Hydrology and Climate of Four Watersheds in Eastern Puerto Rico

By Sheila F. Murphy and Robert F. Stallard

Chapter C of

Water Quality and Landscape Processes of Four Watersheds in Eastern Puerto Rico

Edited by Sheila F. Murphy and Robert F. Stallard

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Abbreviations Used in This Report

km	kilometer
km^2	square kilometer
m	meter
mm	millimeter
mm day^{-1}	millimeters per day
mm h^{-1}	millimeters per hour
mm yr^{-1}	millimeters per year
m s^{-1}	meters per second
m^3 s^{-1}	cubic meters per second
yr	year

AR	autoregressive
BP	before present
ENSO	El Niño–Southern Oscillation
ET	evapotranspiration
IMA	integrated-moving-average
LTER	Long-Term Ecological Research
NOAA	National Oceanographic and Atmospheric Administration
PRISM	parameter-elevation regressions independent slopes model
USGS	U.S. Geological Survey
WEBB	Water, Energy, and Biogeochemical Budgets

Conversion Factors

Multiply	By	To obtain
	Length	
millimeter (mm)	0.03937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)
	Flow rate	
meter per second ($m\ s^{-1}$)	3.281	feet per second ($ft\ s^{-1}$)
cubic meters per second ($m^3\ s^{-1}$)	35.31	cubic feet per second ($ft^3\ s^{-1}$)
millimeters per hour ($mm\ h^{-1}$)	0.03937	inches per hour ($in.\ h^{-1}$)
millimeters per day ($mm\ h^{-1}$)	0.03937	inches per day ($in.\ h^{-1}$)
millimeters per year ($mm\ yr^{-1}$)	0.03937	inches per year ($in.\ yr^{-1}$)

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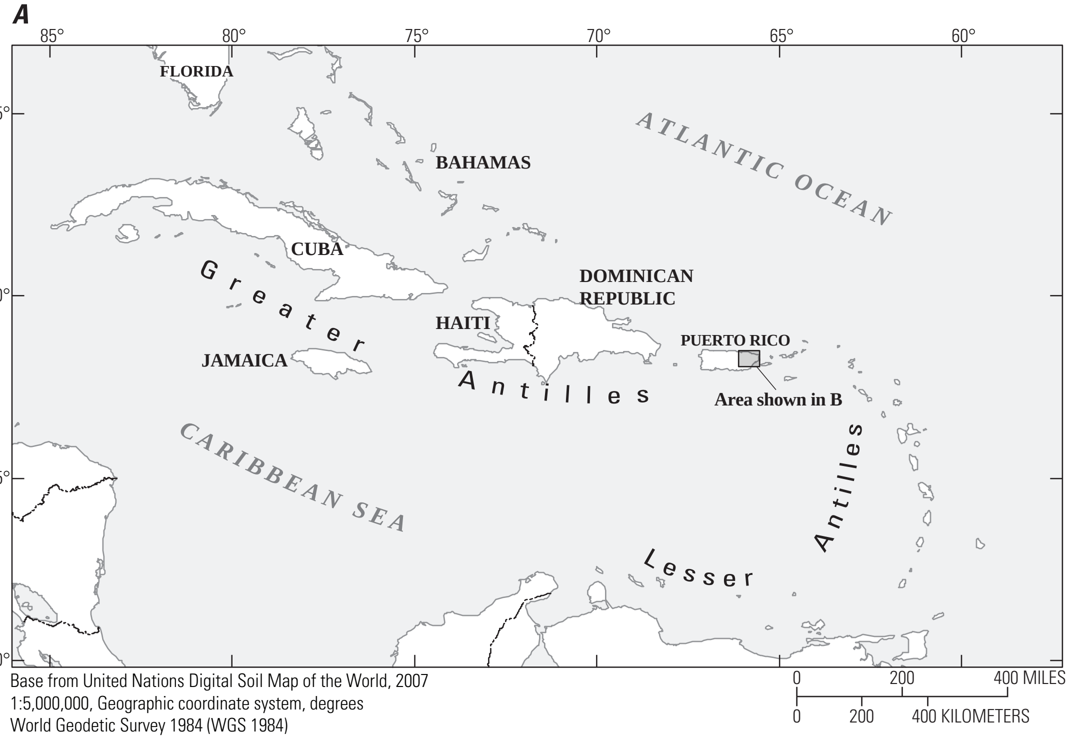
Abstract

Puerto Rico lies directly in the path of the easterly trade winds, which deliver steady rainfall to the mountains and steer tropical wave systems toward the island. Hurricanes and tropical storms derived from these tropical waves differ in frequency and intensity, contributing to substantial interannual variation in precipitation and stream discharge. Puerto Rico's steep topography and small water-storage capacity leave the island's water supply and developed flood plains vulnerable to extreme weather events, such as hurricanes, floods, and droughts. This vulnerability may increase in the future owing to ongoing change, both local (such as land-cover shifts, water-supply projects, and construction of roads and other infrastructure) and regional (climate variability and change). Climate change, which could lead to more intense and prolonged droughts as well as an increase in the magnitude and frequency of destructive storms in the Caribbean, may alter temperature and affect the availability of water for human and ecosystem needs. Accurate assessment of hydrologic regimes and water budgets is therefore crucial for effective management of water resources.

As part of the U.S. Geological Survey's Water, Energy, and Biogeochemical Budgets program, hydrologic and geomorphologic processes and stream chemistry of four small watersheds in eastern Puerto Rico, which differ in geology and land cover, have been studied since 1991. Spatial and temporal characteristics of precipitation and stream discharge, along with water budgets, were determined for the watersheds for the period 1991 to 2005. The locations of the watersheds relative to the Luquillo Mountains and the range's associated rain shadow dominate hydrological processes, dwarfing influences of land cover. The influence of geology is reflected in recession characteristics of the rivers (recession is faster in soils overlying volcaniclastic bedrock) and in hillslope geomorphic processes (sediment is delivered at higher rates from soils overlying granitic bedrock).

Introduction

Five field sites throughout the United States have been monitored since 1991 as part of the U.S. Geological Survey's (USGS) Water, Energy, and Biogeochemical Budgets (WEBB) program (Baedecker and Friedman, 2000). The WEBB site located in eastern Puerto Rico represents a montane, humid-tropical environment. The site consists of four small watersheds that are part of two important water-supply sources for the island: the Luquillo Mountains and the Río Grande de Loíza watershed (fig. 1). River segments within the Icacos and Mameyes watersheds are designated as wild and scenic rivers, which requires that they remain in an essentially primitive condition and free of impoundments (Ortiz-Zayas and Scatena, 2004; Interagency Wild and Scenic Rivers Council, 2008). The four watersheds have different geology and land cover. Two watersheds (Icacos and Cayaguás) are located on coarse-grained granitic rocks, and two (Mameyes and Canóvanas) are located on fine-grained volcanic and volcaniclastic rocks. For each bedrock type, one watershed is dominated by mature wet tropical forest (Icacos and Mameyes), and one watershed has been affected by agricultural land use (Canóvanas and Cayaguás). The four watersheds have been closely monitored since 1991 to evaluate the effects of geology, land cover, geomorphic processes, atmospheric deposition, and other factors on stream water quality and quantity. Geology and land cover are discussed in Murphy and others (2012), geomorphic processes in Larsen (2012), and water quality in Stallard and Murphy (2012). This chapter describes the climate and hydrology of these watersheds, assesses spatial and temporal characteristics of precipitation inputs and stream-discharge outputs, and assesses water budgets by using several methods. This analysis considers stream-discharge, precipitation, and evapotranspiration data, mainly from the USGS, the National Atmospheric and Oceanic Administration (NOAA), and the National Science Foundation-funded Long-Term Ecological Research Program (LTER) Program.



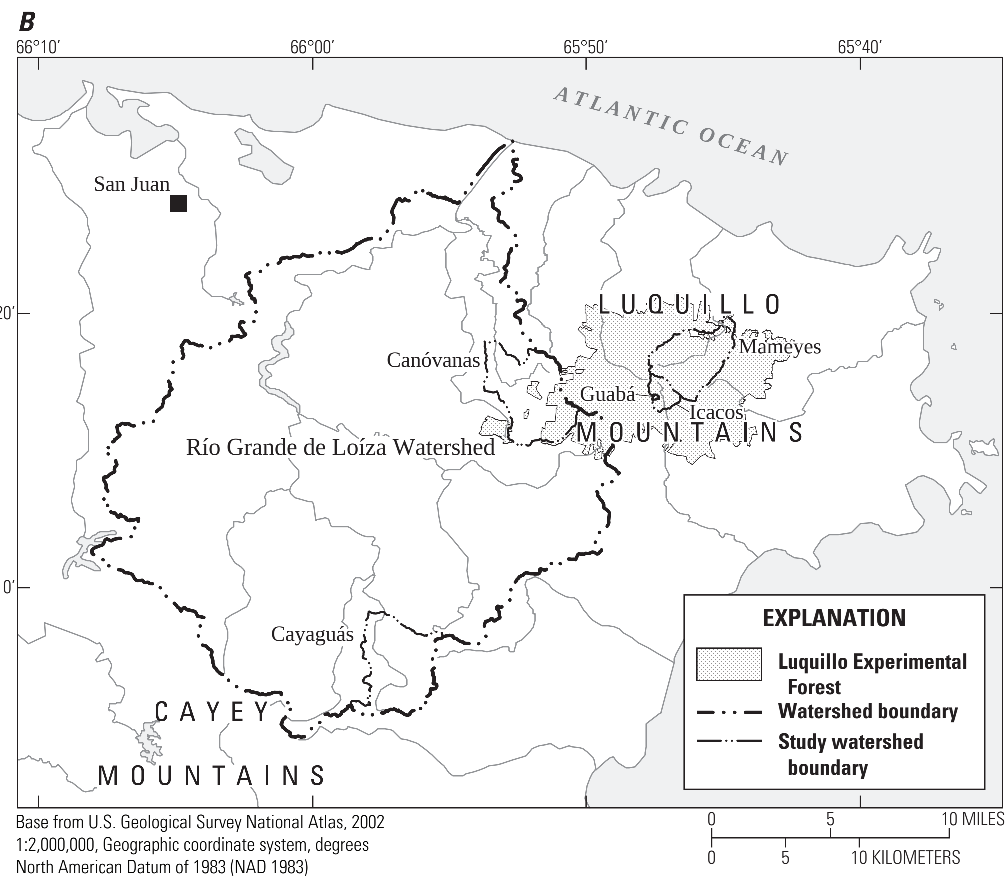


Figure 1. Location of Puerto Rico and study watersheds, eastern Puerto Rico.

Climate and Hydrology of Eastern Puerto Rico

The island of Puerto Rico has a humid tropical climate with a narrow range of daily temperature because of its location in the tropics and the buffering effect of the ocean (table 1). Weather is dominated by the easterly trade winds, which are predominantly from the east-northeast (Calvesbert, 1970). Hurricanes and other large storms embedded in the trade winds deliver about 70 percent of yearly rainfall; such storms affect the Caribbean about nine times a year on average (Calvesbert, 1970; Musk, 1988). Since 1851, 10 hurricanes have passed within 50 kilometers (km) of the Luquillo Mountains (fig. 2). During this study (in 1998), Hurricane Georges, the most destructive hurricane to strike Puerto Rico since San Ciprian in 1932, delivered more than 630 mm of rainfall in the central mountains and triggered extensive flooding and debris flows (Bennett and Mojica, 1998; Smith and others, 2005; Larsen and Webb, 2009). Cold fronts moving from North America into the Caribbean during winter months (December through April) can also cause major rainstorms that last for days; the amount of precipitation caused by these storms depends on the intensity and rate of progression of the cold front (Calvesbert, 1970). Such massive storms can mobilize sediment and debris into stream channels, cause sedimentation of reservoirs, and degrade coral reefs (Zack and Larsen, 1993; Webb and Soler-López, 1997; Warne and others, 2005; Larsen and Webb, 2009).

The path of trade winds over Puerto Rico's substantial topography (fig. 3) causes rainfall to vary greatly throughout the island (fig. 4). Pico del Este, on the southeastern side of the Luquillo Mountains (fig. 5) is the first summit crossed by the trade winds; orographic lifting produces frequent rain showers and the highest annual precipitation recorded in Puerto Rico. About 29 percent of precipitation at higher altitude in the mountains is from trade-wind–associated rainfall (Scholl and others, 2009). Precipitation on the eastern side of the Luquillo Mountains (and thus in the Mameyes and Icacos watersheds) is closely related to elevation: it ranges from 1,500 mm annually on the north coastal plain to almost 5,000 mm at high elevations (Brown and others, 1983). Precipitation on the western side of the Luquillo Mountains, including the Canóvanas watershed, is less well characterized; few data have been collected (table 2) and little work has been done there, except to note the existence of a rain shadow and that forests characteristic of drier conditions are found there (Ewel and Whitmore, 1973; Brown and others, 1983).

Stream valleys in Puerto Rico are narrow, short, and steep owing to the island's east-west-trending mountain chain (Cordillera Central) that divides a relatively narrow north-south dimension (fig. 3). Streams therefore respond rapidly to precipitation; Puerto Rico has the greatest threat of flash flooding of any state or territory under the jurisdiction of the U.S. National Weather Service (Carter, 1997). In order to mitigate flood peaks and to store this water for year-round use, several reservoirs have been constructed. The Loíza Reservoir, which receives water from the Cayaguás and Canóvanas watersheds (fig. 1), supplies about one third of the 11.9 cubic meters per second ($m^3 s^{-1}$) of water delivered to San Juan (population 421,958 in 2000) (U.S. Census Bureau, 2000; Quiñones, 2010). Water withdrawals in and around the Luquillo Experimental Forest provide about 2.2 $m^3 s^{-1}$ of potable water to Puerto Rico (Scatena and Johnson, 2001), which is about 7 percent of the 2010 island consumption of 31.8 $m^3 s^{-1}$ (Quiñones, 2010). In 1999, water extracted from the streams that drain the Luquillo Mountains was estimated to be worth about US$25 million per year in terms of the cost paid by consumers (Larsen and Stallard, 2000). Water shortages are a chronic problem in Puerto Rico. Reservoir storage is lost because of high sedimentation associated with storms (Webb and Soler-López, 1997). In the 20th century, major droughts affected the island in 1966–1968, 1971–1974, 1976–1977, and 1993–1995 (Larsen, 2000). During this study, the 1993–1995 drought led to severe water rationing for the city of San Juan; in response, residents collected water in open containers, which lead to outbreaks of dengue fever (Rigau-Pérez and others, 2001). Droughts may also contribute (through dryness or warming), along with atmospheric chemical changes, to Puerto Rico's ongoing amphibian die-off (Stallard, 2001; Burrowes and others, 2004; Longo and others, 2010). Because of strong orographic controls on the distribution of rainfall and the characteristic patchiness of convective rainfall in the tropics, the intensity of droughts in Puerto Rico can differ markedly in short distances (Larsen, 2000).

Table 1. Temperature statistics for 1991–2005 at meteorological stations in or near study watersheds, eastern Puerto Rico.

[From National Oceanic and Atmospheric Administration (2008), and U.S. Geological Survey Automated Data Processing System internal data, written commun. (2008). ID, identification number; Met, meteorological station; USGS, U.S. Geological Survey; NOAA, National Oceanic and Atmospheric Administration]

Station	Operator	Operator Station ID	Elevation (meters)	Mean daily temperature (degrees Celsius)	Mean minimum daily temperature (degrees Celsius)	Mean maximum daily temperature (degrees Celsius)	Dates excluded[1]
Bisley Met	USGS	50065549	482	22.8	21.2	25.5	1/1991–5/1991, 5/1998–2/2000
Icacos Met	USGS	50075001	600	21.4	19.1	25.3	1/1991–3/1992, 2/1997–2/1999, 3/2002–12/2005
Juncos 1SE	NOAA	665064	65	25.7	20.6	30.6	None
Pico Del Este	NOAA	666992	1,051	18.6	16.4	20.4	7/2005–12/2005

[1]Some dates excluded due to missing data or obvious errors; shorter time periods may also be excluded.

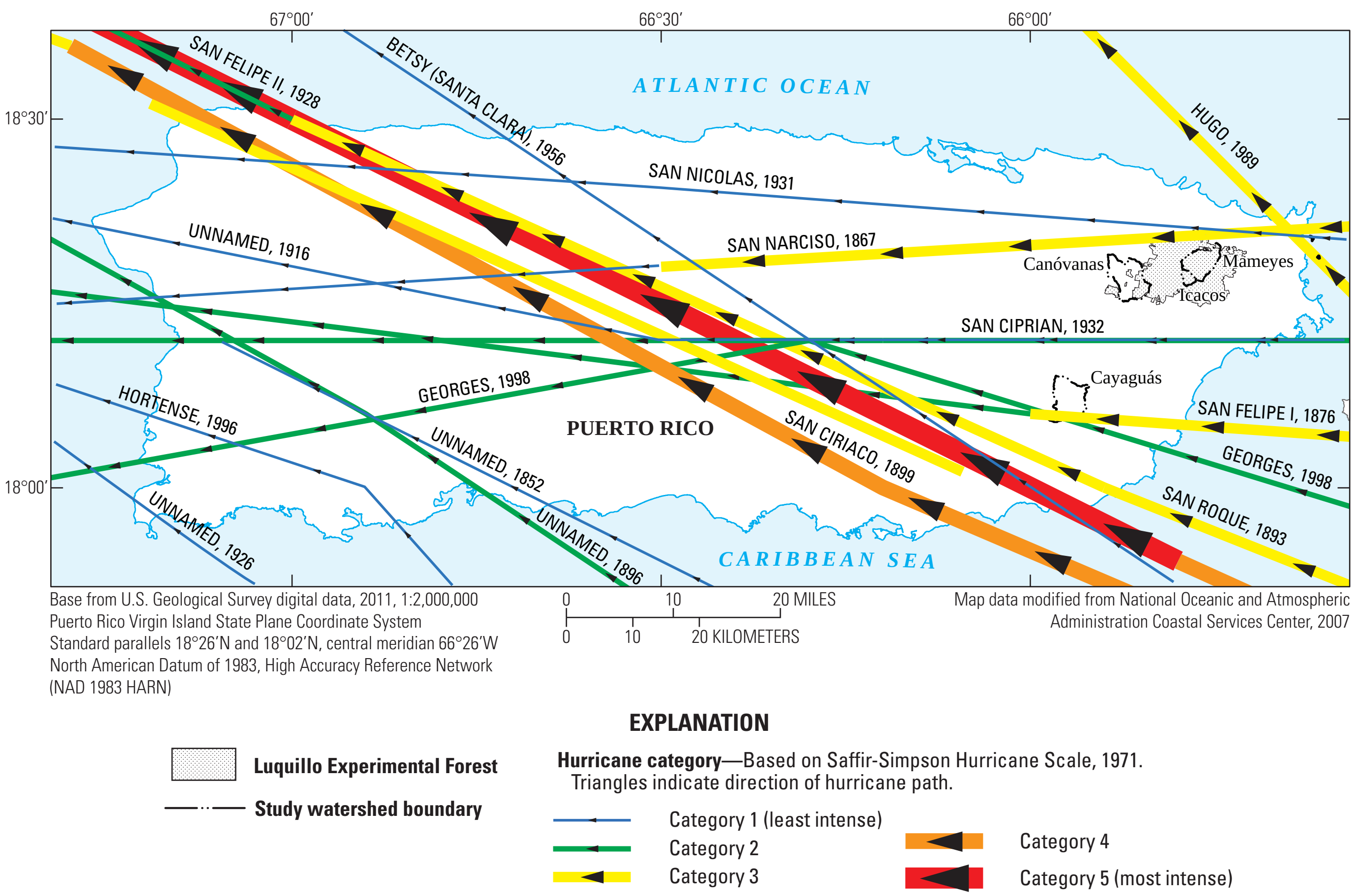


Figure 2. Hurricanes that have passed over or near Puerto Rico since 1850 (from National Oceanic and Atmospheric Administration Coastal Service Center, 2007).

