	10.9	43
Porites astreides	13	71	12.1	0
Siderastraea radians	6	119	20.2	100
S. siderea	9	44	7.5	56
Agaracia agaricites	8	34	5.8	0
Millipora complanata	1	15	2.6	0
Dichocoenia stokesii	1	2	.3	0
Eusmilia fastigiata	3	8	1.4	100
Montastraea cavernosa	6	108	18.4	50
Madracis sp.	4	87	14.8	100
Favia fragun	1	2	.3	0

Total coverage 587 = 58.7%; Total Species = 13; Total Necrotic Colonies = 47.1%; H_ss 2.3816

Table 10. Summary of hard coral transect results for transect b. The locations of the transects are shown in Figure 2.

SPECIES	Total Colonies	Total Coverage	% Coverage by Species	Total Necrotic Colonies
Diploria Labarinthiformes	3	76	18.3	67
Porites Porites	4	38	9.1	50
Porites furcata	1	8	1.9	0
Montastraea annularis	4	28	6.7	25
Porites astreides	6	36	8.7	0
Siderastraea radians	9	100	24.1	33
Sid. siderea	1	19	4.6	100
Agaricia agaricites	17	49	11.8	0
A. sp.	1	4	1.0	0
Millipora complanata	1	12	2.9	0
Dichocoenia stokesil	1	11	2.7	0
Stephanocoenia Michilinii	1	16	3.9	0
Montastraea cavernosa	1	18	4.3	100

Total coverage 415 = 41.5%; Total Species = 13; Necrotic Colonies = 20%; H_ss 2.0315

Table 11 . Summary of hard coral transect results for transect c. The locations of the transects are shown in Figure 2.

SPECIES	Total Colonies	Total Coverage	% Coverage by Species	Total Necrotic Colonies
Porities Porities	9	32	13.2	22.2
Montastraea annularis	11	86	35.7	27.2
Porities astroides	2	11	4.6	50
Siderastraea radians	2	25	10.4	0
Agaricia agaricites	12	60	24.9	8.3
Millipora complanata	1	2	.8	0
Stephanocoenia Michilinii	1	12	4.9	100
Dendrogyra cylindrica	1	9	3.7	0
Eusmilia fastigiata	1	4	1.7	0

Total coverage 241 = 24.1% coverage; Total species =9; Necrotic Colonies = 20%; H_ss 1.8247

Table 12 . Summary of hard coral transect results for transect d. The locations of the transects are shown in Figure 2.

SPECIES	Total Colonies	Total Coverage	% Coverage by Species	Total Necrotic Colonies
Diploria Labarinthiformes	1	6	1.0	
Porities Porities	9	57	9.5	11.1
Montastraea annularis	7	146	24.5	14.2
Porites astroides	12	79	13.2	16.6
Siderastraea radians	9	149	24.9	33.3
Agaricia agaricites	19	67	11.2	10.5
Millipora complanata	3	66	11.1	0
Eusmilia fastigiata	3	27	4.5	0

Total coverage 597 = 59.7%; Total species = 8; Necrotic Colonies = 14.50%; H_ss 1.8571

Table 13 . Summary of hard coral transect results for transect e. The locations of the transects are shown in Figure 2.

SPECIES	Total Colonies	Total Coverage	% Coverage by Species	Total Necrotic Colonies
Porites Porites	12	118	37	17
Porites astroides	5	19	6	0
Siderastraea radians	5	58	18	80
Agaricia agaricites	21	75	24	10
A. sp.	1	5	2	0
Millipora complanata	4	43	14	0

Total coverage 318 = 31.8%; Total Species = 6; Necrotic Colonies = 17%; H_ss 1.5414

Table 14 . Summary of hard coral transect results for transect f. The locations of the transects are shown in Figure 2.

SPECIES	Total Colonies	Total Coverage	% Coverage by Species	Total Necrotic Colonies
Diploria strigosa	1	12	2.4	0
Porites Porites	11	129	26.4	0
Montastraea annularis	27	207	42.3	7.4
Porites asterides	4	59	12.1	
Sid. siderea	1	12	2.4	0
Agaricia agaricites	10	50	10.2	10
Millipora complanata	2	9	1.8	0
Madracis decactis	1	4	0.8	0
Porites wicklundi	1	6	1.2	0

Total coverage 488 = 48.8%; Total Species = 9; Total Necrotic Colonies = 4.8%; H_ss 1.7912 and may indicate the kind of effects on the scleractinian community after airport construction.

