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SEDIMENTATION AND PUERTO RICAN CORAL REEFS
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MARINE RESOURCES

SEDIMENTATION AND PUERTO RICAN CORAL REEFS

Executive Summary

The coral reef inventory of Goenaga and Cintron (1979) found sedimentation problems to be the most serious stress affecting Puerto Rican coastal waters and its coralline resources. This document will provide part of the necessary information and recommendations for the preparation of both an Environmental Impact Statement and a Management Plan.

Loya (1976) summarized the detrimental effects of sedimentation on corals as : " a) causing the death of corals when they are heavily coated or buried by sediments; b) reducing coral growth potential directly, by abrasion and smothering and indirectly by blocking light; c) inhibiting coral planulae settlement and development; and d) modifying growth of corals sometimes towards forms more resistant to sedimentation."

In order to assess properly the effects of sedimentation on reefs, baseline data is needed of the prevailing conditions on the system in terms of suspended matter, sedimentation levels, turbidity, and water transparency.

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Rogers (1977) mentioned at least three conditions that identify sediment stressed reefs: " 1) sediment doses of 200-1000 mg/cm² and more are incompatible with healthy reefs; 2) continual suspended matter concentrations of 10-20 mg/l or more appear to be critically high; and 3) secchi disk depths less than 4 m probably indicate an environment too harsh for coral growth." Brock et al. (1966) found that reef areas with secchi readings of 1.5-4 m had only 10-15% living coral coverage.

Indirect evidence for a reef under stress is given by: 1) the limited number of coral species; 2) the presence of areas overpopulated by fast growing species of colonial zoanthids and anemones (like Palythoa and Zoanthus); 3) extense coverage of substrate by algae; 4) reduced or absent predator populations (e.g. Balistes vetula); and 5) the over abundance of the sea urchin Diadema antillarum (Goenaga and Cintron, 1979).

The relative importances and approximate recurrence intervals for the principal stresses are noted in the coral vulnerability matrix presented on Plate 1. The location and present condition of Puerto Rican coral communities are also displayed. Environments and stresses vary locally so exceptions exist in all regions. The resolution is of regional scale.

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Agricultural techniques that do not use measures to control rill and sheet erosion are the primary source of man-influenced erosion. Agriculture has given way to industry in the last 40 years. This has resulted in lower erosion rates and less sediment delivered to the marine environment (Molinelli, 1982).

Decreased agriculture has reduced the quantity of sediments available to stress coral communities on the Puerto Rico insular shelf. As urban and industrial development increase, however, so do point sources of sediments and associated contaminants. Dredging, land fill, and sand extractions have all had devastating effects on nearby coral systems.

Damming rivers stresses coral communities. Waters offshore of the river mouths become less productive as the flow of nutrient rich fresh water is reduced. Corals feed on phytoplankton. A sharp decrease in phytoplankton productivity resulted after the Answan Dam greatly reduced the flow of the fertile Nile water into the Mediterranean (Wahby and Bishara, in Martin et al., 1980).

When rivers are dammed, muddy river banks cave in and storm waves eat into soft coastal alluvium because the natural supply of sand is trapped on the floors of the reservoirs. The extensive vegetation found in the

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reservoirs contributes large quantities of organic matter to the coastal waters. Healthy estuarine systems trap fine sediments. Bypassing sediments and clearing vegetation in the reservoirs would benefit coralline resources, decrease erosion, and lessen problems with reduced reservoir capacity and water quality.

Investigations should be conducted to determine the best way to bypass sediments through a reservoir. The solution may involve structures, settling basins, pumps, or just a simple modification in gate timing during flood flows. If industrial development is to continue, then it should be limited to areas already stressed by industry. Before approving more port development projects, detailed sediment impact assessments on both the dredged area and the proposed dump site should be required, especially if to be done near healthy coral communities.

The most damaging part of atmospheric disturbances is the associated floods that suffocate coral communities. The recovery rate of healthy coral reefs from physical damage inflicted by hurricanes appears to be shorter than the recurrence interval for hurricanes passing near Puerto Rico (approximately 8 yrs). Hurricanes break corals and distribute the fragments on the reef crest and in the backreef area. Occasional disruption, however, is conducive to reef expansion as the displaced rubble mounds provide a

favorable substrate for the settlement of coral planulae (Macintyre, et al., 1983).

Suspended sediments stressing coral reefs in Puerto Rico are derived from: river input, resuspension of bottom sediments, and suspended organic matter. After periods of heavy rainfall, rivers discharge turbid sediment laden waters into the coastal marine waters. Storm waves resuspend fine sediments previously deposited on the bottom. Terrigenous and marine derived organic matter cloud the waters during calm sunny periods of high biological productivity.

The northern and eastern regions of the Puerto Rico insular shelf are strongly stressed by terrigenous input from the major river systems. Urban and industrial development has had negative impacts on the coralline resources at the ports of San Juan, Arecibo, and Yabucoa. Daming of the Rio Grande of Arecibo and the construction of the breakwater has drastically altered active sedimentary processes in Arecibo bay (Delgado, 1976).

The stressed reefs in the southeastern and southern regions are affected by turbidity and resuspension of terrigenous and lime muds deposited throughout the Holocene. Long period swells, common in the Caribbean, cause the greatest agitation in the areas where the shelf is narrow.

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Industry at Yabucoa, Guayanilla, and Guanica have been point sources of sediments and toxins, though their contribution has decreased in recent years due to lower production rates.

In the western region, the Boqueron reefs suffer from resuspension of the fines trapped in the bay. Escollo Rodriguez is stressed by industrial contamination from Mayaguez in addition to being in the outfall of the Yaguez River.

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1.0 Introduction

Sedimentation is defined as the act or process of depositing sediment by mechanical means from a state of suspension in a liquid, thus forming or accumulating sediment layers, including the transport and actual deposition or settling of the particles (Gary, et al., 1974).

The rugged topography and warm, moist climate of Puerto Rico are conducive to high rates of erosion and sedimentation. These natural processes are essential links in the chain of ecological productivity, supplying nutrients and raw materials to depleted systems. Sedimentation, however, is a mixed blessing. Associated problems include loss of reservoir capacity, water pollution, soil erosion, flooding, beach erosion, and negative impacts on sensitive marine ecosystems.

Coral reefs and seagrass beds ecosystems are susceptible to the effects of turbidity and sedimentation. Reef development is highly influenced by natural environmental factors such as salinity, temperature, hydrodynamics, available light, turbidity and sedimentation. The synergistic effects of these factors, in particular turbidity and sedimentation, exert regional differences on

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reef structure. High turbidity and sedimentation rates strongly inhibit reef growth (Levinton, 1982).

Sedimentation is the dominant stress affecting modern reef growth in shallow tropical waters. Other factors, such as temperature, salinity, physical destruction, and water depth may be important locally during certain events. Healthy reefs support a diverse biological community (Figure 1). When sediments weaken the coral communities, organisms that normally coexist in the area begin to feed on the degrading organic tissues of the dying corals. Others, colonize dead sections of the coral and inhibit recovery (Figure 2).

Turbid waters contain high amounts of suspended sediments that absorb and scatter light. This reduces the light reaching the corals. In turn, this decreases photosynthesis by endozooic algae in corals, thus drastically reducing calcification rates. Siltation occurs as suspended sediments settle out of the water column. These sediments, mostly fines, block the respiratory and digestive systems of the coral polyps. Corals will expend energy removing sediments but if the load is too great they eventually suffocate. Turbidity, thus constitutes a severe stress for light dependent benthic communities.

ZONES

DEAD CORAL ZONE
(beginning of reef island)

OUTER REEF

PORITES ZONE

LAGOON

THALASSIA ZONE

RHIZOPHOM
MANGROVE

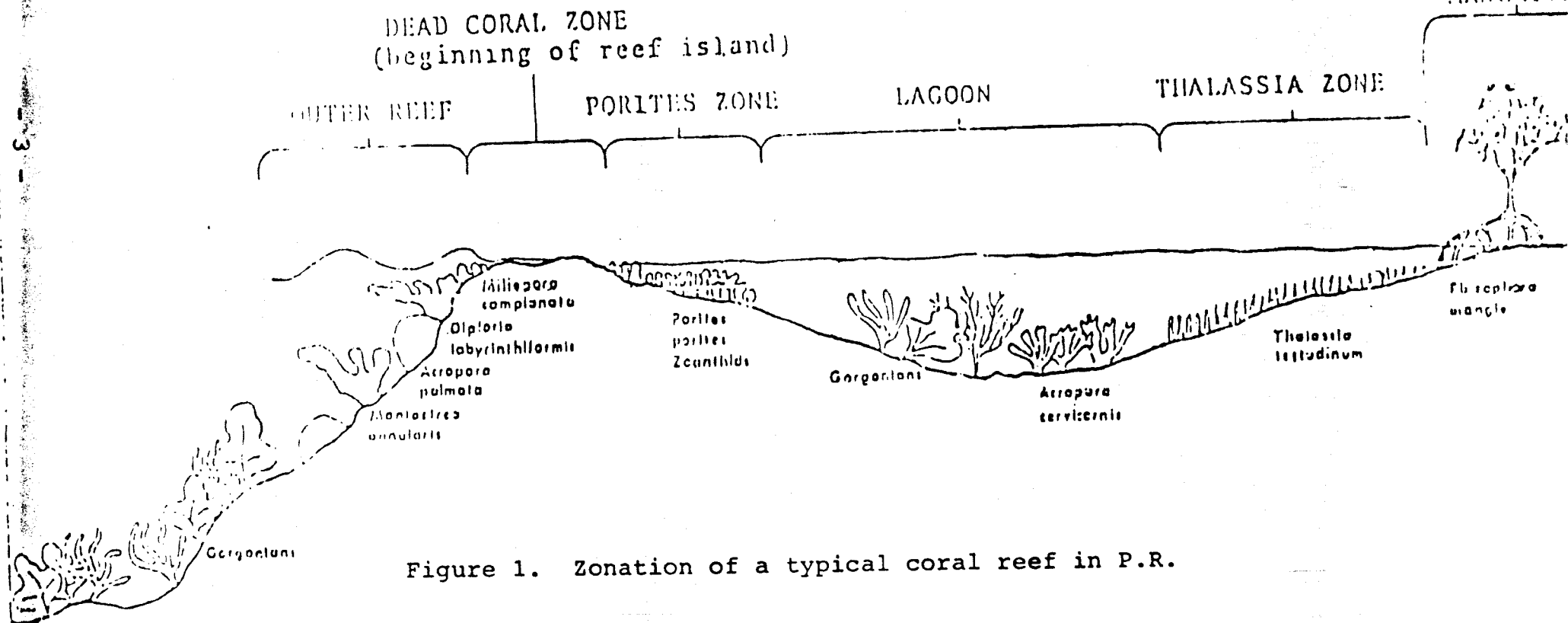
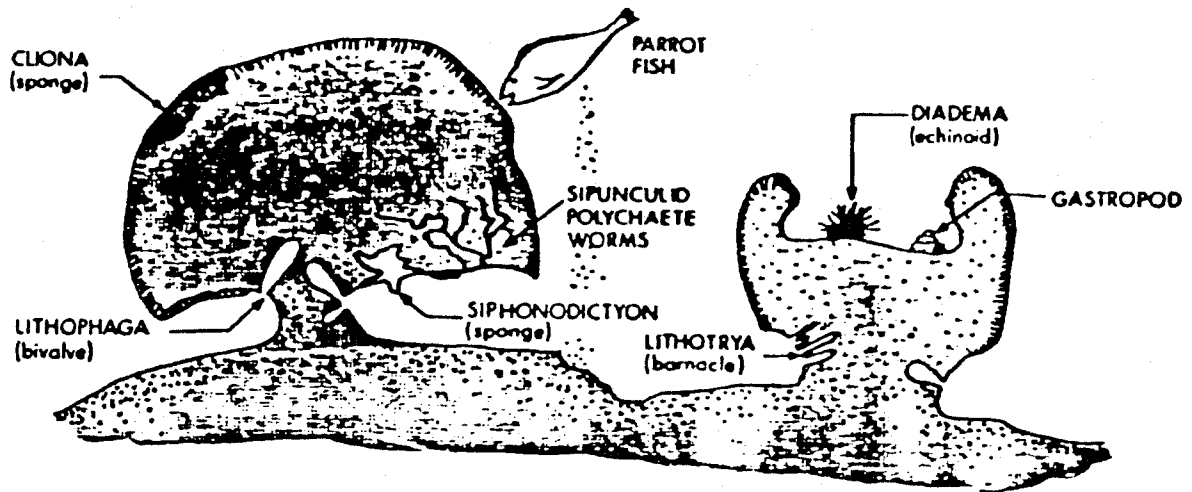


Figure 1. Zonation of a typical coral reef in P.R.

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Figure 2 A sketch of two coral heads and some of the organisms responsible of bioerosion



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Bulk density of corals increases and calcification rates are diminished in reefs with lower water transparency. Platy growths of Montastrea annularis may indicate either deep water or shallow water with reduced light levels due to microhabitat (Graus and Macintyre, 1982, as cited in Goenaga, manuscript) or to a high turbid environment.

Coral reefs grow more rapidly in clear waters with low sedimentation rates. Corals growing on horizontal surfaces suffer the most from sedimentation and usually support poor reef growth (Loya, 1976). Corals could develop in turbid areas if there is good flushing by strong currents to help prevent the build-up of sediments on the coral surface (Marshall and Orr, 1931).

Individual coral species exhibit different levels of tolerance, responses and adaptations for sedimentation and turbidity problems. Colonies with cylindrical branches, like Acropora cervicornis, and those with almost spherical morphology, like Diploria strigosa, are better adapted to large sediment loads (Rogers, 1982). Coral species normally located in areas with strong wave action, like Acropora palmata, are the least resistant to sediment application (op. cit.).

Coral species with large polyps can remove sediments more easily than those with small polyps (Hubbard and

and larvae settlement, and d) dramatic reduction of living coral coverage attains values of 5% or less by few species (Morelock, et al., 1979).

2.0 Stressors that cause sedimentation problems

Upland deforestation, careless land management, and hurricanes are among the stressors that coral reefs are subjected to and may lead to their destruction (Johannes, 1975; Lugo, 1978; Goenaga and Cintron, 1979; Rogers, 1977). Increased coastal development, industrial activity and dredging jeopardize reef development and survival by increasing turbidity and sedimentation levels (Rogers, 1977; Lugo, 1978; Morelock, et al., 1979; Goenaga and Cintron, 1979).

2.1.1 Natural Stressors

Storms and hurricanes

Storms and hurricanes are high energy events that cause disruption of benthic plants, resuspension of sediments, physical changes of cays, formation of islets, and destruction of corals (Glynn, et al., 1965; Gonzalez-Liboy, 1979; Rogers, et al., 1982).

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Physical disruption by storm swells also weakens the corals. Computer simulations by Graus et al. (1984) indicate that the storm wave climate is a determining factor in reef zonation. The model was compared to conditions observed at Discovery Bay, Jamaica as Hurricane Allen passed.

Goenaga (1982) described briefly the impact of hurricanes David and Frederick -both in 1979- on the reefs of La Parguera. During these events plants and coral colonies were uprooted and strewn about either above sea level, where dead coral fragments formed ramparts, into deeper water or close to its original position. Heavy rainfall during storm events increases flood runoff. The discharge into the marine system of muddy sediments by rivers increases turbidity and lowers light penetration and also salinity. Goenaga and Canals (1980) reported salinities of less than 25⁰/oo and high turbidity on a reef close to Rio Fajardo that suffered massive mortality of the hydrocoral Millepora complanata.

2.1.2 Man induced (Anthropogenic)

Upland deforestation and careless land management

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Man's activities on land have had negative impacts in the marine ecosystems. The vegetation promotes the trapping and binding of sediments and enhances the recharge and infiltration of water. Upland and river bank deforestation for housing development, road construction and agriculture, accelerate natural processes of erosion. Consequently, floods and the accompanying loads of fine sediments into the sea by runoff have become increasingly severe. Since the industrial revolution of the mid 40's this trend appears to have slowed.

Johannes (1975) has stated that the exposure of reefs to brackish, silt-laden water associated with flood runoff has probably been the single greatest cause of reef destruction historically. Muddy sediments remain chronically in suspension. These may be transported by currents to areas of important benthic communities. The communities are then affected by the low light levels caused by the increased turbidity and siltation. The destruction of corals by clay size terrigenous sediments is documented for Kaneohe Bay, Hawaii (Maragos, 1972); some areas within the Great Barrier Reef in Australia (Fairbridge and Teichert, 1948, as cited in Johannes, 1975); and large areas of Lindberg Bay, St. Thomas (Grigg and Van Eepoel, 1970).

Industrial activity and sewage effluents

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Coastal ecosystems have suffered the consequences of intensive development and industrialization for the past decades. Most industries have been established close to a body of water that they can use to cool their machinery and to discharge their effluents. The threat of destruction or alteration of marine communities by heated effluents is greatest in the tropics.

Tropical organisms live at temperatures close to their upper lethal limit (Mayer, 1914, as cited in Johannes, 1975). Corals have been found to cease feeding, reduce their reproductive rate, extrude their zooxanthellae, and avoid settlement of planulae at high sublethal temperatures.

Coastal ecosystems associated to industrialized areas may also be affected by abnormal salinities, discharge of chemicals, heavy metals and oil spills among others. Guayanilla and Tallaboa Bays, on the south coast of Puerto Rico, provide a good example of pollution. The industrial development in this area has severely changed the natural conditions threatening the marine ecosystems in the bay. Reefs off Tallaboa are, at present, under high stress conditions due mainly to siltation and the discharge of bilge water (Goenaga and Cintron, 1979). Living coral cover in shallow reef areas is almost zero (op. cit.).

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Sugar mill wastes are another source of sediment damage on reefs in Hawaii and parts of the Caribbean (Johannes, 1975). The extremely turbid water discharged contains silt, bagasse and some rocks that leads to the destruction of corals and associated fauna.

Sewage not only increases turbidity and sedimentation, but brings about the problem of eutrophication. Sewage increases the phosphate concentrations on reefs, leading to a takeover by algae. This prevents settlement of coral planulae or the asexual extension of a colony.

Tropical marine organisms live closer to their lower oxygen limit than biota in colder waters (Johannes, 1975). If oxygen levels decrease below normal levels, many reef inhabitants will die (Kinsey, 1973, as cited in Johannes, 1975). This is likely to occur in reef areas subjected to sewage effluents.

Dredging

The ecological effects of dredging operations along the coast have been reviewed by Levin (1970), Gordon (1973) and Morton (1977). Bottom sediments are mechanically disturbed and resuspended during dredging operations. Gordon (1973) pointed out that turbidity as well as the settling of sediments is an unavoidable effect of dredging. The

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resuspension of sediments during dredging operations affect more dramatically the benthic organisms. It has been calculated that 2.5% of the dredged muds will be dispersed in the water.

Water turbidity adversely affects light penetration and reduces photosynthesis. The layer of sediments deposited on the corals adds the problem of smothering and abrasion due to the unstable, shifting sediments. The dredge suspended sediments increase the biological and chemical oxygen demand. The depression of the normal night-time minimal oxygen level may also constitute a significant stress (Johannes, 1975). Eventually, coverage by alga and seagrasses and coral growth will also diminish. Once these components disappear the entire community progressively collapses due to the lack of the sources of nourishment and refuge.

Bombing

The force of the blast during weapons test in the vicinity of coral reefs cause the undermining of the reef framework, fragmentation of coral colonies and resuspension of sediments. The structural damage inflicted to a coral reef could result in the destruction of the entire community. Continual blasting could impede recovery of the

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reef and decrease their natural resistance to storms, resulting in total devastation of the coral reef.

Rogers, et al. (1978) assessed the disastrous effects of Naval maneuvers on coral reefs in Puerto Rico. They found that Vieques reefs were not irreparably damaged, although increased activities will damage the reefs further more and delay recovery. Macintyre, et al. (1983) reported the total destruction of the eastern nearshore coral community (Porites/Acropora) at Bahia Salina del Sur, Vieques, after a naval bombardment on May, 1978.

A subsequent visit after hurricane David (1980) showed the area completely destroyed, as well as the A. palmata on the south coast. They also noted that dead and living A. palmata, along with coral head debris, migrated several meters over the back reef sands. The unstable bottom produced in these areas may inhibit successful settlement of coral planulae and slow recolonization rates. In Culebra, recolonization has progressed slowly after operations ceased in the area.

3.0 Geological Perspective

This section presents the natural and anthropogenetic sources of sediments and the processes which transport them to areas colonized by coral reefs. Conflicts with coral

resources will be identified according to source and magnitude of the stress, including environmental factors not directly related to sedimentation. By understanding the causes and effects of sedimentation, strategies can be developed to minimize conflicts with the coral communities. The ecological importance of Puerto Rico's coralline resources cannot be underestimated.

3.1 Sedimentation

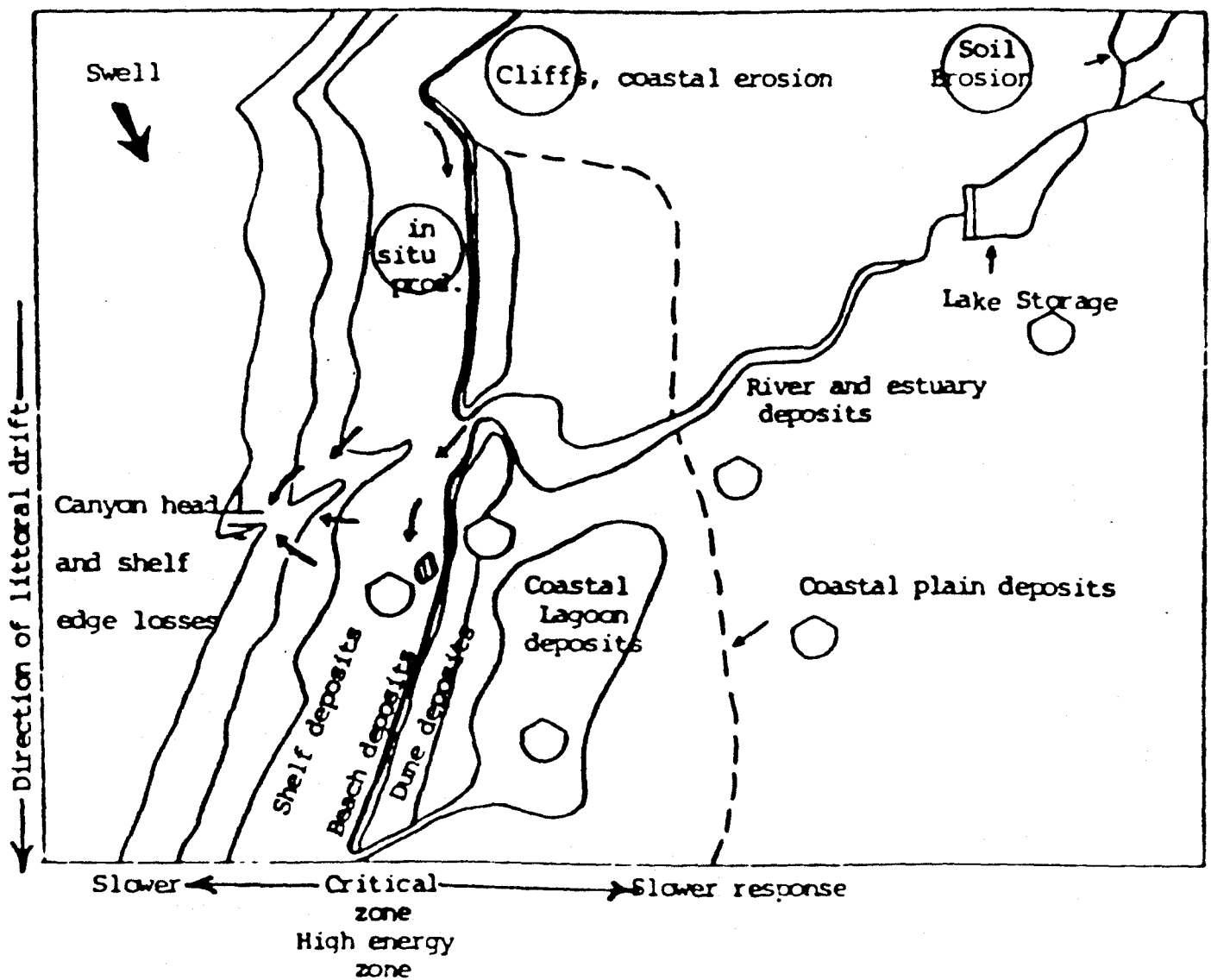
Major sediment storage areas are displayed in Figure 3. The reefs are positioned to emphasize how some events may devastate one reef while leaving a nearby reef untouched.

Sedimentary processes interact with coral communities on a daily basis. When the scope of sedimentation is considered, the occurrence of conflicts is not surprising.

