ANALYSIS OF 20TH CENTURY RAINFALL AND STREAMFLOW TO CHARACTERIZE DROUGHT AND WATER RESOURCES IN PUERTO RICO

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Abstract: During the period from 1990 to 1997, annual rainfall accumulation averaged 87% of normal at the 12 stations with the longest period of record in Puerto Rico, a Caribbean island with a 1999 population of 3.8 million. Streamflow in rivers supplying the La Plata and Loíza reservoirs, the principal water supply of the San Juan metropolitan area, was at or below the 10th flow percentile for 27% to 50% of the time between December 1993 and May 1996. Diminished reservoir levels in 1994 and 1995 affected more than 1 million people in the San Juan metropolitan area. Water rationing was implemented during this period and significant agricultural losses, valued at $165 million, were recorded in 1994. The public endured a year of mandatory water rationing in which sections of the city had their water-distribution networks shut off for 24 to 36 hours on alternate days. During the winter and spring of 1997–1998, water was rationed to more than 200,000 people in northwestern Puerto Rico because water level in the Guajataca reservoir was well below normal for two years because of rainfall deficits. The drought period of 1993–1996 was comparable in magnitude to a drought in 1966–1968, but water rationing was more severe during the 1993–1996 period, indicating that water management issues such as demand, storage capacity, water production and losses, and per capita consumption are increasingly important as population and development in Puerto Rico expand.

INTRODUCTION

The Caribbean island of Puerto Rico (population 3.8 million) is located in the humid tropics and, during the 20th century, received an average annual rainfall of 1654 mm at the 12 stations with the longest period of record. However, mandatory water rationing was implemented three times during the 1990s in two regions of the island. Significant agricultural losses, valued at $165 million, occurred in 1994 (Lugo and García-Martino, 1996). A drought in 1994–1995 affected more than 1 million people in the San Juan metropolitan area who endured one year of mandatory water rationing in which sections of San Juan had their water-distribution networks shut off on alternate days for 24 to 36 hours. During the winter and spring of 1997–1998, more than 200,000 people in northwestern Puerto Rico experienced mandatory rationing of public-supplied water as water level in the Guajataca reservoir fell to the lowest level in 14 years as a result of rainfall deficits (USGS/WRD, 1998, 1999).

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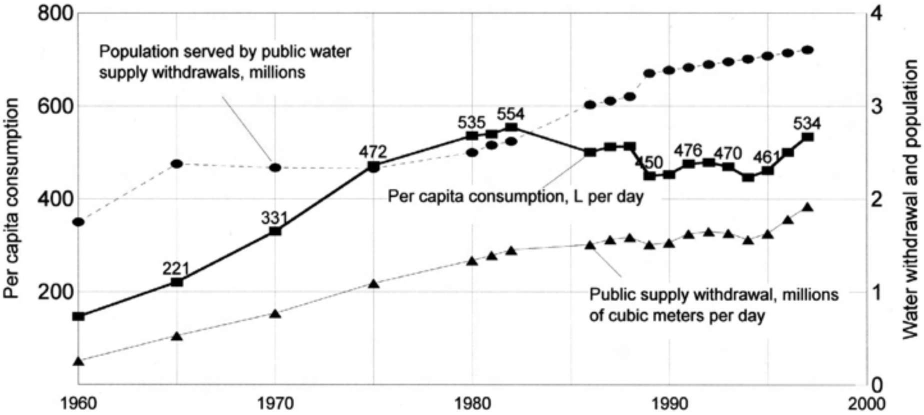

Fig. 1. Public supply water withdrawal for Puerto Rico from 1960 to 1997. Per capita consumption is calculated from population served by public water supply only. Data do not include the portion of the public that is self-supplied, which was an additional 6 percent of the total served by public supply water in 1995. *Source:* Data from USGS (Dopazo and Molina-Rivera, 1995; Molina-Rivera and Dopazo, 1995; Molina-Rivera, 1998; USGS, 1961, 1968, 1972, 1977).

Water Consumption

Efficient management of water resources is as important as rainfall accumulation and streamflow on small, densely populated islands with limited storage capacity such as Puerto Rico and other West Indian islands (Granger, 1983). The limited storage capacity problem is exacerbated by the high sediment discharge of rivers that have been impounded for water supply and electric power generation (Zack and Larsen, 1994; Webb and Soler-López, 1997). For example, the annual rate of storage loss at the Loíza reservoir, located near San Juan, was 1.3%, between 1953 (when the reservoir was impounded) and 1994. In addition, substantial population growth and industrial development have increased the demands on water resources. Between 1959 and 1998, population has grown at an annual rate of 1.1%, increasing from 2.2 million to 3.8 million. During this period, consumption of water resources rose at an average annual rate of 4.3%, from 0.26 million m^3 day^{-1} in 1960 to 1.92 million m^3 day^{-1} in 1997 (Fig. 1). Furthermore, the amount of water produced that is unaccounted for (e.g., leaks and illegal connections along the water-distribution network, poor or nonexistent metering of water, system maintenance, such as backwashing of filters at water filtration plants) has risen steadily since the 1960s to about 40% (Silva-Huyke, 1986; Lugo and García-Martino, 1996; Molina-Rivera, 1998). For comparison, the average rate of wastage in the United States is 10% (Ross, 1994b). Finally, public and private resistance to strategies such as dam construction, aqueduct systems for transporting water across long distances, and transfer of water from agriculture to urban distribution networks also has grown (Milliken and Taylor, 1981). Future conflicts among varying water-resource interests are likely to become more complex as demand for water outstrips the available supply. Recognition of water-resource problems is not new; in 1975, “serious long term consequences were anticipated” because of development trends of that period

(U.S. Water Resources Council, 1978). Major infrastructure projects are now in progress in Puerto Rico to address these problems (Vélez-Arocho et al., 1998).

Drought is a common hydrologic hazard in Puerto Rico although floods and landslides occur more frequently (Colon-Dieppa and Torres-Sierra, 1991; Larsen and Simon, 1993; Zack and Larsen, 1994). According to Colon-Dieppa and Torres-Sierra, 17 major floods and three major droughts occurred between 1899 and 1988. These 17 floods and associated landslides caused 3941 deaths. Most of the fatalities occurred during hurricanes in 1899, 1928, 1932, and 1960. No deaths have been attributed directly to the three major droughts that affected the island in 1966–1968, 1971–1974, and 1976–1977.

The negative effects of drought on human populations have been well documented in a variety of settings. Diminished streamflow also severely affects biotic communities and ecosystem processes in stream channels in Puerto Rico (Covich et al., 1998). Low flow in streams can be induced by episodic, naturally occurring droughts, or by artificial and chronic in-stream extraction of water for public supply. In the latter case, populations of aquatic organisms that migrate between stream headwaters and coastal estuaries and mangroves may be severely and permanently affected (Covich et al., 1998; Pringle and Scatena, 1999).

