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Potential Effects of Runoff, Fluvial Sediment, and Nutrient Discharges on the Coral Reefs of Puerto Rico

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ABSTRACT

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Coral reefs, the foundation and primary structure of many highly productive and diverse tropical marine ecosystems, have been degraded by human activity in much of the earth's tropical oceans. To contribute to improved understanding of this problem, the potential relation between river sediment and nutrient discharges and degradation of coral reefs surrounding Puerto Rico was studied using streamflow, suspended-sediment, and water-quality data. Mean annual runoff for the 8711 km^2 island is 911 mm, about 57% of mean annual precipitation (1600 mm). Mean annual suspended-sediment discharge from Puerto Rico to coastal waters is estimated at 2.7–9.0 million metric tonnes. Storm runoff transports a substantial part of sediment: the highest recorded daily sediment discharge is 1–3.6 times the mean annual sediment discharge. Hurricane Georges (1998) distributed an average of 300 mm of rain across the island, equivalent to a volume of about 2.6 billion m^3. Runoff of more than 1.0 billion m^3 of water and as much as 5 to 10 million metric tonnes of sediment were discharged to the coast and shelf.

Nitrogen and phosphorous concentrations in river waters are as much as 10 times the estimated presettlement levels. Fecal coliform and fecal streptococcus concentrations in many Puerto Rico rivers are near or above regulatory limits. Unlike sediment discharges, which are predominantly episodic and intense, river-borne nutrient and fecal discharge is a less-intense but chronic stressor to coral reefs found near the mouths of rivers. Negative effects of river-derived sediment and nutrient discharge on coral reefs are especially pronounced on the north, southwest, and west coasts.

ADDITIONAL INDEX WORDS: *Anthropogenic disturbance, degradation, fluvial sediment.*

INTRODUCTION

Coral reefs are the foundation and primary structure of many highly productive and diverse marine ecosystems in Puerto Rico (Figure 1). Healthy reefs provide habitats for juvenile and adult marine fauna, dampen wave energy, provide a source of carbonate sand grains for beaches, and are a favorite destination for recreational users. Reefs are a major provider of food to local communities, and through fisheries, are a source of significant annual income. Stressed reefs are commonly overrun with algae and boring worms that, along with episodic storms, contribute to the reduction of the structure and protective capacity of the reef.

Coral reefs thrive within a limited range of temperature, salinity, and turbidity. Many reefs in Puerto Rico and throughout the world are in decline because of the effects of human activity, including increased terrigenous sediment input from modified watersheds; eutrophication caused by increased agrochemical and sewage discharge, dredging, groundings, and turbidity caused by boat and ship traffic; and increased water temperatures (GARDNER *et al.,* 2003; LUGO *et al.,* 2000; MACDONALD, 2007; PANDOLFI *et al.,* 2003; RAMOS-SCHARRÓN; WILKINSON, 2000). WEIL (2004) suggests that terrestrial sediment in runoff may be a source of pathogens that affect coral reefs. Many of the coral reefs of Puerto Rico, along with many other Caribbean reefs, are affected by pathogens (JAMESON *et al.,* 1995; TORRES and MORELOCK, 2002). The Caribbean has been described as a "disease hot spot" because of the fast emergence, high prevalence, and virulence of coral reef diseases and syndromes (WEIL, 2004). Although only about 8% of the world's coral reef area is found in the greater Caribbean, 66% of all coral reef diseases and syndromes were reported there in the year 2000 (WEIL, 2004). However, the problem is global; at least 106 species of corals in 54 nations have been affected by 29 diseases and syndromes (GREEN and BRUCKNER, 2000; WEIL, 2004). BURKE and MAIDENS (2004) related a variety of physical, socioeconomic, and environmental effects on coral reefs to highlight the strong anthropogenic impact on coral reefs in the Caribbean region and note that these reefs are among the most vulnerable in the world.

Coral reefs typically flourish in waters that are oligotrophic (nutrient-poor). Changes in nutrient concentrations in coral reef areas, commonly caused by increased sediment and nutrient discharge from rivers, can fundamentally alter the food web in these ecosystems. High nutrient concentrations promote the proliferation of plankton, which lowers light transmissivity and slows the activity of symbiotic algae living in

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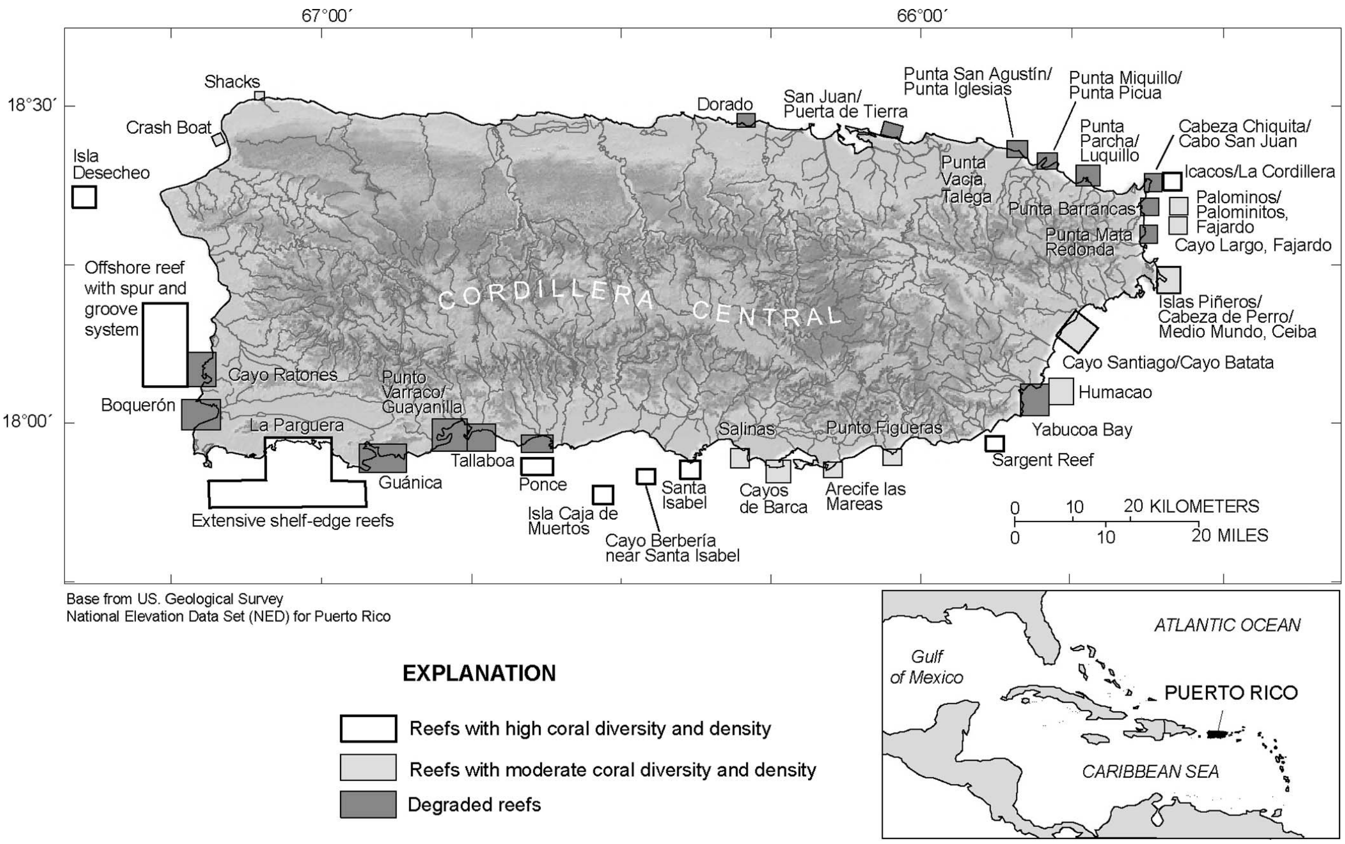

Figure 1. Location and condition of major coral reefs around Puerto Rico. Data from Goenaga and Cintrón (1979) and Simonsen (2000).

coral tissues, thereby slowing coral growth rates. High nutrient concentrations also promote bioerosion by boring sponges and annelids (Highsmith, 1981). Perhaps most importantly, in mesotrophic and eutrophic waters algae and sponges have the capacity for the rapid uptake of nutrients and hence faster growth rates, which gives them a competitive advantage over corals (Johannes, 1975). Algae and sponges, however, do not build the massive and complex reef structure that supports the plentiful and diverse ecosystem that is characteristic of coral reefs.

Puerto Rico is an excellent location to study the effects of fluvial sediment and nutrient discharge on coral reefs. Whereas many reefs develop in clear, nutrient-poor, tropical waters, well removed from the mouths of perennial rivers, the reefs surrounding the mountainous island of Puerto Rico regularly experience influxes of large volumes of river-derived sediment. Before the widespread development of agriculture and industry, nutrient and sediment discharge to a large part of the coast and shelf would have been negligible, so marine waters would have been relatively transparent except during and shortly after relatively uncommon storms. Apparently, most coral reefs of Puerto Rico endured the episodic influx of sediment and nutrients, perhaps because during these episodes of high discharge, mainly tropical disturbances such as hurricanes, waves and currents are also strong, which inhibits sediment deposition and promotes transport of the sediment to the shelf edge and shelf slope. Approximately 20% of the area of island is underlain by Tertiary limestone karst terrain, evidence of the reefs that thrived on extensive carbonate banks in this region during the last 50 million years (Figure 2A) (Monroe, 1976).

This study analyzed the magnitude, frequency, and distribution of river water and suspended-sediment discharge to the Puerto Rico coast to quantify their fluxes and estimate the potential effects on coral reefs. The island-wide average discharge of water and sediment discharge per storm and per year were estimated. The major processes that control (including a large 1998 hurricane) the transport and fate of river-borne sediment and nutrients in the shelf environment are discussed.

STUDY AREA

Climate, Physiography, Geology, and Geomorphology of Puerto Rico

The Cordillera Central region composes about 60% of the 8711-km² island of Puerto Rico and reaches a maximum elevation of 1338 m above mean sea level. Mean annual rainfall for the island for the period 1961 to 1990 was 1600 mm (Díaz *et al.,* 2004). Mean annual evapotranspiration varies across the island, ranging from 27% to 53% of annual rainfall in eastern watersheds (Larsen and Concepción, 1998). In

