PUERTO RICO - Seas at the Millennium

Jack Morelock, Jorge Capella, Jorge R. Garcia, Maritza Barreto

Abstract

Puerto Rico is part of a volcanic island platform that includes Puerto Rico and the Virgin Islands. Puerto Rico's prevailing weather is tropical. The trade winds blow consistently from east-northeast or east in the winter and from east-southeast in the summer. Stronger wind speeds are recorded during summer and winter than in spring and autumn. The narrow island shelf can be described in terms of north, east, south and west provinces. The north is the narrowest and is marked by higher wave energy and more terrigenous sediments. The east, south and west are carbonate platforms with coral reefs and dominantly carbonate sediments. Each of these provinces has different physical energies. Marine habitats are being diminished by excessive influxes of sediments and nutrients and by overfishing. During the past 50 years, more than 50 percent of the living coral has been lost and the rate of loss of reef areas has accelerated during the past 20 years. The high population density (>1,000 people per square mile) and a shift of population to coastal areas has had a strong effect.

Although the problems of loss of habitat are generally recognized, very little has been done to protect the environment. Local resources for protection are meager, and Federal (United States) efforts are directed to Florida, Hawaii and the Pacific in terms of coral reef preservation.

Introduction

The Island was born at the leading edge of the Caribbean plate as the Puerto Rico Trench subduction zone developed. Limestones filled in between volcanic flows to form an island 35 by 110 miles. This occurred over the last 65 million years, but the actual shape and size of the Island was essentially completed 40 million years ago. Active volcanism lasted from Cretaceous through Eocene time. The central mountain chain, a core of volcanic material and batholiths, lies south of the centerline, so that the coastal plain is wider on the north than the south, and most of the river drainage is to the north coast. Figure 1 defines the part of the platform occupied by Puerto Rico and the smaller islands of Vieques and Culebra. The insular shelf is limited in size and drops abruptly to deep water. Variations in the character of the habitat are controlled by wave and current energies, sediment types and sediment influx, and bottom features. The north and northwest insular shelf are a different marine ecosystem from the west, south and east shelves.

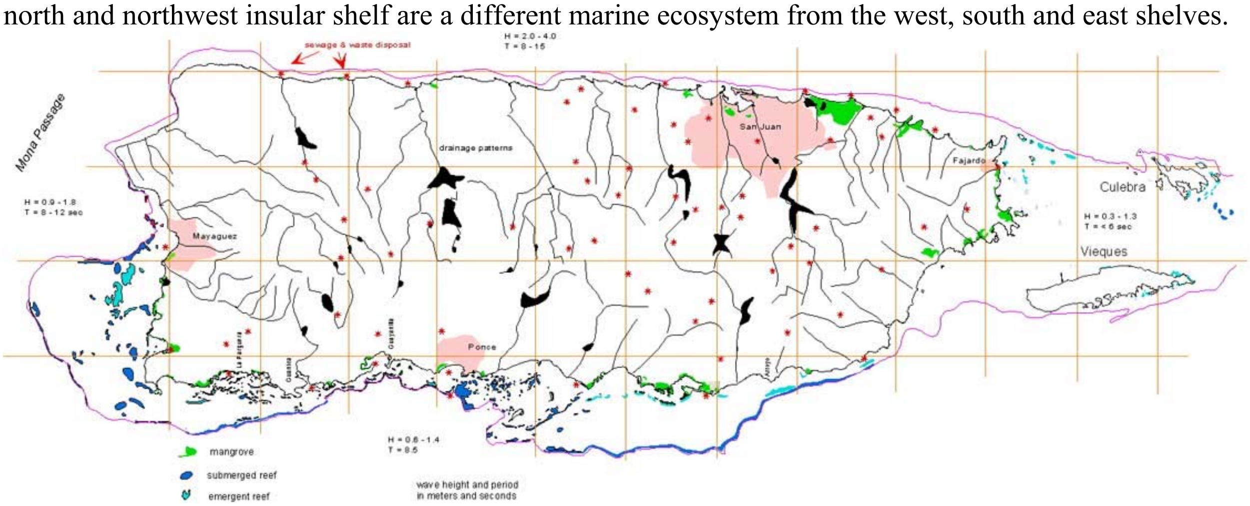

Figure 1. Puerto Rico coastal and shelf features

Geology of the Island

The basic structure of a central mountain volcanic core flanked by limestone deposits (with karst erosion patterns) is modified by clastic coastal plains and alluvial fans to the north and south forming three main physiographic units (Figure 2). During part of the Island's development, it was subjected to periods of intense deformation resulting in extensive folding and faulting. Morelock, 1978