In contrast to the continents, where droughts typically affect extensive regions (e.g., the eastern United States drought of 1999; Showstack, 1999), droughts in Puerto Rico vary significantly over distances of a few 10s of kilometers (Morris and Vázquez, 1990). The 1966–1968 drought was severe in the east-central Puerto Rico Loíza and La Plata watersheds but was barely discernible in the southwest corner of the island (Morris and Vázquez, 1990). Nonetheless, Morris and Vázquez show that the 1966–1968, 1971–1974, and 1976–1977 droughts in Puerto Rico had regional expression because they also occurred in the Lesser Antilles (Fig. 2).

What Causes Droughts in the Caribbean?

If drought on Caribbean islands is a regional phenomena, what controls its timing and intensity? Malmgren et al. (1998) demonstrated that the variation in the North Atlantic Oscillation (NAO) index during winter is inversely related to mean annual precipitation. Dry periods in 1919–1923, 1972–1976, and 1988–1994 correspond to high NAO values. Conversely, wet periods between the 1930s and 1960s match times of low NAO values (Malmgren et al., 1998). Other researchers have shown that El Niño–Southern Oscillation (ENSO) events are associated with dry and warm summers in the Caribbean as well as periods of suppressed tropical storm formation (Ropelewski and Halpert, 1987; Kiladis and Diaz, 1989; Diaz, 1996; Poveda and Mesa, 1997). Winter et al. (1998) demonstrated that maximum sea surface temperatures off the southwest coast of Puerto Rico were greater than average for the years 1987–1994. Furthermore, over the past 30 years, maximum summer sea surface temperature has increased by 0.7°C (Winter et al., 1998). Strong ENSO periods have been shown to reduce the number and intensity of hurricanes in the Atlantic (Gray, 1984). The 1991–1994 ENSO event was associated with a 50-year low in Atlantic hurricane frequency (Landsea, 1993). Conversely, increased Atlantic hurricane frequency has been correlated with years of enhanced

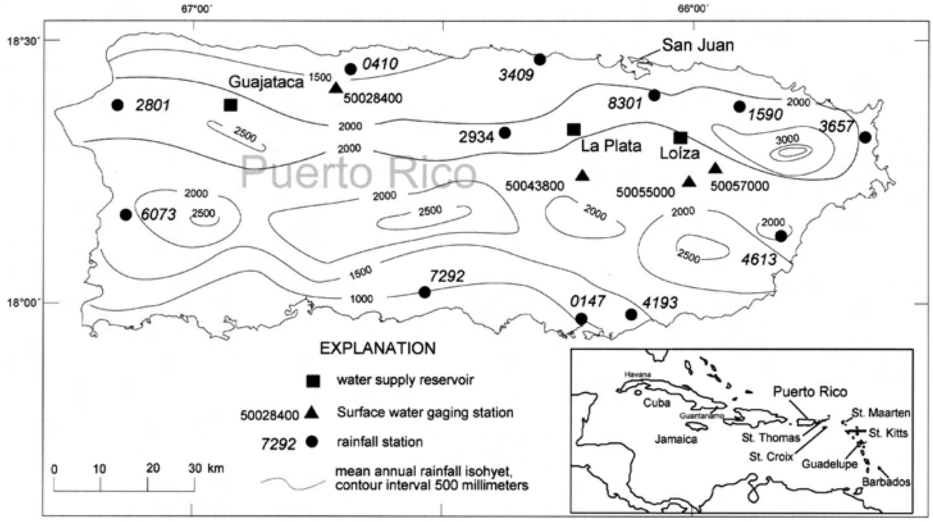

Fig. 2. Puerto Rico, showing mean annual rainfall isohyets and locations of selected reservoirs, NOAA daily rainfall stations, and USGS streamflow gaging stations. Inset map shows location of other islands in the West Indies.

rainfall in the Sahel region of Africa (Landsea and Gray, 1992). Hurricanes and other types of tropical disturbances of lesser intensity are capable of delivering a large portion of mean annual rainfall to the island of Puerto Rico. For example, in September 1996, rainfall accumulation of as much as 600 mm was associated with the passage of Hurricane Hortense (Torres-Sierra, 1997). While this large input of rainfall may result in an above-average month or year with respect to rainfall accumulation records, rapid runoff from the mountainous island means that most of the moisture is lost to the ocean. Low rainfall during the summer is typical of Caribbean islands because of the strengthening of the Bermuda High (Granger, 1985). During the summer of 1994, high pressure over the central tropical Atlantic was more extensive and longer lasting than usual, leading to drier than normal conditions (W. Gray, Colorado State University, pers. comm., 1994).

The objective of this paper is to characterize recent droughts of Puerto Rico in terms of rainfall accumulation, streamflow in rivers feeding the principal reservoirs, and public supply reservoir levels. These droughts are compared to the droughts recorded during the 1960s and 1970s. The droughts are discussed in the context of the Puerto Rican setting, an island in the humid tropics with short, high gradient streams, small watersheds and reservoirs, and where, during the past 40 years, population and per capita water consumption have increased dramatically, while reservoir storage capacity has declined.

DEFINITIONS OF DROUGHT

Unlike most other natural hazards, droughts are often poorly defined in space and time. Droughts may begin and end gradually and the affected region may vary in location and extent. Urban droughts have been defined as an adverse change in the urban water balance between supply and demand, altered by natural and human factors (Changnon, 2000). Droughts are commonly defined as meteorological, agricultural, or hydrological. These three types follow a gradient of increasing intensity. Meteorological droughts are periods of below-normal precipitation. Agricultural droughts, also described as soil moisture or vegetative droughts, follow meteorological droughts and affect crops as well as natural flora and fauna. A hydrological drought is the drought end stage and is manifested by reduced streamflow, and lowered groundwater and lake levels. Droughts typically begin and end in this sequence: precipitation decreases, which affects vegetation, and finally, surface- and groundwater levels are reduced. Recovery is first manifested by increased precipitation, which enhances vegetative growth and lastly appears as greater surface- and groundwater levels. Thus the start and end of hydrological droughts tend to lag meteorological droughts.

A number of drought classifications exist, including the Palmer Drought Index, Crop Moisture Index, Surface Water Supply Index, deciles, daily streamflow percentiles, and percent of normal precipitation (Palmer, 1965, 1968; Gibbs and Maher, 1967; Schafer and Dezman, 1982; Wilhite and Glantz, 1985; Smith et al., 1993). A new drought severity classification developed jointly by the National Oceanic and Atmospheric Administration Climate Prediction Center, U.S. Department of Agriculture, and the National Drought Mitigation Center (NOAA/USDA/NDMC) lists five levels of drought. A simplified version of the classification is shown in Table 1 (National Drought Mitigation Center, 1999). In this paper, droughts that occurred in Puerto Rico during the 1990s are characterized with deciles and according to the NOAA/USDA/NDMC classification using percent of normal precipitation and daily streamflow percentiles.

