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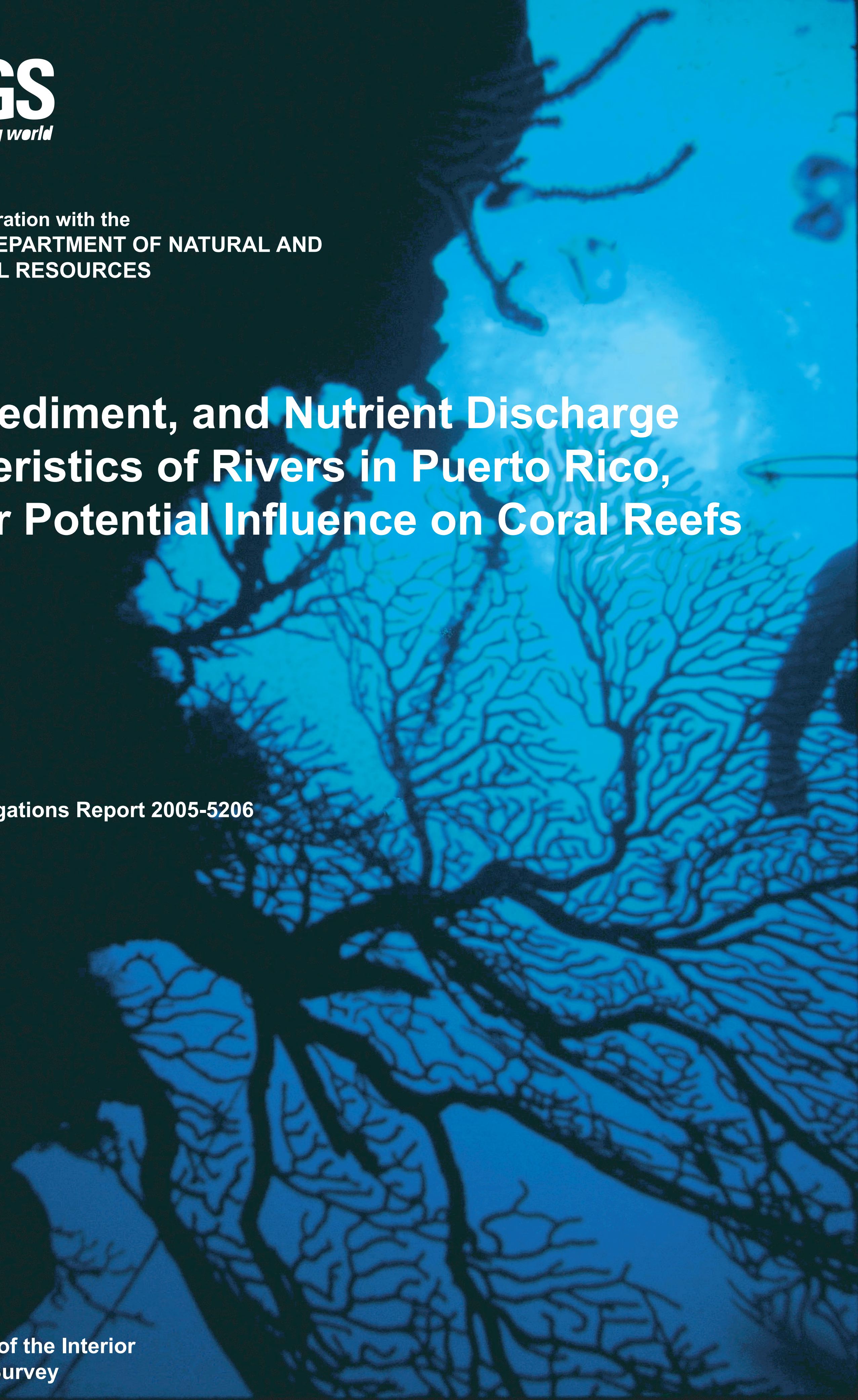
Water, Sediment, and Nutrient Discharge Characteristics of Rivers in Puerto Rico, and their Potential Influence on Coral Reefs



Scientific Investigations Report 2005-5206

U.S. Department of the Interior
U.S. Geological Survey

Cover photograph

View of a gorgonian coral near Playa Carabinero, Isla de Mona, Puerto Rico.
Photograph taken by John E. Parks, June 1993.

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By Andrew G. Warne, Richard M.T. Webb, and Matthew C. Larsen

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Conversion Factors and Datum, Water-Quality Units, and Acronyms

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square meter (m^2)	0.0002471	acre
square kilometer (km^2)	247.1	acre
square centimeter (cm^2)	0.001076	square foot (ft^2)
square meter (m^2)	10.76	square foot (ft^2)
square kilometer (km^2)	0.3861	square mile (mi^2)
	Volume	
liter (L)	33.82	ounce, fluid (fl. oz)
cubic meter (m^3)	264.2	gallon (gal)
cubic meter (m^3)	0.0002642	million gallons (Mgal)
	Flow rate	
cubic meter per second (m^3/s)	70.07	acre-foot per day (acre-ft/d)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)
millimeter per year (mm/yr)	0.03937	inch per year (in/yr)
	Mass	
gram (g)	0.03527	ounce, avoirdupois (oz)
kilogram (kg)	2.205	pound avoirdupois (lb)
megagram (Mg)	1.102	ton, short (2,000 lb)
megagram (Mg)	0.9842	ton, long (2,240 lb)
metric ton per day	1.102	ton per day (ton/d)
	Density	
kilogram per cubic meter (kg/m^3)	0.06242	pound per cubic foot (lb/ft^3)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

°F = (1.8 x °C) + 32

Datum:

Horizontal Datum - Puerto Rico Datum, 1940 Adjustment

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929) - a geodetic datum derived from a general adjustment of the first-order level nets of the United States and Canada, formerly called "Sea Level Datum of 1929".

Abbreviated water-quality units used in this report:

mg/L	milligrams per liter
mL	milliliter

Water, Sediment, and Nutrient Discharge Characteristics of Rivers in Puerto Rico, and their Potential Influence on Coral Reefs

By Andrew G. Warne, Richard M.T. Webb, and Matthew C. Larsen

Abstract

Data from 29 streamflow-gaging stations, including 9 stations with daily suspended-sediment concentration, and data from 24 water-quality stations were compiled and analyzed to investigate the potential effects of river sediment and nutrient discharges on the coral reefs of Puerto Rico. The largely mountainous watersheds of the 8,711-square-kilometer island of Puerto Rico are small, channel gradients are steep, stream valleys tend to be well-incised and narrow, and major storms tend to be intense but brief; hence flooding is rapid with peak discharges several orders of magnitude above base discharge, and flood waters recede quickly. Storm runoff transports a substantial part of fluvial suspended sediment from uplands to the coast, as indicated by sediment data from a set of nine streamflow-gaging stations representative of runoff from watersheds considered typical of conditions in Puerto Rico. For example, the highest recorded daily sediment discharge is 1 to 3.6 times the annual suspended-sediment discharge, and runoff from major storms induces sediment transport 1 to 32 times the median annual sediment load. Precipitation associated with Hurricane Georges in September 1998 is estimated to have averaged 300 millimeters across the island, which is equivalent to a volume of about 2.6 billion cubic meters. Analysis of runoff and sediment yield from Hurricane Georges indicates that more than 1.0 billion cubic meters of water and at least 2.4 million metric tonnes of sediment (and as much as 5 to 10 million metric tonnes), were discharged to the coast and shelf as a result of this major storm.

Because of their relatively small size, dams and reservoirs of Puerto Rico have relatively little effect on total discharge of water and sediment to the coastal marine waters during major storms. The presence of reservoirs, however, may be detrimental to coral reefs for two reasons: (1) coarse sediments deposited in the reservoir can be replaced by finer sediments scoured, if available, from the river channels and flood plains below the dam; and (2) the loads of phosphorus and ammonia reaching the coastal waters may increase as organic matter decomposes in the anoxic bottom waters of the reservoir.

Rainfall, water discharge, sediment discharge, and sediment yield vary across the island. Mean annual runoff for the island is estimated to be 910 millimeters, about 57 percent of mean annual precipitation (1,600 millimeters). 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. Hydrologic and sediment data associated with Hurricane Georges indicate that sediment yield is generally proportional to the depth of storm runoff. Discharge and sediment-concentration data indicate that during this storm, river water and sediment that discharged into the marine environment generally formed hypopycnal plumes (buoyant suspension layers). Generally, hyperpycnal (density) plumes can develop in areas with high discharges and sediment concentrations. Both hypopycnal and hyperpycnal plumes distribute suspended sediment over broad areas of the Puerto Rico shelf and shelf slope. Comparison of long-term suspended-sediment discharge and watershed characteristics for Puerto Rico with those of other river systems around the world indicates that Puerto Rico rivers are similar to temperate and tropical upland river systems.

Prior to 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 reef areas of Puerto Rico were able to endure 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 deposition and promotes transport of the sediment to the shelf edge and shelf slope.

Beginning in the early 19th century, substantial land clearing and modification, first for agriculture and later for urban development, resulted in increased sediment yields, and increased sediment and nutrient influx to coral reef areas. This terrestrial sediment in runoff may be a source of pathogens that affect coral reefs. Large parts of Puerto Rico have been reforested since the mid-1940s, but sediment transported into the river valleys during the agricultural period is still being transported through the river systems. Although, nitrogen and phosphorous concentrations in river waters are well within regulatory limits, current concentrations are as much as 10 times the estimated pre-settlement 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. The constant anthropogenically increased sediment and nutrient discharge to the Puerto Rico shelf are believed to have contributed to widespread degradation of coral reefs in Puerto Rico. Negative effects of river-derived sediment and nutrient discharge on coral reefs are especially pronounced in nearshore areas of the north, southwest, and west coasts of the island. A comprehensive and systematic survey of Puerto Rico coral reefs would enable the establishment of a baseline with which to determine which reef areas are at risk, and what measures can be taken to protect and restore these valuable natural resources.

Introduction

Coral reefs are the foundation and primary structure of many highly productive and diverse tropical marine ecosystems. The coast and shelf of Puerto Rico support numerous coral reefs (fig. 1), and these living carbonate structures accommodate a number of ecosystem and socioeconomic functions including protection and feeding areas for fish, tourism, recreation, dampening of potentially erosive waves, and creation of sand material for beaches.

Coral reefs flourish 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 global warming, increased terrigenous sediment input from modified watersheds, eutrophication caused by increased agrochemical and sewage discharge, dredging, turbidity caused by boats and ships, and increased water temperatures (Goenaga and Cintrón, 1979; Velazco-Domínguez and others, 1985; Acevedo and others, 1989; Bell, 1992; Brown and Ogden, 1993; Hunter and Arbona, 1995; Larcombe and others, 1995; Smith and others, 1996; Bruckner and Bruckner, 1997; Wilkinson, 2000; Kuta and Richardson, 2002; Patterson and others, 2002; Weil, 2004). Weil (2004) suggests that terrestrial sediment in runoff may be a source of pathogens that affect coral reefs. The majority of coral reefs of Puerto Rico, along with many other Caribbean reefs, are either already affected by pathogens or are at especially high risk (Jameson and others, 1995; Torres and Morelock, 2002). According to Weil (2004), 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. Furthermore, although the greater Caribbean is host to only about 8 percent of the world's coral reef area, 66 percent of all coral reef diseases and syndromes were reported there in the year 2000. The problem is global, however; 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) emphasize the great vulnerability of coral reefs in the Caribbean. Their work compiles extensive data and model results to relate a variety of physical, socioeconomic, and environmental effects on coral reefs. They highlight the strong anthropogenic impact on coral reefs in the Caribbean region and note that Caribbean 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 phosphorous concentrations suppress calcium mineralization by coral reef organisms, slowing growth rates (Kinsley and Davis, 1979). High nutrient concentrations promote the proliferation of planktonic algae, which lowers light transmissivity of water, 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 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 aquatic 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. Because the volume of sediment, water, and nutrient discharge and the shelf width vary around the island, it is possible to study the range of effects of sediment and nutrient influx on coral reef distribution and health. The U.S. Geological Survey (USGS) currently (2004) maintains and compiles data for 98 streamflow, 26 daily sediment, and 58 water-quality gaging stations around the island. In addition, there are numerous USGS stream, sediment, and water-quality gaging stations that have been discontinued, but provide high-quality, archival, river-discharge information. These data can be used to reasonably estimate river water and sediment discharge, on an island-wide basis, from the uplands to the coast and shelf.

Purpose and Scope

The purpose of this report is to provide a quantitative analysis of the magnitude, frequency, and distribution of river water and suspended-sediment discharge to the Puerto Rico coast and shelf to identify and characterize the types of storms that transport river-derived sediments and nutrients to coral reef areas. Estimates of island-wide water and sediment discharge (mean annual and a recent large storm—Hurricane Georges) are provided. River water and sediment discharge characteristics are related to the location and condition of the reefs around the island (fig. 1), and major processes that control the transport and fate of river-borne sediment and nutrients in the shelf environment are identified.

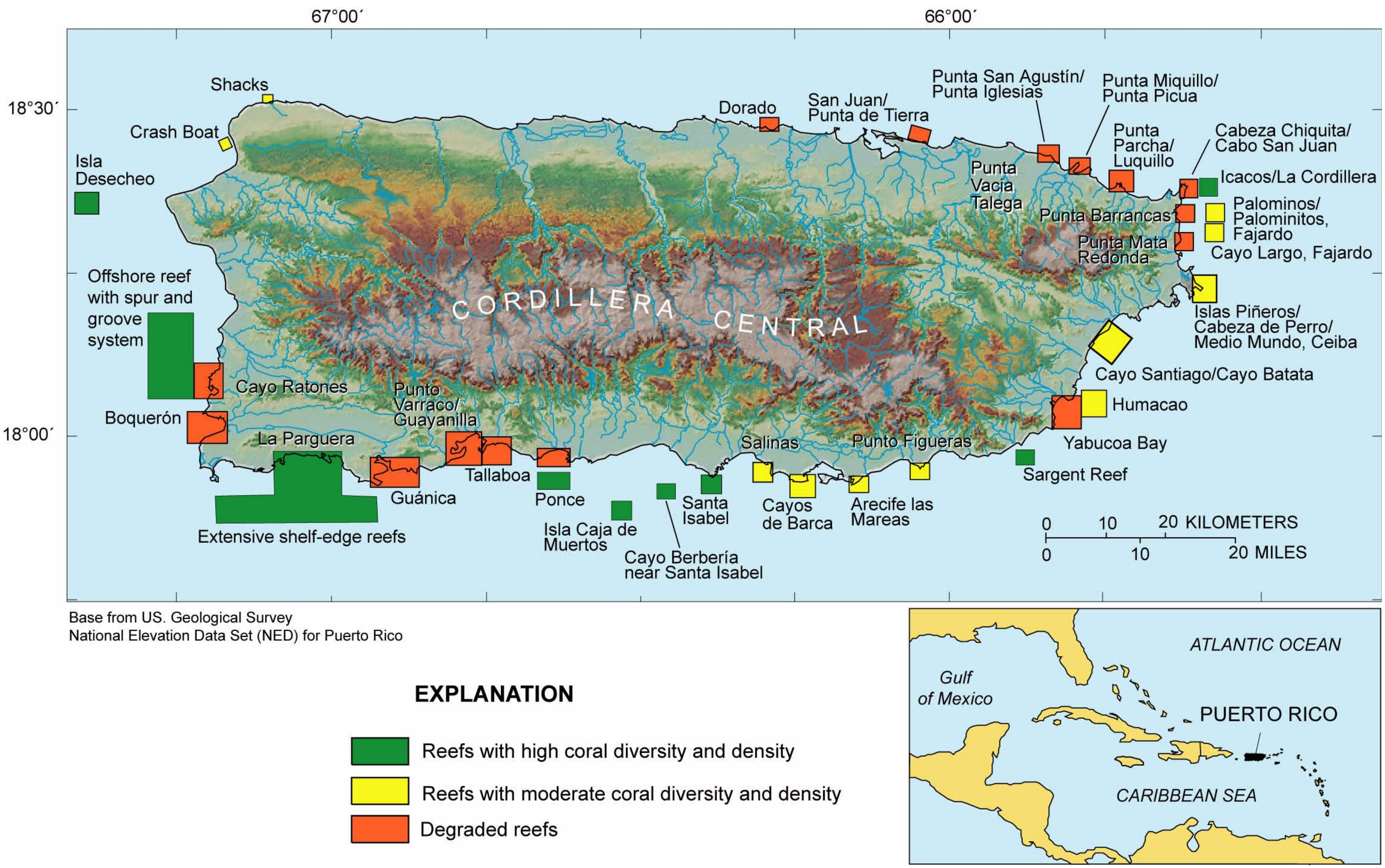


Figure 1. Location and condition of major coral reefs around Puerto Rico. Data from Goenaga and Cintrón (1979) and Simonsen (2000).

The report describes the results of analysis of river water and sediment discharge data to identify and evaluate characteristics of rivers that potentially influence the distribution and health of insular coral reefs. The results of analyses of river and coastal water-quality data are summarized to determine the potential effect of nutrient loading on insular coral reefs. The report summarizes what is known about the marine hydrodynamic regime around the island. Finally, the report describes the interaction of river and shelf processes, particularly during large storms, and discusses how river-marine interactions may influence the distribution and health of coral reefs around the island.

Acknowledgments

The late Carlos Goenaga of the University of Puerto Rico conducted a number of reconnaissance coral surveys and provided helpful insights to the authors. John R. Gray, Robert F. Stallard, and Carolyn Rogers (USGS) provided reviews and helpful suggestions. Robert H. Meade (USGS) provided useful comments and suggestions regarding characterization of river water and sediment discharge. Fernando Gilbes and Roy Armstrong of the University of Puerto Rico processed and made available the SeaWiFS imagery. Ramón Carrasquillo, María del Carmen Álvarez, Gilberto Rodríguez, Ivette Reyes, and Robert Fitzhugh (USGS, Caribbean Water Science Center) provided essential support. Francisco Maldonado, Ruth I. Guzmán, and María del Carmen Rivera (USGS, Caribbean Water Science Center) were instrumental in preparing the report graphs, tables, and text. Many USGS hydrologic technicians contributed to the collection of water and sediment data presented in this report; the analysis presented herein would not be possible without their data collection and compilation efforts. Finally, this report was made possible by the efforts and contributions of the first author, Andrew G. Warne, who passed away before seeing this work completed. His enthusiasm, scientific discipline, and dedication are greatly missed.

Methods

A comprehensive literature survey was conducted to provide a basis for understanding the influence of river water and suspended-sediment discharges on coral reefs around Puerto Rico. Principal subjects evaluated during the literature survey included climate, erosion and suspended-sediment transport, oceanography of the coast and shelf, water quality of rivers and coastal areas, major coral reef stressors, and coral reef distribution and health.

Water-discharge data from 29 USGS streamflow-gaging stations were analyzed to characterize suspended-sediment and water discharge in Puerto Rico (tables 1-3; fig. 2). Mean annual discharge, mean annual runoff, and highest daily mean discharge were compiled and used to characterize water discharge from the island (tables 1, 2). To characterize river discharge 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 are believed to provide a reasonable estimate of runoff from all regions of Puerto Rico (fig. 2). The 24 stations have a total contributing area of 3,875 square kilometers (km^2) or 44 percent of the island land area. Mean annual runoff for the island was approximated using the mean runoff of the 24 stations. Eleven years of data (water years 1990 to 2000) were compiled from the USGS National Water Inventory System database (see http://waterdata.usgs.gov/nwis/), and from Curtis and others (1991, 1992) and Díaz and others (1993-2001). 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 considered to be a representative sample of long-term conditions, because this period included a severe drought (1994-1995) and periods of high rainfall accumulation associated with major hurricanes (1996, 1998) (Torres-Sierra, 1996; Larsen, 2000). 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) (table 3, figs. 2, 3). This small number of sediment stations 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. Bedload sediment transport, not discussed in this report, has been characterized in only a few locations in Puerto Rico (Larsen, 1997; Simon and Guzmán-Ríos, 1990) and few bedload sediment data have been published. It is unlikely, however, that bedload sediment would commonly affect coral reefs because transport of bedload beyond the vicinity of estuaries and river mouths has not been observed.

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 and others, 1999-2002, 2004). Data for silt and clay percentages were compared to runoff, calculated from the published instantaneous discharge, to normalize for drainage area.

Table 1. Information for 29 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 2. Data from Curtis and others (1991, 1992), and Díaz and others (1993 to 2001).

[km^2, square kilometer; m^3/s, 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^3/s)	Mean annual runoff (mm)
Río Grande de Arecibo	50027750	451	Y	April 1982 - October 2000	10.1	706
Río Grande de Manatí	50038100	510	N	February 1970 - October 2000	10.7	663
Río Cibuco	50039500	256	N	January 1973 - October 2000	3.5	429
Río de la Plata	50046000	539	Y	January 1960 - October 2000	7.2	442
Río de Bayamón	50048000	186	Y	November 1962 - December 1966	3	506
Río Piedras	50049100	40	N	January 1988 - October 2000	1.5	1,250
Río Grande de Loíza	50059050	541	Y	December1986 - October 2000	7.3	427
Río Espíritu Santo	50063800	22	N	August 1966 - October 2000	2.9	4,060
Río Mameyes	50066000	35	N	July 1997 - October 2000	2.8	1,240
Río Fajardo	50071000	39	N	March 1961 - October 2000	1.9	1,550
Río Humacao	50081000	17	N	October 1987 - October 2000	0.6	1,170
Río Maunabo	50090500	14	N	February 1972 - January 1985, February 1991 - October 2000	0.5	1,200
Río Grande de Patillas	50092000	47	N	January 1966 - October 2000	1.6	1,090
Río Lapas	50100200	26	N	September 1988 - October 2000	0.2	216
Río Majada	50100450	43	N	September 1988 - October 2000	0.2	157
Río Descalabrado	50108000	33	N	February 1984 - October 2000	0.3	296
Río Bucaná	50114390	64	Y	August 1987 - October 2000	1.4	688
Río Jacaguas	50111500	129	Y	March 1984 - October 2000	1.3	317
Río Portugués	50115900	48	N	July 1997 - October 2000	1.5	914
Río Guayanilla	50124200	49	N	March 1981 - October 2000	0.6	419
Río Rosario	50136400	47	N	October 1985 - October 2000	1.4	958
Río Guanajibo	50138000	311	N	January 1973 - October 2000	5.5	556
Río Grande de Añasco	50144000	244	N	March 1963 - October 2000	9.1	1,170
Río Culebrinas	50147800	184	N	July 1967 - October 2000	8.3	1,430
Total (T) and Mean (M)		(T) 3,875				(M) 911
Upstream stations used for suspended-sediment data but not included in island runoff estimate above						
Río de la Plata	50045010	448	Y	July 1989 - October 2000	4.8	340
Río de Bayamón	50047560	21	N	November 1990 - October 2000	0.5	785
Río Mameyes	50065500	18	N	August 1967 - December 1973, June 1983 - October 2000	1.6	2,810
Toa Vaca	50110900	37	N	April 1989 - October 2000	0.4	396
Río Portugués	50114900	19	N	October 1997 - October 2000	0.6	1,020

Table 2. Proportion of annual water discharge contributed by the maximum daily discharge at 24 streamflow-gaging stations in Puerto Rico, water years 1990 to 2000. Station locations shown on figure 2. Calculated using data from water years 1990 to 2000 (Curtis and others, 1991, 1992; Díaz and others, 1993 to 2001).