Sedimentation includes consideration of:

- 1) the sources from which the sediments are derived;
- 2) the methods of transportation from the places of origin to those of deposition;
- 3) the methods, agents, and environments of deposition;
- 4) The chemical and other changes taking place in the sediments from the times of their production to their ultimate consolidation;

Figure 3 Schematic distribution of major sand sources, movement and storage areas in a coastal segment



- 5) the climatic and other environmental conditions prevailing at the places of origin, over the regions through which transportation takes place, and in the places of deposition;
- 6) the structures developed in connection with deposition and consolidation.

The following discussion centers on the sources, sinks and transportation mechanisms of fine sands, silts, and clays. This highly mobile sediment population poses the most risk to coral communities. Fine sediments travel almost exclusively in the suspended sediment population. Quartz grains finer than 170 to 200 μm will tend to go directly into suspension under minimal energy conditions (Bagnold, 1966; McCave, 1971: as cited in Wanless, 1981). Readers interested in a wider view of sedimentation on a global scale can begin their search with Friedman and Sanders (1978).

In the past, terrigenous grains carried by the rivers were considered the only significant source of suspended sediments and the abyssal plains considered the greatest sink. Suspended sediment levels on the continental shelves were assumed to rely almost completely on the proximity to a river mouth. Meade (1972) states that not only are other sources and sinks present, but that, globally, they are of equal or greater importance.

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Sources other than river input include resuspension and organic production. The vast majority of river born sediments settle out in the estuaries or near the river mouths. The concentration of terrigenous detritus decreases seaward across continental shelves at a greater rate than the concentration of total suspended matter.

Resuspension of sediments on the shelf bottom, in wetlands, and in the littoral zone is the most important factor in sediment stressed reefs not located adjacent to river mouths.

Areas of high planktonic productivity experience high levels of turbidity as light is absorbed and utilized in photosynthesis. Most of the suspended matter in surface waters of outer shelves is combustible organic matter.

Sinks other than the deep abyssal plains include beach and shelf deposits and wetlands such as estuaries, lagoons, and mangrove swamps. River damming, land fill, and canalization along with other human intervention has damaged or eliminated many of these important sediment trapping areas.

Sediments in the water column are measured directly as suspended sediments or indirectly as turbidity, secchi depth, light extinction, or accumulation rates. Each of

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these measures, however, reflect different aspects of the local environment. In addition, nuances in sampling and analytical methods can produce uncomparable data within the same measure.

Suspended sediments stress corals directly by settling on their surface (siltation) and by reducing the light reaching the bottom (turbidity). Measuring suspended sediments is the best way to estimate the magnitude of these two negative effects. Water samples are filtered and the mass retained is commonly reported as milligrams per liter (mg/l). Results are precise and easily reproducible. The data, however, represents a specific water parcel at a specific point in time. If the water is stratified the results may be misleading. For this reason, suspended sediments should be measured at several depths from the surface to the bottom.

Turbidity in water is caused by suspended matter, such as clay, silt, finely divided organic and inorganic matter, soluble colored organic compounds, and plankton and other microscopic organisms. Turbidity is an expression of the optical property that causes light to be scattered and absorbed rather than transmitted in straight lines through the sample. Correlation of turbidity with the weight concentration of suspended matter is difficult because the

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size, shape, and refractive index of the particles also affect the light-scattering properties of the suspension.

Turbid waters reduce the amount of light reaching coral colonies. Reduced light initiates slower calcification rates and morphological changes in coral structure (Graus and Macintyre, 1976). Turbidity has commonly been reported in Jackson Turbidity Units (JTU). This method measures the path length needed to obscure a candle flame. The accepted method today uses a Formazin solution as a standard and the units read from a turbidimeter are reported in Nephelometric Turbidity Units (NTU). A 40 NTU solution measures 40 JTU (American Public Health Assoc., 1981). This is one common point and by no means does it apply to the entire scale. Similar to suspended sediments, the samples tag a specific point and time but give a more accurate description of the light conditions encountered below. Submergible nephelometers, though not as precise as laboratory analysis, can be used to make turbidity profiles.

Secchi depths are determined by measuring the point, in meters (m), at which a white disk lowered into the water is no longer visible. This method averages water properties of the water column above the disk. The results, though, are sensitive to observer experience, the angle of the sun and other atmospheric conditions.

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Light extinction coefficients (k_e) are derived from data obtained by lowering, in steps, a photometer through the water column. Exponential regression of the data yields the coefficient which is related to the secchi depth by the formula: $K_e = 1.7/d$. Results are more precise than the secchi depth though it shares the sensitivity to solar and atmospheric conditions.

Siltation by itself is difficult to measure with precision. The absolute accumulation rate (mm/yr) of sediments can be calculated by a number of radiometric dating techniques. The relation between absolute accumulation and coral health has not been satisfactorily determined. Corals do not distinguish between new fines arriving from a nearby river mouth and those resuspended from the local area which resettle on top of the corals. Sediment traps seem to offer a solution in that they trap both new and resuspended sediments. Their use, however, has met with varying degrees of success as they may under or overtrap sediments depending on trap geometry and flow conditions (Gardner, 1980). The quantity of sediments in the traps are commonly reported as milligrams per square centimeter per day ($\text{mg}/\text{cm}^2/\text{day}$).

Most sediment stresses on coral communities are episodic. Figure 4 shows the magnitude versus characteristic recurrence intervals for some important

Figure 4 Graph of magnitude vs. characteristic recurrence intervals for some important sediment processes which can stress coral communities (Dott, 1982)

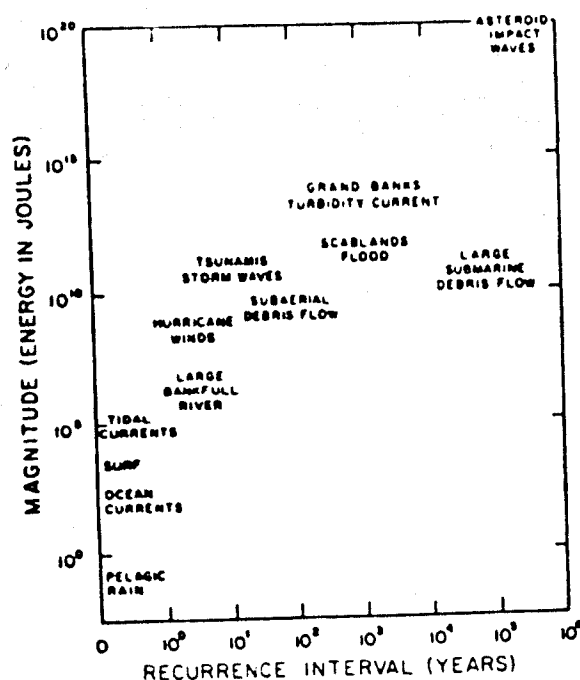
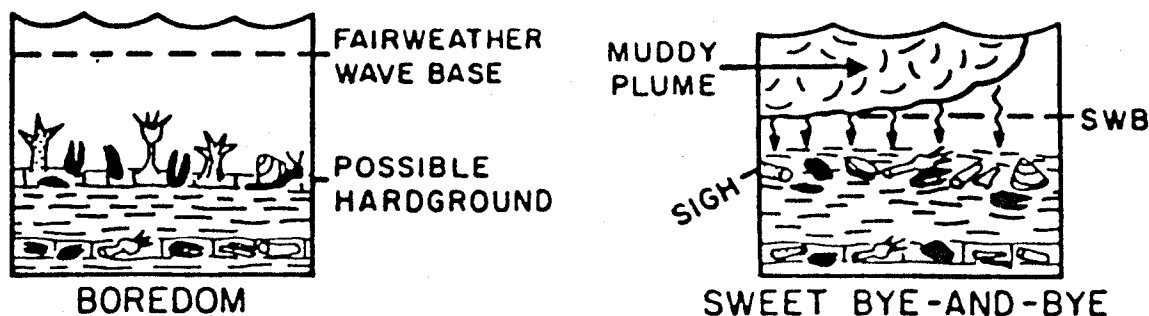
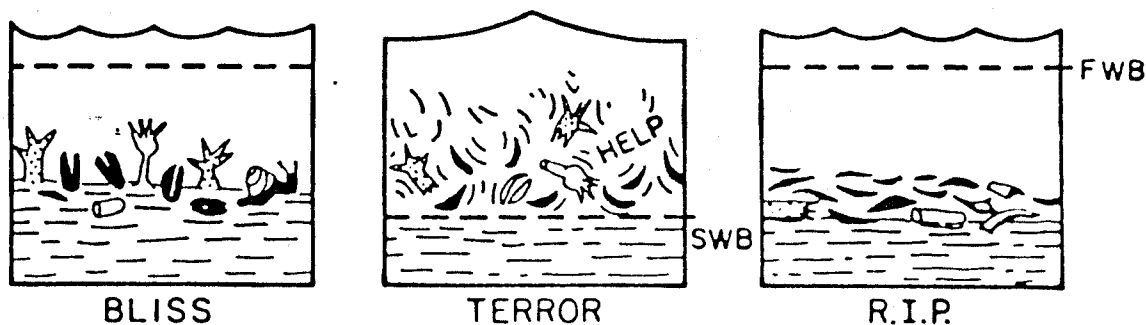


Figure 5. Diagram of the two most common mechanisms involved in coral mortality, suffocation and physical disruption. SWB indicates storm-wave base. FWB indicates fair-weather wave base. (Dott, 1982).

SUDDEN DEATH BY QUIET SUFFOCATION



BY RUDE UPROOTING



sedimentary processes which can stress coral communities. The majority of the annual weathering and transportation of terrigenous material takes place during a few days of torrential rains. Rainfall, however, does nothing to resuspend bottom sediments on the insular shelf. Storm swells not only resuspend the sediments, but may also do physical damage to the reef framework. High planktonic productivity can result in high continuous levels of turbidity. Figure 5 shows the two most common mechanisms involved in coral mortality, suffocation and physical disruption. The dominant factor at any one site depends on the fair and stormy weather wave bases.

Coralline resources are sensitive to sediment producing events occurring both on land and in the marine environment. The load of terrigenous grains is determined by the climate, geology, geomorphology, and land use of nearby watersheds. The bottom sediments, currents and wave climate, bathymetry, biological productivity of the area surrounding the reef will determine the importance of the terrigenous sources in comparison to sediments generated in the local marine environment.

3.2 Terrigenous systems

Terrigenous sedimentation encompasses the uplands and coastal plains. The fines are ultimately derived from

weathering of the mountainous core made up of both intrusive and extrusive igneous rocks. Rainwater pushes the sediments out of the steep valleys onto the broad and flat coastal plains. These sediments may be permanently locked up on the bottom of streams and rivers, in upland reservoirs, on the plains, in estuaries, or in beach deposits. Sediments that bypass these and other traps pose a threat to coral communities. Table 1 presents sediment accumulation rates as observed in several reservoirs in Puerto Rico. These values are measured upstream of the river mouths and may be quite different from the actual quantities entering the marine environment. The amount of terrigenous sediments that are discharged from a particular drainage basin into the ocean is a factor of the local climate, geology, geomorphology, and land use.

Table 1. Sediment Accumulation rates for several Puerto Rican Reservoirs

<u>Reservoir</u>	<u>Accumulation Rate (m^3/year)</u>
Comerio 2	140,180
Caonillas	292,373
Patillas	18,219
Guayabal	45,959
Coamo	70,444
Loiza	317,191
Cidra	7,303

(Modified from Lugo et al., 1980)

3.2.1 Climate

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Tropical sunshine, trade winds, and the moderating influence of the warm waters make the climate of Puerto Rico most agreeable. The only abrupt temperature changes occur in winter, when cold fronts from North America occasionally bring cold air into the area.

The normal range at Munoz Marin International Airport in Isla Verde between the warmest month (27.4°C) August and the coolest month January (24.1°C) is 3.3°C . The mean diurnal range in San Juan is 7.4°C .

Being in the belt of trade winds, the island is exposed to persistent air flow from the east-northeast. The moist air from the reaches of the Atlantic condense and precipitate as the air mass moves up and over the mountains. This is known as the orographic effect and can be seen in Figure 6. The Caribbean National Rain forest receives over 500 cm of rain annually, while the south coast, in a distinct rain shadow, receives less than 100 cm.

Activities that produce large amounts of sediments or expose soil to the erosive effects of rainfall should be limited to months of typically low precipitation. This would allow stabilization of the soil before torrential rains carry the fines to the ocean where they could stress

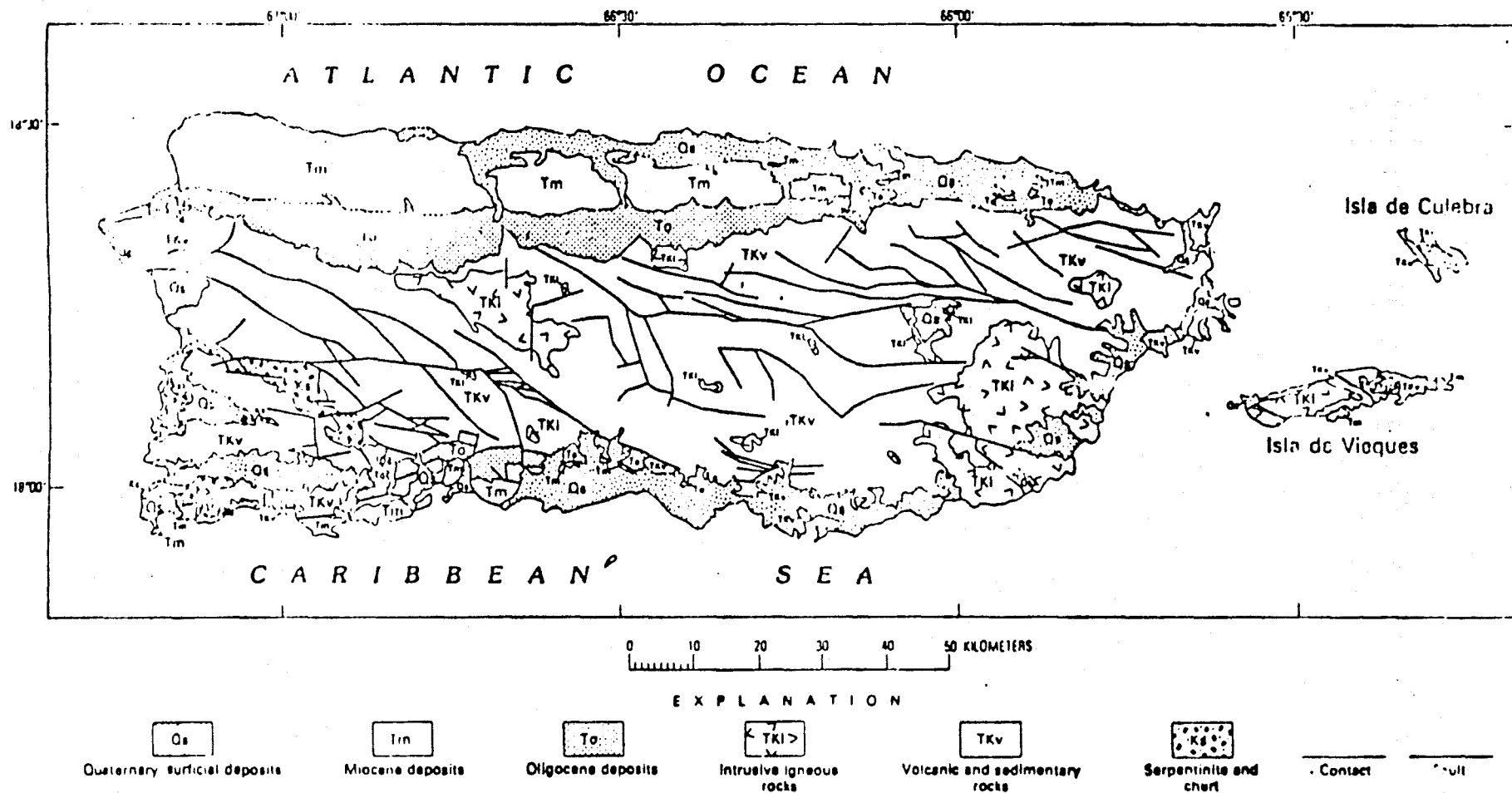


Figure 6. Generalized map of the geology of Puerto Rico.

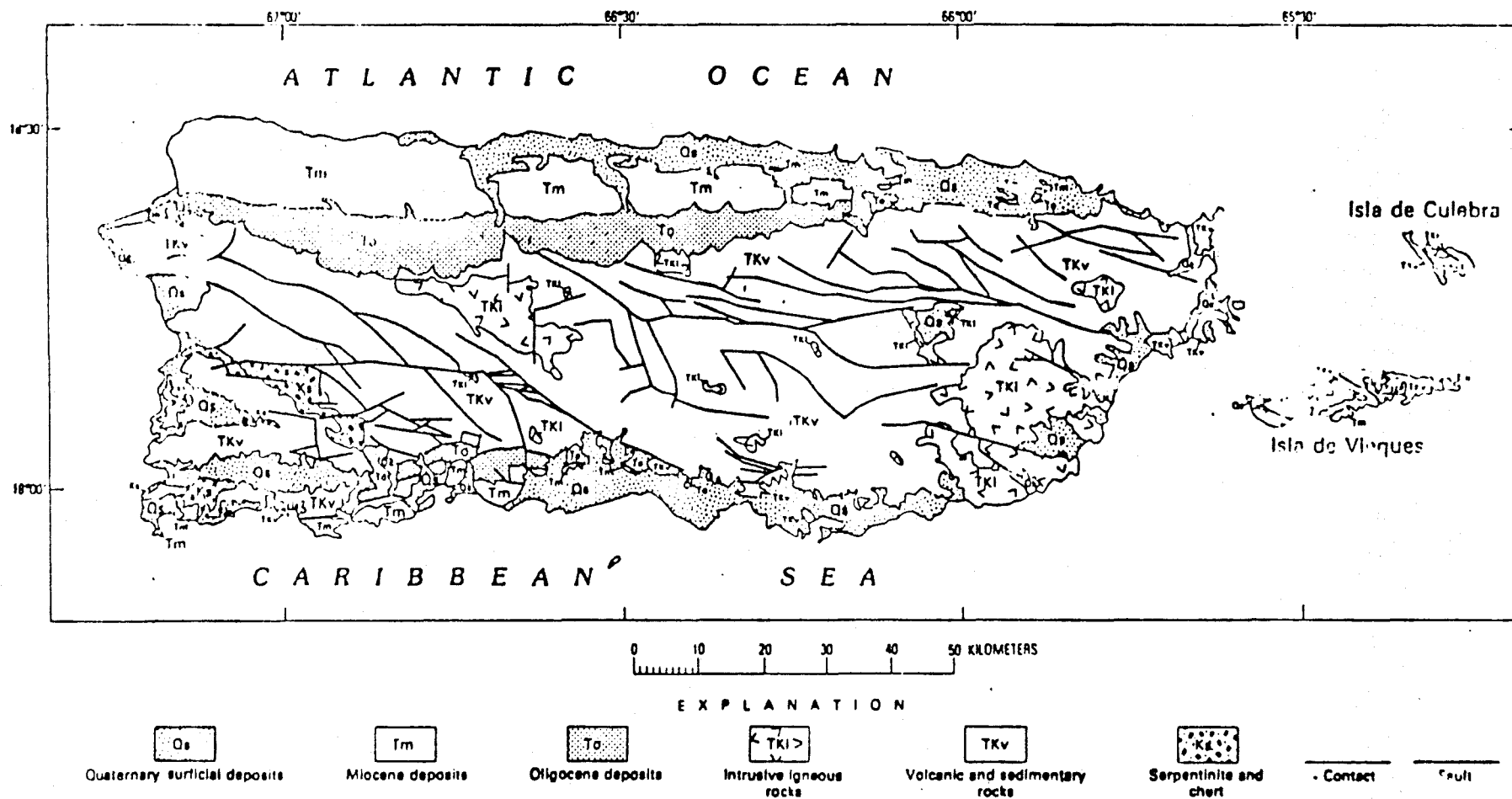


FIGURE 4. - Generalized map of the geology of Puerto Rico.

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coral communities. The variation of rainfall in the year at several places is shown in Figure 7. The pattern for Humacao and Garzas Dam is typical for much of the Island (Bogart et al., 1964). The dry winter period is followed by the moderate peak caused by spring rains and a lull in the first part of summer. The late summer and fall typically is the wettest period, reaching a maximum in September and October. The graph for San Juan in Figure 7 shows a somewhat different distribution that applies to the north coast and foothills area.

All of Puerto Rico's fresh water supply comes from rainfall. Approximately 53% of the area of Puerto Rico drains north into the Atlantic Ocean. Due to the the amount of rainfall over the area, however, almost 60% of the water discharged from Puerto Rico exits through the north coast. In contrast, approximately 24% of the area of Puerto Rico drains to the south coast, though only about 8% of the water discharges across the southern coast (Wilson and Iseri, 1969). This is a direct result of the arid conditions on the south side of the island.

The tropical cyclone season in the Atlantic extends from May through November; Puerto Rico being affected mainly from July through October (NOAA, 1974). The most damaging floods in the last century were associated with major hurricanes and tropical depressions (Figure 8).

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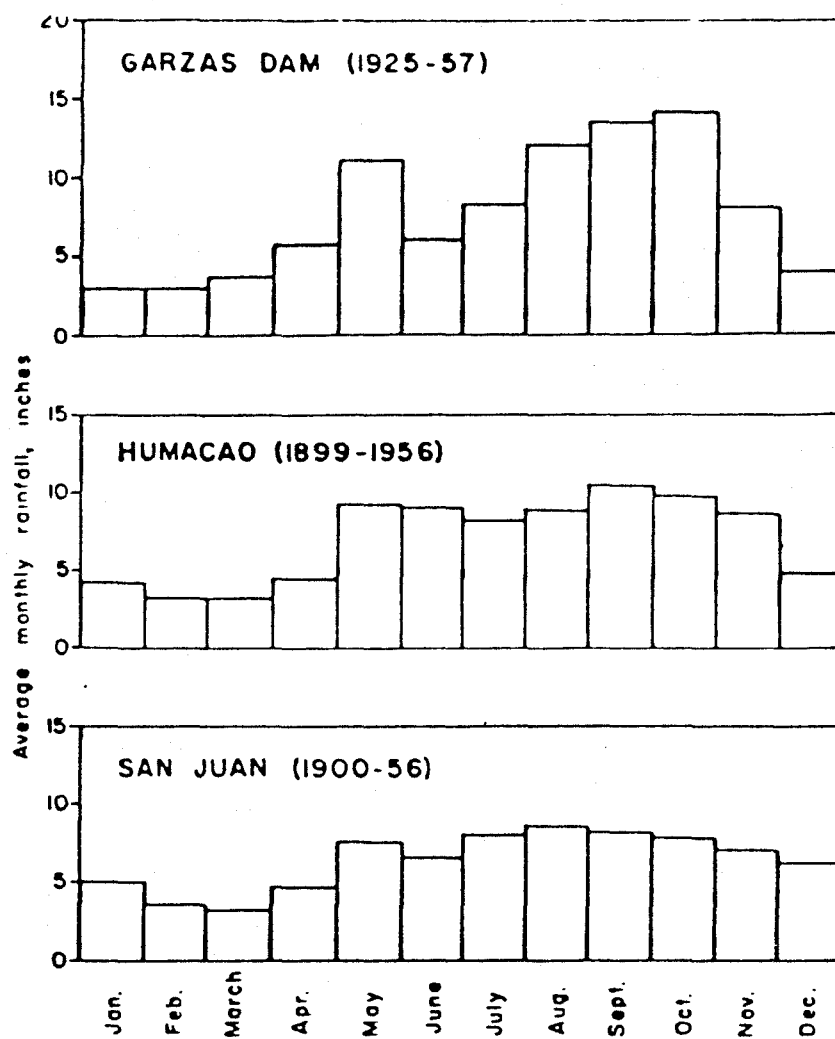
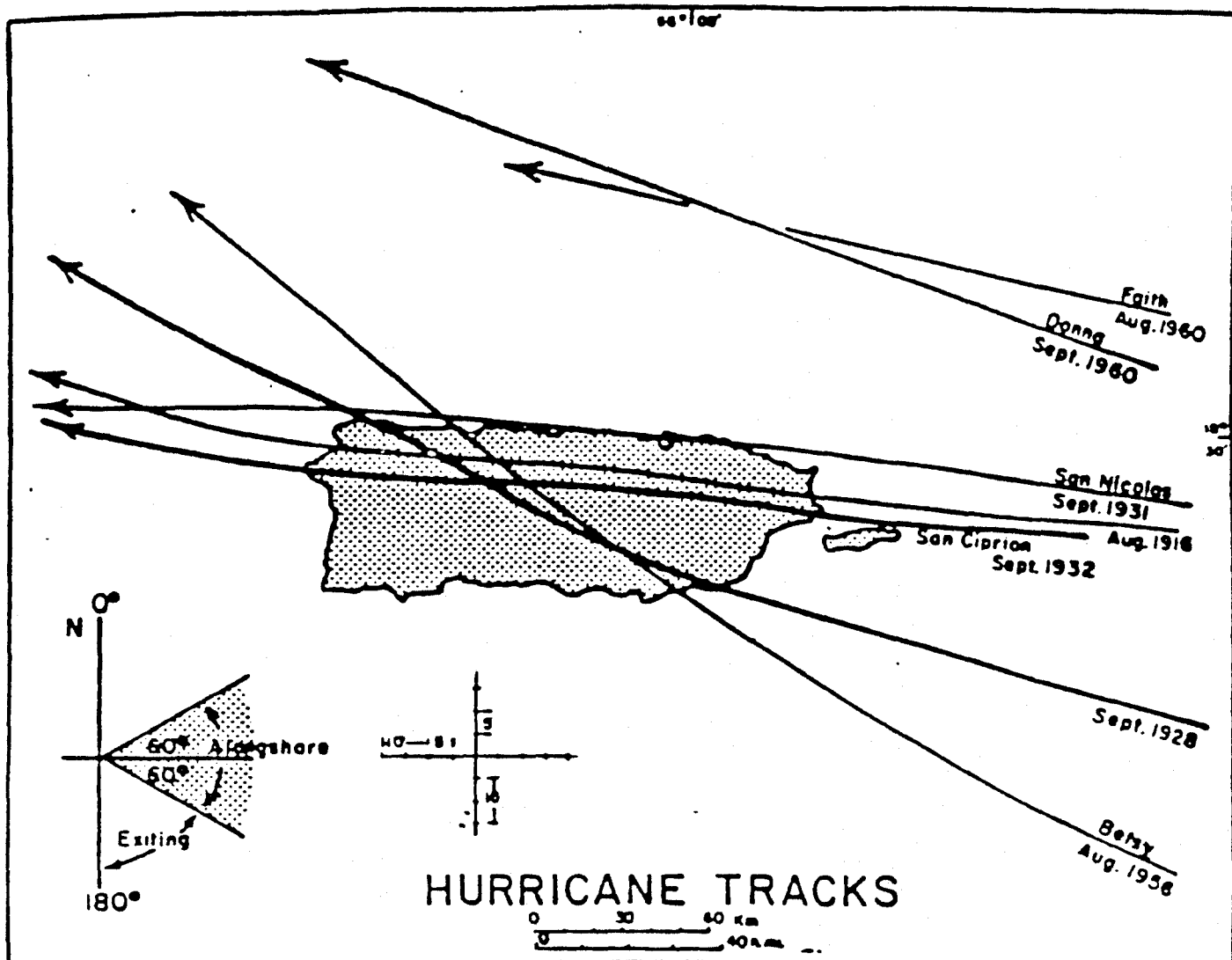


Figure 7. Annual pattern of rainfall at selected stations in Puerto Rico. (Bogart, 1964).