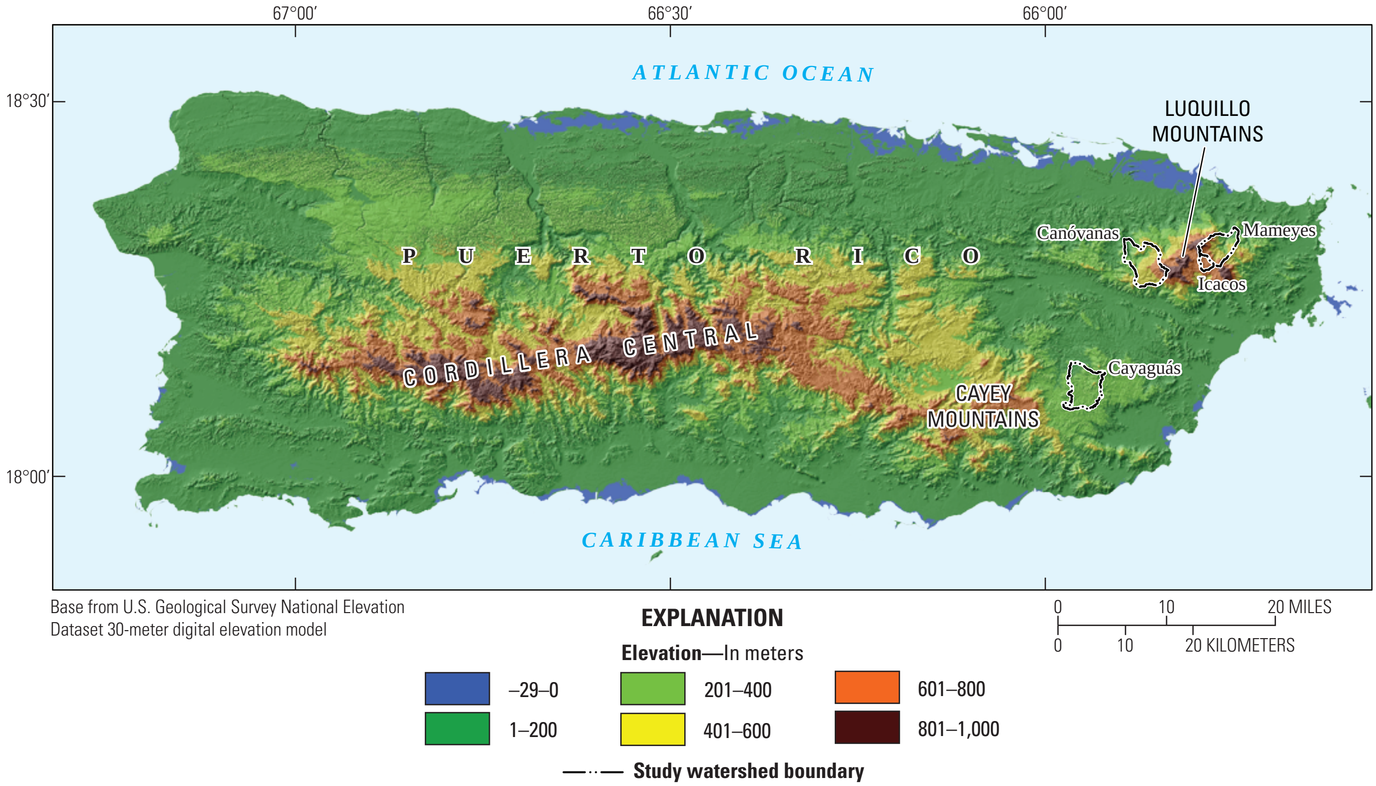


Figure 3. Elevation and relief of Puerto Rico.

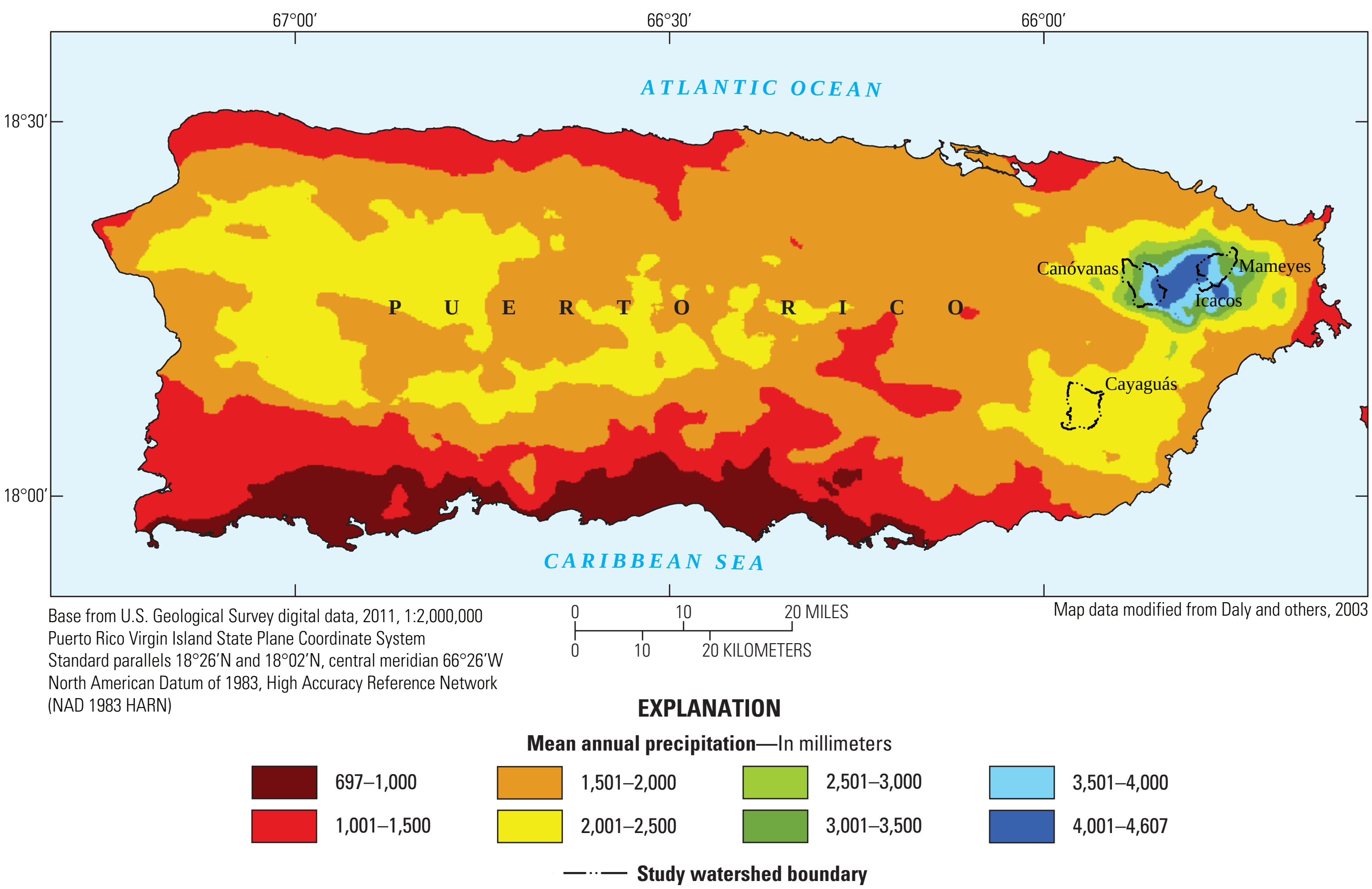


Figure 4. Mean annual precipitation of Puerto Rico, based on PRISM model for 1963 to 1995 (from Daly and others, 2003).

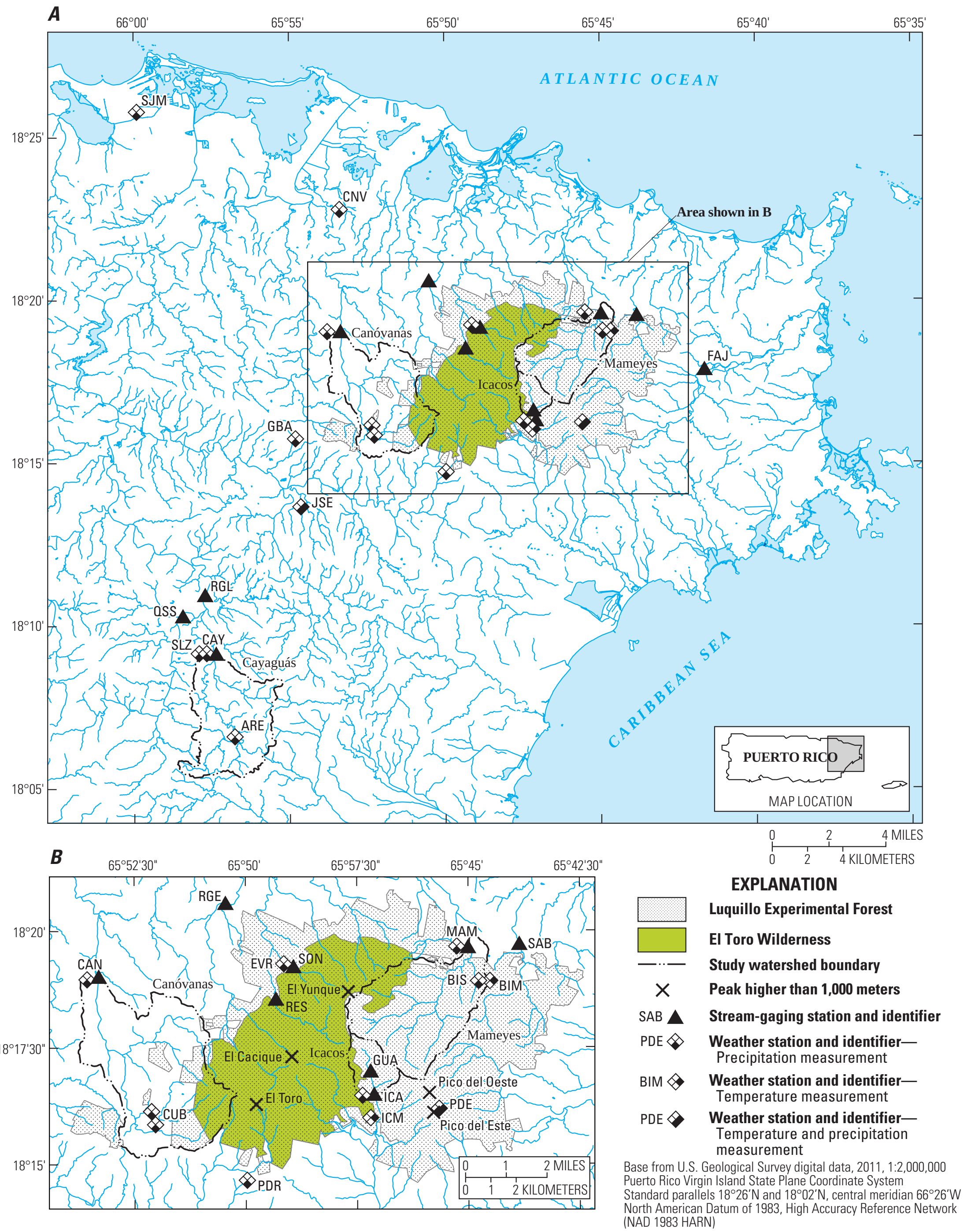


Figure 5. Location of stations, Luquillo Experimental Forest, and El Toro Wilderness (refer to table 2 for names of stations represented here by three initials; "CUB" was located at the southern site from 1986 to 1996 and at the northern site from 1996 to present).

Table 2. Stream-gaging and precipitation stations, eastern Puerto Rico.

[--, not available; m, meters; ID, identification code; USGS, U.S. Geological Survey; LTER, Long-Term Ecological Research; NOAA, National Oceanic and Atmospheric Administration; P, precipitation station; T, air temperature station; S, stream-gaging station]

ID	Station	Operator	Operator station ID	Elevation (m)	Type	Land cover[1]
ARE	Quebrada Arenas	USGS	50999960	270	P	Pasture, lowland wet forest
BIM	Bisley Meteorological Station	USGS	50065549	482	T	Tabonuco forest
BIS	Bisley Tower	LTER	--	360	P	Tabonuco forest
CAN	Río Canóvanas near Campo Rico	USGS	50061800	68	P, S	Pasture
CAY	Río Cayaguás at Cerro Gordo	USGS	50051310	150	P, S	Pasture, urban, moist forest
CNV	Canóvanas (NOAA)	NOAA	661590	9	P	Urban, wetlands
CUB	Cubuy	NOAA	663113	600[2]	P	Pasture, montane wet forest
EVR	El Verde	LTER	--	350	P	Tabonuco forest
FAJ	Río Fajardo near Fajardo	USGS	50071000	42	S	Lowland moist forest, pasture
GBA	Gurabo Abajo	USGS	50999959	285	P	Pasture, moist forest
GUA	Quebrada Guabá near Naguabo	USGS	50074950	640[3]	S	Colorado forest, palm forest
ICA	Río Icacos near Naguabo	USGS	50075000	616[4]	P, S	Colorado forest, palm forest
ICM	Icacos Meteorological Station	USGS	50075001	600	T	Tabonuco forest
JSE	Juncos 1SE	NOAA	665064	65	P, T	Urban, pasture
MAM	Río Mameyes near Sabana	USGS	50065500	84	P, S	Tabonuco forest
PDE	Pico del Este	NOAA	666992	1,051	P, T	Palm forest, colorado forest
PDR	Pueblito del Río	USGS	50999958	341	P	Pasture, moist forest
QSS	Quebrada Salvatierra near San Lorenzo	USGS	50051180	100	S	Pasture, moist forest
RES	Río Espíritu Santo near Río Grande	USGS	50063800	12	S	Tabonuco forest
RGE	Río Grande near El Verde	USGS	50064200	40	S	Moist forest, pasture
RGL	Río Grande de Loíza at Highway 183 near San Lorenzo	USGS	50051800	80	S	Pasture, urban, moist forest
RSS	Río Sabana at Sabana	USGS	50067000	80	S	Montane wet forest
SJM	San Juan LM Marin Airport	NOAA	668812	3	P	Urban
SLZ	San Lorenzo 3S	NOAA	668815	155	P	Pasture, urban
SON	Quebrada Sonadora near El Verde[5]	USGS	50063435	375	S	Tabonuco forest

[1]Gould and others, 2008.

[2]Located at 600 m from 1996 to 2005 (northern site, fig. 5), and at 500 m from 1991 to 1996 (southern site, fig. 5).

[3]Rain gage located at 648 m, but not included owing to potential underestimates (see Interpretive Approach section).

[4]Rain gage located at 643 m.

[5]Owing to large number of missing years during this study, precipitation data not used.

Climate Variability and Change

The climate of Puerto Rico is influenced by several global-scale climate patterns. The El Niño–Southern Oscillation (ENSO), which involves both ocean and atmospheric interactions, has an average recurrence interval of 3.8 years for El Niño episodes of moderate and greater intensity (Quinn and others, 1987). A negative Southern Oscillation Index, which corresponds with an El Niño episode, tends to be associated with warmer years and fewer tropical storms in Puerto Rico (Gray, 1984; Malmgren and others, 1998). The North Atlantic Oscillation, which is strictly atmospheric, is a slower and more irregular (8–10 years) climate fluctuation (Hurrell and others, 2003). A low North Atlantic Oscillation appears to force storms south towards the Caribbean (Elsner and others, 2000) and results in higher mean annual precipitation in Puerto Rico (Malmgren and others, 1998). The Atlantic Multidecadal Oscillation involves both the ocean and the atmosphere and is manifested as a 0.4°C fluctuation of North Atlantic sea-surface temperatures that lasts several decades (Kerr, 2000, 2005; Knight and others, 2006). Long-term records of tree rings (Gray and others, 2004) and African lake sediments (Shanahan and others, 2009) indicate that this oscillation has persisted for at least 3,000 years as strong, well-coupled oscillations in 30- to 50-year cycles. A high Atlantic Multidecadal Oscillation corresponds to a wet Sahel and to more frequent and intense hurricanes in the Atlantic Ocean (Landsea and Gray, 1992; Kerr, 2005; Knight and others, 2006). The effects of warming on hurricanes may be strictly physical (Knight and others, 2006); however, Sahel rainfall is best modeled with vegetative feedbacks acting on oscillation-induced temperature fluctuations, which produce both lags and amplifications (Zeng and others, 1999). Saharan dust appears to suppress hurricane formation (Dunion and Veldon, 2004), offering an alternative physical explanation of why wetter times in the Sahel (which generate less dust) might increase the formation or intensity of hurricanes. During the 15 years of this study, the Southern Oscillation Index, North Atlantic Oscillation, and Atlantic Multidecadal Oscillation indices varied widely (fig. 6). The Atlantic Multidecadal Oscillation, after several decades of predominantly negative values, reversed to positive values in 1995 and remained so for most of this study. The close relations between these indices and precipitation complicate the interpretation of long-term hydrologic trends, and they suggest that rigorous characterizations of precipitation or streamflow in the region will require many decades, particularly if the effects of climate change are being evaluated.