Transect d was about equidistant from Black Point and High Point. Of the six transects it has the highest percent coverage of live corals (59.7 percent) and a low incidence of necrotic colonies (14.5 percent). The number of species (8) and the diversity index (1.8571 nats) were similar to Transect c.

Transect e was censused near the outer edge of the small channel through the reef near the northwestern portion of the bay. The bottom in this area is covered with debris and heavy concentrations of silt. The low coverage by live corals (31.8 percent), lowest species diversity (1.5414 nats), and lowest number of species (6) occurrences, all indicate that this area is undergoing degradative change. The relatively low frequency of necrotic colonies (17 percent) may indicate that coral mortality may have been greater in the past.

Transect f may represent the closest to an aboriginal situation that we measured. Coverage by live corals was identical with the average for all six transects (42.9 percent), diversity was about average, 1.7912 nats, while the average for the six transects was 1.9275 nats, and the frequency of necrotic colonies about one quarter of the average was 4.8 percent.

The summary of the "ground truth" quadrats is shown in Table 5 . The quadrats at site A were censused in the bordering sand and algal plane community. Previous work has shown that the spermatophyte <u>Halophila</u> <u>baillonis</u> which dominated the samples is characteristic of unstable substrates. Survey work in the offshore near Red Point, to the east of the airport (Olsen et. al. 1977), has shown that this form dominates most of the bottom area. From the samples collected on an extension of the offshore algal plane community we infer that it has, as a result of heavy sedimentation in the basin between Saba and Savanna Islands, become increasingly dominated by the spermatophyte Halophila baillonis. It appears the quadrat site D was also collected from a similar inshore extension of this community. Besides the faunal similarities, the benthos only covers about 40 percent of the area in both cases.

The remaining three quadrat sites were all collected from Thallassia testudineum dominated communities. Only site E showed significant abundance of the manatee grass, Syringodium filiforme. Future changes in the aerial distribution of the grass communities may be apparent in the shallower portions of the bay but we would predict that greatly increased turbidity will reduce the value of aerial photography as a monitoring technique.

The transect data also permit some predictions about changes in the species abundances which may result from the airport construction. Siltation appears to be the overwhelming limiting factor in Perserverance Bay. It causes the death of corals by upsetting the metabolic energy balance and weakens their resistance to pathalogic agents in the environment. Oscillatoria submembranacea a blue green algae that has been shown to cause coral mortality (Antonius, 1973) was observed

Table 15. Common coral species in Perserverance Bay ranked according to susceptibility to necrotic damage. Only species which occurred ten or more times are listed.

Most Susceptible

Rank		% Colonies Showing Necrosis
1	Siderastraea radians	51.6
2	S. siderea	18.2
3	Montastraea annularis	17.9
4	Porites porites	13.4
5	Agoricia agaricites	8.6
6	Porites astreoides	7.1
7*	Millipora complorata	0

Least Susceptible

*Not a scleractinian coral.

in Perserverance Bay. Several species of sponges were observed overgrowing live corals. The frequency of necrosis may well be a predictor with regards to future survivors. Tables 8, 15 gives results of the present study. Siderastrea radians had a high proportion of necrotic colonies and may well be disappearing from the bay. Future surveys may well reveal dominance by Porites asteroides and Agaricia agaricites. Fire Coral (Millipora complanata) may also increase in abundance from the 5.61 percent shown in Table 8 .

The results of this study suggest that the scleractinian community is already under severe stress from siltation. Loya (1976) in a study of two Puerto Rican reefs which were under heavy sedimentation regimes had greater coverage by live corals on the vertical reef faces than on the flat reef. Transect b was censused on a flat area and had the lowest cover of the six sites (24 percent). This value was half of the value reported by Loya for a Puerto Rican reef flat. Loya's study also had greater coverage on the vertical faces. We interpret our results to indicate an extremely high silt load in Perserverance Bay. Additional silt loads from the airport construction project could well decimate the scleractinian community, not only in Perserverance Bay but also throughout a greater area along the south coast and adjacent cays.