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Figure 8 Predominant hurricane tracks for several hurricanes passing near Puerto Rico. (Nichols and Cerco, 1983).



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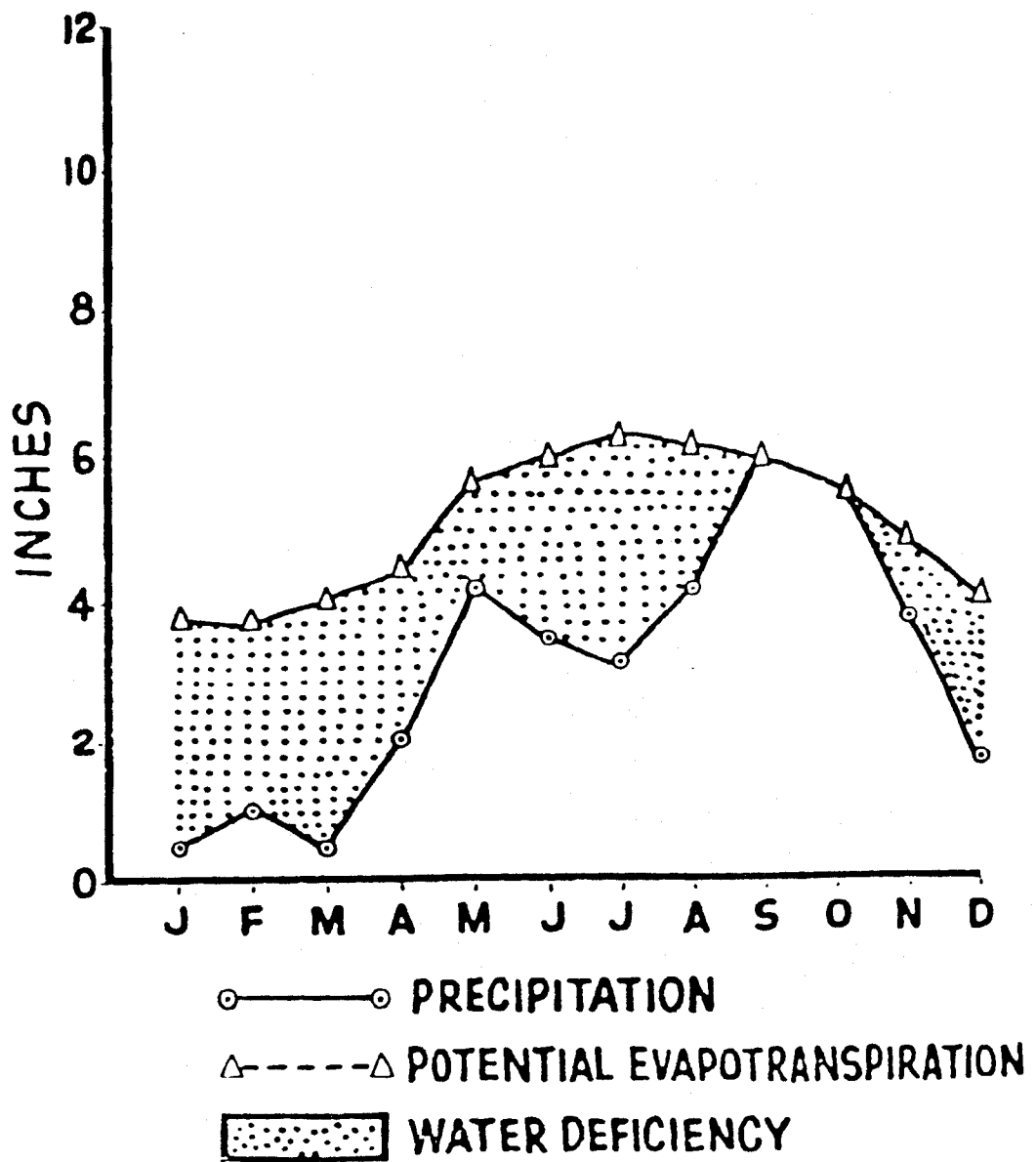
Only a fraction of the total precipitation drains away as surface runoff. The water budget for Puerto Rico shows the distribution of the 69 inches of average annual rainfall: 42 inches evapotranspiration, 23 inches stream runoff, and 4 inches ground-water discharge to the sea. Figure 9 shows that for most of the year, the rate of evapotranspiration exceeds the amount of total precipitation in the southern province. This results in periods of zero discharge for south coast streams (Figure 10).

The rivers of Puerto Rico discharge up to 70% of their annual sediment flux during the few days of torrential rains that occur through the year (Lugo, et al., 1980). Major floods produce even greater deviations from average sediment discharge rates.

Between October 4 and October 9, 1970, up to 35 inches of rain fell on the southern and eastern coasts; a third to a half of the average annual rainfall. Precipitation information to 1899 indicates the amount of rain that fell surpasses any other three day total in over 100 years (Haire, 1972). On October 6, 6,000 tons per square mile were discharged from the Rio Piedras Basin (Reed and Kiser, 1972) (normally, stream basins yield sediment at a rate of 1,000 to 6,000 tons per square mile annually). In total, over 200,000 tons of sediments, mostly fines, were probably

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Figure 9 Generalized south coast water balance diagram



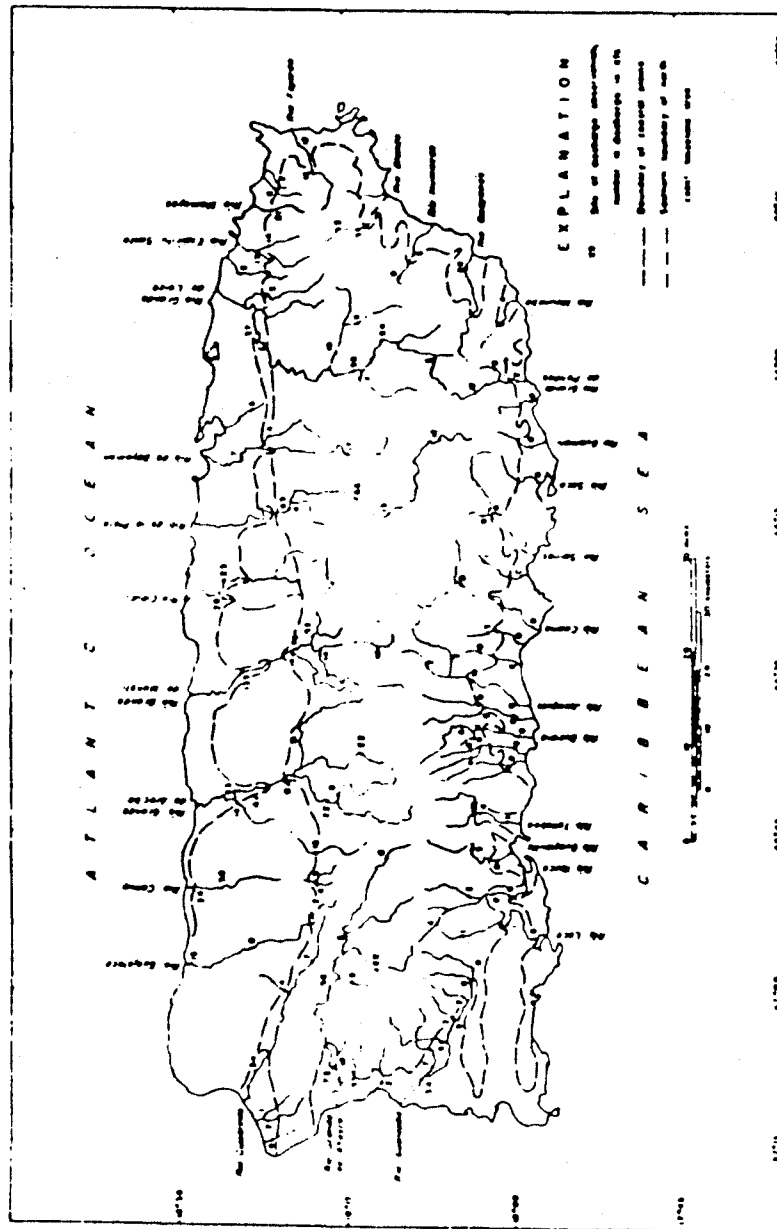


Figure 10. Periods of zero discharge for the south coast. (Bogart, 1964).

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delivered to the southern end of San Juan Bay during the flood.

The importance of rare events in sediment discharge is illustrated by the analysis of three years of water quality data from station 115000 on the Rio Portugues near Ponce. The discharge for the three years is as follows:

<u>Hydrologic Year</u>	<u>Discharge of Suspended Sediments</u>
1978-79	225,699 toneladas
1979-80	38,655
1980-81	79,056
TOTAL	343,410

An analysis of suspended sediments reveals that on August 31, 1979, 95,900 tons of sediments were discharged from Rio Portugues due to the torrential rains of Hurricane David (DNR, undated). This quantity exceeded the total annual discharge of sediments for the two years. As illustrated in Table 2, the discharge of sediments on that day represented 27% of the total discharged for the three years. Eleven days of high discharges account for 65% of the total discharge for three years.

When torrential rains occur, many environmental conditions come into play. Rain swollen rivers overflow their banks depositing sands, silts, and clays on the surrounding land. Sediment-laden waters dump the majority of their load in the sheltered estuaries. Any sandbars

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blocking the mouths of the rivers are broken down and washed away by the river. Plumes of fine material belch out of river mouths settling slowly upon the benthic communities on the insular shelf.

Table 2. Percentage of sediments discharged during extreme events.

Days		Percent of total
		sediment discharge
Number	Percent	
1	0.1	27
5	0.5	51
11	1.0	65
22	2.0	79

Data from 10/1/79 to 9/30/81

Weathering is also directly related to the amount of rainfall. Physical and chemical weathering processes introduce substances and grains in suspension into the water where they begin their journey towards the sea.

Weathering refers to the chemical and mechanical breakdown of solid rock into smaller components. In humid, tropical climates such as Puerto Rico's, the vast majority of weathering is due to chemical processes. Mechanical weathering results when rocks are impacted, abraded, or fracture due to internal stresses. Chemical weathering

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occurs as rocks which formed at high temperatures or pressures degrade into constituents which are more at equilibrium with the conditions present at the surface of the earth. Soils develop as horizons or layers within weathered material.

Clays derived from the northern provinces are more weathered than those from the southern province. The northern clays have a high percentage of 7 angstrom minerals in comparison to the higher percentage of geologically immature 14 angstrom clays found in the southern sediments (Breyer and Ehrlmann, 1981).

3.2.2 Geomorphology

Puerto Rico is readily divided into three broad geologic provinces: volcanic-plutonic; Tertiary marine deposits; and unconsolidated surficial sediments (Fig. #). The largest of these, the mountainous volcanic-plutonic province, dates back to the formation of the island in the late Jurassic or early Cretaceous (Cox and Briggs, 1973). Arching of the island in the Oligocene (45,000,000 years ago) was followed by deposition of marine deposits on the northern and southern flanks. Further tectonic activity in the Miocene lifted and dessicated these limestones that form the familiar northern and southern karst regions.

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Unconsolidated surficial deposits cover more than 15% of the area of Puerto Rico. The insular shelf is a combination of these groups, commonly an irregular Pleistocene erosional surface covered by varying thicknesses of recent and relict sediments.

The USDA Soil Conservation Service (1968) estimated that erosion problems of severe and moderate degree exist in 48% and 22%, respectively, of the total area of the island (Lugo et al., 1980). Their analysis reflects the high slopes found over much of the island. Approximately 20% of the total area of the Cordillera Central has slopes from 0-5% (5% = 5V:100H), in 10% of the area from 6-15%, 40% of the area from 16-59%, and the remaining 30% has slopes greater than 50% (Lugo et al., 1980).

The Cordillera Central makes up the backbone of Puerto Rico. To the northeast, the Sierra de Luquillo encloses El Yunque and the Caribbean National Rain Forest. The Sierra de Cayey forms the mountains in the southeastern corner of the island.

Though limestone occurs on both coasts, the North Coast province is the only one which is extensive enough to influence hydrologic and geologic processes. Monroe (1980a) presents the current state of knowledge on the geology of the Middle Tertiary.

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The coastal plains are nearly flat areas that slope very gently upward from the shore to the foothills. At most places, the relief is very low, but projecting out of the plain at places are isolated hills of volcanic, intrusive, or sedimentary bedrock material. The coastal plains grade into alluvial plains of the larger rivers. In the interfluvial areas, the plains reach altitudes of less than 10m in northern Puerto Rico (Monroe, 1980b). In southern Puerto Rico, the plains consist of a wide belt of coalescing alluvial fans that rise to 25m or slightly more east of Ponce.

Large scale estuarine systems, such as Chesapeake Bay, are absent in Puerto Rico. Instead, the mixing of fresh water with sea water takes place in very localized areas, such as coastal lagoons or sheltered embayments lined with mangroves. Natural and man-made salt flats and marshes also exist at various sites along the coast. These biologically rich areas are a crucial link in the islands ecosystem. They are vulnerable to perturbations in the levels of sedimentation and water quality.

Any particular problem with sedimentation in Puerto Rico will fall into one of three broad physical environments: uplands; coastal plains; or insular shelf. The coastal plains begin at the base of the upland foothills and extend seaward to encompass the shoreline. The lower

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limit of the intertidal zone divides the drainage basins (uplands and coastal plains) and the insular shelf. The insular shelf includes the subtidal area from the shore out to the shelf break. The scope of this report is limited to these areas, though problems with sedimentation may occur in the depths beyond the shelf break during trans-oceanic cable laying, OTEC plant operations, or as a result of spoil dumping.

A drainage basin is simply an area where all the water drains, or flows, towards a common destination. This destination may be general, such as the Atlantic Ocean, or it may be quite specific, referring to all waters flowing into a particular river. Along these lines, we commonly label a drainage basin by the name of the major river which empties into the ocean, such as the Rio de Loiza Basin, or the Rio de La Plata Basin.

3.2.3 Land Use

Coral reefs have been silent witnesses of man's activities on the Island. Similar to the Tainos, the corals have suffered from the presence of a civilization far out of tune with nature. Soil lost due to ill-planned land usage from colonial days through present has been the principal human-related stress on coral reefs. The impact of civilization on corals is hard to quantify for a number of

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reasons. The principal reason is the long time period between cause and effect; on the order of a hundred years or even millenia (Meade, 1980 in Martin et al., 1980).

Denudation of upland terrain for agricultural purposes increases the quantity of sediments washed into the rivers. The erosion, however, occurs in pulses, during rainy periods. As conditions return to normal, the sediments settle out in stream beds or in small lakes. Several years may pass before the eroded sediments are finally recorded at a suspended sediment station downstream. The bed load transport, that fraction which is dragged along the bottom by the currents, is even more difficult to measure than the sediments in suspension.

With these difficulties in mind, the following sections document historical land uses in light of the sediments generated and factors affecting their transport to the oceans.

In its pristine condition at the time of discovery in 1493, Puerto Rico was mostly forested (Bogart et al., 1964). Areas of savanna and marsh existed, but their extent was relatively small. The forest cover ranged from dense rain forest to arid-land scrub, with jungle-type growth predominating. The agrarian society of the Tainos were practiced in horticulture, or subsistence farming.

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The structure of vegetation retards erosion and sediment transport. The canopy formed by the upper branches and leaves and the debris covering the ground intercepts the rain. In addition, vegetation slows the erosion process by reducing the area of exposed soil impacted by rain drops (Ellison, 1948 in Lugo et al., 1980). Forests also increase infiltration and percolation of the rain and reduce runoff.

During the 19th century, almost all of the trees with economic potential were removed from the fertile lands to be used for wood and charcoal and to make room for agriculture (Lugo et al., 1980). By 1978 forests covered only 34% of the land (DNR Scientific Inventory, unpublished data).

The spaniards were originally interested only in gold. After discovering that the fertile grounds were ideal for growing sugar cane, agriculture became the economic base for Puerto Rico as it did in adjacent islands. Agriculture peaked during the first quarter of this century, at which time crops covered over three-quarters of the land.

On the average, erosion is more intense by a factor of 4 to 5 in the croplands and areas under construction than under pastures and forests (Molinelli, 1982).

During industrialization and colonization by the north americans the once extensive croplands lapsed into pastures.

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Table 3 documents the lapse of cultivated land into pasture and the concurrent increase in urban development.

Table 3. Use of land in Puerto Rico in 1958 and 1967.

<u>Use</u>	1958	1967
	<u>Percent of total</u>	<u>Percent of total</u>
Urban	4.4	5.2
Farming	35.7	29.8
Pastures	31.2	38.5
Forests	21.2	17.5
Federal land	4.4	4.4
Other uses	3.1	4.6

(Modified from Lugo et al., 1980)

Presently, rill and sheetwash erosion are at an all-time low (Molinelli, 1982). Strategies should be aimed at preventing a change in the present trend of declining erosion.

With the introduction of mechanized dredging at the beginning of the century, port development was no longer limited to construction above the water line. Shallow sheltered areas could be deepened to accomodate deep draft vessels.

Wadsworth (1968) estimated that dredging and construction in the coastal zones have caused a reduction of

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approximately 75% of the mangroves of the island and the complete elimination of 13 of the 62 estuarine zones.

Wetlands trap large amounts of sediments before they reach the sea. The expansion of agriculture between 1890 and 1920 contributed to the drainage and destruction of the wetlands (Lugo et al., 1980).

Mining and construction are local point sources of sediments. Though they locally create exceptionally high amounts of sediments, their total contribution to the sediment discharge is minimal. Mining activities generate large amounts of sediments as the tailings are washed by rainwater. Control measures recommended by Pool and Lugo (1974) for mining and construction are listed in section 5.0.

Since the 1940's water development projects have increased in size and scope. Reservoirs were constructed to produce hydroelectric power and serve as a source of water for urban, agricultural and industrial use. These large-scale projects bring with them large-scale problems. The problems include sedimentation, flooding, water quality, and long term changes in downstream sediment mass balances.

Sedimentation in the recently constructed reservoirs and ensuing loss of storage capacity is one of the greatest

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problems facing water managers in Puerto Rico. Deltas form as sediment charged rivers dump their load in the calm waters of a reservoir. The Comerio Dam on the La Plata river could hold over 6,000,000 m³ of water when it was constructed in 1913. By 1951 sediments had reduced the storage capacity to only 740,000 m³ (Lugo et al., 1980).

Molinelli (1982) analyzed the sediment yields of the Rio de La Plata and The Rio Grande de Loiza watersheds. He found that the Loiza Lake watershed with an estimated total erosion of 1,289,409 tons per year, delivers approximately 450,207 tons per year to Loiza Lake. In La Plata Lake watershed the total erosion is estimated to be 1,480,216 tons per year. In both watersheds, soil erosion in pastures is the most important source of lake sediment followed by forest, croplands and areas under construction. Natural erosion accounts for 85% of the total sediment yield while erosion caused by man accounts for the remaining 15%.

Dredging the sediments deposited in the reservoirs would devastate the ecology of the lake and downstream areas. Agitated anaerobic estuarine sediments can consume over 100,000 mg/l of oxygen per hour (EPA, 1970). Reduced, foul smelling organic matter would cloud the waters. Coral communities in the path of the river discharge would suffer from increased turbidity from fines, humus, and a possible plankton bloom set off by the nutrient influx. Strategies

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involving natural scouring by oxygen-rich flood waters or artificial aeration of bottom sediments should be developed. Future accumulation may be reduced by trapping the fines at the head of the reservoir, revised land management, or by opening the gates during the first stages of floods when discharges are low and suspended sediment levels high.

The port of Arecibo has gone through particularly noticeable changes due to human intervention. In 1942, the Rio Grande of Arecibo was dammed and a breakwater was constructed. Dredging from 1944 through 1975 combined with the earlier events resulted in higher turbidity in the bay and reorientation of the shoreline (Delgado, 1979). The eastern section of the bay supposedly accreted while the central and western sections experienced erosion. Morelock (1984) points out that the eastern section was filled, suggesting that the accretion measured by Delgado was not natural.

Dredged material from ports bordered by industries, like San Juan Bay, often contain potentially toxic metals, organics, and nutrients. Metals like manganese, mercury, lead, cadmium, nickel, iron, and zinc are dangerous in their natural and reduced forms. The toxicity of chlorinated hydrocarbon pesticides, PCBs and chlorine is well documented. Seawater is usually alkaline. Continuous discharge of dredged sediments releasing large quantities of

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ammonia ion ($\text{NH}_4\text{-N}$) may be hazardous to marine life if alkaline pH conditions exist at the disposal site where nontoxic $\text{NH}_4\text{-N}$ can be converted to very toxic ammonia ($\text{NH}_3\text{-N}$) (Brannon, 1978). Contingency plans should be developed to dispose of dredged materials found high in toxins.

Sanitary and industrial wastewater treatment facilities on the island are, with few exceptions, inadequate (DPW, 1974). Approximately 13 million gallons per day (15.8% of the total sewage generated) is discharged into the ocean without any treatment. Raw sewage discharge occurs at Arroyo, Guayama, Ponce, Mayaguez, and Aguadilla and two other sites (idem).

In coming years, toxins adsorbed to the sediments will become a significant factor to consider when calculating sediment stress on coral communities. The toxins that industry has been dumping upland and in the bays during the last 50 years are gradually being shifted towards the insular shelf. Toxins damage corals more than normal clays and silts.

3.3 Marine Systems

The insular shelf of Puerto Rico sustains productive and diverse biological communities. These produce large

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quantities of fines that can be resuspended by waves and stress the coral polyps. The narrow, steep, high energy northern shelf is the only shelf without these extensive fine producing carbonate factories.