Assessing long-term climate change in Puerto Rico is difficult owing to the lack of robust climate proxies, such as tree rings or natural lakes, which would provide pollen records to assess past vegetation and hence climate. However, pollen from lake sediments in nearby Haiti provides clues to the climate of the region (Hodell and others, 1991; Higuera-Gundy and others, 1999). Pollen at the base of a lake core (estimated to be 10,000 years old) indicates cool, dry conditions. Xeric vegetation persisted until a forest expansion at about 7,000 years before present (BP). During the mid-Holocene (7,000 years to 3,500 years BP), lake levels were high and moist-forest vegetation was at its most abundant. Since 3,500 years BP, vegetation reflected ongoing drying conditions; many of the land mammals went extinct in this interval. Other circum-Caribbean sites show parallel trends (Higuera-Gundy and others, 1999). Historical data in Puerto Rico, such as the loss of water from springs and wells that had historically been used for water supply, corroborate ongoing drying for the last 500 years (Zack and Larsen, 1993; Scatena, 1998; Larsen, 2000); however, for these indicators of drying it would be difficult to entirely separate climate shifts from locally driven land-use changes, such as deforestation and soil compaction by grazing and agriculture.

Climate models produced by the Intergovernmental Panel on Climate Change (Christensen and others, 2007) have forecast that the trend of increasing dryness in Puerto Rico will continue. An increase in the frequency and severity of droughts, and changes in the temperature and humidity of the lower atmosphere, could lead to an increase in the altitude of the typical cloud base and the concomitant upward shift of ecological zones on mountains (Still and others, 1999; Lawton and others, 2001; van der Molen and others, 2006). This higher elevation of cloud base could help to decrease orographic precipitation, which provides about 30 percent of annual precipitation in the Luquillo Mountains (Scholl and others, 2009), and could reduce part of Puerto Rico's water supply. The intensity and number of large hurricanes in the Atlantic are predicted to increase this century (Emanuel, 2005), which could lead to greater loss of human life, infrastructure, and habitat as a result of mass wasting, flooding, and defoliation. Hurricane Hugo nearly decimated the population of the endangered Puerto Rican parrot (*Amazona vittata*), which had already been made vulnerable through decades of deforestation and the encroachment of nest-site competitors (Beissinger and others, 2008).

Relation of Land Cover to Climate and Hydrology

In less than 500 years, Puerto Rico was transformed from an island covered by about 95 percent forest (before European settlement) to about 6 percent forest in the 1950s (Wadsworth, 1950; Birdsey and Weaver, 1982; Kennaway and Helmer, 2007). A shift from an agricultural to an industrial economy, and a subsequent population migration from rural to urban areas, has led to a regrowth of forests; today, about half of the island is mature or secondary forest (Kennaway and Helmer, 2007; Gould and others, 2012). The reforestation of Puerto Rico, including two of the watersheds in this study (Canóvanas and Cayaguás), may affect local climate and hydrologic processes. Nonforested landscapes tend to have lower rates of evapotranspiration owing to the reduction of canopy interception and transpiration compared to forests (Lawton and others, 2001, and references therein), leading to an increase in annual runoff of typically 300 to 500 mm (Bruijnzeel, 2004; Jackson and others, 2005). Deforestation may also modify flood peaks (Bruijnzeel, 2004; Center for International Forestry Research, 2005; Bradshaw and others, 2007; Alila and others, 2009; van Dijk and others, 2009). Where soil and drainage patterns are not highly disturbed, increased runoff from deforestation infiltrates soil and may be manifested as increased base flow. When soil is compacted or additional drainage networks such as trails and roads are created, much of the increase is in near-surface or surface flow; storm peaks increase and streams rise and fall more quickly in response to storms. These changes may have a pronounced downstream effect only in watersheds less than 100 km^2 in area (Center for International Forestry Research, 2005).

Cloud Forest

One of the primary factors controlling vegetation type in the Luquillo Mountains is cloud-base elevation (Wadsworth, 1951; Ewel and Whitmore, 1973; Brown and others, 1983). The highest peaks in the Luquillo Mountains are often shrouded in clouds, which typically form when trade winds force air upslope (Roe, 2005). The elevation of the cloud base is related to the trade-wind boundary layer, a zone of turbulently mixed air below the base of trade-wind cumulus clouds. Over the oceans, complex feedbacks associated with moisture transport (cloud growth and rain) driven by shallow-cumulus convection, control the elevation of the trade-wind boundary layer and the rate of sea-surface evaporation (Rauber and others, 2007). Accordingly, the elevation of the cloud base is largely controlled by sea-surface conditions, but its altitude is susceptible to changes in regional climate, sea-surface temperature, and land cover. The cloud base over the ocean region to the east of Puerto Rico is typically around 600 meters (m), but it can be as low as 400 m (Snodgrass and others, 2009, and references therein). In the Luquillo Mountains, the cloud condensation level is typically between 600 and 800 m (Eugster and others, 2006), and the cloud base moves up during the day and down at night. We do not have a precise description of this

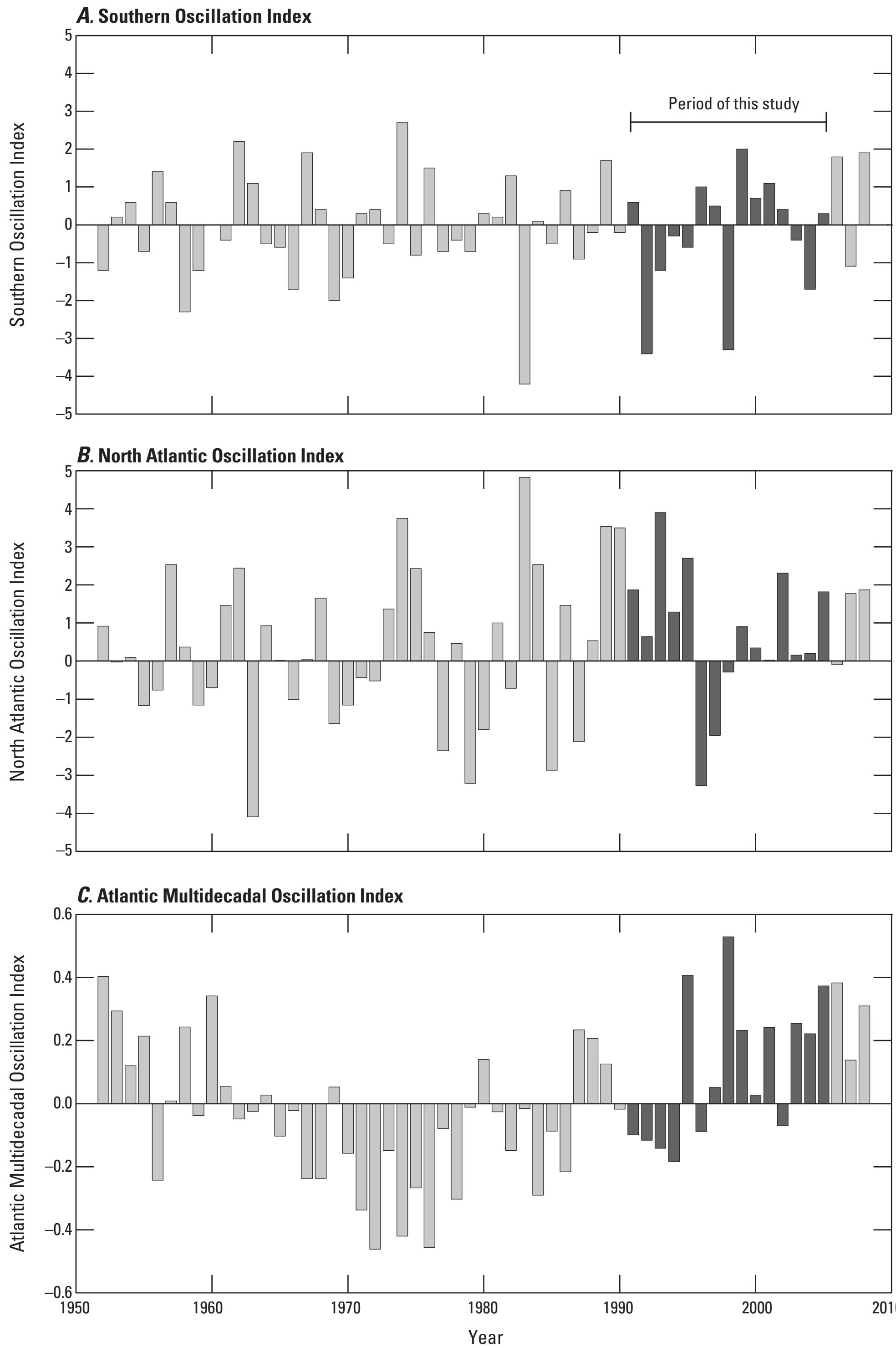


Figure 6. Indices of oscillations that affected Puerto Rico, 1950–2010 (National Oceanic and Atmospheric Administration, 2010).

cycle, but we have observed that as the day progresses, cloud base rises tens of meters above the low divide between the Mameyes and Icacos watersheds (at about 750-m elevation). Cloud forest vegetation (colorado forest, mixed palm forest, elfin cloud forest, and montane shrublands) grows above about 600 m and is adapted to high humidity, droplet deposition, reduced transpiration, and low-light conditions (Murphy and others, 2012).

Conversely, land cover can influence the altitude of the cloud base, and even the presence or absence of trade-wind cumuli, in eastern Puerto Rico. Trade wind velocities in the region are typically 1 to 5 meters per second ($m\ s^{-1}$) (Lawton and others, 2001), and the Luquillo Mountains are less than 20 km from the coast, so air from the ocean has about 1 to 5 hours to interact with land before reaching the mountain summits. At these time scales, terrestrial heating and evapotranspiration may decrease or increase precipitation, depending on land cover. For example, the defoliation of much of the east flank of the Luquillo Mountains by Hurricane Hugo in 1989 was associated with an observable increase in the altitude of the cloud base (Scatena and Larsen, 1991).

Interpretive Approach

Hydrology in the Luquillo Experimental Forest, which contains the Mameyes and Icacos watersheds, has been studied by many researchers (including Lugo, 1986; McDowell and others, 1992; Scatena, 1995, 2001; García-Martinó and others, 1996; Larsen and Concepción, 1998; Pringle, 2000; Schellekens and others, 2000, 2004; Scatena and Johnson, 2001; Rivera-Ramírez and others, 2002; Ortiz-Zayas and Scatena, 2004; Peters and others, 2006; Crook and others, 2007; and many others). Much less work has been done on the hydrology of the Cayaguás and Canóvanas watersheds (Larsen and Concepción, 1998; Larsen and Simon, 1993). Our analysis of precipitation, discharge, and evapotranspiration data in eastern Puerto Rico for the period 1991 to 2005 had three objectives: (1) comparison of the spatial and temporal characteristics of precipitation inputs and stream-discharge outputs for the four WEBB watersheds, (2) determination of water budgets, and (3) hydrologic interpretation to allow accurate assessments of weathering rates and fluxes of dissolved constituents and sediment (Larsen, 2012; Stallard, 2012; Stallard and Murphy, 2012).

Precipitation

Precipitation in eastern Puerto Rico shows wide spatial variation related to elevation, topographic position, and proximity to the ocean (fig. 4). Therefore, the density of precipitation stations in the region (fig. 5) is not ideal for estimating precipitation at the local scale. The Canóvanas watershed is particularly challenging, owing to its wide range in elevation (70 to 960 m) and the sparcity of precipitation stations in and near the watershed. Three methods were used to estimate mean annual precipitation in the study watersheds: (1) the relation between elevation and precipitation; (2) a spatially based model of precipitation in Puerto Rico (Daly and others, 2003; and (3) reported evapotranspiration and precipitation data for land-cover types within each watershed. Land-cover-based estimates of water budgets have numerous methodological difficulties, but because of earlier deforestation and recent afforestation, they are used here as a guide to the potential effects of the ongoing afforestation in the Canóvanas and Cayaguás watersheds.

Daily precipitation data from NOAA (National Oceanic and Atmospheric Administration, 2008), the USGS (Automated Data Processing System internal data, written commun., 2008), and the Luquillo LTER program (Long Term Ecological Research Network, 2008) for stations in and near the watersheds were summed to obtain annual precipitation during the study period (1991–2005). Hourly data from the NOAA cooperator station Cubuy, within the Canóvanas watershed (CUB, fig. 5), were summed to obtain daily and annual precipitation in order to improve spatial coverage (data for this station are reported only on days when precipitation is recorded). Annual precipitation data for the LTER Bisley Tower station (BIS, fig. 5) were obtained from Heartsill-Scaley and others (2007) and from F.N. Scatena, University of Pennsylvania (written commun., 2009). Mean annual precipitation during the study period was then calculated for each station.

In or near the Icacos and Mameyes watersheds, precipitation stations included in this analysis are located at the stream-gaging stations at the mouth of each watershed (ICA and MAM), within the Mameyes watershed at the LTER Bisley Tower (BIS), and at two stations located within 4 km of the watershed boundaries (EVR and PDE) (table 2, fig. 5). Precipitation data from the USGS Guabá stream-gaging station and the USGS Bisley and Icacos meteorological stations were not included because we believe that these stations underreport precipitation. Mean annual precipitation values were anomalously low for their elevations, and precipitation at the USGS Bisley station was much lower than at the nearby LTER Bisley Tower station. The USGS Bisley station is located at the top of a ridge that is exposed to high winds; precipitation has been observed to fall at 45 degree angles and not enter the gage (Angel Torres-Sánchez, USGS, oral commun., 2008). The Guabá station is located along a narrow road and is overshadowed by forest canopy, which probably prevents some precipitation from reaching the station.

In or near the Canóvanas watershed, precipitation stations included in this analysis are located at the stream-gaging station at the mouth of the watershed (CAN), within the watershed (CUB), and at three stations located between 2 and 5 km from the watershed boundary (GBA, JSE, and PDR) (table 2, fig. 5). Precipitation stations located within or near the Cayaguás watershed included in this analysis are located within the watershed (ARE), and at or near the mouth of the watershed (CAY and SLZ).

We also evaluated variable-time-step precipitation data from USGS stations at the mouth of each of the four studied watersheds to evaluate storm duration and maximum precipitation events. These data were obtained internally from the USGS (on file at the Caribbean Water Science Center, Guaynabo, Puerto Rico) and converted to 15-minute and 1-hour intervals. Missing data were interpolated.

In order to evaluate the effect of climate variability on precipitation and runoff in eastern Puerto Rico, the relations of three climate indices (El Niño–Southern Oscillation, North Atlantic Oscillation, and Atlantic Multidecadal Oscillation) with precipitation and runoff were evaluated with a least-squares linear regression. The NOAA precipitation stations Pico del Este (PDE) and Canóvanas (CNV, which is in a different location than the USGS stream-gaging station of the same name; table 2, fig. 5) have the longest records in eastern Puerto Rico and were thus used in this assessment. Only one stream-gaging station in eastern Puerto Rico, on the Río Fajardo (station 50071000, Río Fajardo near Fajardo; FAJ on fig. 5), has a discharge record adequately long to compare with multidecade climate indices. In order to assess how much variance in annual precipitation in eastern Puerto Rico can be accounted for by regional-scale climate events, a simple linear regression was performed to determine how well precipitation at each station can be predicted by precipitation at nearby stations.

Regression Model of Precipitation Based on Elevation

Elevation and precipitation have been found to be closely related in the Luquillo Experimental Forest, on the basis of stations located on the northern and eastern side of the Luquillo Mountains (Brown and others, 1983; García-Martino and others, 1996). Following García-Martino and others' (1996) evaluation of 18 stations, a simple polynomial regression of elevation (in meters) and mean annual precipitation (in millimeters) was developed by using the Pico del Este, Icacos, Mameyes, LTER Bisley Tower, and El Verde stations for the study period. The equation

$$\text{Mean annual precipitation} = 2{,}177.7 + 4.498 \bullet \text{elevation} - 0.0023 \bullet (\text{elevation})^2 \quad (1)$$

is very similar to that of García-Martino and others (1996) ($2{,}301.21 + 3.8 \bullet \text{elevation} - 0.0016 \bullet (\text{elevation}^2)$). For the WEBB watersheds on the eastern side of the Luquillo Mountains (Icacos and Mameyes), we used equation 1 to estimate precipitation at the midpoint elevation of 50-m contour intervals (determined for each watershed by using a geographic information system, *http://www.esri.com/*), multiplied precipitation at each interval by the fraction of watershed within that interval, and summed to obtain total precipitation. Owing to the lack of precipitation data on the western side of the Luquillo Mountains, the extent of the rain shadow they cause is not well known; stations west of the Luquillo Experimental Forest (fig. 5) do not have the close relation of elevation and precipitation. To accommodate for rain-shadow effects in the Canóvanas and Cayaguás watersheds, we corrected equation 1 as follows. For each watershed (the two watersheds were handled separately, because we assumed different rain-shadow effects), we calculated the rainfall that would be expected for each nearby precipitation station on the basis of equation 1. Observed and predicted precipitation at nearby stations were each averaged, and the ratio of observed to predicted was used to calculate a "rain shadow correction" —one for the Canóvanas watershed (0.560), and one for the Cayaguás (0.721). We multiplied the precipitation estimated by equation 1 at 50-m contour elevation midpoints by the correction factor for each watershed, and then we estimated total precipitation in each watershed by weighting for elevation.

Spatially Based Precipitation Model

A spatially based model of precipitation was also used to estimate precipitation in the watersheds. The PRISM (parameter-elevation regressions independent slopes model) mean annual precipitation dataset (Daly and others, 2003) incorporates point data, a digital elevation model, and other geographic data sets to generate gridded estimates of precipitation (fig. 4) and other climatic parameters. These data were overlain with the four watershed boundaries using geographic information systems to estimate mean precipitation in the watersheds.