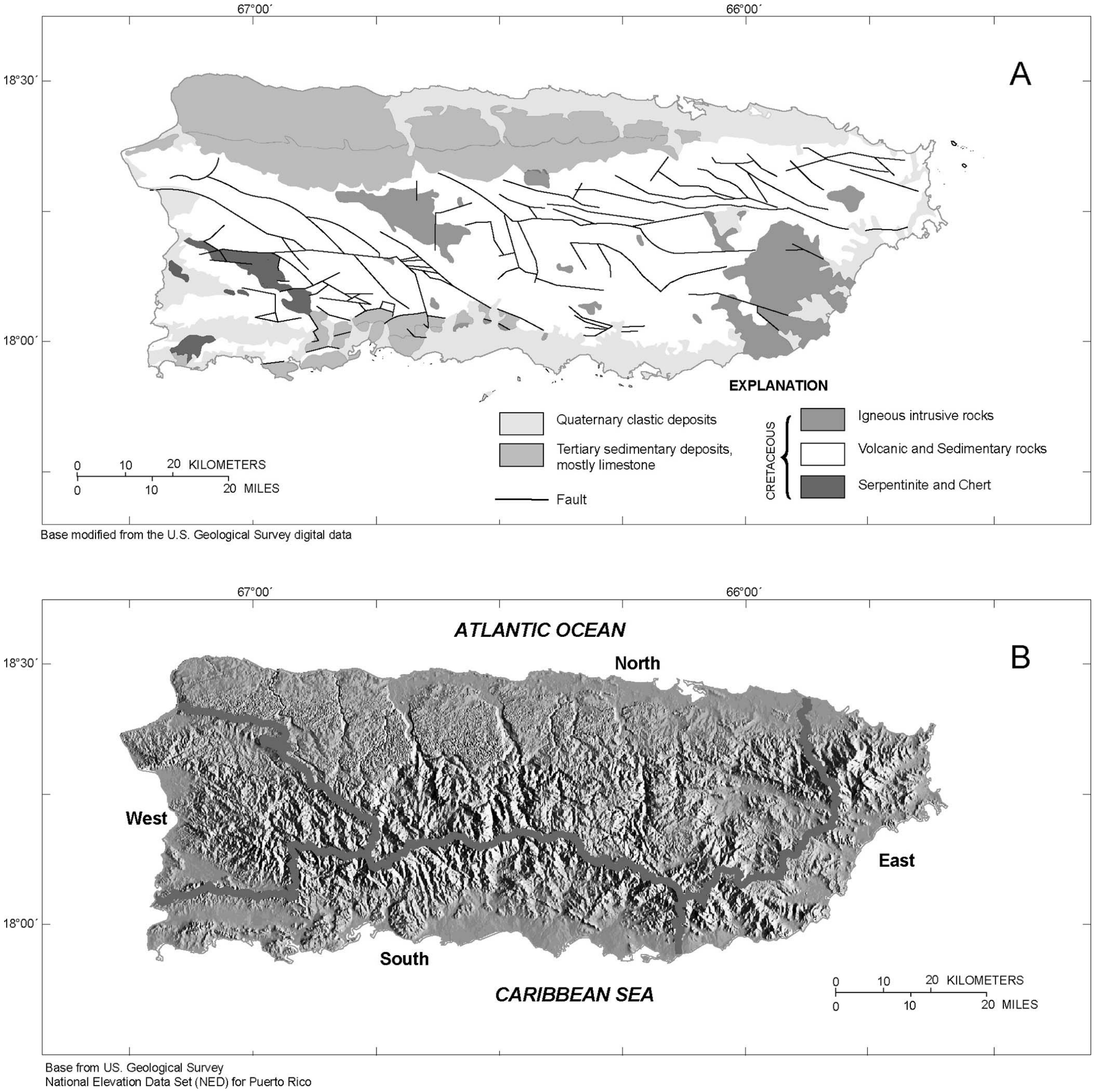

Figure 2. Geologic and physiographic setting of Puerto Rico. (A) General geology simplified from Briggs and Akers (1965). (B) Shaded-relief image derived from a 100-m digital elevation model showing dissected uplands and planar exposure of Tertiary sedimentary rocks along north–central and northwest coast. Cretaceous intrusive rock is expressed topographically as eroded, lower elevation surfaces. Zones indicate the four major runoff (climatological) regions of Puerto Rico (simplified from National Oceanic and Atmospheric Administration, 1999)

contrast, the mean annual potential evapotranspiration in dry southern coastal areas is estimated to equal or exceed mean annual rainfall (Calvesbert, 1970).

The island can be subdivided into four drainage regions: north, south, east, and west, largely based upon the configuration of the Cordillera Central (Figure 2B). The northern and eastern regions receive abundant orographic rainfall associated with northeast trade winds.

Runoff from intense precipitation delivered mainly by hurricanes and other tropical disturbances transports large volumes of sediment-rich waters to the coast and shelf (Gupta, 2000). A major hurricane passes over Puerto Rico, on average, once every 10 to 20 years (Neuman *et al.,* 1990; Scatena and Larsen, 1991). Winter frontal storms also produce substantial runoff that erodes and transports large amounts of sediment to the coast.

The combination of steep slopes, warm temperatures, high mean annual rainfall, episodic high-intensity storms, and deeply weathered soils developed on the Cretaceous volcaniclastic and intrusive rocks of the Cordillera Central results in a large number of landslides and debris flows, especially in areas that have been anthropogenically disturbed (Figure 2) (Larsen and Simon, 1993; Larsen and Torres-Sánchez, 1992, 1998). These landslides and debris flows produce large volumes of sediment that are available for transport by streams and rivers (Larsen and Santiago-Román, 2001).

Puerto Rico Coast and Shelf

The morphology of the coast and shelf of Puerto Rico varies from zones of rocky headlands at the northeast corner of the island, to alluvial plains along most of the southern and west coasts, limestone cliffs along the northwest coast, to alluvial plains with swamps and lagoons along the north coast (Warne *et al.,* 2005). Unlike many shelf settings around the world, where the shelf morphology and sediment distribution are relict, the Puerto Rico shelf morphology and sediment distribution are in equilibrium with modern processes (Pilkey *et al.,* 1978; Schneidermann *et al.,* 1976). The widespread calcareous sand substrates of the shelf indicate that much of the terrigenous sediments are transported to and deposited along the shelf edge and slope (Rodríguez *et al.,* 1992, 1998; Schneidermann *et al.,* 1976). Bush (1991) documented that storm-induced, across-shelf transport processes dominate, and he calculated that 90% of the river sediment discharged at the coast is transported to the shelf edge and slope within a few months.

Shallow littoral currents are to the west and generally shore-parallel, and the mean tidal range along the coast is 0.34 m (Puerto Rico Oceanographic Project, 1972). Ebb tides along the north coast can carry some sediment several kilometers to the east of the river mouths; nonetheless, the majority of the sediment discharged to the north coast is deposited to the north and west of the river mouths (Bush, 1991).

WATER QUALITY OF PUERTO RICO RIVERS AND COAST

The Puerto Rico Environmental Quality Board (2000) indicates that municipal and industrial point sources, landfills, flow regulation/modification, and debris and dredge spoils are major causes of poor coastal water quality. High ammonia (unionized), low dissolved oxygen, and high turbidity are also identified as important causes of poor coastal water quality (Puerto Rico Environmental Quality Board, 2000). Coral reefs growing close to sanitary discharge outfalls show proliferations of green algae, which commonly outcompete the corals for space by overgrowing them, resulting in increased coral mortality (Webb *et al.,* 2000). McDowell and Asbury (1994) evaluated nitrogen discharge from relatively undisturbed, forested watersheds of eastern Puerto Rico, and provide a baseline to evaluate nutrient concentrations in anthropogenically disturbed watersheds. They reported total dissolved nitrogen concentrations of about 0.15–0.25 mg L^{-1} equivalent to 4–9 kg ha^{-1} export of total nitrogen, and total dissolved phosphorous concentrations of 0.002 mg L^{-1} in eastern Puerto Rico streams.

REEFS OF PUERTO RICO

The areal extent of living corals (Figure 1) varied from less than 5% in areas affected by direct river discharge and sewage disposal to 50% to 60% for the offshore reefs around La Parguera in the southwest, when the last comprehensive assessment was published (Goenaga and Cintrón, 1979). Different reef types develop depending on substrate, water depth, water quality, and wave and current conditions. Rock reefs, which are shallow Quaternary eoleanite platforms that are thinly veneered by stony corals, are common along the north coast of the island (Goenaga and Cintrón, 1979). Patch reefs are common and are commonly intermixed with other reef types. Fringing reefs are common along the northeast and east coasts and are sometimes separated from the shore by a shallow lagoon. Bank or ribbon reefs, which develop on calcarenite ridges along the middle and outer shelfs, are common in the southwest. Shelf-edge and slope reefs, with a distinctive groove and spur structure, extend from the outer shelf down the insular slope to depths greater than 30 m. Shelf-edge and slope reefs, which are characterized by high coral density and diversity, are nearly continuous along the southwestern shelf margin (Goenaga and Cintrón, 1979). Coral reef diversity and density are greatest off the southwest corner of Puerto Rico (Figure 1).

Effects of Suspended Sediment and Sedimentation on Coral Reefs

Coral reefs grow within a limited range of temperature, salinity, nutrient, wave energy, and turbidity conditions. When conditions are outside one or more of these ranges, reefs become stressed (Rogers, 1977). There are a number of reef stressors, including high sedimentation rates; high water turbidity; extreme water temperatures; changes in salinity; high nutrient loads; eutrophication; physical damage by storms; overfishing; physical damage by boats, ships, and fishing gear; and atmospheric deposition of contaminants or pathogens by aeolian dust (Brown and Ogden, 1993; Glynn, 2000; Harvell *et al.,* 1999; Shinn *et al.,* 2000; Torres and Morelock, 2002) (Table 1). Indicators of coral reef stress include slow coral growth rate, coral bleaching, low coral-species diversity and low population density, high density of filamentous and fleshy algae, high density of sponges, and coral colonies covered by fine sediment.

Suspended sediment may contain organic matter that can serve as an energy source that promotes coral growth up to a maximum continual concentration of 10–20 m L^{-1} or a depositional rate of 200–1000 mg cm^{-2} d^{-1} (Rogers, 1977). Chronic concentrations or depositional rates above these levels cause a reduction in coral growth rates because of smothering and reduced light levels (Hubbard, 1986; Rogers,

Table 1. *Summary of major coral reef stressors.*

Reef Stress	Common Result of Stress	References
Sedimentation	Lower species diversity, with some species absent, less live coral, lower growth rates	Johannes (1975); Goenaga and Cintrón (1979); Rogers (1977, 1990); Velazco-Domínguez *et al*. (1985, 1986); Hubbard (1986)
Turbidity	Lower species diversity, with some species absent, less live coral, lower growth rates; shift of the lower limit of coral growth to a shallower depth, resulting in a compressed depth zonation among reef communities	Goenaga and Cintrón (1979); Rogers (1977, 1990); Acevedo and Goenaga (1986)
Temperature	Coral bleaching	Winter *et al*. (1998); Normile (2000); National Oceanic and Atmospheric Administration (2001); Wellington *et al*. (2001); Burke *et al*. (2004); Sammarco *et al*. (2006)
Changes in salinity	Coral mortality, coral bleaching	Goenaga and Cintrón (1979); Acevedo and Goenaga (1986)
High nutrient loading[1]	Replacement by algae	Gabric and Bell (1993)
Eutrophication[1]	Coral bleaching; replacement by algae	Bell (1992); Velazco-Domínguez *et al*. (1985, 1986)
Storms	Broken coral, sediment-covered coral	Shinn and Halley (1992); Vicente (1993); Rodríguez *et al*. (1994); Garrison *et al*. (2000)
Overfishing	Replacement by algae	Goenaga and Cintrón (1979)
Boats and ships	Broken corals, sediment-covered coral	Goenaga and Cintrón (1979)
African dust	Coral mortality from disease, contaminant deposition	Shinn *et al*. (2000)
Diseases	All above results	Bruckner and Bruckner (1997); Harvell *et al*. (1999); Green and Bruckner (2000); Kuta and Richardson (2002); Patterson *et al*. (2002); Smith *et al*. (1996); Weil (2004)

[1] High nutrient loading refers to the chronic influx of human-introduced nutrients to coral reef areas, whereas eutrophication refers to periodic nutrient levels that promote algal blooms and anoxia.

1990; Tomasick and Sander, 1985). Rogers (1977, 1990) proposed that (1) sediment influx of 200–1000 mg cm^{-2} d^{-1} and more is incompatible with healthy reefs; (2) continual suspended-sediment concentrations of 10–20 mg L^{-1} or more appear to be critically high; and (3) Secchi disk depths of less than 4 m probably indicate an environment in which coral reefs are stressed. In a study of coral cover and linear extension rates at five sites in southwestern Puerto Rico, Torres and Morelock (2002) documented sediment deposition rates that ranged from less than 1 mg cm^{-2} d^{-1} to approximately 10 mg cm^{-2} d^{-1}. They noted that among the species studied (*Montastrea annularis, Siderastrea siderea,* and *Porites astreoides*), *M. annularis* cover decreased substantially where sedimentation was high, whereas the cover of *S. sidereal* and *P. astreoides* was not affected.