Salt Pond Biota

Judging from evidence of vegetational succession and the large areas of dry and just-damp former swamp relative to that now flooded, the ponds seem to be relatively old and far advanced in their development. Red mangrove, the pioneer species which advances new growth into the water, is found only in the smaller, wetter western pond. The larger central and eastern areas contain white and black mangroves, many of which are dead or dying. Most of these areas were only damp when observed or contained a thin layer of water. Buttonwood (Conocarpus) and Casha (Acacia spp.) are encroaching on the margins of the ponds, indicating transition of the area to lowland scrub forest. The aerial photograph shows a large flat area of secondary mangrove growth (whites and blacks) not flooded and this is confirmed by site inspection to be former mangrove swamp filled by alluvium and organic matter and in transition to more terrestrial vegetation. The general impression of the area is that of an old pond decreasing in size with upland vegetation encroaching on all sides.

Pond wildlife was not spectacular when observed, but a few unidentified ducks and wading birds were seen in the western pond. A brief search for aquatic organisms revealed only insects (blackswimmers, diving beetles and some mosquito larvae). The ponds probably are good breeding sites for mosquitoes as several species will breed in water up to 7 ppt. salinity. In the absence of predaceous fish some mosquitoes can breed in sea water (about 36 ppt. salinity) and at least one local species, *Aedes taenioryznchus*, can breed at 70-100 ppt. salinity. There are large numbers of fiddler crabs, *Uca pugnax* at the pond edges. On slightly higher elevations on damp ground the land crab, *Cardisoma guanhumi*, is common.

Such confined hypersaline ponds usually contain large numbers of brine shrimp, *Artemia salina*, but only if fish are absent and the salinity is greater than 45 ppt. The salina fly, *Ephydra gracilis*, also a characteristic inhabitant of hypersaline ponds, was not observed here either. The absence of these hypersaline indicators, in the collateral absence of predaceous fish, suggests that pond salinity is less than 45 ppt. This condition is unlike that of more typical closed salt ponds where salinity is usually greater than 60 ppt.

10. Summary of Scientific Findings and Recommendations for Management

A. The bay develops its varied character from the effects of geologic submergence and the action of marine processes. The bay began to form more than 4,000 years ago when the rise of sea level inundated the coast and waves built a barrier spit across inner reaches forming a lagoon behind it. As the barrier built upward, it sealed the lagoon entrance and transformed the lagoon into a pond. Infilling of the ponds with landborne sediment continues to build the pond floor upward and to reduce the pond area.

A significant change in the shore configuration or bottom geometry of the bay or salt ponds may be detrimental to the circulation, water quality and ecology. The substrate of the salt ponds, which is underpinned with soft clay and peat, precludes surface construction without deep footings. Even burial with "solid" fill is likely to be unstable over long periods. Dredge and fill plans should be carefully evaluated for potential ecological effects consistent with protective management.

B. The watershed is a source of freshwater runoff and fine sediment to the bay and ponds during storms. Future development on steep slopes will increase the potential for flash flooding and change the rate and quality of runoff.

Any effort to control erosion and sedimentation at its source in the watershed will enhance water quality in the bay and prolong life of the salt ponds. Because vegetation cover in washes, guts and flood plains tends to filter out fine sediment and modulate flash flooding, natural drainage channels should be preserved and protected. The relevant management practice is to avoid sediment erosion through enforcement of the Earth Change Law regarding development in the watershed. Activities that expose soil or alter drainage ways by excavation, grading or land clearing should be controlled.

C. The salt ponds act as natural catchments that buffer the bay and its reefs against extreme freshwater inflow and sediment influx. The ponds are isolated from the bay by a sandy cobble ridge more than 1.6 m high. Elevation of the pond floor is close to mean low water in the bay. East Pond is 9 cm (0.3 feet) shoaler than West Pond owing to more rapid sedimentation. In turn, the pond is drier for longer periods in the dry season, salinity is higher and dying or dead mangroves are more extensive.

A significant change in drainage of the ponds or their bottom geometry may be detrimental to their ecology. Since the floor of the ponds is already silted up close to mean low water, there is little advantage to providing circulation or drainage by opening a channel to the bay.