Precipitation Based on Land Cover

Published mean annual precipitation values for land-cover types present in the four studied watersheds were averaged to obtain mean annual precipitation for each land-cover type (table 3). The mean annual precipitation for each land cover was then multiplied by the percentage of land cover in each watershed (see Murphy and others, 2012, their table 4), and these values were summed to obtain the mean annual precipitation for each watershed. Precipitation data have not been reported for secondary montane wet forest and montane wet shrubland or woodland, so these land-cover types were assigned mean annual precipitation of the most similar land-cover type, tabonuco forest. Because urban land, barren land, and water totaled less than 7 percent of the area in each watershed and they were typically located next to pasture (Murphy and others, 2012, their fig. 9), mean annual precipitation for pasture was used for these land-cover types.

Cloud Drip

Direct deposition of water from clouds onto vegetation is an important, but difficult to quantify, ecological and hydrological phenomenon in higher tropical mountains. Researchers have estimated that cloud drip contributes an additional

Table 3. Precipitation and evapotranspiration rates reported in literature, eastern Puerto Rico.

[Mean values rounded to three significant figures. km, kilometers; m, meters; mm yr^{-1}, millimeters per year; P, precipitation; ET, evapotranspiration; --, used value from previous study (see P method); LEF, Luquillo Experimental Forest]

Study	Region	Land cover	Elevation (m)	Annual P (mm yr^{-1})	Annual ET (mm yr^{-1})	P method	ET method
Pasture							
Van der Molen, 2002	15 km west of San Juan	Pasture (*Paspalum*)	2	1,700	1,383	Climate station data	Penman-Monteith method
Van der Molen, 2002	Fajardo airport	Grassland	30	1,625	1,011	Climate station data	Penman-Monteith method
Mean				1,660	1,200		
Lowland moist forest							
Ewel and Whitmore, 1973	San Juan airport	Subtropical moist forest	4	1,632	1,341	Climate station data	Tosi method (Ewel and others, 1968)
Van der Molen, 2002	15 km west of San Juan	Lowland wetland forest[1]	2	1,700	1,219	Climate station data	Penman-Monteith method
Mean				1,670	1,280		
Tabonuco							
Odum, Moore, and Burns, 1970	Espíritu Santo watershed (within LEF)	Tabonuco	424	3,869	1,558[2]	Measured	Field experiments (throughfall, stemflow, transpiration)
García-Martino and others, 1996	LEF	Tabonuco	402[3]	3,537	1,707	Precipitation-elevation regression	Water budget
Schellekens and others, 2000	Bisley (within Mameyes)	Tabonuco	265–456	3,584[2]	1,093[2]	Measured	Penman-Monteith and temperature fluctuation methods
Van der Molen, 2002	LEF	Tabonuco	356	--	1,066	García-Martino and others (1996)	Penman-Monteith method
Wu and others, 2006	LEF	Tabonuco	<600	--	1,252	Garcia-Martino and others (1996)	Satellite imagery and model[4]
Mean				3,660	1,340		
Colorado							
García-Martino and others, 1996	LEF	Colorado	720[3]	4,191	994	Precipitation-elevation regression	Water budget
Van der Molen, 2002	LEF	Colorado	780	--	1,044	García-Martino and others (1996)	Penman-Monteith method
Wu and others, 2006	LEF	Colorado	600–900	--	1,069	García-Martino and others (1996)	Satellite imagery and model[4]
Mean				4,190	1,040		
Palm							
Frangi and Lugo, 1985	Espíritu Santo watershed (within LEF)	Palm	750	3,725	831	Measured	Field experiment (throughfall, stemflow, transpiration)
García-Martino and others, 1996	LEF	Palm	711[3]	4,167	1,009	Precipitation-elevation regression	Water budget
Van der Molen, 2002	LEF	Palm	900	--	694	García-Martino and others (1996)	Penman-Monteith method
Wu and others, 2006	LEF	Palm	600–900	--	1,051	García-Martino and others (1996)	Satellite imagery and model[4]
Mean				4,020	900		
Elfin							
García-Martino and others, 1996	LEF	Elfin	897[3]	4,408[5]	1,144	Precipitation-elevation regression	Water budget
Van der Molen, 2002	LEF	Short cloud forest	>900	--	704	García-Martino and others (1996)	Penman-Monteith method
Wu and others, 2006	LEF	Elfin	>900	--	591	García-Martino and others (1996)	Satellite imagery and model[4]
Mean				4,410	810		

[1]*Pterocarpus officinalis*.

[2]Average of two values.

[3]Weighted average elevation of forest type in Luquillo Experimental Forest.

[4]Granger and Gray (1989).

[5]Does not include 10 percent addition for cloud moisture reported in García-Martino and others (1996).

6.6 to 18 percent to measured rainfall in the eastern Luquillo Mountains (Baynton, 1969; Weaver, 1972; Schellekens and others, 1998; Holwerda and others, 2006). Holwerda and others (2006) estimated annual cloud drip at 1,010-m elevation on Pico del Este to be 770 millimeters per year (mm yr^{-1}) by using a water budget method and 785 mm yr^{-1} by using the eddy-covariance method (which was corrected by using the water budget method). We estimated cloud drip at different elevations in the Icacos and Mameyes watersheds by interpolation, assigning a rate of zero mm yr^{-1} at 600 m, and Holwerda's water budget rate of 770 mm yr^{-1} at 1,000 m. To simplify the calculation we assigned interpolated values to 50-m elevation zones: 600 to 650 m, 650 to 700 m, and so on. We then calculated the percentage of each watershed in the 50-m elevation zones, estimated the total cloud drip from each elevation zone, and summed to estimate total cloud drip contribution for the Icacos and Mameyes watersheds.

It is uncertain to what degree cloud drip in a watershed is affected by the rain shadow west of the Luquillo Mountains. Leeward sites on Pico del Este receive about 60 percent less cloud drip than windward sites (Weaver, 1972), similar to the ratio of observed to predicted rainfall (0.560) that was used to calculate a correction for rainfall in the Canóvanas watershed. We therefore calculated the amount of cloud drip in the Canóvanas watershed by the same method as we used for the Icacos and Mameyes watersheds, then multiplied that amount by 0.560 to correct for this watershed's leeward location. The maximum elevation of the Cayaguás watershed is 445 m (Murphy and others, 2012, their table 1), below the cloud condensation level in eastern Puerto Rico, and therefore this watershed is assumed to not receive any cloud drip.

Runoff

Instantaneous discharge data were obtained internally for the five USGS WEBB stream-gaging stations: four located at the mouths of the studied watersheds (CAN, CAY, ICA, and MAM), plus one station within the Icacos watershed that is near the mouth of the Quebrada Guabá watershed (GUA) (table 2, fig. 5) (U.S. Geological Survey, 2010). The Icacos, Guabá, Cayaguás, and Canóvanas stations typically record discharge every 15 minutes; discharge at the Mameyes station is typically recorded every 5 minutes. All stream gages had gaps in discharge data during the study period, ranging from 30 minutes to more than a year. The longest data gaps were generally associated with the time needed to rebuild a gage lost in a large storm. For data gaps of less than 1 day, real-time discharge values were linearly interpolated from adjacent data. For all longer data gaps, discharge data were interpolated from daily-mean-discharge data using cubic splines on cumulative daily discharge (appendix 1). The Canóvanas and Guabá stream-gaging stations had especially long data gaps in 1991 and 1992. Discharge data from the Guabá stream-gaging station (activated in June 1992) are considered dubious after April 2003, when a large storm severely altered the Guabá stream channel. Available daily mean-discharge values for the Canóvanas and Guabá stream-gaging stations correlate well with discharge at the Cayaguás and Icacos stream-gaging stations, respectively, so linear regressions (Helsel and Hirsch, 2002) were used to estimate discharge for the missing data. Corrections to discharge data for the Icacos stream-gaging station caused by a gradual datum shift from 1973 to 1993 (recognized in 2003) were also included in this analysis (appendix 1).

Discharge from each watershed was converted to runoff by dividing by drainage area. The drainage area of the Guabá stream-gaging station has been previously reported as 0.13 or 0.31 km^2, and reported runoff was based on those drainage areas (U.S. Geological Survey, 1994–2006). We estimate a drainage area of 0.115 km^2, on the basis of walking the drainage divide, recording the route with a global positioning system, and confirming the route by using satellite imagery. Calendar-year annual runoff values are reported for the study period (1991–2005) and were used to calculate mean annual runoff for that period.

Annual runoff values for the periods of record for the WEBB stream-gaging stations, along with those from the nearby Río Fajardo stream-gaging station (which has the longest runoff record in eastern Puerto Rico; fig. 5) were evaluated for statistical properties and variability. Annual runoff for every year was normalized to the geometric mean of annual runoff (normalized runoff=raw runoff/geometric mean) for the period of record for each river (based on the assumption that the processes that drive the variance around the geometric means of annual runoff behave similarly in the watersheds). The resulting normalized mean for each river was thus zero; this mean, along with the standard deviation of the log-runoff data, was used to calculate the lowest 1 percent of annual runoff (a one-in-one-hundred-years dry year) and the highest 1 percent (a one-in-one-hundred-years wet year). Annual runoff for all watersheds was aggregated into one dataset, and the variance of the aggregated data was evaluated. Also, a simple linear regression was used to test how well annual runoff for each WEBB river can be predicted by annual runoff in nearby rivers (Helsel and Hirsch, 2002).

Flow duration, maximum runoff events, and recession characteristics were evaluated from corrected 15-minute and hourly runoff data at the five USGS WEBB stream-gaging stations (CAN, CAY, GUA, ICA, and MAM, table 2). Runoff-rate percentile classes, which are based on the amount of time a river is within a given runoff range, were developed using an approach similar to that used by USGS WaterWatch (U.S. Geological Survey, 2009). The runoff rates in each percentile class for each river were calculated using all real-time runoff measurements during the 15-year study period.

Base-flow recession curves were assessed for the five USGS WEBB stream-gaging stations. Periods with monotonically decreasing runoff were identified from smoothed 5- or 15-minute measurements recorded at stream-gaging stations and from daily average data (appendix 1) and confirmed by a lack of precipitation at nearby rain gages. A rise in discharge indicated a new storm and signaled the end of each recession. Following standard practice, the first 2 days of each recession were excluded to eliminate the influence of shallow-soil flow paths. We used observed discharge at 24-hour intervals rather than mean daily discharge and started data tabulation from the end of the recession and worked backward to minimize the lag period.

Mathematical formulations of base-flow recession curves can be empirical or based on reservoir models. The simplest recession model, and the only valid model for recessions of less than 10 days, is a linear (short for log-linear) recession (Chapman, 1999):

$$Q_t = Q_0 \bullet e^{-t/\tau} = Q_0 \bullet k^t, \quad (2)$$

where Q is discharge (in our calculations, we used runoff, $R=Q$/area, to compare watersheds of different drainage areas), Q_0 is discharge at the beginning of the recession, t is time (t=0 at the start of recession), τ is the turnover time, and k is the recession constant. A large k value indicates slow drainage (and greater storage), whereas a smaller k value indicates rapid drainage (and little storage). If many distinct groundwater reservoirs exist, a nonlinear model may be required (Chapman, 1999).

Assuming a simple aquifer with linear response, storage, S, is given by

$$S_t = Q_t \bullet \tau = Q_t / \ln(k). \quad (3)$$

Rivera-Ramírez and others (2002) examined recessions in the Río Fajardo and Río Espíritu Santo, in eastern Puerto Rico, using a variety of graphical and statistical approaches, and concluded that two regression approaches developed by Vogel and Kroll (1996) for interpreting the linear recession were the most robust. These approaches treat consecutive pairs of discharge measurements as either an integrated-moving-average (IMA) process or as a simple autoregressive (AR(1)) process, both of which have straightforward least-squares solutions for k. We evaluated recessions using these two approaches. We divided the predicted runoff rate at the end of recessions by the observed rate and calculated a margin of error at 95 percent confidence for this ratio for all modeled recessions. We also calculated the length of time needed to recede from the 10-percent runoff-rate percentile to the 1-percent runoff-rate percentile, and from the 1-percent runoff-rate percentile to the minimum runoff recorded at each river during the study period.

Groundwater and Storage

The four studied watersheds are underlain primarily by granitic, volcanic, and densely cemented volcaniclastic rocks (Murphy and others, 2012) that are typically not noted for being highly permeable. Springs are not common in the watersheds. Limestones are rare, and karst topography is nonexistent. Eastern Puerto Rico streams respond quickly to precipitation; recession curves suggest that little water remains in storage (Rivera-Ramírez and others, 2002). Groundwater in storage in these upland watersheds is not well characterized but is sufficient to maintain flow in rivers that drain the studied watersheds, even during the driest periods. In general, base flow represents groundwater drainage, and we posit our assessment of groundwater storage on this assumption. Hall (1968) presents numerous mathematical formulations of base-flow recession curves; some are based on reservoir models and others are empirical. The recession curves discussed in the previous section were used to estimate base flow, and hence groundwater storage (as an average depth throughout the area of the watershed, or linear storage) for the 1-percent runoff-rate percentile, S_I (subscript $_I$ refers to the IMA recession model), and for the minimum observed runoff rate, S_A (subscript $_A$ refers to the AR(1) recession model). We used the effective water column needed to support the 1-percent runoff-rate to estimate and compare groundwater storage in the watersheds and for estimating errors in this intercomparison.

Water-Supply Inputs and Outputs

Comprehensive reviews of water intakes in the Luquillo Experimental Forest are available from Larsen and Concepción (1998) and Crook and others (2007, 2009). Thirty-one water intakes withdraw water from rivers draining this forest, including six that were added between 1994 and 2004. Few of these intakes are upstream of the USGS stream-gaging station evaluated here. There are no intakes in the Icacos watershed. U.S. Department of Agriculture Forest Service facilities withdraw less than 4 mm annually from the Mameyes watershed, and much of this water remains within the watershed (Larsen and Concepción, 1998). Documented public supply withdrawals are few in the Canóvanas and Cayaguás watersheds and total about 46 and 3 mm annually, respectively (Larsen and Concepción, 1998; Crook and others, 2007). Not only are these withdrawals small, but in order to be used to correct a water budget, the water must cross a drainage divide and bypass the watershed outlet, which is unlikely for these watersheds. Larsen and Concepción (1998) estimate that 78 percent and 89 percent of households in the Canóvanas and Cayaguás watersheds, respectively, have septic systems; using U.S. Census data and mean water consumption rates, they estimated that septic systems contribute about 10 and 5 mm to these watersheds.

Evapotranspiration

Evapotranspiration (ET) consists of several distinct sources: evaporation from the soil surface (E_S), evaporation from wet canopy (E_C), and transpiration (T), which is the transfer of water through plant stomata during photosynthesis:

$$ET = E_S + E_C + T. \quad (4)$$

All of these sources can be difficult to quantify. Some workers have calculated potential ET, or maximum ET under conditions of unlimited moisture supply, in the Luquillo Experimental Forest (Schellekens and others, 2000; Van der Molen, 2002; Wang and others, 2003) (table 3). This equation can be used to estimate wind-caused evaporation (which is essentially zero with either no wind or 100 percent humidity) and solar-radiation-driven evaporation (which is zero in darkness and reduced under low light) (Monteith, 1965; Howell and Evett, 2004). Other workers have also estimated ET in this forest with field experiments (Odum, Moore, and Burns, 1970; Frangi and Lugo, 1985), water budgets (García-Martino and others, 1996; Larsen and Concepción, 1998; Crook and others, 2007), and hydrologic models combined with satellite imagery (Wu and others, 2006) (table 3). These studies describe ET rates that generally decrease with increasing elevation in the forest. Reported ET rates are highest in the tabonuco forest (elevations below 600 m; table 3); ET in lowland rainforest, such as the tabonuco forest, is driven predominantly by solar radiation (Dietrich and others, 1982). ET is lowest in the elfin forest (elevations over 900 m), where frequent clouds and humidity near 100 percent for much of the time reduce ET substantially.

Few studies of ET have been undertaken in eastern Puerto Rico in the two major land covers in the Cayaguás and Canóvanas watersheds, pasture and lowland moist forest (Lugo, 1986; van der Molen, 2002). These studies typically suggest higher rates of ET in pasture and lowland moist forest than in the other forest types, with the exception of tabonuco forest. Nonforested landscapes tend to have lower rates of ET than forested watersheds, owing to the reduction of canopy interception (Lawton and others, 2001, and references therein). One study in Puerto Rico, however, had opposite results: van der Molen and others (2006) found grasslands to be cooler and more humid than nearby forest. However, this study compared an unusually wet grassland to a coastal monodominant forest type, a *Pterocarpus* swamp forest (Ewel and Whitmore, 1973). Water in the *Pterocarpus* swamp is brackish and soils are presumably anoxic; both characteristics would reduce ET, leading to both less cooling and drier conditions.

Evapotranspiration estimates for different land-cover types (table 3) were averaged to obtain mean ET values for each land-cover type in each watershed. The mean ET for each land cover was multiplied by the percentage of land cover in each watershed; these values were summed to obtain the mean ET for each watershed.

Evapotranspiration was also estimated from water budgets by subtracting watershed outputs from inputs:

$$ET = P + D + S - R - W - G, \quad (5)$$

where P is precipitation, D is cloud drip, S is septic sources, R is runoff, W is withdrawals, and G is groundwater recharge. If we assume that errors and uncertainty are small, the differences between outputs and inputs for each watershed should approximate ET estimated by use of land cover estimations.

Error Estimation for Water Budgets

Many potential errors exist in measuring rainfall, both systematic (related to gage height and design, evaporation losses, splash in and out, and wind speed over the gage) and nonsystematic (related to site-specific factors, instrument malfunction, and observer error) (Barry, 2008). The overall systematic error for rain gages has been estimated to be about 5 to 15 percent for rainfall (Barry, 2008). The high level of spatial variability in precipitation in eastern Puerto Rico adds potential error when one estimates watershed-wide precipitation. Daly and others (2003) estimated error in the PRISM model for Puerto Rico with cross-validation and found that errors were greatest where spatial precipitation gradients are greatest and there is the most station-to-station variability in precipitation; in eastern Puerto Rico, error ranged from 0 to 35 percent (Daly and others, 2003, their fig. 12). A simple linear regression between one precipitation station and another in eastern Puerto Rico accounts for between 61 and 84 percent of variance; estimating precipitation at one station from three other stations accounts for between 75 and 94 percent of variance. It is unlikely that measurement error would exceed variance; therefore we estimate a maximum error in precipitation for the 15-year period of this study to be 15 percent, on the basis of the higher end of the error range of Barry (2008).

For error in cloud drip, we estimated an error of 45 percent, based on the error reported by Holwerda and others (2006) for hourly cloud-drip measurements.