Although coral polyps are capable of physically removing sediment, this action requires energy that then becomes unavailable for skeletal growth or reproduction; in situations where corals are covered with a thick layer of sediment, the colony quickly dies (Rogers, 1990). Reduced transparency of the water in which corals live limits the amount of light available for the symbiotic zooxanthellae. In addition to stress caused by smothering and reduced light transmission, high rates of sediment influx and resultant deposition covers hard substrates, thereby reducing locations available for coral larvae to become established and start new colonies.

In reef zones where sedimentation rates are high, Rogers (1990) suggests that, relative to areas with less sedimentation, there is (1) lower species diversity, with less sediment-tolerant species absent; (2) greater abundance of branching forms and species resistant to sediment and to reduced light levels; (3) less live coral; (4) lower coral growth rates; and (5) an upward shift, or compression, in depth zonation to maintain sufficient light-intensity levels.

METHODS

Water-discharge data from 29 U.S. Geological Survey (USGS) streamflow-gaging stations were analyzed to characterize suspended-sediment discharge and runoff in Puerto Rico (Table 2, Figure 3). To characterize river discharge and mean annual runoff to the ocean, 24 streamflow-gaging stations in the lower reaches of rivers were selected. These stations are distributed on all four coasts of the rectilinear island and provide a reasonable estimate of runoff from all regions of Puerto Rico (Figure 3). The 24 stations have a total contributing area of 3875 km^2 or 44% of the island land area. Eleven years of data (water years 1990 to 2000) were compiled from the USGS National Water Inventory System database (U.S. Geological Survey, 2007; Díaz *et al.,* 2004). Water year refers to the period from October 1 through September 30 of the following year. Although episodic processes such as sediment discharge are best analyzed using long-term (for example, decadal) data sets, this 11-year period is a representative sample of long-term conditions, including a severe drought (1994–1995) and periods of high rainfall accumulation associated with major hurricanes (1996, 1998) (Larsen, 2000; Smith *et al.,* 2005). For five stations on the island, the mean annual discharge for the period of record (greater than 11 years) was compared to the calculated 11-year mean annual discharge; the two calculated means were similar for all stations that were evaluated, indicating that the 1990 to 2000 water years are a reasonable representation of long-term hydrometeorologic conditions for the island.

Suspended-sediment concentration and suspended-sediment yield estimates were based on data from nine streamflow-gaging stations at which suspended-sediment data are collected (hereafter referred to as sediment stations) (Tables 3 and 4, Figure 3). This small number of sediment stations

Table 2. *Information for 29 USGS streamflow-gaging stations used to characterize water and sediment discharge in Puerto Rico. The first 24 stations listed are the most downstream stations for each river. Station locations shown on Figure 3. Data from Díaz* et al. *(2004). km^2 = square kilometer, m^3s^{-1} = cubic meter per second, ID = identification number, mm = millimeter, Y = yes, N = no.*

Stream Name	Station ID	Drainage Area (km^2)	Dam(s) Above Gaging Station	Period of Daily Record	Mean Annual Discharge (m^3s^{-1})	Mean Annual Runoff (mm)
Río Grande de Arecibo	50027750	451	Y	4/82–10/00	10.1	706
Río Grande de Manatí	50038100	510	N	2/70–10/00	10.7	663
Río Cibuco	50039500	256	N	1/73–10/00	3.5	429
Río de la Plata	50046000	539	Y	1/60–10/00	7.2	442
Río de Bayamón	50048000	186	Y	11/62–12/66	3	506
Río Piedras	50049100	40	N	1/88–10/00	1.5	1250
Río Grande de Loíza	50059050	541	Y	12/86–10/00	7.3	427
Río Espíritu Santo	50063800	22	N	8/66–10/00	2.9	4060
Río Mameyes	50066000	35	N	7/97–10/00	2.8	1240
Río Fajardo	50071000	39	N	3/61–10/00	1.9	1550
Río Humacao	50081000	17	N	10/87–10/00	0.6	1170
Río Maunabo	50090500	14	N	2/72–1/85 2/91–10/00	0.5	1200
Río Grande de Patillas	50092000	47	N	1/66–10/00	1.6	1090
Río Lapas	50100200	26	N	9/88–10/00	0.2	216
Río Majada	50100450	43	N	9/88–10/00	0.2	157
Río Descalabrado	50108000	33	N	2/84–10/00	0.3	296
Río Bucana	50114390	64	Y	8/87–10/00	1.4	688
Río Jacaguas	50111500	129	Y	3/84–10/00	1.3	317
Río Portugués	50115900	48	N	7/97–10/00	1.5	914
Río Guayanilla	50124200	49	N	3/81–10/00	0.6	419
Río Rosario	50136400	47	N	10/85–10/00	1.4	958
Río Guanajibo	50138000	311	N	1/73–10/00	5.5	556
Río Grande de Añasco	50144000	244	N	3/63–10/00	9.1	1170
Río Culebrinas	50147800	184	N	7/67–10/00	8.3	1430
Total (T) and Mean (M)		(T) 3875				(M) 911
Upstream Stations Used for Suspended-Sediment Data but not Included in Island Runoff Estimate Above						
Río de la Plata	50045010	448	Y	7/89–10/00	4.8	340
Río de Bayamón	50047560	21	N	11/90–10/00	0.5	785
Río Mameyes	50065500	18	N	8/67–12/73 6/83–10/00	1.6	2810
Toa Vaca	50110900	37	N	4/89–10/00	0.4	396
Río Portugués	50114900	19	N	10/97–10/00	0.6	1020

does not permit a definitive assessment of sediment yield from the island overall, but is sufficient to approximate total suspended-sediment discharges and to provide insights into regional variability of sediment yields. The USGS data for 56 suspended-sediment samples collected between October 1, 1997, and September 30, 2002, at five of the nine sediment stations were compiled to characterize the particle-size distribution of sediment in suspension (DÍAZ *et al.,* 2004). Data for silt and clay percentages were compared to runoff, calculated from the published instantaneous discharge, to normalize for drainage area.

Mean annual suspended-sediment discharge from the island to the sea was approximated for water years 1990 to 2000 using four runoff regions described below (Table 5). The range of sediment yield for each region was estimated from the nine sediment stations. The area of sediment yield was computationally reduced for each of the four regions to account for reduced delivery ratios in downstream, low-gradient areas. The northern and western regions were assumed to contribute sediment from only one-half of their total drainage area, and the eastern and southern regions were assumed to contribute sediment for two-thirds of their total drainage area because of steeper gradients and relatively shorter river lengths (Figures 2 and 3; also see the watershed maps in DÍAZ *et al.,* 2004). Additionally, sediment-discharge characteristics were compared with other areas of the world (Figure 4) to evaluate whether Puerto Rico reefs are subject to a relatively low, average, or high influx of terrigenous sediment.

Sediment and water data were used to evaluate the magnitude and frequency of storm runoff that transports upland and coastal plain sediments to the coast and shelf. The rainfall, runoff, and suspended-sediment discharges associated with Hurricane Georges, a high-magnitude storm that struck the island on September 21–22, 1998, were estimated (Figure 5, Table 6). Rainfall accumulation and runoff associated with Hurricane Georges was calculated for the period of September 20–25 for four island runoff (climatologic) regions from rainfall using an isohyet map (Figure 6B) created by contouring total precipitation observed at 55 National Weather Service rainfall stations (NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION, 1999). A grid of cells measuring 100 m on a side was created using the ArcInfo TOPOGRID routine, and the values were extracted using the ZONALSTATS function (ENVIRONMENTAL SYSTEMS RESEARCH INSTITUTE, 1993). [The use of product names is for descriptive purposes only and does not imply endorsement by USGS.]

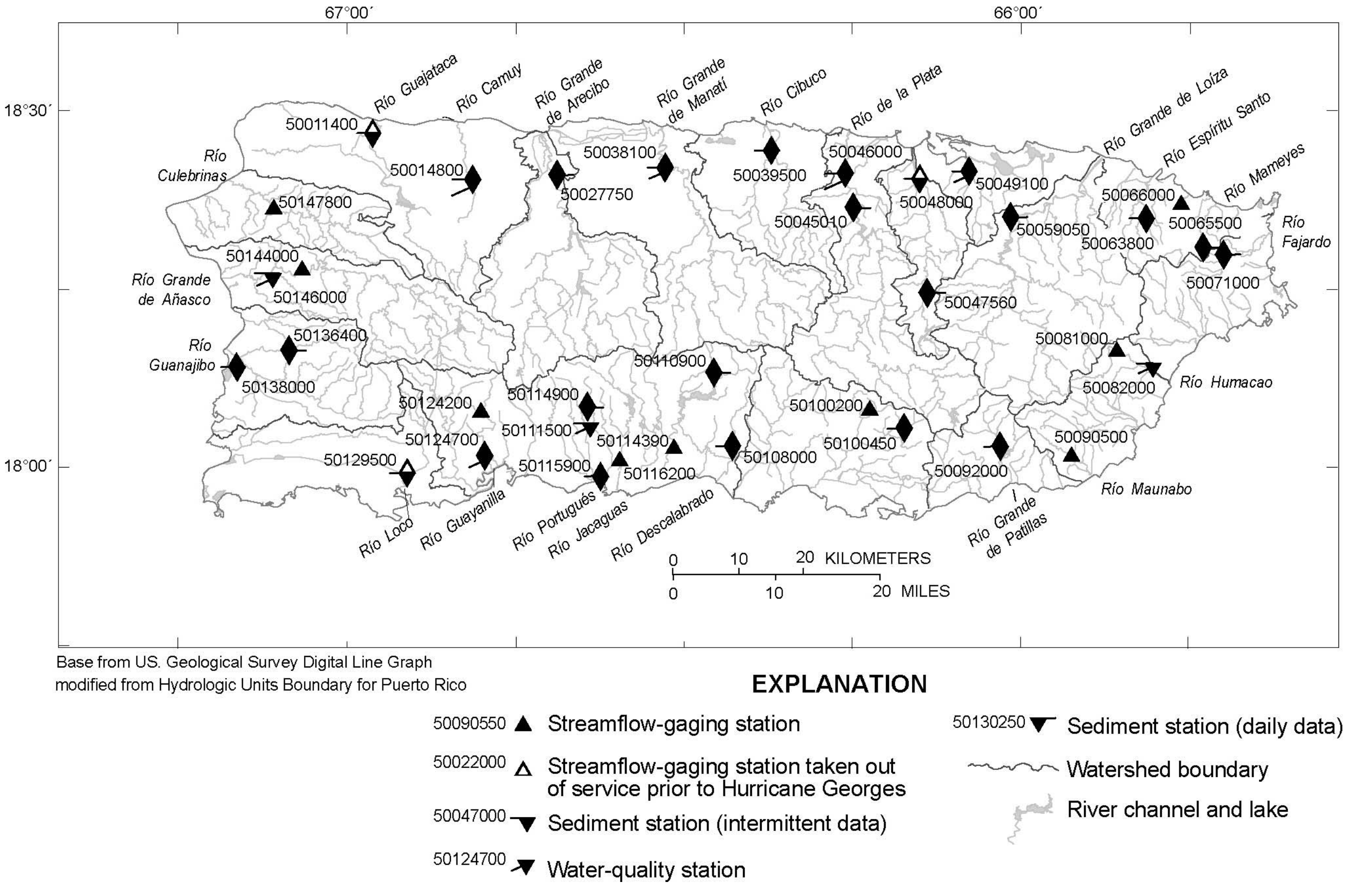

Figure 3. Location of the USGS streamflow-gaging stations, sediment stations, and water-quality stations used in this study.