SETTING

Puerto Rico is the smallest island (8655 km^2 surface area) of the Greater Antilles, located about 1700 km southeast of Miami, Florida (Fig. 2). The island is in the trade-wind belt at the boundary between the Caribbean Sea and the Atlantic Ocean at latitude 18°N, longitude 66°W. Winds are predominantly from the east-northeast (Calvesbert, 1970). An east-west trending central mountain range dominates the island physiography, and rises to a maximum 1300 m elevation. Narrow coastal plains up to 16 km in width occur along most of the island perimeter. Strong orographic control on island rainfall distribution results in annual rainfall totals that range from 4000 to 5000 mm in northeastern rainforest-covered mountains to less than 1000 mm in the southwest (Calvesbert, 1970). Because of its location near the boundary of the tropics, Puerto Rico is exposed to tropical systems from the east as well as synoptic frontal systems from the north. Much of the annual precipitation occurs in medium- to high-intensity showers associated with easterly waves and tropical disturbances that occur from May to October. The balance is derived from northerly frontal systems and localized convection. Rainfall is evenly distributed throughout the year but a relative dry season occurs from January to April. Stream-

Table 1. Preliminary Classification of Drought Severity Showing Typical Ranges for Selected Parameters[a]

Category	Description	Impacts	Palmer Drought Index or Crop Moisture Index	Daily streamflow (percentiles)	Percent of normal precipitation
D0	Dry	Minor, but cause for concern	–0.6 to –2.0	20–30	<50% 30 days
D1	Drought (standard)	Some damage to crops, pastures; fire risk high; streams, reservoirs, or wells low, some water shortages developing or imminent	–2.0 to –3.0	10–20	50%–60% 2–3 months
D2	Drought (severe)	Moderate crop or pasture losses likely; fire risk very high; water shortages common	–3.0 to –4.0	5–10	40%–50% 2–3 months
D3	Drought (severe)	Major crop/pasture losses; severe fire danger; widespread water shortages	–4.0 to –5.0	1–5	30%–40% 2–3 months
D4	Drought (extreme)	Exceptional and widespread crop/pasture losses; large-scale and extreme fire risk; shortages of water in reservoirs, streams, and/or wells causing widespread rationing and restrictions	–5.0 or less	1	<30% 2–3 months

[a] The classification was developed jointly by the National Oceanic and Atmospheric Administration Climate Prediction Center, U.S. Department of Agriculture, and the National Drought Mitigation Center. It is posted on the National Drought Mitigation Center website: http://enso.unl.edu/monitor/archive/99/classify.htm at the University of Nebraska. The complete drought severity classification table includes ranges for CPC Soil Moisture Model and USDA/NASS Topsoil Moisture, and Satellite Vegetation Health Index, not shown here.

flow peaks are flashy and few runoff events last more than a day (García-Martino et al., 1996; Larsen and Concepción, 1998; USGS, 1999).

As in the United States, most of the island population depends on surface water (reservoirs, rivers) and receives potable water through a public-utility network of pipelines, pumping stations, and filtration plants (Molina-Rivera, 1998; Changnon, 2000). Total freshwater withdrawals for domestic, commercial, industrial, and public use were 2.14 million m^3 per day in 1995 (Molina-Rivera, 1998). Surface water accounted for 74% of the total and the balance, 24%, was derived from groundwater. Freshwater is produced from desalinization of seawater for one offshore island community of 1600, and accounted for only 492 m^3 per day in 1995.

Fig. 3. Arial view of the northern section of the Loíza reservoir and dam, Puerto Rico, 1991, showing high degree of landscape development, including housing, commercial buildings, secondary road, and expressway. Light gray area on reservoir surface behind dam is a floating mat of water hyacinths (*Eichhornia crassipes*). Dam measures 210 m across top.

Seven water-supply reservoirs are used to store surface water for public consumption in Puerto Rico; three of these—Guajataca, La Plata, and Loíza—are described in this article. The reservoir-contributing areas are small by continental standards, and range from 78 to 539 km^2. Land use in the basins varies (Fig. 3) and includes extensive regions of agriculture, industry, and housing (López et al., 1998; Gellis et al., 1999). A total of 17 water-treatment filtration plants extract streamwater at multiple locations upstream of the three reservoirs. In addition, 8 sewage-treatment plants introduce effluent into rivers upstream of the three reservoirs (Atkins et al., 1999).

Storage capacity has declined because of sedimentation in all three of the water-supply reservoirs. At the Guajataca reservoir, total storage capacity decreased from 48.46 million m^3 in 1928 to 42.28 million m^3 in 1999, which represents a loss of 6.18 million m^3 or about 13% of storage capacity (Soler-López et al., 1999a). The average sedimentation rate is 87,000 m^3 y^{-1} or 0.2% capacity loss per year, and results from a watershed sediment yield of 1190 Mg km^{-2}y-1. At the La Plata reservoir, storage capacity decreased from 40.21 million m^3 in 1974 to 35.46 million m^3 in 1998, about a 12% capacity loss in 24 years, or 0.5% per year (Soler-López et al., 1999b). The average annual sediment deposition rate at La Plata results from a watershed sediment yield of 483 Mg km^{-2}. Total storage capacity of the Loíza reservoir decreased from 26.80 million m^3 in 1953 to 14.19 million m^3 in 1994, a loss of 47% of the original storage capacity (Webb and Soler-López, 1997). The annual rate of capacity loss since impoundment has fluctuated between 1.13% and 1.45%, equivalent to a watershed sediment yield of 750 to 900 Mg km^{-2} y^{-1}. Although average surface runoff in the Loíza reservoir catchment is four times the demand in a given year, the effective storage capacity is only one-tenth of the yearly demand according to Webb and Soler-López. In September 1999, a two-year dredging effort was completed, at a cost of $60.1 million, in which approximately 5 million m^3 of sediment were removed from the Loíza reservoir (Vega and Terrasa-Soler, 1998; Delfin, 1999). Regular dredging is planned for removal of 500,000 m^3 of sediment every two years.

DATA AND METHODOLOGY

Monthly and annual rainfall accumulation, mean daily streamflow, and daily reservoir pool elevation data were analyzed for this study. A total of 12 stations were selected from a National Weather Service (NWS) database of monthly rainfall totals for sites in Puerto Rico. These stations had the longest and most complete period of record, most dating from 1900 to 2000 (U.S. Dept. of Commerce, 1901–2000). To compare the Puerto Rico data with rainfall trends elsewhere in the Caribbean, several stations in St. Thomas and St. Croix, U.S. Virgin Islands, were included from the NWS database, using the same criteria for selection. In addition, a World Meteorological Organization (WMO) database was searched for stations with long monthly rainfall data time series (World Meteorological Organization, 1998). Very few of the 231 stations in this database had more than 20 years of data, precluding detailed analysis of rainfall trends in this data set. However, seven stations on five islands were selected at sites in the Lesser and Greater Antilles to provide a regional context. The records at most NWS and WMO stations included some months with missing rainfall totals; missing values were estimated using simple linear regression models based on nearby stations.