[Water year refers to the period from October 1 through September 30 of the following year. ID, identification number]

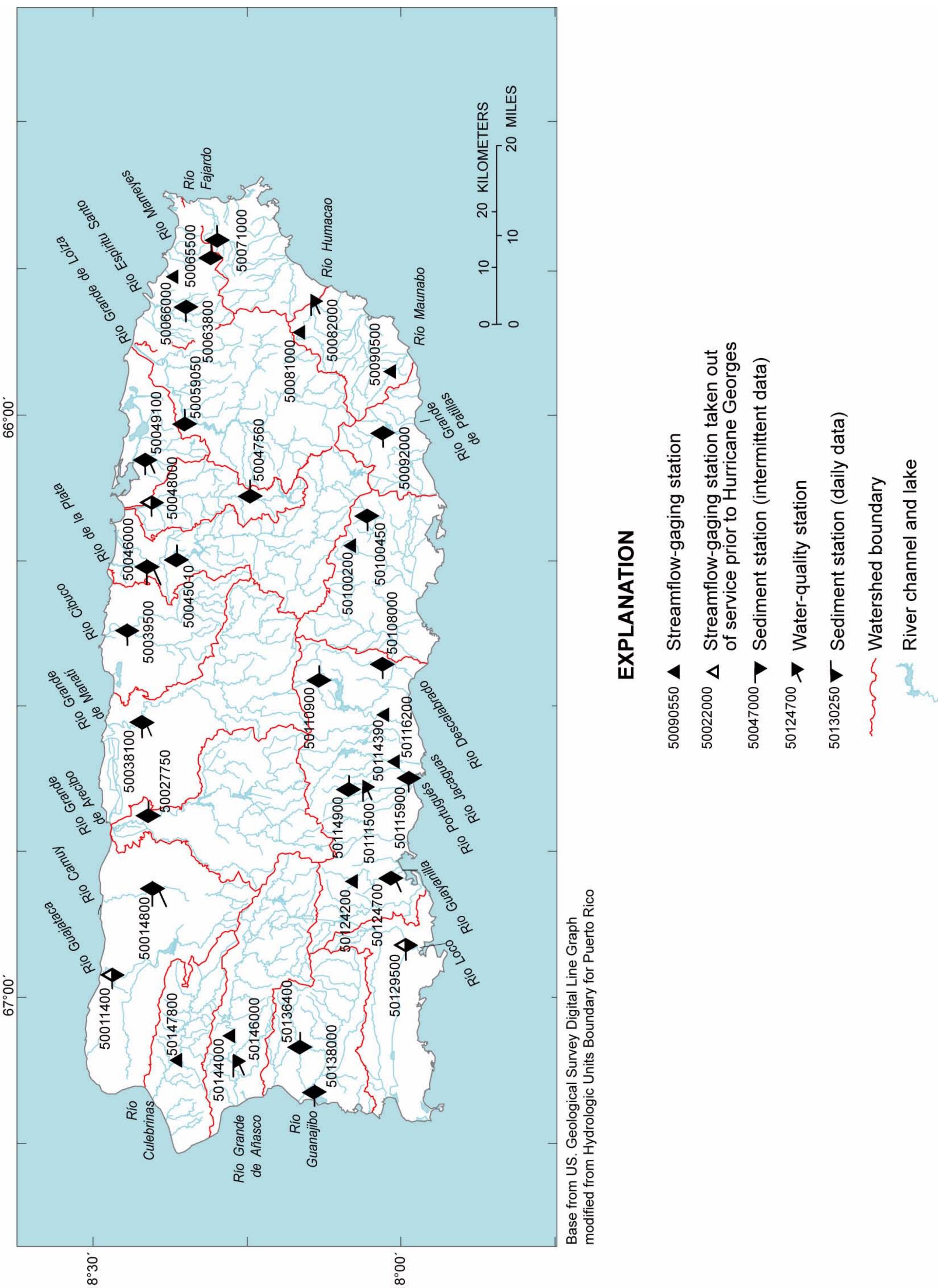
Stream name	Station ID	Proportion of annual water discharge contributed by maximum daily discharge (for the year), in percent	Highest proportion of annual water discharge contributed by the maximum daily discharge (for the year), in percent
Río Grande de Arecibo	50027750	3.3	7.8
Río Grande de Manatí	50038100	12	42
Río Cibuco	50039500	7.6	21
Río de La Plata	50046000	25	59
Río de Bayamón	50048000	10	41
Río Piedras	50049100	5.7	17
Río Grande de Loíza	50059050	21	62
Río Espíritu Santo	50063800	4.5	8.9
Río Mameyes	50066000	3.9	7.2
Río Fajardo	50071000	4.7	9.4
Río Humacao	50081000	6.5	19
Río Maunabo	50090500	6.1	13
Río Grande de Patillas	50092000	6.1	14
Río Lapas	50100200	16	54
Río Majada	50100450	15	52
Río Descalabrado	50108000	17	66
Río Bucaná	50114390	8.4	18
Río Jacaguas	50111500	8.4	25
Río Portugués	50115900	11	26
Río Guayanilla	50124200	4.7	11
Río Rosario	50136400	3.9	20
Río Guanajibo	50138000	4.9	22
Río Grande de Añasco	50144000	6.7	37
Río Culebrinas	50147800	5.7	12

Table 3. Sediment and water discharge data from 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, cubic meter per second; mm, millimeter; mm/d, millimeter per day; mg/L; milligrams per liter]

Stream name	Station ID[1]	Hurricane Georges highest mean daily water discharge[2] (m^3/s)	Hurricane Georges highest mean daily water runoff (mm/d)	Total Hurricane Georges water runoff (mm)	Total Hurricane Georges runoff/mean annual runoff[3]	Mean daily sediment concentration (mg/L) during Hurricane Georges' highest daily mean water discharge[2]
Río Grande de Arecibo	50027750	206	39	77	0.11	3,500
Río de la Plata	50045010	2,140	413	583	1.70	2,500
Río de Bayamón	50047560	58	239	289	0.37	790
Río Grande de Loíza	50059050	1,870	299	366	0.86	3,400
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 2.
[2] Data from Díaz and others (1999).
[3] Mean annual runoff listed in table 1.



Base from US. Geological Survey Digital Line Graph
modified from Hydrologic Units Boundary for Puerto Rico

Figure 2. Location of streamflow-gaging stations, sediment stations, and water-quality stations used in this study.

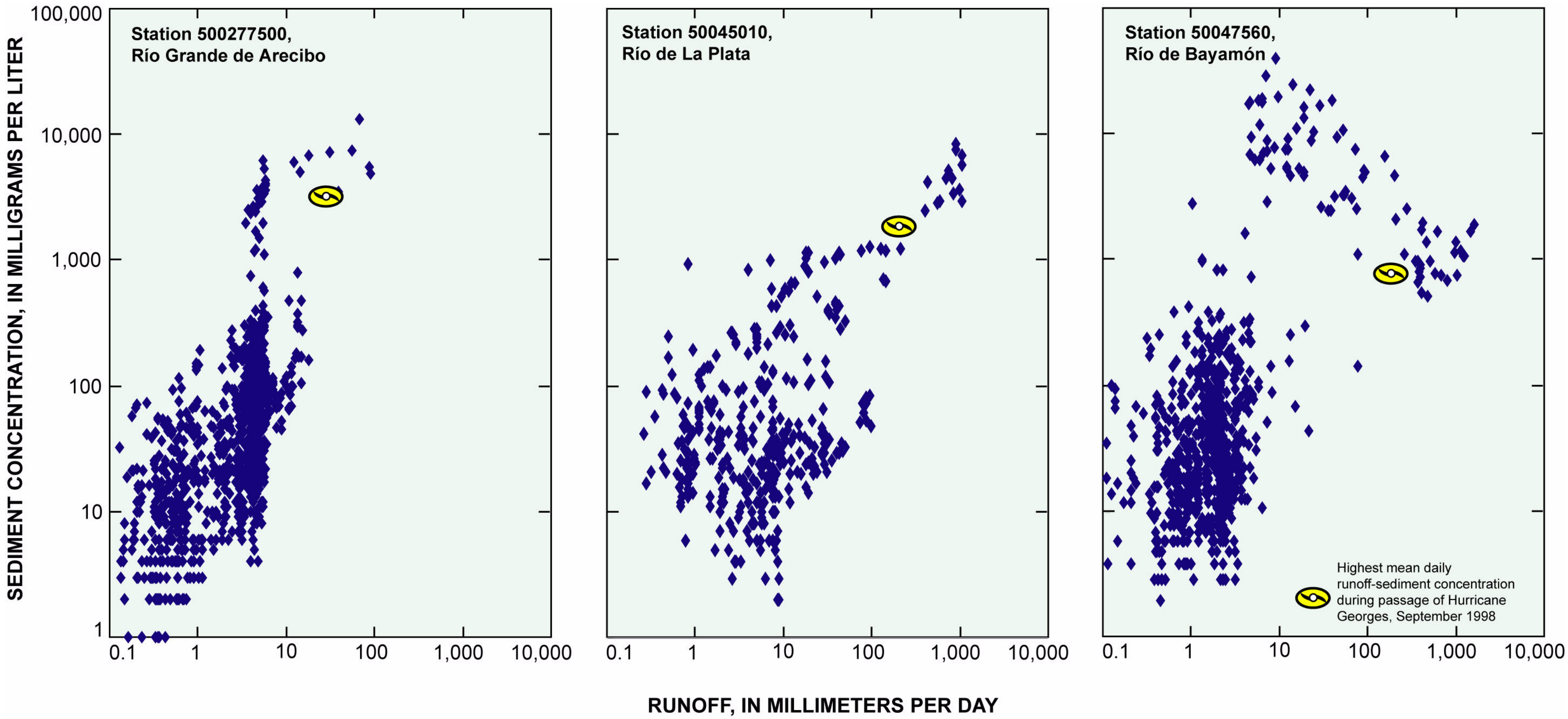


Figure 3. Relation between suspended-sediment concentration and runoff at nine daily sediment stations. See figure 2 for station locations.

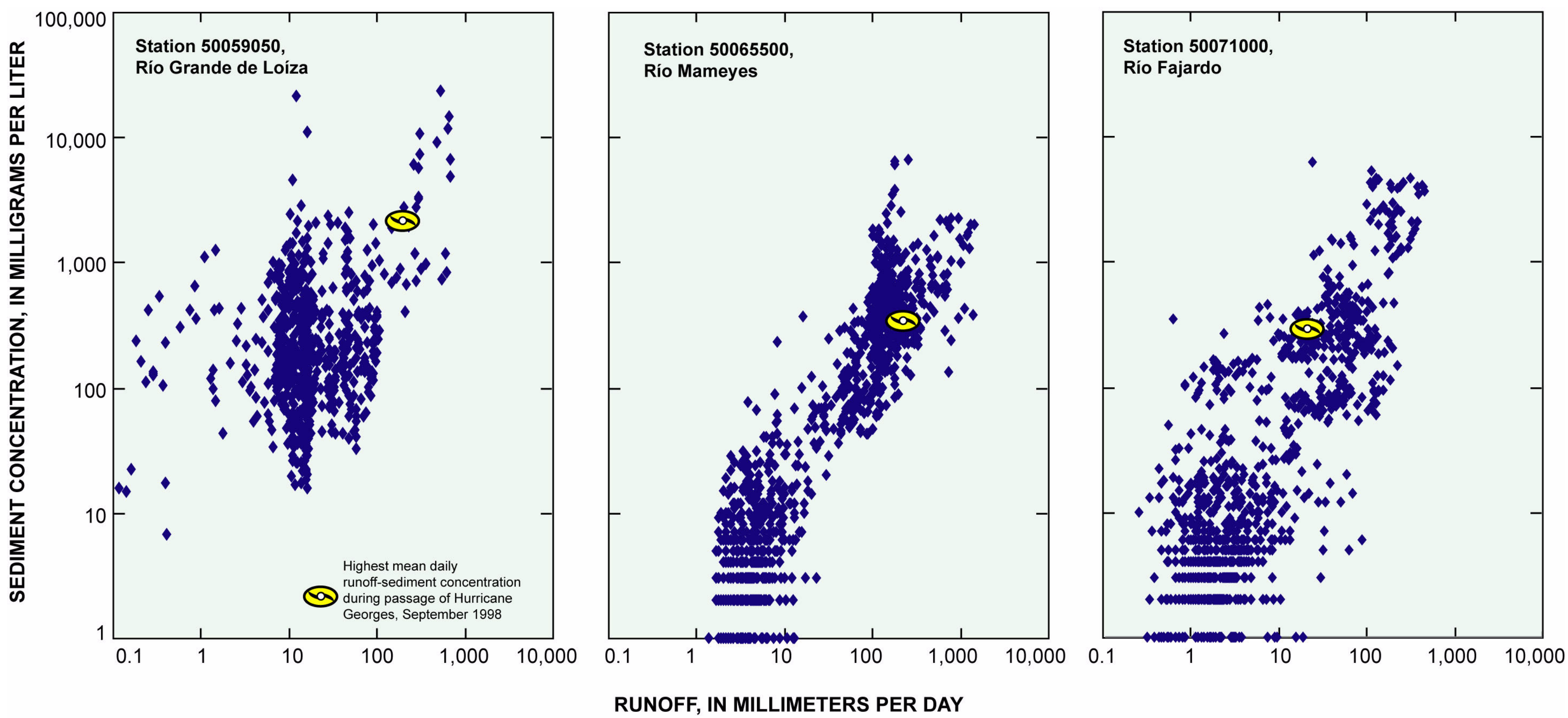


Figure 3. Relation between suspended-sediment concentration and runoff at nine daily sediment stations. See figure 2 for station locations.—Continued

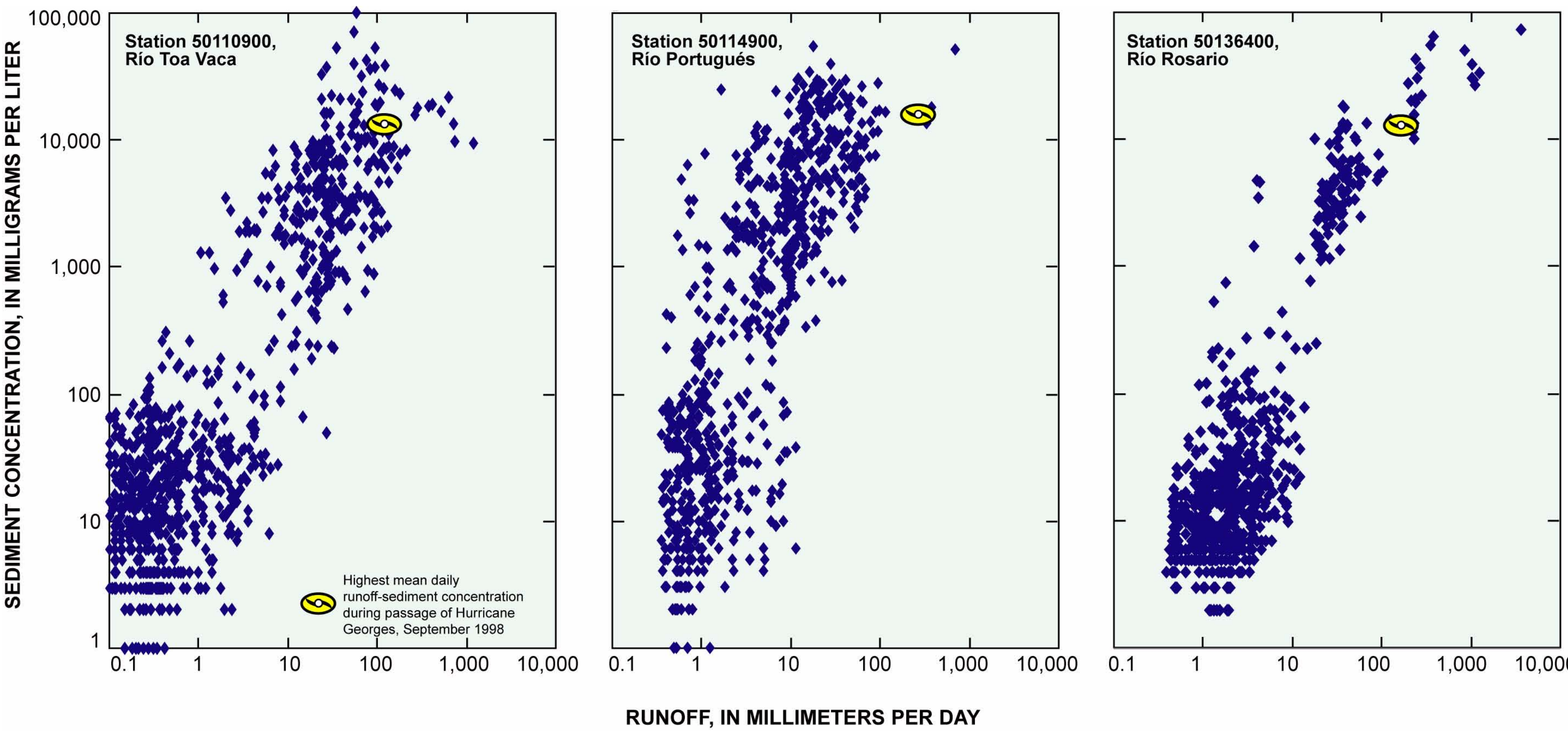


Figure 3. Relation between suspended-sediment concentration and runoff at nine daily sediment stations. See figure 2 for station locations.—Continued

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 4). 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 (see watershed maps in Díaz and others, 2002). Additionally, sediment-discharge characteristics were compared with other areas of the world (fig. 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 (tables 3, 5-8). Rainfall accumulation associated with Hurricane Georges was calculated for the period September 20-25 for four island runoff (climatologic) regions from rainfall isohyet maps 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 meters (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). Runoff for the period September 20-25, 1998, was estimated from the same grid (table 5).

Basic water-quality data were compiled from 24 USGS water-quality monitoring stations located in the downstream reaches of rivers around Puerto Rico. Water-quality data compiled and evaluated included total dissolved solids (estimated from specific conductance), total dissolved nitrogen and phosphorus, and concentrations of fecal coliform and fecal streptococci. Nitrogen and phosphorus are nutrients. 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 number of colonies per 100 milliliters of sample.

Data from five water-quality monitoring stations (fig. 5) were selected to represent water quality in rivers draining the north, east, south, and west coasts of the island. Fecal coliform, fecal streptococcus, nitrogen, and phosphorus concentrations for the water years 1990 to 2000 were plotted to evaluate changes in river water quality over time (fig. 5). Fecal coliform and total dissolved solids were plotted against river discharge values that were recorded at the time of sampling (fig. 6) to gain insight into the volume of nutrient discharge to the island shelf during storms. Total dissolved solids data were used to infer nutrient data because there were few instances where discharge was recorded at the time of nitrogen and phosphorus sampling, and total dissolved solids data compare well to concentrations of nitrogen and phosphorus. The decrease in total dissolved solids with increased discharge, and the lack of a clear relation between fecal coliform concentration and discharge are common attributes of storm flows observed at the water-quality stations around the island (fig. 6) (Díaz and others, 2001).

Table 4. 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 6; drainage areas and regions from table 5 and figure 15; contributing areas shown below estimated as 50 percent of North and West regions, 66 percent of South and East regions, see text for explanation; *Mean calculated as minimum and maximum yield divided by total contributing area. km^2, square kilometer]

Region of island	Mean annual suspended-sediment yield, metric tonnes/km^2	Contributing area, km^2	Mean annual suspended- sediment discharge, metric tonnes
North	120 to 1,000	2,317	280,000 to 2,300,000
East	140 to 520	356	51,000 to 180,000
South	1,000 to 4,300	1,300	1,400,000 to 5,600,000
West	1,200	783	960,000
	Mean: 570 to 1,900*	Total: 4,786	Total: 2.7 to 9.0 million

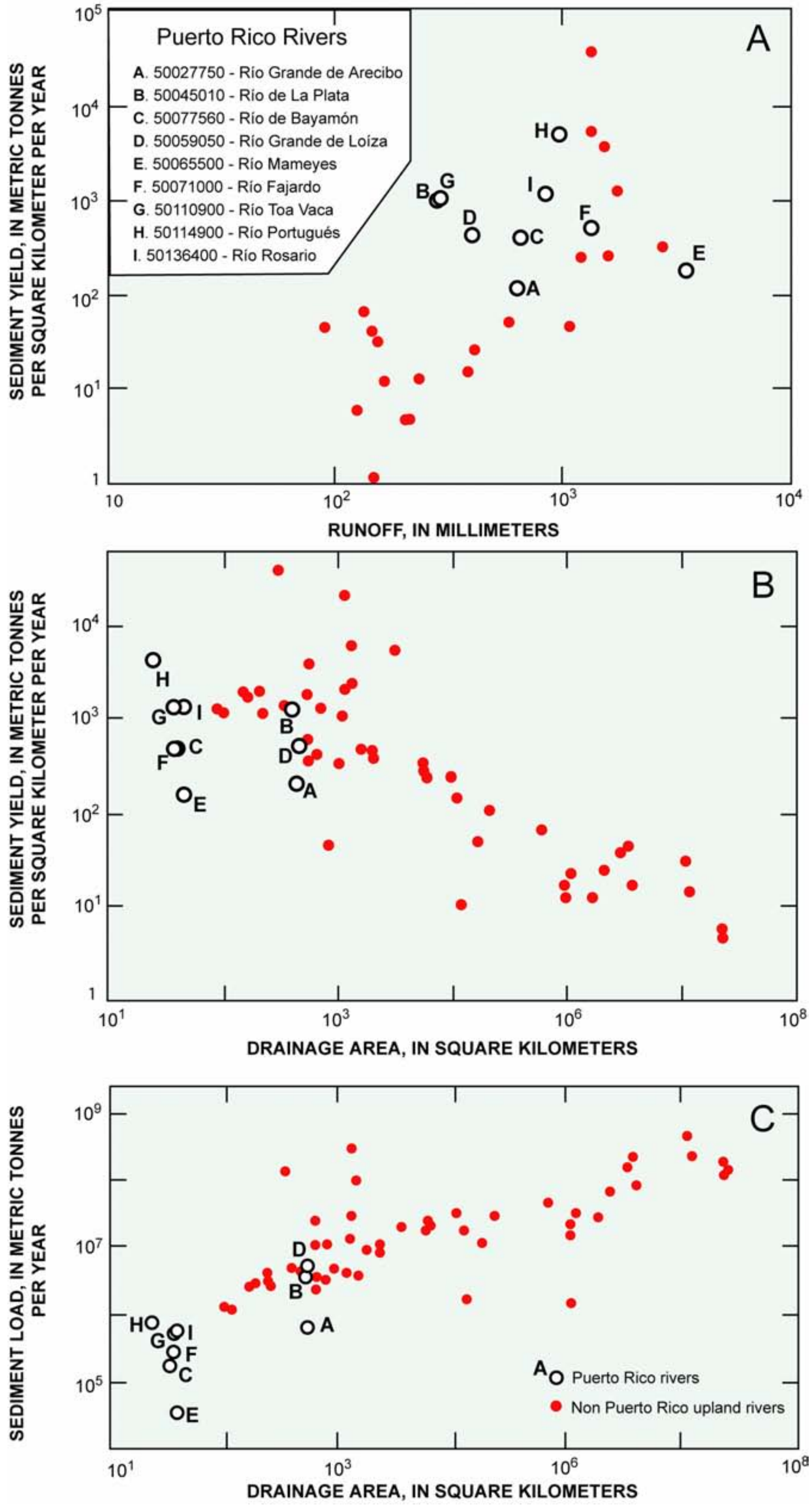


Figure 4. Sediment yield and discharge characteristics of Puerto Rico rivers in relation to other upland settings around the world (data from Milliman and Syvitski, 1992). (A) Relation between suspended sediment yield and runoff, (B) Relation between suspended sediment yield and drainage area, (C) Relation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

Table 5. 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, 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
North	4,635	0.53	280	1,300	0.45	581	0.57	130	21
East	540	0.06	200	110	0.55	58.9	0.06	110	18
South	1,970	0.23	320	630	0.22	136	0.13	69	12
West	1,566	0.18	360	560	0.45	250	0.24	160	27
Area-weighted average			300		0.40			120	20
Total	8,711	1.00		2,600		1,000	1.00		

Table 6. Summary statistics of suspended-sediment discharge for selected sediment monitoring stations in Puerto Rico, October 1990 to September 2000.