Table 3. *Water discharge and sediment concentration data from nine suspended-sediment monitoring stations used to characterize sediment discharges associated with Hurricane Georges in Puerto Rico. Total Hurricane Georges runoff is calculated for the period September 20–25, 1998. Hurricane Georges crossed the island on September 21–22, 1998. ID = identification number, $m^3 s^{-1}$ = cubic meter per second, mm = millimeter, mm d^{-1} = millimeter per day, mg L^{-1} = milligrams per liter.*

Stream Name	Station ID[1]	Hurricane Georges Highest Mean Daily Water Discharge[2] (m^3s^{-1})	Hurricane Georges Highest Mean Daily Water Runoff (mm D^{-1})	Total Hurricane Georges Water Runoff (mm)	Total Hurricane Georges Runoff/Mean Annual Runoff[3]	Mean Daily Sediment Concentration (mg L^{-1}) During Hurricane Georges Highest Daily Mean Water Discharge[2]
Río Grande de Arecibo	50027750	206	39	77	0.11	3500
Río de la Plata	50045010	2140	413	583	1.70	2500
Río de Bayamón	50047560	58	239	289	0.37	790
Río Grande de Loíza	50059050	1870	299	366	0.86	3400
Río Mameyes	50065500	42	202	341	0.12	310
Río Fajardo	50071000	22	49	98	0.06	290
Río Jacaguas	50110900	49	114	214	0.54	12,000
Río Portugués	50114900	85	387	458	0.45	18,000
Río Rosario	50136400	125	230	291	0.30	16,000

[1] Station locations shown in Figure 4.
[2] Data from Díaz *et al*. (2004).
[3] Mean annual runoff listed in Table 1.

Table 4. *Summary statistics of suspended-sediment discharge for selected sediment monitoring stations in Puerto Rico, October 1990 to September 2000. ID = identification number, km² = square kilometers, I = Tropical Storm Isabel-October 6, 1985, H = Hurricane Hortense-September 10, 1996, G = Hurricane Georges-September 22, 1998.*

Stream Name	Station ID[1]	Highest Recorded Daily Sediment Discharge and Associated Storm[2] (metric tonnes)	Mean Annual Sediment Discharge[2] (metric tonnes)	Median Annual Sediment Discharge[2] (metric tonnes)	Mean of Highest Daily Water Discharge (for the year)/Total Annual Water Discharge[3]	Mean Annual Sediment Yield[3] (metric tonnes/km²/year)	Highest Recorded Daily Sediment Discharge/Mean Annual Sediment Discharge[3]	Highest Recorded Daily Water Discharge Volume/Mean Annual Water Discharge Volume[3]	Highest Recorded Daily Sediment Discharge/Median Annual Sediment Discharge[3]	Hurricane Georges Highest Daily Sediment Discharge/Median Annual Sediment Discharge[3]
Río Grande de Arecibo	50027750	77,000 (G)	54,000[4]	43,000[3]	0.29	120	1.4	0.11	1.8	1.8
Río de La Plata	50045010	1,600,000 (H)	450,000	52,000	0.42	1000	3.6	2.26	31.6	9.2
Río de Bayamón	50047560	25,000 (H)	11,000	11,000	0.42	540	2.2	0.79	2.4	0.3
Río Grande de Loíza	50059050	1,400,000 (H)	378,000	280,000	0.58	700	3.6	1.17	4.8	3.3
Río Mameyes	50065500	4900 (G)	5000	4300	0.31	140	1.0	0.14	1.1	1.1
Río Fajardo	50071000	20,000 (I)	20,000[4]	19,000[3]	0.23	520	1.0	0.36	1.0	0.1
Río Jacaguas	50110900	85,000 (G)	38,000	18,000	0.36	1000	2.2	0.34	4.8	4.8
Río Portugués	50114900	130,000 (G)	81,000[5]	40,000[4]	0.43	4300	1.6	0.38	3.2	3.2
Río Rosario	50136400	320,000 (G)	58,000	17,000	0.31	1200	5.6	0.24	19.0	19.0

[1] Station locations shown in Figure 3.
[2] Data from Díaz *et al.* (2004).
[3] Calculated using annual discharge data for water years 1991 to 2000 (Díaz *et al.*, 2004).
[4] Station has only 5 years of data (1996–2000).
[5] Station has only 3 years of data (1998–2000).

Basic water-quality data were compiled from 24 USGS water-quality monitoring stations located in the downstream reaches of rivers around Puerto Rico (Warne *et al.,* 2005). Water-quality data compiled and evaluated included total dissolved solids (estimated from specific conductance), total dissolved nitrogen and phosphorus (nutrients), and concentrations of fecal coliform and fecal streptococci. Fecal coliform bacteria are present in the intestines or feces of warm-blooded animals and often are used as indicators of the sanitary quality of water. Fecal streptococcal bacteria also are found in the intestines of warm-blooded animals. Their presence in water is considered to verify the presence of fecal pollution. Fecal coliform and streptococci concentrations are expressed as the number of colonies per 100 milliliters of sample.

Data from three water-quality monitoring stations were selected to provide examples of water quality in rivers draining the north, southeast, and southwest coasts of the island (Figure 7). Additional water-quality data plots are available in Warne *et al.* (2005).

RESULTS

Surface-Water Discharge, Sediment Discharge, and Water Quality

Mean annual runoff to the coast for the water years 1990 to 2000 is estimated at 911 mm (Table 2) or 57% of the mean annual precipitation of 1600 mm. In a typical year, the largest daily discharge accounts for 3% to 25% of the total annual discharge (Warne *et al.,* 2005). The proportion of the highest recorded daily water discharge relative to the mean annual total is much less than the proportion of the highest recorded daily sediment discharge relative to the mean annual total (Table 4). This difference reflects the incapacity of baseflow (low streamflow conditions) discharge, which comprises a substantial portion of the annual water discharge volume, to transport a large mass of suspended sediment. Mean annual suspended-sediment discharge from Puerto Rico into surrounding coastal waters is estimated to range from 2.7 to 9.0 million metric tonnes (t) for the water years 1990 to 2000 (Table 5). Estimated mean annual suspended-sediment yield ranges from 570 t km^{-2} to 1900 t km^{-2}. The mean maximum daily water discharge at the nine suspended-sediment stations accounts for 23% to 58% of water discharged during a typical year (Table 4). During the year with the highest recorded daily sediment discharge (in most cases, associated with Hurricane Hortense in 1996 or Hurricane Georges in 1998), the maximum daily sediment discharge was between 44% and 90% of the total sediment discharge for that year. The highest recorded daily sediment discharge was between 1.0 and 5.6 times the mean annual discharge and 1.0 and 32 times the median annual discharge for water years 1990 to 2000 (Table 4).

The particle-size distribution of sediment in suspension at the five sediment stations with recently published data shows that 89% of the samples contained 80% or more silt and clay. These data represented runoff that ranged from 1 mm/d to 1500 mm/d (Díaz *et al.,* 2004). Fine sediments such as these could easily be transported across the insular shelf in turbulent suspension during large storms. Although the fine sed-

Table 5. *Estimated mean annual suspended-sediment discharge from Puerto Rico to coastal waters for the period from October 1990 to September 2000. Sediment data from Table 4; drainage areas and regions from Table 2 and Figure 2; contributing areas shown below estimated as 50% of north and west regions, 66% of south and east regions, see text for explanation. km² = square kilometer.*

Region of Island	Mean Annual Suspended-Sediment Yield (metric tonnes km²)	Contributing Area (km²)	Mean Annual Suspended-Sediment Discharge (metric tonnes)
North	120 to 1000	2317	280,000 to 2,300,000
East	140 to 520	356	51,000 to 180,000
South	1000 to 4300	1300	1,400,000 to 5,600,000
West	1200	783	960,000
	Mean: 570 to 1900[1]	Total: 4786	Total: 2.7 to 9.0 million

[1] Mean calculated as minimum and maximum yield divided by total contributing area.

iment could reach coral reefs around the island, it is not known how much of this sediment is likely to be deposited on reefs. The high wave energy normally associated with meteorological conditions producing heavy rain, tropical disturbances, and winter cold fronts would inhibit deposition of fine sediment in near-shore areas (SCHNEIDERMANN *et al.,* 1976). Bedload sediment, characterized in only a few locations in Puerto Rico by SIMON and GUZMÁN-RÍOS (1990), has been observed in deposits discharged in the vicinity of a river mouth where it is sorted by waves and currents. Coarse material becomes incorporated into the active beach system, whereas finer sands and silts move offshore (BUSH, 1991). Bed material effects are therefore likely to be limited to fringing and patch reefs within the littoral zone.

Nitrogen and phosphorus concentrations in the 24 rivers examined in this study were within the safe drinking-water standards established by the U.S. ENVIRONMENTAL PROTECTION AGENCY (2000) and the PUERTO RICO ENVIRONMENTAL QUALITY BOARD (1990). As noted by WARNE *et al.* (2005), the concentration of dissolved solids is not highly responsive to discharge (for example, the Río Grande de Manatí station 50038100, which is typical of many rivers in Puerto Rico and elsewhere) (DÍAZ *et al.,* 2004; MILLIMAN and SYVITSKI, 1992; STALLARD, 1995). Even though there is a slight decrease in concentrations of dissolved solids (including nutrients) with increasing discharge, it is not nearly enough to offset the increase of mass loading associated with increased discharge during floods. Most samples, however, were collected during relatively low-flow conditions and may not be representative of dissolved-solids concentrations during flood discharges. Fecal coliform and fecal streptococcus concentrations at the 24 water-quality gaging stations typically do not meet the sanitary-water standards established by the PUERTO RICO ENVIRONMENTAL QUALITY BOARD (1990) (Figure 7). Additionally, high fecal coliform concentrations are associated with eutrophic conditions that can result in a proliferation of macroalgae (Table 1). There is a slight increase in fecal coliform concentration with increasing discharge, which may be attributable to flushing of ephemeral channels and riparian areas in rural areas of the island with little to no sewage treatment (HUNTER and ARBONA, 1995; LARSEN and CONCEPCIÓN, 1998). Most samples, however, were collected during relatively low-flow conditions and may not be representative of fecal concentrations during floods.

River Water and Sediment Discharge Associated with Hurricane Georges

Stormflow is the dominant process that transports sediment and nutrients from uplands to the sea. Hurricane Georges was evaluated to determine storm effects on the discharge of sediment and nutrients to the coast and shelf. On September 21, 1998, the eye of Hurricane Georges made landfall in eastern Puerto Rico (SMITH *et al.,* 2005). Hurricane-force winds and torrential rains affected the entire island until the storm moved off the western shore about 18 hours later. The Category-3 hurricane produced heavy rainfall, with 2-day rainfall totals that ranged from 10 cm to about 63 cm (Figure 6B), resulting in severe flooding and numerous landslides in the Cordillera Central (LARSEN and SANTIAGO-ROMÁN, 2001). Hurricane Georges caused the highest recorded daily discharges in nine of the 29 streamflow-gaging stations evaluated in this study. Peak flow recurrence interval data indicate that Hurricane Georges had a highly variable impact across the island, but was especially severe in the west (RAMOS-GINÉS, 1999).

Precipitation and discharge estimates by island region indicate that about 2.6 billion m³ of precipitation fell on the island from September 20–25, 1998, and about 1.0 billion m³ (40%) was converted to direct runoff (Table 6, Figure 5). The precipitation estimates indicate that 6-day totals ranged from 200 mm in the east to 360 mm in the west, and the island-wide average accumulation was 300 mm. Total daily runoff for the entire island is estimated to have been 120 mm from September 20–25, 1998 (equal to 13% of the estimated mean annual runoff of 911 mm). Most of the 180-mm difference between rainfall and runoff (1.6 billion m³) would have infiltrated into temporary soil storage and long-term groundwater storage, with evapotranspiration accounting for the rest. Evapotranspiration rates in low elevation areas of the island generally are less than 5 mm/d (HARMSEN *et al.,* 2003). Groundwater levels responded relatively quickly to the heavy rains; for example, between September 20 and 30, 1998, eight wells around the island exceeded their recorded high groundwater levels (DÍAZ *et al.,* 2004).