Mean daily discharge data for four rivers draining northern Puerto Rico were used to quantify the hydrologic response to decreased rainfall during the period from 1993 to 1998 (USGS, 1994–1999). Three of the rivers were selected because they drain into the La Plata and Loíza reservoirs and because flow duration data have been calculated (Atkins et al., 1999). The principal river supplying the Guajataca reservoir is not gaged. The Tanamá River, in a nearby watershed, was selected because its gaging station is close (23 km) to the Guajataca reservoir and streamflow was expected to be closely comparable to that in the Guajataca watershed. Streamflow data for the two principal rivers that flow into the Loíza reservoir are available for the droughts that occurred in the 1960s and 1970s and were compared to the streamflow data from the 1990s, however, the La Plata and Tanamá streamflow stations did not exist at that time. Finally, the 1990–1998 daily pool elevation data for the three reservoirs were compared to precipitation and streamflow (USGS, 1990–1999; unpublished data, Puerto Rico Electric and Power Authority).

Data from all 12 NWS rainfall stations in Puerto Rico were used to calculate a mean for the island. Because of the variability in rainfall distribution in Puerto Rico, however, stations were also paired and means calculated so that regional differences could be seen. Four stations, Arecibo, Dorado, Guayama, and Río Piedras,

Table 2. Annual Rainfall Accumulation, in mm, at the 12 NOAA Daily Observer Stations in Puerto Rico with the Longest Period of Record

Name	Station number	Elevation m	Start year	Mean/ median[b]	Mean, 20th century[b]	Mean, 1990 to 1997	1990 to 1997 mean/20th century mean
Aguirre	0147	8	1900	1.01	1,045	912	0.87
Arecibo	0410	3	1900	1.05	1,456	1,243	0.85
Canóvanas	1590	9	1900	1.02	1,931	1,747	0.90
Coloso	2801	12	1905	1.01	2,050	1,736	0.85
Corozal	2934	198	1900	1.02	1,919	1,658	0.86
Dorado	3409	2	1907	1.02	1,653	1,493	0.90
Fajardo[a]	3657	7	1900	1.03	1,621	1,383	0.85
Guayama	4193	22	1907	1.04	1,346	1,252	0.93
Humacao[a]	4613	40	1900	1.04	2,159	1,761	0.82
Mayagüez	6073	23	1900	1.01	1,913	1,541	0.81
Ponce	7292	21	1900	1.04	910	882	0.97
Río Piedras	8301	28	1907	1.02	1,845	1,574	0.85
Mean, all				1.03	1,654	1,432	0.87

[a] Fajardo and Humacao were discontinued at the end of 1995.

[b] 1900 to 1998.

were not included in the regional groups because of shorter records or proximity to another station.

The severity of meteorological drought in Puerto Rico was evaluated using a simple rainfall index in which annual rainfall for individual stations was divided by mean rainfall for the period of record, 99 years in most cases. This value was then subtracted from one and plotted against time (Morris and Vázquez, 1990). The rainfall index has the advantage of providing a measure of normalized departure from the long-term means, which facilitates comparison among different recording stations. Although a common technique, this method sometimes suffers because annual rainfall data are often not normally distributed. However, the mean and the median rainfall for the period of record of the 12 Puerto Rican rainfall stations used in this study are very close. On average, the mean was 3% greater than the median (Table 2).

To examine the timing and intensity of dry periods in four regions of the island, a rainfall index was calculated for the monthly precipitation data for the period from 1987 to 1998 using the 99-year monthly mean for four stations (Arecibo, Canóvanas, Mayagüez, and Ponce). Although the monthly accumulation data from these stations may not completely characterize their respective regions, they provide insight into the spatial and temporal variability of drought periods. In addition to calculating the rainfall index, a second approach using deciles was used for the

Table 3. River Names, USGS Identification Numbers, Drainage Areas, and Streamflow Duration Characteristics of Four Rivers in Northern Puerto Rico[a]

	Discharge, m^3/s			
Percentile	Río Tanamá 50023800 149.2 km^2 WF1 STP0	Río de la Plata 50043800 282 km^2 WF7 STP5	Río Grande de Loíza 50055000 232.6 km^2 WF7 STP1	Río Gurabo 50057000 155.9 km^2 WF2 STP1
1	0.31	0.22	0.62	0.24
2	0.37	0.25	0.68	0.28
5	0.57	0.37	0.88	0.40
10	0.76	0.45	1.13	0.51
20	1.08	0.57	1.61	0.74
30	1.30	0.65	2.07	0.91
50	1.81	0.96	3.09	1.42
70	2.61	1.53	4.73	2.35
80	3.43	2.10	6.23	3.34
90	5.01	3.68	10.14	5.92
95	7.08	8.16	17.67	10.79
98	10.65	19.40	36.82	22.94
99	13.82	38.80	63.72	41.63

[a] The values following WF and STP indicate the numbers of water filtration and sewage-treatment plants located upstream of the surface water gaging stations.

Source: Data from Atkins et al. (1999).

same four stations. Evaluation of droughts using deciles was developed in Australia for use with long time series of data (Gibbs and Maher, 1967). By arranging monthly precipitation into categories for each 10% of the rainfall distribution, each category, or decile, describes a component of the long-term precipitation record. The deciles are commonly grouped into five classifications: lowest 20%, next lowest 20%, middle 20%, next highest 20%, and highest 20%.

Frequency distributions of mean daily discharge values for the two periods in the 1990s and the three periods in the 1960s and 1970s were generated for streamflow data at the rivers noted previously (Fig. 2; Table 3). Mean daily discharge for the period of record (1960–1998) at the Loiza and Gurabo streamflow stations is 6.11 m^3s^{-1} and 3.63 m^3s^{-1}, respectively. The combined drainage area for the two stations, 388.5 km^2, represents 72% of the Loiza reservoir catchment area. Mean daily discharge at the Loiza streamflow station accounts for 63% of the flow of the two stations and is thus more important with respect to the reservoir downstream.

Mean daily discharge was grouped according to flow percentiles published by Atkins et al. (1999). The flow percentiles and discharge data include the additive

Table 4. Magnitude and Frequency of Annual Low Flows for Three Surface Water Gaging Stations in Puerto Rico

Recurrence interval,years	Lowest-average flow, for indicated number of consecutive days, $m^3 s^{-1}$			
	7 days	14 days	30 days	60 days
Río Tanamá, 50023800				
2	0.82	0.85	0.91	1.02
10	0.34	0.37	0.48	0.57
Río Grande de Loíza, 50055000				
2	0.96	1.10	1.42	1.78
10	0.51	0.59	0.76	0.99
Río Gurabo, 50057000				
2	0.42	0.48	0.59	0.74
10	0.22	0.25	0.31	0.42

Source: Data from Santiago-Rivera (1992, 1998).

and subtractive effects of instream water filtration and effluent from sewage-treatment plants from each river (Atkins et al., 1999). Low-flow, or base-flow discharge values are published for some streams in Puerto Rico (Santiago-Rivera, 1992, 1998; Table 4). Mean daily discharge for the period October 1, 1992, through September 30, 1998, was compared to low-flow discharge values to determine how flow during droughts contrasted with recorded low-flow conditions.