[ID, identification number; km^2, 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[3] (metric tonnes)	Median annual sediment discharge[3] (metric tonnes)	Mean of highest daily water discharge (for the year)/ total annual water discharge[3]	Mean annual sediment yield[3] (metric tonnes/ km^2/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	1,000	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	4,900 (G)	5,000	4,300	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	1,000	2.2	0.34	4.8	4.8
Río Portugués	50114900	130,000 (G)	81,000[5]	40,000[4]	0.43	4,300	1.6	0.38	3.2	3.2
Río Rosario	50136400	320,000 (G)	58,000	17,000	0.31	1,200	5.6	0.24	19.0	19.0

[1] Station locations shown in figure 2.
[2] Data from Díaz and others (2001).
[3] Calculated using annual discharge data for water years 1991 to 2000 (Curtis and others, 1991, 1992; Díaz and others, 1993-2001).
[4] Station has only 5 years of data (1996-2000).
[5] Station has only 3 years of data (1998-2000).

Table 7. Storm discharge characteristics for selected streamflow-gaging stations in Puerto Rico.

[ID, identification number; m^3/s, square meter per second; mm/d, millimeter per day; nd, not determined; na, not available or not applicable; >, greater than; <, less than; A, Tropical Depression Arlene-August 5, 1963; D, Hurricane David-August 31, 1979; E, Hurricane Eloise-September 16, 1975; I, Tropical Storm Isabel-October 6, 1985; H, Hurricane Hortense-September 10, 1996; Hu, Hurricane Hugo-September 18, 1989; G, Hurricane Georges-September 22, 1998; T, Three Kings Day storm-January 6, 1992]

Stream name	Station ID[1]	Highest mean daily discharge[2] (m^3/s)	Date of highest mean daily discharge[2] and storm name, if known	Hurricane Georges (September 21 or 22, 1998) mean daily discharge[2] (m^3/s)	Hurricane Georges runoff[2] (mm/d)	Hurricane Georges peak discharge[2]	Estimated recurrence interval for Hurricane Georges discharge[4]
Río Guajataca	50011400	122	5/18/1985	122[4]	159	na	na
Río Grande de Arecibo	50027750	419	9/22/1998 (G)	206	40	nd	na
Río Grande de Manatí	50038100	2,280	12/13/1981	2,280	386	136,000	25 to 50
Río Cibuco	50039500	414	9/10/1996 (H)	101	34	7,650	2 to 5
Río de la Plata	50045010	3,990	9/10/1996 (H)	2,140	413	122,000	na
Río de la Plata	50046000	1,930	9/10/1996 (H)	1,330	214	104,000	10 to 25
Río de Bayamón	50048000	164	12/10/1975	164[3]	76	nd	na
Río Piedras	50049100	129	9/10/1996 (H)	61	131	5,700	Na
Río Grande de Loíza	50059050	3,120	12/7/1987	1,870	298	155,000	na
Río Espíritu Santo	50063800	74	9/18/1989 (Hu)	67	261	13,500	5 to 10
Río Mameyes	50065500	79	9/21/1998 (G)	42	203	12,600	2 to 5
Río Mameyes	50066000	75	9/18/1989 (Hu)	75	187	18,400	na
Río Fajardo	50071000	249	9/10/1996 (H)	22	48	8,480	2 to 5
Río Humacao	50081000	57	8/31/1979 (D)	17	84	2,120	<2
Río Maunabo	50090500	70	9/16/1975 (E)	19	117	2,550	2 to 5
Río Grande de Patillas	50092000	135	9/10/1996 (H)	127	232	nd	na
Río Lapas	50100200	54	9/10/1996 (H)	22	75	7,320	na
Río Majada	50100450	64	9/10/1996 (H)	31	61	12,800	na
Río Descalabrado	50010800	283	1/6/1992 (T)	48	124	9,180	5 to 10
Río Bucaná	50114390	123	9/10/1996 (H)	99	133	931	<2
Río Toa Vaca	50110900	58	9/22/1998 (G)	49	115	>15,000	na
Río Jacaguas	50111500	242	9/22/1998 (G)	242	161	376,000	na
Río Portugués	50114900	85	9/22/1998 (G)	85	390	10,000	na
Río Portugués	50115900	158	10/7/1985 (I)	158	283	16,300	25 to 50
Río Guayanilla	50124200	43	9/22/1998 (G)	26	47	187,000	>500
Río Loco	50129500	20	8/5/1963 (A)	20[3]	32	nd	na
Río Rosario	50136400	125	9/16/1975 (E)	125	228	nd	na
Río Guanajibo	50138000	991	9/22/1998 (G)	572	159	40,600	5 to 10
Río Grande de Añasco	50144000	1,980	9/22/1998 (G)	1,980	700	163,000	100 to 500
Río Culebrinas	50147800	481	9/22/1998 (G)	481	226	36,900	5 to 10

[1] Station locations shown in figure 2.
[2] Data from Díaz and others (2000).
[3] Station was discontinued prior to Hurricane Georges; the highest recorded mean daily discharge at the station was used to estimate water and sediment runoff from Hurricane Georges.
[4] Estimates are based on log-Pearson Type III estimates (Ramos-Ginés, 1999).

Table 8. 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, 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)	Fraction of water discharge recorded on day of greatest discharge	Sediment discharge (metric tonnes)	Maximum 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)	Maximum 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	1,100
Río de Bayamón	50047560	6,070,000	5,020,000	0.83	4,700	3,000	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	1,700
Río Mameyes	50065500	6,140,000	3,620,000	0.59	5,400	5,000	0.90	203	270
Río Fajardo	50071000	3,810,000	1,860,000	0.49	2,200	2,000	0.89	48	50
Río Toa Vaca	50110900	7,930,000	4,260,000	0.54	137,000	85,000	0.62	115	2,300
Río Portugués	50114900	8,710,000	7,340,000	0.84	148,000	130,000	0.88	386	6,900
Río Rosario	50136400	13,700,000	10,800,000	0.79	325,000	320,000	0.99	230	6,890
Totals		540,000,000	497,000,000	0.73	2,450,000	2,000,000	0.84		

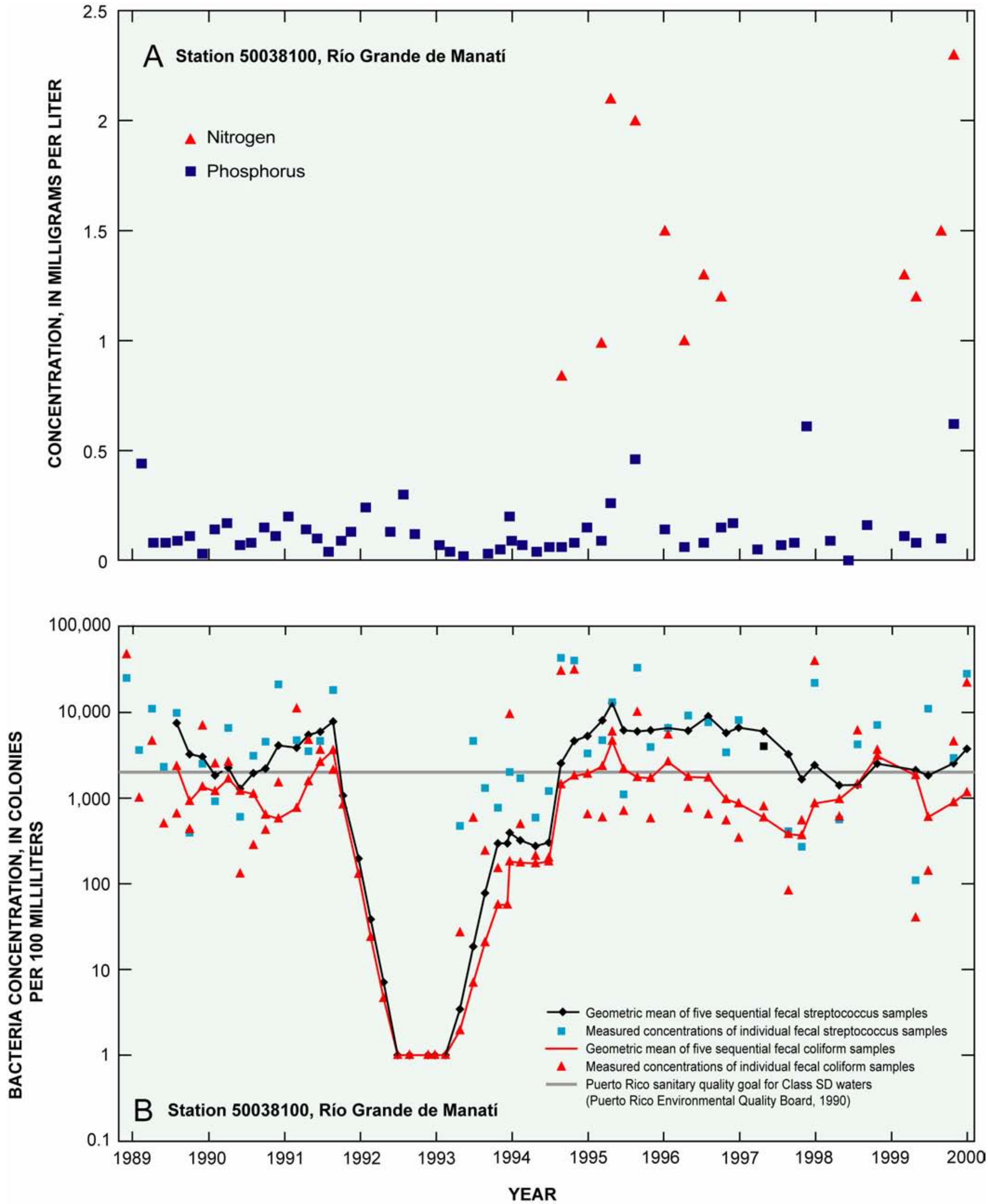
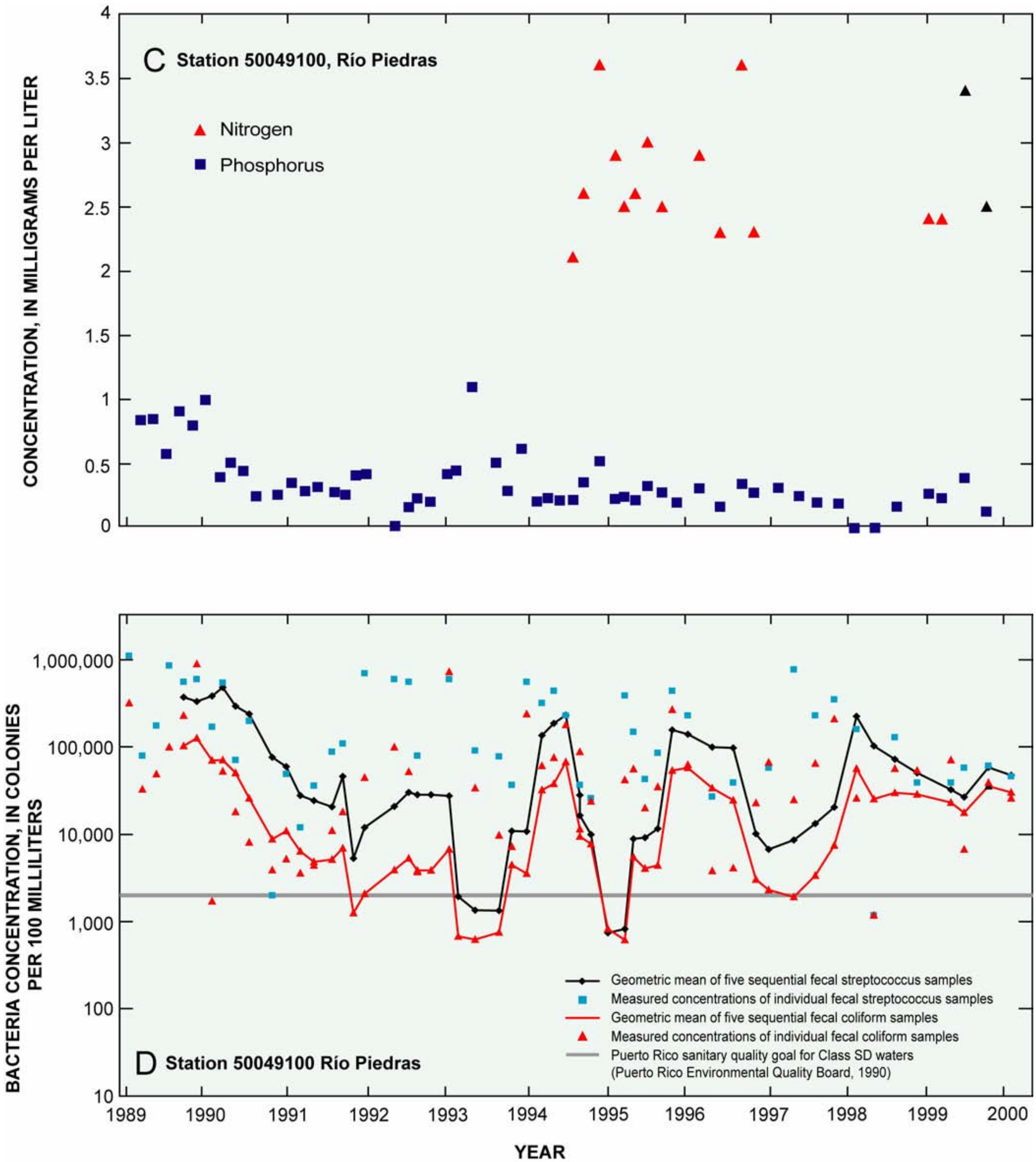


Figure 5. Concentrations of nutrients and bacteria for five water-quality monitoring stations for the period September 1989 to October 2000 (water years 1990-2000). Nitrogen and phosphorous concentrations (A, C, E, G, I) are calculated from individual samples. Total dissolved nitrogen is reported as N, and total dissolved phosphorous as P.



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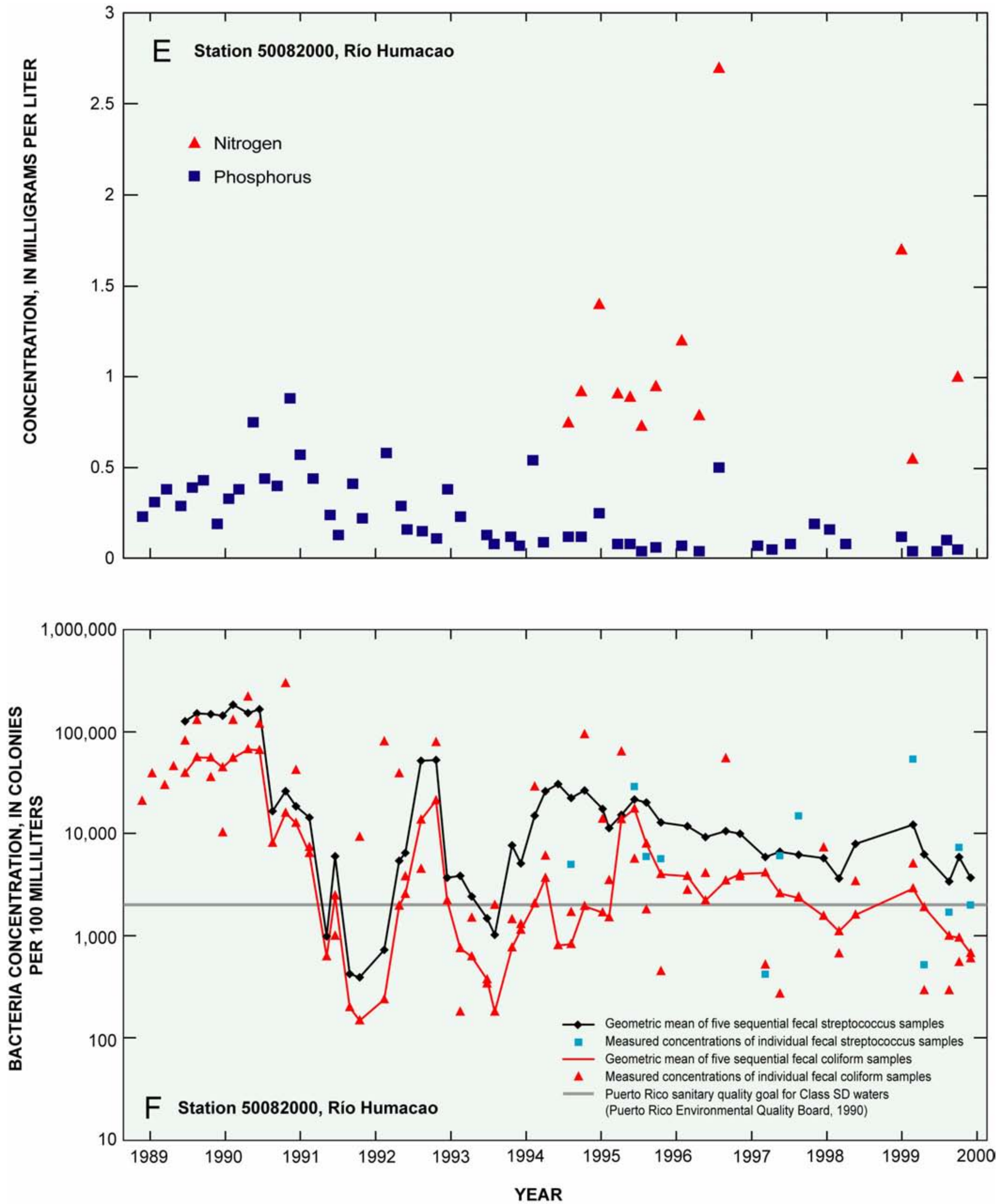

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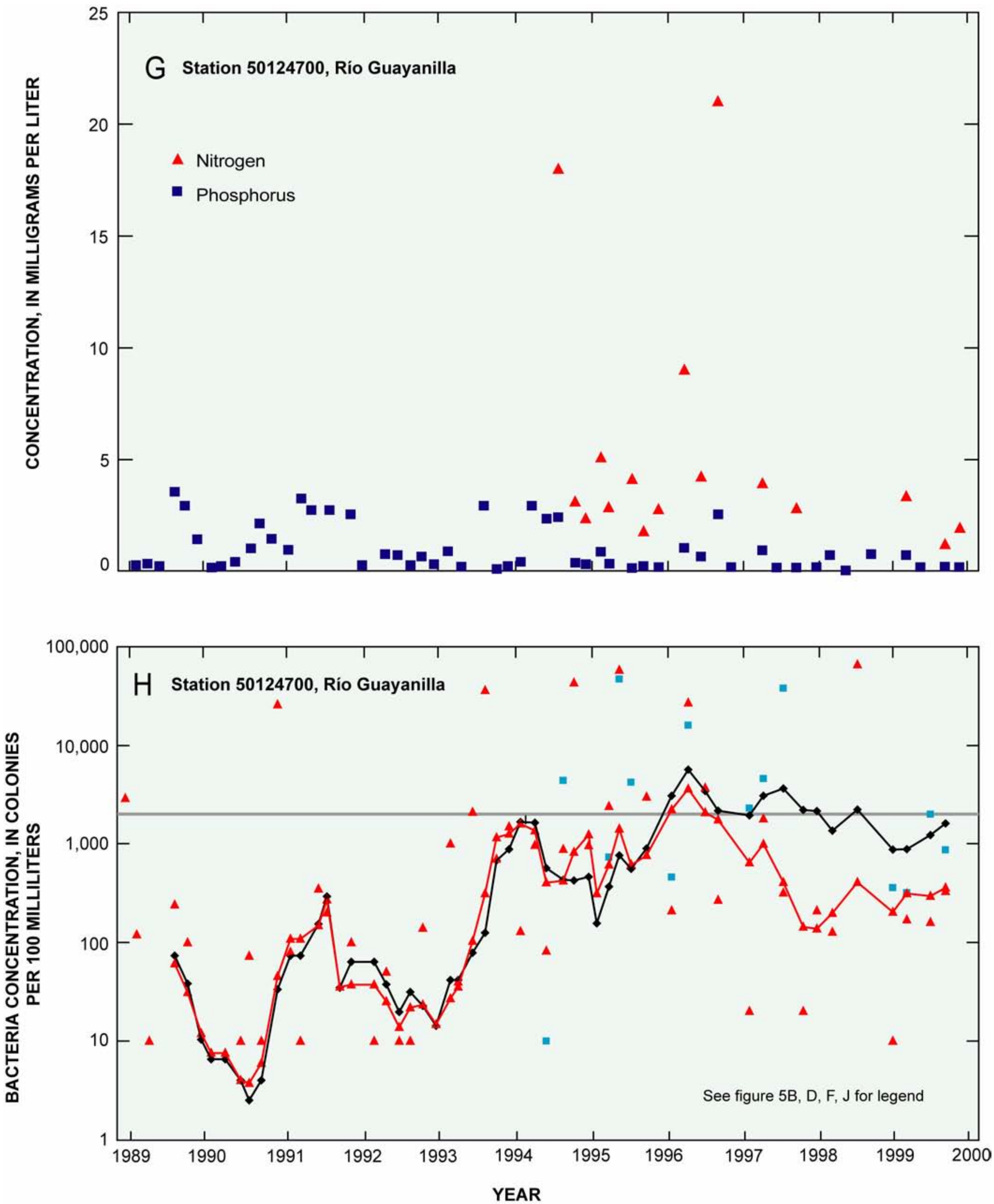

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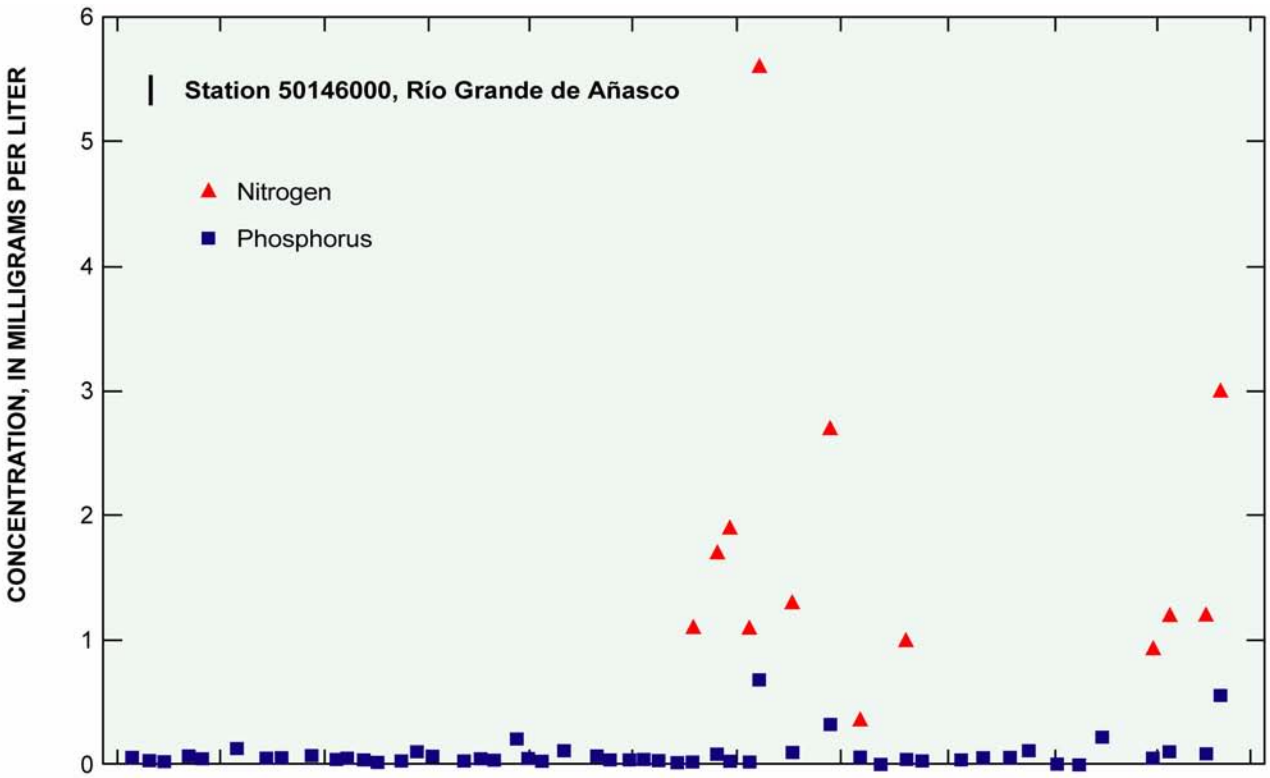