The accuracy of discharge measurements can be affected by several factors, such as cross-section uniformity, velocity uniformity, and streambed conditions (Sauer and Meyer, 1992). The accuracy of the USGS stream-gaging stations is described in water-data reports as “excellent” (about 95 percent of the daily discharges is within 5 percent); “good” (within 10 percent); “fair” (within 15 percent) and “poor” (less than “fair” accuracy). Records for WEBB stream-gaging stations were considered fair during the study period with the exception of the Cayaguás, which was poor owing to shifting waves of sand (Díaz and others, 2004). A simple linear regression between runoff for any WEBB river and another eastern Puerto Rico river accounts for 78 to 86 percent of variance; estimating runoff for a WEBB river using runoff for three nearby rivers accounted for between 94 and 99 percent of variance. It is unlikely that measurement error would exceed variance; therefore we estimate a maximum error in discharge for the 15-year period of this study to be 15 percent for the Icacos, Mameyes, and Canóvanas rivers, and 20 percent for the Cayaguás rivers, on the basis of USGS estimates of accuracy for these stream-gaging stations.

The net water input or output for a watershed is zero if water is withdrawn from within a watershed and then recycled within the watershed. It is impractical to determine the cycle for all withdrawals and septic systems in the watersheds. In addition, the accuracy of reported values is probably low; 63 percent of the total water deliveries in Puerto Rico are unaccounted for, owing to leaks in the distribution system (half of the total deliveries), illegal connections, or accounting errors (Quiñones, 2010). Therefore, we have estimated an error of 100 percent for water withdrawals and septic system inputs.

Groundwater storage was estimated from recession curves and converted to an average depth throughout the area of each watershed. The 95-percent confidence interval of the logarithms (Helsel and Hirsch, 2002) of predicted base flow to the observed base flow was used to estimate error in effective groundwater storage.

Errors in estimating evapotranspiration from water budgets were calculated as the square root of the sum of squares for errors (Helsel and Hirsch, 2002) of each budget component.

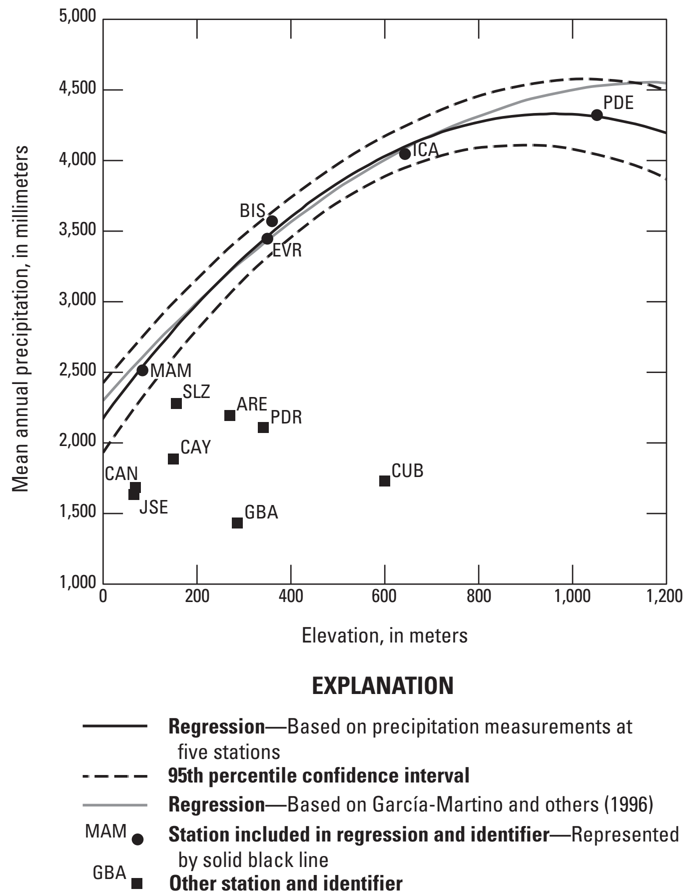


Figure 7. Elevation compared with mean annual precipitation (1991–2005) at stations in or near the study watersheds (Refer to table 2 for names of stations represented here by three initials).

Precipitation and Runoff in Eastern Puerto Rico

Mean annual precipitation at stations on the eastern side of the Luquillo Mountains (and hence the Mameyes and Icacos watersheds) ranged from about 2,500 mm to more than 4,000 mm (about 6.8 to 11 mm per day (mm day^{-1})) during the study period, and it was closely correlated with elevation (table 4; figs. 7, 8). Precipitation at stations in and near the Canóvanas and Cayaguás watersheds, on the western and southwestern side of the mountains, was substantially lower and not well correlated with elevation. Differences in precipitation at stations of similar elevations there may be due to differing rain-shadow effects, local topography, or recording errors.

As with precipitation, runoff was higher from the Icacos and Mameyes watersheds than from the Canóvanas and Cayaguás watersheds (table 5, fig. 9). While all four watersheds had substantial interannual variation in precipitation and runoff, mean annual runoff during the 1991–2005 study period was similar to the mean annual runoff for the periods of record (tables 5 and 6). A simple linear regression between runoff from any of the four watersheds and another eastern Puerto Rico river accounts for between 78 and 86 percent of variance (table 7), indicating that regional-scale weather patterns account for most of the interannual variability of runoff. Some of these regional weather patterns are related to climate oscillations (fig. 6); three climate indices (El Nino–Southern Oscillation, North Atlantic Oscillation, and Atlantic Multidecadal Oscillation) accounted for 46 percent of annual variance in precipitation at Pico del Este. The period of the longest climate cycle that affects the region, the Atlantic Multidecadal Oscillation (60 to 80 years; Kerr, 2000, 2005), is substantially longer than the longest period of record for any river in the region (47 years; table 6). Therefore, continued long-term streamflow monitoring will be needed to determine the effects of secular climate change, as compared to natural cycles, in these watersheds.

For WEBB rivers with the longest periods of record (Canóvanas, Cayaguás, and Mameyes), and the nearby Río Fajardo (FAJ in fig. 5), distributions of mean annual runoff are nearly log normal (fig. 10). When all the data are normalized to their geometric means and aggregated into a single data set, the distribution is even closer to normal (table 6). Because most of the interannual variability of the rivers appears to be caused by regional weather patterns (table 7), it is probable that rivers with shorter periods of records (Icacos and Guabá) are also log normal. Therefore we can calculate the lowest and highest 1 percent of annual runoff (that is, the one-in-one-hundred-years driest year, and the one-in-one-hundred-years wettest year, respectively) for all rivers; these percentiles are about a factor of 1.5 to 2.6 greater or less than the geometric mean (table 6). The rivers with the lowest mean-annual runoff (Canóvanas, Cayaguás, and Fajardo; table 6) have the highest fractions, indicating deeper droughts

Table 4. Total annual precipitation at stations in or near study watersheds, 1991–2005.

[For information on sources and locations, see table 2. --, not available; mm d^{-1}, millimeters per day; mm yr^{-1}, millimeters per year; P, precipitation]

Year	Quebrada Arenas	Bisley Tower	Río Canóvanas	Río Cayaguás	Cubuy	El Verde	Gurabo Abajo	Río Icacos	Juncos 1SE	Río Mameyes	Pico del Este[1]	Pueblito del Río	San Lorenzo 3S
	Annual precipitation (mm yr^{-1})												
1991	1,890	2,880	--	1,490	1,550	2,650	990	--	1,140	--	3,860	1,060	1,910
1992	2,870	3,860	--	1,810	1,950	1,880	1,620	--	1,600	2,220	4,930	2,110	2,390
1993	2,210	3,340	--	1,670	1,770	2,610	1,130	2,890	1,630	--	4,010	1,920	2,190
1994	1,860	2,680	1,000	1,280	1,420	1,320	800	3,240	1,180	1,980	3,460	1,940	1,690
1995	2,050	3,290	1,840	1,360	1,730	3,530	1,490	3,310	1,490	2,550	3,650	1,990	1,860
1996	2,050	3,750	2,200	2,280	1,950	4,580	--	4,880	1,950	3,040	5,380	2,880	2,860
1997	2,050	3,490	1,230	1,770	1,490	3,320	970	3,680	1,440	2,080	4,240	1,780	2,010
1998	2,590	4,010	1,630	2,710	2,220	5,290	2,110	4,970	2,430	2,890	5,120	3,190	2,970
1999	2,290	3,840	2,140	2,020	1,880	3,990	1,490	4,290	1,670	1,990	4,900	2,440	2,280
2000	1,640	2,690	1,270	1,770	1,380	2,830	1,280	3,600	1,310	1,760	3,840	1,720	2,010
2001	2,040	3,240	1,720	1,830	1,810	3,400	1,390	4,220	1,620	2,270	4,140	2,150	1,890
2002	1,780	2,650	1,310	1,500	1,640	3,130	1,240	3,670	1,100	1,970	3,870	1,720	1,820
2003	2,740	5,060	1,670	2,600	1,720	4,150	2,040	4,740	2,520	3,660	4,960	1,360	3,020
2004	2,300	4,500	2,080	2,110	1,690	5,210	1,400	5,000	1,440	3,410	4,020	3,130	2,640
2005	2,570	4,300	2,150	2,070	--	3,810	2,100	4,120	1,980	2,900	4,470	2,230	2,650
Mean[2]	2,200	3,570[3]	1,690	1,880	1,730[4]	3,450	1,430	4,050	1,630	2,520	4,320	2,110	2,280
Years of missing data	None	None	1991–1993	None	2005	None	1996	1991–1992	None	1990–1991, 1993	None[1]	None	None
Maximum daily P, mm d^{-1}	240	--	310	504	246	243	427	458	313	343	318	396	315
Date of maximum daily P, mm d^{-1}	8/22/2001	--	9/10/1996	9/10/1996	9/21/1998	11/8/2001	9/22/1998	9/10/1996	9/10/1996	4/17/2003	11/12/03[5]	9/10/1996	9/22/1998

[1]Several dates were missing for this station; a regression based on the relation between precipitation at the Pico del Este station and the Icacos and El Verde stations was used to estimate daily precipitation on missing dates (Precipitation at Pico del Este = 0.649 • Precipitation at El Verde + 0.599 • Precipitation at Icacos).

[2]Calculated from daily data, unless noted; if more than 10 percent of daily data were missing in a year, that year was excluded from calculating the annual mean.

[3]Calculated from annual totals from Heartsill-Scaley and others (2007) and F.N. Scatena, University of Pennsylvania.

[4]Obtained from daily totals of hourly precipitation.

[5]A higher value of 550 mm was recorded on 9/11/96, but because no value was recorded on 9/10/96, the value was divided over the 2-day period.

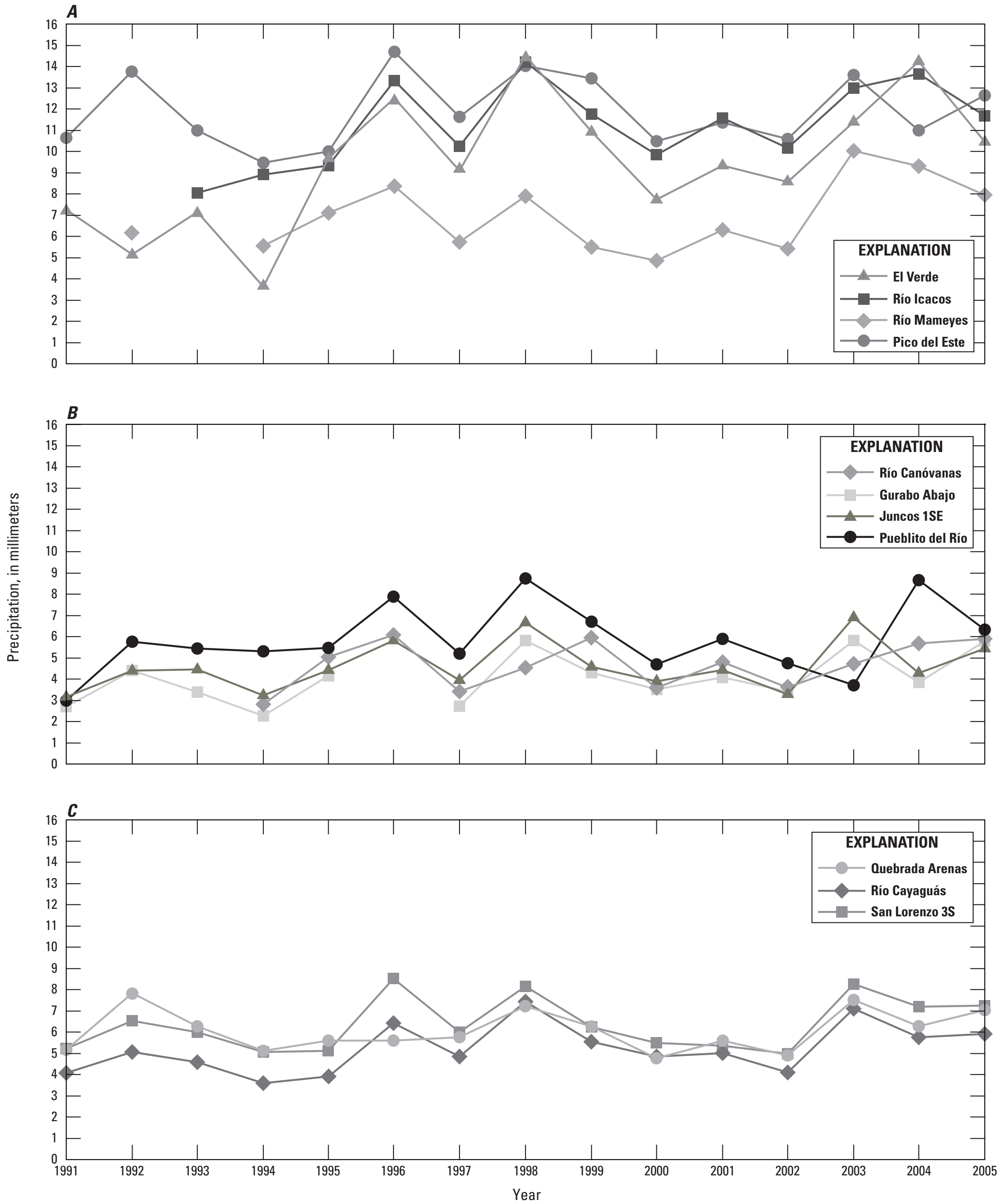


Figure 8. Mean daily precipitation by year at stations in or near study watersheds, eastern Puerto Rico. *A*, Mameyes and Icacos watersheds, *B*, Canóvanas watershed, and *C*, Cayaguás watershed (from Long Term Ecological Research Network, 2008; National Oceanic and Atmospheric Administration, 2008; U.S. Geological Survey Automated Data Processing System internal data, written commun., 2008). Missing data for Pico del Este estimated by regression with El Verde and Icacos stations.

Table 5. Annual runoff, stream statistics, and stream characteristics of study watersheds.

[km, kilometers; km^2, square kilometers; m, meters; m^3 s^{-1}, cubic meters per second; mm d^{-1}, millimeters per day; mm yr^{-1}, millimeters per year; -- not determined]

Parameter	Canóvanas[1]	Cayaguás	Guabá[2]	Icacos	Mameyes
	Annual runoff[3] (mm yr^{-1})				
1991	470	650	2,700	3,090	2,330
1992	910	1,550	4,210	3,550	2,900
1993	670	1,600	2,960	2,940	2,690
1994	370	850	2,510	2,380	1,680
1995	810	940	2,760	3,510	2,320
1996	1,450	2,240	4,110	4,990	2,930
1997	700	1,760	3,480	3,930	2,430
1998	1,550	3,300	4,250	4,960	3,650
1999	1,310	2,120	4,120	4,190	3,250
2000	600	1,340	3,490	3,330	2,220
2001	710	1,060	3,520	3,400	2,630
2002	680	900	2,960	3,100	2,400
2003	1,420	1,910	4,450	4,170	3,400
2004	1,540	1,770	4,590	4,610	3,550
2005	1,450	2,240	4,260	4,290	2,930
Mean, 1991–2005	970	1,620	3,630	3,760	2,750
Mean daily runoff, mm d^{-1}	2.7	4.4	9.9	10	7.5
Highest daily runoff, mm d^{-1}	410	480	490[4]	430	257
Date of maximum daily runoff, mm d^{-1}	9/10/1996	9/10/1996	9/10/1996	9/10/1996	9/10/1996
	Period of record statistics				
Period of record[5]	1967–2006	1977–2006	1992–2002	1945–1953, 1979–2006	1967–1973, 1983–2006
Mean annual discharge[6], m^3 s^{-1}	0.80	1.3	0.012	0.41	1.6
Mean annual runoff[6], mm yr^{-1}	990	1,580	3,450[4]	3,940	2,860
Highest daily mean discharge, m^3 s^{-1}	120.0	140.0	0.65	20.0	80.0
Highest daily mean runoff, mm d^{-1}	410	480	490[4]	430	380
Date of highest daily mean runoff	9/10/1996	9/10/1996	9/10/1996	9/10/1996	9/18/1989
Lowest daily mean discharge, m^3 s^{-1}	0.023	0.20	0.002	0.042	0.20
Lowest daily mean runoff, mm d^{-1}	0.077	0.66	1.3	1.1	0.95
Date of lowest daily mean runoff	7/24/1977	2/4/1981	5/31/1999	3/22/1946	4/20/1970
Maximum peak flow, m^3 s^{-1}	489.9	402.1	3.3	--	580.6
Date of maximum peak flow	9/21/1998	8/22/2001	5/30/2002	4/17/2003	9/18/1989
Instantaneous low flow, m^3 s^{-1}	0.023	0.20	0.001	--	0.14
Date of instantaneous low flow	7/24/1977	2/4/1981	5/1/1997	--	4/8/1970
	Stream characteristics				
Elevation of gage, m	68	150	640	616	84
Mean elevation of watershed, m	464	287	702	686	508
Maximum elevation of watershed, m	956	445	767	832	1,050
Drainage area, km^2	25.5	26.4	0.114[4]	3.26	17.8
Stream order[7]	4	4	--	2	3
Mean channel slope[7]	0.15	0.12	--	0.073	0.21
Main channel length[7], km	21.3	23.5	--	2.0	13.6
Total channel length[7], km	34.4	49.5	--	2.9	24.0

[1]Runoff in parts of 1991 and 1992 estimated from regression with Cayaguás stream-gaging station.

[2]Runoff in 1991, 2004, 2005 and parts of 1992 and 2003 estimated from regression with Icacos stream-gaging station.