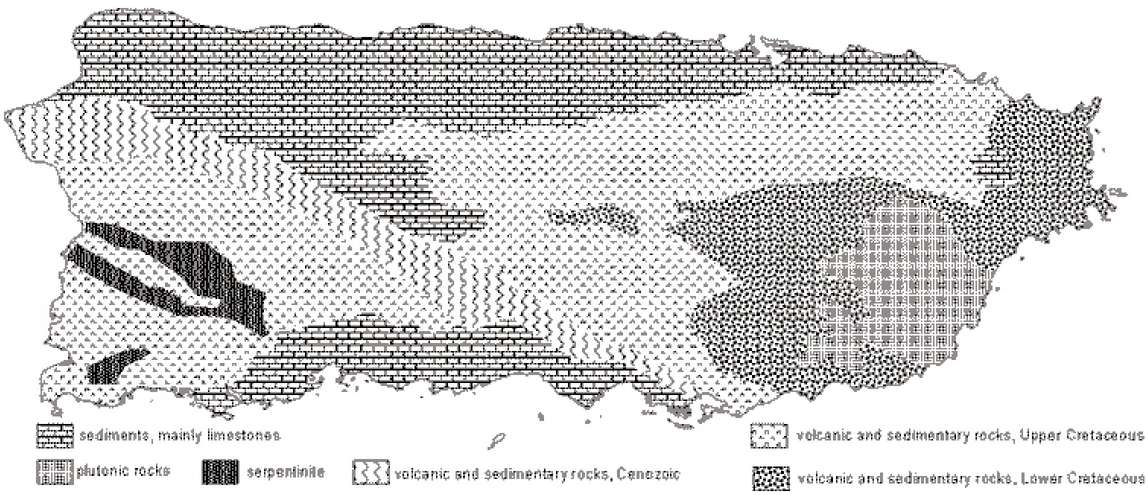

Figure 2. Geology of Puerto Rico

The north coast is Tertiary limestones and Recent deposits of alluvial plains, sand dunes, beachrock, and eolianites except for volcanic material in the northeast. The limestones are cemented and only slowly erode by solution to form karst terrain in contrast to the Recent deposits which are unconsolidated or weakly cemented and therefore easily eroded.

The south coast has similar rock types except for intrusive igneous rocks at the eastern end, and a large area of alluvial fan deposits in the eastern part of this coast. Cretaceous and Tertiary limestones are more common in the western half of the south coast.

The east and west coasts are normal to the structural trends of the Island. The west coast has a pattern of rocky shorelines of limestone and volcaniclastic rocks alternating with alluvial valley deposits, beaches, swamp and mangrove shorelines. On the east coast, the rocky shorelines are volcanic and intrusive igneous rocks alternating with the same pattern of modern alluvial deposits as the west coast.

Physical parameters

Local, everyday weather in our region is determined by the interplay between the land topography of this archipelago and the mid-latitude high pressure cell in the North Atlantic, westward traveling tropical waves, and cold fronts arriving from the north and northeast. The northeastern Caribbean lies along the northern edge of the Trade Wind belt which circles the globe from east to west; locally the Trade Winds are associated with the mid-latitude high pressure cell, whose center is periodically displaced along the Bermudas-Azores latitude band. This clockwise rotating, high surface pressure system generates easterly winds (Trade Winds) over our region (winds from the east). The actual wind direction varies from northeast to southeast, depending on the geographical distribution of the isobars over the North and Tropical Atlantic.

Wave Climate

The most frequent wave climate in our region consists of a background field of eastward moving seas and swell generated by the Trade Winds that is locally modified by bottom topography and by the behavior of the wind as it hits the multiple islands. Most islands create shadow wind and wave regions over their leeward (western) waters. As the easterly waves approach the islands and feel the bottom they refract and turn towards shore creating a westward longshore current. Under steady easterly winds a windward facing coastline receives wind and swell head on throughout the day but the west coast is generally much calmer. A typical forecast under these conditions is for 1-2 meter waves and swell throughout the region. Local winds close to the islands are additionally influenced by the diurnal land-sea heating cycle which often induces a strong sea breeze from the west during the afternoons and very calm conditions at night along the western coastline.

Westward moving tropical waves are best known for the "low" part of the surface pressure cycle as the "highs" are indicative of dry windy weather. Tropical lows generally exhibit variable weaker winds, and increased cloudiness and precipitation. Wave conditions under a tropical low are usually calmer on the average, except near centers of strong precipitation, which are accompanied by strong winds (and large seas) of short duration. During the hurricane season in the Atlantic, from June to November, the high sea surface temperatures and favorable atmospheric conditions allow the development of these tropical lows into tropical depressions, tropical storms, and hurricanes. Hurricanes can develop 15-20 meter waves near their center and swell is radiated asymmetrically along their trajectory.

Whereas tropical waves move westward, mid-latitude weather systems propagate towards the east. Frontal systems over the North American continent result from the surface displacement of cold air masses from high latitudes (Alaska and Canada). These systems move towards the south and east and sustain strong winds along the cold-warm air boundary. As these systems exit the east coast of the U.S. towards the Atlantic the strong winds generate high seas which decay into large swell waves that propagate southwards into the northern Caribbean. Large swell (12-16 sec periods, breakers of 3-3.5 m but up to 4 m) is common along exposed northern Puerto Rico coastlines during the winter season (November-April). Arrival at the islands is easily predicted by following the quasi-periodic behavior of the continental cold fronts. The arrival of a cold front generally means large swell along the north coast and flat seas along the south coast.

Surface waves in the ocean are generally divided into two major groups, seas and swell. Seas are formed by the local wind stress and are therefore strongly dependent on the speed and direction of the overlaying wind. Swell is formed far away and its speed and direction are in a straight line from its source, most noticeably far-ranging storm events. Whereas seas have periods of a few seconds and wavelengths in the order of several to tens of meters, swell peaks are spread hundred of meters apart and as any surfer knows, they travel in groups and you only have 10-15 seconds before the next big one in the group.

Long term studies of the wave and currents patterns for Puerto Rico are rare, with most of the available data coming from the Summary of Synoptic Meteorological Observations (SSMO) and local consulting reports. Three wave regimes occur in Puerto Rico waters: 1) easterlies seas, 2) North Atlantic wave regime, and 3) Caribbean wave regime. The easterlies produce low energy seas that approach from the northeast to southeast affecting all of the Island's waters, except for the leeward west coast. The North Atlantic wave regime consists of waves generated in middle latitudes, that can travel long distances from the generation location to Puerto Rican waters.

The west and north coasts have deep water wave heights from 1.2 to 1.8 meters with occurrence of 25 to 10 percent respectively during a one year period (SSMO). Highest short period waves occur from May to September and long period waves are more frequent from January to July. Swells approaching from east and northeast are the most frequent with wave heights ranging from 0.3 to 3.6 meters. Wave heights of more than 4 meters are less than 5 percent occurrence. During storm conditions, the normal swells shift to higher amplitude waves.