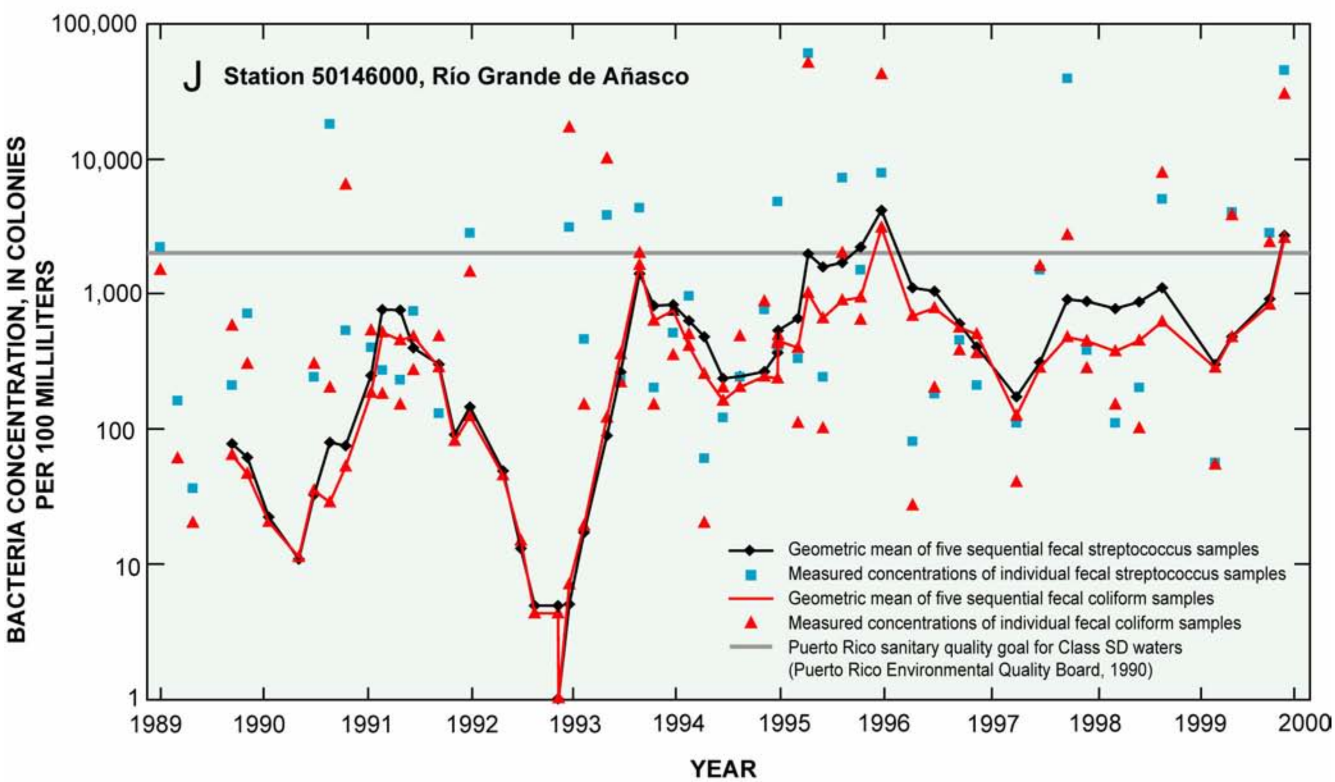

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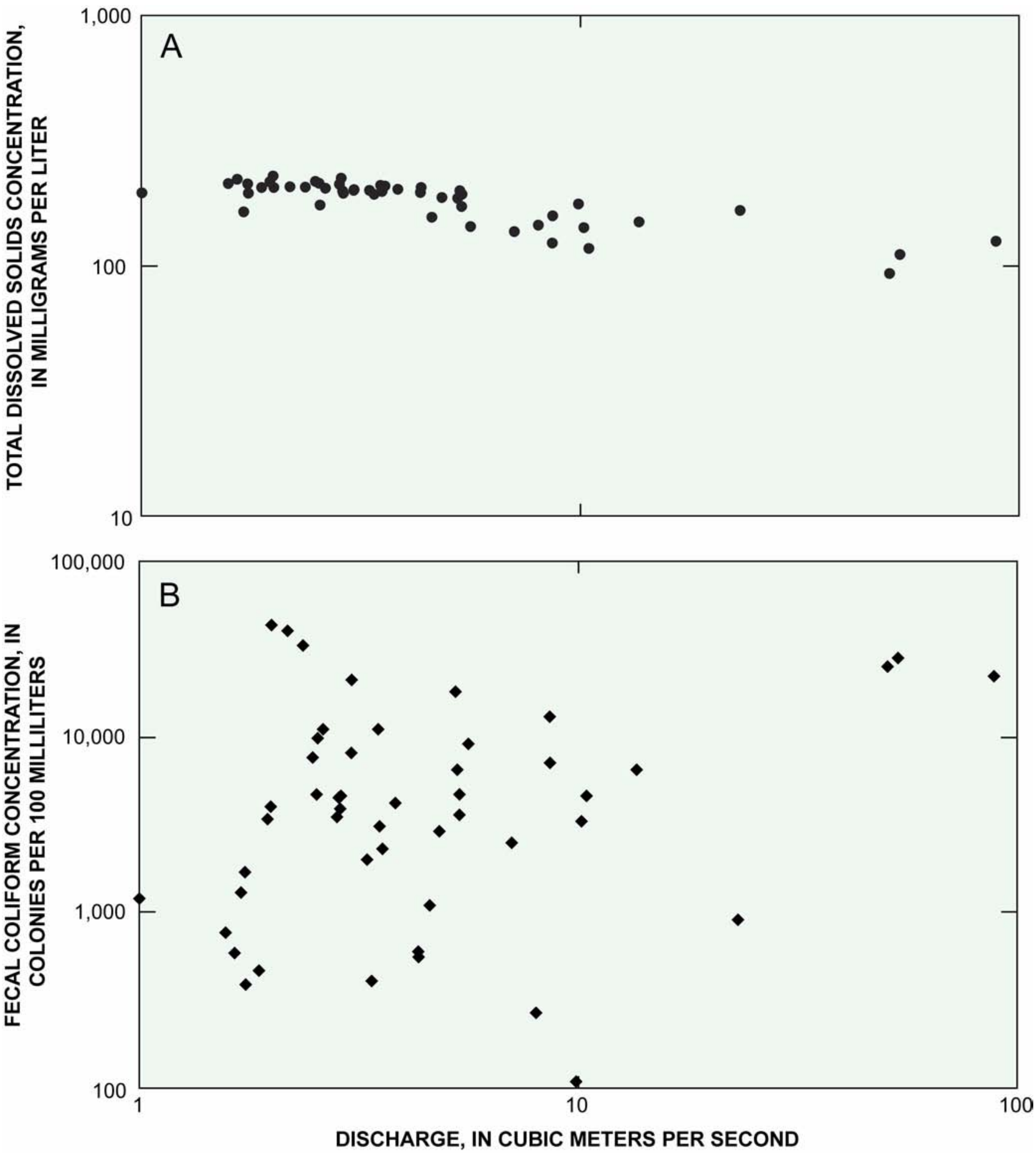

Figure 6. Total dissolved solids (A) and fecal coliform concentration (B) as a function of discharge at station 50038100, Río Grande de Manatí.

Description of Study Area

Puerto Rico's location at a tectonic plate boundary in the Caribbean Sea results in a combination of mountains with high relief and warm, moist climate. These geographic factors foster the growth of coral because of warm ocean water temperature and a supply of nutrients delivered by numerous rivers draining the island.

Climate, Physiography, Geology, and Geomorphology of Puerto Rico

The Cordillera Central region comprises about 60 percent of the 8,711-km^2 island of Puerto Rico, and reaches a maximum elevation of 1,338 m above mean sea level. Most peaks and ridges, however, do not exceed 900 m. The Cordillera Central has been deeply eroded and faulted such that steep hill slopes are common (figs. 1, 7). The limestone region in the northwest (fig. 7A) comprises about 20 percent of the island and is typified by mature karst topography consisting of mogotes (tower karst) cone karst, closed depressions, and underground streams (Monroe, 1976). Coalesced, Quaternary-age, alluvial fans are present along the southern insular margin, and a relatively flat coastal plain comprises the north-central margin (fig. 7).

The principal island surface-water drainage divide is along the east-west trending Cordillera Central (fig. 8A), which is also an orographic barrier affecting the distribution of rainfall (fig. 8B). Mean annual rainfall for the island for the period 1961 to 1990 is 1,600 millimeters (mm) (Díaz and others, 2001). Mean annual evapotranspiration varies across the island, ranging from 27 to 53 percent of annual rainfall in eastern watersheds (Larsen and Concepción, 1998). In 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 (figs. 7B, 8A). The northern and eastern regions receive abundant orographic rainfall as the warm, moist, northeast trade winds are forced upward by the Cordillera Central. The southern region, located in a rain shadow, is relatively dry. A strong land-sea breeze effect dominates the rainfall regime in the western region. During the afternoon, the land becomes warmer than the adjacent sea, which creates an eastward flow of air from the sea onto the land; moist air rising along the western slopes of the Cordillera Central mixes with the southwestward flowing trade winds, producing abundant rainfall (fig. 8B).

Hurricanes and tropical storms that pass over or near the island produce great runoff that transports large volumes of sediment-rich waters to the coast and shelf (Gupta, 1988, 2000; Ahmad and others, 1993; Soler-López, 2001). A major hurricane passes over Puerto Rico, on average, once every 10 to 20 years (Ho, 1975; Neuman and others, 1990; Scatena and Larsen, 1991). Winter frontal storms (for example, January 6, 1992; Torres-Sierra, 1996) 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 a high proportion of labile minerals in 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 (Larsen and Simon, 1993; Larsen and Torres-Sánchez, 1992, 1998; Larsen and Stallard, 2000). These landslides and debris flows produce large volumes of sediment that are available for transport by streams and rivers (Ahmad and others, 1993; Larsen and Santiago-Román, 2001). Although the limestone area in the northwest has substantially lower sediment yields than most other areas (table 6, station 50027750), the major rivers in this area are deeply entrenched (fig. 7B), and therefore, efficiently transport upland sediments to the ocean during large storms.

Puerto Rico Coast and Shelf

The morphology of the coast and shelf of Puerto Rico is variable and can be subdivided into at least five major coastal zones (table 9; fig. 8B). This geomorphic variability enhances local differences in coast and shelf hydrodynamics. The shelf ranges from less than 2 kilometers (km) wide north of Río Grande de Arecibo to more than 25 km wide west of Río Guanajibo (fig. 9). Shelf slope gradients along the north coast range from 1:15 to 1:50 (Bush, 1991). The shelf extends eastward more than 65 km to encompass Culebra, Vieques, and the U.S. Virgin Islands with the exception of St. Croix. Unlike many shelf settings around the world, where the shelf morphology and sediment distribution are relict, research has shown that the Puerto Rico shelf morphology and sediment distribution are in equilibrium with modern processes (Schneidermann and others, 1976; Pilkey and others, 1978; Grove and others, 1982). The widespread calcareous sand substrates of the shelf (fig. 9) indicate that much of the river-borne sediments are transported to and deposited along the shelf edge and slope (Schneidermann and others, 1976; Rodríguez and others, 1992, 1998). Bush (1991) documented that storm-induced, across-shelf transport processes dominate, and he calculated that 90 percent of the river sediment discharged at the coast is transported to the shelf edge and slope within a few months.

Several oceanographic surveys have been conducted along the island coast and shelf (Kaye, 1959; Puerto Rico Oceanographic Project, 1972; Morelock, 1984; Morelock and others, 1985). The results of these studies, which are summarized in table 10, indicate that, although shallow littoral currents are to the west and generally shore-parallel, there is considerable variability in local current directions.

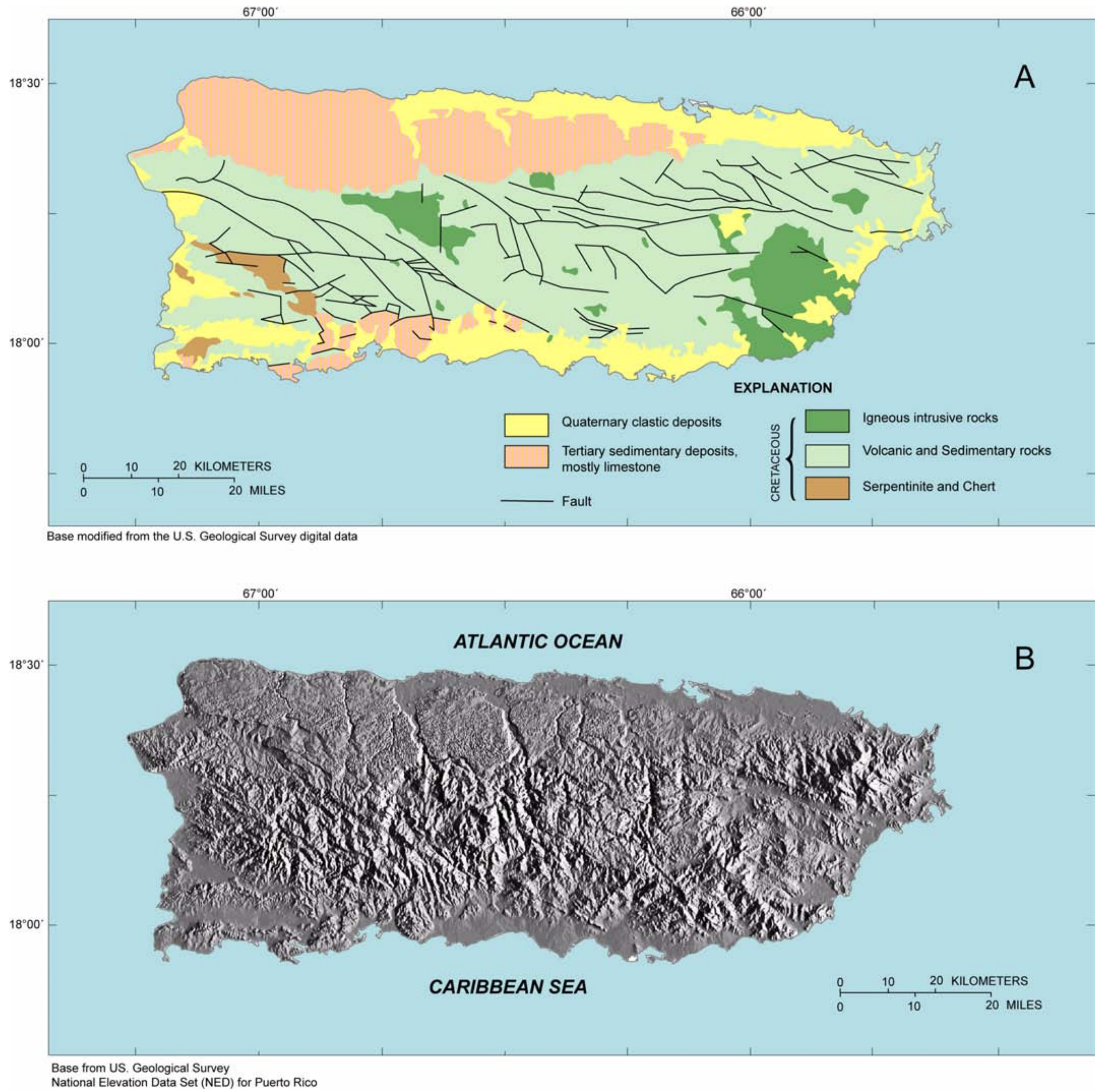

Figure 7. General geology (A) of Puerto Rico (simplified from Briggs and Akers, 1965), and shaded-relief image (B) derived from 100-meter digital elevation model, showing dissected uplands and planar exposure of Tertiary sedimentary rocks along north-central and north-west coast. Cretaceous intrusive rock are expressed topographically as eroded, lower elevation surfaces.

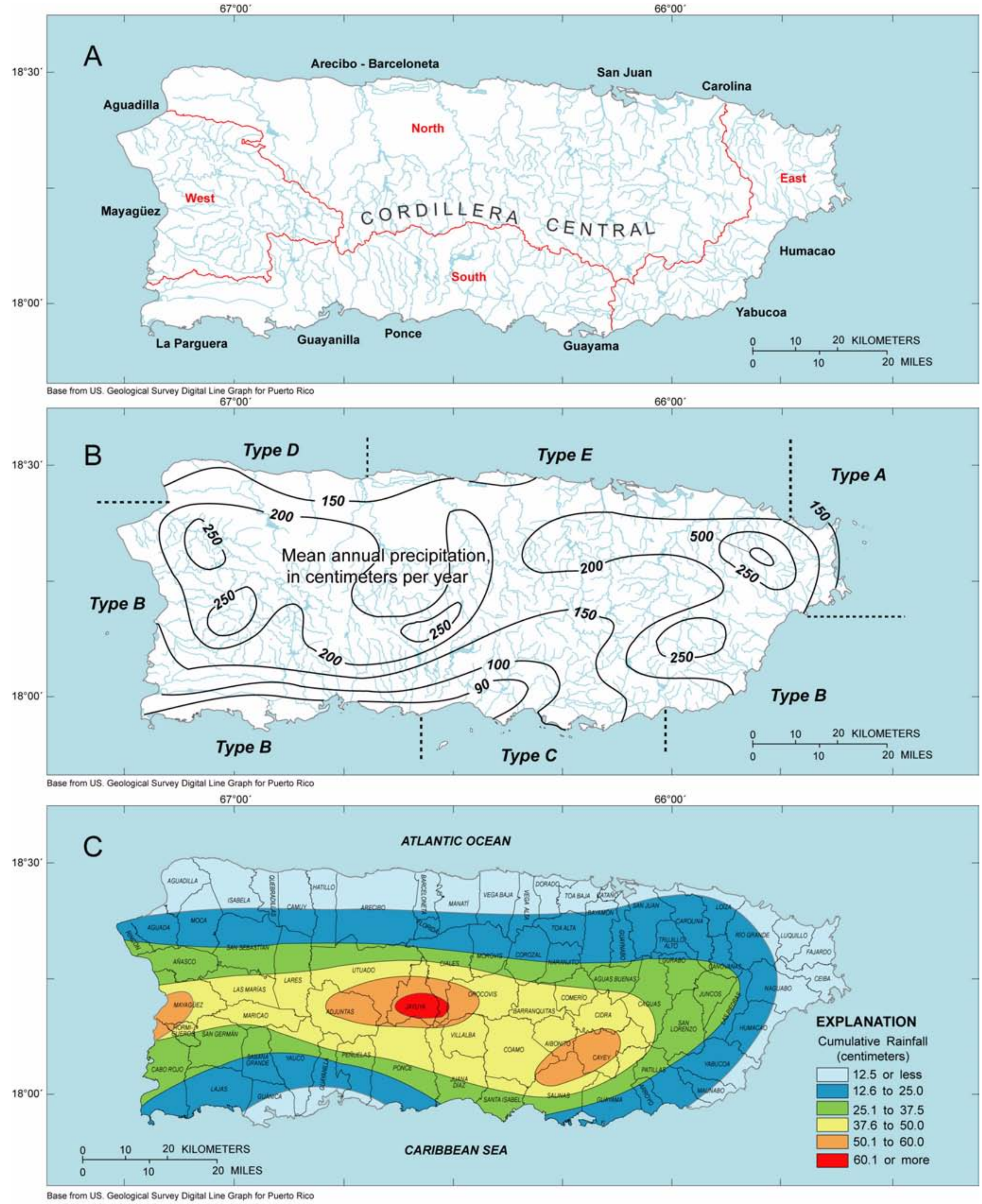

Figure 8. Rainfall-runoff characteristics of Puerto Rico: (A) The four major runoff (climatological) regions of Puerto Rico (simplified from National Oceanic and Atmospheric Administration, 1999). (B) Mean annual rainfall distribution (modified from Calvesbert, 1970) and the major coastal zones of Puerto Rico (after Kaye, 1959); see table 11 for a description of the coastal zones. (C) Cumulative precipitation associated with Hurricane Georges, September 21-22, 1998 (modified from U.S. Geological Survey, 1999).

Table 9. Coastal zone types of Puerto Rico.[1]

Coastal zone type	Description
Type A	Highly indented with many small offshore islands; rocky headlands and islands are remnants of the Sierra de Luquillo; the shelf is broad and shallow.
Type B	Large rocky headlands and broad alluviated valleys; the valleys are fronted by long arcuate beaches of siliceous sand; along the south coast, fringing reefs and sand cays are common; on the west coast, reefs occur as far north as Mayagüez.
Type C	A piedmont alluvial plain; narrow beaches of dark-colored siliceous sand and andesitic gravel alternating with mangrove swamps; the shore is strongly cuspate with deep, somewhat asymmetric embayments; fringing reefs occur along part of the shore, and further seaward ribbon reefs and sand cays occur along an east-west trend.
Type D	A nearly uninterrupted limestone cliff forms the shore or is separated from the shore by a narrow rock or sandy bench; the shelf is very narrow; there are scattered patch reefs and caves offshore.
Type E	Low-lying alluvial plain broken by several large swamps and lagoons; cemented sand dunes and Pleistocene reef rock occur along most of this stretch, resulting in a shore line of alternating rocky coast and sandy beach; the shelf is very narrow; shore-parallel, cemented dunes are common along the shelf and range from submerged to partially emergent; the offshore submerged dunes may be as much as 10 meters above the sea floor and provide habitat for reefs in areas that might otherwise have too high concentrations of suspended particular material.

[1] From Kaye (1959); see figure 8B for locations of the shoreline types.

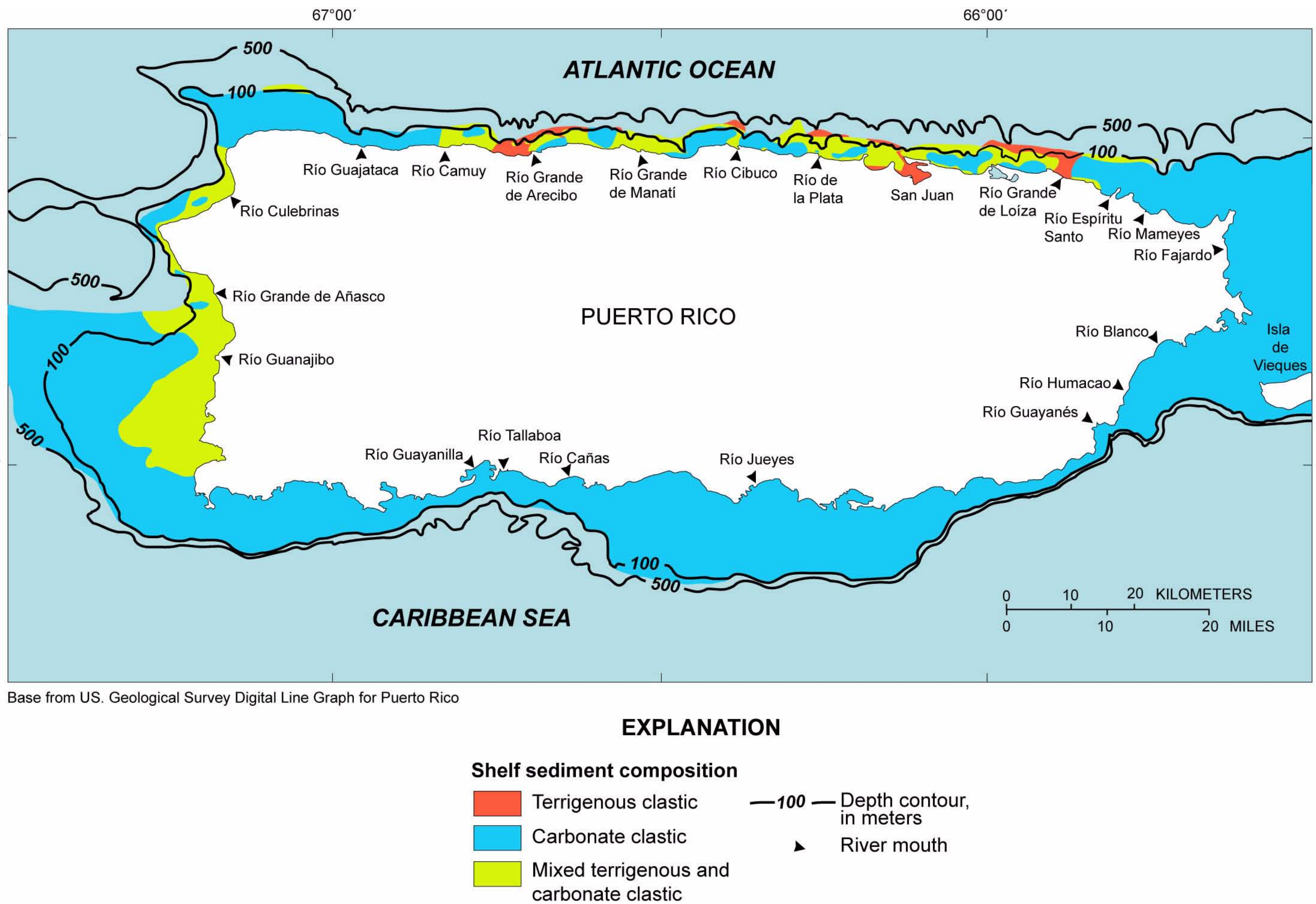

Figure 9. Texture and composition of surficial sediment and their distribution on the insular shelf of Puerto Rico (compiled from Beach and Trumbull, 1981; Trumbull and Trias, 1982; Grove, 1983; Pilkey, 1987; Trias, 1990; Rodríguez and others, 1992, 1998; Scanlon and others, 2001).