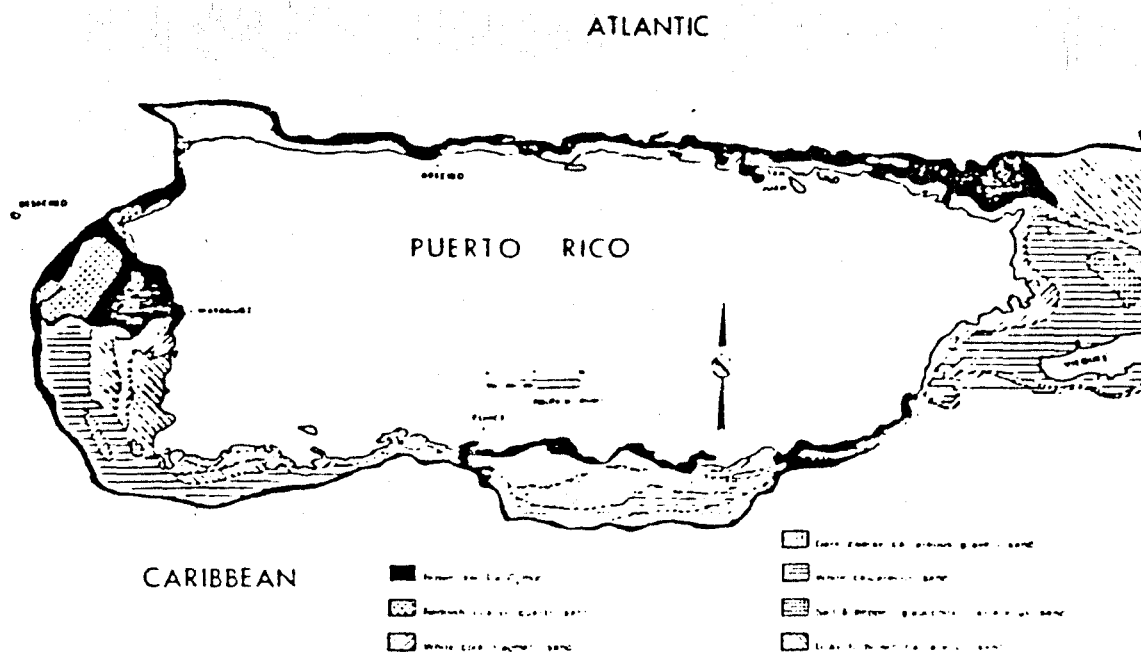
The south coast has two attributes which favor coral reef development. First, the southern drainage basin is limited and steep. The coarse sediments in the rivers and on the flood plains move less frequently than north coast sediments. Once in the marine environment, hydrodynamics limit the distribution of the sediment to the nearshore zone; on the northern shelf the fines are evenly distributed across the shelf. Second, the southern insular shelf is much wider than the northern shelf. Long period, high amplitude waves are damped by the shallow bottom resulting in less resuspension of bottom sediments in the mid and inner-shelf regions.

3.3.1 Bottom Sediments

By comparing the map of surficial sediments on the insular shelf of Puerto Rico (Figure 11)(Schneidermann et al, 1976) with Plate 1, the correlation between stressed areas and the presence of fine sediments is immediately apparent. Fines are transient sediments which quickly become resuspended when the energy of the system increases

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Figure 11 Sediment types on the Puerto Rico insular shelf (Schneidermann et al, 1976).



Major Sediment Types	Subdivisions	Where Found	General Description
BROWN, LOW CaCO ₃ MUD	Carbonaceous, silty mud	Mangrove-lined bays	<i>Halimeda</i> —Pelecypod fragment sand fraction; 60% to 80% CaCO ₃ .
	Backreef silty mud	Backreef lagoons	Heavily bored molluscan fragments, coral and <i>Halimeda</i> sand fraction; silt fraction largely skeletal debris.
	Terrigenous silty and sandy mud	On shelf off river	Quartz, foraminifera and mollusc fragment sand fraction; some relict components.
	Pelagic muds	Upper insular slope	Foraminifera, pteropods and siliceous sponge spicules and fraction; typically 75% CaCO ₃ ; abundant clay-sized coccoliths.
REDDISH COARSE QUARTZ SAND		Mayaguez Bay and NW shelf	Yellow to reddish brown quartz sand; possibly relict beach sediment.
WHITE CORAL FRAGMENT SAND	Coral <i>Halimeda</i> sand	Reef vicinity	Coral and <i>Halimeda</i> plus mollusc, coralline algae fragments and echinoderm fragments
	<i>Halimeda</i> sand	Reef flat and nearshore area	Similar to above subdivision but coral fragments are minor.
DARK COARSE GRAVELLY, CALCAREOUS SAND	Sandy gravel	Vicinity of submerged reefs	Coarse fragments of coral, molluscs, coralline algae and <i>Halimeda</i> ; poorly sorted; very "old" appearance.
	Gray gravelly sand	Portions of middle and outer North shelf	Abundant lithoclasts, mollusc fragments, agglutinated foraminifera and bryozoa; particles often abraded.
WHITE, CALCAREOUS SAND		Large areas of middle shelf	Well sorted fine sand with benthonic foraminifera, mollusc and algal fragments
		Mainly SW shelf	Iron oxide stained, glauconitized and pitted shells and tests; relict sediment.
SALT AND PEPPER SAND			
GRAY TO BROWN CALCAREOUS SAND	Coarse brown skeletal sand	Middle and outer shelf	Well sorted sand with polished or rounded fragments; may have algal balls; largely relict.
	Coralline algae sand	Pockets on rock bottoms	Algae coral fragments and lithoclasts.

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and then settle out once the energy decreases. The most extensive fine containing areas are located near the river mouths. These are predominantly terrigenous grains deposited on the shelf after periods of high rainfall. In areas removed from the influence of river sediments, lime muds and other fine carbonate particles may dominate.

3.3.2 Hydrodynamics

Hydrodynamics play a determining role in coral reef development. Currents and waves disperse planulae, bring in food, carry away wastes, and clear surfaces of sediment. Conversely, currents can also bring in sediments. Storm swells can rip up coral polyps, turn over coral heads, and resuspend sediments in local areas. If the energy is too high, corals will not be able to attach themselves even if favorable substrate exists.

Variations in sea bottom morphology, wind, waves and tidal fluctuations are the predominant factors that influence type, velocity, and direction of currents. Currents are capable of carrying suspended sediments many miles. The Rio Grande de Loiza is the easternmost river on the northern coast to discharge significant amounts of sediments into the ocean. The area is under the influence of west flowing equatorial current though easterly currents

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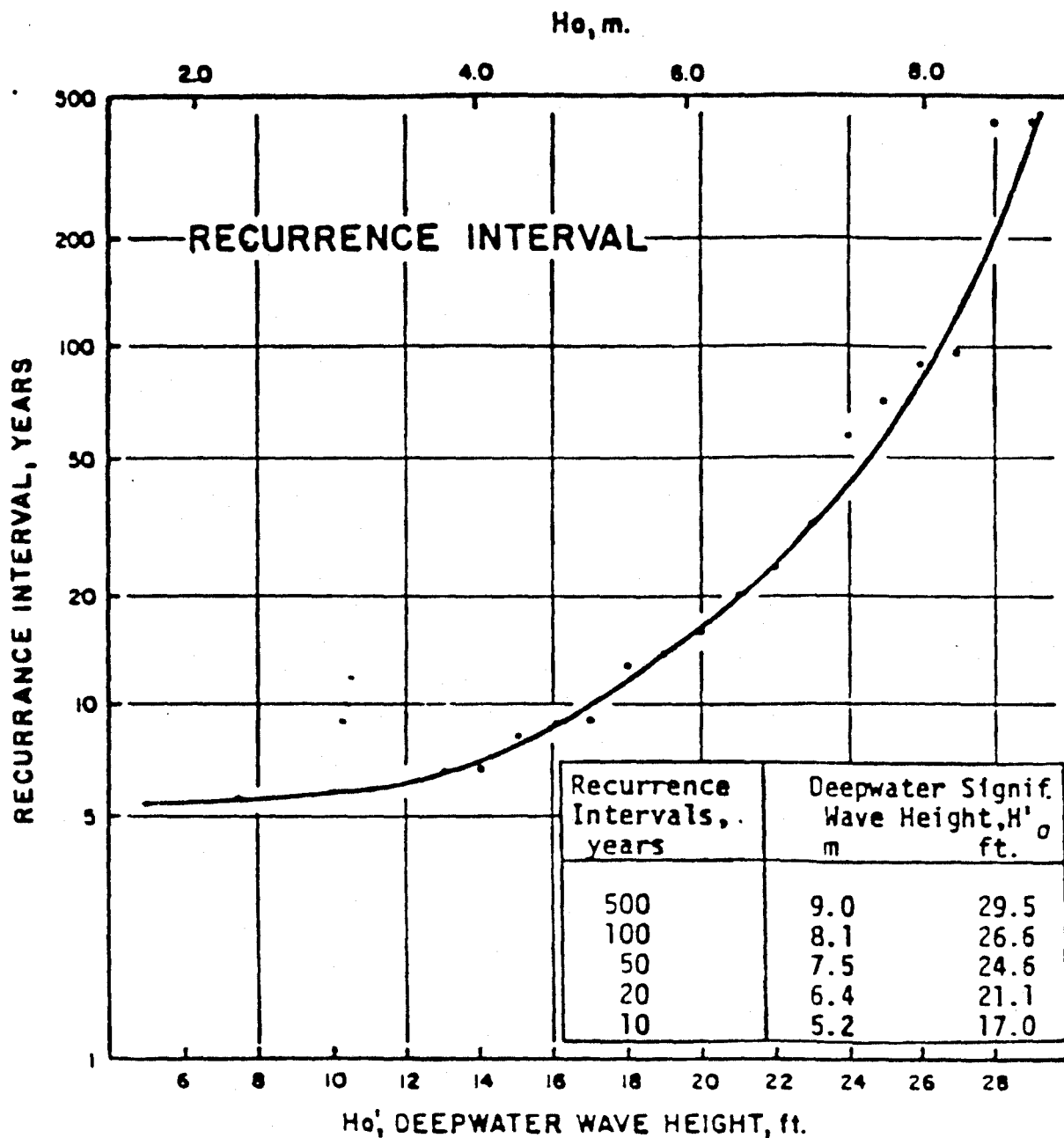
are not uncommon during flood stage. Extensive coral communities on the northern shelf only exist east of this river.

Colonization of the bottom by algae or seagrass can stabilize the bottom. A dense cover of Thalassia blades completely protects the bottom from tidal currents of up to 70 cm/sec. Extensive removal of seagrass begins at 150 cm/s in dense seagrass (Wanless, 1981). Seagrass blades are not nearly as effective in preventing resuspension by wave action.

One meter high ocean swells with a period of 15 seconds will resuspend fine grained sand in water depths of 30 meters (Komar, 1976). An analysis of the wave conditions southwest of Cabo Rojo indicated that sediments in the nearshore zone are resuspended over 90% of the time (DNR, 1984). Chronically suspended sediments inhibit coral development more than infrequent wave disruption. Figure 12 presents the wave recurrence interval for storm waves along the north coast (Nichols and Cerco, 1983). During these periods the entire shelf is turbid with suspended sediments as the wave break at the shelf edge.

Currents and waves combine with bathymetry to determine the transport paths of the sediments. Waves arriving at an angle to the coast set up longshore currents that are the

Figure 12 Recurrence interval curves for maximum deep water significant wave height (H_a') on the north coast after modification for storm speed and direction. (Nichols and Cerco, 1983).



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dominant sediment movers in the nearshore zone. Hernandez-Avila (1976, 1977 as cited in DNR, 1980) reported that longshore currents measured in different segments of the coast range from 0 to a reported maximum of 10 cm/s, depending on wave parameters and characteristics. Longshore currents at Punta del Medio in Isla Verde recorded pulses of longshore currents exceeding 25 cm/s.

Pilkey et al. (1985) documented the transport paths of sediments of different textures and compositions. The muds discharged from Rio de La Plata move progressively offshore towards the insular slope. Coarser sands and heavy minerals, however, are dispersed laterally in the nearshore and mid-shelf regions. Pockets of recent sediments as thick as 40 m are found in canyon heads in the vicinity of major rivers (Fugro, 1974 as cited in DNR, 1980).

The tidal range for the coastal waters of Puerto Rico is comparatively slight. The mean tidal range, as measured by the CGS (US Department of Commerce, 1975), is 0.34 m at Bahia de Fajardo, 0.18 m at Ponce, and 0.25 m at Puerto Real.

The tides are normally semidiurnal (two tidal cycles daily) except on the south coast where, according to US Hydrographic Office (ob. cit.), the tides are more or less diurnal (one tidal cycle daily).

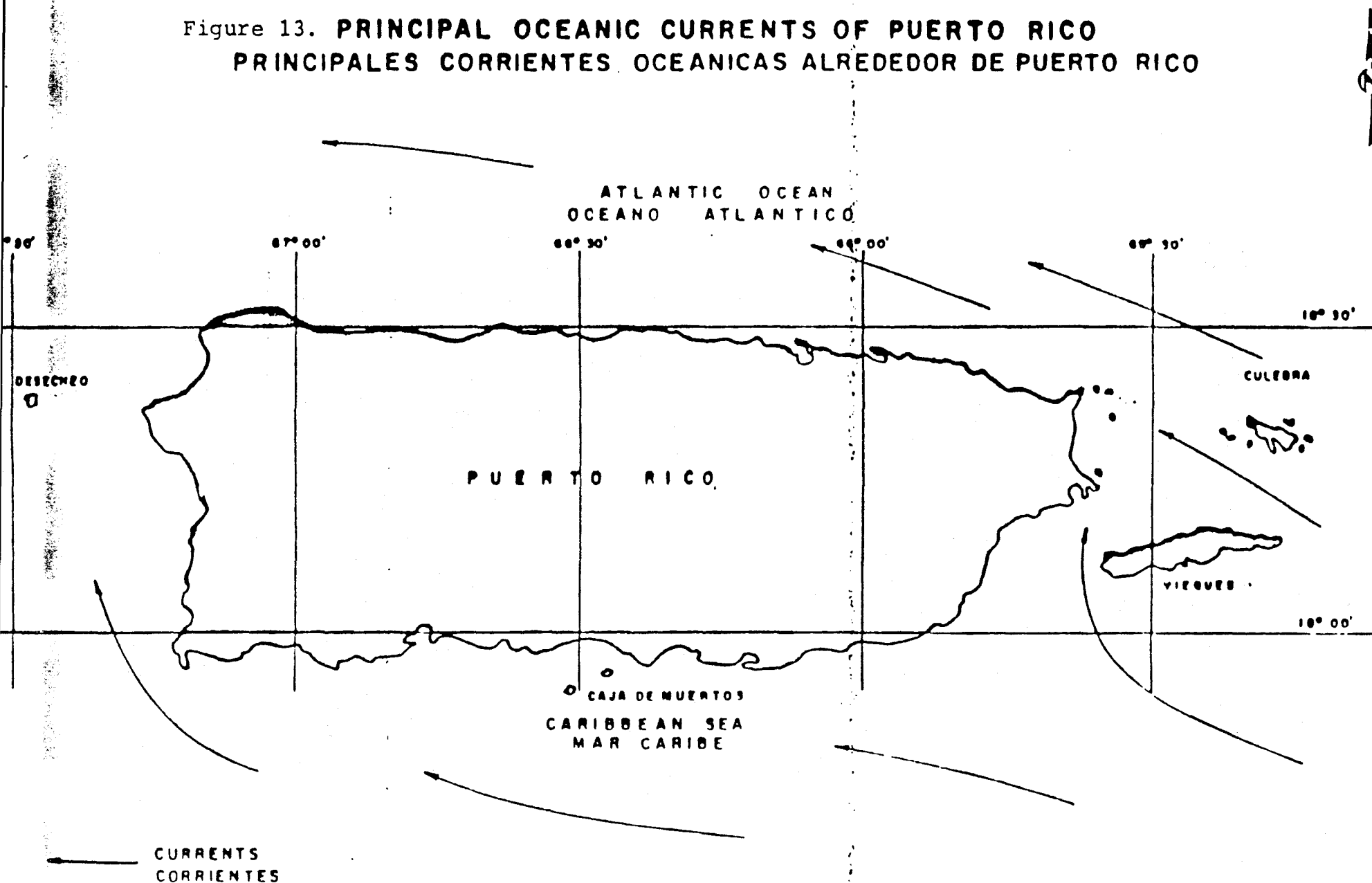
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The major offshore currents around Puerto Rico are presented in Figure 13. Currents measured nearshore can change from one day to the next depending on the wave regime. Offshore currents fluctuate daily with flood and ebb tides. Seasonal fluctuations result as wind patterns out of the east to northeast during the summer shift to east-southeasterly during the winter. Quasi-stable gyres have been measured off the northeast and western coasts (DNR, 1980).

High ocean swells generated in storms thousands of miles to the north lose little energy travelling through deep water on their way to Puerto Rico. Figure 14 shows the location of the storm of October, 1982 that sent storm swells crashing against the coast for three days. The waters off the north coast were thick with resuspended sediments all the way out to the shelf edge.

The monthly averages of wave heights vary with the wind intensities throughout the year. July, the month having the highest average winds, 13.2 knots, also has the highest average wave height, 5 feet (NOAA, 1974). The maximum frequency of wave heights equal to or above the average occurs in mid-winter (50.8%) and mid-summer (55.3%), with the primary minimum occurring in late summer and early fall (30-34%). Table 4 presents observed frequencies of wave heights and periods for Mona Passage.

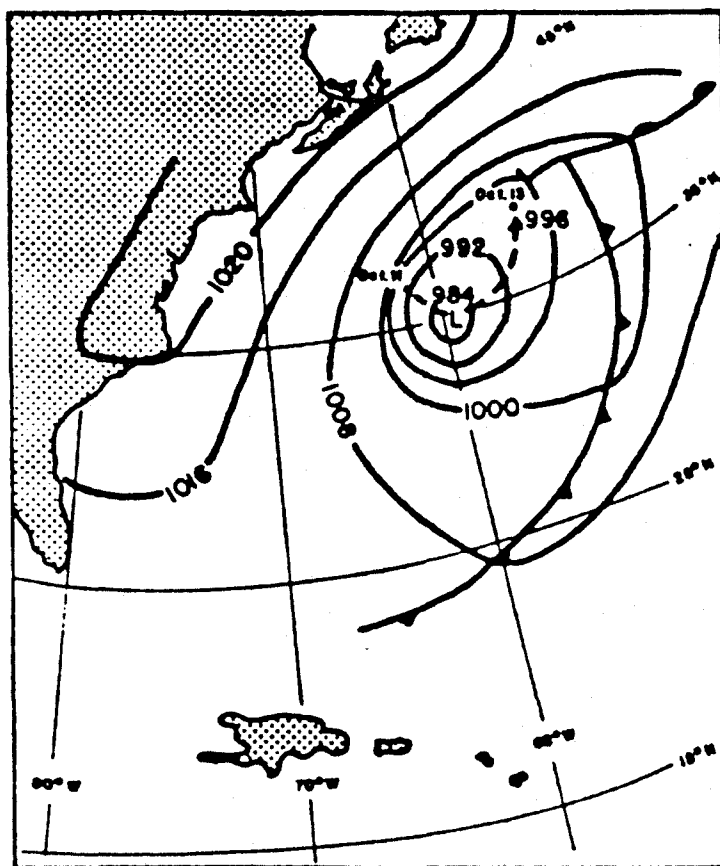
Figure 13. **PRINCIPAL OCEANIC CURRENTS OF PUERTO RICO**
PRINCIPALES CORRIENTES OCEANICAS ALREDEDOR DE PUERTO RICO



SOURCE
 FUENTE
 KAYE, 1959b

FIGURE
 FIGURA

Figure 14 Weather map of the Atlantic Ocean, October 12, 1982 (Nichols and Cerco, 1983).



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Table 4. Observed Frequencies of Wave Heights vs Period for
Mona Passage (1949-1970)

Period (sec)	Wave Height (Feet)								
	<1	1-2	3-4	5-6	7	8-9	10-11	12	13-16
<6	2.6	14.6	21.7	9.2	2.3	0.6	0.2	*	*
6-7	0.1	1.4	7.8	11.1	4.5	1.5	0.5	0.1	0.1
8-9	*	0.4	1.4	2.6	2.8	1.0	0.4	0.2	0.1
10-11	0.0	0.3	0.4	0.5	0.6	0.5	0.2	0.1	*
12-13	0.0	0.0	0.3	0.2	0.1	0.1	0.1	0.1	*
>13	0.0	0.0	0.0	0.2	0.1	0.1	*	*	*
indet	2.4	1.8	2.0	1.3	0.7	0.2	0.1	*	*
TOTAL									
PCT.	5.1	18.6	33.7	25.1	11.1	4.0	1.5	0.5	0.3

(Modified from DPW, 1974)

Internal waves have the potential to wipe out vast areas of coral reefs. The damage is done by drastic temperature changes, not physical disruption or sediment loads. These waves have their greatest amplitude at the thermocline and have only several centimeters of relief in the surface. Internal waves measured off the southern coast had an amplitude of 30 m and a semidiurnal period (Fornshell, personal communication, 1983). When syzygy occurred in 1982 internal waves with periods of 20 minutes were measured.

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3.3.3 Bathymetry

Puerto Rico lies on a submarine platform which includes Culebra, Vieques, and the Virgin Islands to the east. The 100 meter contour line (see Plate 1) roughly delineates the extent of the insular shelf. The shelf break north of the island occurs in approximately 100 meters of water; to the south the break is found in waters as shallow as 20 meters. The western coast is a mix of the two possessing some of the narrowest and widest sections of the insular shelf.

The present shelf bathymetry, geomorphic features and sediments on the coast and shelf have been controlled to some extent by sea level fluctuations associated with glaciation in Pleistocene time. These fluctuations continue today.

Maximum sea level lowering occurred approximately 15,000 years ago when the sea level was over 100 meters below its present level (DNR, 1978). Kaye (1959) suggests that sea level has been static for the last 5,000 years. Carbon-14 dating of a peat sample from a raised (2 m) terrace suggests that a pulse of emergence may have interrupted a rather steady Holocene transgression (Seiders et al., 1972). Sediment accumulation rates have slowed from 3.9 mm/year to 2 mm/year in the last 4000 years (Macintyre, 1983). Tide gages in Florida and the Bahamas suggest that

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in the last 50 years sea level has been rising at 2 mm/y (Wanless, 1982).

Geomorphic features on the shelf include discontinuous terraces, rocky outcrops and patchy reef distribution. Narrow linear reefs along portions of the north shore are fossil sand dunes that formed during lower sea level. North of Isla Verde and in other areas these ridges are exposed as small rocky islets.

Many coral reefs, particularly off the southern coast, at the shelf edge have failed to keep up with the sea level rise. The limited light available at depths greater than 15 meters limits the development of stony corals. Most of these submerged reefs have only a few living corals present which are mainly scattered colonies of encrusting or massive species that are contributing little to the present structure (Macintyre, 1971).

3.3.4 In-situ Production

Sediments that form as solids in the depositional basin include (1) skeletal debris, (2) nonskeletal calcium carbonate materials, (3) evaporite materials that were physically transported, and (4) glauconites.

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Many one-celled foraminifers keep making tests throughout their lives. The discarded tests become significant constituents of many marine sediments. Forams are good indicators of environment; some preferring seagrass beds, while others prefer reef communities.

The silt and clay-size components of carbonate sediments are collectively designated as lime mud. Most lime mud consists of tiny needles and platelets of carbonate crystals too small to resolve by binocular or petrographic microscopes.

Perhaps the greatest producer of lime mud are algae. Green algae, especially the algae Penicillus sp., produce fine crystals of aragonite ($<15\mu\text{m}$) within the sheaths of their filaments. The present rate of production of aragonite needles by Penicillus sp. alone can account for all the mud on the inner Florida reef tract and one-third of the mud on northeastern Florida Bay (Friedman and Sanders, 1978).

Water Quality

Sediments in the water column are measured as suspended sediments (mg/l), turbidity (Nephelometric Turbidity Units), secchi depth (m), light extinction (k_e), or accumulation rates ($\text{gm}/\text{cm}^2/\text{day}$). The magnitudes and frequencies of

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stress are deduced from information presented in previous sections.

During 1983 and 1984 the Environmental Quality Board measured the turbidity (NTU) of seawater sampled from 57 nearshore sites around the island. Table 5 presents the minimum, maximum and modified means of the data. The bimonthly sampling mainly reflected resuspension in the nearshore zone though flooding resulted in the greatest levels of turbidity. Flood waters may show an inverse relationship as the turbid fresh water floats out on top of the denser salt water.