The highest daily sediment discharges caused by Hurricane Georges were more than the median annual discharges for seven of the nine daily sediment stations evaluated (Tables 4 and 7). Single-day water discharges ranged from 11% to 226% of the mean annual discharge volume, and sediment

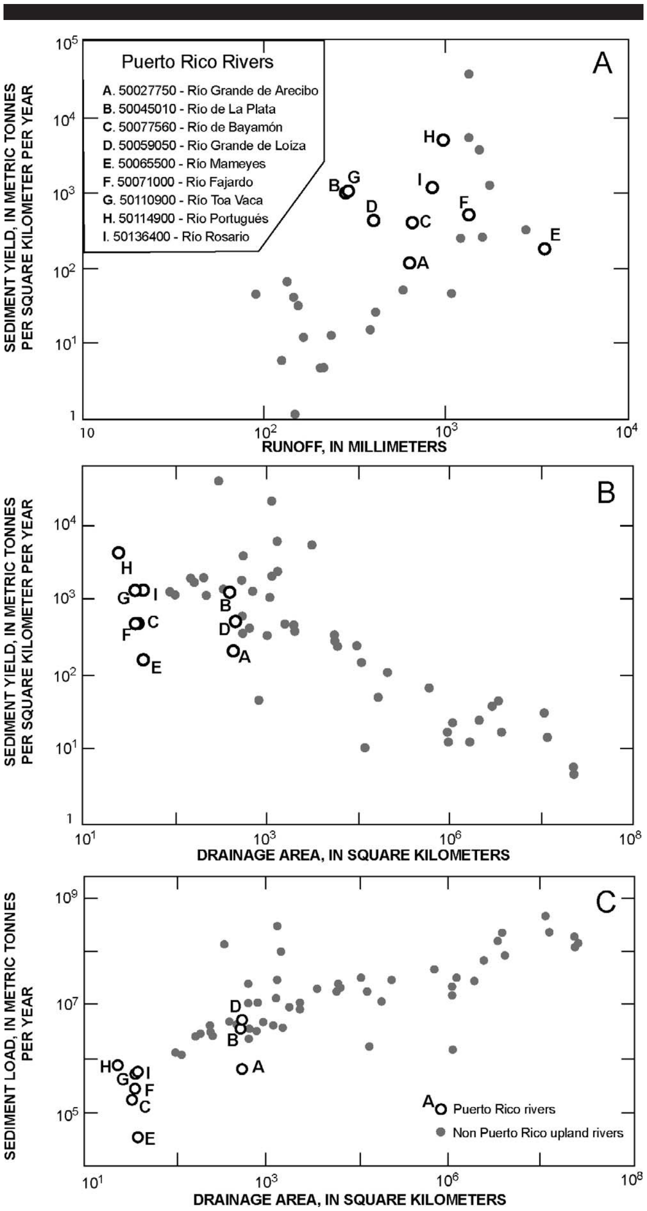

Figure 4. Sediment yield and discharge characteristics of Puerto Rico rivers in relation to other upland settings around the world (terrains between 100 and 500 m elevation, varying latitude; data from Milliman and Syvitski, 1992). (A) Relation between suspended sediment yield and runoff, (B) relation between suspended sediment yield and drainage area, and (C) relation between suspended sediment load and discharge area.

discharge was up to 19 times greater than the median annual sediment discharge. Discharge and sediment concentration rose rapidly and diminished rapidly following passage of Hurricane Georges. From 62% to 99% of the sediment discharge associated with hurricane stormflows was recorded on a single day. Maximum daily sediment yields associated with Hurricane Georges generally were proportional to runoff but spatially variable, ranging from 50 t km^{-2} d^{-1} to 6900 t km^{-2} d^{-1} (Table 7). There is, however, a consistent regional pattern: sediment yield was moderate in the north, low in the east (where rainfall and runoff were relatively low and the sediment stations are downstream from areas with extensive forest cover), and high in the south and west, where rainfall and runoff were high (Figure 5).

During the period of September 20–25, 1998, a total of 2.4 million metric tonnes of suspended sediment is estimated to have been transported past the nine sediment stations, with most sediment transport (84%) occurring on the day of highest discharge. Because these nine stations represent only 19% (1622 km^2) of the island area, sediment discharge to the coast may have been on the order of five times this amount, or about 12 million metric tonnes. Actual island-wide sediment discharges are likely to have been less than this, however, because of the low-relief coastal plain, which reduces sediment production and yield and provides opportunities for sediment deposition as river gradients decrease and channels widen near the coast (Figure 2B). A reasonable estimate of total sediment discharge would likely range between two and four times the cumulative amount represented by the nine sediment stations: 5–10 million metric tones (570–1150 t km^{-2}). Most of the sediment was discharged from the western, southern, and northern rivers, whereas the eastern rivers had relatively little sediment discharge. In comparison, floods associated with Super-Typhoon Herb (1996) in tectonically-active Taiwan (32,260 km^2) are estimated to have been 217 million metric tonnes (673 t km^{-2}), according to MILLIMAN and KAO (2005).

Nutrient discharge associated with Hurricane Georges was estimated conservatively at 1000 metric tonnes of nitrogen and 500 metric tonnes of phosphorous assuming average concentrations in streamflow (Figure 7, Table 6). The discharge of fecal material to the coast and shelf during Hurricane Georges varied among the rivers. Data are insufficient to estimate total fecal discharge volumes; however, analysis of Sea-viewing Wide Field of view Sensor (SeaWiFS) satellite imagery used for monitoring plankton and sedimentation levels in the oceans for the period of September 19, 1998, to October 15, 1998, indicates that discharge of nutrient-rich water induced a substantial increase in chlorophyll-a (planktonic algae) concentrations across and seaward of the Puerto Rico shelf (GILBES *et al.,* 2001; WARNE *et al.,* 2005).

DISCUSSION

River and Sediment Discharge to Coast and Shelf

Mean annual runoff from Puerto Rico is estimated at 911 mm, bearing in mind uncertainties associated with groundwater contributions to streamflow and evapotranspiration in coastal areas. Mean annual suspended-sediment discharge to surrounding coastal waters is estimated to range from 2.7 to 9.0 million metric tonnes for the water years 1990 to 2000. The relation between mean annual sediment yield (and mean annual sediment load) *vs.* drainage area for Puerto Rico rivers is comparable to that of other rivers of the world draining similar terrain (Figure 4). Mean annual sediment yield *vs.* runoff, however, indicates that Puerto Rico rivers are sensitive to the high frequency and magnitude of the tropical rainfall characteristic of this region (LARSEN and SIMON, 1993).

Sediment discharge from the island is highly episodic and

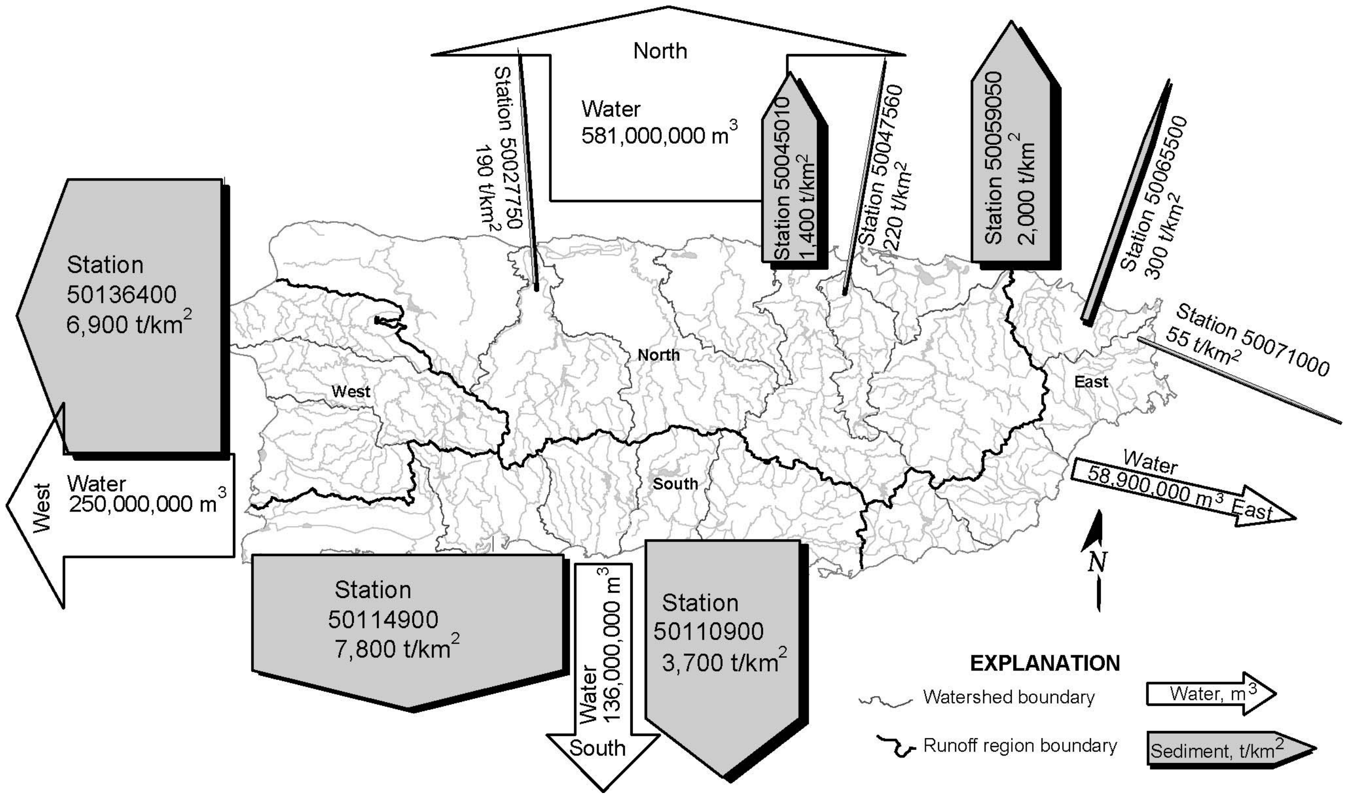

Figure 5. Spatial distribution of water discharge and suspended-sediment yield during the passage of Hurricane Georges, September 20–25, 1998, in Puerto Rico. Water discharge, in cubic meters, is shown as the total by runoff region of the island. Sediment yield, in metric tonnes per square kilometer, is shown for nine sediment stations listed in Table 3. The width of the arrows is proportional to mass flux of water and sediment.

spatially variable. Once offshore, the sediment is reworked and redistributed by waves and currents. During the water years 1984 to 1993, 80% of the annual suspended-sediment load was transported into Lago Loíza in 4 to 24 days from the Rio Gurabo branch and in 7 to 12 days from the Río Grande de Loíza branch (GELLIS *et al.,* 2006). Average sediment concentrations in slopewash measured by GELLIS *et al.* (2006) ranged from 2000 ppm from forested areas to more than 60,000 ppm for waters flowing across bare ground at construction sites. In comparison, the average annual discharge-weighted sediment concentration was only 270 ppm from the Río Bairoa, a watershed with 6% pasture and forest (GELLIS *et al.,* 2006). CRUISE and MILLER (1994) estimated that runoff induced by large rainstorms in August 1988 and October 1989 produced 72% and 81%, respectively, of the sediment yields to the Río Guanajibo for the respective years. Discharge in northwestern Puerto Rico on October 21, 1989, resulted in sediment plumes that extended up to 12 km offshore (Figure 8). Suspended-sediment loads measured at the Río Rosario (USGS station 500136400, drainage area 47 km^2), a tributary of the Río Guanajibo, totaled 1800 metric tonnes for the 4-day storm represented, in part, by the October 21, 1989, image and equaled about 6% of the annual total.