Table 10. Summary of wave, tide, littoral current, turbidity, and temperature characteristics of the coast and shelf of Puerto Rico.[1]

[NE, northeast; SW, southwest; NW, northwest; SSE, south-southeast; na, not available; cm/s, centimeter per second; m, meter; mg/L, milligrams per liter, $mg/cm^2/d$, milligrams per square centimeter per day; >, greater than]

Survey location[2]	Shallow (5 m) Littoral Current: Principal direction and velocity	Middle and Deep (8 to 20 m) Littoral Current: Principal direction and velocity	Horizontal water density distribution	Vertical water density distribution	Comments
San Juan	Variable, largely westward; 12-18 cm/s	Eastward, westward, and southward; 12-15 cm/s	Pronounced density contrast associated with bay	Pronounced density contrast associated with bay	Currents are variable and apparently influenced by tides.
Carolina	Mostly eastward; 20-50 cm/s	Mostly eastward, 20-50 cm/s	Well-defined around the mouth of Río Grande de Loíza	Well-defined but small	Current patterns are complex with easterly flow during falling tide and westerly flow during rising tide for the majority of observations. Apparently, the wave and current regime during the survey period was sufficient to mix the Río Grande de Loíza water such that there was only a small vertical density gradient.
Humacao/Yabucoa	Generally westward; about 8-20 cm/s	Generally southward to southeastward; about 12-20 cm/s	Slightly lower density closer to shore	Little	Low density gradients indicate thorough mixing of waters.
Guayama	Generally west with an onshore component; 12-30 cm/s	Generally eastward; 9-20 cm/s	Weak seaward gradient	Little	The different methods of measuring current produced a variety of results indicating complex current patterns and well-mixed waters.
Ponce	Generally northwest and shoreward; 9-30 cm/s	Northwest to southeast; 6-28 cm/s	No density structure apparent in the inshore area	Well defined below the shelf break.	Currents show no correlation with tides.
La Parguera, San Cristobal Reef	Generally south and west	na	na	na	Data from Rogers (1977), who also presented temperature, suspended material concentration, sedimentation rate, and salinity data.
Guayanilla	Bimodal: primarily northwestward but with a southward component; 6-30 cm/s	Bimodal: eastward and southward; 5-29 cm/s	Gradient apparent between the bay and open ocean	Little if any in the bay, but develops seaward of shelf break	There currently is no explanation for the bimodal currents. Data compiled by Morelock and others (1983, their fig. 5) is similar to the Puerto Rico Oceanographic Project (1972) data.

Table 10. Summary of wave, tide, littoral current, turbidity, and temperature characteristics of the coast and shelf of Puerto Rico.[1] —Continued

[NE, northeast; SW, southwest; NW, northwest; SSE, south-southeast; na, not available; cm/s, centimeter per second; m, meter; mg/L, milligrams per liter, $mg/cm^2/d$, milligrams per square centimeter per day; >, greater than]

Survey location[2]	Shallow (5 m) Littoral Current: Principal direction and velocity	Middle and Deep (8 to 20 m) Littoral Current: Principal direction and velocity	Horizontal water density distribution	Vertical water density distribution	Comments
Mayagüez	Shore-parallel, NW during ebb tide and SSE during flood tide; 6-17 cm/s	Bimodal: north (ebb tide) and south (flood tide); 4-16 cm/s	Little	Weak in shallow water but better defined in deep water	Waters are influenced by discharge from Río Guanajibo. Loya (1976) reported deposition rates of 3 to 15 $mg/cm^2/d$ for the Negro Bank coral reefs, southwest of Mayagüez.
Aguadilla	Shore-parallel, SW (flood tide) and NE (ebb tide); 5-40 cm/s	SW (flood tide) and NE (ebb tide); 5-42 cm/s	Low density plume at mouth of Río Culebrinas	Rather well developed	The coastal waters are influenced by discharge from Río Culebrinas. Rainstorms induce discharge of large volumes of turbid water to the coast.
Arecibo/Barceloneta	Shore-parallel east (flood tide) and west (ebb tide), 25 cm/s knots	East (flood tide) and west (ebb tide); 20 cm/s	Density plume apparent at mouth of Río Grande de Arecibo	Moderately developed in deeper water	The shelf is particularly narrow and steep along this part of the island. The Río Grande de Arecibo and Río Grande de Manatí influence coastal waters. Insufficient water-density data to define plume at mouth of Río Grande de Manatí.

[1] From Puerto Rico Oceanographic Project (1972).
[2] Oceanographic survey locations shown in figure 8A.

Table 10. Summary of wave, tide, littoral current, turbidity, and temperature characteristics of the coast and shelf of Puerto Rico.—Continued

[na, not available; m, meter; mg/L, milligrams per liter]

Survey location	Secchi disk depths (m)	Phosphate (mg/L)	Silicate (mg/L)	Biological oxygen demand (mg/L)	Dissolved oxygen (mg/L)	Comments
San Juan	4-19	0.00 - 0.12	0.02-0.50	0.31-0.50	3.9-6.7	Secchi disk depth reading follow shoreline with no major turbidity tongues.
Carolina	1-29	trace	0.20-0.60	na	4.9-6.7	Turbidity associated with discharge from Río Grande de Loíza varied from one survey day to another.
Humacao/Yabucoa	2-24	0.01-0.02	0.09-0.51	na	5.4-6.70	Generally no turbid plume, although some indication of a plume, perhaps associated with discharge from Río Humacao.
Guayama	4-20	0.00-0.08	0.00-0.35	na	6.0-7.0	No major zones of turbid water.
Ponce	1.5-24	0.00-0.03	0.00-0.10	na	6.1-7.2	Generally turbid waters; dissolved oxygen near saturation.
Ponce	3.5-8					Secchi disk readings at Tasmaian and Cardona reefs, respectively (Acevedo and Morelock, 1988).
La Parguera	5 to >25	na	na	na	Na	Secchi disk depth readings along the shelf edge (Acevedo and Morelock, 1988).
La Parguera	15	na	na	na	Na	Secchi disk depth readings at Turrumote and Enrique reefs (Acevedo and Morelock, 1988), and at San Cristobal reef (Rogers, 1977).
Guayanilla	2-9	0.00-0.02	0.00-0.02		5.3-7.0	Waters are turbid in the bay.
Guayanilla	18	na	na	na	Na	Secchi disk depth reading s at Peñuelas reef near the shelf edge (Acevedo and Morelock, 1988).
Mayagüez	6-76	0.01-0.02	0.04-0.33	0.00-1.37	4.3-5.2	
Aguadilla	4-22	0.01-0.05	0.08-0.64	NA	6.3-8.9	Turbidity plume at mouth of Río Culebrinas.
Arecibo/Barceloneta	4.5-22	0.00-0.03	0.00-0.23	0.06-0.71	6.6-8.4	Turbidity plume apparent at mouth of the Río Grande de Arecibo; insufficient data to define plume at mouth of Río Grande de Manatí.

The mean tidal range along the coast is generally 0.34 m, with neap tides of about 0.2 m and spring tides of about 0.4 m, and a maximum range of about 0.9 m (Puerto Rico Oceanographic Project, 1972). Tides are not considered to have a significant effect on this marine-hydrodynamic regime. Reversing tidal flow superimposed on the seasonally shifting equatorial flows dictates the general flow patterns around the island. Nearshore currents reflect local wave and wind conditions. The reversing tidal currents in the Vieques Passage maintain the shape and configuration of the Escollo de Arenas, an unconsolidated sand body of more 80 million cubic meters (m^3) off the northwest tip of Vieques (Cintrón and others, 1984; Delorey and others, 1993). Ebb tides along the north coast can carry some sediments 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).

Along most of the coast, waves are refracted by the complex coastal configuration, promoting complex and dynamic nearshore wave and current regimes. The north coast is exposed to high-energy waves generated by storms in the north-central Atlantic Ocean. These waves normally approach the coast from the north and northeast (Fields and Jordan, 1972). Waves generally have mean heights of 0.6 to 1.8 m and mean periods between 6 and 12 seconds. Long-period waves, with heights of 0.9 to 2.0 m and periods from 10 to 13 seconds, are generated by storms in the North Atlantic during the winter months (Kaye, 1959; Bush, 1991). The north-coast shelf is relatively narrow and steep (fig. 9), so the shelf does not substantially reduce energy of the incoming waves. Waves associated with tropical storms and hurricanes affect the inner and middle shelf, whereas waves associated with major winter storms generate oscillatory currents that affect the entire shelf (Bush, 1991). Wave energy is lower along the east, south, west coasts where open-ocean fetch is relatively small and shelf width is relatively wide.

The littoral current regime of the island is controlled largely by the North Equatorial current, which flows towards the west and northwest (table 10). Close to shore, this current is deflected and refracted by the irregular coast and shelf, resulting in a variety of local nearshore current regimes that may change seasonally (Kaye, 1959; Morelock and others, 1985). West- and/or northwest-directed longshore currents predominate along most of the north and south coast, although areas with east-directed (eddy) currents are common.

Along the insular shelf, Secchi disk depths generally increase from 3 to 4 m nearshore to more than 15 m offshore (table 10). Waters are substantially more turbid at the mouths of rivers, where Secchi disk depth readings of less than 2 m are common. Turbidity at the mouths of rivers varies daily, and rivers commonly produce turbidity plumes during storm runoff (Kaye, 1959; Puerto Rico Oceanographic Project, 1972). Miller and others (1994) state that in the Mayagüez Bay, wind-driven resuspension of bottom sediment is commonly more important in controlling water turbidity than sediment discharge from Río Añasco, Río Yagüez, and Río Guanajibo.

Open-sea temperatures around the island typically range from a minimum of 25 degrees Celsius in March to a maximum of 29 degrees Celsius in September (Kaye, 1959; Winter and others, 1998). Winter and others (1998), using a 30-year, continuous shallow water-temperature record from La Parguera area (southwestern Puerto Rico), demonstrated that temperatures ranged from a minimum of 25.6 degrees Celsius in the winter to 29.5 degrees Celsius in the summer. The data show an increase in mean annual temperature of 0.7 degree Celsius over the 30 years of record.

Water Quality of Puerto Rico Rivers and Coast

Water-quality standards for the coast, rivers, lakes, and ground water were established by the Puerto Rico Environmental Quality Board (1990). They also established a water classification system based on designated and potential use (tables 11, 12). As mandated by section 305(b) of the Clean Water Act, a coastal water-quality monitoring network was established in Puerto Rico by the Puerto Rico Environmental Quality Board (PREQB). The monitoring network consists of 88 stations around the 410-km-long island coast (Puerto Rico Environmental Quality Board, 1998, their fig. III.2; 2000, their appendix 3). In their latest water-quality assessment for the island, the Puerto Rico Environmental Quality Board (2000) determined that 86 percent of the coastal zone contains waters that are beneficial to aquatic life. The report does not identify or delineate the 14 percent of the coastal zone with poor water quality. The report indicates that municipal and industrial point sources, land disposal, flow regulation/modification, and debris and bottom deposits are major causes of poor coastal water quality (Puerto Rico Environmental Quality Board, 2000, their tables 6.17 and 6.18). The report identifies high ammonia (un-ionized), low dissolved oxygen, and high turbidity as important causes of poor coastal water quality (Puerto Rico Environmental Quality Board, 2000, their table 6.16).

Water quality in rivers, lakes, and coasts is commonly evaluated and classified using fecal coliform and fecal streptococcus concentrations (table 12). Fecal coliform and fecal streptococcus are not pathogenic to humans, but have been correlated with several waterborne diseases. Moreover, coral reefs growing close to sanitary discharge outfalls show proliferations of green algae, which commonly "out-compete" the corals for space by overgrowing them (Webb and others, 2000).

Two studies have evaluated nitrogen discharge from watersheds in Puerto Rico: Steudler and others (1991) for Río Mameyes and McDowell and Ashbury (1994) for Río Icacos, Quebradas Sonadora and Toronja. These studies were conducted in undisturbed, forested watersheds of eastern Puerto Rico, and therefore, provide a baseline to evaluate nutrient concentrations in anthropogenically disturbed watersheds. McDowell and Ashbury (1994) reported total dissolved nitrogen concentrations of about 0.15 to 0.25 milligrams per liter (mg/L) and total dissolved phosphorous concentrations of 0.002 mg/L in eastern Puerto Rico streams.

Table 11. Classification of Puerto Rico surface waters by designated use (Puerto Rico Environmental Quality Board, 1990).

Classification	Description
Class SA	Coastal and marine waters of high quality and/or exceptional ecological or recreational value whose existing characteristics should not be altered except by natural causes, in order to preserve the existing natural phenomena.
Class SB	Coastal and marine waters designated for primary and secondary contact recreation, and propagation and preservation of desirable species.
Class SC	Coastal and marine waters designated for secondary contact recreation and propagation and preservation of desirable species.
Class SD	Inland surface waters designated as a raw source of public water supply, propagation and preservation of desirable species, and for primary and secondary contact recreation.
Class SE	Inland surface waters and wetlands of exceptional ecological value, whose existing characteristics should not be altered in order to preserve the existing natural phenomena.

Table 12. Selected water-quality standards for designated water-use classes, Puerto Rico.[1]

[NTU Nephelometric Turbidity Unit; ns, not specified; mg/L, milligrams per liter; mL, milliliters; µg/L; micrograms per liter]

Property	Water-use classifications[2]		
	SB	SC	SD
Nitrate + Nitrite (as N)	ns	ns	10 mg/L
Nitrogen (NO_3, NO_2, NH_3)	5,000 µg/L	5 mg/L	ns
Dissolved oxygen	Not less than 5 mg/L	Not less than 4 mg/L	Not less than 5 mg/L
Fecal coliform	[3]	[4]	[4]
PH	7.3-8.5	6.0-9.0	
Turbidity	10 NTU	10 NTU	50 NTU
Total phosphorus	ns	ns	1 mg/L

[1] See Puerto Rico Environmental Quality Board (1990, 1998) for a complete list of standards.

[2] See table 11 for definitions of water-use classifications.

[3] The geometric mean concentration, of a series of representative samples (at least five samples) of the waters taken sequentially, shall not exceed 200 colonies per 100 mL, and not more than 20 percent of the samples shall exceed 400 colonies per 100 mL. In waters of primary contact recreation, the enterococci density in terms of geometric mean of at least five representative samples taken sequentially shall not exceed 35 colonies per 100 mL. No single sample should exceed the upper confidence limit of 75 percent using 0.7 as the log standard deviation until sufficient data exists to establish a site-specific log standard deviation.

[4] The geometric mean concentration, of a series of representative samples (at least five samples) of the waters taken sequentially, shall not exceed 10,000 colonies per 100 mL of total coliform or 2,000 colonies per 100 mL of fecal coliform. Not more than 20 percent of the fecal-coliform samples shall exceed 4,000 colonies per 100 mL.

Reefs of Puerto Rico

The insular shelf sustains numerous coral reefs (fig. 1). Coverage of living corals varies from less than 5 percent in areas affected by direct river discharge and sewage disposal to 50 to 60 percent for the offshore reefs around at La Parguera in the southwest (Goenaga and Cintrón, 1979). Goenaga and Cintrón (1979) presented a comprehensive summary of the health of coral reefs in Puerto Rico (figs. 10, 11). In addition, there have been a number of local studies of coral health, including those of Seiglie (1968), Loya (1976), Rogers (1977; 1990), Morelock and others (1980), Acevedo and Goenaga (1986), Acevedo and Morelock (1988), Acevedo and others (1989), Goenaga and others (1989), Yoshioka and Yoshioka (1989, 1991), Goenaga and Canales (1990), Bunkley-Williams and others (1991), Winter and others (1998), and Shinn and Halley (1992).

Different reef types develop according to 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, which are isolated coral colonies commonly surrounded by sandy bottom and located close to shore, are common along the northeast, east, south, west, and northwest coasts. Patch reefs are commonly intermixed with other reef types. Fringing reefs develop directly adjacent to the shore and are sometimes separated from the shore by a shallow lagoon; fringing reefs are common along the northeast and east coasts. 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, which commonly develop a distinctive groove and spur structure, extend from the outer shelf down the insular slope to depths greater than 100 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 (fig. 1). Goenaga and Cintrón (1979) reported reefs with high coral diversity and density at (1) La Cordillera (including Palomino and Cayo Largo), Fajardo; (2) Sargent Reef, Maunabo; (3) between Bahía de Jobos and Santa Isabel, including Berberia and Caja de Muertos; (4) Ratones, Ponce; (5) La Parguera, Lajas; (6) Tourmaline and El Negro reef complex, Mayagüez; and (7) the southern and western insular shelf margin. Extensive coral reef degradation has been reported at (1) all reefs from San Juan to Las Cabezas de San Juan, northeastern Puerto Rico; (2) inshore Fajardo; (3) Humacao; (4) Puerto Yabucoa; (5) inshore Ponce; (6) Bahía de Guayanilla and Bahía de Tallaboa; (7) Guánica; (8) all west coast inshore reefs (from Boquerón to Rincón); (9) Arecibo; and (10) Dorado (fig. 1) (Goenaga and Cintrón, 1979).

Effects of Suspended Sediment and Sedimentation on Coral Reefs

Coral reefs flourish 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) defined stress as a factor that disrupts the normal energy flow in a system either by increasing energy drains, removing physical structure, or modifying energy inputs. There are a number of reef stressors, including high-sedimentation rates, high-water turbidity, high-water temperatures, changes in salinity, high nutrient loads, eutrophication, physical damage by storms, overfishing, physical damage by boats and ships, and possibly, introduction of disease by aeolian African dust (Smith, 1977; Brown and Ogden, 1993; Harvell and others, 1999; Glynn, 2000; Shinn and others, 2000; Prospero, 2001; Torres and Morelock, 2002) (table 13).

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 encrusting algae, high density of sponges, low fish populations, coral colonies covered by fine sediment, and turbid water (table 13). In recent years, reef stress has been widely recognized by a phenomenon known as coral bleaching (Brown and Ogden, 1993). Bleaching involves the loss (expulsion) of single-cell symbiotic algae that live within the gastrodermal cells of a coral host. In the absence of the pigmented algae, the coral colony appears bleached white. Most reef frame-building corals depend on the algae for survival (Porter and others, 1989), and bleaching has been correlated to substantial reductions in coral skeleton growth rates (Bunkley-Williams and others 1991). Since 1982, reefs worldwide, including many around Puerto Rico, have experienced increased frequency of coral bleaching (Moore and others, 1976; Pilkey and others, 1988; Jameson and others, 1995). A number of potential causes for the increased incidence of coral bleaching in the Caribbean have been proposed, including enhanced sedimentation, influx of large volumes of freshwater, eutrophication, increased water temperatures, increased ultraviolet light, and influx of African dust (Acevedo and Goenaga, 1986; Goenaga and others, 1989; Goenaga and Canales, 1990; Bunkley-Williams and others, 1991; Vicente, 1993; Winter and others, 1998; Shinn and others, 2000).

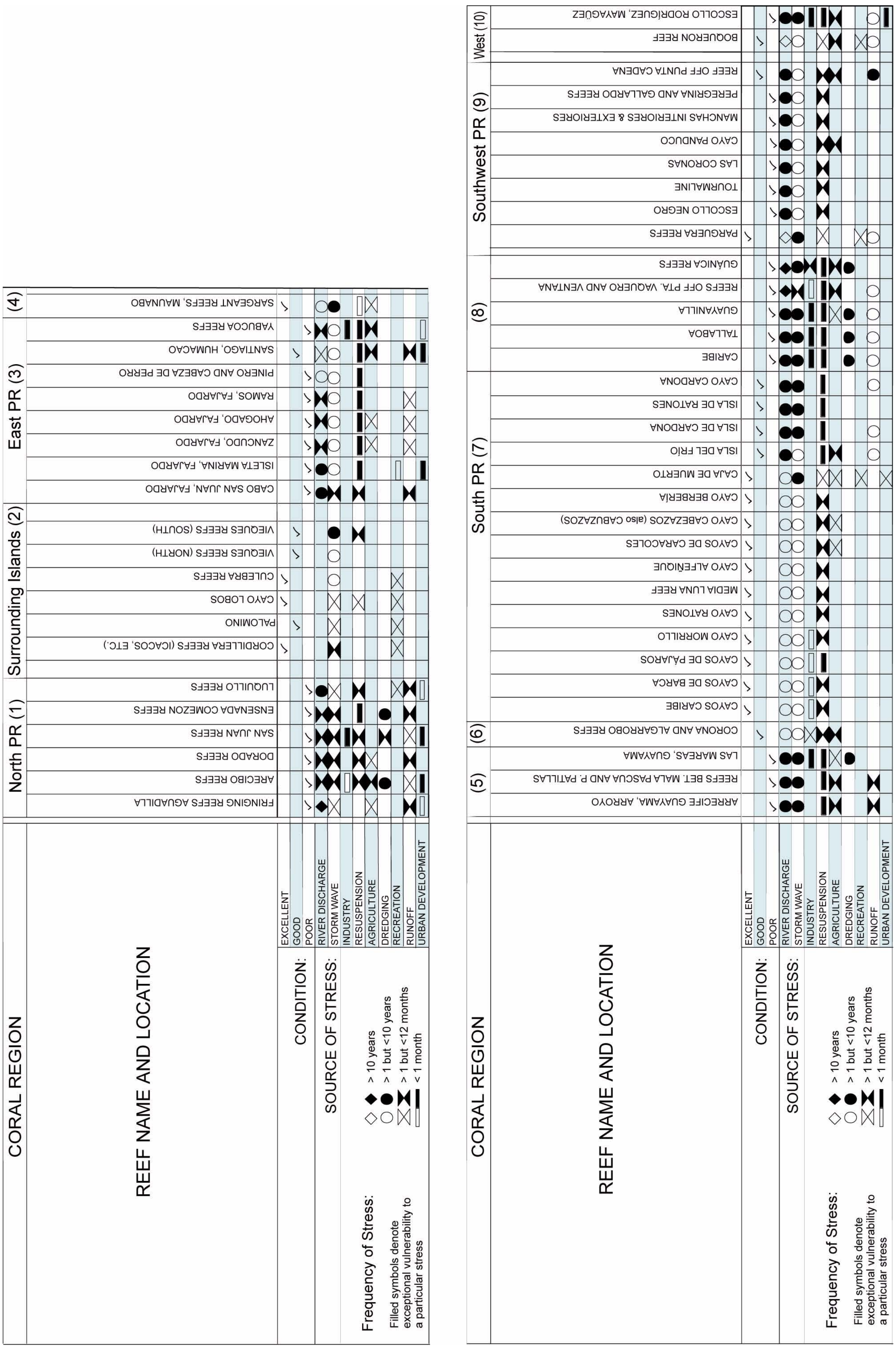

Figure 10. Summary of the health of Puerto Rico reefs, the types of reef stressors affecting them, and the magnitude and frequency of each stressor on individual reefs. Numbers in parenthesis refer to coral regions shown in figure 11. Data from Velazco-Domínguez and others (1986) and Goenaga and Cintrón (1979).