[3]Based on corrected daily values for calendar year, as described in text.

[4]Based on area determined as described in text (which is different from that reported in U.S. Geological Survey, 2006).

[5]From U.S. Geological Survey (2006), except for Guabá (Díaz and others, 2004). A large storm on April 17, 2003, severely damaged the Guabá gage; data reported after that date are not used in this report.

[6]Water year (October 1–September 30).

[7]From Larsen (1997).

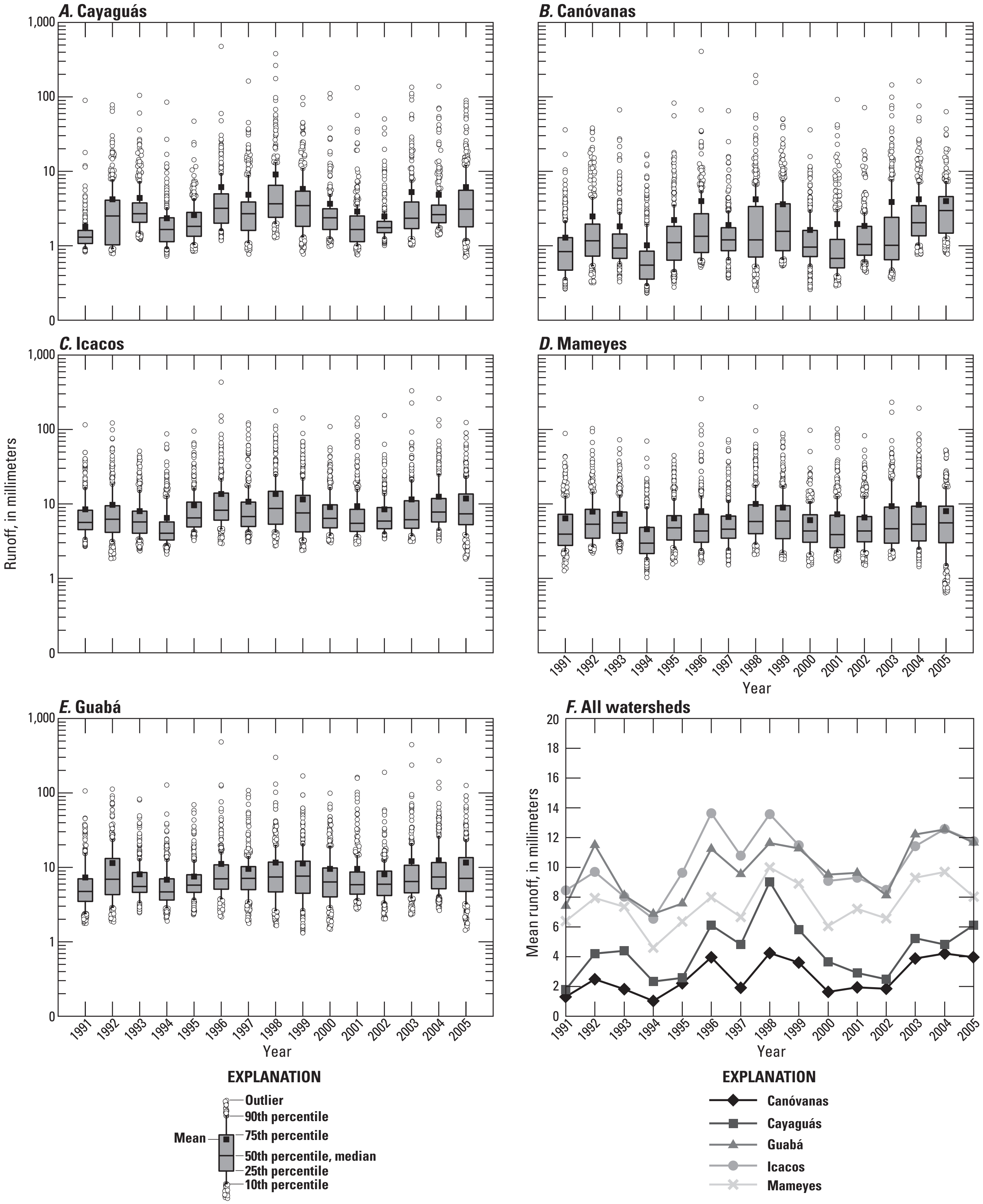


Figure 9. Mean daily runoff by year at U.S. Geological Survey stream-gaging stations (estimated from 5- or 15-minute discharge data from U.S. Geological Survey, 2010), eastern Puerto Rico. *A–E*, Standard box plots (Helsel and Hirsch, 2008) showing interquartile range in five watersheds; *F*, mean annual precipitation of same five watersheds. Runoff for Guabá in years 1991, 2004, and 2005 and portions of 1992 and 2003 estimated by regression with Icacos station; runoff for Canóvanas for portions of years 1991 and 1992 estimated by regression with Cayaguás station.

Table 6. Statistical properties of annual runoff of study watersheds and Río Fajardo (stream-gaging station 50071000, Río Fajardo near Fajardo) for years of record.

[mm yr^{-1}, millimeters per year; --, not applicable]

Property	Watershed						All rivers, combined and normalized
	Fajardo	Canóvanas	Cayaguás	Mameyes	Icacos	Guabá	
Years of record	47	41	31	31	14	10	174
Annual runoff (mm yr^{-1})							
Mean	1,540	990	1,550	2,830	3,810	3,420	--
Geometric mean	1,460	910	1,440	2,760	3,730	3,370	--
Median	1,460	840	1,550	2,750	3,770	3,490	--
Standard deviation	520	420	590	620	740	580	--
Skewness	1.08	1.08	0.73	1.21	–0.08	0.03	--
Kurtosis	2.15	1.14	0.66	3.23	–0.57	–1.35	--
Log of runoff							
Mean	3.16	2.96	3.16	3.44	3.57	3.53	0.00
Median	3.16	2.93	3.19	3.44	3.58	3.54	–0.01
Standard deviation	0.14	0.18	0.17	0.09	0.09	0.07	0.14
Skewness	0.08	0.10	–0.22	0.25	–0.53	–0.19	0.00
Kurtosis	–0.19	–0.23	–0.41	1.19	0.06	–1.20	0.26
Highest and lowest 1 percent of mean annual runoff							
Lowest 1 percent (fraction of geometric mean)	0.47	0.39	0.41	0.61	0.62	0.67	0.47
Highest 1 percent (fraction of geometric mean)	2.1	2.6	2.5	1.6	1.6	1.5	2.1
1-in-100-year dry year, mm yr^{-1}	680	350	580	1,690	2,330	2,260	--
1-in-100-year wet year, mm yr^{-1}	3,130	2,340	3,540	4,510	5,970	5,030	--

and relatively greater wet conditions for the wettest years. During the periods of records, annual runoff values greater than the one-in-one-hundred-years wet year occurred in the Mameyes in 1970 and in the Fajardo in 1979 (U.S. Geological Survey, 2010). Annual runoff values less than the one-in-one hundred-years dry year occurred in the Mameyes in 1994; runoff from the Canóvanas that year was very close to the driest year (U.S. Geological Survey, 2010). Runoff from the Canóvanas watershed (2,340 mm yr^{-1}) during the wettest 1 percent of years is only slightly greater than the driest 1 percent of years for the Icacos watershed (2,330 mm yr^{-1}).

The driest time of the year in eastern Puerto Rico is typically January through April, and March is the driest month (fig. 11). According to the criterion used by tropical forest biologists to indicate a markedly dry season—at least 3 consecutive months of precipitation averaging less than 100 mm per month (Ashton and others, 2004)—none of the studied watersheds have a markedly dry season. Precipitation is typically greatest September through November; stations on the north and east sides of the Luquillo Mountains commonly also record high precipitation in May. Monthly runoff generally follows the same trend as monthly rainfall, and runoff typically is least during February through April and greatest during September through December (fig. 12).

On average, rain fell between 11 percent (Canóvanas and Cayaguás) and 21 percent (Icacos) of the time (on an hourly basis) in the study watersheds during the study period (fig. 13). Rainfall intensities greater than 10 mm h^{-1} occurred 0.8 percent of the time that rain fell; when rainless time is included, this percentage is about 0.008 percent (about 42 minutes) of a year. Peak hourly rainfall ranged from 64 mm (at the Canóvanas stream-gaging station) to 93 mm (at the Icacos stream-gaging station), and peak 15-minute rainfall ranged from 27 mm (at the Canóvanas stream-gaging station) to 34 mm (at the Mameyes stream-gaging station) (table 8).

For 84 percent of the time or more, on an hourly basis, runoff from the studied watersheds was in the lowest 50th percentile (table 9). At these lower runoff rates, the hourly runoff from the WEBB rivers were arrayed in the same sequence as annual runoff; at the 50th percentile, runoff from the Canóvanas was 0.25 mm h^{-1}, and runoff from the Icacos was 0.57 mm h^{-1}. Runoff from the WEBB watersheds was in the top 10th percentile only between 0.06 and 0.33 percent of the time; at this runoff percentile, runoff rates for the watersheds ranged from 5 to 11 mm h^{-1} and were not proportional to annual runoff (fig. 14). Maximum runoff rates for the largest storms were commonly similar among all four study watersheds (table 9), suggesting that higher annual runoff in the Icacos and Mameyes watersheds is probably controlled by frequent, smaller rain events related to orographic precipitation.

The flow duration curves for all studied watersheds are generally steep (fig. 14), consistent with streams that have highly variable flows and are dominated by direct runoff (Searcy, 1959). The steep slope at the ends of the curves suggests a negligible amount of storage.

Greatest precipitation and runoff (both totals and rates) during the study period are associated with major storms that struck eastern Puerto Rico, such as Hurricane Hortense in 1996, Hurricane Georges in 1998, an upper level trough and a tropical wave in 2003, and Tropical Storm Jeanne in 2004

Table 7. Summaries of successive regressions of annual runoff and precipitation in eastern Puerto Rico.

[For river and stream-gage abbreviations, see table 2. mm yr^{-1}, millimeters per year; r, correlation coefficient]

Stream gage		Constant (mm yr^{-1})		River A				River B				River C			r	Variance (percent)
				Slope		Runoff (mm yr^{-1})		Slope		Runoff (mm yr^{-1})		Slope		Runoff (mm yr^{-1})		
Canóvanas																
CAN	=	–105	+	0.723	×	FAJ		--		--		--		--	0.93	86
CAN	=	–337	+	0.546	×	FAJ	+	0.212	×	SON		--		--	0.96	91
CAN	=	–425	+	0.362	×	FAJ	+	0.176	×	SON	+	0.483	×	RGL	0.98	97
Cayaguás																
CAY	=	–193	+	0.775	×	RES		--		--		--		--	0.88	78
CAY	=	–387	+	0.432	×	RES	+	1.075	×	RGL		--		--	0.93	85
CAY	=	–87	+	0.570	×	RES	+	1.198	×	RGL	+	–0.314	×	SON	0.95	90
Icacos																
ICA	=	1,684	+	0.891	×	RES		--		--		--		--	0.93	86
ICA	=	1,387	+	0.654	×	RES	+	0.480	×	RSS		--		--	0.96	92
ICA	=	1,533	+	0.475	×	RES	+	0.337	×	RSS	+	0.538	×	CAN	0.97	93
Mameyes																
MAM	=	1,614	+	1.169	×	CAN		--		--		--		--	0.90	81
MAM	=	1,465	+	0.668	×	CAN	+	0.351	×	RGE		--		--	0.93	86
MAM	=	1,390	+	0.313	×	CAN	+	0.425	×	RGE	+	0.473	×	QSS	0.94	88

Rain gage		Constant (mm yr^{-1})		River A				River B				River C			r	Variance (percent)
				Slope		Rain gage A (mm yr^{-1})		Slope		Rain gage B (mm yr^{-1})		Slope		Rain gage C (mm yr^{-1})		
Canóvanas																
CAN	=	179	+	1.033	×	SJM		--		--		--		--	0.78	61
CAN	=	180	+	1.380	×	SJM	+	–0.293	×	JSE		--		--	0.83	65
CAN	=	–11	+	1.167	×	SJM	+	–0.511	×	JSE	+	0.235	×	BIS	0.88	75
Cayaguás																
CAY	=	–191	+	0.940	×	SLZ		--		--		--		--	0.956	91
CAY	=	–802	+	0.655	×	SJM	+	0.295	×	PDE		--		--	0.979	95
CAY		–649	+	0.837	×	SJM	+	0.222	×	JSE	+	–0.102	×	MAM	0.981	96
Cubuy																
CUB	=	629	+	0.784	×	SJM		--		--		--		--	0.91	83
CUB	=	674	+	1.001	×	SJM	+	–0.139	×	MAM		--		--	0.95	89
CUB	=	719	+	1.254	×	SJM	+	–0.149	×	MAM	+	–0.230	×	CNR	0.97	94
Gurabo Abajo																
GBA	=	–173	+	1.168	×	SJM		--		--		--		--	0.81	66
GBA	=	–174	+	0.522	×	SJM	+	0.546	×	JSE		--		--	0.94	86
GBA	=	–164	+	1.024	×	SJM	+	0.390	×	JSE	+	–0.207	×	PDR	0.95	89
Icacos																
ICA	=	1,414	+	1.494	×	CNR		--		--		--		--	0.92	84
ICA	=	2,546	+	2.271	×	CNR	+	–1.481	×	CUB		--		--	0.96	90
ICA	=	1,993	+	2.067	×	CNR	+	–1.731	×	CUB	+	0.318	×	PDE	0.97	94
Mameyes																
MAM	=	–109	+	0.724	×	BIS		--		--		--		--	0.89	80
MAM	=	930	+	0.942	×	BIS	+	–0.430	×	PDE		--		--	0.93	85
MAM	=	1,536	+	0.827	×	BIS	+	–0.734	×	PDE	+	0.765	×	GBA	0.97	94

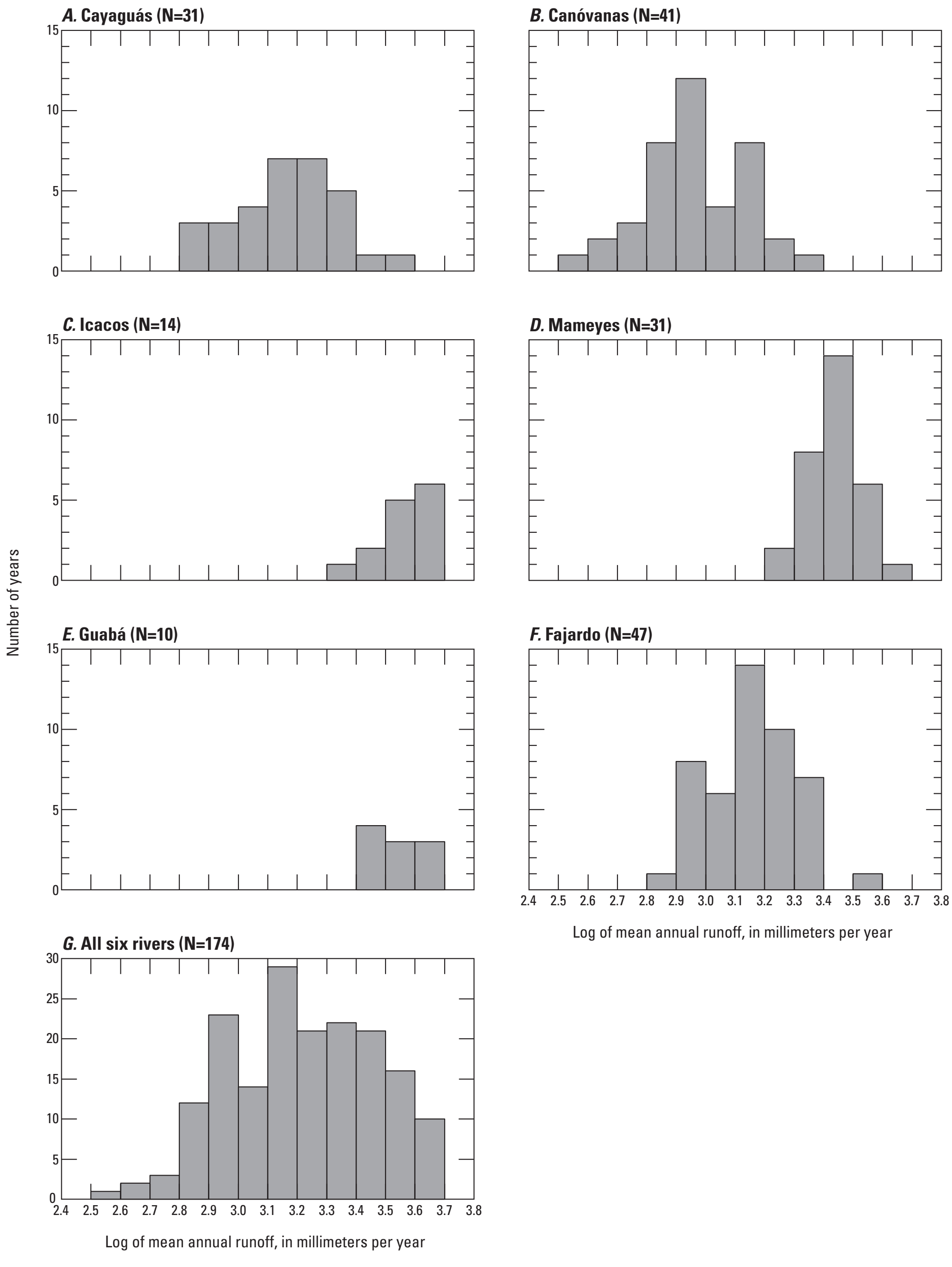


Figure 10. Distribution of log of mean annual runoff from study watersheds and Río Fajardo (stream-gaging station 50071000, Río Fajardo near Fajardo) for periods of record.