Turbidity values for all stations were higher in 1983 than in 1984 (Table 5). In 1983 the lowest value measured was .35 NTU (Isabela, September); the highest, 650 NTU (west of Rio Grande de Manati in Barceloneta, May). In 1984 the lowest value was .04 NTU (Luquillo, September); the highest, 190 NTU (west of Rio Fajardo, November). The most persistent turbidity occurs where waves are washing out fines deposited in the past. Highest instantaneous turbidities are measured during flood discharges. The clearest waters were from open unsheltered shorelines where the high energy resulted in low residence times for fine suspended sediments. No seasonal trends are immediately apparent. The sampling frequency, bimonthly, is much

Table 5. Turbidity data, 1983 and 1984

Turbidity Data Collected by the Environmental Quality Board during 1983 and 1984.

(Statistics calculated from bimonthly sampling. Minimum and maximum values discarded to calculate mean)

Lat/Long	Description	-----1983-----				-----1984-----			
		Minimum	Maximum	Mean(±1NTU)		Minimum	Maximum	Mean(±1NTU)	
=====									
SOUTH COAST									
17.59.35/65.53.39	Maunabo E. Rio Maunabo	1	10	4.2	****	.22	6.4	2.3	**
17.57.50/66.02.20	Arroyo-Punta Guilarte	1	9.6	3.8	****	.15	8	2	**
17.56.03/66.09.04	Guayama E. Punta Ola	1.5	16	3.2	***	.4	4.9	1.1	*
17.56.21/66.09.29	Guayama-Phillips Petrol.	.63	6	2.4	**	.15	1.6	1	*
17.57.12/66.11.03	Guayama Jobos Bay	1.5	6.2	3.8	****	.12	13	3	***
17.57.07/66.13.20	Salinas Jobos Bay	.8	6.3	1.8	**	.3	4.5	1.9	**
17.57.23/66.24.29	Sta. Isabel-End road #63	3.5	15	7.3	*****	.1	7.5	1.5	**
17.58.21/66.37.05	Ponce-Ponce Pier	.61	4.5	1.7	**	.1	1.3	.6	*
17.59.00/66.37.34	Ponce-W. Rio Portugues	1.9	6.3	3.9	****	.13	5.5	.6	*
17.58.22/66.40.38	Ponce-El Tuque	5.7	350	22.2	*****	.08	19	1.4	*
17.59.33/66.44.00	Penuelas-Tallaboa Bay 1	2.9	15	6.5	*****	.1	10	.6	*
17.59.26/66.44.57	Penuelas-Tallaboa Bay 2	4.6	13	7.4	*****	.08	8	1.3	*
17.59.49/66.45.29	Guayanilla-Guay. Bay 1	2.1	6.7	3.3	***	.14	1.6	.5	*
18.00.27/66.46.06	Guayanilla-Guay. Bay 2	1.7	10	3.6	****	.1	1.3	.4	*
17.59.57/66.47.03	Guayanilla-Guay. Bay 3	2.4	12	6.1	*****	.2	27	.7	*
17.58.00/66.48.34	Guayanilla-Punta Ventana	.97	4.1	2.5	***	.1	4.6	1	*
17.57.16/66.52.56	Guanica Cuna Gorda beach	3.2	5.5	4.7	*****	.06	12	.9	*
17.57.59/66.54.31	Guanica-Guanica Bay	1.5	5.7	4.3	****	.3	4.5	.9	*
17.58.30/67.03.02	Lajas-La Parguera	1.3	2.5	2.1	**	.13	3	1	*
WEST COAST									
18.00.58/67.10.24	Cabo Rojo-Boqueron Bay	1.6	6.4	4.3	****	.09	2.5	1	*
18.11.48/67.09.23	Mayaguez-Mayaguez Bay 1	12	24	14.4	*****	.2	17	4.1	****
18.13.14/67.09.47	Mayaguez-Mayaguez Bay 2	6.2	20	10.9	*****	.17	3.4	1.3	*
18.17.10/67.11.34	Anasco-Cabanus Anasco	5.5	24	10.9	*****	.6	9.2	3.6	****
18.25.10/67.09.30	Aguadilla-Aguadilla Bay	.55	3.5	1.3	*	.15	1.8	.6	*

Table 5. (Cont.)

Turbidity Data Collected by the Environmental Quality Board during 1983 and 1984.

(Statistics calculated from bimonthly sampling. Minimum and maximum values discarded to calculate mean)

		-----1983-----				-----1984-----			
Lat/Long	Description	Minimum	Maximum	Mean(±1NTU)		Minimum	Maximum	Mean(±1NTU)	
=====									
NORTH COAST									
18.30.48/67.01.23	Isabela-W.P. Sardinera	.35	8.5	2.4	**	.07	5.5	.4	*
18.29.29/66.57.33	Isabela-W.Rio Guajataca	.44	4.3	2	**	.07	1.3	.8	*
18.29.22/66.49.38	Hatillo-E. Rio Camuy	.5	12	2.3	**	.15	.75	.5	*
18.28.32/66.42.46	Arecibo-Arecibo port	1	15	3.9	****	.1	10	4.3	****
18.29.18/66.40.41	Arecibo-PtaCaracoles	.25	8	2.2	**	.05	3.4	.9	*
18.29.00/66.32.08	Barceloneta-W.RioG.Manati	1.5	650	3.6	****	.09	15	4.9	*****
18.29.29/63.23.36	Vega Baja-PN Pub Beach	.47	7	2.7	***	.11	3.3	1.6	**
18.29.02/66.20.29	Vega Alta-Cerro Gordo B.	.6	22	2.6	***	.13	2	.9	*
18.28.49/66.15.50	Dorado-West La Plata	.5	3.4	1.1	*	.12	7.2	1.5	**
18.28.24/66.11.12	Toa Baja-Punta Salinas	1.5	7	3.3	***	.11	20	3.9	****
18.27.42/66.10.04	Toa Baja-Boca Vieja	2.2	10	5.8	*****	.4	9	3.7	****
18.27.42/66.05.02	San Juan-Dos Hermanos	.73	7.5	3.2	***	.06	1.7	1	*
18.27.42/66.04.55	San Juan-Holiday Inn	1.1	7.5	2.1	**	.14	4	1.5	**
18.27.32/66.04.48	San Juan-Condado lagoon	.92	6.5	2.5	***	.15	1.7	.8	*
18.27.25/66.04.40	San Juan-Cond.boat pier	1.5	9.5	2.6	***	.09	3.3	1.5	**
18.27.37/66.04.25	San Juan-La Concha Hotel	1.3	9.7	2.9	***	.07	3.2	.9	*
18.27.33/66.04.14	San Juan-Dupont Plaza	1	8	3.1	***	.16	3.6	1.2	*
18.27.33/66.03.56	San Juan-Ashford Hosp.	2.4	8.7	3	***	.12	1.2	.7	*
18.27.25/66.03.40	San Juan-Ocean Park	2.6	10	4.1	****	.2	4.5	2.1	**
18.27.19/66.02.54	San Juan-Barbosa B. Res.	2	13	6.8	*****	.12	5.9	2.4	**
18.26.47/66.01.19	Carolina-San Juan Hotel	2.5	25	8.2	*****	.23	14	5.3	*****
18.26.57/66.00.05	Carolina-Isla Verde	3.7	16	7.9	*****	.12	12	2.1	**
18.26.30/65.52.45	Loiza-West R.Gran. Loiza	2	33	4.3	****	.26	16	3.4	***
18.24.48/65.48.24	Rio Grande-W.Espir.Santo	1.8	51	2.3	**	.1	52	6.2	*****
18.23.01/65.44.08	Luquillo-Luquillo beach	1	35	6.4	*****	.04	23	1.7	**
EAST COAST									
18.22.16/65.38.07	Fajardo-Las Croabas	.5	5	2.8	***	.05	14	3.6	****
18.19.53/65.37.39	Fajardo-W. Rio Fajardo	2	140	21.8	*****	.31	190	5.9	*****
18.11.20/65.43.37	Naguabo-Nag.Trop. Beach	2	31	8	*****	.36	11	3.5	****
18.11.18/65.42.42	Naguabo-Nag.Pub.Beach	1.7	25	6.2	*****	.2	37	8.1	*****
18.09.25/65.45.40	Humacao-Hum.Pub.Beach	1.6	22	3.4	***	.32	16	3.2	***
18.07.15/65.46.50	Humacao-E.Rio Humacao	3.5	48	7.1	*****	.42	10.1	5.7	*****
18.03.52/65.49.14	Yabucoa-Yabucoa port	1.5	33	5.7	*****	.17	4.8	2.1	**
18.03.03/65.49.54	Yabucoa-Guayanes Pub.Bch	.57	7.1	1.9	**	.13	4.9	1.4	*

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greater than the duration of significant turbidity creating events so further statistical treatment is not warranted.

4.0 Coral reef research in Puerto Rico related to sedimentation

Puerto Rico's northern shelf is narrow and steep, exposed to high energy waves. Most of the island's land area drains to the north. Coral reefs are absent from the western two thirds of the north coast of Puerto Rico (Kaye, 1959), whereas the southwest coast of the island is the richest area in corals (Almy and Carrion-Torres, 1963). Kaye explained this absence in terms of the heavy rainfall and high rate of river runoff, that resulted in increased erosion and sedimentation rates relative to the rest of the island.

Distinct hydrodynamic conditions exist on the four coasts of Puerto Rico. Fines discharged onto the northern shelf are dispersed and transported from the shore across the shelf to the shelf edge (Pilkey et al., 1978). Benthic communities are subjected to doses of sediment after periods of high river runoff. In contrast, currents and waves on the southern shelf drive discharged fines back against the coast. The deposition of the terrigenous fines in the

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nearshore zone enables the progradation of the extensive mangrove stands common along the coast. Offshore coral reefs on the southern shelf are affected more by turbidity and resuspension of biochemically generated fines rather than sediment doses as occurs on the northern shelf. Figure 15 shows how resuspension of bottom sediments can increase turbidity near the bottom.

Goenaga and Cintron (1979) completed an inventory of Puerto Rican coral reefs, where they described the condition of each of the reefs visited. They classified the reefs in two groups;

- 1) Reefs of very high quality:
 - a) la Cordillera, Fajardo;
 - b) Sargent reef, Maunabo;
 - c) all offshore reefs between Bahia de Jobos and Santa Isabel (including Berberia and Caja de Muertos);
 - d) Ratones, Ponce;
 - e) offshore reefs of La Parguera, Lajas;
 - f) Tourmaline and El Negro reef complex, Mayaguez
 - g) submerged barrier reefs at the edge of the southern and western insular shelf; and
- 2) reefs with extensive degradation:
 - a) all reefs from San Juan to Las Cabezas de San Juan;
 - b) inshore Fajardo reefs;
 - c) Humacao reefs;
 - d) annular reef off Puerto Yabucoa;
 - e) inshore Ponce reefs;
 - f) all reefs off Bahia Tallaboa and Bahia Guayanilla;
 - g) all reefs off and fringing Guanica;
 - h) all off Arecibo; and
 - i) all off Dorado

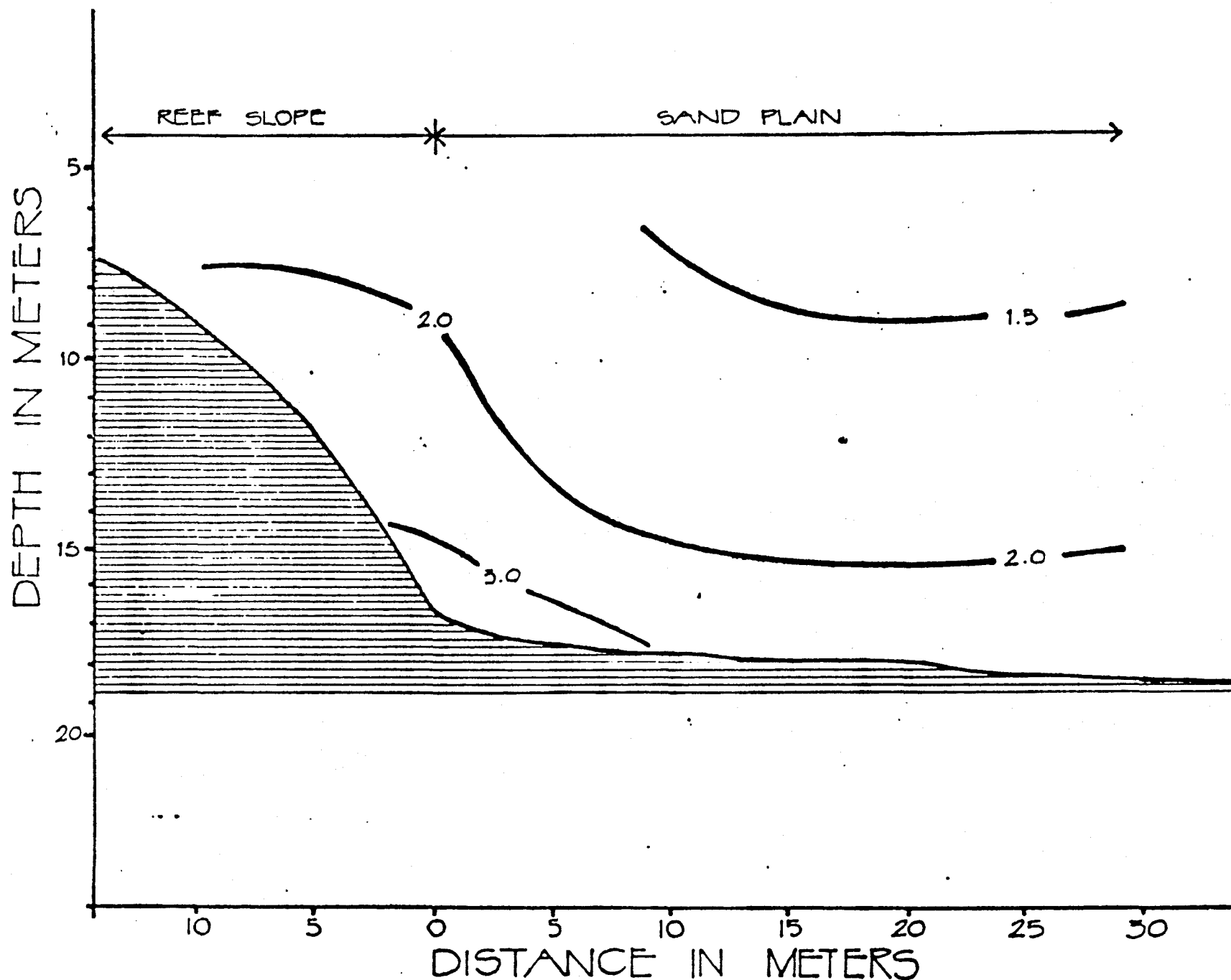


Figure 15. Turbidity profile at the reef face, turbidity expressed in formazin turbidity units.

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The following section presents geological, physical, chemical, biological and anthropogenic aspects that form or modify specific coral inhabited regions around Puerto Rico.

4.1 Specific Regions

North Shelf (Region 1 on Plate 1)

The north coast is subjected to the highest wave energies, the largest influx of river sediment and has few coral reefs. On other shelf areas, coral reefs and mangrove forests play an important role in the distribution of sediment (Schneidermann et al., 1976).

Reef development along the western two thirds of the north coast of the island is poor. Only several coral colonies grow in Arecibo and only patch reefs exist off Camuy and Puerto Tortuguero.

The inner shelf areas lying off the northern and eastern coasts experience the greatest stress from sedimentation. The EQB measurements show that flood waters can increase turbidity at least 200 times the background level. Chronic levels of suspended sediments and turbidity are measured in the arcuate embayments common on the

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northern and eastern coasts. As the sea transgresses, the waves resuspend the fines that make up the coastal plains.

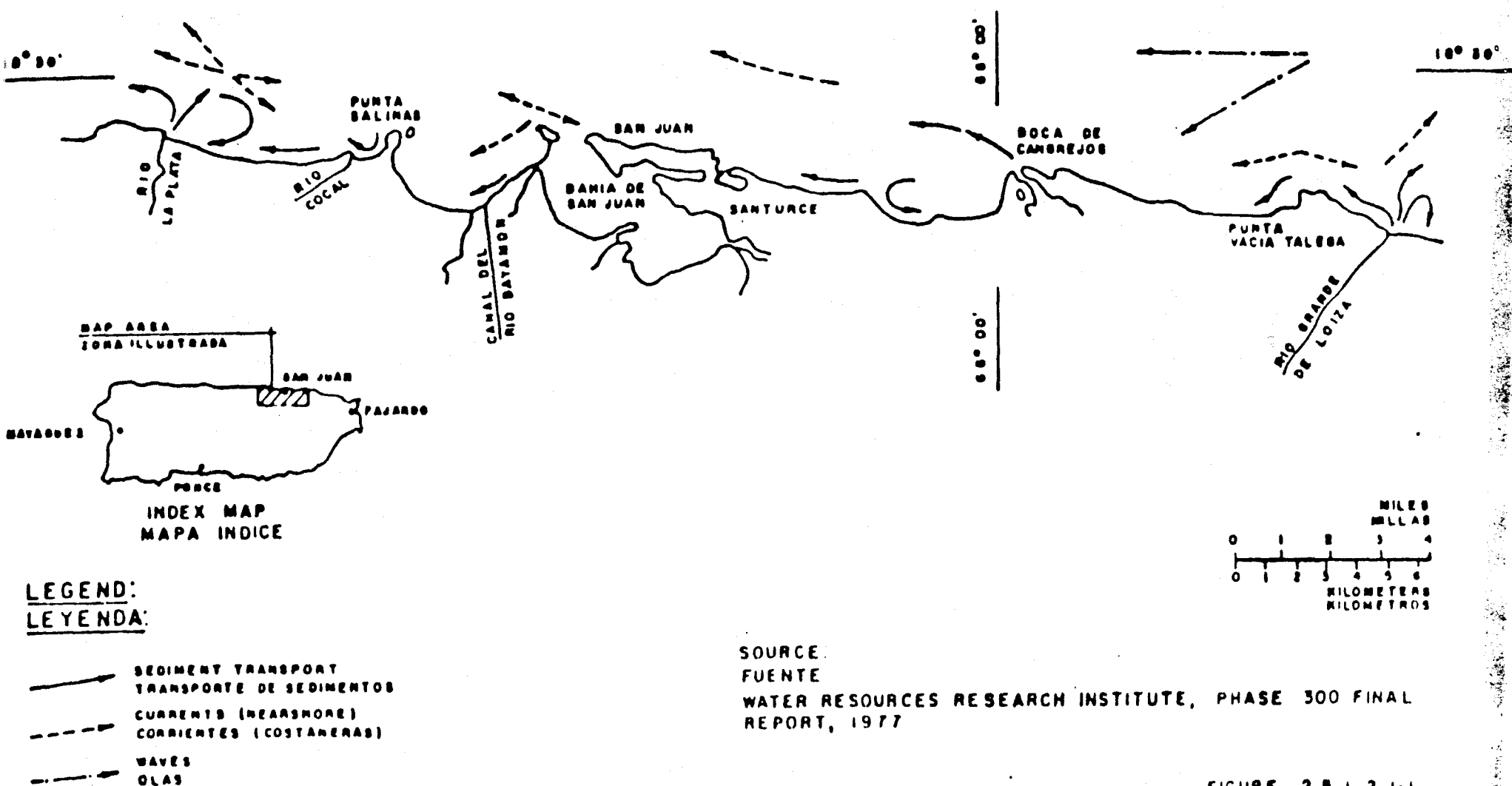
In dry times with gentle seas, north coast waters are clearer than those off any other coast. Local high levels of turbidity are recorded near the major river mouths and in the shallow embayments. The waters, however, quickly become turbid after periods of heavy rain. West of the Rio Grande de Manatí, 650 NTU was recorded after a minor flooding in May of 1983 (Table 5). Isla Verde and some other embayments experience chronic turbidity as wave action resuspends fine sediments deposited when the areas were sheltered estuaries. Arecibo Bay averaged approximately 5 NTU while Punta Caracoles, on open coast 4 kilometers to the east, averaged less than 2 NTU.

Sediment transport paths along a section of the north coast displays the effects of local currents and waves (Figure 16).

Currents off Isabela ranged from 4 to 21 cm/s dominantly towards the west-northwest (Bogart-Spectrum Associates, 1970).

North of Arecibo currents reach speeds greater than 50 cm/s. Here the wave induced and tidal current components are significant. During the ebb tidal cycle, flow is

Figure 16. SEDIMENT TRANSPORT AND CIRCULATION PATTERNS
FOR A SEGMENT OF THE NORTH COAST OF PUERTO RICO
PATRONES DE TRANSPORTE Y CIRCULACION DE SEDIMENTOS
A LO LARGO DE UNA PORCION DE LA COSTA NORTE DE PUERTO RICO



generally offshore toward the northwest; during the flood tide, flow is generally toward the shore in a southeasterly direction. Current velocities of the surface layers range from approximately 1 - 48 cm/s.

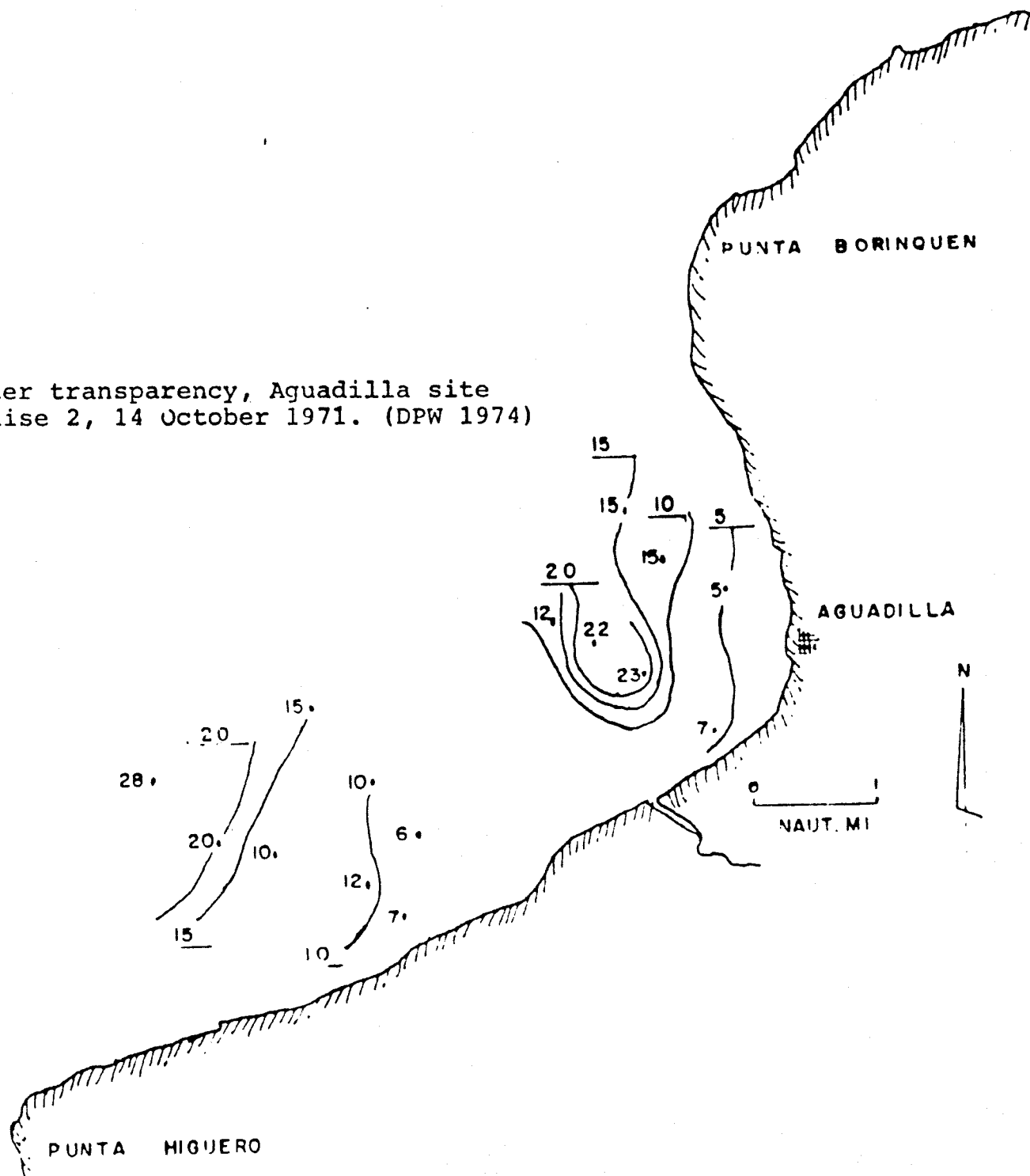
Secchi depths measured in the waters off Aguadilla, Arecibo, San Juan, and Carolina are shown in Figures 17-20 (DPW,, 1974).

East of San Juan lies a poorly developed and heavily stressed discontinuous chain of rock reefs about 1.5 km offshore. These consist of a relatively thin coral veneer growing on a shallow eolianite platform.