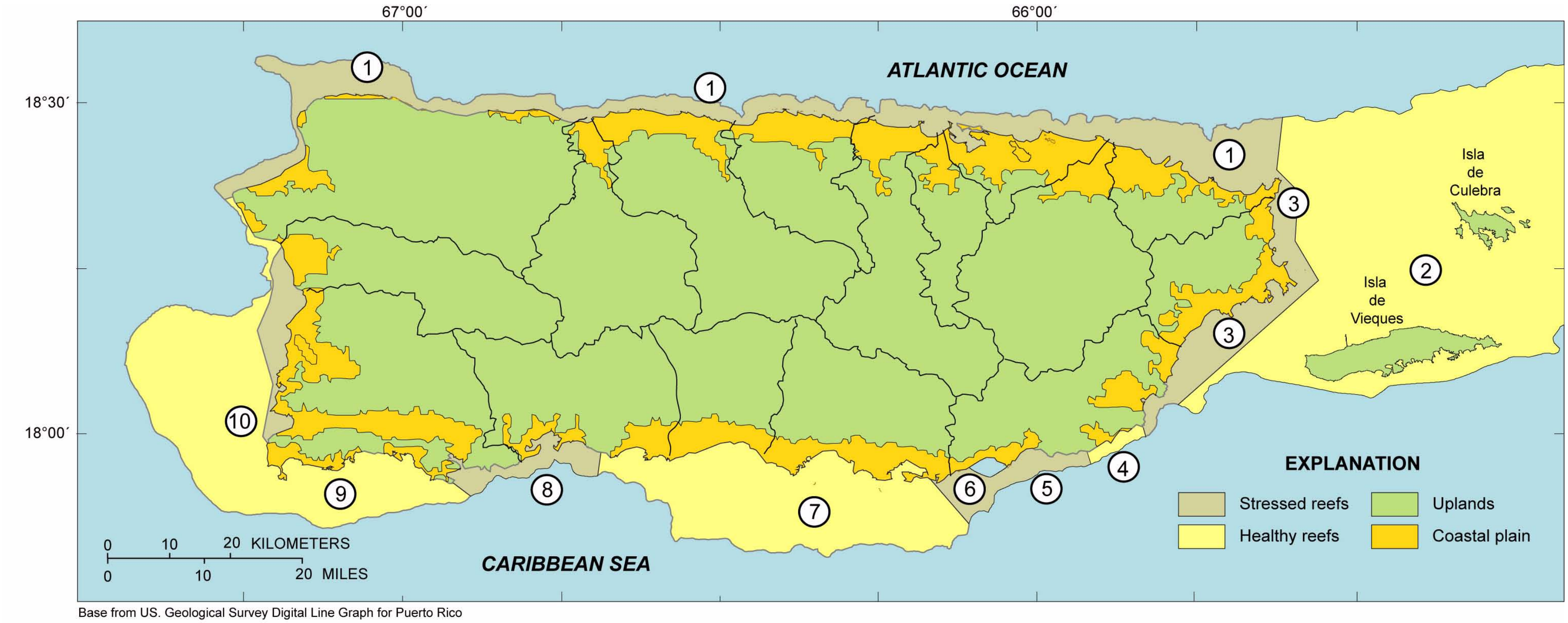

Figure 11. Map of Puerto Rico showing coral reef regions. Numbers in circles refer to coral regions described in figure 10 (modified from Velazco-Domínguez and others, 1985; Goenaga and Cintrón, 1979).

Table 13. 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 and others (1985, 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 and others (1998); Normile (2000); National Oceanic and Atmospheric Administration (2001); Wellington and others (2001)
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 and others (1985, 1986)
Storms	Broken coral, sediment-covered coral	Shinn and Halley (1992); Vicente (1993); Rodríguez and others (1994); Garrison and others (2000)
Overfishing	Replacement by algae	Goenaga and Cintrón (1979)
Boats and ships	Broken corals, sediment-covered coral	Goenaga and Cintrón (1979)
African dust	Widespread coral bleaching; widespread mortality of specific reef species	Shinn and others (2000); Harvell and others (1999)
Diseases	All above results	Bruckner and Bruckner (1997); Harvel and others (1999); Green and Bruckner (2000); Kuta and Richardson (2002); Patterson and others (2002); 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.

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 to 20 mg/L (or a depositional rate of 200 to 1,000 milligrams per square centimeter per day [mg/cm^2/d]) (Rogers, 1977). Chronic concentrations or depositional rates above these levels cause a reduction in coral growth rates because of smothering and reduced light levels (Tomasick and Sander, 1985; Rogers, 1990). Rogers (1977, 1990) proposed that (1) sediment influx of 200 to 1000 mg/cm^2/d and more is incompatible with healthy reefs; (2) continual suspended-sediment concentrations of 10 to 20 mg/L 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 to approximately 10 mg/cm^2/d. 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. siderea* and *P. astreoides* was not affected.

Although corallites (individuals within the coral colony) are capable of physically removing sediment, this action requires energy that then becomes unavailable for skeletal growth; 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 green algae. 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 forms and species with greater resistance to sediment smothering and/or tolerance to reduced light levels; (3) less live coral (percent cover); (4) lower coral growth rates; (5) an upward shift in depth zonation to maintain sufficient light-intensity levels; and (6) a greater abundance of branching forms.

Analysis of Water and Sediment Discharge

A general summary of river water, suspended sediment, and river water quality is presented below. This summary is followed by presentation of streamflow and sediment data associated with a single large storm, Hurricane Georges, which resulted in the erosion and transport of large amounts of sediment from uplands to the sea.

Surface-Water Discharge in Puerto Rico

Mean annual runoff to the coast for the water years 1990 to 2000 is estimated at 911 millimeters per year (mm/year) (table 1). This is 57 percent of mean annual precipitation of 1,600 mm. To characterize the variability of river-water discharge, the proportion of the annual discharge contributed by the maximum daily discharge for each year was calculated, and the mean of this proportion for the water years 1990 to 2000 then was calculated for 24 streamflow-gaging stations (table 2). These results indicate that in a typical year, between 3 and 25 percent of the total annual water discharges in one day. For the water year having the highest daily discharge, this value comprised between 8 and 66 percent of the total annual discharge.

The relatively small reservoirs and dams in Puerto Rico have little influence on the magnitude of maximum mean daily discharge. For example, Río de la Plata and Río Grande de Loíza are regulated by dams, but for the period 1990 to 2000, the proportion of annual water discharge contributed by maximum daily discharges was 21 to 25 percent (table 2). The water-holding capacity of many Puerto Rico reservoirs is small relative to annual discharge, so during heavy rainfall, these relatively narrow reservoirs are quickly filled to capacity and behave as river channels (Soler-López, 2001). The Río Grande de Arecibo, however, which is a highly regulated system with multiple dams (and located in the karst region), has the lowest proportion of discharge volume contributed by high-magnitude rainfall (table 2).

Watershed size and the proportion of the total annual discharge contributed by the maximum daily discharge do not correlate well in Puerto Rico (tables 1, 2), which likely reflects the large spatial variability of rainfall distribution, intensity and duration that is typical of tropical, convective rainfall (Giusti and López, 1967; Hastenrath, 1991). In addition, the east-west trending central mountain range, which is the dominant topographic feature of the island, has an axis that is 11 km south of the center line of the island (Puerto Rico measures approximately 58 km wide from the north coast to the south coast, but the crest of the central mountains is located approximately 40 km from the north coast). This offset affects rainfall and runoff distribution as follows: (1) north-draining watersheds are comparatively large and receive high mean annual rainfall because they generally face the prevailing (trade) winds; (2) south-draining watersheds are smaller and steeper than their north-facing counterparts, and they receive less mean annual rainfall because of rain-shadow effects; (3) east-facing watersheds are relatively small because of the island shape, but generally receive high rainfall because the eastern mountains commonly receive the first landfall of approaching rainfall in the tradewinds; and (4) west-facing watersheds also are relatively small because of the island shape, but receive high rainfall associated with the interaction of diurnal land-sea breezes and the easterly tradewinds (Calvesbert, 1970).

In an attempt to better understand discharge characteristics of ungaged watersheds, a number of watershed characteristics of the gaged sites were compared to determine if there are systematic relations among watershed climate, geomorphology, and hydrology. Characteristics evaluated included the highest recorded mean daily discharge and drainage area, mean annual runoff and drainage area, and total annual rainfall and total annual discharge. No clear trends are apparent unless the rivers are subdivided into the four above-mentioned major surface-water drainage areas (fig. 8A). Northern rivers have relatively large watersheds and a low mean annual runoff; eastern rivers have small watersheds and moderate to high mean annual runoff; southern rivers have small watersheds and low mean annual runoff; and western rivers have moderate-size watersheds and low to moderate mean annual runoff (fig. 12; table 1).

River Sediment Discharge in Puerto Rico

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 for the water years 1990 to 2000 (table 4). Estimated mean annual suspended-sediment yield ranges from 570 to 1,900 metric tonnes per square kilometer (metric tonnes/km^2). The mean maximum daily water discharge for the nine suspended-sediment stations accounts for 23 to 58 percent of water discharged during a typical year (table 6). During the year with the highest recorded daily sediment discharge (in most cases, this was associated with Hurricane Hortense in 1996 or Hurricane Georges in 1998), the maximum daily sediment discharge was between 44 and 90 percent 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 6).

The proportion of highest recorded daily water discharge relative to the mean annual total is substantially less than the proportion of highest recorded daily sediment discharge relative to the mean annual total (table 6). This difference reflects the incapacity of baseflow (low streamflow conditions) discharge, which makes up a substantial portion of the annual water discharge volume, to transport substantial masses of suspended sediment.

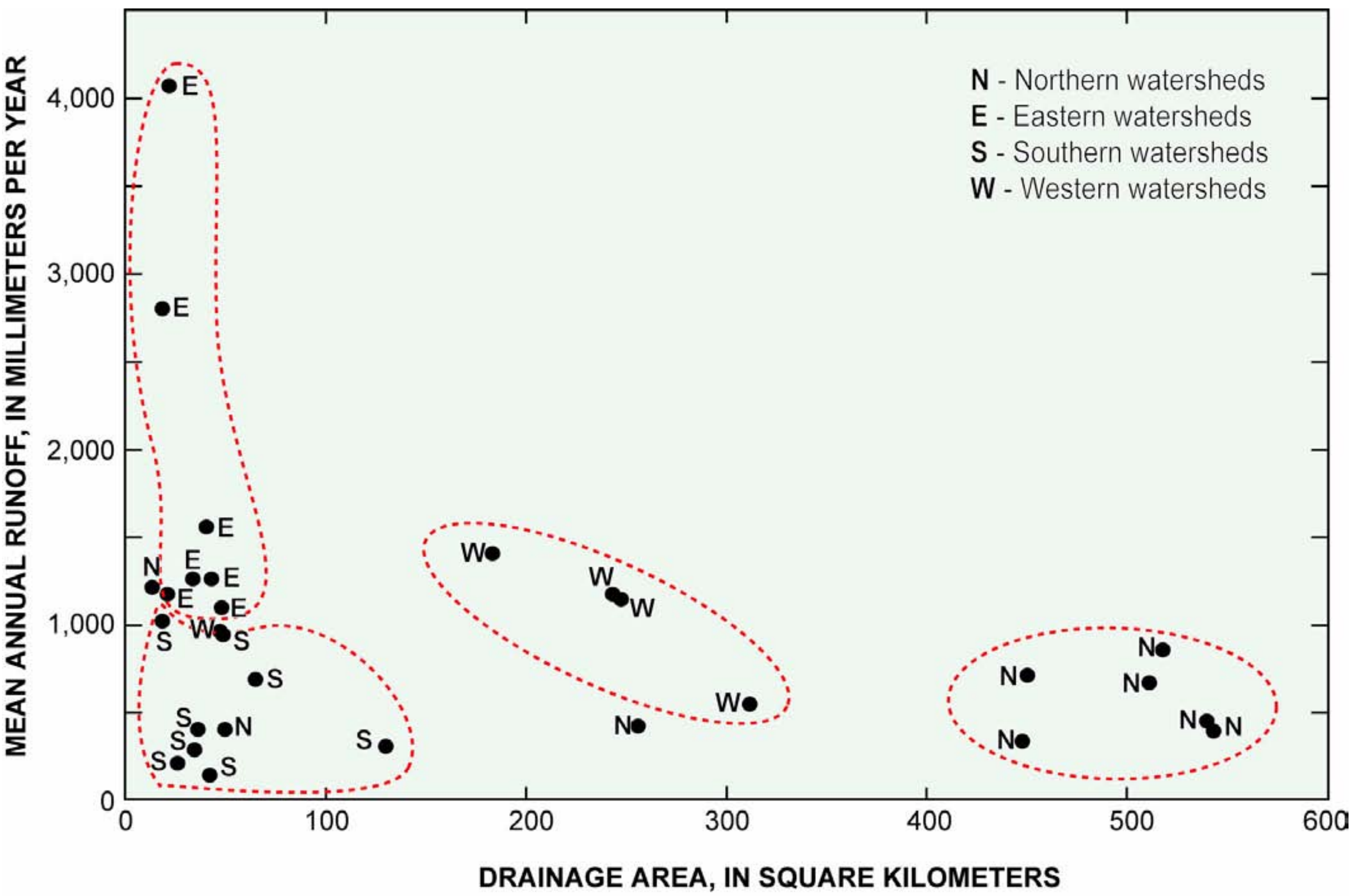

Figure 12. Relation between drainage area and mean annual runoff for watersheds in Puerto Rico, by region. Dotted lines indicate approximate groupings. See figure 8A for location of the drainage regions.

The particle-size distribution of sediment in suspension at the five sediment stations with recently published data shows that 89 percent of the samples contained silt and clay percentages that composed 80 percent or more of the sample mass. These data represented runoff that ranged from 1 to 1,500 millimeters per day (mm/d) (Díaz and others, 1999, 2000, 2001, 2002, 2004). Fine sediments such as these could easily be transported across the insular shelf in turbulent suspension during large storms. Although the fine sediment 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 common producers of heavy rain, tropical disturbances and winter cold fronts, would inhibit deposition of fine sediment in near-shore areas.

Milliman and Syvitski (1992) subdivided a global dataset into seven topographic settings. Puerto Rico was plotted with the upland data, which Milliman and Syvitski (1992) define as terrains between 100- and 500-m elevation. Mean annual sediment yields range from 120 to 4,300 metric tonnes per square kilometer per year (metric tonnes/km^2/yr) (table 6), which are comparable to the estimates of Reed and Kiser (1972), Sanders and Young (1982), and Milliman (1995) for Puerto Rico and elsewhere in the world. Comparison of long-term watershed and water- and sediment-discharge characteristics with other areas of the world (fig. 4) indicates that Puerto Rico hydrologic and geomorphologic responses are consistent with upland regions (terraines between 100 and 500 m elevation). Sediment yields in Puerto Rico are low in comparison to the mountainous islands of the Pacific (Milliman and Syvitski, 1992). The watersheds of northeastern Puerto Rico have relatively low sediment yields, the northern watersheds have moderate to high sediment yields, the eastern watersheds have low to moderate sediment yields, and the watersheds of southern and western Puerto Rico have high sediment yields (table 6, figs. 2, 3). The sediment yields for rivers in the southern and western parts of Puerto Rico are similar to the Santa Clara and Eel Rivers (1,400 and 1,700 metric tonnes/km^2/yr, respectively), which drain tectonically active, mountainous coastal areas of California (Mertes and Warrick, 2001).

River Water Quality in Puerto Rico

Nitrogen and phosphorus concentrations in the 24 rivers examined in this study indicate that, in most Puerto Rico watersheds, nutrient concentrations of river water discharging to the coast were within the safe drinking- water standards established by the U.S. Environmental Protection Agency (2000) and the Puerto Rico Environmental Quality Board (1990) (fig. 5A, C, E, G, I; table 11). The concentration of dissolved solids is not highly sensitive to discharge at the Río Grande de Manatí station 50038100, which is typical of many rivers in Puerto Rico and elsewhere (Díaz and others, 2001; Milliman and Meade, 1983; Stallard, 1995a, 1995b). There is a slight decrease in dissolved-solids (including nutrients) concentrations with increasing discharge (fig. 6), which indicates that floods do not necessarily promote high nutrient loadings along the coast and shelf. Most samples, however, were collected during relatively low-flow conditions and may not be representative of dissolved-solids concentrations during flood discharges. For example, for the Río Grande de Manatí, the highest total dissolved-solid concentrations were measured during flows from 1 to 100 cubic meters per second (m^3/s), whereas the highest mean daily discharge during Hurricane Georges was more than 2,200 m^3/s (fig. 6A; table 7).

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) (fig. 5B, D, F, H, J). Although no link has been found between high fecal coliform concentrations and disease in corals, the influx of organic material promotes eutrophic conditions, that can result in a proliferation of macroalgae (table 13). 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, extensive areas of which are unsewered (Larsen and Concepción, 1998) (fig. 6B). 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 (U.S. Geological Survey, 1999; Torres-Sierra, 2002). Hurricane-force winds and torrential rains affected the entire island until the storm moved off the western shore about 18 hours later. Hurricane Georges, a category-3 hurricane on the Saffir-Simpson scale, produced heavy rainfall, especially in the central and western mountains (U.S. Geological Survey, 1999). The USGS and the National Weather Service rain-gage networks recorded 2-day rainfall totals that ranged from 10 centimeters (cm) to about 63 cm (fig. 8C). On September 22, there was severe flooding in most of the mountainous interior and northern, southwestern, and western watersheds. The heavy rainfall also caused many landslides in the Cordillera Central (Larsen and Santiago-Román, 2001; U.S. Geological Survey, 1999).

Hurricane Georges caused the highest recorded daily discharges in 9 of the 30 streamflow-gaging stations evaluated in this study (table 7); however, at some stations, discharges were substantially less than the highest recorded mean daily discharge, especially in the eastern rivers. Peak flow recurrence interval data (table 7) indicate that Hurricane Georges had a highly variable impact across the island, but was especially severe in the west (Ramos-Ginés, 1999).

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 (table 6). During passage of Hurricane Georges (September 20-25, 1998), single-day water discharges ranged from 11 to 226 percent of the mean annual discharge volume, and sediment discharge was up to 19 times greater than the median annual sediment discharge (tables 1, 6). Discharge and sediment concentration rose rapidly and diminished rapidly following passage of Hurricane Georges (fig. 13). From 62 to 99 percent of the sediment discharge associated with hurricane stormflows was recorded on a single day—September 21 in the east and September 22 in the central and west (table 8). Hence, estimates of sediment discharge associated with the highest daily water discharge provide a simple but representative account of sediment discharge induced by Hurricane Georges.

Maximum daily sediment yields associated with Hurricane Georges generally were proportional to runoff but spatially variable, ranging from 50 to 6,900 metric tonnes per square kilometer per day (table 8; fig. 14). 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 of areas with extensive forest cover), and high in the south and west, where rainfall and runoff were high. As expected, storm runoff was a major determinate of sediment yield (figs. 14, 15; table 5).

Precipitation and discharge estimates by island region indicate that about 2.6 billion m^3 of precipitation fell on the island from September 20-25, 1998, and about 1.0 billion m^3 (40 percent) was converted to direct runoff (table 5; fig. 15). 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 percent of the estimated mean annual runoff of 911 mm). Most of the 180-mm difference between rainfall and runoff (1.6 billion m^3), would have infiltrated into temporary soil storage and long-term ground-water storage, with evapotranspiration accounting for the rest. Evapotranspiration rates in low elevation areas of the island generally are less than 5 mm/d (Harmsen and others, 2003). Ground-water 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 ground-water levels (Díaz and others, 1999, see their table 3).

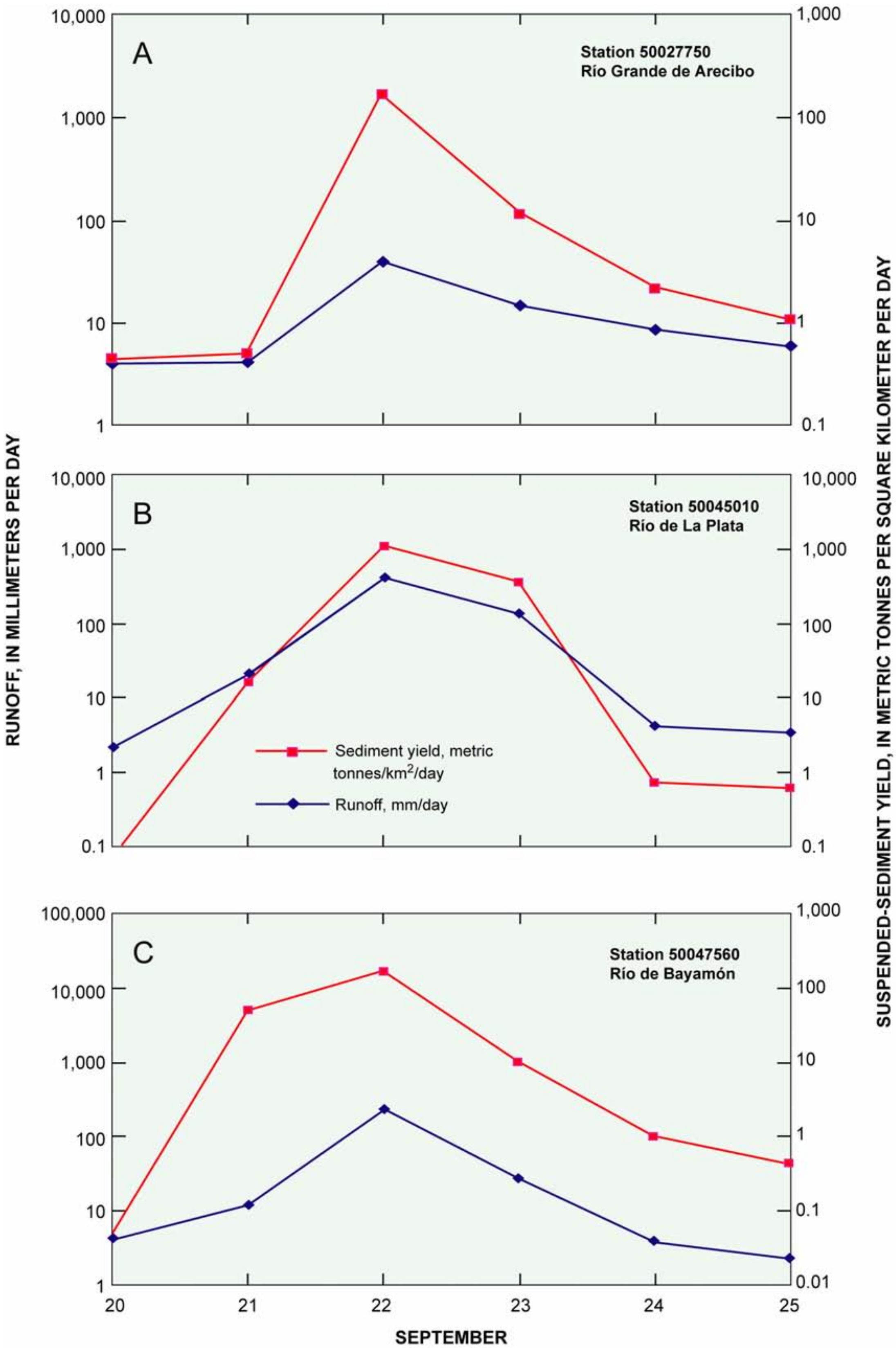

Figure 13. Daily runoff and suspended-sediment yield during passage of Hurricane Georges, September 20-25, 1998, recorded at nine daily sediment gaging stations in Puerto Rico. See figure 2 for location of gaging stations.