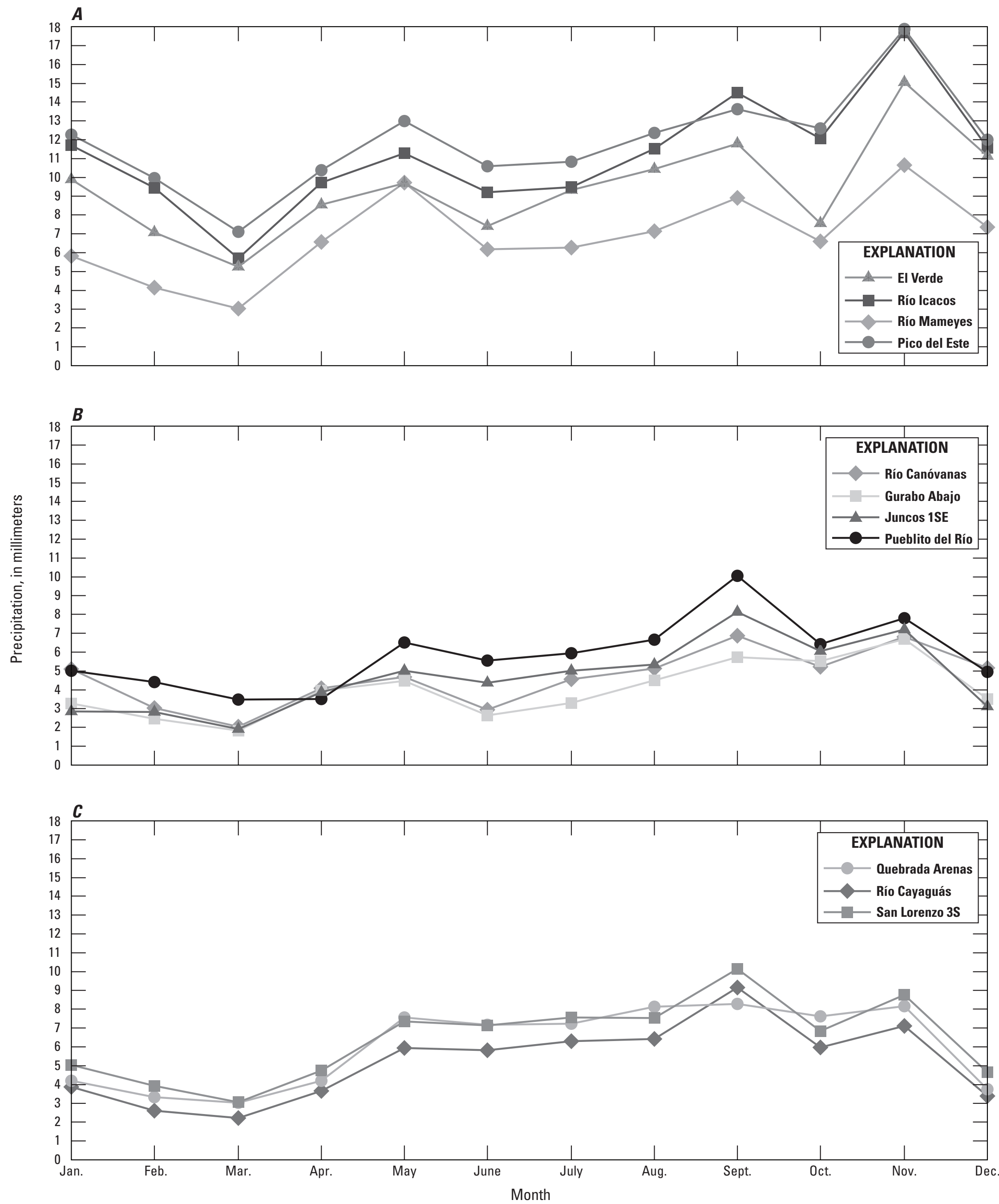


Figure 11. Mean daily precipitation by month at stations in or near study watersheds. *A*, Mameyes and Icacos watersheds, *B*, Canóvanas watershed, and *C*, Cayaguás watershed (from Long Term Ecological Research Network, 2008; National Oceanic and Atmospheric Administration, 2008; U.S. Geological Survey Automated Data Processing System internal data, written commun., 2008). Missing data for Pico del Este estimated by regression with El Verde and Icacos stations.

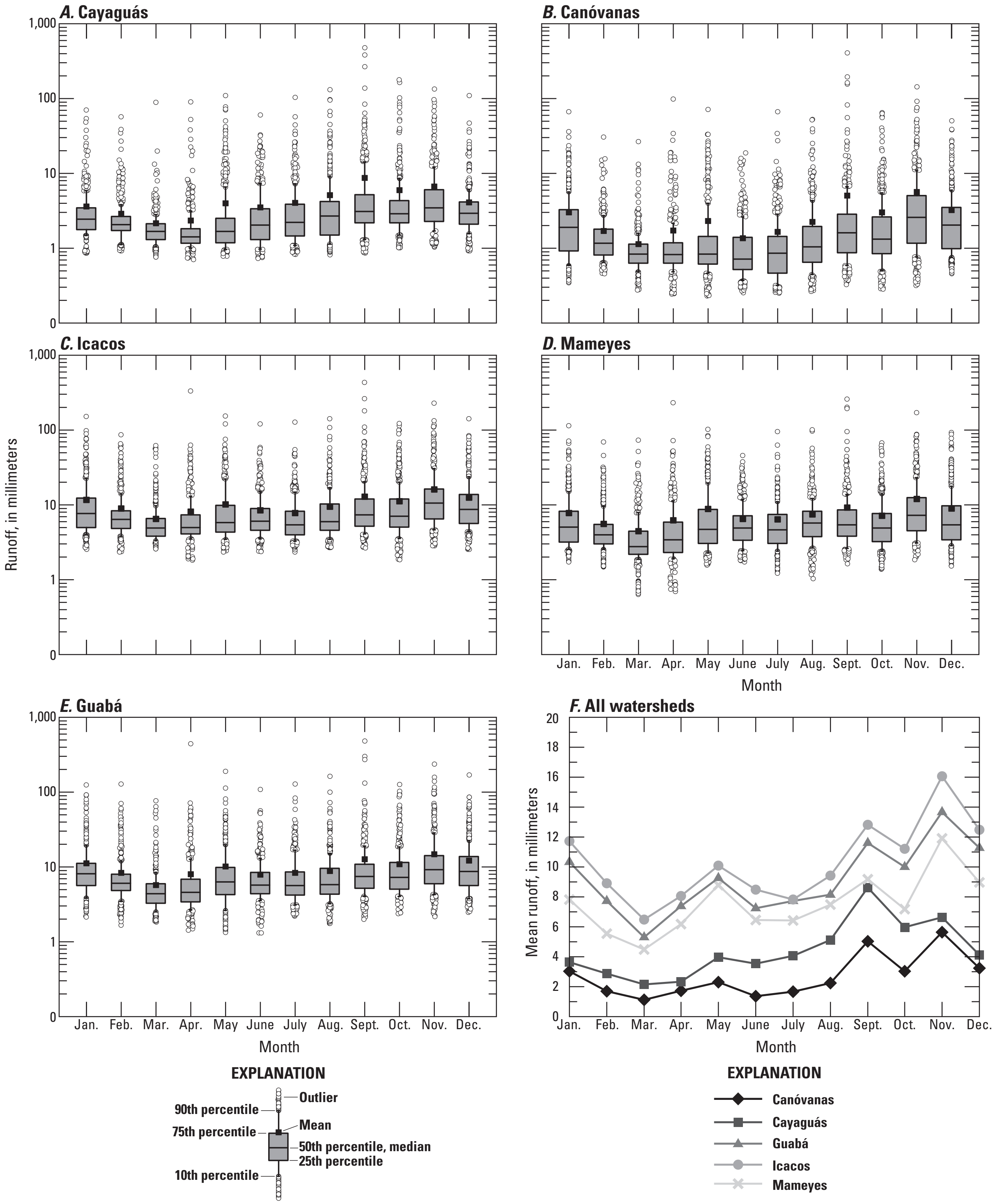


Figure 12. Mean daily runoff by month at U.S. Geological Survey stream-gaging stations (estimated from 5- or 15-minute discharge data from U.S. Geological Survey, 2010). *A–E*, Standard box plots (Helsel and Hirsch, 2008) showing interquartile range in five watersheds; *F*, mean annual precipitation of same five watersheds. Runoff for Guabá in years 1991, 2004, and 2005 and portions of 1992 and 2003 estimated by regression with Icacos station; runoff for Canóvanas for portions of years 1991 and 1992 estimated by regression with Cayaguás station.

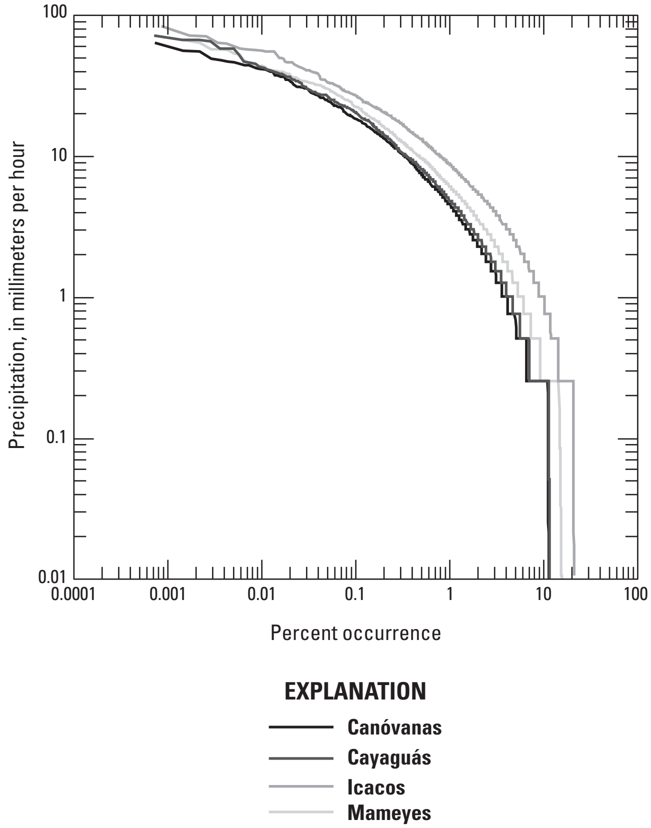


Figure 13. Percent occurrence of hourly precipitation intensity at U.S. Geological Survey stream-gaging stations (1991–2005).

Table 8. Rainfall intensity at U.S. Geological Survey stations during major storms in eastern Puerto Rico, 1991–2005.

[From U.S. Geological Survey Automated Data Processing System internal data, written commun., 2008. --, not available; h, hour; mm h^{-1}, millimeters per hour]

Date	Event	Canóvanas			Cayaguás			Guabá			Icacos			Mameyes		
		Time period (h)			Time period (h)			Time period (h)			Time period (h)			Time period (h)		
		0.25	1	24	0.25	1	24	0.25	1	24	0.25	1	24	0.25	1	24
		Rainfall intensity (mm h^{-1})														
25-Feb-1995	Unknown	28	17	2	12	4	0	64	29	3	125	83	6	44	18	3
13-May-1996	Unknown	12	3	0	4	1	0	52	28	3	60	28	4	136	64	9
10-Sep-1996	Hurricane Hortense	76	37	13[1]	76	72	21	96	48	17	108	47	19	36	29	12
21-Sep-1998	Hurricane Georges	96	64	5	84	67	9	72	51	9	96	72	12	36	34	5
22-Oct-1998	Unknown	84	28	4	88	45	8	40	32	5	72	38	6	44	20	3
22-Aug-2001	Tropical Storm Dean	108	46	4	132	76	9	88	58	10	76	57	11	109	71	7
17-Apr-2003	Upper-level trough	40	19	5	56	40	5	120	92	15	124	93	18	88	71	14
12-Nov-2003	Tropical wave	--	--	--	44	18	6	64	53	12	68	55	14	72	58	11
15-Sep-2004	Tropical Storm Jeanne	88	55	9	52	27	6	80	57	9	96	60	14	76	57	13
11-Apr-2005	Unknown	4	1	0	125	40	4	52	29	2	48	32	2	36	30	2
Maximum		108	64	13	132	76	21	120	92	17	125	93	19	136	71	14

[1]The hurricane destroyed the gage during storm, so precipitation may actually have been higher.

Table 9. Runoff rates (1991–2005) from study watersheds and percentage of time that hourly runoff was below those rates, at percentiles of annual runoff volume.

[mm h^{-1}, millimeters per hour]

Watershed	Minimum runoff	Percentile of annual runoff volume 1	5	10	25	50	75	90	95	99	Maximum runoff
Runoff rate (mm h^{-1})											
Canóvanas	0.009	0.019	0.030	0.041	0.083	0.25	1.4	8.1	20	43	66
Cayaguás	0.020	0.042	0.057	0.073	0.11	0.27	1.8	7.8	18	41	54
Guabá	0.036	0.11	0.16	0.20	0.29	0.48	1.8	11	25	64	98
Icacos	0.059	0.13	0.17	0.20	0.29	0.57	2.1	7.5	14	36	85
Mameyes	0.024	0.084	0.12	0.14	0.22	0.46	1.5	4.9	11	43	86
Time spent below given runoff (percent)											
Canóvanas	0	7	26	42	72	93	99.3	99.94	99.981	99.998	100
Cayaguás	0	5	19	33	63	91	99.0	99.89	99.967	99.996	100
Guabá	0	5	17	29	55	84	98	99.82	99.951	99.995	100
Icacos	0	4	16	28	57	86	98	99.67	99.901	99.991	100
Mameyes	0	5	18	31	59	86	98	99.68	99.921	99.994	100

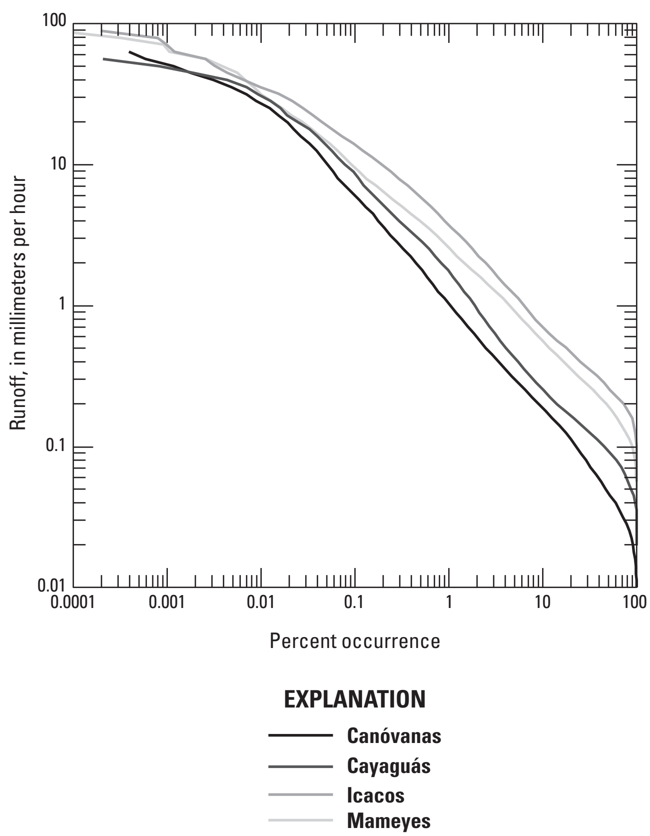


Figure 14. Percent occurrence of hourly runoff intensity at U.S. Geological Survey stream-gaging stations (1991–2005).

(table 8). Discharge caused by such storms can be several hundred times greater than average discharge and can deliver a substantial fraction of annual discharge. For example, Hurricane Hortense delivered more than 500 mm of rain in eastern Puerto Rico in less than 3 days, which produced the highest daily runoff (about 260–490 mm day^{-1}) of all studied watersheds during the study period (table 5); this 1 day of runoff accounted for about 28 percent of total annual discharge from the Canóvanas watershed in 1996. An upper-level trough in April 2003 produced more than 400 mm rain in 3 days. This storm was particularly intense in the Icacos watershed, where it delivered more than 90 mm in 1 hour (table 8) and altered the Guabá's stream channel so severely that discharge data at the Guabá stream-gaging station after that date are not useable.

At the high runoff rates that result from these large storms, hydrologic flow paths shift from moving into groundwater to shallower, lateral flow paths or overland flow (Schellekens and others, 2004), and water is rapidly transported to streams. Runoff can increase from base flow to peak discharge in minutes; high flows typically last only a few hours, and rivers typically return to base-flow conditions a few hours later. For example, when Tropical Storm Dean passed through eastern Puerto Rico in August 2001, the rise to peak discharge in the studied watersheds occurred in minutes to a few hours, and the recession typically lasted less than a day (fig. 15). This storm was selected because it was large enough to affect all of the studied watersheds but did not destroy any stream or rain gages, and it was preceded and followed by relatively rainless periods.

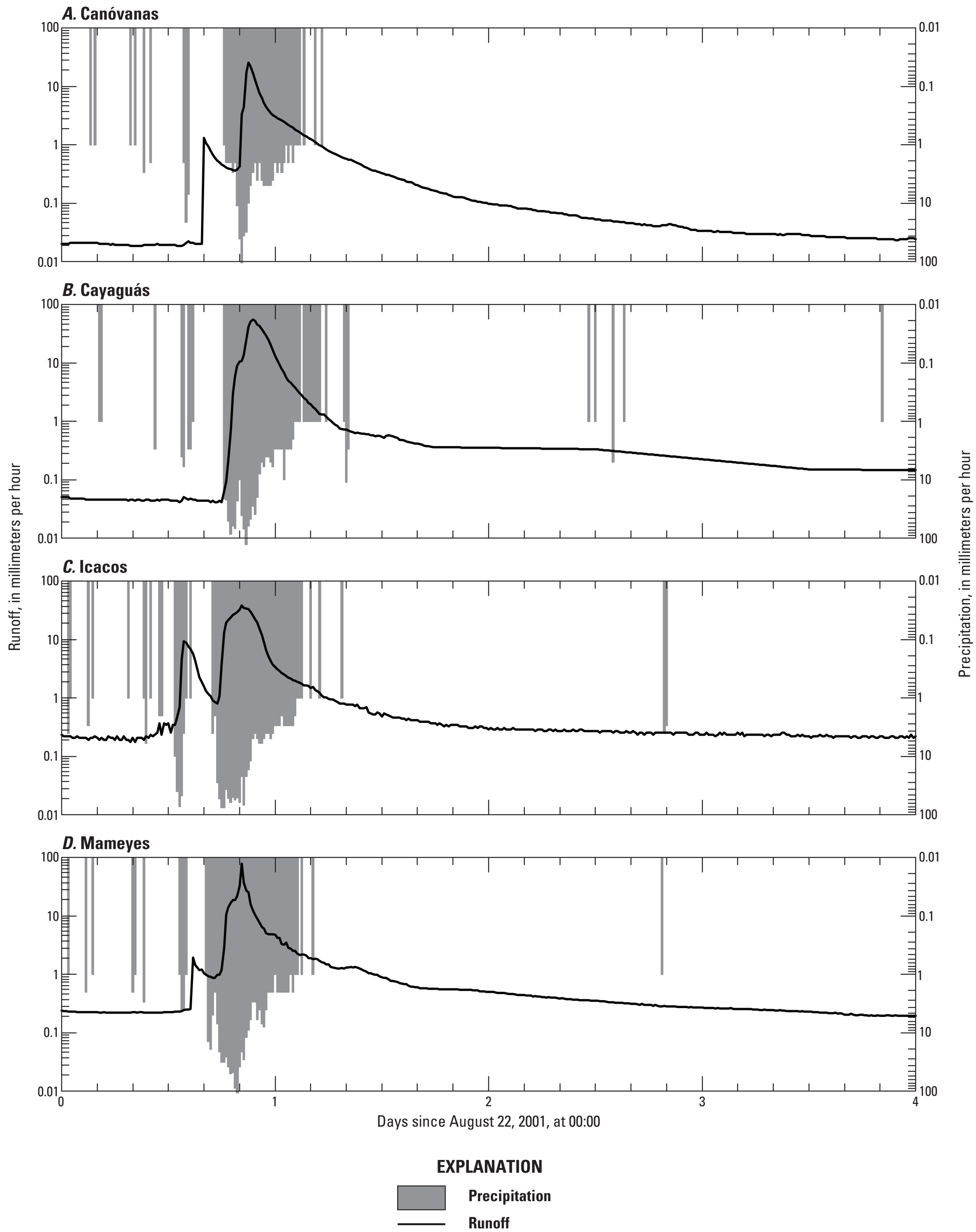


Figure 15. Runoff and precipitation at U.S. Geological Survey stream-gaging stations during and after Tropical Storm Dean, August 2001 (runoff and precipitation shown in 15-minute increments, adjusted to units of millimeters per hour; from U.S. Geological Survey Automated Data Processing System internal data, written commun., 2008; U.S. Geological Survey, 2010).