The episodic nature of sediment export from the island of Puerto Rico is typical of many tropical and temperate regions

Table 6. *Estimates of precipitation and river discharge for the 6-day period from September 20–25, 1998. Hurricane Georges crossed the island on September 21–22, 1998. km^2 = square kilometer, mm = millimeter, m^3 = cubic meter, mm d^{-1} = millimeter per day.*

Region of Island	Area Draining to Coast (km^2)	Fraction of Total Island Area	Precipitation (mm)	Precipitation Volume (million m^3)	Rainfall Runoff Ratio	Discharge (million m^3)	Fraction of Total Island Runoff	Total Runoff (mm)	Mean Runoff (mm d^{-1})
North	4635	0.53	280	1300	0.45	581	0.57	130	21
East	540	0.06	200	110	0.55	58.9	0.06	110	18
South	1970	0.23	320	630	0.22	136	0.13	69	12
West	1566	0.18	360	560	0.45	250	0.24	160	27
Area-weighted average			300		0.40			120	20
Total	8711	1.00		2600		1026	1.00		

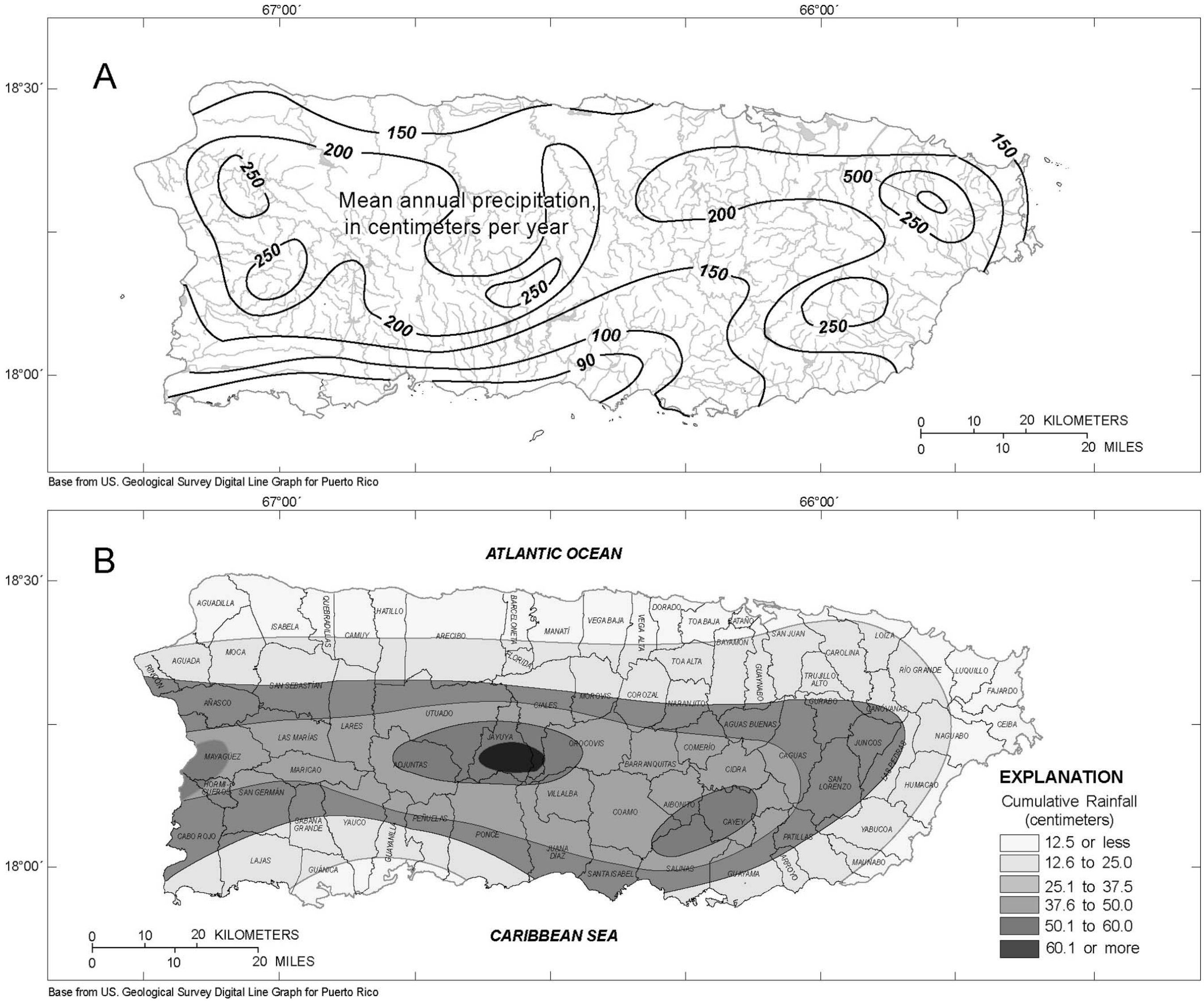

Figure 6. Rainfall runoff characteristics of Puerto Rico: (A) mean annual rainfall distribution (modified from Calvesbert, 1970) and (B) cumulative precipitation associated with Hurricane Georges, September 21–22, 1998 (modified from U.S. Geological Survey, 1999).

(Gellis *et al.,* 2006; Gupta, 2000; Larsen and Santiago-Román, 2001; Meade *et al.,* 1990; Sommerfield and Nittrouer, 1999). Meade *et al.* (1990) demonstrated that sediment is discharged during 1% (about 4 days) of the year in North American rivers and varies regionally. About 10% of annual sediment loads are discharged during 1% of the year in the coastal plain rivers of North Carolina, whereas 60% to 93% of the sediment is discharged during 1% of the year in the Pacific Coast ranges (Meade *et al.,* 1990). The present study demonstrates that for the water year with the highest daily discharge volume, the daily discharge comprised between 8% and 66% of the total annual water discharge volume and that up to six times the mean annual sediment load is discharged in a single day. Additionally, during a large storm such as Hurricane Georges, the maximum daily sediment discharge may be many times the mean (and median) annual load (Table 7). Because sediment yields during Hurricane Georges were based upon sediment discharges at sediment stations located in downstream river reaches, rather than from sites of hillslope erosion, the sediment yields should reasonably approximate the volume of sediment that was transported from the uplands and river valleys to the coast during the storm.

In the large watersheds of mainland United States, only about 10% of the sediment eroded from uplands is transported directly to the oceans by rivers (Meade *et al.,* 1990). Some of the eroded sediment is trapped in reservoirs, but most is stored on hillslopes, flood plains, and other parts of stream valleys. In Puerto Rico, where stream lengths are relatively short, channel gradients are high and stream valleys are

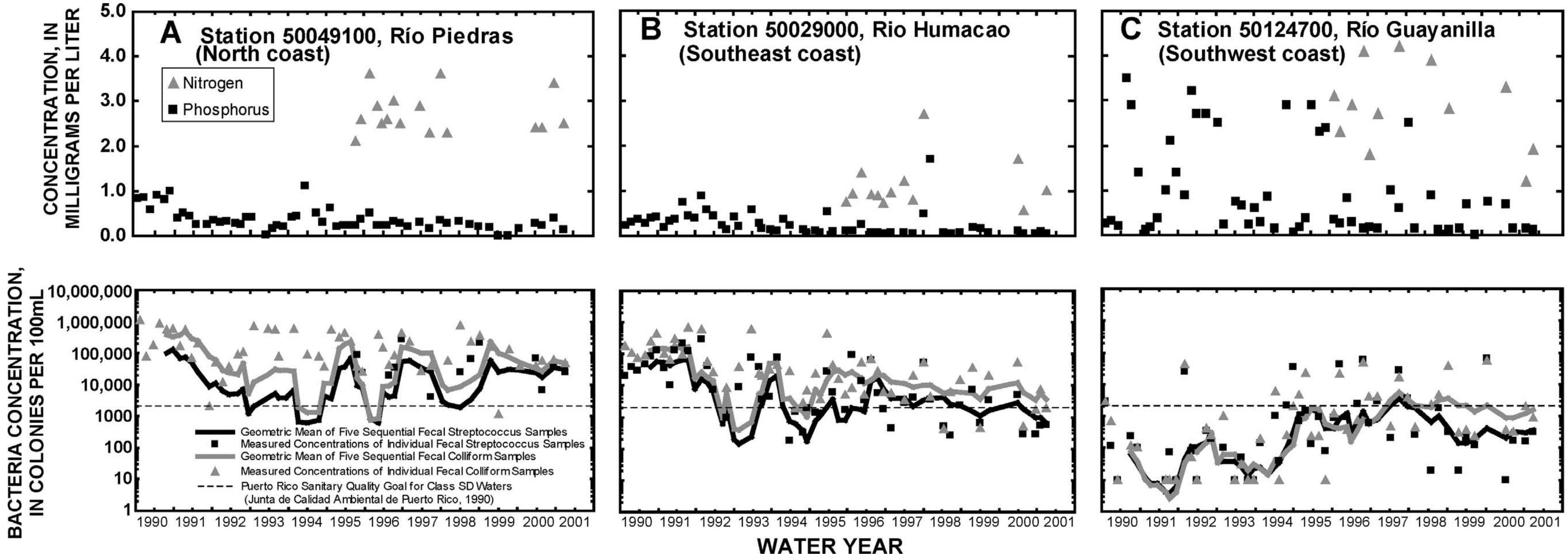

Figure 7. Concentrations of nutrients and bacteria for three water-quality monitoring stations for the period September 1989 to October 2000 (water years 1990–2000). Nitrogen and phosphorous concentrations are calculated from individual samples. Total dissolved nitrogen is reported as N, and total dissolved phosphorous as P. (A) Río Piedras. (B) Río Humacao. (C) Río Guayanilla. Note: to keep a consistent y-axis, the following measurements of nitrate made at the Rio Guayanilla are not shown: 6/23/1995—18 mg/L. 1/19/1996—5.1 mg/L, 3/6/1997—9.0 mg/L. 8/20/1997—21.1 mg/L.

Table 7. *Summary of water and suspended-sediment discharge at selected stations, Puerto Rico, September 20–25, 1998. Hurricane Georges crossed the island on September 21–22, 1998. ID = identification number, m^3 = cubic meter, $m^3\ d^{-1}$ = cubic meter per day, mm = millimeter.*

Stream Name	Station ID	Total Hurricane Georges Discharge (m^3)	Maximum Daily Water Discharge During Hurricane Georges ($m^3\ d^{-1}$)	Fraction of Water Discharge Recorded on Day of Greatest Discharge	Sediment Discharge (metric tonnes)	Maxium Daily Sediment Discharge During Hurricane Georges (metric tonnes)	Fraction of Sediment Discharge Recorded on Day of Greatest Discharge	Maximum Mean Daily Runoff During Hurricane Georges (mm)	Daily Sediment Yield During Hurricane Georges (metric tonnes per square kilometer)
Río Grande de Arecibo	50027750	34,700,000	17,800,000	0.51	84,000	77,000	0.83	40	170
Río de la Plata	50045010	261,000,000	185,000,000	0.71	640,000	480,000	0.74	413	1100
Río de Bayamón	50047560	6,070,000	5,020,000	0.83	4700	3000	0.73	233	160
Río Grande de Loíza	50059050	198,000,000	161,000,000	0.81	1,100,000	930,000	0.88	298	1700
Río Mameyes	50065500	6,140,000	3,620,000	0.59	5400	5000	0.90	203	270
Río Fajardo	50071000	3,810,000	1,860,000	0.49	2200	2000	0.89	48	50
Río Toa Vaca	50110900	7,930,000	4,260,000	0.54	137,000	85,000	0.62	115	2300
Río Portugués	50114900	8,710,000	7,340,000	0.84	148,000	130,000	0.88	386	6900
Río Rosario	50136400	13,700,000	10,800,000	0.79	325,000	320,000	0.99	230	6890
Totals		540,000,000	497,000,000	0.73	2,450,000	2,000,000	0.84		