RESULTS

Rainfall

Mean annual rainfall accumulation during the period from 1900 to 1998 for the 12 NWS stations with the longest period of record was 1654 mm and ranged from 910 to 2159 mm (Table 2). There were three dry periods of three or more years, in which annual rainfall accumulation in this group of stations was 10% or more below normal; these dry periods developed during 1966, 1971, and 1993 (Fig. 4A). On average, rainfall during these three sets of years was 20%, 13%, and 18% below normal, respectively. This indicates that the meteorologic drought of 1966–1968 was the most severe of the century but that the rainfall deficit of 1993–1995 drought was almost as severe. The driest year of the century, 1967, was recorded during the drought of 1966–1968, according to the 12 stations used in this study (Table 5). Although the 1976–1978 drought had one extremely dry year, 1976, when rainfall was 25% below normal, rainfall was only 6% to 7% below normal in 1977 and 1978 (Fig. 4A).

Table 5. Rank of 10 Driest Years of the 20th Century (1900–1999) in Puerto Rico[a]

Year	Mean annual rainfall, mm 12 stations	Rank
1967	1,065	1
1997	1,141	2
1994	1,171	3
1964	1,255	4
1976	1,259	5
1991	1,261	6
1930	1,308	7
1980	1,319	8
1947	1,342	9
1957	1,352	10

[a] Mean annual rainfall was calculated from the 12 stations listed in Table 2.

Regional variation of drought is evident in that the pairs of stations in the north and west regions had only two below-average years during the droughts of 1966–1968 and 1971–1974 (Figs. 4B, 4C). In contrast, the 1966–1968 drought began in 1964 and lasted five years on the south coast and rainfall, on average, was 32% below normal (Fig. 4E).

The years 1997, 1994, and 1991 were the second, third, and sixth driest years of the 20th century, based on the mean annual rainfall calculated for the 12 stations (Table 5). However, the 10 driest years of the century are otherwise distributed relatively evenly through the century, with most decades represented. Although 1993 to 1995 was the period of the 1990s with the greatest rainfall deficit, the 8-year period from 1990 to 1997 was generally a time of below-average rainfall at all 12 NWS stations, with 87% of the norm (Table 2). This, in spite of an above-average year in 1996 when Hurricane Hortense delivered as much as 600 mm of rainfall to the eastern and southern parts of the island (Torres-Sierra, 1997). It is possible that the generally dry period that began in 1989–1990 has ended. In 1998, rainfall at the 12 NWS stations was, on average, 24% above normal.

To better characterize the drought period of the 1990s, time series of monthly rainfall accumulation were examined (Fig. 5). As noted previously, these data may not fully represent their respective regions, but they indicate that the beginning and end of the drought periods have varied regionally. In general, 1989 marked the start of a lower-than-average monthly rainfall accumulation at all four stations. In 1998, a period of normal to greater-than-normal rainfall began at the stations on the north and south (Figs. 5B, 5C, 5D). However, at the Mayagüez station, the generally below-average accumulation pattern of the 1990s continued into 1998 (Fig. 5A). Regional variability of drought is further illustrated by the drought severity classifi-

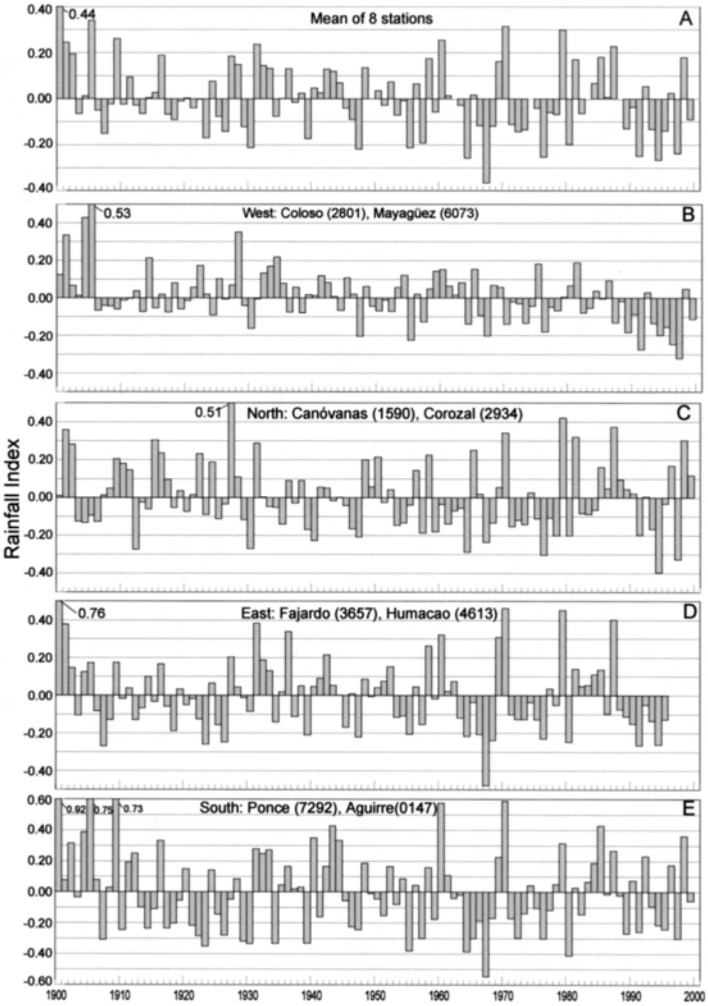

Fig. 4. Annual rainfall departure from 20th-century mean (1900–1998) calculated for pairs of stations representing four regions of Puerto Rico (station locations shown in Fig. 2). Rainfall index = (annual rainfall/mean rainfall) – 1. Data from NOAA-NWS daily observer stations (the Fajardo and Humacao stations were discontinued at the end of 1995).

cation shown, by month, across the tops of the graphs in Figure 5 (Table 1). These drought categories indicate that meteorologic drought was severe (D2, D3) to extreme (D4) during intermittent periods of two to three months from 1987 to 1995 and again in 1997 at the Ponce station (Fig. 5D). Drought was severe at the Mayagüez station at the end of 1989, the end of 1990, and in 1994. Extreme drought was recorded at the Mayagüez station during four periods between August 1996 and December 1998 (Fig. 5A). At the Arecibo station, drought was severe in 1989,1990, 1993, 1994, and again in late 1997 (Fig. 5C). Extreme drought was