Barely any living coral exists northwest of Boca de Cangrejos, once a well developed reef system. This reef was virtually destroyed by sediments derived from extensive dredging within the Torrecilla lagoon and organic sediments discharged by sewage treatment plants nearby.

Scattered patch reefs break the surface occasionally east of Punta Vacia Talega. Water conditions nearshore are characterized by high levels of suspended particles and low visibility. Patch reefs adjacent to shore are dead. Living corals are present only in the offshore reefs.

Figure 17. Water transparency, Aguadilla site
Cruise 2, 14 October 1971. (DPW 1974)



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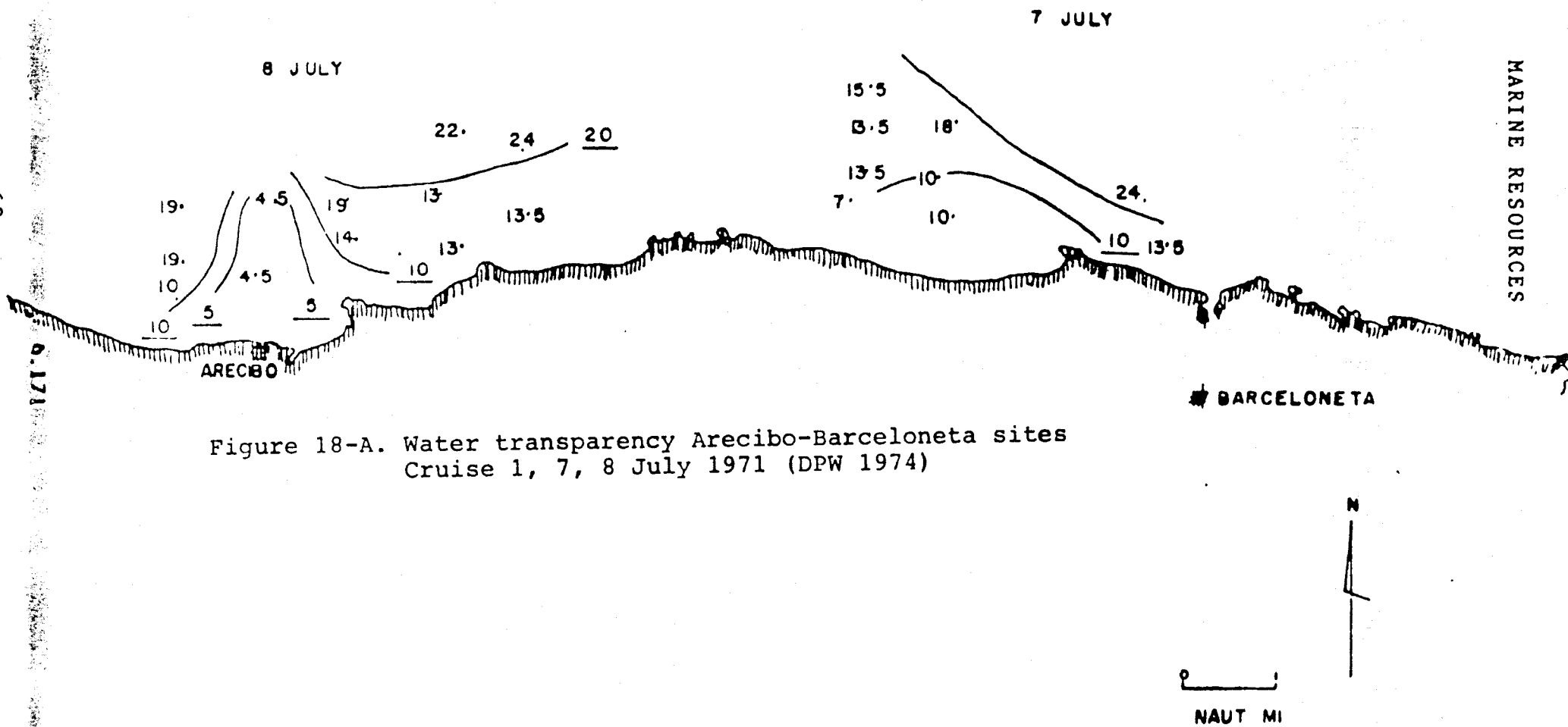
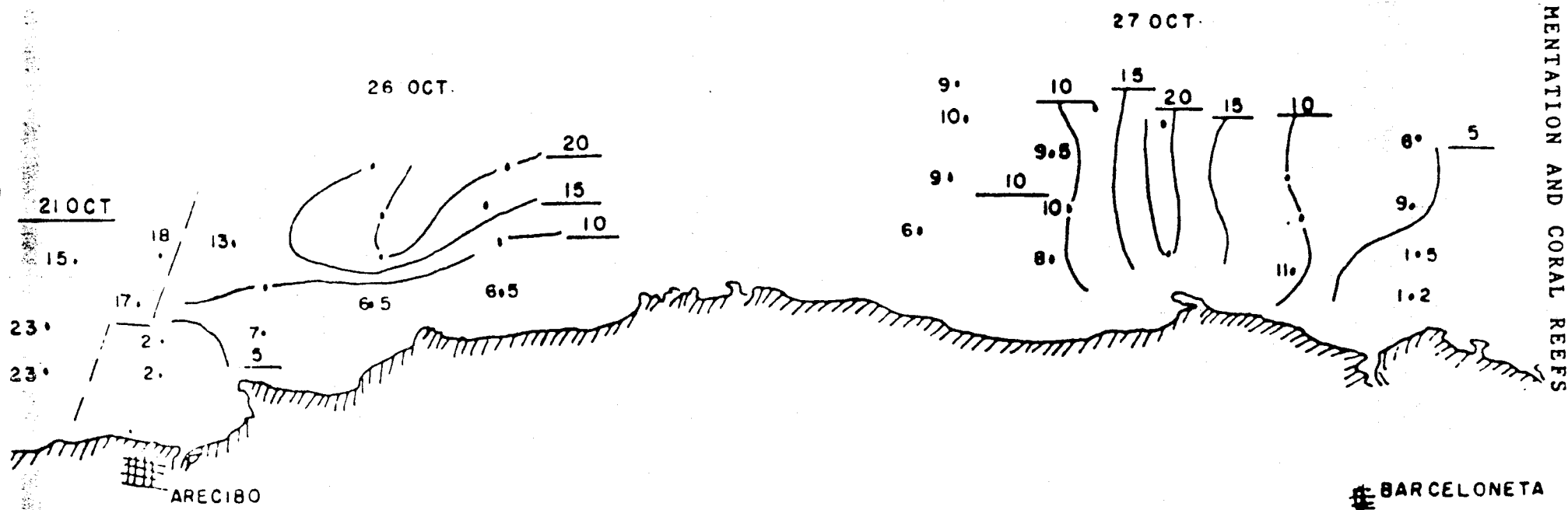


Figure 18-A. Water transparency Arecibo-Barceloneta sites
Cruise 1, 7, 8 July 1971 (DPW 1974)

Figure 18-B. Water transparency, Arecibo-Barceloneta sites
Cruise 2, 21, 26, 27 October 1971 (DPW, 1974)



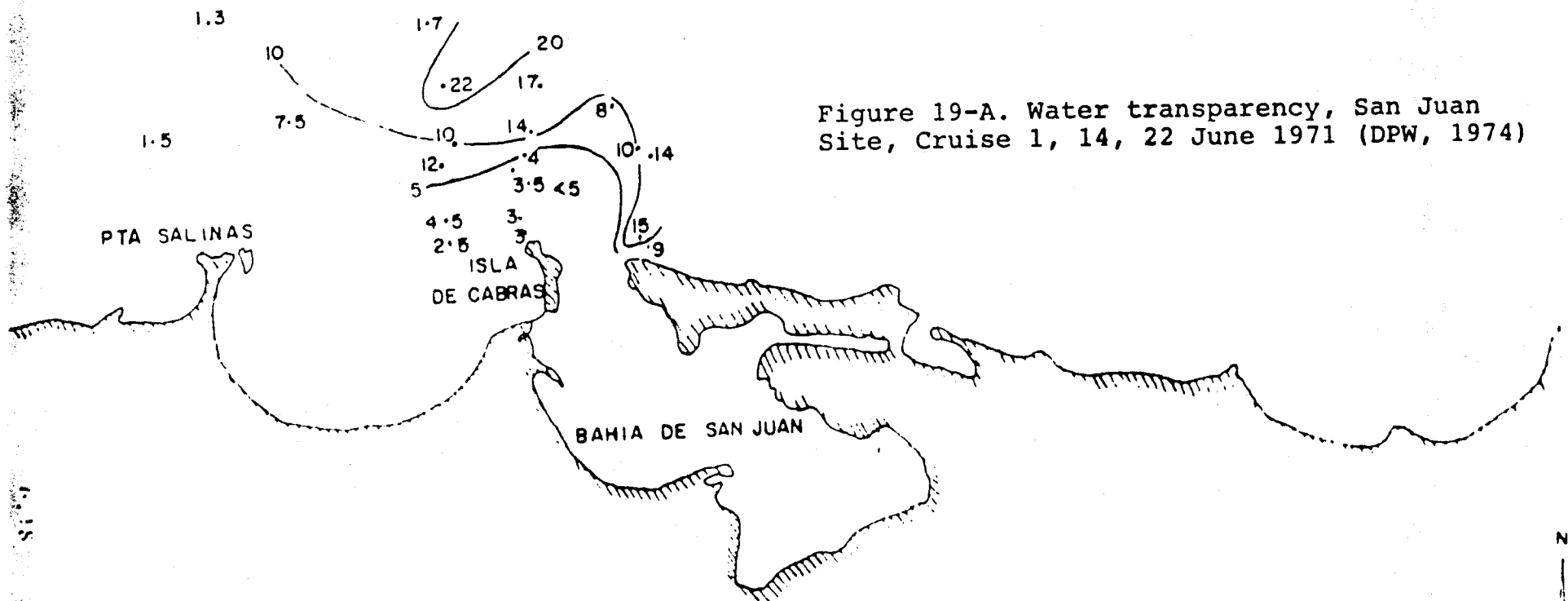
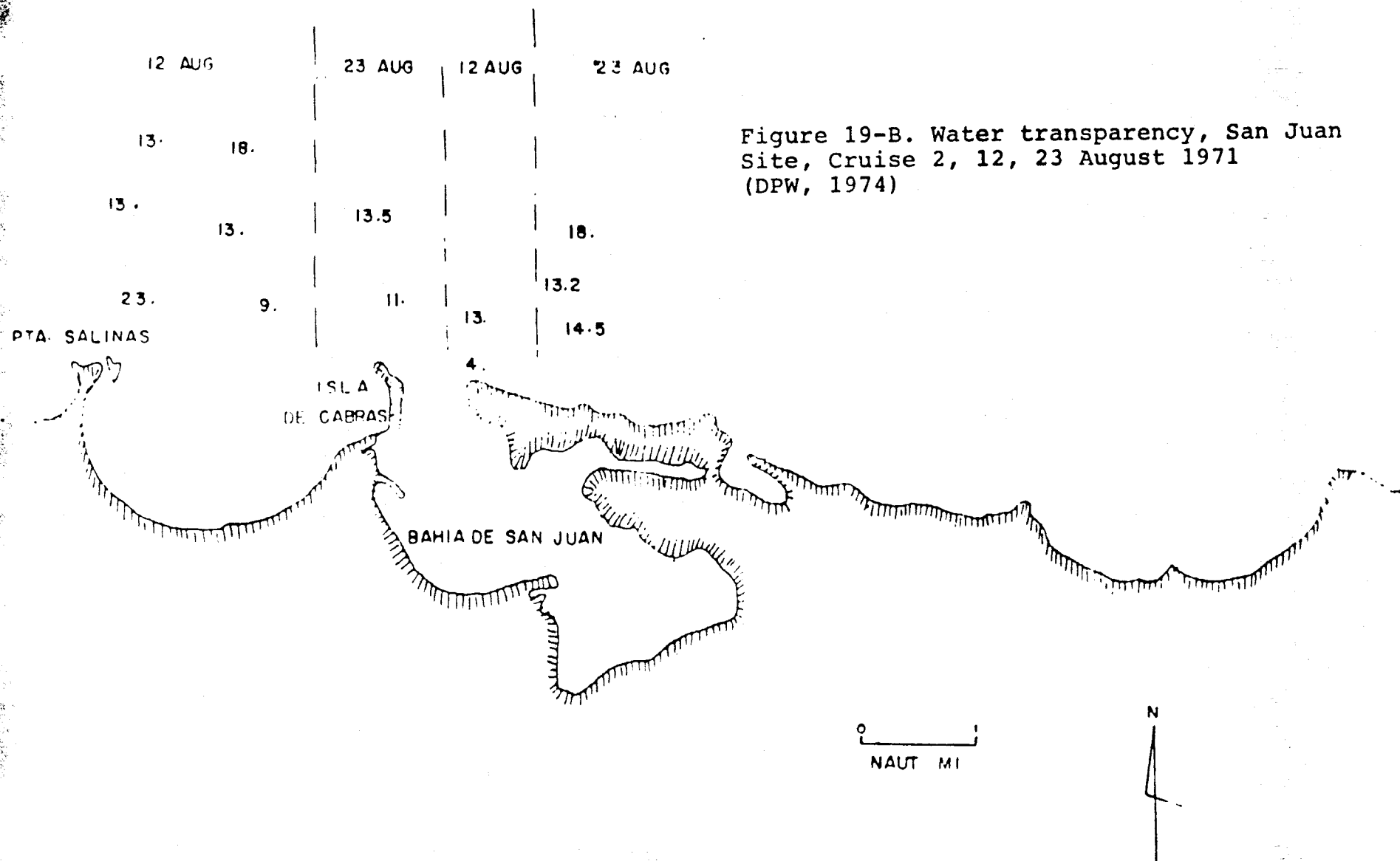
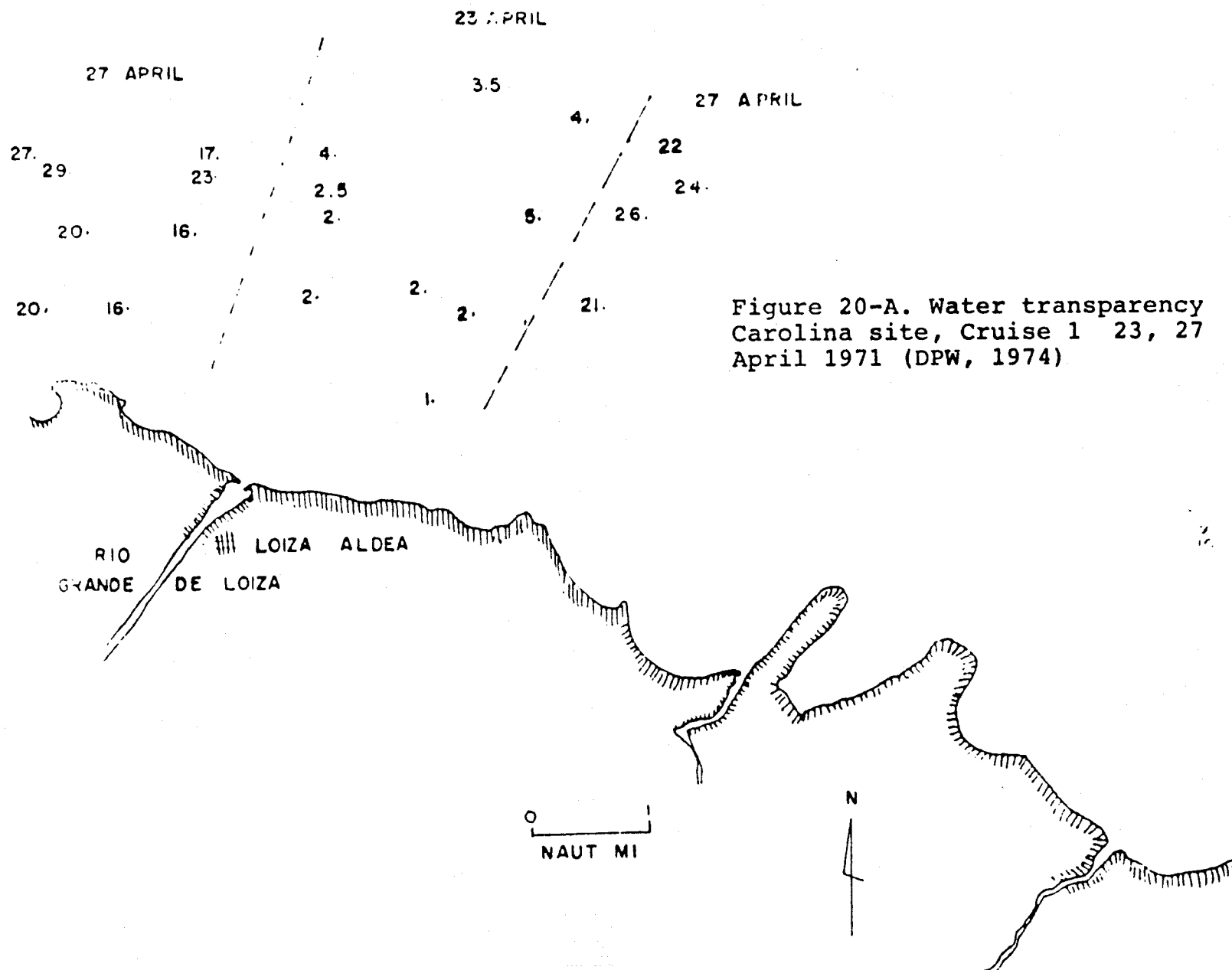


Figure 19-A. Water transparency, San Juan Site, Cruise 1, 14, 22 June 1971 (DPW, 1974)

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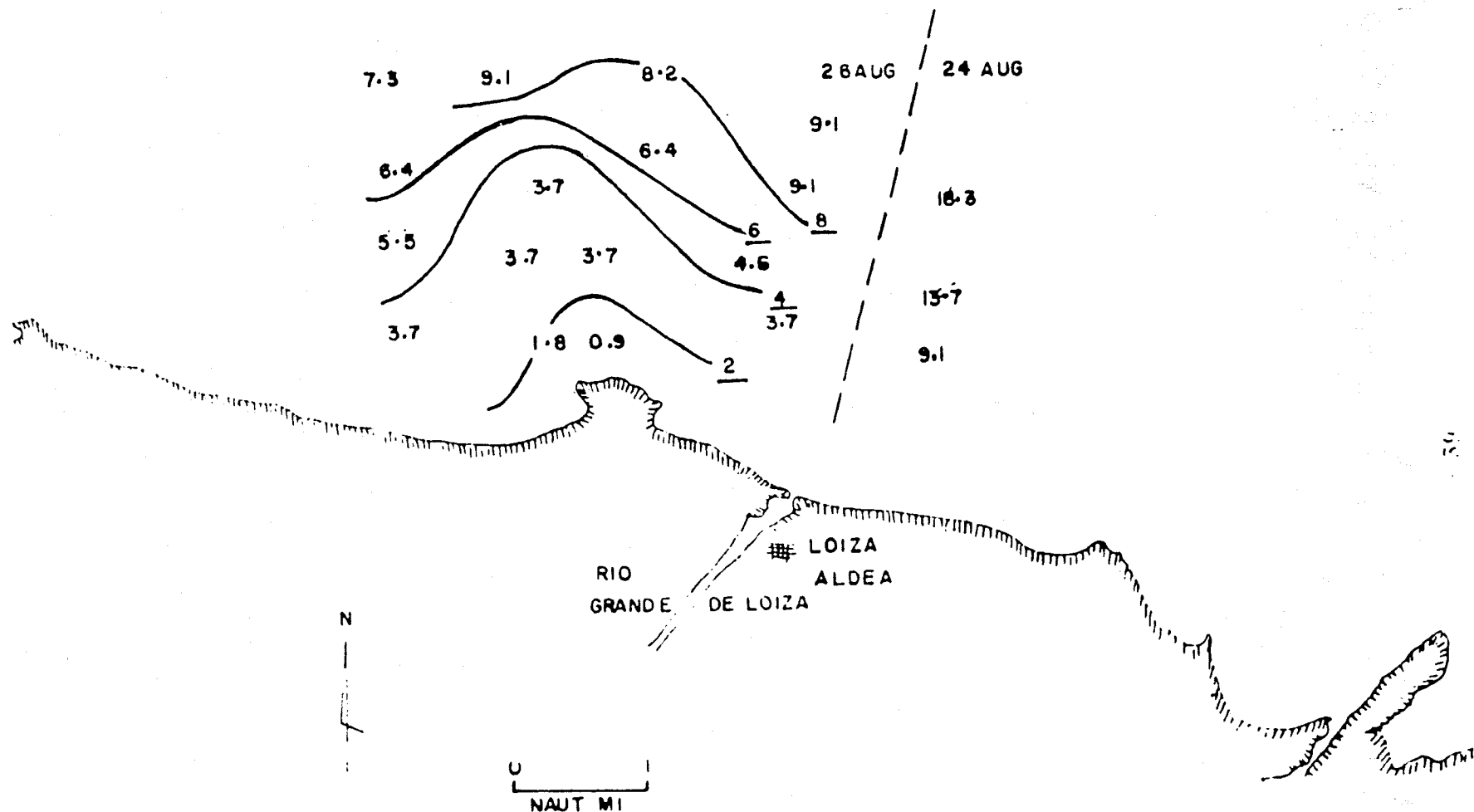


Figure 20-B. Water transparency Carolina site, Cruise 2 24, 26 August 1971 (DPW, 1974)

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Fringing reefs of about a quarter of a mile wide border both Punta Miquillo and Punta Picua. This reef system has suffered serious perturbations and partial destruction of its components as a result of the dredging of a channel parallel to the shoreline.

To the east, lies a complex of barrier, fringing and patch reefs resting on rock and sand foundations. These reefs have undergone various stages of degradation, specially those surrounding the northern and eastern ends of the Luquillo beach.

A significant reef system fringes the northeast portion of the island from Cabo San Juan to La Cordillera cays. Recently, reefs associated to Cabo San Juan have undergone rapid degradation due to siltation and coral extractions.

Virgin Island Platform (Region 2 on Plate 1)

Conditions on the the shallow platform est of Puerto Rico are ideal for coral development. The main stresses being hurricanes and bombing. The bathymetry to the east of Puerto Rico directs the tidal currents commonly measured in the area. Net flow through Vieques Sound is towards the west. The coral reefs of the Cordillera, Culebra, and Vieques are upstream of the east coast river discharges and therefore are not affected by flood discharges. The Escollo

de Arenas forms the southern wall of a venturi, accelerating currents to over 150 cm/s.

Water transparency off Vieques can be divided into three zones: nearshore, intermediate, and offshore (Fig 21, Gilberto's).

Reefs associated to La Cordillera cays are extensive with a high diversity and living coral cover. Some accessible islets such as Icacos, Palominos and Palominitos provide relatively shallow protected areas which exhibit a fairly high coral development.

Eastern Coast - Nearshore zone (Region 3 on Plate 1)

The east coast sites had persistently high levels of turbidity. The fines discharged from east coast river mouths are pushed back against the coast by the winds, waves, and currents out of the east. The situation is similar to spraying water towards a fan. This pressure effect combined with increased sedimentation due to agricultural, industrial and urban development result in the highest average levels of turbidity of any of the four coasts.