Wave energy decreases toward the south and east coasts. Wave heights for the Caribbean wave regime are smaller than the North Atlantic, but higher than east coast seas. [Lugo, *et al*. 1994] Reduction in wave height is caused by an increase in island sheltering and because Caribbean and easterlies waves are lower energy. In eastern waters, more waves are of short period (less than 6 seconds) and low amplitude (from 0.3 to 0.92 m); generated by the combination of local sea breezes and easterlies. The strength of seas varies according to seasonal trends with the highest waves during summer and winter when the easterly breeze is stronger. Waves with periods of 6 seconds occur from October and December.

The combination of local shadow zones from the prevalent Trade Winds, wave refraction due to bottom topography, and the interference patterns created by multiple wave sources creates complex wave patterns between the closely spaced Virgin Islands. Even under the "normal" conditions treacherous waves may develop in narrow channels between the islands due to the focusing of wave energy by the bottom topography.

Winds and Hurricanes

Puerto Rico and the Virgin Islands are subject to easterly seas of 3-5 feet under steady Trade Wind conditions, with shadow zones commonly found toward the western end of the individual islands. The east-west orientation of the PR-VI platform causes north-south gradients in the surface wave field so that under northeasterly winds the north coasts are exposed to wave action and the south coasts are protected. This reverses under southeasterly winds and is modified by the land-sea breeze diurnal cycle. During the winter months large, surfer-friendly, swell arrives every couple of weeks along the north coast and some of it squeezes through the exposed passages between the islands. Extreme wave events accompany the arrival of tropical storms and hurricanes.

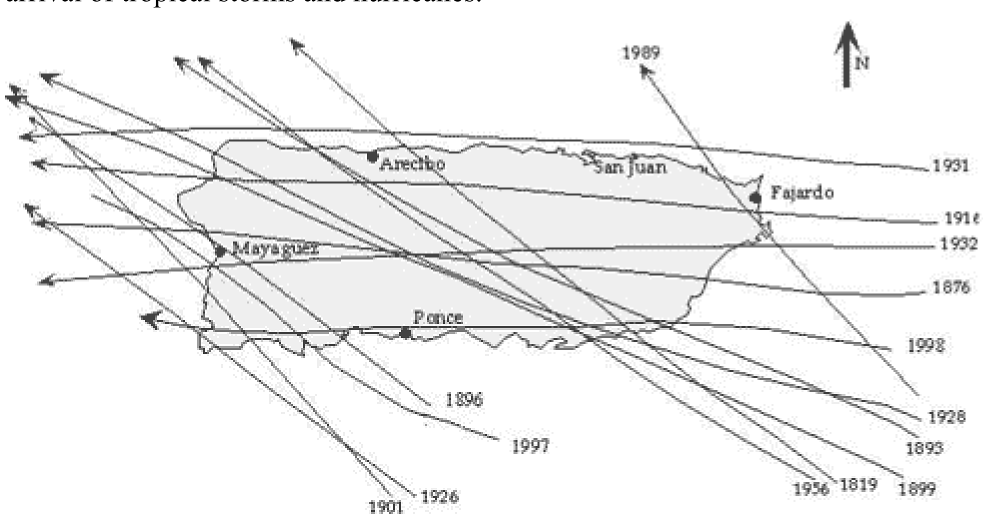

Figure 3. Hurricane tracts crossing Puerto Rico

Hurricane recurrence studies to 1998 reported more than 130 hurricanes in the Tropical Atlantic zone with 21 coming within 60 miles of Puerto Rico. [Neumann, *et al*., 1978; pers. data to 1999] About 30 hurricanes passed less than 400 kms south or north of San Juan from since 1940 (Figure 3). Extratropical storm systems are significant energy contributors to the north, northeast and northwest coast of Puerto Rico. These storms are very well organized systems of low pressure generated in high latitudes of the Atlantic Ocean. The swells from these events have the capability to generate significant wave power upon reaching the coastal areas. The Caribbean Sea is a semi-enclosed basin bounded by the Lesser Antilles to the east, the Greater Antilles (Cuba, Hispaniola, and Puerto Rico) to the north, and by Central America to the west. Passages between the various islands allow the inflow of North Atlantic, Tropical Atlantic, and Equatorial waters into the basin. The main outflow is through the Yucatan Channel between Cuba and the Yucatan Peninsula.

Water Bodies and Their Circulation

Caribbean waters are well stratified with depth which means that at different depths the fluid is moving in different directions, according to the sources and sinks for each water mass. In the ocean around of Puerto Rico (and this varies within the Caribbean), we find the Caribbean Surface Water, the local mixed-layer, whose lower boundary is known as the seasonal thermocline (technically it is the pycnocline but these two boundaries approximately coincide in depth); Subtropic Underwater to about 180m; Sargasso Sea Water to about 325m; Tropical Atlantic Central Water to just over 700 m; Antarctic Intermediate Water to 900m; and North Atlantic Deep Water reaching the bottom. The island passages do not allow Atlantic bottom water to enter the Caribbean.

The structure and composition of the Caribbean Surface Water, that in which most human activity occurs, exhibit a well defined seasonal pattern. In the northeastern Caribbean Sea the depth of the thermocline reaches a maximum of close to 100 m in the spring (January-March) and a minimum in the order of 25 m in the fall (September-October). Density, temperature, and salinity follow the same seasonal pattern with temperatures ranging from 26 to 30 °C and salinities from 36.3 to 34 PSU, respectively. The large range in offshore surface salinities is due to the northwards advection-mixing of South American riverine outflow in the eastern Caribbean Sea, specially from the Orinoco River; the seasonal surface salinity range is therefore narrower northwards into the North Atlantic. While the Orinoco effect creates a seasonal north-south surface salinity gradient in the eastern Caribbean, the Amazon River outflow becomes entrained in pools or eddies that after a circuitous trajectory through the Tropical Atlantic arrive at the Windward Islands as pools of green (high chlorophyll content, low salinity) water and enter the Caribbean from the east.