During the 1991–2005 study period, 130 recessions that lasted 5 days or more, including 7 recessions that lasted longer than 10 days, were identified in the studied watersheds (table 10). Recession models using integrated moving average and simple autoregressive regressions yielded tight 95-percent confidence intervals for recession constants (*k*) and similar average model recession end runoff rates for each river. Watersheds underlain by granitic rocks (Icacos, Guabá, and Cayaguás) had both higher k_I (subscript I refers to the IMA recession model) and k_A (subscript A refers to the AR(1) recession model) values, suggesting slower drainage and greater storage (table 10). Watersheds underlain by volcaniclastic rocks (Mameyes and Canóvanas) had lower k_I and k_A values, which were 95 percent likely to be different from those of the granitic watersheds; these values were spanned by k_I and k_A values reported for the geologically similar Espíritu Santo and Fajardo Rivers (Rivera-Ramírez and others, 2002), further suggesting that bedrock controls recession properties. Effective groundwater reservoir turnover times, τ_I, and τ_A, were also similar among rock types: shorter in the volcaniclastic watersheds (12 to 19 days, depending on the regression) than in the granitic watersheds (23 to 32 days). These results are consistent with water in the deep-soil environment having about twice the contact time in the granitic watersheds as in the volcaniclastic watersheds.

Field studies have found that surface infiltration was faster and hydraulic conductivities were greater in the Icacos watershed than in the Mameyes watershed (McDowell and others, 1992; Larsen, 1995). In both kinds of soil, macropore flow is likely important; soil pipes are visible along cut banks and steep slopes in hillslope and alluvial soils. Soil pore pressure response measurements by Simon and others (1990) found that granitic soils responded about three times as fast as volcaniclastic soils, suggesting that granitic soils are more permeable to a greater depth than volcaniclastic soils. Dense clays in the volcaniclastic soils likely retard deep infiltration and cause water to follow a shallower trajectory and thus reach streams more quickly (McDowell and others, 1992).

The recession analysis suggested that it would take between 6 and 19 days for runoff in the studied watersheds to drop from a 10-percent runoff rate (which occurs about 28 to 42 percent of the time; table 9) to a 1-percent runoff rate (which occurs about 4 to 7 percent of the time), and an additional 10 to 29 days to drop to minimum observed runoff rates (table 10). The length of time for such decreases was not strongly related to rock type, nor was the effective water column remaining in storage at the lowest flows. This stored water was greatest in the wettest watersheds (Icacos and Guabá) and least in the driest (Canóvanas). The effective water storage at 1-percent runoff rates, which were used to estimate groundwater storage, represents less than 3 percent of mean annual runoff from any watershed (table 10). It is therefore unlikely that long-term storage is a major factor in the interannual water budget. However, there was sufficient storage that none of the rivers completely dried up during the study, even during the 1993–1995 drought (table 10, fig. 9), when minimum hourly runoff ranged from 0.009 mm h^{-1} (Canóvanas) to 0.059 mm h^{-1} (Icacos). During the periods of record for the gages, lowest daily mean runoff was 0.077 mm day^{-1} (0.003 mm h^{-1}) or greater (table 5).

Water Budgets for Study Watersheds

Three methods of estimating precipitation in the Icacos and Mameyes watersheds resulted in values within about 5 percent of each other (between 3,980 and 4,160 mm in the Icacos watershed and between 3,660 and 3,830 mm in the Mameyes watershed (table 11)). In the Cayaguás watershed, the elevation-weighted method and PRISM resulted in similar estimates of mean annual precipitation (about 2,350 mm), whereas calculations based on land cover were about 11 percent lower (2,100 mm). Estimates of mean annual precipitation in the Canóvanas watershed ranged widely, from 2,070 mm (elevation-weighted method) to about 3,480 mm (PRISM). PRISM therefore appears to model precipitation in the Cayaguás, Icacos, and Mameyes watersheds effectively, but it does not capture rain-shadow effects in the Canóvanas watershed accurately. Owing to the lack of precipitation data for pasture and lowland forest, the dominant land covers in the Canóvanas and Cayaguás watersheds (Murphy and others, 2012), estimating precipitation from land cover is not likely to be highly accurate in these watersheds. Therefore precipitation based on elevation (adjusted for rain-shadow when necessary) was used in water budgets (table 12).

Rainfall is the dominant input to all watersheds; runoff and ET are the dominant outputs, with differing importance in the watersheds (table 12). Elevation-weighted estimates indicate that cloud drip adds about 1, 2, and 4 percent to the annual precipitation budget in the Canóvanas, Mameyes, and Icacos watersheds, respectively (table 12). Inputs from septic systems, and outputs from withdrawals and groundwater storage, are minor. Runoff is about 47 percent of precipitation plus cloud drip in the Canóvanas watershed, about 70 percent in the Mameyes and Cayaguás watersheds, and about 87 percent in the Icacos watershed. Evapotranspiration values estimated from water budgets ranged from 450 mm yr^{-1} in the Icacos watershed to about 1,070 mm yr^{-1} in the Canóvanas watershed. Evapotranspiration values estimated from land cover were slightly higher (12 and 15 percent, respectively, of ET estimated from water budgets) in the Mameyes and Canóvanas watersheds, but much higher (77 and 127 percent, respectively) in the Cayaguás and Icacos watersheds (table 12). The high runoff-to-precipitation ratio and substantial discrepancy in ET estimated from water budgets and from land cover in the undeveloped Icacos watershed suggest that evapotranspiration is lower than reported in vegetation-based estimates (table 3), or precipitation is greater than recorded, or both. Most ET studies in the Luquillo Experimental Forest were done in the Espíritu Santo (RES, table 2, fig. 5) and Mameyes watersheds; ET may be lower in the Icacos watershed because

Table 10. Modeled recessions for study watersheds after storm events, eastern Puerto Rico.

[Following Vogel and Kroll (1996) for instantaneous runoff. Includes recessions that lasted 5 days or more; first 2 days excluded from recession. AR(1), autoregressive; h, hour; IMA, integrated moving average; *k*, recession constant; km^2, square kilometers; mm, millimeters; mm h^{-1}, millimeters per hour; mm yr^{-1}, millimeters per year; %, percent]

Watershed	Annual runoff[1] (mm yr^{-1})	Interval (minutes)	Number of recessions	Recession points	Maximum runoff during recessions[2] (mm h^{-1})	Average runoff at recession end (mm h^{-1})	Minimum runoff during recessions (mm h^{-1})	Runoff at 10% (mm h^{-1})	Runoff at 1% (mm h^{-1})	Minimum observed runoff[3] (mm h^{-1})
Canóvanas	970	15	34	190	0.24	0.062	0.012	0.041	0.019	0.008
Cayaguás	1,620	15	29	157	0.20	0.061	0.030	0.073	0.042	0.020
Guabá	3,630	15	8	19	0.48	0.21	0.13	0.20	0.11	0.040
Icacos	3,760	15	16	86	0.71	0.22	0.13	0.20	0.13	0.059
Mameyes	2,750	5	43	228	0.57	0.12	0.039	0.14	0.084	0.025

Watershed	*k* (fraction/ day)	95% error in *k* (fraction/ day)	*k* (% / day)	Modeled average runoff at recession end (mm h^{-1})	95% error in modeled average runoff at recession end (%)	Turnover time[4] (days)	Time from 10% to 1% of average runoff (days)	Time from 1% to minimum runoff (days)	Linear storage[5] at 1% runoff (mm)	Linear storage at minimum runoff (mm)	Storage at 1% runoff (% of mean annual runoff)	Storage at minimum runoff (% of mean annual runoff)
[6]IMA regression to determine k_I												
Canóvanas	0.95	0.007	–5.4	0.067	–7.8	18	14	15	8	4	0.9	0.4
Cayaguás	0.97	0.005	–3.2	0.063	–5.3	31	18	23	32	15	2.0	0.9
Guabá	0.97	0.014	–3.3	0.21	–2.9	30	19	29	76	29	2.1	0.8
Icacos	0.97	0.008	–3.1	0.23	–4.5	32	14	25	100	45	2.6	1.2
Mameyes	0.95	0.005	–5.2	0.13	–8.4	19	10	23	37	11	1.4	0.4
[7]AR(1) regression to determine k_A												
Canóvanas	0.92	0.007	–7.9	0.058	10	12	9	10	6	2	0.6	0.2
Cayaguás	0.96	0.006	–3.8	0.061	5.5	26	15	20	27	13	1.7	0.8
Guabá	0.96	0.015	–3.5	0.21	3.1	28	17	27	70	26	1.9	0.7
Icacos	0.96	0.008	–4.3	0.21	4.9	23	10	18	72	33	1.9	0.9
Mameyes	0.92	0.007	–8.1	0.11	12	12	6	14	23	7	0.9	0.3

[1]1991–2005; from table 5.

[2]Excluding first 2 days after storm event.

[3]During 1991–2005 period.

[4]Turnover time (τ in Precipitation and Runoff in Eastern Puerto Rico section) = 1/ln(*k*).

[5]Water in excess of the field capacity in the soil available for drainage, or aquifer water.

[6]The error for the recession constant, k_I in the IMA regression, treats the estimate for ln(*k*) as a population average.

[7]The error for the recession constant, k_A in the AR(1) regression, which determines ln(*k*) from the slope of a regression forced through 0,0, is based on the error of that slope.

Table 11. Annual precipitation estimated by three methods.

[PRISM, parameter-elevation regressions independent slopes model (Daly and others, 2003). mm yr^{-1}, millimeters per year]

Watershed	Annual precipitation (mm yr^{-1})		
	Elevation-weighted regression[1]	PRISM	Calculated from land cover[2]
Canóvanas	2,070	3,480	2,770
Cayaguás	2,350	2,350	2,100
Icacos	4,150	3,980	4,160
Mameyes	3,760	3,660	3,830

[1] Rain-shadow-adjusted for Canóvanas and Cayaguás (see Interpretive Approach section).

[2] Based on 2003 land cover from Gould and others (2008) and land-cover types from literature (table 3).

Table 12. Annual water budgets of study watersheds.

[All values are millimeters per year unless otherwise noted]

Watershed	Inputs					
	Precipitation[1]		Cloud drip[2]		Septic[3]	
	Estimated	Error	Estimated	Error	Estimated	Error
Canóvanas	2,070	310	22	10	10	10
Cayaguás	2,350	350	0	0	5	5
Icacos	4,150	620	160	72	0	1
Mameyes	3,760	560	84	38	0	1

Watershed	Outputs					
	Runoff[4]		Withdrawals[3]		Groundwater[5]	
	Estimated	Error	Estimated	Error	Estimated	Error
Canóvanas	980	150	46	46	8	1
Cayaguás	1,620	320	3	3	32	2
Icacos	3,760	560	0	0	100	5
Mameyes	2,750	410	4	4	37	3

Watershed	Outputs/inputs (percent)	Runoff (as percent of precipitation + cloud drip)	Evapotranspiration		
			From water budget		From land cover[6]
			Estimated	Error	
Canóvanas	49	47	1,070	350	1,230
Cayaguás	70	69	700	470	1,240
Icacos	90	87	450	840	1,020
Mameyes	73	72	1,050	700	1,180

[1]Based on elevation-weighted regression; rain-shadow-adjusted for Canóvanas and Cayaguás.

[2]Based on Schellekens and others (2000), adjusted for elevation.

[3]From Larsen and Concepción (1998).

[4]U.S. Geological Survey stream-gaging stations, mean of 1991–2005.

[5]From recession calculations (table 10).

[6]Based on 2003 land cover from Gould and others (2008) and land-cover types from literature (table 3).

it less exposed to winds from the east and southeast (Murphy and others, 2012). The high humidity, often completely soaked conditions, and the cloudiness of the cloud-forest zone all contribute to much-reduced rates of evapotranspiration. Studies on nearby Pico del Este (elevation 1,051 m) and El Yunque (elevation 1,059 m; U.S. Geological Survey, 1967) have shown that relative humidity was usually at or near 100 percent, which would cause ET to be very low (Briscoe, 1966; Weaver, 1972). It is possible that precipitation is higher than recorded in this watershed; cloud drip contribution is poorly understood, and the elevation of the watershed is higher than average cloud base. Also, horizontal precipitation during rainstorms is often undermeasured by rain gages; as such, precipitation recorded on windy ridgetops, such as at the Pico del Este station, may underrepresent rainfall accumulation (García-Martino and others, 1996).

In the Cayaguás watershed, the water budget estimate for ET was 700 mm, whereas land cover suggested 1,240 mm (table 12). Although there are few ET data for the dominant land-cover types in this watershed (about 57 percent pasture and 20 percent lowland forest; Murphy and others, 2012), annual ET in lowland tropical forests is typically about 1,400 mm (Leigh, 1999), and nonforested landscapes tend to have lower rates of ET (Lawton and others, 2001). Therefore, the land-cover estimate of ET for this watershed seems more plausible than the lower water budget estimate. The low ET estimated by water budget could be due to greater actual precipitation than is recorded, erroneously high runoff measurements, or under-reported septic system inputs. Substantial differences in two precipitation stations near the mouth of the Cayaguás watershed (Río Cayaguás and San Lorenzo 3S, table 4; CAY and SLZ, fig. 5) indicate considerable short-range variation in precipitation or that some precipitation measurements are erroneous. Runoff data for the Cayaguás stream-gaging station have high uncertainty because of episodic scour and deposition of approximately 1 m in the sandy streambed (Larsen and Santiago-Román, 2001; Díaz and others, 2004). Finally, the Cayaguás watershed has a growing population, so it is possible that septic input is greater than reported, particularly if some households import water from another basin, although this possibility is unlikely.

Summary

Hydrologic regimes in the four U.S. Geological Survey Water, Energy, and Biogeochemical Budgets watersheds in eastern Puerto Rico are dominated by their location relative to the Luquillo Mountains. The Icacos and Mameyes watersheds, located in the eastern half of the mountains, are the wettest of the four watersheds, annually receiving more than 4,300 millimeters and 3,800 millimeters, respectively, of combined rainfall and cloud drip. Precipitation is closely correlated with elevation in these watersheds. The Canóvanas and Cayaguás watersheds, located in the rain shadow to the east and southeast of the mountains, receive roughly half the precipitation recorded for the Icacos and Mamyes watersheds. Precipitation and watershed elevation are not well correlated in these leeward watersheds, and differences in precipitation are probably related to local topography. Therefore, estimates of watershed-wide precipitation are likely to be much more accurate in windward watersheds (such as the Icacos and Mameyes) than in leeward watersheds (such as the Canóvanas and Cayaguás) in eastern Puerto Rico.

Precipitation and runoff in all watersheds show large interannual variation, which is partly explained by several large-scale climate oscillations. Precipitation and runoff are substantially higher in years when major storms strike Puerto Rico. These large storms typically result in similar runoff in all of the study watersheds, suggesting that higher annual runoff in the Icacos and Mameyes watersheds results from frequent, smaller storms related to orographic precipitation.

Precipitation leaves all of the studied watersheds primarily through runoff and evapotranspiration. Evapotranspiration estimates based on land cover and on water budgets were similar in the Mameyes and Canóvanas watersheds, but they differed substantially in the Icacos and Cayaguás watersheds. In the Icacos watershed, this discrepancy is probably due to reduced actual evapotranspiration caused by high humidity, extensive cloud cover, and reduced wind from eastern and southeastern directions, or greater actual water input than recorded by precipitation stations (owing to cloud drip or horizontal precipitation), or both. In the Cayaguás watershed, the discrepancy is likely due to measurement deficiencies in precipitation, runoff, or septic inputs, leading to low estimates of evapotranspiration by water budgets.

Because of the influence of windward-leeward effects, differences in hydrologic regimes in the four watersheds associated with bedrock geology or land cover are difficult to detect. Groundwater storage is small compared with annual runoff in all watersheds. Geology appears to control the recession characteristics of the rivers; recession is faster in volcaniclastic soils, probably because of impermeable clay layers, than in granitic rocks.

The effects of reforestation or climate change with time are difficult to distinguish from the large interannual variations in weather and the occasional large storm. Similarly, potentially increased evapotranspiration and subsequent decrease in runoff due to ongoing afforestation in the Canóvanas and Cayaguás watersheds would be a small factor compared to the windward-leeward differences. However, climate change may increase Puerto Rico's vulnerability to hurricanes, flooding, and drought, so afforestation remains an important topic for future study. If the effects of climate and land-use change are to be addressed in eastern Puerto Rico, better spatial density of precipitation stations, longer periods of both precipitation and stream-gaging station data, and additional studies of evapotranspiration in different land covers are needed.

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