D. Deep water waves are significantly modified in the bay by shore configuration and shallow nearshore platforms. There is a large change in the wave field from east to west across the bay as a result of orientation to predominate easterly waves. As the waves act on the shore, they stir up the bottom and induce a littoral current directed inward toward the west bay head. This convergence is a trap for oil and floating debris. A littoral current intermittently transports fine sediment westward from Brewers Bay into Perserverance Bay, where the sediment disperses and deposits in central reaches. There is a potential for floatable materials supplied from the airport construction area to continue to accumulate in the bay under the influence of flood currents, southeasterly waves and longshore drift. Such materials include oil and grease leaked from aircraft operations or accidental spills, fire-fighting foam, plastic litter and wood debris.

The relevant management practice is to control discharge of floatable materials at their source, both during runway construction and during airport operation. Special attention should be given to the control of toxic substances. Aircraft maintenance should incorporate facilities for handling wastes and spillage that is subject to discharge during storm runoff. Existing waste disposal zones need to be buried during construction and stabilized to deter release of floatables or leaching of toxic substances.

E. Currents in the bay are driven in response to the tide and to a semi-permanent flow that sets to the east through offshore reaches. The resultant current pattern consists of a counterclockwise spin around the bay with an indraft on the east side and an outflow on the west side. Its result is to drive cool salty water into the eastern bay along the bottom and in turn, to diminish the oxygen content. Its further effect is to exchange bay water with the sea and to mix it into a single water mass with relatively uniform temperature and salinity. As a result of the counterclockwise circulation, currents in the central bay are attenuated and thus provide a sink for fine sediment and potential pollutants.

Circulation of the bay is mainly linked to offshore flow derived from the west at mid-depth and near the bottom. Black Point partly segments the flow of Brewers and Perserverance Bays into cell-like patterns. However, Perserverance Bay receives flow directly from Brewers Bay during flood tide and at times when littoral currents are active during southeasterly waves.

Extension of the airport runway seaward 780 m (0.5 mile) will dampen wave and current energy in Perserverance Bay. The central bay circulatory sink will be enhanced while resuspension from the bed will be reduced.

To maintain natural flow across reefs and optimal flushing of fine sediment through the bay, large size conduit openings through the runway extension are needed. A potential increase of bay turbidity created by runway construction should be partly alleviated by the net easterly offshore flow. Additionally, attenuation of wave and current energy in the bay by the runway structure will reduce local resuspension. Fine sediment, silt and clay, contained in prospective fill, has a mean size of 19 microns and thus should settle to the bed during slack water periods where bed shear stress is reduced to a low level. The proposed runway structure will also attenuate waves from the east and southeast, and thus markedly reduce the longshore current in Brewers Bay. In turn, the existing longshore current into Perserverance Bay, which is charged with sediment, should be markedly reduced.

Although the energy "shadow" created by the new runway structure should improve turbidity in bay water over the long-term, corals will probably suffer. By reducing wave and current energy on reefs, mucus and sediment will tend to deposit rather than flush off raised surfaces. Accumulation of sediment will retard coral growth and bring about their eventual death. Coral planulae cannot set and survive on unconsolidated substrate. Reefs in eastern and central reaches of the bay are the most susceptible to dampened energy. These are the same zones where corals are now suffering degradative change and mortality.

F. Water quality in the bay is excellent with respect to temperature, salinity, dissolved oxygen and pH. Near-bottom water is slightly cooler and more saline than near-surface water. As this water intrudes into the eastern bay, it creates lower surface temperatures and a slightly reduced dissolved oxygen content. Turbidity increases near the bay floor to maximal values of 1.0 JTU, or three times the values in near-surface water. Dissolved oxygen is about 0.4 mg/l lower in deeper water, but as a whole bay water is well-oxygenated with concentrations ranging 6.8 to 7.6 mg/l.

Water quality varies within very narrow limits from January to July. Temperature was about $1^{o}C$ warmer in July than in January whereas salinity, dissolved oxygen and pH showed essentially no change. Turbidity near the bed was about

30 percent (0.2 to 0.4 JTU units) higher during moderate to high energy conditions in July than under low energy conditions in January. The current pattern observed in July was generally similar to that observed in January, however, resultant speeds were faster, especially off headlands, High Point and Black Point.