The mean circulation pattern of the wind-driven surface waters around the PR-USVI-BVI shelf is in a west-southwest direction; these waters join the general western flow of the Caribbean towards Yucatan Strait. This archipelago is bounded to the east by Anegada Passage and to the west by Mona Passage, both of great strategic and economic importance to the region (see figure 1).

In the Caribbean Sea the meridional distribution of the zonal wind stress generates a circulation cell where deep waters upwell along the north coast of South America and surface waters (enriched by upwelling and by the Orinoco loading) are advected northwards into our region, specially during the fall season. Satellite images in the visible spectrum (CZCS and SEAWIFS) clearly show the meridional spreading of green water in the eastern Caribbean. The northward edge of the Orinoco plume does not extend far to the north of PR. A persistent feature of the geostrophic flow south of PR is the generally eastward transport in the upper 100 m, in a direction that is the opposite of the expected westward advection of Caribbean Sea waters. Eastward geostrophic flow is limited to near surface waters, while deeper flow is generally westward . These observations are consistent with a net eastward geostrophic transport in the northeastern Caribbean, south of the Puerto Rico - Virgin Islands platform.

In the North Atlantic, the curl of the wind stress induces a large-scale Sverdrup transport towards the south that is then compensated by the intense northwards flowing Gulf Stream along the east coast of the U.S. The northeastern Caribbean receives part of this large-scale, climatological, southwestward transport. The convergence of these two distinct, Caribbean and North Atlantic, dynamical regimes defines our region as a boundary zone, with the edge of the green Orinoco plume often referred to by local researchers as the Caribbean Front.

There are no named current systems in our vicinity, which is not characterized by persistent extreme surface currents. The main axis of the Caribbean Current flows south of us, from the southeastern Antillean passages, through roughly the north-south center of the Caribbean Basin, west of Jamaica, and out through the Yucatan Channel. Seasonal changes associated with the north-south excursion of the Inter Tropical Convergence Zone (ITCZ) result in maximum mean surface currents in the central Caribbean during the summer.

Superimposed on the mean circulation, tidal currents are the dominant component of the offshore currents; this is to be expected given the oceanic character of our region. The oscillatory, usually elliptical, tidal flows are mostly cancelled (vector averaged) in the calculation of the mean flow. In the open waters of Mona Passage typical peak tidal currents are in the order of 50-75cm/sec, corresponding to mean speeds over a tidal cycle of 25-30 cm/sec, whereas the mean resultant velocity (the vector average) is only about 15 cm/sec. The mean transport through Mona Channel is of 1-2 Sv into the Caribbean (one Sv = one million cubic meters per second). The tidal current ellipses in surface and near-surface waters in Mona Passage are mixed semidiurnal and rotate in a clockwise sense. Tidal currents vary in magnitude in phase with the astronomical tidal forcing cycles of perigee-apogee and lunar declination. Due to the highly stratified nature of Caribbean waters current speeds drop quickly with depth below the mixed layer.

Low frequency variability at time scales of weeks and months is additionally observed in current time series in the region. As an example of counterintuitive flows consider the trajectory of a surface drifter deployed north of Puerto Rico in October 1980. The trajectory followed by this drifter started initially in a southwestward direction and then turned eastward along the north coast of Puerto Rico before describing a large anticyclonic gyre. This drifter passed very close to its initial position four months after deployment. Note that the long-term mean is in the "right" direction but the instantaneous velocities at short time scales are not.

During the passage of Hurricane Georges on September 22, 1998 currents of nearly 150 cm/sec were measured at a depth of 34 m in the western Mona Passage.

Satellite altimetry and numerical modeling studies, have shown high levels of mesoscale activity superimposed on, or averaging into, the mean circulation of the Caribbean Sea and of the western Tropical Atlantic to the east. Just upstream from the eastern Caribbean, these mesoscale features consist of anticyclonic eddies that arrive at the eastern Caribbean from interaction of the equatorial long-wave field with the Brazil Current Retroflection. Model simulations show the dissipation of these eddies upon impact with the southeastern Antilles, in the vicinity of Barbados and the transfer of mass, energy, and vorticity into the Caribbean resulting in the spawning of new eddies west of the islands. Both cyclonic and anticyclonic eddies have been observed inside the Caribbean Basin where they are advected westward, in the direction of the mean flow. Modeling studies show anticyclonic eddies reaching all the way to the Yucatan Channel where they have a profound effect on the Loop Current in the Gulf of

Mexico. Several mechanisms have been proposed for the formation of eddies inside the Caribbean Sea: island-flow dynamics, bottom-flow dynamics (due to the Aves Ridge and other bathymetric features), and eddy-boundary dynamics.

Coastal currents around PR-USVI are mainly tidally and wind driven. Whereas the tide along north and western Puerto Rico is mainly semidiurnal (two cycles per day), along the south coast the diurnal (one cycle per day) component predominates. The narrow and shallow shelf is in most places directly exposed to the open ocean, especially along the north coast. With the exception of bays and lagoons coastal flows are steered by the coastline-shelf topography and are therefore east-west along the north and south coasts, north-south in Mona Passage, and variable on the shallow VI platform. Typical peak tidal speeds of 10-20 cm/sec have been observed at numerous sites in the region; the mean vector velocity is usually less than 5 cm/sec. The typical pattern is that of oscillatory currents parallel to the coastline.