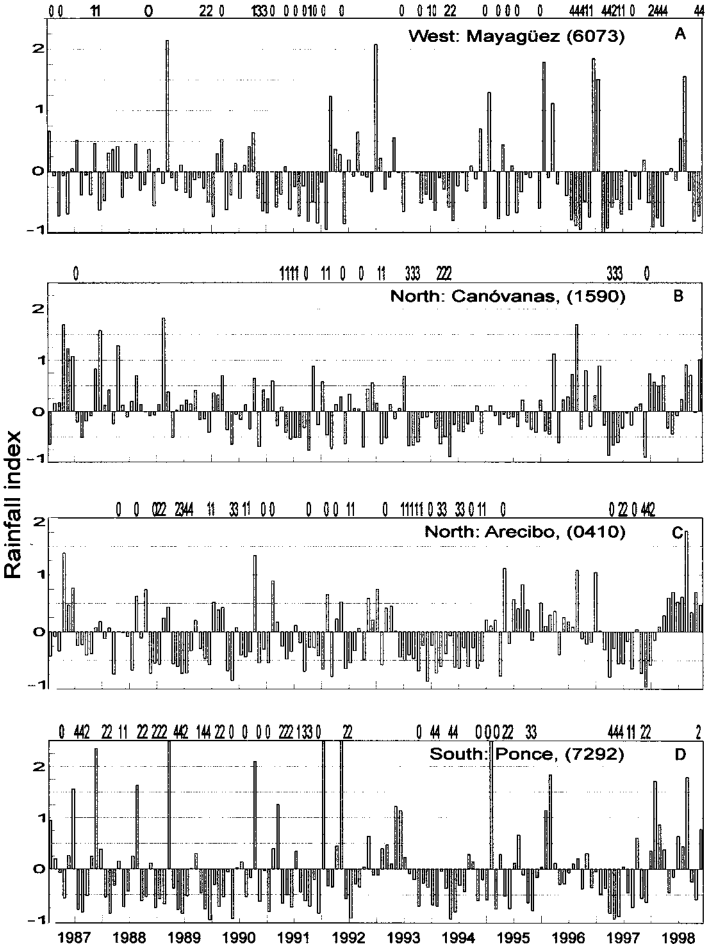

Fig. 5. Departure from 20th-century mean (1990–1998) at four stations with the complete monthly data for the period January 1987 to December 1998. Index = (monthly rainfall/monthly mean rainfall) – 1. Numbers 0 through 4 at top of each plot designate NOAA/USDA/NDMS drought severity as described in Table 1.

recorded at Arecibo in the summer of 1989 and during the winter of 1997–1998. The Canóvanas station had the fewest number of drought months, and never reached extreme (D4) conditions (Fig. 5B).

According to the decile distributions at these stations, the drought of 1993–1995 was the worst at Mayagüez among the drought periods of the 1960s, 1970s, and 1990s (Table 6). The droughts of 1966–1968 and 1976–1978 were the worst for the remaining three stations. On average, the droughts of 1966–1968 and 1976–1978 were the worst of the four droughts, with much below normal monthly rainfall 27% to 28% of the time and below-normal monthly rainfall 48% to 55% of the time, respectively. At the Arecibo, Canóvanas, Mayagüez, and Ponce stations, monthly rainfall for the period January 1993 and December 1995 was much below normal

Table 6. Classification of Monthly Rainfall by Deciles during Four Drought Periods in the 1960s, 1970s, and 1990s at Selected Stations with the Complete Monthly Data Sets in Puerto Rico[a]

		Cumulative distribution of monthly rainfall by deciles				
	Monthly rainfall:	Much below normal	Below normal	Near normal	Above normal	Much above normal
	Deciles:	1,2	3,4	5,6	7,8	9,10
	Classification:	Lowest 20%	Next lowest 20%	Middle 20%	Next highest 20%	Highest 20%
Mayagüez	Jan 1966 to Dec 1968	0.28	0.42	0.64	0.86	1.00
	Jan 1971 to Dec 1974	0.17	0.46	0.65	0.85	1.00
	Jan 1976 to Dec 1978	0.28	0.50	0.69	0.89	1.00
	Jan 1993 to Dec 1995	0.17	0.53	0.67	0.83	1.00
	Oct 1996 to Mar 1998	0.39	0.78	0.89	0.94	1.00
Canóvanas	Jan 1966 to Dec 1968	0.31	0.50	0.69	0.92	1.00
	Jan 1971 to Dec 1974	0.17	0.50	0.69	0.92	1.00
	Jan 1976 to Dec 1978	0.22	0.56	0.72	0.86	1.00
	Jan 1993 to Dec 1995	0.25	0.47	0.78	0.97	1.00
	Oct 1996 to Mar 1998	0.28	0.39	0.61	0.83	1.00
Arecibo	Jan 1966 to Dec 1968	0.25	0.50	0.75	0.86	1.00
	Jan 1971 to Dec 1974	0.31	0.44	0.67	0.83	1.00
	Jan 1976 to Dec 1978	0.28	0.50	0.72	0.83	1.00
	Jan 1993 to Dec 1995	0.31	0.50	0.64	0.89	1.00
	Oct 1996 to Mar 1998	0.44	0.61	0.83	0.94	1.00
Ponce	Jan 1966 to Dec 1968	0.25	0.50	0.72	0.89	1.00
	Jan 1971 to Dec 1974	0.25	0.48	0.60	0.88	1.00
	Jan 1976 to Dec 1978	0.33	0.64	0.69	0.83	1.00
	Jan 1993 to Dec 1995	0.17	0.39	0.64	0.81	1.00
	Oct 1996 to Mar 1998	0.22	0.44	0.72	0.89	1.00
Mean of four stations	Jan 1966 to Dec 1968	0.27	0.48	0.70	0.88	1.00
	Jan 1971 to Dec 1974	0.22	0.47	0.65	0.87	1.00
	Jan 1976 to Dec 1978	0.28	0.55	0.71	0.85	1.00
	Jan 1993 to Dec 1995	0.22	0.47	0.68	0.88	1.00
	Oct 1996 to Mar 1998	0.33	0.56	0.76	0.90	1.00

[a] Deciles were generated from data collected continuously from 1900 to 1998 (1188 months).

(in the lowest two deciles) for 17% to 31% of the time, or below normal (lowest 4 deciles) for 39% to 53% of the time (Table 6). Above-normal rainfall (the upper 40% of normal distribution) during this same period was recorded in 22% to 36% of the months. The frequency of below-normal deciles was greatest at the Mayagüez station, where below-normal rainfall was recorded in 53% of the months. The drought

Table 7. Summary of Rainfall Characterisitcs, at Selected WMO and NOAA Rainfall Stations in the West Indies (RainfallTotals in mm)

Station location	Station number	Start year	Annual mean, period of record	Annual mean, Jan1990 to Dec 1997	Mean for 1990 to 1997/ mean for period of record
Barbados (Grantley Adams, Caribbean Meteorologic)	WMO 7895400, 7895500	1900	1,281	897	0.70
Le Raizet, Guadelupe	WMO 7889700	1951	1,786	1,572	0.88
Juliana, St. Maarten	WMO 7886600	1951	1,032	977	0.95
St. Croix (Christiansted, Anna's Hope)	NOAA 1740, 0260	1900	1,092	892	0.82
Wintberg, St. Thomas	NOAA 9450	1931	1,100	897	0.82
Kingston, Jamaica	WMO 7839700	1900	816	688	0.84
Guantanamo Bay, Cuba	WMO5411	1945	598	560	0.94
Havana, Cuba	WMO 7832500	1900	1,166	1,243	1.07
Mean, all stations			1,109	966	0.88

of 1993–1995 is least apparent in the monthly rainfall accumulation records at the Ponce station where the decile distribution is very close to normal (Table 6).