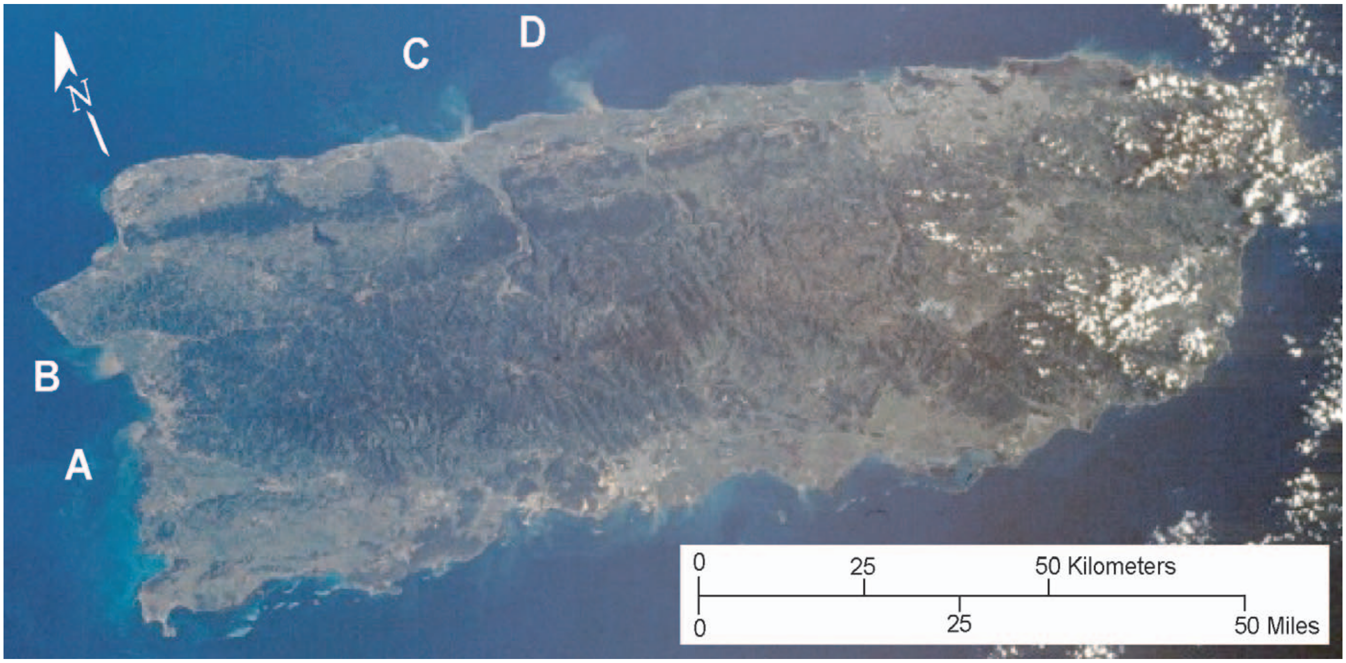

Figure 8. Space shuttle photograph of Puerto Rico showing sediment plumes at the river mouths of (A) Río Guanajibo, (B) Río Grande de Añasco, (C) Río Grande de Arecibo, and (D) Río Grande de Manatí. The brown color of vegetation in eastern Puerto Rico is the result of defoliation caused by Hurricane Hugo, which struck the island on September 18, 1989. Image STS034-076-088, taken on October 21, 1989, at 12:51 GMT. Courtesy of NASA (http://www.nasa.gov/multimedia/imagegallery/). Spacecraft elevation 179 nautical miles (332 kilometers), sun angle 32 degrees.

steep and narrow, and where intense rainfall and high runoff are common, it is likely that well more than 10% of the sediment eroded from uplands is discharged to the coast. MERTES and WARRICK (2001) indicate that the transfer of sediment to the ocean from steep, small- to moderate-size, coastal watersheds is relatively efficient because (1) sediment yields are high in comparison to sediment yields of large rivers; (2) the steep narrow flood plains do not have the capacity to store large volumes of sediment; and (3) mountainous coastal watersheds typically lack estuaries and deltas that could retain sediment. The relatively high sediment yield with respect to runoff from Puerto Rico rivers as compared to other rivers is seen in Figure 4A.

Relatively little is known about the type, frequency, and intensity of shelf processes that transport terrigenous sediment to the shelf edge (PILKEY *et al.,* 1978; RODRÍGUEZ *et al.,* 1992, 1998; SCHNEIDERMANN *et al.,* 1976). BUSH (1991), however, documented that storm-induced, across-shelf transport processes are predominate along the north coast of Puerto Rico, and he calculated that 90% of the river sediment discharged at the coast is transported to the shelf edge and slope within a few months. Along the east coast, easterly winds and currents confine river discharge to nearshore areas, resulting in chronically turbid waters unfavorable for coral development. However, within a kilometer eastward and upcurrent, clear ocean waters are home to some of the best developed reefs on the insular shelf. At any point on the insular shelf, the average water quality reflects the interaction of waves and ocean currents with contributions of active and relict carbonate and terrestrial sediment sources.

Nutrient Discharge to the Coast and Shelf

Particulate and dissolved carbon and nitrogen are common companions to river-borne sediments and are also dominant components in mangrove forests and coastal mudflats. Nutrient-rich sediments rejuvenate flood plains and are an important energy source for the flora and fauna of coastal lagoons, but can have deleterious effects on coral reefs. When nutrients are introduced into normally oligotrophic coastal waters, the growth of photosynthetic algae is enhanced.

The blue-green ratio of backscattered sunlight detected with a radiometer can be used to estimate the concentrations of chlorophyll-a. Radiometers aboard the SeaWiFS satellite were used to quantify chlorophyll-a concentrations around Puerto Rico before, during, and after the passage of Hurricane Georges (Figure 9, GILBES *et al.,* 2001). The images show increased phytoplankton in the coastal areas around Puerto Rico that presumably resulted from the assimilation of nutrients that were discharged from the island during Hurricane Georges. The areas of high chlorophyll-a concentration are most intense off the west and south coasts where flood discharge was the greatest. It should be noted that humic acids are concentrated in mangrove wetland swamps. These substances absorb blue light, like chlorophyll-a. As such, some fraction of the estimated chlorophyll-a concentra-

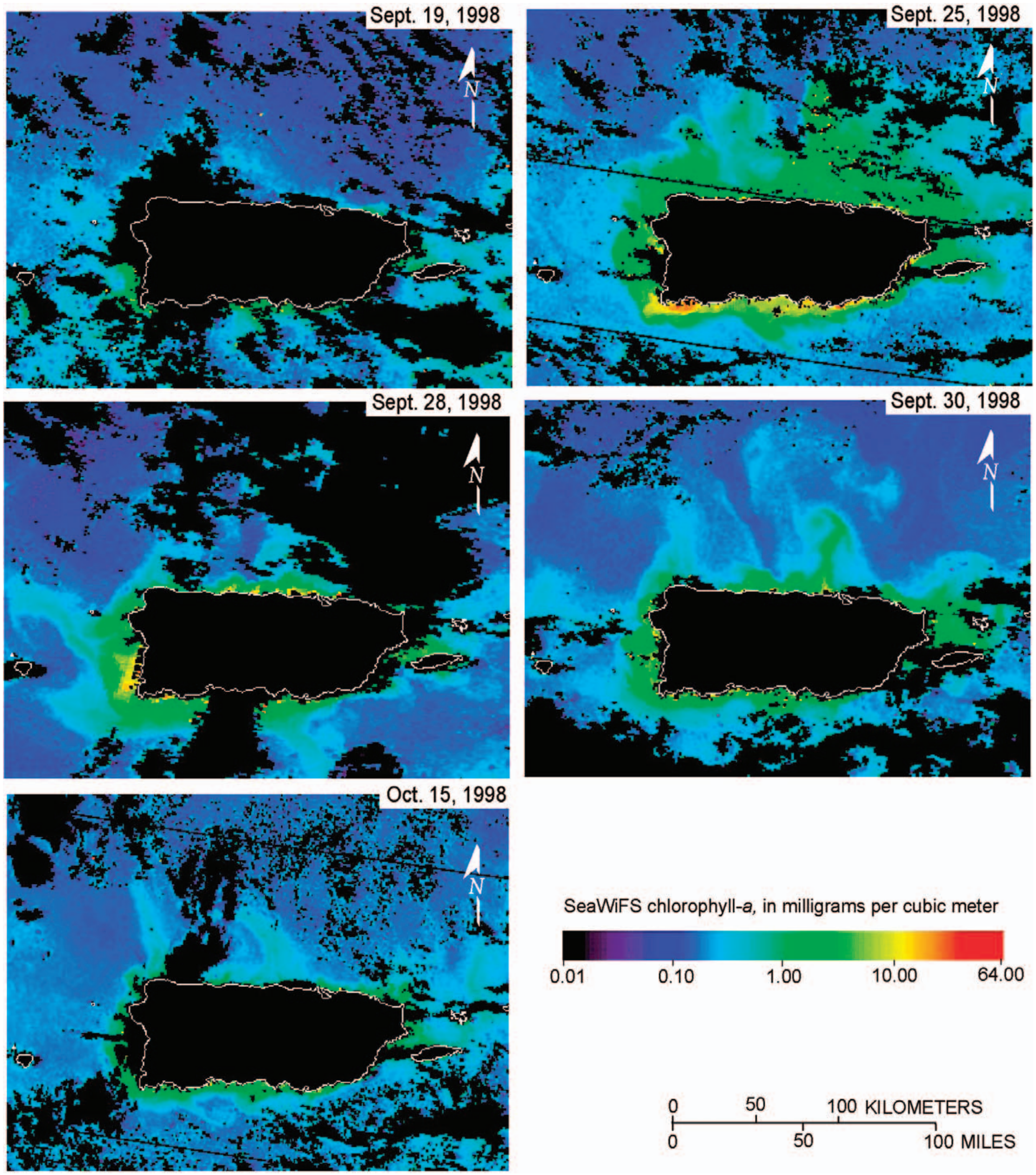

Figure 9. Chlorophyll-a as estimated using the SeaWiFS satellite sensor just before and 4 days after Hurricane Georges crossed over the Caribbean region. Increased concentrations of chlorophyll-a around Puerto Rico after Hurricane Georges reflect an increase in phytoplankton. The increase in phytoplankton is assumed to be the result of a high discharge of nutrient–rich river water. SeaWiFS images courtesy of the University of Puerto Rico Space Information Laboratory (Gilbes *et al.,* 2001).

tions may be misclassified, especially in and around mangrove forests.

Coral Reef Degradation and Land Use

Coral reef degradation is widespread in waters surrounding the island, but is generally greatest offshore from watersheds such as those in and near San Juan, where the population is high and terrestrial discharges of water and sediment are high (Figure 1). Samples with some of the highest bacteria concentrations measured at USGS streamflow stations are collected from station 50049100 (Río Piedras), which drains into San Juan Bay on the north coast (Figures 3 and 7A). Although portions of the southcentral and southwest coasts have relatively healthy reefs, disease outbreaks have been reported in these areas by WEIL (2004), as described below. Watersheds that contribute runoff to these areas are not highly populated, and mean annual runoff is relatively low. Continued urbanization, however, may further threaten these areas. In 1896, approximately 21% of the island was in active cropland. In 1939, active cropland reached a high of 48% (BIRDSEY and WEAVER, 1987). Active cropland is a major source of sediment that is entrained during storms and transported to coastal areas (LARSEN and SANTIAGO-ROMÁN, 2001). Agricultural land in Puerto Rico has been observed by the authors to be in frequent transition between active cropland and pasture, which likely maintains high sediment yield in these areas (GELLIS *et al.,* 2006). Forest cover reached a low of 7% in the mid 1940s, but a shift from predominantly agricultural to a manufacturing economy resulted in an increase in forest cover to 33% by the 1990s. Currently, new construction is widespread and as undeveloped space in urban areas diminishes, development on steep slopes increases (HELMER *et al.,* 2002), which contributes to an increase in sediment erosion and transport to the coast.