The local wind stress, dominated by the easterly Trade Winds, pushes surface waters towards the west, the same direction as the large-scale offshore mean flow. Coastal geomorphic net drift indicators also show the westward dominance on the north coast. [Morelock, et al., 1985] However, during times of weak easterly winds near bottom waters are commonly observed to flow towards the west. This behavior is known to occur along the north and south coasts of PR and has been attributed to

- a reverse pressure gradient resulting from the action of the mean flow on the abrupt island topography, and/or
- a mean eastward external geostrophic transport

Specific examples for Mayagüez (west coast of Puerto Rico) and Guayanilla (a protected bay along the south coast) reveal the different diurnal vs. semidurnal tidal regimes. The mean speeds (scalar means) of the currents in Mayagüez-Añasco Bay are always larger than the net speeds (resultant vector) as is typical of oscillatory currents such as tidally dominated flows. These currents flow back and forth along an axis and result in a small net transport towards the south. The net flow represents what is left over after subtracting the oscillatory tidal flow, while the mean flow is roughly half the tidal current amplitude. The situation in the MAB is that of a semidiurnal tidal current with a maximum amplitude of about 20 cm/s, typically 10-14 cm/s, that is amplified in one preferred direction along its principal axis of oscillation due to the presence of a large-scale mean flow (the net flow). A net south flow can be ascertained from the geomorphic data presented in Grove. [1998]

The subsurface currents in Guayanilla Bay are tidally driven, following the prevailing diurnal tide with a weak semidiurnal component. Tidal current vectors rotate along a topographically flattened tidal ellipse in a clockwise sense. As expected, the tidal currents lag the tidal elevations by a 6 hour time lag. These tidal currents are bottom intensified and could well account for the high levels of turbidity observed in Guayanilla Bay. Residual near-bottom currents enter the bay along the eastern side of the channel and exit along the western side, suggesting a counterclockwise residual flow within the bay. Tidal volume exchange across the entrance channel exceeds previous estimates and is calculated in the average to be at least in the order of 15-40% of the volume of the bay. The mean observed currents are from Tallaboa Bay into Guayanilla Bay (east to west).

Tides

Tides throughout the northeastern Caribbean Sea exhibit a complex behavior. Along the south coasts of PR and Vieques the tide is principally diurnal while the tide along the north and west coasts of PR is semidiurnal. The diurnal band actually extends south across most of the Caribbean and is surrounded by areas where the semidiurnal tide is stronger. This is further complicated as we approach Vieques due to the presence of the semidiurnal anticlockwise rotating amphidromic system, centered south of St. Croix. Accurate numerical prediction of the oceanic tide close to the islands becomes rather difficult due to the steep bathymetry of the Antillean Island Arc (and the lack of high resolution bathymetry) and the proximity of the M2, N2, and S2 amphidromes. For the prediction of the coastal surface tide we have used the TIDE.1 software from Micronautics; this program uses the tidal constants at NOAA tidal stations to predict tidal elevations and also provides useful astronomical data.

Vertical oscillations in the water column driven by the barotropic tide, known as internal tides, are observed to extend from the seasonal thermocline to the maximum observed depth. The amplitudes of these tidal oscillations are inversely proportional to the stability of the water column, resulting in a general increase in amplitude with increasing depth.

Shelf morphology and sediments

Composition of the coastlines can also be categorized as:

1. hard (resistant) composed of limestone or igneous rock
2. semi durable composed of eolianite or beachrock which is less cemented and more erodible than the first group
3. erodible unconsolidated deposits such as beach, alluvial fan, alluvial plain, or dune

Another category, mangrove shorelines, lies between group 2 and 3, and often shows accretion. These mangrove shorelines are restricted to low energy conditions. Morelock and Trumbull, 1985; Barreto, et al., 1994

Insular shelf and slope morphology varies greatly in Puerto Rico with differences in shelf width, shelf and slope inclination, shelf break depth, and the extent of natural barriers. The shelf has inclinations ranging from 0.1 to 3.0 degrees and widths ranging from 0.3 to 21 kms. The insular shelf is extremely small in comparison to continental shelves.

On the west coast, moderate shelf inclination varies from 0.1 to 0.5 degrees with shelf widths ranging from 0.4 to 6.6 kms. On the north coast, the shelf inclination varies from 0.22 to 11 degrees. The shelf width ranges from 0.3 to 3.2 km.

The flattest shelves were found on the east and south coasts, where the platform is inclined from 0.1 to 0.7 degrees. On the east, shelf inclination varies from 0.1 to 0.3 degrees. On the south, shelf inclination is from 0.1 to 0.7 degrees. The south coast has a wider insular shelf ranging from 5 to 21 kms. The shelf break is in depths of 10 to 40 meters around the Island. On the west and north, the shelf break is at 10 to 40 meters of depth. On the east, the shelf break is 15 to 30 meters deep and the south coast shelf break ranges from 15 to 40 meters.

The thin, recent, unconsolidated sediment cover of the Puerto Rico Insular shelf is very diverse with little lateral continuity, because of large variations in physical and biological parameters controlling sedimentation. The north shelf is subjected to the highest wave energies, largest influx of river sediment, and has few coral reefs. Except for inner shelf zones, much of the sediment there contains enough silt and clay to be described as mud. The lower wave energy shelf around the rest of the Island is dominated by coral reefs and mangrove forests that play important roles in the distribution of sediment. The dominant sediment type is calcareous skeletal sand. There are extensive white carbonate sand facies on the larger carbonate platforms of the west, south and east insular shelf. Sediment patches with more than 50% mud are present across the shelf at mouths of the major rivers. The upper insular slope is blanketed by a sandy mud containing less than 50% sand. The most important physical factors controlling the type of sediment are: wave energy, dilution by rivers and presence of reefs. Schneidermann, *et al*., 1976 Other environmental parameters including, bottom topography, depth, coastal configuration, coastal rock type, reefs and mangroves, affect carbonate sedimentation by controlling the terrigenous sediment supply. Sediments on the insular shelf are mapped in three groups for this report (Figure 4):

- Carbonate sands, hardground and reef
- Terrigenous sands and muds with carbonate sands and hardground
- Terrigenous muds