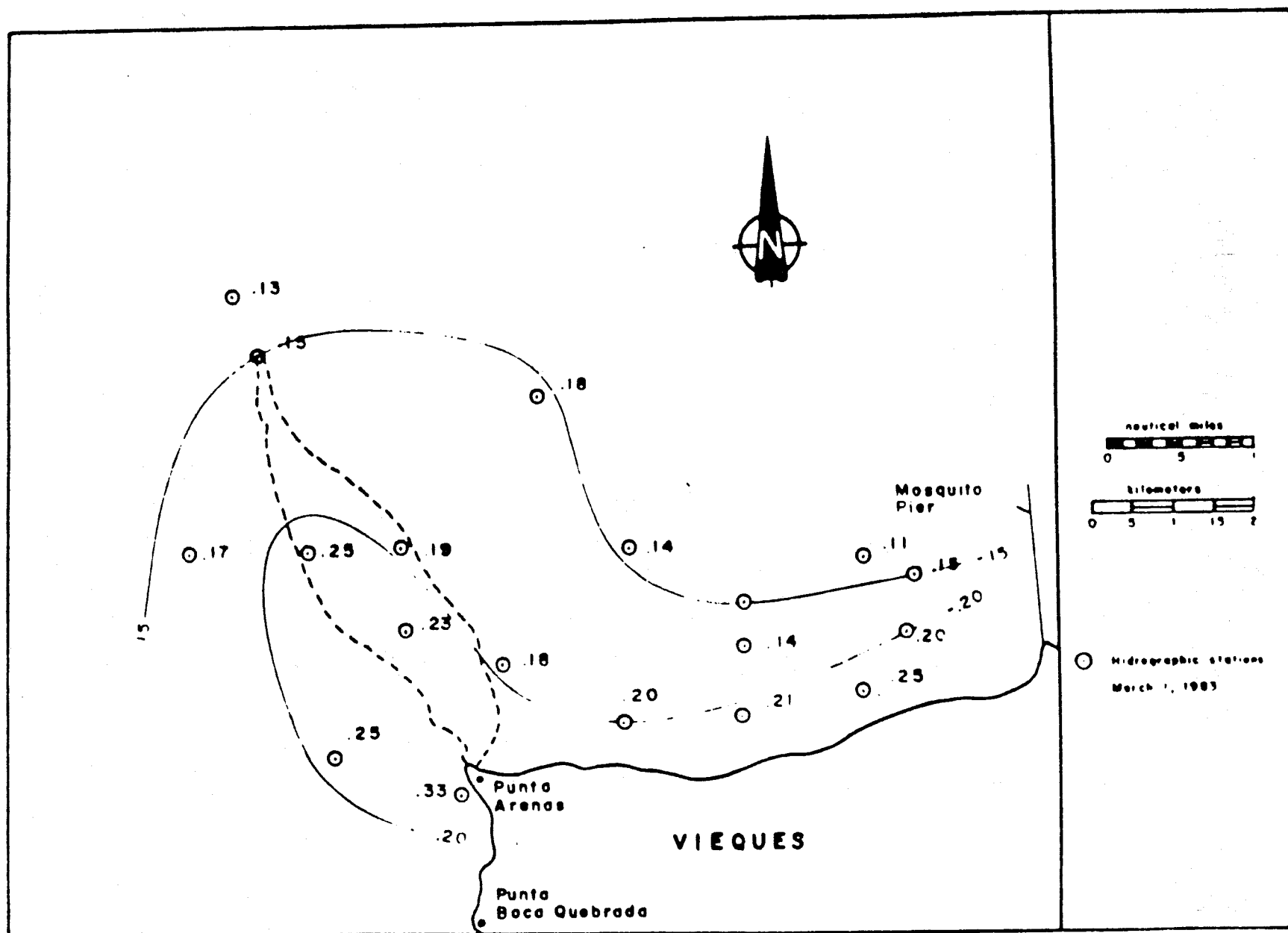


Figure 21. Extinction coefficients for photosynthetically active radiation (PHAR) in the 400-700 nm band. LI-COR Quantum sensor. (Cintrón, et al., 1984)

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Secchi depths measured off of Humacao and Yabucoa are presented in Figures 22 A,B

Off of Humacao the currents are westerly with speeds ranging from 1.5 to 35 cm/s (DPW, 1974). At Yabucoa the currents are southwesterly with speeds ranging from 2.2 to 17.2 cm/s.

From Playa Sardinera to Punta Barrancas there are no coral reefs fringing the coast. This may result from the influence of Rio Fajardo that often carries significant amounts of silt.

Occasional small fringing and patch reefs border the southeast coast. Here, high sediment levels originating from upland erosion and dredging of river mouths reduce water transparency.

Maunabo (Region 4 on Plate 1)

The insular break lies only one km off of Maunabo; the narrowest stretch in Puerto Rico. The associated high energy wave conditions and reversing tides flush Sargeant reef clean of any sediments discharged from Humacao or other nearby rivers.

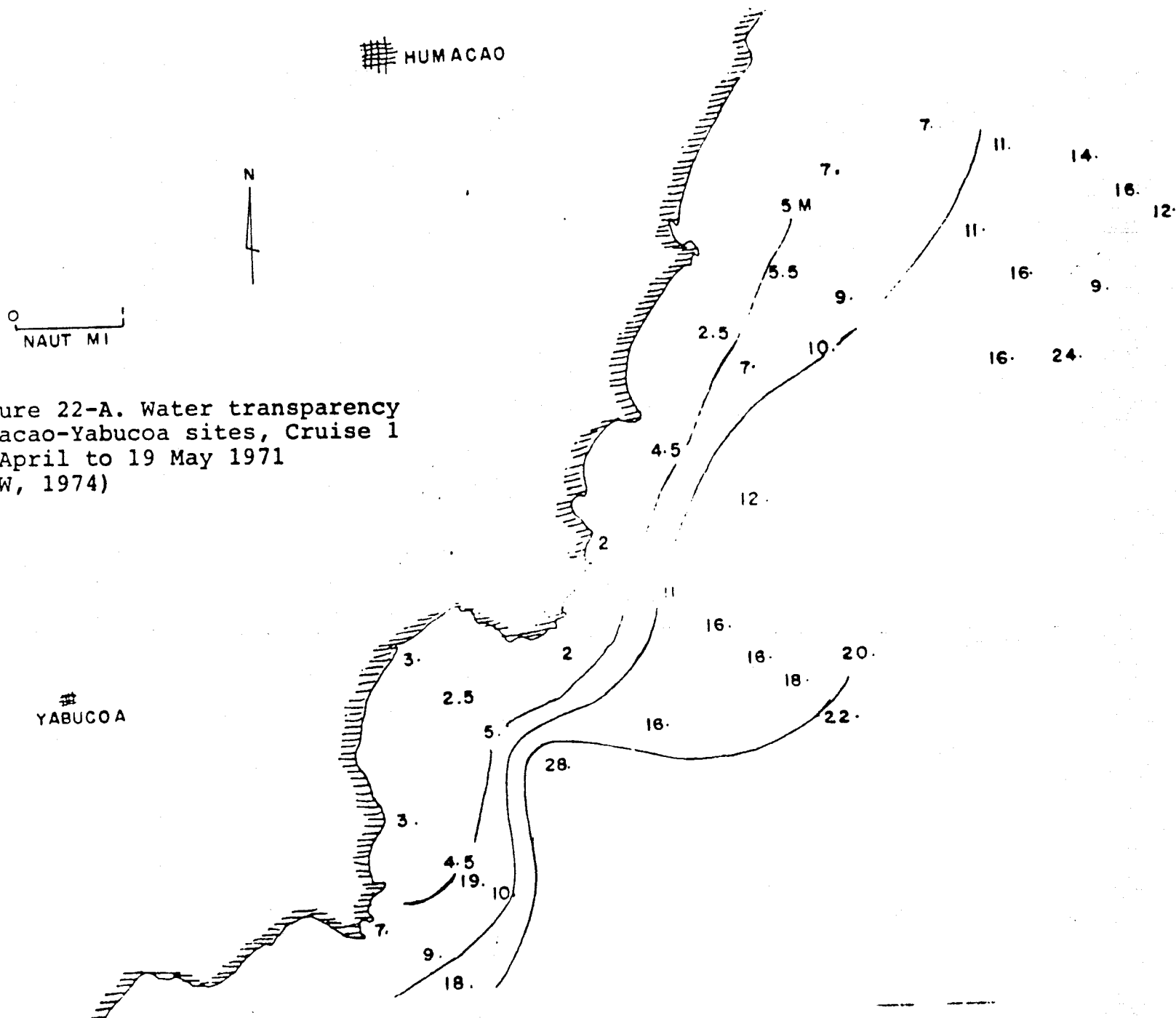


Figure 22-A. Water transparency
Humacao-Yabucoa sites, Cruise 1
30 April to 19 May 1971
(DPW, 1974)

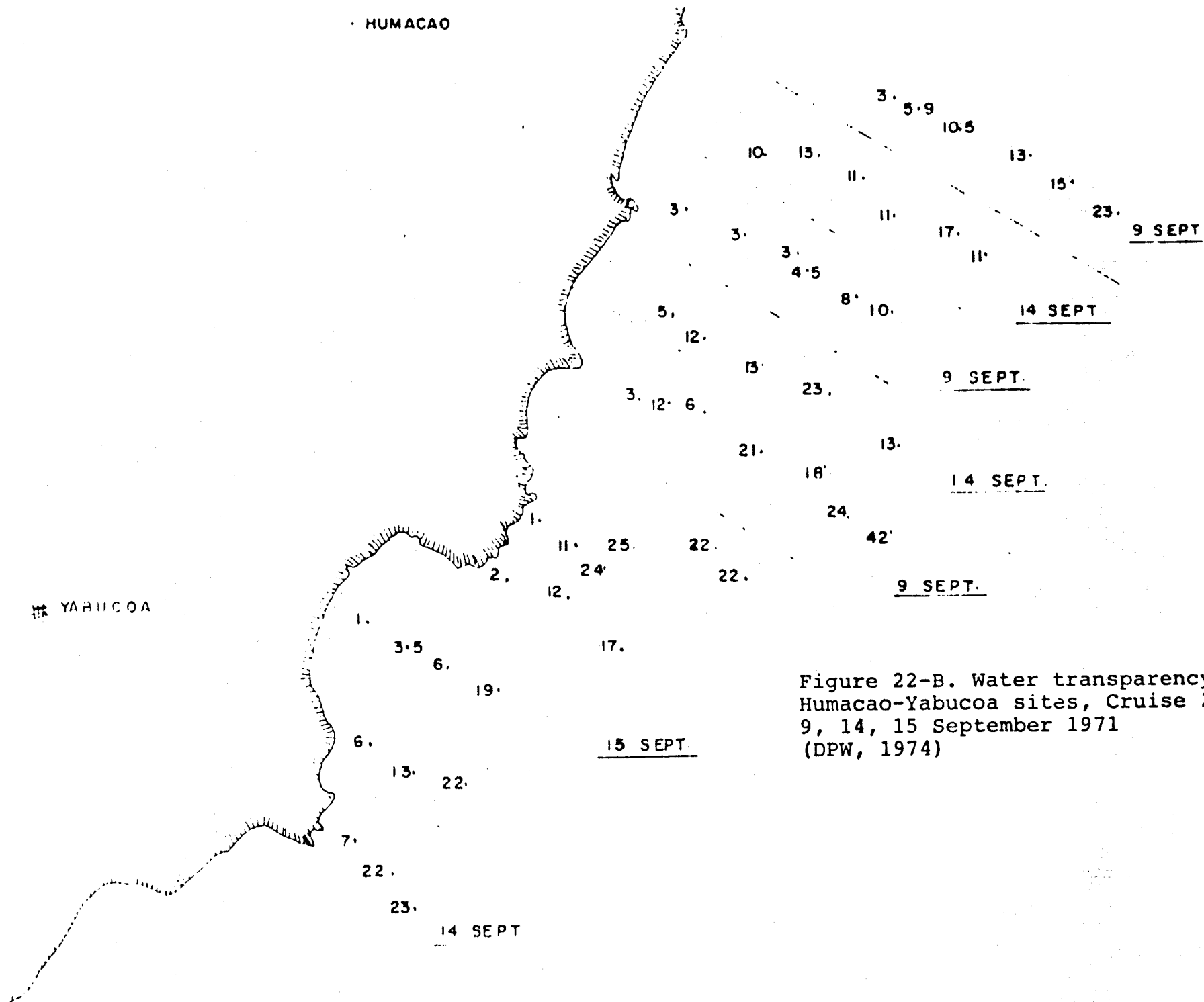


Figure 22-B. Water transparency
Humacao-Yabucoa sites, Cruise 2
9, 14, 15 September 1971
(DPW, 1974)

Las Mareas - Patillas (Region 5 on Plate 1)

In the south coast, the extensive dredging during the construction of the artificial harbor at Las Mareas have contributed to high sediment levels in this area. Coral reefs in the vicinity of Las Mareas are nearly devoid of living coral.

Arroyo (Region 6 on Plate 1)

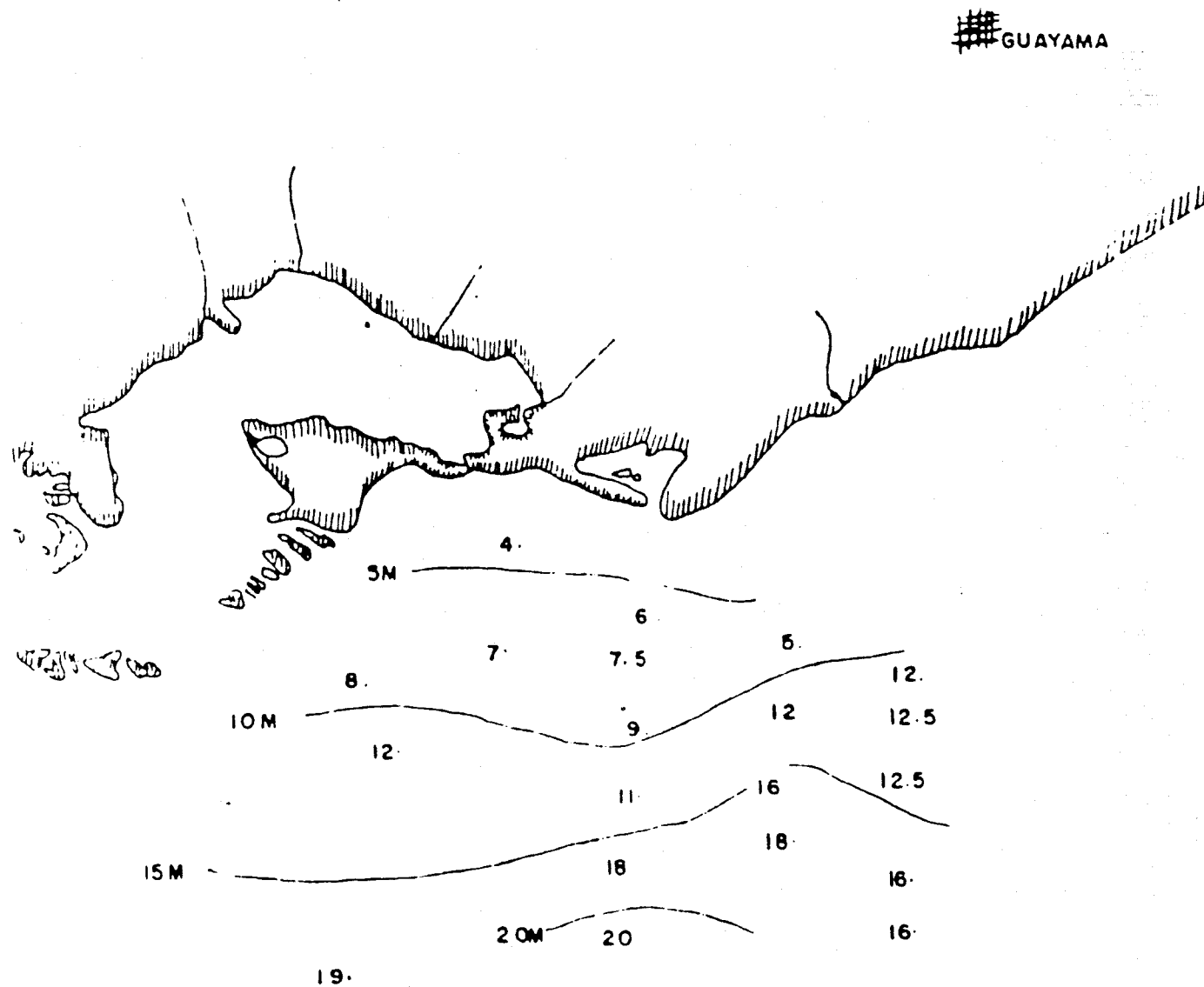
The Corona and Algarrobo patch reefs appear relatively healthy and not much affected by siltation.

Ponce - Jobos (Region 7 on Plate 1)

River influx, resuspended sediments, and industrial development result in point sources of turbidity on the south coast. The poorly sorted fill used at El Tuque west of Ponce is easily eroded and resuspended by even moderate wave action. Turbidity here averaged over 20 NTU during 1983. Secchi depths measured off of Guayama are presented in Figure 23 (DPW, 1974)

The island of Caja de Muertos and Cayo Berberias rest on a mid-platform ridge which divides the Ponce Basin to the west from the Outer Shelf Province to the east. Silts and clays floor the Ponce Basin (Beach and Trumbull, 1981).

Figure 23. Water transparency, Guayama site
Cruise 1 25, 26 May 1971 (DPW, 1974)



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Thalassia on the mid-platform ridge traps fines and is inhabited by a diverse benthic community. Coarse relict mollusk and coral fragments are found on the outer shelf.

Wind driven currents are important on much of the broad shallow southern insular shelf. Off Maunabo and south of Guayanilla, the shelf is narrow. Here, waves and tides are the dominant influences on currents. The dominant flow direction is towards the west-northwest though there are marked diurnal variations. Easterly flows are turbulent and slow. Westerly flow are smoother and have higher mean kinetic energy (Fornshell, personal communication, 1983). Current measurements range from 2.1 to 40 cm/s with an average of approximately 18 cm/s (DNR, 1980).

Westerly currents pile up water along the southern coast as explained by the Eckman spiral and the coriolis effect. Pluvial sediment discharges usually settle out in the nearshore zone. This is one of the principal reasons for the extensive development of mangrove systems along the southern coast. Terrigenous muds deposited in pockets in mid and outer shelf regions are relict deposits from times of lower sea levels. This contrasts directly with the north coast where the fines are moved almost immediately offshore and the sediment cover appears to be in equilibrium with processes active today (Pilkey et al., 1978).

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Figure 24 shows the average secchi depths for readings taken over 2 years. Highly turbid water covers much of the Ponce Basin, which is floored by silt and clay.

The fringing-barrier reef of Punta Pozuelo show a moderate living coral cover. Coral development increases westward with the numerous offshore keys south of Salinas. Here, coral reefs are in a very healthy state with high living coral cover and supporting rich benthic populations.

Guanica - Guayanilla - Tallaboa (Region 8 on Plate 1)

Kamel and Hadjitheodorou (1970 as cited in DNR, 1980) concluded from their study that wind drift and tidal currents are the predominant types in the Guayanilla Bay and Punta Ventana areas.

Secchi depths for Guayanilla are presented in Figure 25 (DPW, 1974).

The offshore reefs of Bahia de Guayanilla and Tallaboa have suffered significant alterations due to industrial development of the area. Periodic dredging of ship channels in the bays produce high levels of turbidity and siltation. In general, living coral is absent in the shallow reef area, with some isolated colonies surviving in the seaward side.

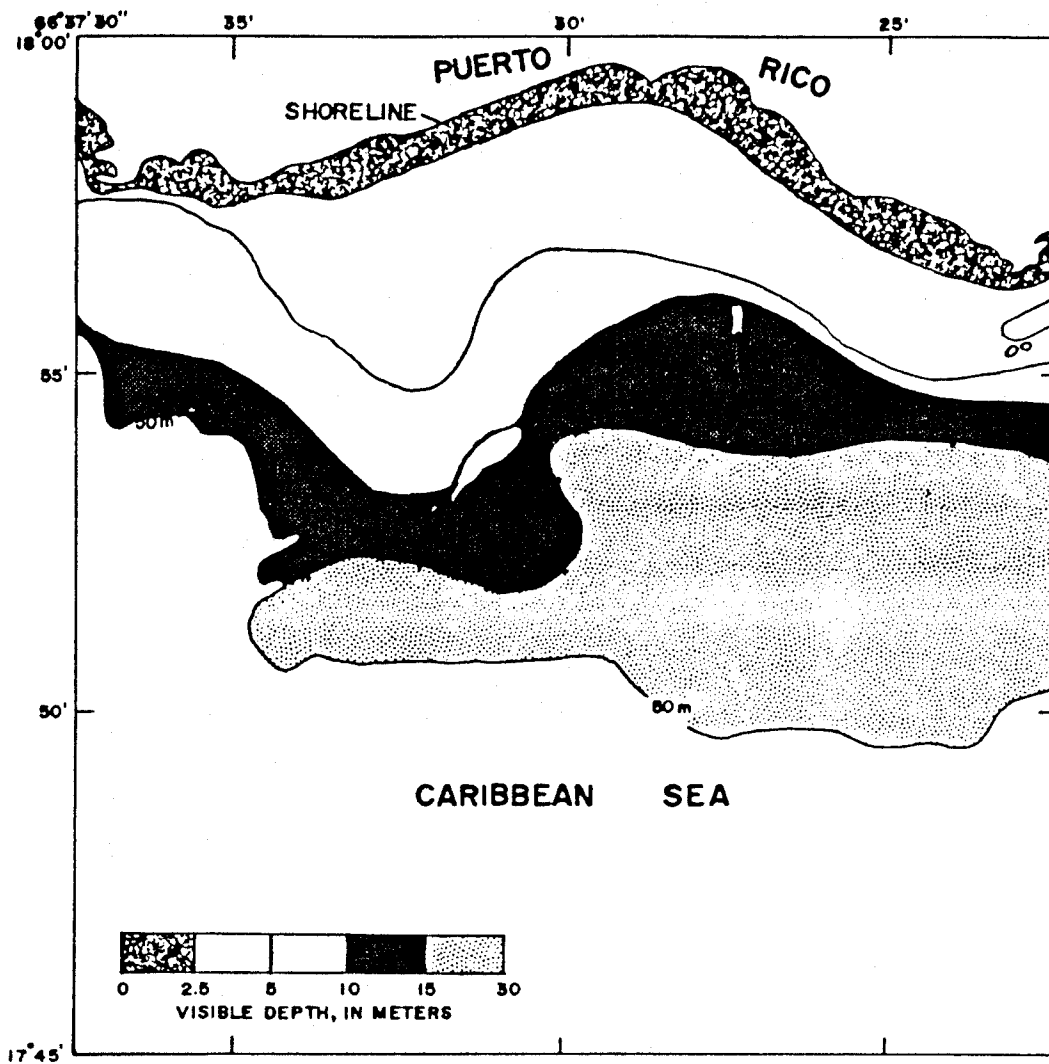
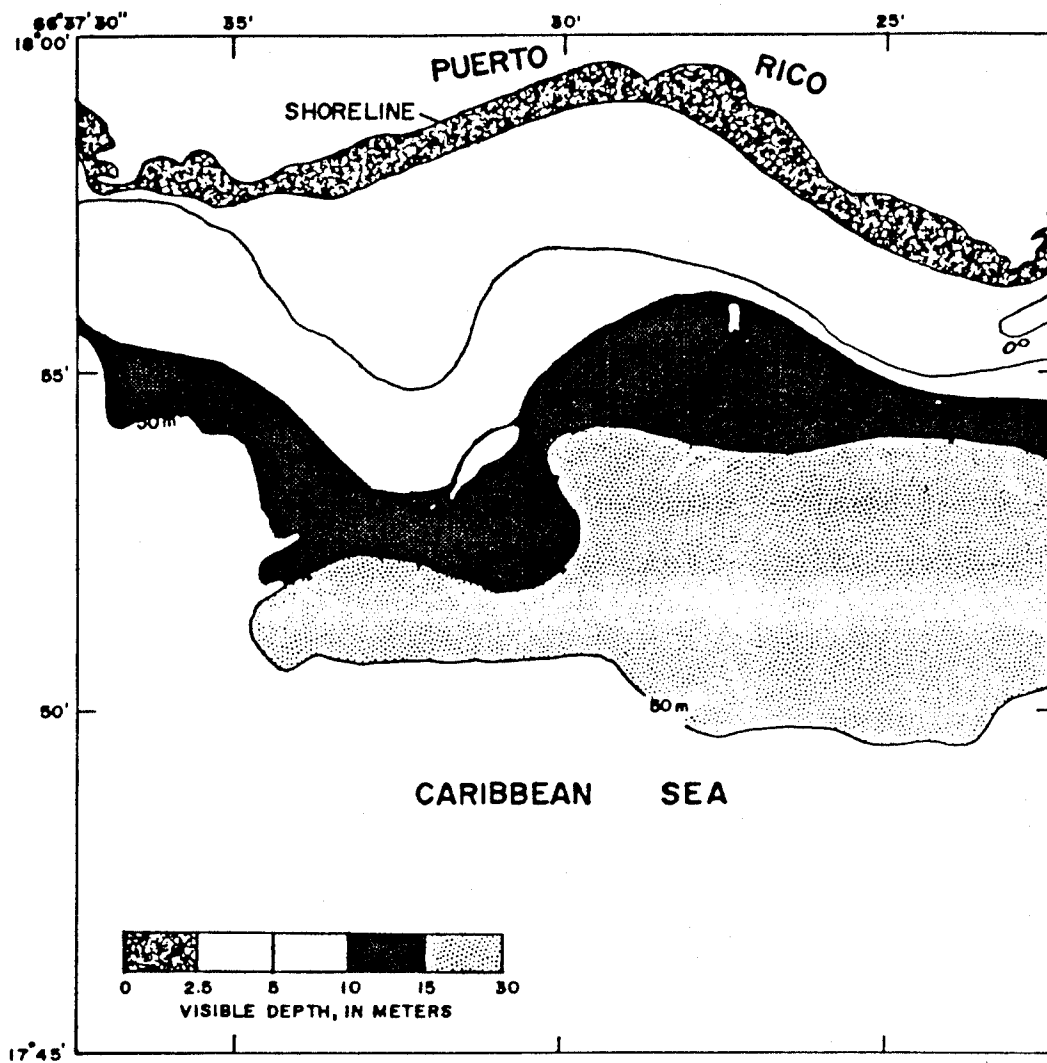
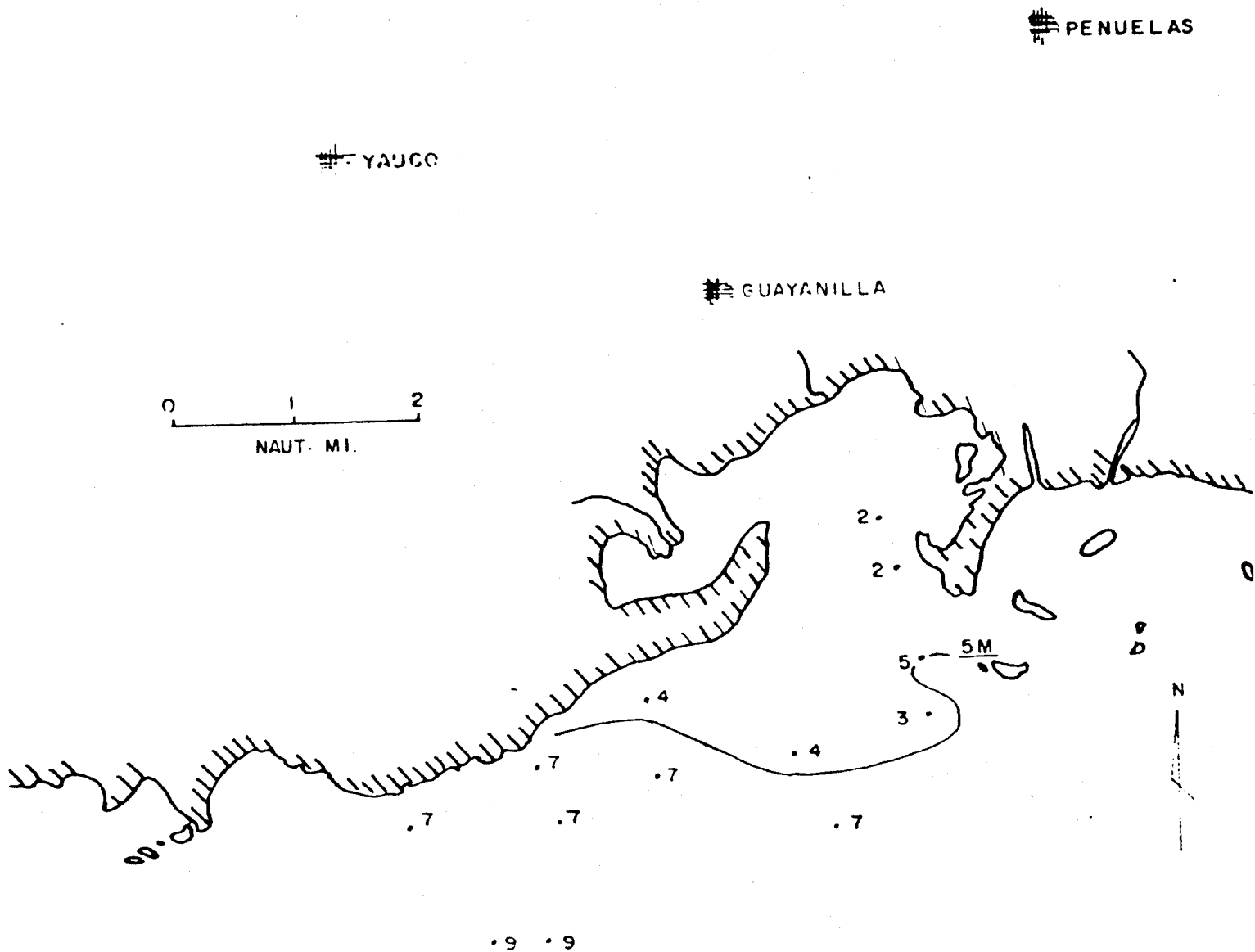