Monthly rainfall totals during the 18-month period from 1997 to 1998 were, on average, much below normal 33% of the time and below normal for 56% of the time at the Arecibo, Canóvanas, Mayagüez, and Ponce stations (Table 6). Conditions were close to normal at the Canóvanas and Ponce stations and well below normal, 61% and 78%, respectively, at the Arecibo and Mayagüez stations. The period of diminished rainfall was severe but relatively short lived at these stations on the west end of the island.

Rainfall accumulation data from seven other Caribbean islands of the Greater and Lesser Antilles show a regional pattern of deficits during the 1990s. These seven WMO and NWS stations are not an exhaustive representation of regional precipitation stations, but do have the longest continuous records. Annual rainfall accumulation during the period January 1990 to December 1997 was 87% (ranging from 70% to 102%) of the 20th-century mean on these islands(Table 7). Havana, Cuba, located at the western border of the Caribbean island region, is the only station where rainfall exceeded (slightly) the long-term mean. Barbados and the two islands closest to Puerto Rico, St. Croix and St. Thomas, had the greatest rainfall deficit among the seven islands listed.

Streamflow

Mean daily discharge data for the period January 1993 to September 1998 are shown along with the 10th, 20th, and 30th flow percentiles for each of the four

Table 8. Cumulative Percentage of Days with Discharge at or below Flow Percentiles for Four Rivers in Northern Puerto Rico during Selected Periods from 1993 to 1998

	Cumulative percentage of days with discharge at or below listed flow percentile							
	Río Tanamá		Río de la Plata		Río Grande de Loiza		Río Gurabo	
Percentile	Dec 1993 through May 1996	Feb 1997 through Mar 1998	Dec 1993 through May 1996	Feb 1997 through Mar 1998	Dec 1993 through May 1996	Feb 1997 through Mar 1998	Dec 1993 through May 1996	Feb 1997 through Mar 1998
1	0	0	2	0	4	0	8	0
2	0	0	6	0	7	0	15	3
5	0	0	19	4	16	4	37	13
10	11	3	27	12	27	8	50	23
20	32	25	38	17	41	15	65	51
30	41	46	45	21	56	26	71	63
50	64	67	62	45	74	59	81	81
70	80	88	73	71	85	80	89	90
80	85	93	79	85	90	87	94	93
90	92	98	88	92	94	92	97	96
95	96	99	94	96	97	96	98	98
98	99	100	98	99	99	99	99	100
99	100	100	99	99	100	100	100	100

Source: Data from USGS (1994–1999).

streamflow stations selected to represent hydrologic conditions in the three reservoir catchments (Fig. 6; Table 8). Between December 1993 and May 1996, discharge at the Gurabo, La Plata, and Loíza stations was in the 1st percentile for 2% to 8% of the time, generally indicating D4, or extreme hydrologic drought conditions. Severe hydrologic drought (D2 and D3) is characterized by streamflow in the 1st to 10th flow percentiles. During the period December 1993 and May 1996, discharge at all four stations was in or below this range for 11% to 50% of the time (Table 8). Discharge was at or below standard drought (D1) conditions, when flows are in the 10th to 20th percentiles, for 32% to 65% of the time between December 1993 and May 1996. Discharge was least at the Gurabo station during this period, while at the west end of the island at the Tanamá station, hydrologic drought was less pronounced.

Streamflow during the dry period of February 1997 to March 1998 did not reach the extreme hydrologic drought condition marked by flows in the 1st percentile at any of the four stations listed in Table 8. Severe hydrologic drought was recorded at the Gurabo station during 23% of this period. At the other three stations, streamflows indicating severe hydrologic drought were recorded only 3% to 12% of the time. Mean daily discharge within or below the range of standard drought condi-

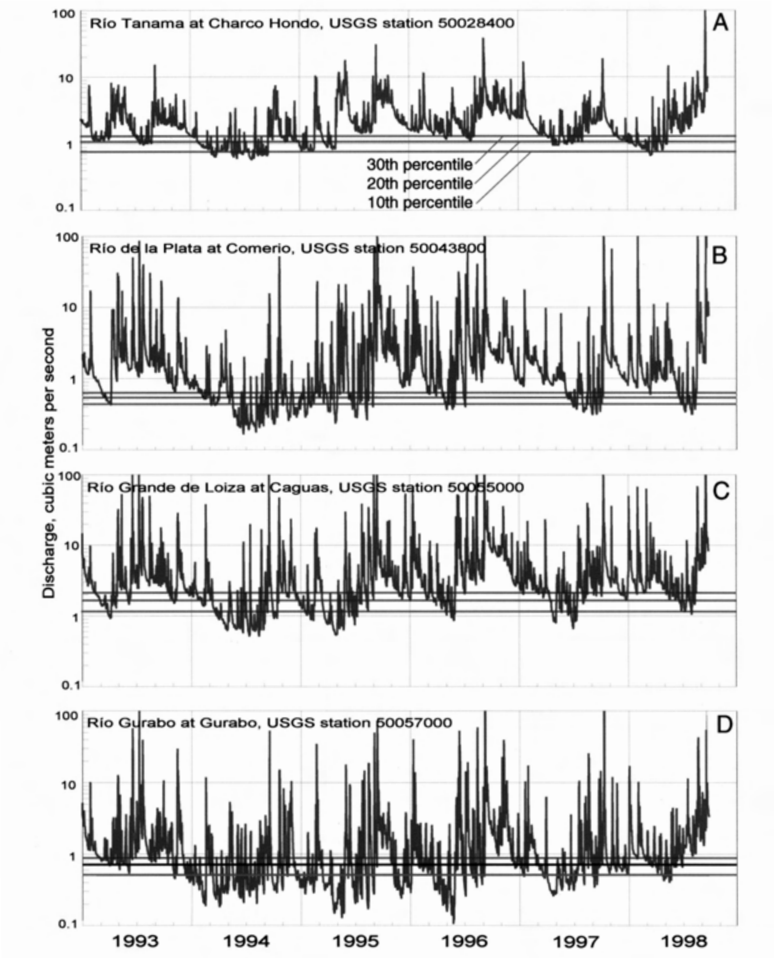

Fig. 6. Mean daily discharge at four USGS streamflow gaging stations in northern Puerto Rico, January 1, 1993, through September 30, 1998 (station locations shown in Fig. 2). Horizontal lines show 10th, 20th, and 30th flow percentiles. Streamflow and flow percentiles include effects of withdrawals and additions by filtration- and sewage-treatment plants. Note that the y-axis has been truncated and some high discharges are not shown.

tions was recorded for 15% to 51% of the time and was most common at the Gurabo station.