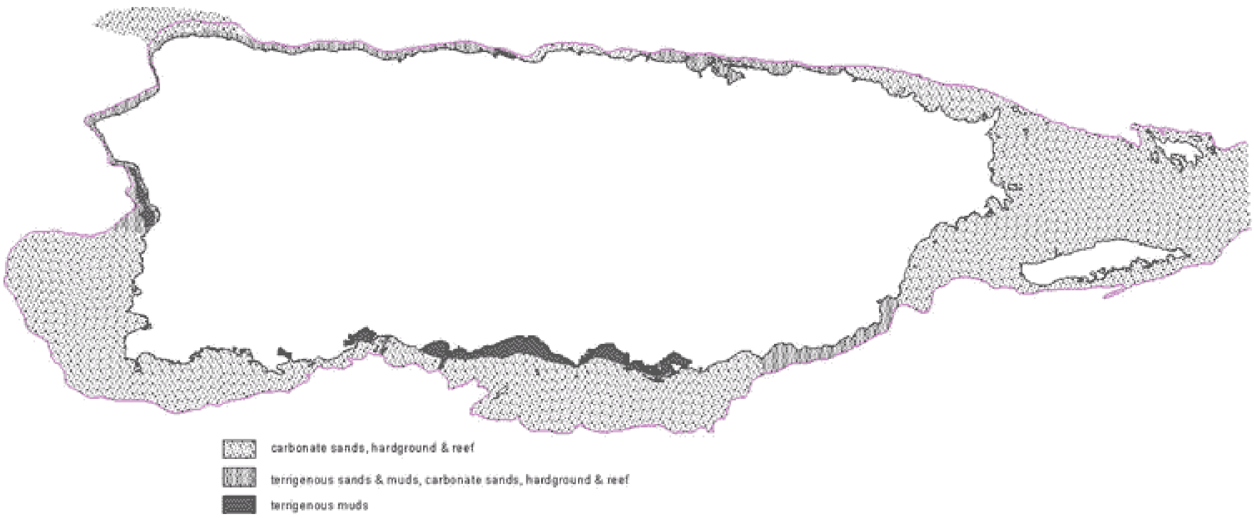

Figure 4. Shelf sediments, Puerto Rico

Terrigenous sand facies are associated with river discharge or coastal erosion. At times, the river discharge disperses laterally (mainly to the west on the north coast) on the inner shelf, and at other times, the fluvial load is transported offshore during floods. Pilkey, et al., 1978

Mixed sediment facies are the result of river sediments mixed with local in situ carbonate production. Variability in the components of the mixture along the inner shelf depends on the proximity of local sediment sources and the physical forces that produced mixing.

Most of the hardgrounds such as eolianites, beach rock, dead coral reef and rock promontories are found along the inner shelf of Puerto Rico. Extensive and continuous hardgrounds are present along the northwest and northeast inner shelf. These are eolianites, dead coral and beach rock with very little sand. Hardground constitutes the outer rocky shelf from La Parguera to Ponce, but the nearshore is sand and mud.

Shallow water and coastal habitats - coral, *Thalassia*, mangrove

Three tropical habitats are present: coral reefs, *Thalassia* meadows, and mangrove forests. The rest of the insular shelf is sediment covered or hardground. The general distribution of coral reefs has been mapped Morelock, pers. data; Garcia, *et al*., in press) and an image analysis program of mapping is being conducted by NOS-

NOAA. The distribution of mangrove forests is mapped from USGS topographic sheets, but these are not current. Very little mapping has been done of the *Thalassia* meadows.

Mangrove

Mangrove forests can be found around most of the Island, but the largest forests are at the east end of the north coast around to the north part of the east coast and the south coast wrapping around to the southern part of the west coast (see figure 1). The mangroves form the shoreline in most areas, except for the north coast where they lie behind beach deposits or in interior river basins. Although no accurate measurement is available, Wadsworth [1968] reported more than 150 square miles in seven of the northeast mangrove forests. Mangrove lagoons are fairly common around the Island, forming distinctive habitats.

Reefs

Three types of reefs are recognized on the Puerto Rican shelf. Coral reefs are mostly found as fringing, patch, shelf and submerged shelf-edge reefs. Fringing reefs occur adjacent to land with little or no separation from shore. A low input of terrigenous sediment is important, and the best-developed fringing reefs occur off shorelines where rainfall is low, there is little relief, or the hillsides are stabilized by heavy vegetation. Clearing of natural vegetation has resulted in the loss of most of these reefs in Puerto Rico.