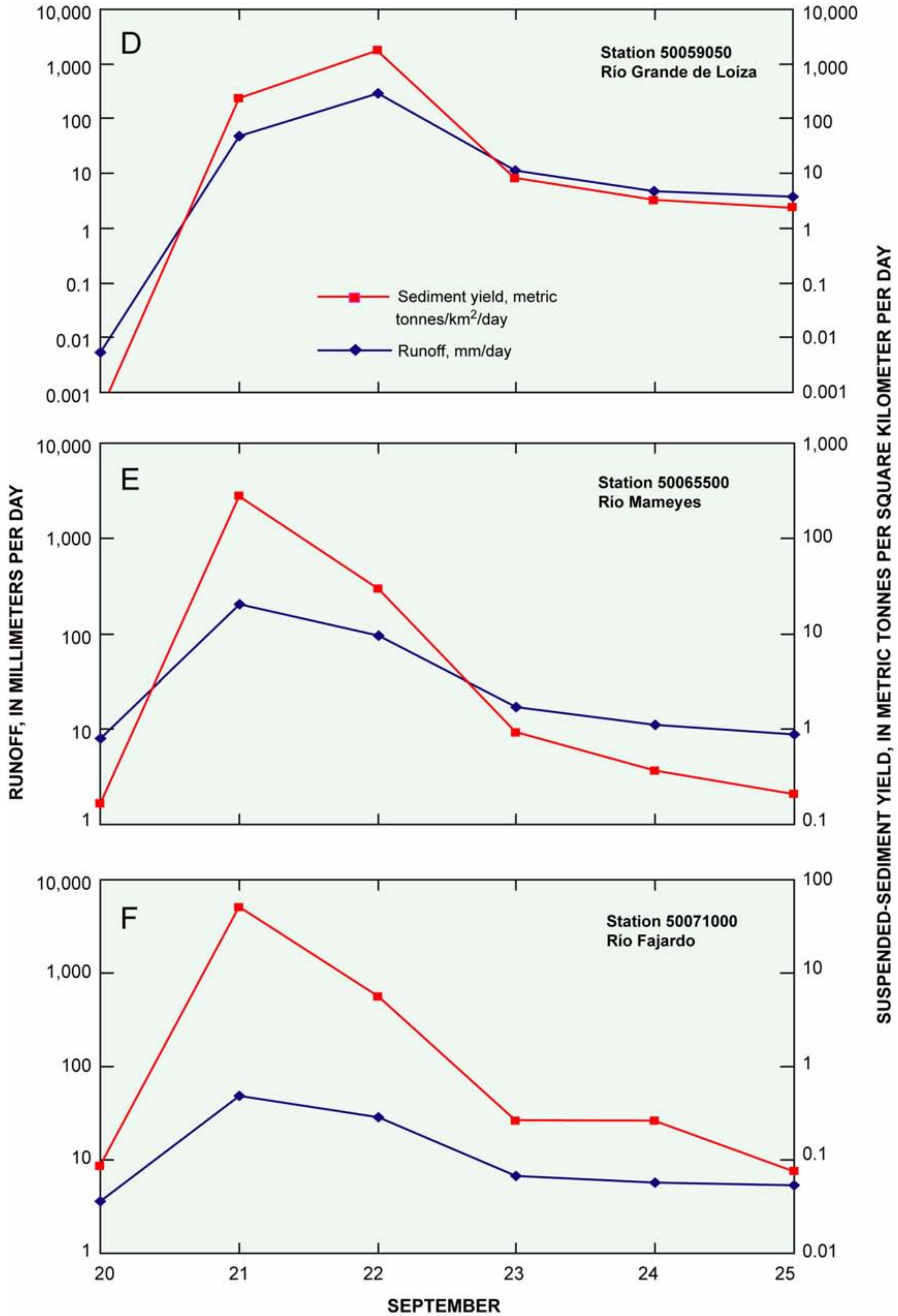

Figure 13. Daily runoff and suspended-sediment yield during passage of Hurricane Georges, September 20-25, 1998, recorded at nine daily sediment gaging stations in Puerto Rico. See figure 2 for location of gaging stations.—Continued

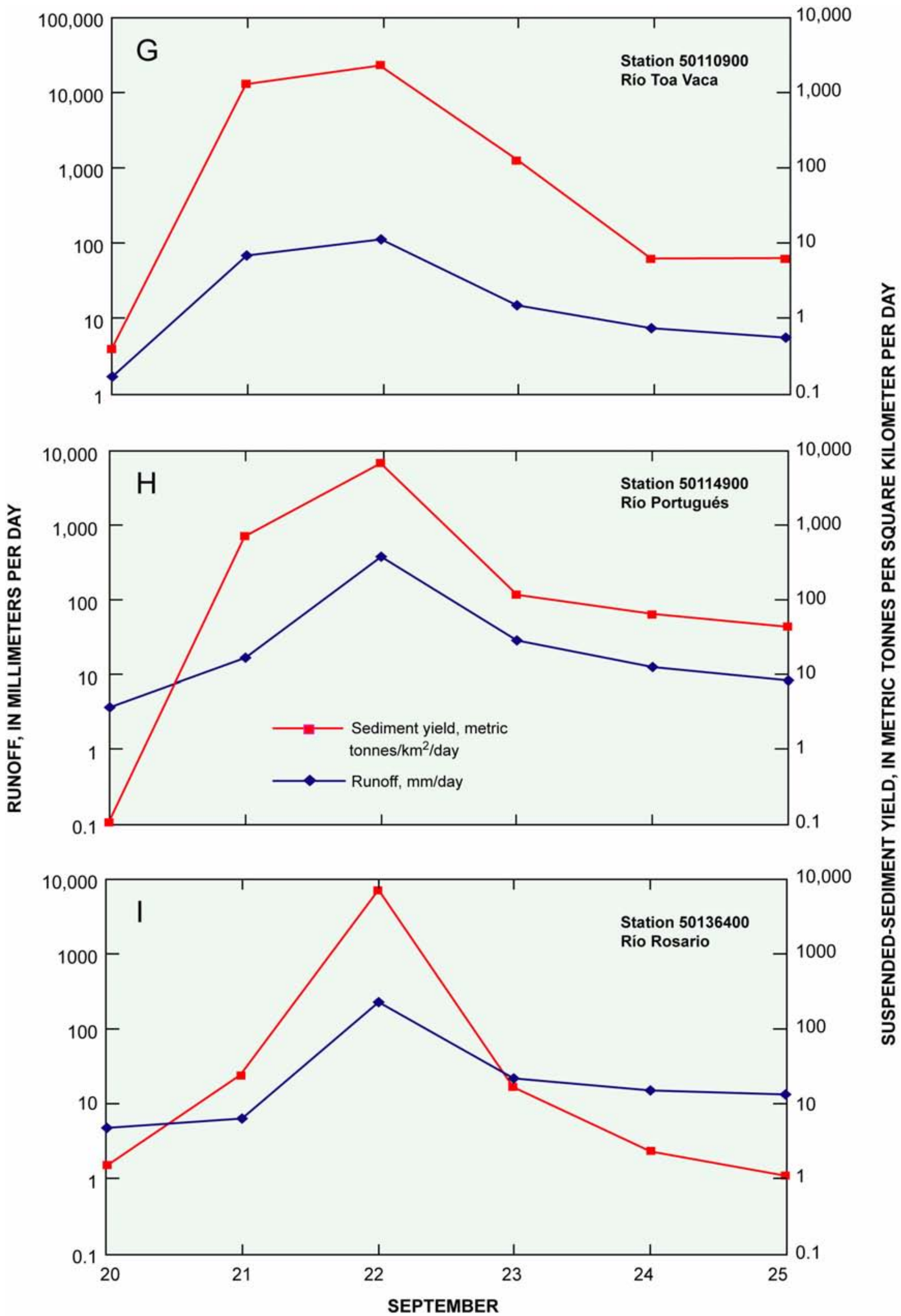

Figure 13. Daily runoff and suspended-sediment yield during passage of Hurricane Georges, September 20-25, 1998, recorded at nine daily sediment gaging stations in Puerto Rico. See figure 2 for location of gaging stations.—Continued

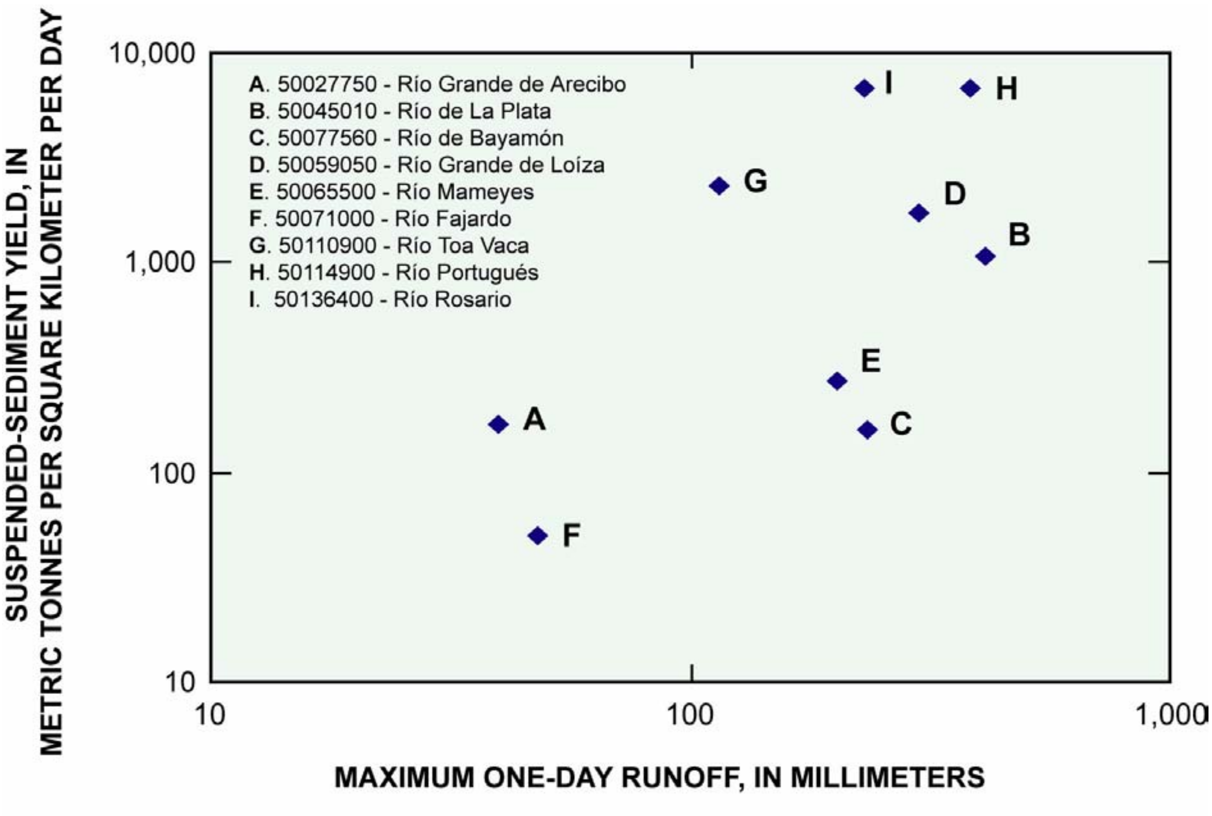

Figure 14. Relation between suspended-sediment yield and runoff during Hurricane Georges, September 21-22, 1998, for the nine downstream-most sediment stations in Puerto Rico. The station locations are shown in figure 2.

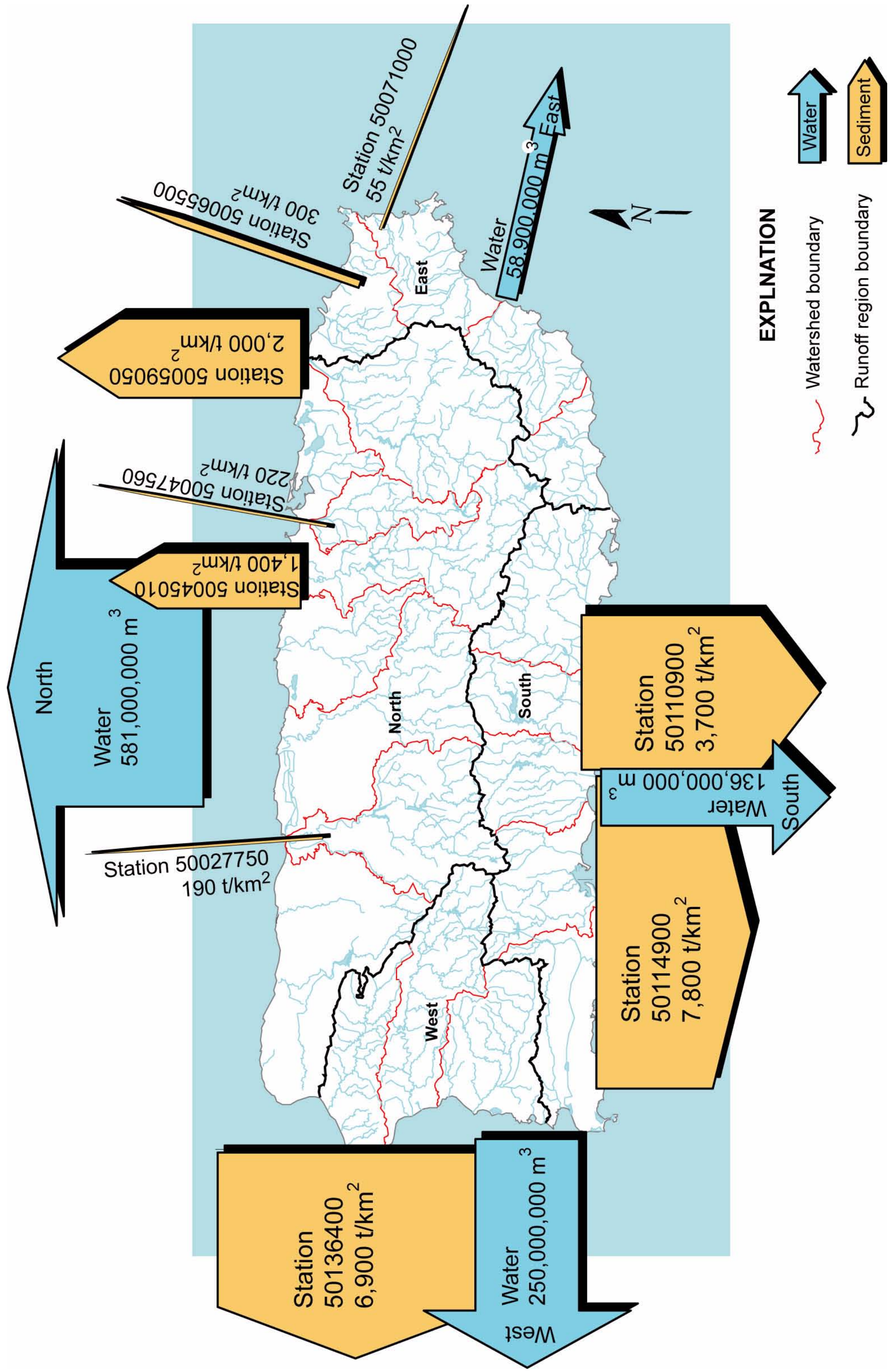

Figure 15. Spatial distribution of water discharge and suspended-sediment yield during passage of Hurricane Georges, September 20-25, 1998. Water discharge, in cubic meters, represents the total for each of four runoff regions of the island. Sediment yield, in metric tonnes per square kilometer, is shown for nine sediment stations listed in table 3. Width of arrows is proportional to mass flux of water and sediment.

It is noteworthy that in two watersheds in the east, which include coastal and lowland areas, runoff accounts for 32 to 61 percent of the total rainfall during a typical year (Larsen and Concepción, 1998; Larsen and Stallard, 2000; Schellekens and others, 2000). Rainfall during August and September 1998 (prior to Hurricane Georges) equaled or exceeded the monthly normal at 54 of 63 stations (National Oceanic and Atmospheric Administration, 1999), and therefore, it is likely that the ground was nearly saturated prior to Hurricane Georges, thus enhancing runoff.

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 percent) occurring on the day of highest discharge (September 21 in the east, September 22 towards the west). Because these nine stations represent only 19 percent (1,622 km^2) of the island area (total area of 8,711 km^2), 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 factors such as the part of the island that is a 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. A reasonable estimate of total sediment discharge would likely range between two and four times the cumulative amount represented by the nine sediment stations, which is in the range of 5 to 10 million metric tonnes. Based on data from the nine sediment stations, most of the sediment was discharged from the western, southern, and northern rivers whereas the eastern rivers had relatively little sediment discharge.

Nutrient discharge for runoff associated with Hurricane Georges can be approximated using the following estimates, bearing in mind that such estimates have large uncertainties: assuming an average nitrogen concentration of 1 gram per cubic meter (g/m^3) (figs. 5A, C, E, G, I, 6A), and assuming an island-wide, highest daily discharge of 1.03 billion m^3 (table 6), nitrogen discharge to the insular shelf was about 1,000 metric tonnes (Gilbes and others, 2001). Assuming a phosphorus concentration of 0.5 g/m^3, phosphorus discharge was about 500 metric tonnes. Discharge of fecal material to the coast and shelf during Hurricane Georges varied among the rivers (figs. 5B, D, F, H, J, 6B). Data are insufficient to estimate total fecal discharge volumes; however, analysis of a Sea-viewing Wide Field of view Sensor (SeaWiFS, satellite imagery used for monitoring plankton and sedimentation levels in the oceans) data for the period of September 19 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 and others, 2001) (fig. 16).

River and Sediment Discharge to Puerto Rico's Coast and Shelf

Mean annual runoff is estimated at 911 mm, based on streamflow data from the 24 stations listed in table 1. These streamflow stations are not located at river mouths, and as a result, the runoff estimate is expected to be slightly lower because it does not account for the downstream runoff losses between the station and the coast owing to ground-water infiltration and evapotranspiration. These stations have varying periods of record, but as a whole, represent hydrologic conditions for the period of 1970 to 2000. Mean annual suspended-sediment discharge from Puerto Rico to surrounding coastal waters is estimated to range from 2.7 to 9.0 million metric tonnes for the water years 1990 to 2000. Lugo and others (1980) estimated that the rivers of Puerto Rico discharge up to 70 percent of their annual sediment load during a few days of torrential rains during the year. Gellis and others (1999) reported that during the water years 1984 to 1993, 80 percent of the annual suspended-sediment load was transported from the Lago Loíza watershed in 4 to 24 days. Cruise and Miller (1994) estimated that runoff induced by large rainstorms in August 1988 and October 1989 produced 72 and 81 percent, respectively, of the sediment yields from the Río Guanajibo watershed for the respective years. Discharge in northwestern Puerto Rico on October 21, 1989, resulted in sediment plumes that extended up to 12 km offshore (fig. 17). Suspended-sediment loads measured at the Río Rosario (USGS station 500136400, drainage area 47.4 km^2), a tributary of the Río Guanajibo, totaled 1,800 metric tonnes for the 4-day storm represented in part, by the October 21, 1989, image, and equaled about 6 percent of the annual total (Curtis and others, 1991). Meade and others (1990) demonstrated that sediment is discharged during 1 percent (about 4 days) of the year in North American rivers and varies regionally. About 10 percent of annual sediment loads are discharged during 1 percent of the year in coastal plain rivers of North Carolina, whereas 60 to 93 percent of the sediment is discharged during 1 percent of the year in the Pacific Coast Ranges (Meade and others, 1990, their table 1). The present study demonstrates that for the water year with the highest daily discharge volume, the daily discharge comprised between 8 and 66 percent 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 6). Sediment yields (during Hurricane Georges) calculated for this study (table 6) were based upon sediment discharges at the nine daily sediment stations located in downstream river reaches, rather than from sites of hillslope erosion. Therefore, these sediment yields should reasonably approximate the volume of sediment that was transported from the uplands and river valleys to the coast during the storm.

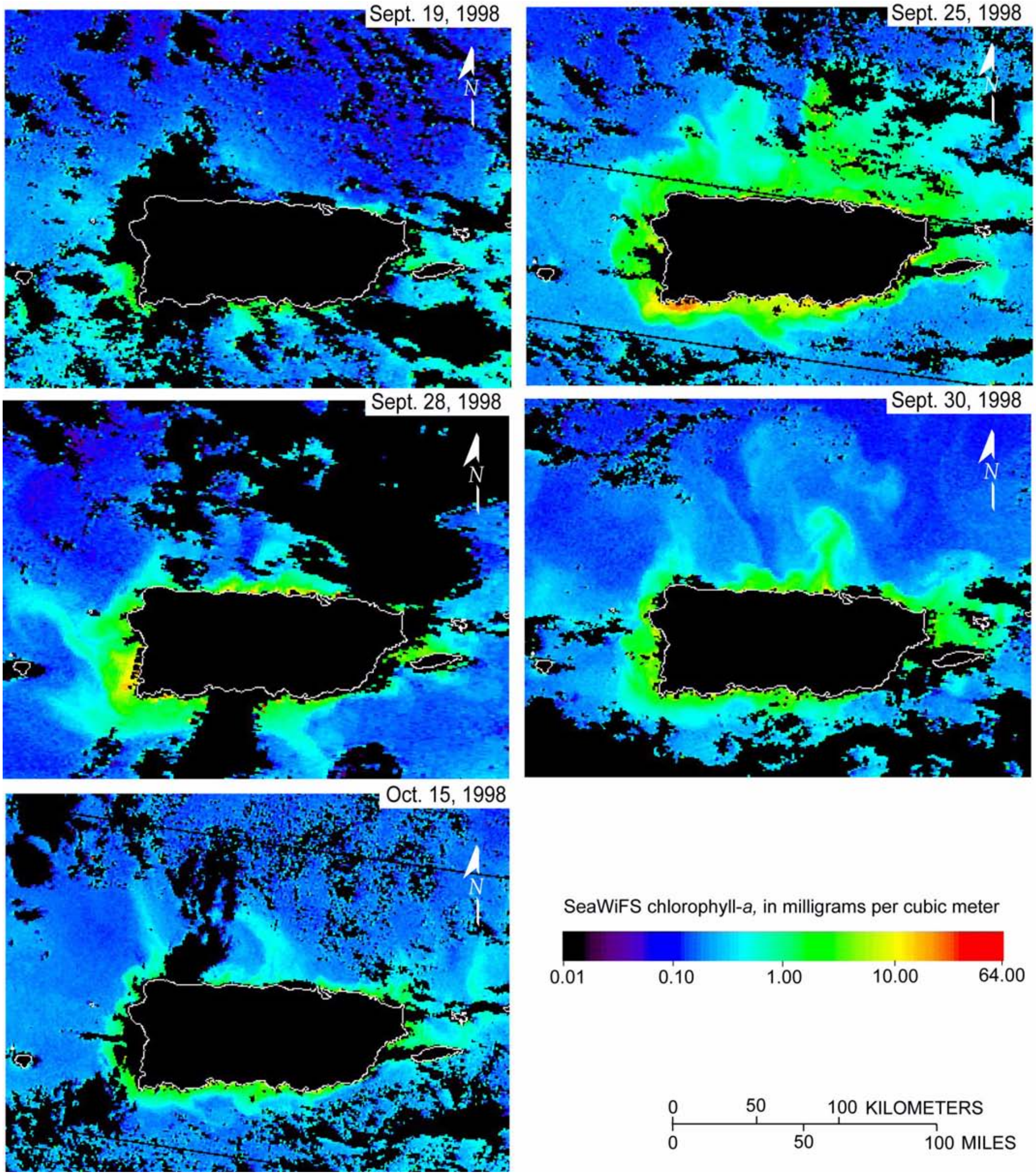

Figure 16. Chlorophyll-*a* as estimated using the SeaWIFS satellite sensor before and after Hurricane Georges crossed over the Caribbean region. Increased concentrations of chlorophyll-*a* around Puerto Rico following Hurricane Georges reflect an increase in phytoplankton. The increase in phytoplankton is assumed to be the result of high discharge of nutrient-rich river water. SeaWiFS images courtesy of the University of Puerto Rico Space Information Laboratory.