Excellent water quality of the bay can be maintained by avoiding any significant alteration of the natural hydrographic and drainage regime and by preserving the natural flow of water. Discharge of turbid materials needs to be controlled at the source by controlling development in the watershed and restricting dredge and fill operations along the shore or in the bays. Release of oxygen demanding materials , toxic substances, and nutrients to the bay should be prevented through safeguards and precautions. It is essential that remaining grass beds, coral reefs and salt ponds be insulated and free of human disturbance.

Because the coral reefs, grass beds and salt ponds are an essential natural resource for continued ecological viability of the bay, and because they cannot stand more degradation without a total loss, they should be protected as a natural preserve within the territorial park system.

Because the bay is subject to occasional discharge of sediment supplied by transient westerly currents, it is recommended that dredge and fill operations of runway construction be monitored to insure that excess turbidity does not develop in the bay. Monitoring should give attention to the multi-varied flow directions and the potential for widespread dispersal during moderate to high (storm) energy conditions. Natural or "background" variations may be expected to vary diurnally, tidally and with hydrologic events. Additionally, observations should be made in nearshore zones of convergence and in the central bay where materials accumulate in circulatory traps. Since tidal resuspension of bed materials is active, sampling should include near-bottom as well as near-surface and mid-depth points. If background variables can be monitored on a continuous basis at critical points, it may be possible to program certain operations to take advantage of the circulatory movement or water quality conditions that occur.

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APPENDIX I

Chemical procedures for analyses of sediments and ground water.

Total Volatile Solids (%TS, %VS)

The sediment samples were dried in an oven at 103^{o} to constant weight, (dry weight/wet weight x 100 = percent total solids). The dried samples were placed in a muffle furnace for one hour at 550-600^{o}C. The decrease in weight after ashing was reported as volatile solids.

Chemical Oxygen Demand (COD)

The parameter was determined by the dichromate reflux method. The oxidizable substances were oxidized by a standard solution of potassium dichromate in sulfuric acid. The excess dichromate was titrated with standard ferrous ammonium sulfate. Silver sulfate was used as a catalyst; mercuric sulfate was used to eliminate the interference to chloride ions.

Total Kjeldahl Nitrogen (TKN)

The samples were digested with a solution containing sulfuric acid, potassium sulfate, and mercuric sulfate converting organic nitrogen to ammonium sulfate. The digested samples were steam-distilled into a saturated boric acid solution and titrated with standard hydrochloric acid.

Total Phosphorus (TP)

The samples were digested in concentrated HNO_3 and evaporated to dryness; concentrated H_2SO_4 was added and heated until the solution cleared. Water was added and the samples were filtered through a glass filter. The filtrates were analyzed for total phosphorus by the single solution method, using ascorbic acid as the reducing agent. The developed samples were read on a Klett-Summerson Photoelectric colorimeter, model 900-3.

Metals (Cd, Cu, Zn and Pb)

One gram of sample was heated to fuming with ten milliliters of concentrated HNO_3 acid. After cooling, ten additional milliliters of acid were added, heated and cooled. The samples were centrifuged and the supernatants measured for volume and analyzed on a Varian Atomic Absorption Spectrophotometer, model AA-5.

Mercury (Hg)

The samples were digested with concentrated H_2SO_4 overnight. The digested samples were oxidized with 5 percent $KMNO_4$ and transferred to 300 ml BOD bottles. After the addition of reductant solution the BOD bottles were immediately attached to the aeration apparatus of a Coleman Mercury Analyzer MAS-50. Mercury concentrations were determined from standard curves. The composition of reductant solution is as follows:

H_2O	600 ml
H_2SO_3	100 ml
NaCl	5 grams
$(NH_2OH)_2SO_4$	20 grams
q.s. to 1 liter	

Oil and Grease (O & G)

The sediment samples were dried with magnesium sulfate monohydrate, the soxhlet-extracted with hexane (Standard Methods for the Examinations of Water and Wastewater, 12th Ed., APHA, Inc., N.Y., 1965; 531-532). The hexane was then evaporated to dryness. The weight of solid residue from the solvent evaporation yields oil and grease.