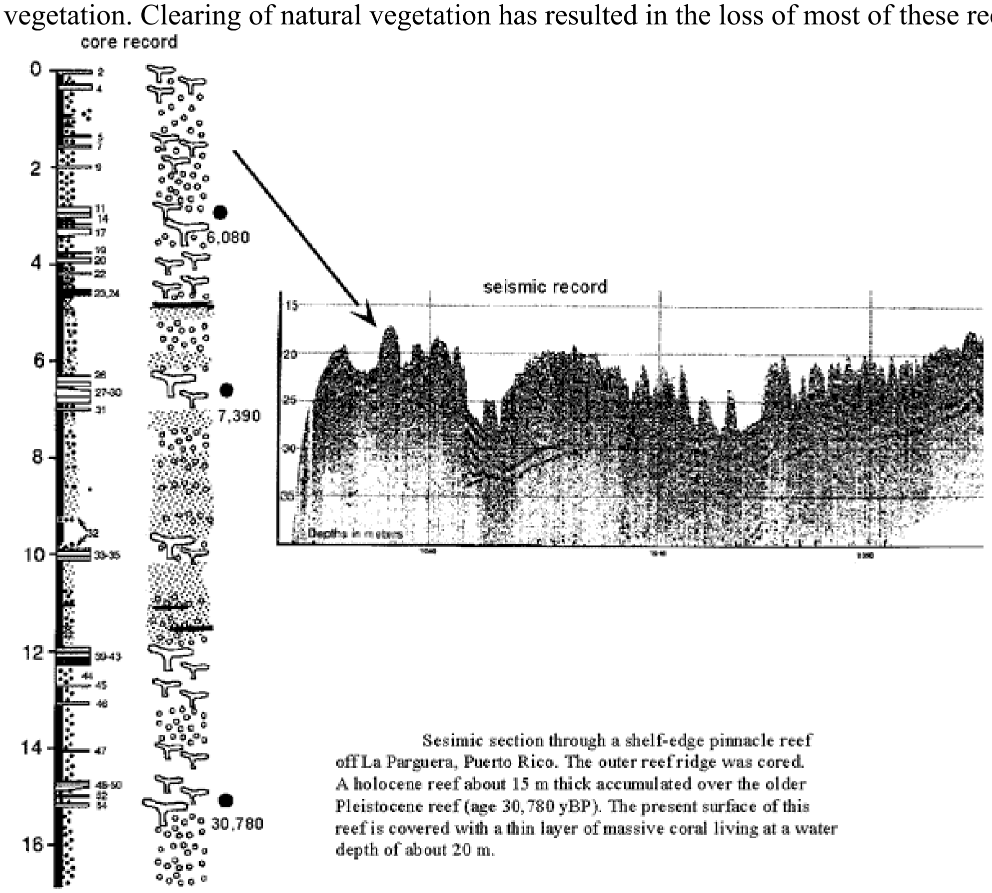

Figure 5. History of Holocene reef development

Fringing coral reefs are found throughout most of the northeast, east and southern coastlines associated with erosional "rocky" features of the shelf. Patch reefs are smaller features, roughly equant in plan view. While many of these have reached sea level, many Puerto Rico patch reefs are submerged with the tops more than four meters below the water surface. Most of the patch reefs in Puerto Rico are on the open shelf as pinnacles. Submerged shelf-reefs are Caribbean platform margins that presently sit in water depths greater than 15 meters after being flooded by rising sea level 6,000 - 10,000 years ago. Since then, they have not been able to offset the effects of deepening water and limiting base area, so many of them have been left behind (Figure 5). While coral and other calcifying organisms occur along most of these margins, they are not producing carbonate at a rate sufficient for the reef to 'catch up' with sea level. The present influx of sediments and nutrients into reef areas is actually causing loss of the existing coral. Barrier reefs are separated from the shoreline by a moderately deep body of water - the lagoon, which has a characteristic sediment facies. These may form at the shelf edge, or may be located more inshore, usually on an antecedent break in slope. Barrier reefs are not present, but instead a common reef type in Puerto Rico has been called a shelf reef, which falls between the criteria for barrier or patch reefs. [Morelock, et al., 1977] They are similar to patch reefs in shape, but are usually larger, more linear, and are aligned in roughly shore-parallel sets (Figure 6). The sediments behind these reefs are similar to those in front; no lagoonal type sediments occur.

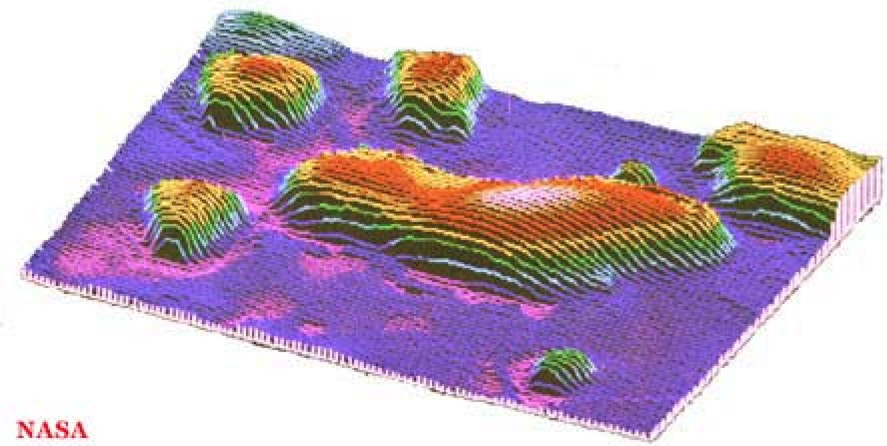

Figure 6. Shelf reefs and patch reefs

Rock reefs are submerged hard substrate features of moderate to high topographic relief with low to very low coral cover, mostly colonized by turf algae and other encrusting biota. Coral colonies are abundant in some cases (*i.e*. *Diploria* spp., *Porites astreoides, Acropora palmata*), but grow mostly as encrusting forms, providing minimal topographic relief. These are coastlines subjected to high wave energy, abrasion and sedimentation stress. The underlying substrate may be any rock type, more commonly igneous rocks, eolianites, beachrock. These reefs are important habitats for fish and macroinvertebrates since they usually are the only available structure providing underwater topographic relief in these areas. Some have developed on submerged rocky headlands and are characterized by the development of coralline communities adapted to grow under severe wave action and strong currents. They are mostly flat, eolianite platforms ranging in depth from 5 to 30 meters largely covered by turf algae, encrusting sponges and scattered patches of stony corals. Coral colonies are typically encrusting forms, perhaps an adaptation to the extremely high wave energy which prevails seasonally on the north coast.

Mud reefs are formed in shallow wave protected areas where secondary frame builders such as *Thalassia* and *Porites* can grow upward while trapping sand and mud.

Corals grow throughout most of the insular shelf of Puerto Rico (see figure 1), yet the physical, climatological and oceanographical conditions which influence coral reef development vary markedly among the insular shelf segments. The shelf of the north and northwest coasts is narrow (less than 3 Km) and shallow communities are subjected to mechanical abrasion and sedimentation produced by high waves, particularly during winter, as cold fronts from the North Atlantic reach the Caribbean Antilles. These are local rock reefs with coral cover of less than ten percent. They are too small areally to appear on the map. The west coast receives substantial sediment and nutrient loading from river discharge. The northeast coast has a wider shelf, partially protected from wave action by a chain of small emergent rock reefs aligned east- west between the main Island and the Island of Culebra. The northeast coast is upstream from the discharge of major rivers resulting in more appropriate conditions for coral reef development. The east coast is characterized by extensive sand deposits (unconsolidated) which constrain coral reef development, but scattered rock formations within this shelf section have been colonized by corals. Isla de Culebra and Isla de Vieques lie at the eastern boundary of the Puerto Rican shelf in clear waters that promotes growth of coral.