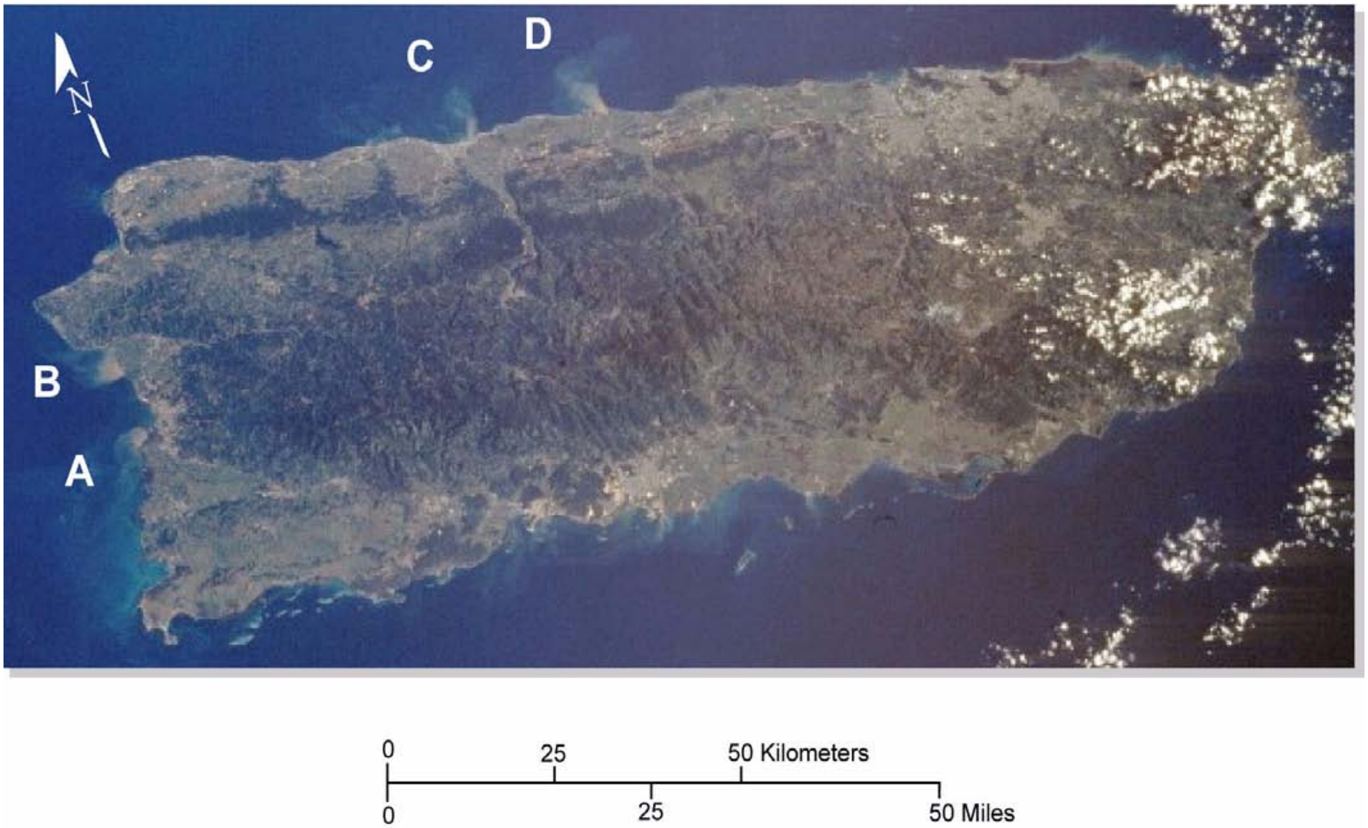

Figure 17. Satellite image of Puerto Rico showing hypopycnal sediment plumes at river mouths of (A) Río Guanajibo, (B) Río Grande de Añasco, (C) Río Grande de Arecibo, and (D) Río Grande de Manatí. Brown color of vegetation in eastern Puerto Rico is the result of defoliation caused by Hurricane Hugo, which struck the island on September 18, 1989. Image STS034-076-088, taken on October 21, 1989, at 12:51 Greenwich Mean Time (GMT). Courtesy of NASA (http://www.jsc.nasa.gov). Spacecraft elevation 179 nautical miles (332 kilometers), sun angle 32 degrees.

In the mainland United States, about 10 percent of the sediment eroded from uplands is transported directly to the oceans by rivers (Meade and Parker, 1985; Meade and others, 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, stream valleys are steep and narrow, and where intense rainfall and high runoff are common, it is likely that more than 10 percent of the sediment eroded from uplands is discharged to the coast. Mertes and Warrick (2001) indicate that 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.

During flood discharges, river water entering the ocean either (1) forms a hypopycnal plume (bouyant suspension layer, fig. 18A; for example, the sediment plumes visible in fig. 17) if the river water is less dense than ocean water; (2) rapidly mixes with ocean water if the density of the river water is about the same as ocean water (homopycnal flow and rapid sedimentation); or (3) forms a hyperpycnal plume (density layer) (fig. 18B) if the density of river water is greater than the density of ocean water (Wright and Coleman, 1971; Otero and others, 1992; Nemec, 1995; Mertes and Warrick, 2001). River discharge rate, intensity of marine waves and currents, and coast and shelf geomorphology also determine whether, and to what degree, hypopycnal, homopycnal, or hyperpycnal conditions will develop, especially if the densities of river and ocean waters are nearly equal. Additionally, the settling of clay particles from suspension is enhanced as river water enters the sea where increased salinity causes flocculation (Collinson and Thompson, 1982). The density of water is controlled primarily by the concentration of suspended sediments and dissolved solids. Dissolved-solid concentration is not an important factor in river-water density (at least in comparison to marine water), so substantial changes in river-water density are mainly attributable to suspended-sediment concentrations.

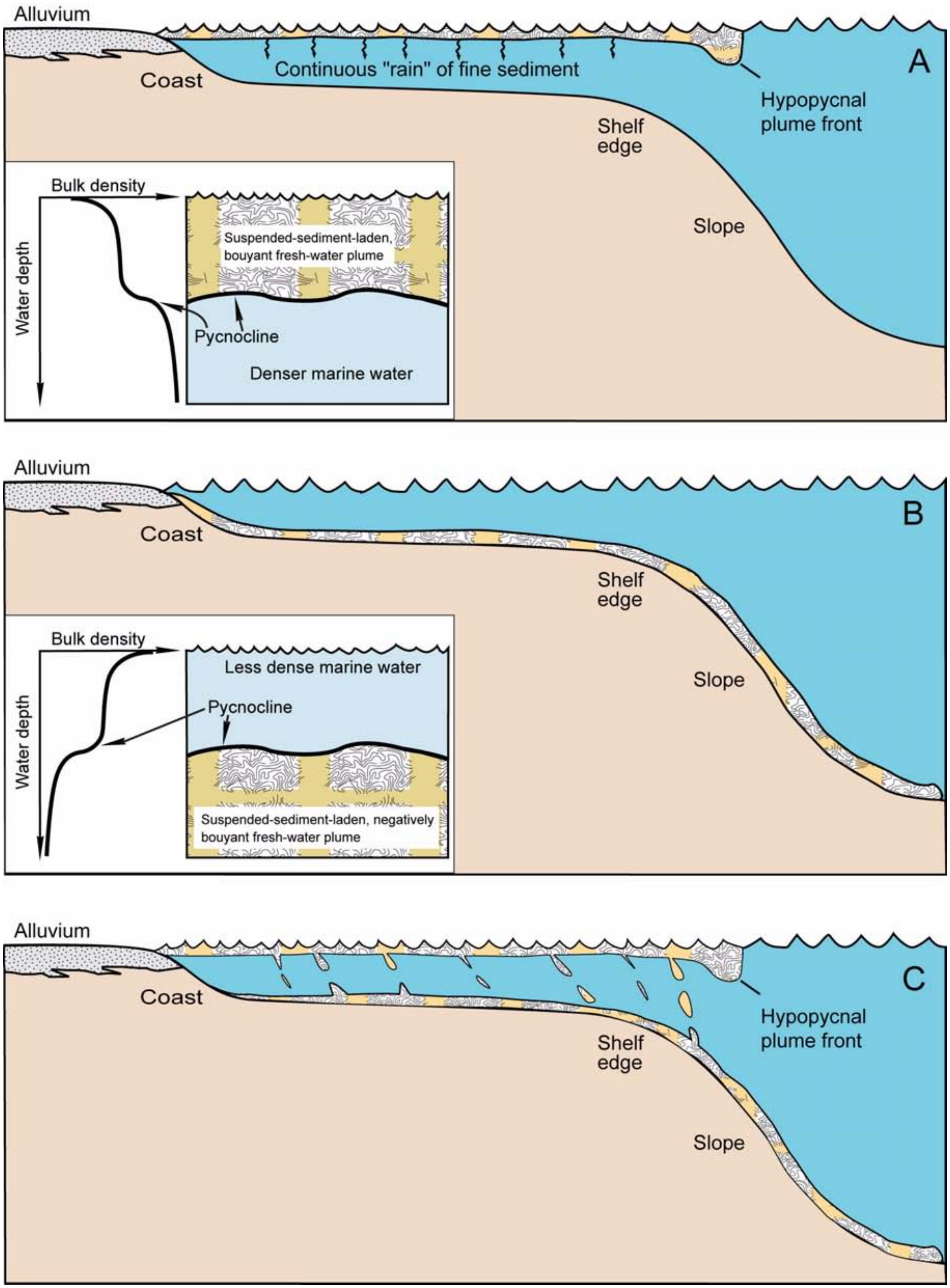

Figure 18. Basic characteristics of (A) hypopycnal, (B) hyperpycnal, and (C) combination hypo/hyperpycnal sediment plumes (modified from Nemec, 1995; Parsons and others, 2001).

The density of ocean water normally is about 1,025 to 1,038 grams per liter (g/L), depending on the concentration of hemipelagic matter (Syvitski and others, 1987; Nemec, 1995). River water with suspended-sediment concentrations less than 25 g/L (25,000 mg/L) tend to form hypopycnal plumes, whereas river water with sediment concentrations greater than 38 g/L tend to form hyperpycnal plumes (Syvitski and others, 1987; Nemec, 1995; Mertes and Warrick, 2001). Recent studies by Parsons and others (2001) indicate that hyperpycnal plumes develop out of hypopycnal plumes that have suspended-sediment concentrations of less than 25 g/L, resulting in a combination hypo/hyperpycnal plume (fig. 18C). For most of Puerto Rico, the maximum daily mean sediment concentrations during Hurricane Georges were substantially less than 25 g/L (table 3). Because water discharge and sediment concentrations vary rapidly during floods; however, it is possible that sediment concentrations fluctuated from less than 25 g/L to more than 38 g/L in streams in the southwest and west where the greatest suspended-sediment concentrations were measured (fig. 3). In these areas, river discharge to the shelf during Hurricane Georges may have fluctuated between hyperpycnal, homopycnal, and hypopycnal flow. Relatively low sediment concentrations are sufficient to make sediment plumes visible from satellite imagery. An example is the suspended-sediment concentration for the October 1989 storm that resulted in hypopycnal sediment plumes at the mouth of the Río Guanajibo and averaged 0.4 g/L (fig. 17).

Negatively buoyant hyperpycnal plumes typically flow for great distances along the bottom, often scouring the seafloor surface (fig. 18B). Currently, there are no oceanographic data that document hyperpycnal plume development in Puerto Rico. Hurricane Georges data and peak-flow recurrence analyses (tables 3, 7) indicate that hyperpycnal plumes form in Puerto Rico only during the most extreme storms, such as those with recurrence intervals of 100 years or more.

Sediment-concentration data (table 3) indicate that hypopycnal plumes developed at the mouths of most Puerto Rico rivers during passage of Hurricane Georges. In areas where hypopycnal plumes developed, river water and suspended-sediment loads spread out on top of the marine waters and did not mix with the marine waters until well out to sea, causing suspended sediment to be dispersed over a broad area of the shelf. Although inhibited by the pycnocline (fig. 18A), suspended sediment settles out of hypopycnal plumes, giving rise to a continuous "rain" of fine sediment that covers the shelf and slope. Relatively little is known about the type, frequency, and intensity of shelf processes that transport terrigenous sediment to the shelf edge (Schneidermann and others 1976; Pilkey and others, 1978; Grove and others, 1982; Rodríguez and others, 1992, 1998). Bush (1991), however, documented that storm-induced, across-shelf transport processes are predominate in Puerto Rico, and he calculated that 90 percent of the river sediment discharged at the coast is transported to the shelf edge and slope within a few months.

A time series of SeaWiFS satellite images document chlorophyll-*a* concentrations around Puerto Rico before, during, and after the passage of Hurricane Georges (fig. 16). Chlorophyll-*a* is contained within and serves as a proxy for phytoplankton biomass. The images show increased phytoplankton in the oceans around Puerto Rico that presumably resulted from the assimilation of nutrients that were discharged from the island during Hurricane Georges (Gilbes and others, 2001). The areas of high chlorophyll-*a* concentration are notable off the west and south coasts where flood discharge was greatest. The areas of high chlorophyll-a concentrations extend well seaward of the shelf edge in many areas, indicating that hypopycnal plumes extended far out to sea.

Shelf configuration and the wave and current regime are critical to maintaining the water-quality and substrate conditions that are conducive to coral reef development around the island. Nutrient and sediment discharges to a large part of the Puerto Rico's coast and shelf are believed to have been relatively low prior to large-scale land-use changes during the 19th and 20th centuries, except during the few days a year when most of the river sediment is discharged to the coast (fig. 17). Before widespread development of the island, marine waters would have been relatively transparent most of the time, and waves and currents presumably transported the most recent, fluvially derived sediments off the shelf (Bush, 1991). Most coral reef areas were probably relatively unaffected by the episodic influx of terrigenous sediment and nutrients, perhaps because during these periods of high discharge, (tropical disturbances) waves and currents are strong, thereby inhibiting deposition and promoting transport of the sediment to the shelf edge and slope.

Effects of Human Activity on Puerto Rico Watersheds, River Systems, and Reefs

Although living coral reefs are present around Puerto Rico, they are degraded, largely because of increased sediment and nutrient discharge resulting from anthropogenic modifications of the densely populated island. These modifications are associated with intensive land clearing, agricultural and industrial development, and a steady increase in the standard of living (Goenaga and Cintrón, 1979; Morelock and others, 1980, 1983, 1985; Rogers, 1990; Acevedo and Morelock, 1988; Acevedo and others, 1989; Clark and Wilcock, 2000; Larsen, 2000; Larsen and Santiago-Román, 2001; Torres and Morelock, 2002; Weil, 2004). Coral reef degradation is widespread in waters surrounding the island, but generally greatest offshore of watersheds where population is high and terrestrial discharge of water and sediment are high (figs. 1, 11). Although portions of the south central 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. Future changes in land use, however, may further threaten these areas. In 1896, approximately 21 percent of the island was in cropland. In 1939, cropland reached a high of 48 percent. Forest cover reached a low of 7 percent in the mid 1940s, but a shift from predominantly agricultural to a manufacturing economy resulted in an increase in forest cover to 33 percent (Clark and Wilcock, 2000; Larsen and Santiago-Román, 2001). Currently, new construction is widespread and, as undeveloped space in urban areas diminishes, development on steep slopes increases (Helmer and others, 2002; Thomlinson and others, 1996), which contributes to an increase in sediment erosion and transport to the coast.

Numerous studies have documented the effect of human modifications of the landscape on water and sediment discharge in Puerto Rico (Gellis, 1991; Cruise and Miller, 1994; Larsen, 1997; Thomlinson and others, 1996; Gellis and others, 1999; Clark and Wilcock, 2000; Larsen and Santiago-Román, 2001). In a study of a construction site located along a tributary to the Río Grande de Loíza, Gellis (1991) demonstrated that sediment yield associated with a small storm was four to eight times greater in the disturbed area than in adjacent, undisturbed areas. Gellis (1991) also reported that two streamflow-gaging stations, located in watersheds with construction activity, had sediment yields three to five times greater than in a nearby, largely rural basin. Elsewhere, Hill and others (1997, 1998) and Wong and Young (2001) documented a 10-fold increase in sediment yield as a result of highway construction through a forested, mountainous tropical watershed in Oahu, Hawaii. MacDonald and others (2001) documented the entrainment and transport of sediment from unpaved roads in St. John, U.S. Virgin Islands, and showed that annual sediment yields were as high as 15 kilograms per cubic meters (kg/m^3) of road surface. They also demonstrated that erosion of the road surface was generally initiated when storm rainfall exceeded 6 mm. St. John is located about 80 km east of Puerto Rico and has similar geology and climate to that of southern Puerto Rico. Unpaved roads in Puerto Rico would be expected to be comparable to those in St. John, with respect to availability of sediment particles for entrainment and transport to the sea.

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 5,000 metric tonnes per square kilometer (metric tonnes/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 and others, 1998; Larsen and Santiago-Román, 2001). Larsen and Santiago-Román (2001) provided evidence that during the period of widespread agricultural activity, the massive quantity of sediment eroded from the hillslopes was stored temporarily 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 and others (1999) 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.

Clark and Wilcock (2000) suggested that during the period of intense agriculture (1830-1950), runoff at several rivers in northeastern Puerto Rico increased by 50 percent from pre-European settlement levels, and sediment supply to rivers increased by an order of magnitude. During the shift from agricultural to industrial and residential land uses over the past 50 years, sediment concentrations have remained at the estimated 1830-1950 levels, but the sediment supply to valleys and riparian areas has decreased, so that during the past 50 years, rivers have been transporting seaward the sediment that was temporarily stored in the alluvial valleys. Clark and Wilcock (2000) demonstrated that in-channel gravel bars are more common downstream than upstream along the Río Mameyes, Río Sabana, and Río Fajardo. They also demonstrated that channel cross-sectional area decreases and frequency of overbank flooding increases downstream along these three rivers. They attributed the downstream decrease in channel size to a mass of coarse-grained sediment, delivered to the channel systems during the agricultural period, that is currently moving seaward through the channels. Clark and Wilcock (2000) predicted that the channel systems will adjust to the current runoff sediment-supply conditions, including eventual downcutting of the lower channels as the mass of agricultural-period-derived sediment moves through the system and onto the coast and shelf. The studies described above 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 several decades to perhaps a century or more.

Increased turbidity along the shelf, seaward of Ponce and La Parguera (figs. 1, 17), is believed to be the result of conversion of adjacent upland areas from forest to agricultural and then to urban-industrial use. The increased turbidity has 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 and others, 1989). Acevedo and Morelock (1988) and Acevedo and others (1989) documented diminished coral cover, reduced species diversity, and a shift to slower-growing coral species with increasing turbidity in the Ponce area. Morelock and others (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. Weil (2004) noted that 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 has combined with industrial effluents discharged directly into the Mayagüez Bay to reduce the living coral cover on the Algarrobo Reef and Escollo Rodríguez to less than 2 percent (Morelock and others, 1983).

Continual resuspension and transport of dredged sediments can cause reef degradation years after dredging ceases (Rogers, 1990). Dredging within the Torrecilla Lagoon left behind deep anoxic pits with ammonia concentrations exceeding 15 mg/L and biological oxygen demand exceeding 200 mg/L (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. Prior to dredging, the reef included extensive coral communities that extended from the sea surface down to more than 10 m. Few living corals exist at this location below a depth of about 1.5 m, according to Goenaga and Cintrón (1979).

Negative impacts 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 are outcompeting the coral planulae in colonizing available substrates (Weil, 2004).

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 to 2.5 mg/L (fig. 5A, C, E, G, I); in comparison, streams draining the relatively undisturbed forests of eastern Puerto Rico have nitrogen concentrations ranging from 0.15 to 0.25 mg/L (McDowell and Ashbury, 1994). Phosphorus concentrations in most rivers of Puerto Rico range from 0.1 to 0.8 mg/L, whereas in the relatively undisturbed forests of eastern Puerto Rico, total dissolved-phosphorus concentrations of 0.002 mg/L are common (McDowell and Ashbury, 1994). This limited analysis indicates that human modification of the island landscape has caused nitrogen and phosphorus concentrations to increase 10-fold. Although the natural concentrations of nitrogen and phosphorus are low (McDowell and Ashbury, 1994) and nutrient concentrations are well within safe drinking-water standards (U.S. Environmental Protection Agency, 2000), the combined increase in concentration of fecal material, nitrogen, and phosphorus in river water discharging to the shelf likely provides a competitive advantage to algae and sponges, which dominate many Puerto Rico reefs (Goenaga and Cintrón, 1979). A recent (November 2000) outbreak of Patchy Necrosis syndrome 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 also 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 (Díaz and others, 2001). 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 and others (2002) have suggested that untreated sewage may be a source for some coral diseases.

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/yr, which is about 57 percent of the mean annual precipitation of 1,600 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 discharge; flood waters recede quickly, on the order of hours to a few days. As a result of these storms, 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. In a typical year, the mean maximum daily discharge accounts for 23 to 58 percent of the total annual water discharge. Major storms result in sediment discharges that are 1 to 32 times the median annual volume. The relatively small dams and reservoirs of Puerto Rico have minor effects on total water and sediment discharge during major storms. Comparison of long-term sediment discharge and watershed characteristics with those of other river systems around the world indicates that Puerto Rico rivers are similar to other upland river systems with varying land use.

Sediment discharge and sediment yield vary regionally across the island. The northern river systems, which comprise about half the island drainage area, generally have moderate to high sediment yield and moderate to high annual runoff; the eastern river systems generally have low to moderate sediment yield and high annual runoff; the southern river systems generally have high sediment yield and low annual runoff; and western river systems generally have moderate to high sediment yield and high annual runoff. The river systems in the karst region of the northwest have relatively low sediment yields, low peak water and sediment discharges, and moderate annual runoff. Coral reef degradation is widespread in waters surrounding the island, but generally greatest offshore of watersheds where population density is high and terrestrial discharge of water and sediment are high. Watersheds that contribute runoff to much of the south coast are not highly populated and mean annual runoff is relatively low. Land-use change in the future is likely to threaten these areas. Although portions of the south central and southwest coasts have relatively healthy reefs, 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. Analysis of runoff and sediment yield from Hurricane Georges indicates that more than 1.0 billion m^3 of water and at least 2.4 million metric tonnes of sediment (and as much as 5 to 10 million metric tonnes), were discharged to the coast and shelf as a result of this one large storm. Long-term data show regional differences in sediment yield and water discharge, however, analysis of Hurricane Georges data indicates that sediment yield was strongly storm-controlled; sediment yield was proportional with storm runoff throughout the island.

During intense storms, sediment concentrations measured in island rivers generally are less than 25 g/L (25,000 mg/L), so river water and sediment discharges to the marine environment tend to form hypopycnal plumes (buoyant suspension layers) that distribute the suspended sediment over broad areas of the shelf and slope. During extreme floods, sediment concentrations can exceed 25 g/L and in some cases even 38 g/L, so a combination of hypopycnal, homopycnal, and hyperpycnal plumes may develop.

Based on drainage-basin area size, about one-half of the sediment discharges through the northern rivers. 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. Additionally, sediment plumes would have been more buoyant because they would have carried less sediment. 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 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. Although nitrogen and phosphorous concentrations in river waters are well within regulatory limits, current concentrations are 10 times greater than the estimated pre-settlement levels. 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.

The effects of river-derived sediment and nutrient discharge on the coral reefs 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 are outcompeting the coral planulae in colonizing available substrates.

In an effort to present what is currently known about the effects of river discharge on the reefs of Puerto Rico, this report 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; 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. Moreover, there have been no long-term wave and current studies to determine seasonal variations and the effects of storms on the shelf. 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) an important indicator of climate change, (3) a key element in maintaining biodiversity, (4) a key component in the tourism industry, and (5) an effective barrier for storm-wave erosion of coastal areas. There is a need for a systematic survey of coral reef types, settings, and composition. These studies are essential components for establishing a baseline with which to measure future change (related to human modification of the island and global climate change), and to determine which reef areas are at risk and measures that can be taken to protect them.

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