Extensive hillslope erosion associated with 19th and 20th century agricultural practices in the upper Río Grande de Loíza watershed is estimated to have delivered annually more than 5000 t km^{-2} of hillslope-derived sediment to river channels for decades (LARSEN and SANTIAGO-ROMÁN, 2001). The erosion of hillslope soil cover was estimated to be equivalent to lowering the entire watershed by 66 cm (BROWN *et al.,* 1998). LARSEN and SANTIAGO-ROMÁN (2001) provided evidence that during the period of widespread agricultural activity, a massive quantity of sediment eroded from the hillslopes was deposited on the lower hillslopes and in the stream valleys. Sediment in these near-channel areas provides an abundant, easily available source of material for transport by moderate to large storms. LARSEN and SANTIAGO-ROMÁN (2001) estimated that the stored sediment could sustain disturbance levels of sediment yield for a century or more. GELLIS *et al.* (2006) reported that sediment discharge is higher than presumed pre-European background levels in the upper Río Grande de Loíza watershed, even though much of the watershed was converted from agriculture back to forested cover more than 30 years before. They proposed that after the watershed was reforested, about 30 years were required to flush the stored sediment through the system, and sediment discharges would then begin to return to predisturbance levels. These studies indicate that the island shelf, particularly seaward of river mouths, will be strongly influenced by the influx of agricultural-period–derived sediment for at least the next several decades to perhaps a century or more.

Increased turbidity along the shelf, seaward of Ponce and La Parguera (Figures 1 and 8), is believed to be the result of the conversion of adjacent upland areas from forest to agricultural and then to urban-industrial use. The increased turbidity may have resulted in a compression of coral depth zonation accompanied by changes in the relative abundance of coral species, which is directly related to individual species tolerance to sediment stress (ACEVEDO *et al.,* 1989; HUBBARD, 1986). ACEVEDO and MORELOCK (1988) and ACEVEDO *et al.* (1989) documented diminished coral cover, reduced species diversity, and a shift to slower-growing coral species with increasing turbidity in the Ponce area. MORELOCK *et al.* (1980) documented the decline of coral reefs in the Guayanilla and Tallaboa Bays and in the adjacent submarine canyon system on the south coast of Puerto Rico. They attributed reef decline to increased sediment discharge from the Río Yauco, Río Guayanilla, and Río Tallaboa, and from resuspension of bottom sediments by ship traffic (also note the bacteria increase, 1990–2000, Río Guayanilla, Figure 7C). According to WEIL (2004), tissue necrosis affects coral colonies of *Montastraea faveolata* at depths of about 10 m in several reefs off the south coast. WEIL (2004) also indicated that White Pox disease, Patchy Necrosis syndrome, and Dark Spots syndrome are present in coral reefs in local areas off the south and southwest coast of Puerto Rico. Increased river-sediment discharge, resulting from agriculture and construction, combined with industrial effluents discharged directly into the Mayagüez Bay, are suspected of causing a reduction in living coral cover on the Algarrobo Reef and Escollo Rodríguez to less than 2% (MORELOCK *et al.,* 1983).

Continual resuspension and transport of dredged sediments can cause reef degradation years after dredging ceases (ROGERS, 1990). Dredging within the Torrecilla Lagoon in the 1950s and 1960s left behind deep anoxic pits with ammonia concentrations exceeding 15 mg L^{-1} and biological oxygen demand exceeding 200 mg L^{-1} (ELLIS, 1976). Occasional turbulent mixing of these stagnant, nutrient-rich waters with surface waters was likely responsible for the destruction of the well-developed reef system northwest of Boca de Cangrejos (GOENAGA and CINTRÓN, 1979). The sediments of the lagoon included discharge from sewage-treatment plants. Before dredging, the reef included extensive coral communities that extended from the sea surface down to more than 10 m. After dredging, few living corals exist at this location below a depth of about 1.5 m according to GOENAGA and CINTRÓN (1979). With the regenerative capacity of the barrier reef gone, the average wave energy has likely increased, as has been shown in studies of the 2004 tsunami in the Indian Ocean where more damage occurred on land where natural coastal buffers (*e.g.,* mangrove forests, reefs) had been degraded (CHATENOUX and PEDUZZI, 2007). Negative effects of river-derived sediment and nutrient discharge are especially pronounced in nearshore areas of the north, southwest, and west coasts. Major effects include reduced coral abundance and concomitant increased algal and sponge density and diversity. Fast-growing algae and sponges outcompete coral planulae in colonizing available substrates (WEIL, 2004).

Nutrients and Coral Conditions

High nutrient and fecal concentrations in river water are a potential threat to Puerto Rico coral reefs. Nitrogen concentrations in most rivers typically range from 1.0 mg L^{-1} to 2.5 mg L^{-1} (Figure 7). In comparison, streams draining the relatively undisturbed forests of eastern Puerto Rico have nitrogen concentrations ranging from 0.15 mg L^{-1} to 0.25 mg L^{-1} (MCDOWELL and ASBURY, 1994). Phosphorus concentrations in most rivers of Puerto Rico range from 0.1 mg L^{-1} to 0.8 mg L^{-1}, whereas in the relatively undisturbed forests of eastern Puerto Rico, total dissolved-phosphorus concentrations of 0.002 mg L^{-1} are common (MCDOWELL and ASBURY, 1994). This limited comparison suggests that human modification of the island landscape has caused nitrogen and phosphorus concentrations to increase 10-fold. However, as a result of changes in wastewater collection and treatment brought about in response to the Clean Water Act of 1972 (33 U.S.C. 1251 *et seq.*), concentrations of nitrogen, phosphorus, and bacteria measured in the streams and lagoon of the San Juan metropolitan area began to fall beginning around 1985 (WEBB and GÓMEZ-GÓMEZ, 1998). Although the concentrations of nitrogen and phosphorus are decreasing and nutrient concentrations are within drinking-water standards (U.S. ENVIRONMENTAL PROTECTION AGENCY, 2000), the overall increase in concentration of fecal material, nitrogen, and phosphorus in river water in comparison to predevelopment levels provides a competitive advantage to algae and sponges, which now dominate many Puerto Rico reefs (GOENAGA and CINTRÓN, 1979). An outbreak of Patchy Necrosis syndrome in November 2000 was documented on a Puerto Rico reef after a 15-day period of no wind, little water movement, minimal cloud cover, and above-normal sea surface temperatures. Although WEIL (2004) attributes this incident to elevated levels of fecal material from marine fauna that were observed to be deposited directly onto coral, it is possible that sewage effluent may have played a role. The month of November 2000 was one of relatively low runoff for most of the island, except for the east coast. During periods of low runoff, effluent from sewage-treatment plants and untreated sources reaches the coast with less dilution than normal, thereby contributing above-average concentrations of nutrients and other human, agricultural, and industrial waste material. PATTERSON *et al.* (2002) have suggested that untreated sewage may be a source for some coral diseases. During the decade 1990–2000, bacteria concentrations increased at a river in this part of the island (see Río Guayanilla, station 50124700, Figures 3 and 7C).

SUMMARY AND CONCLUSIONS

Watersheds in Puerto Rico are small and mountainous, channel gradients are steep, and stream valleys tend to be well incised and narrow. Mean annual runoff to the coast for the water years 1990 to 2000 is estimated at 911 mm, which is about 57% of the mean annual precipitation of 1600 mm. Major storms generally are intense but brief, so flooding occurs rapidly. During floods, maximum daily water discharges are two to three orders of magnitude above base discharge, and sediment discharges are three to four orders of magnitude above base sediment discharge. Rivers transport a substantial amount of sediment from upland watersheds to the coast. Mean annual suspended-sediment discharge from Puerto Rico into surrounding coastal waters is estimated to have ranged from 2.7 to 9.0 million metric tonnes for the water years 1990 to 2000. On average during this period, the maximum mean daily discharge accounts for 23% to 58% of the total annual water discharge.

The effects of river-derived sediment and nutrient discharge on the coral reefs are especially apparent in nearshore areas of the north, southwest, and west coasts. Major effects include reduced coral abundance and concomitant increased algal and sponge density and diversity where fast-growing algae and sponges outcompete the coral for space. Coral reef degradation is widespread in waters surrounding the island, but is generally greatest offshore from watersheds with the greatest amount of urbanization. Although watersheds along much of the south coast are not highly populated and mean annual runoff is relatively low, land-use change is likely to threaten these areas. Portions of the southcentral and southwest coasts have relatively healthy reefs, but disease outbreaks have been reported there.

Precipitation associated with Hurricane Georges is estimated to have averaged 300 mm across the island, which is equal to a volume of about 2.6 billion m^3. More than 1.0 billion m^3 of water, at least 2.4 million metric tonnes of sediment (and as much as 5 to 10 million metric tonnes), 1000 metric tonnes of nitrogen, and 500 metric tonnes of phosphorous were discharged to the coast and shelf. Hurricane Georges sediment discharge was equal to 15% to 48% of the average annual sediment discharge for the island. The estimated discharge of 1000 metric tonnes of nitrogen during the hurricane is 1300 to 2900 times the annual rate of discharge of nitrogen from undisturbed forest in Puerto Rico (4–9 kg ha^{-1} total nitrogen, reported by MCDOWELL and ASBURY, 1994).

Prior to the peak period of island-wide land-use conversion from forest to agriculture in the 19th and early 20th centuries, nutrient and sediment discharge to a large portion of the coast and shelf would have been negligible, and marine waters would have been relatively transparent, except during brief storms. Most coral reefs should have been able to endure the episodic influx of sediment and nutrients, perhaps because during periods of high discharge (typically tropical disturbances) waves and currents are strong, which inhibits sedimentation and promotes transport of the sediment to the shelf edge and slope. The widespread distribution of carbonate clastic shelf substrate indicates that, except near the mouths of rivers, the shelf wave and current regime is capable of transporting almost all fine terrigenous sediment to the shelf edge and slope.

Land clearing and modification, first for agriculture and later for urban development, has increased watershed sediment and nutrient yield, thereby increasing sediment and nutrient discharge to the shelf, which has likely contributed to the widespread degradation of coral reefs that surround the island. Although large portions of the island have been reforested during the past 60 years, sediment eroded from hillslopes and deposited on footslopes and valley floors during the agricultural period is still being transported through the river systems. Nitrogen and phosphorous concentrations in river waters are within regulatory limits, but current concentrations are 10 times greater than the estimated presettlement levels and most likely above preferred concentrations in the reef environment. Fecal coliform and fecal streptococcus concentrations in many rivers of Puerto Rico are near or above regulatory limits. Unlike sediment discharge, which is episodic and intense, river-borne nutrient and fecal discharge is a less-intense but chronic stressor to coral reefs located near the mouths of rivers.

In an effort to present what is currently known about the effects of river discharge on the reefs of Puerto Rico, this study also highlights deficiencies in information regarding these important natural resources. It has been more than 25 years since the last systematic survey of coral reefs around Puerto Rico was conducted; many reefs have undergone substantial change since that time. It has been more than 35 years since the last systematic oceanographic survey of the insular shelf was conducted. These types of studies are important to better understand the effect of increased sediment and nutrient loads on coral reefs.

Coral reefs are a vital natural resource for Puerto Rico. Coral reefs are economically and ecologically important because they are (1) a critical part of the life cycle of many commercial fish and seafood species; (2) a key element in maintaining biodiversity; (3) a key component in the Puerto Rico economy, particularly with respect to tourism; and (4) an effective barrier for storm-wave erosion of coastal areas. The condition of coral reefs can also be used as an important indicator of climate change (Harvell *et al.,* 1999). There is a pressing need for a comprehensive and systematic survey of Puerto Rico coral reefs to determine the location, relative health, composition, relative risk for further degradation, and best actions for protecting and allowing recovery of these valuable natural resources.

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