The south coast has lower wave energy and the insular shelf is generally wider with a broad carbonate shelf from Mayagüez on the west to Guanica on the south coast and from Ponce to Arroyo on the south coast. Rivers with smaller drainage basins discharge on the southeast coast and only small intermittent creeks discharge on the southwest coast, which has been classified as a semi-arid forest. The south coast also features a series of embayments and submarine canyons. [Acevedo and Morelock, 1989] Small mangrove islets fringe the south coast and many of these provide hard substrate for coral development.

The shelf-edge drops off at about 20 meters with an abrupt, steep (sometimes vertical) slope. At the top of the shelf-edge lies a submerged coral reef formation which gives protection to other reefs, seagrass and mangrove systems of the inner shelf. The southwest coast is relatively wide and dry, with many emergent and submerged coral reefs that provide adequate conditions for development of seagrass beds and fringing mangroves. Modern shelf-edge reefs formed in Puerto Rico some 8,000 yrs bp (see figure 5 ; [Hubbard, et al., 1996]). Inner reefs, formed on top of submerged banks and sandy bottoms of the flooded erosional shelf are believed to be about 6,000 years old. The rise in sea level associated with the last Pleistocene glaciation flooded the lower limestone ridges of the shelf, providing appropriate sites for coral growth and subsequent reef development. [Glynn, 1973] Cross-shelf seismic profiles provided by Morelock, *et al*. [1994] support the theory of Kaye (1959), which states that reefs on the southwest coast developed on drowned calcarenite cuestas formed as eolianite structures parallel to the coastline during the Wisconsin glacial period. Proper substrate, depth, and water transparency conditions in the southwest coast allowed for extensive development of coral reefs during the mid-Holocene period.

The outer shelf is irregular as a consequence of the karst bedrock surface and subsequent reef growth. Holocene and possibly Pleistocene deposits form a thin veneer over the late Pleistocene erosional surface. The shape and development of both the reef and the unconsolidated deposits have been strongly influenced by the morphology of the surface, the duration of inundation, the availability of sediment, and the energy of the environment. The shelf edge is formed by an almost continuous submerged reef. This reef is a double ridge along much of its length. The inner ridge is a platform surface 14 to 18 meters below sea level; the crest of the narrow outer reef ridge is at 16 to 22 m. The valleys between the ridges range from 20 to 35 m deep.

Population development and land use - effects from urban and industrial activities (including sewage)

Only two land use studies have been done in Puerto Rico, one for DNER in 1970 and another for EPA in 1997. A general pattern of conversion of naturally vegetated areas into sugar cane farmland began with the Spanish colonization. A later pattern was conversion of mangrove coastal vegetation to coconut groves. This change of cover led to excessive sediment runoff and the loss of many areas of coral.

Industrialization and urbanization that gained momentum after World War II has greatly increased the influx of sediments onto the shelf and brought a new problem, nutrient influx. The past decade has been marked by rapid urbanization of coastal areas with both a heavy increase of sediment influx from home construction and a heavy load on the existing sewer facilities. Visual examination of the shelf reefs and rock formations suggest that at least half of the existing living coral has been lost in the past five decades. Morelock, 1997

Sewage and solid waste disposal have been a major problem in terms of environmental quality. Both ocean outfalls and interior discharge are shown in figure 1. This is an island of almost four million people occupying 3,500 square miles; a population density of 1,090 people per square mile.

Coastal erosion and landfill

Coastal erosion is not severe, but much of the coast does show erosion (Figure 7; Morelock, 1984). Movement of this sediment into coral reef areas has occurred to only a small extent. However, the high rate of erosion east of Jobos Bay has resulted in sediments covering the lower 20 feet of the fringing reef at Cayo Caribe.

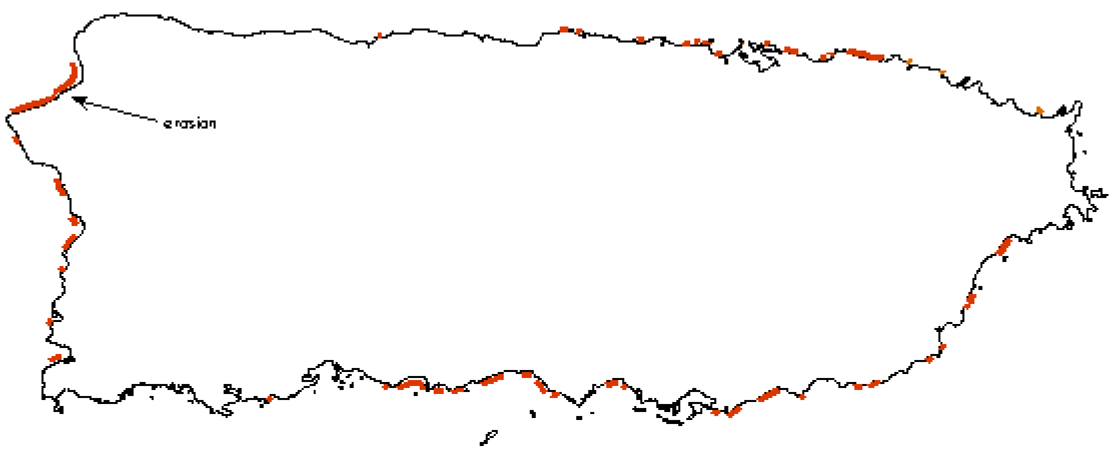

Figure 6. Areas of coastal erosion

Protective measures

Very little has been done to preserve the natural features of the marine environment in Puerto Rico. One area has been designated a US National Estuarine Sanctuary (Jobos: under NOAA supervision) and several areas have been designated as reserves by the Puerto Rico government.

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