Figure 24. Map showing turbidity of shelf waters as measured by visible depth of the secchi disk. An average of readings taken over a period of two years. (Beach and Trumbull, 1981)



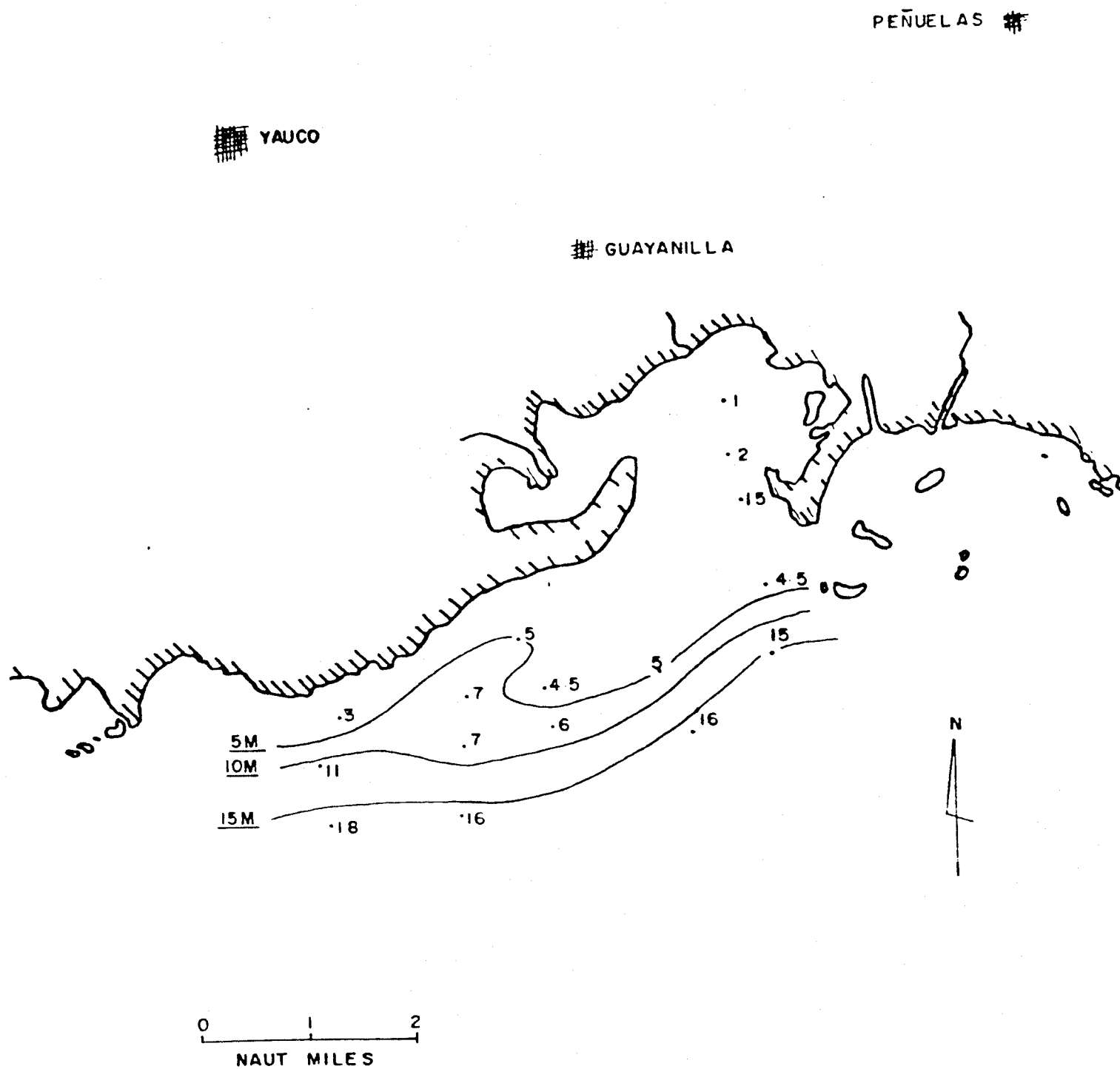
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Figure 25 A Water transparency, Guayanilla site, Cruise 1
9 June 1971 (DPW, 1974)



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Figure 25 B Water transparency, Guayanilla site, Cruise 2
4 October 1971 (DPW, 1974)



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The pattern of sedimentation off Guayanilla developed from an interaction of sea level changes, wave and current patterns, coral reef growth, and river discharge (Morelock et al., 1980). Until very recent time, reef growth was more vigorous than in the present environment with numerous patch reefs present in the bay areas. Chemicals and heated effluents are the most important pollutants in Guayanilla Bay (Sieglie, 1973).

Morelock, et al. (1979) studied the community structure of a sediment stressed coral reef of the Guayanilla Canyon system. The chronic state of suspended sediments is attributed in great part by the disturbance created by ship traffic. The corals present exist close to their limits of tolerance of available light and sedimentation. The additional stress produced by river discharge, ship traffic and industrial activities is enough to destroy the system.

Parguera - Rincon (Region 9 on Plate 1)

Coral reefs become more prolific and complex near the southwest corner of Puerto Rico. The limited amount of rain fall, minimum runoff, low wave energy and great quantities of dissolved organic matter have contributed to the formation of an extensive healthy and highly developed system. The most important of these are La Parguera reefs

which form a series of provinces breaking the surface as far as two nautical miles offshore.

Rogers (1977) studied the natural sedimentation rates and the response of the dominant coral species to application of sediments in San Cristobal Reef at La Parguera. Coral cover was about 70% with an average sedimentation rate of $2.5 \text{ mg/cm}^2/\text{day}$ in traps 50 cm above the substrate and $9.6 \text{ mg/cm}^2/\text{day}$ for the 10 cm traps. During the tropical storm Eloise (1975), accumulation rates increased to $14.4 \text{ mg/cm}^2/\text{day}$ for the bottom traps and 5.6 for the 50 cm traps. Overall mean sedimentation rates were 1 to $21 \text{ mg/cm}^2/\text{day}$ (Table 6), and suspended matter averaged 0.4 to 2.4 mg/l .

Table 6. Average Sedimentation Values for some Coral Reefs in Puerto Rico

Coral Reefs	Sedimentation ($\text{mg/cm}^2/\text{day}$)	Study
=====	=====	=====
Cayo Ratones	23.4 - 41.4	Ferrer, et al., 1985
Cayo Berberia	8.4 - 14.3	Ferrer, et al., 1985
Guayanilla Reefs	1.1 - 9.8	Morelock, et al., 1979
San Cristobal Reef	1.1 - 21.0	Rogers, 1977
El Negro Reef	3.0 - 15.0	Loya, 1976

Diploria strigosa and Montastrea annularis were the most resistant species to sediment application experiments. Death of local areas was observed after a single application of 800 mg/cm^2 to M. annularis, but could recover four weeks

after an application of 400 mg/cm². Acropora palmata was the least resistant species, unable to tolerate a dose of 200 mg/cm².

Suspended sediment levels were measured Southwest of Cabo Rojo in 1984 (Figures 26 A,B) (Cintron et al., 1984).

Boqueron - Anasco (Region 10 on Plate 1)

Mayaguez Bay and Anasco to the north are sheltered areas on the west coast. Turbidities averaged over 10 NTU at these sites in 1983 and then lowered to approximately 4 NTU in 1984.

Sheltered Boqueron Bay on the west coast is floored by a mixture of volcanic and metamorphic rock fragments with forams, Halimeda and mollusk fragments (Shideler, 1980). Mud ranges from 10% around the reefs protecting the entrance to the bay to over 80% in the eastern half of the bay. Visibility in the waters off the public beach rarely exceeds a couple of feet.

The Boqueron Reefs emphasize the need for a clearer definition of reef health. The reefs have a high density of living corals indicating a healthy environment. The corals, however, are predominantly gorgonians, indicating high suspended sediment levels.

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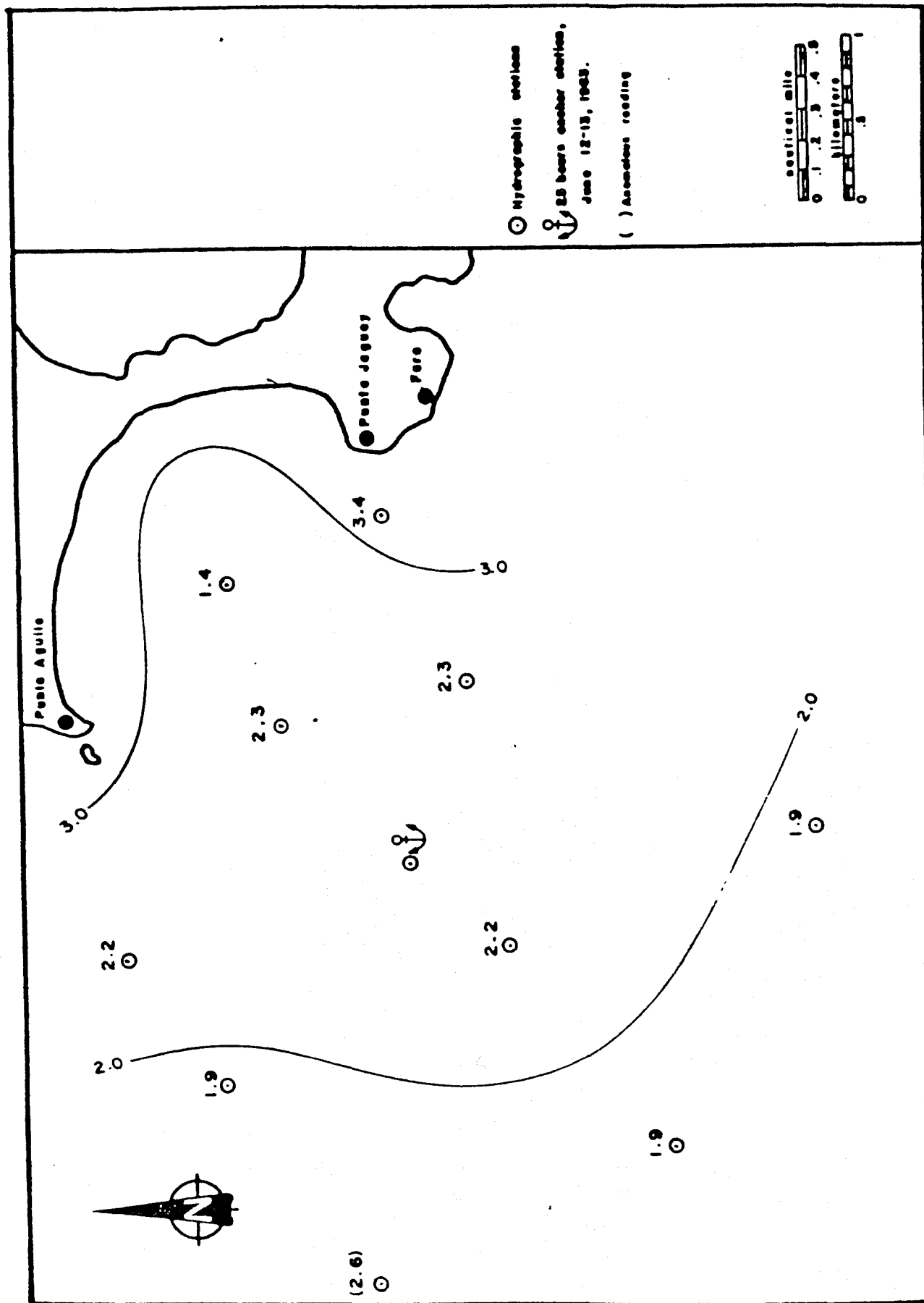


Figure 26-A Values for Suspended matter (mg/l) at the surface.

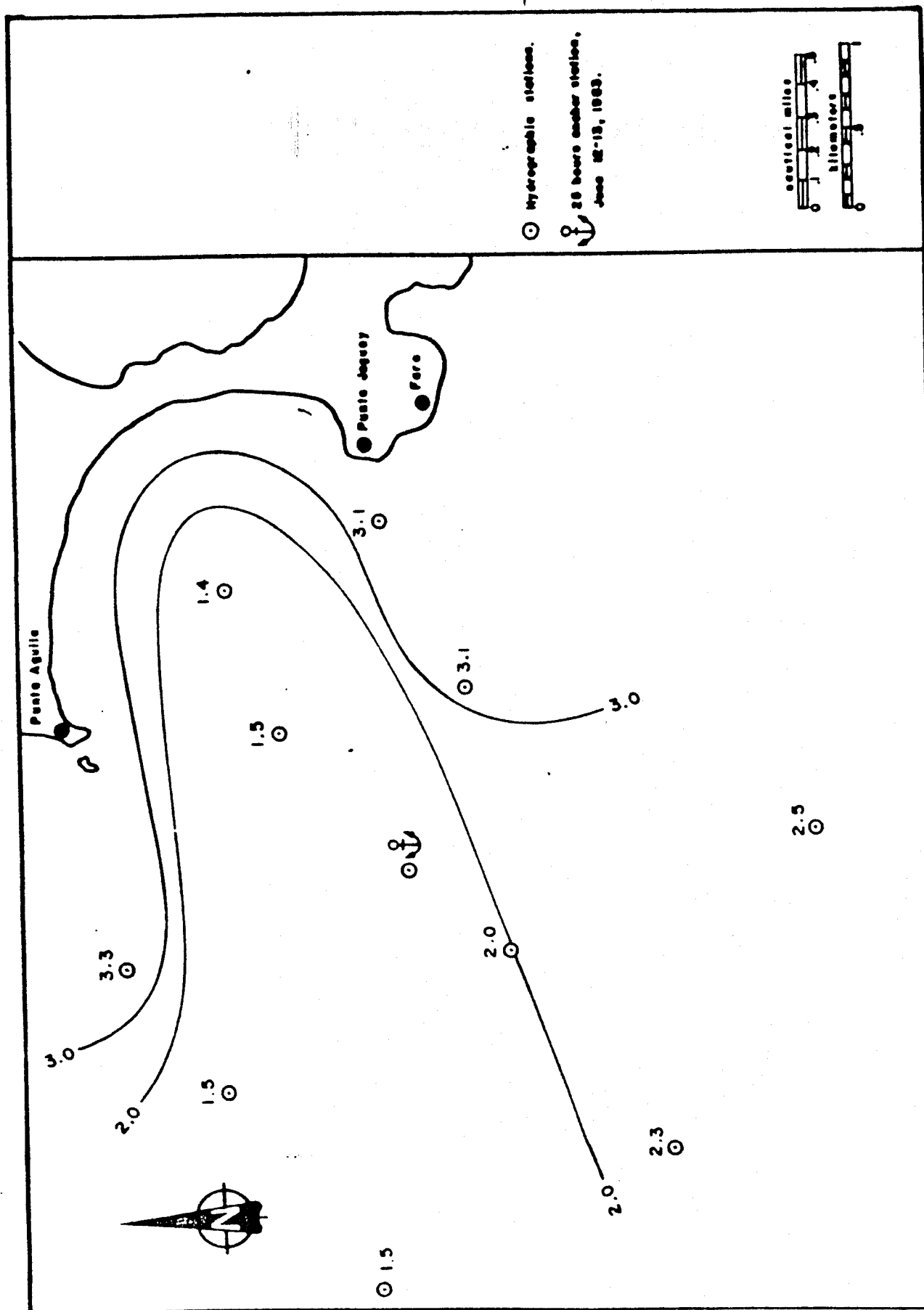


Figure 26-B. Values for suspended matter (mg/l), near bottom.

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Sedimentation patterns off Mayaguez result from currents, wave refraction, geology, and relict sediments. Reef environments are being replaced by spreading of the terrigenous-mud facies (Morelock et al., 1983). Both Algorrobo and Escollo Rodriguez reef are being silted over, with the likelihood of future burial by sediments.

The west coast current flows are generally towards the north and northeast with rotary and reversing current components superimposed (DNR, 1980). Breezes blowing away from land during the night and towards land during the day have pronounced effects on the nearshore current patterns.

Coral reef development along the west coast is moderate. Fringing reefs between Cabo Rojo and Mayaguez are suffering from high turbidity, heavy land drainage and sediment loads from the adjacent Guanajibo River. Offshore reefs, where water transparency is high, often show a more vigorous growth.

Loya (1976) studied the effects of turbidity and sedimentation in El Negro reef complex, Mayaguez. This reef receives the impact of the discharge of alluvial sediments originating from two rivers. The water in the vicinity of the West reef was turbid whereas the East reef was relatively clear during the study. Sedimentation rates measured averaged $3-5 \text{ mg/cm}^2/\text{day}$ in the upper parts of the

east reef and about $15 \text{ mg/cm}^2/\text{day}$ at the bottom of the reef and towards the west reef (Cintron, et al., 1974, as cited in Loya, 1976) (Table 6). Loya found that coral diversity and living cover at the upper East reef were higher than at the turbid West reef. The main pollutants in Mayaguez Bay are organic materials (from sewage outfalls) and to a lesser extent pesticides (Sieglie, 1973).

Kolehmainen (1973) studied the effects of prolonged siltation in this same reef. He found that Montastrea cavernosa and Diploria strigosa removed more sediment and suffered lower mortality than Siderastrea siderea under similar conditions.

Poorly developed fringing reefs occur on the north side of Rincon, from Punta Higuero to Punta del Boqueron. North of this point, only scattered, undeveloped coral growth occurs.

For more detailed information regarding the condition of these and other Puerto Rican reefs and their basic community structure, refer to the publication of Goenaga and Cintron (1979).

5.0 Recommendations on protection and management of coral resources

This section provides the necessary technical support for the preparation of the coralline resources EIS and Management plan.

Inland

- 1) Reforestation of river banks with natural vegetation or bamboo (or restoration of gallery forests).
- 2) Develop reforestation programs in upland areas to increase water catchment and infiltration.
- 3) Protect and restore wetland areas such as savannas, forests and herbaceous swamps between rivers and agricultural land, to serve as buffer zone as they are natural biofilters.
- 4) Discourage or prevent alterations to fresh and brackish wetlands that may reduce their value as natural sedimentation basins, as control of riverine and estuarine flooding, for water catchment and renewal of natural fertility of soil.

5) Control soil erosion and runoff from construction and mining activities.

Erosion control techniques that may be used should:

a) Entrap eroding sediments using vegetative barriers and/or sediment stilling basins.

b) Protect natural vegetation and/or seed grasses and other species to bind the soil in erosion prone areas.

c) Provide for stable slopes which can be quickly vegetated. Steep slopes are unstable, prone to sliding and cannot be adequately stabilized by vegetation.

d) Land reclamation by revegetation and earth moving to return drainage routes to original conditions.

e) Separation of natural waters from mining waters and the recycling and treatment of the slurries and drilling muds.

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6) Utilize agricultural practices which reduce or minimize soil losses. These are:

- a) Terracing
- b) Contouring
- c) Water control
- d) Soil treatments
- e) Tillage methods
- Interplanting
- f) Timing of field operations

Agricultural methods must provide for proper access roads so that erosion is not increased.

7) Discourage monoculture when it leads to soil depletion and erosion.

8) Forestry activities must not be of the clearant type or where this is necessary, provide for erosion control during the restoration process. Logging roads and trails must be adequately planned and banks seeded and stabilized.

9) Provide for the systematic replanting of logged areas with native trees or suitable harvest.

10) Control the use of heavy equipment on soils subject to compaction or easy erosion.

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11) All proposed earthmoving activities on sloping terrains should require an analysis of drainage patterns to assure that runoff will not drain into critical habitats, downhill developments, historical sites, or agricultural fields. It should provide a diversion and entrapment plan for potentially destructive sediment runoff.

12) During construction, vegetation should be removed only from the specific site where construction will take place. Surrounding vegetation should not be removed.

Effluents

13) Prohibit toxic waste outfall and solid waste disposal into coastal waters.

14) Locate sewage outfall pipes well beyond nearshore habitats and away from coral reef systems.

15) Monitor water quality regularly around industrial plants, sewage outfalls, marinas and other tourism infrastructures.

Dredging

16) Seafloor dredging in inshore waters should be discouraged.

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17) As for offshore deposits, any activity should be preceeded by a careful study and impact assessment and also include alternatives to dredging. This must include studies on the hydrodynamics, characterization of benthic communities and potential adverse effects upon them, benthic geomorphology, sedimentology and water quality.

18) The dredging methods with the least potential impact must be selected, regardless of its operational cost. Economics should not be the major consideration.

19) The dredging area and general operation must be continuously monitored by expert personel.

Bombing

20) Prohibit the use of explosives in or near living reefs or seagrass ecosystems.

21) Prohibit firing targets at the reefs and bays, even with practice ordnance.

Other human activities

22) Protect the most critical reef ecosystems with special status and provide for supervision and law

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enforcement to avoid structural damage from human activities like standing, kicking, grabbing spearing, and anchoring.

23) Place permanent moorings and prohibit anchoring in reef and seagrass areas that are popular anchorages.

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