Mean daily discharge recorded at the Loiza and Gurabo stations was well below normal during the droughts of the 1960s and 1970s (Fig. 7). Discharge on the Tanamá and La Plata rivers could not be evaluated because streamflow stations were not yet in operation at that time. During the drought of 1966–1968, streamflow at the Loiza and Gurabo stations was at or below the 1st flow percentile for 7% to 8% of the time, indicating extreme hydrologic drought (Table 9). Streamflow indicating severe drought was recorded for 34% to 40% of the time and streamflow indicating

Table 9. Cumulative Percentage of Days with Discharge at or below Flow Percentiles for Two Rivers in Northern Puerto Rico during Selected Periods from 1966 to 1977

	Cumulative percentage of days with discharge at or below listed flow percentile					
	Río Grande de Loiza			Río Gurabo		
Percentile	Jan 1966 through June 1968	June 1971 through June 1974	Jan 1976 through Dec 1977	Jan 1966 through June 1968	June 1971 through June 1974	Jan 1976 through Dec 1977
1	7	1	1	8	0	0
2	9	1	2	15	1	0
5	21	3	5	30	4	2
10	34	6	12	40	7	8
20	50	20	20	55	21	22
30	59	36	29	62	34	34
50	75	62	54	76	62	59
70	88	84	72	89	81	73
80	93	90	81	93	89	81
90	97	96	91	96	95	90
95	99	98	97	98	98	95
98	100	99	99	99	99	99
99	100	100	99	100	100	99

Source: Data from USGS, (1968–1979).

standard drought was recorded for 50% to 55% of the time at the two stations. The droughts of 1971–1974 and 1976–1977 were relatively mild compared to that of 1966–1968, according to these hydrologic data. Mean daily discharge was very close to normal, with the flows at or below the 20th percentile for 20% to 22% of the time (Table 9).

During April and May 1995, streamflow at the Gurabo station was below or equal to the 10-year/30-day and the 10-year/7-day recurrence intervals for low flow (Santiago-Rivera, 1992; USGS, 1996, 1998). During the same period, flow at the Loíza station was only slightly above the 10-year/30-day, but was below the 10-year/14-day recurrence interval for low flow (Table 4; Fig. 6). In April 1997, streamflow at the Gurabo station was only slightly (0.30 m^3s^{-1}, as opposed to 0.25 m^3s^{-1}) above the 10-year/14-day recurrence interval for low flow. In May 1996, streamflow at the Gurabo station was below the 10-year/7-day recurrence interval for low flow. Low flows at the Tanamá station did not reach the extremes recorded at the Gurabo and Loíza stations. However, during the periods April–May 1994, June–September 1994, January–February 1995, and February–March 1998, streamflow at

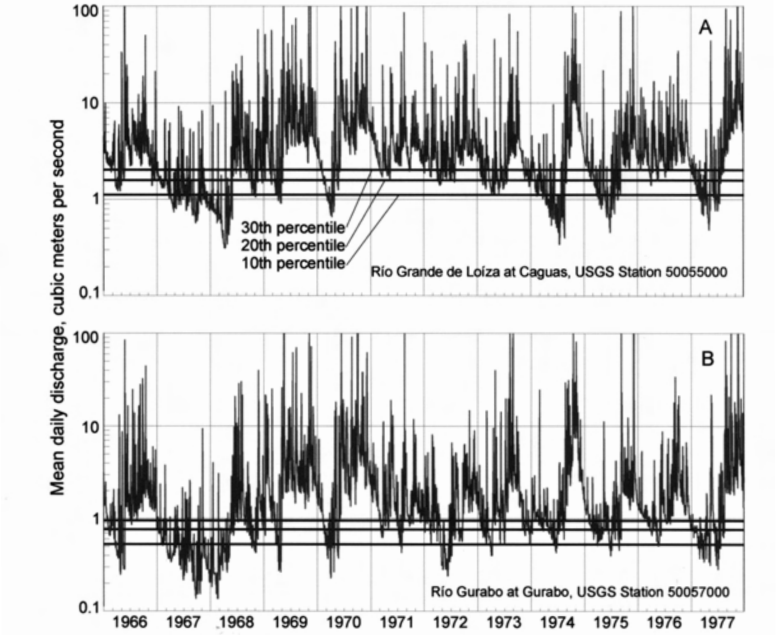

Fig. 7. Mean daily discharge at USGS streamflow gaging stations 50055000 and 50057000 in northern Puerto Rico, January 1, 1966, to December 31, 1977. Horizontal lines show 10th, 20th, and 30th flow percentiles. Daily discharge data and flow percentiles include the effects of withdrawals and additions by filtration- and sewage-treatment plants. Note that the y-axis has been truncated ans some high discharges are not shown.

the Tanamá station was equal or below the 2-year/60-day recurrence interval for low flow (Santiago-Rivera, 1998; USGS, 1996, 1999).

Reservoirs

Insight into the effects of temporal and spatial variability of rainfall and runoff is provided by time series of pool elevation data at three important water-supply reservoirs in Puerto Rico (Fig. 8). The catchment area for the Loíza reservoir yields enough runoff to keep the reservoir filled for a much larger portion of time when compared to the record at the Guajataca and La Plata reservoirs (Fig. 8). The Guajataca reservoir very rarely has been filled during the past four years, largely because of its small catchment area, which is about 15% of that of the Loíza reservoir. The regularly occurring dry season of late spring is apparent in the record of daily pool elevation for all three reservoirs as a slight elevation decrease (Fig. 8). The two regional droughts (1994–1995 and 1997–1998) are apparent in the reservoir record, and were brief in the La Plata and Loíza watersheds but continued until March 1998 in the Guajataca watershed. The three reservoirs responded more or less simultaneously to regional drying trends during the 1990s when mandatory rationing of water from the reservoirs was carried out six times during three different

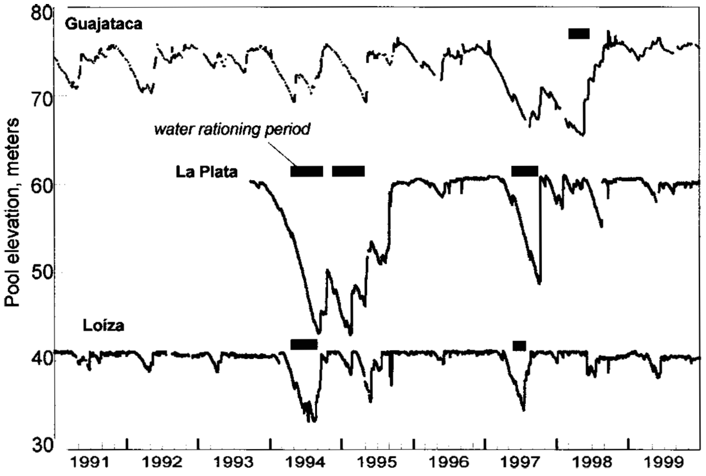

Fig. 8. Mean daily water surface elevation above arbitrary datum at the Guajataca (50010800), La Plata (50045000), and Loíza (50059000) reservoirs, Puerto Rico, 1991 to 1999. Horizontal bars indicate periods of water rationing. *Source:* Water surface elevation data from USGS lake elevation stations (USGS, 2000 and unpublished Puerto Rico Electrical Power Authority records.

periods. Storms of high enough magnitude to the fill the reservoirs are patchy and localized, typical of convective rainfall in the tropics (Hastenrath, 1978). For example, the drought that began in late 1993 and early 1994 in the La Plata and Loíza watersheds ended a year earlier in the Loíza (when several storms combined to fill the reservoir). A major storm in October 1997 ended a period of water rationing for the population supplied by the La Plata reservoir (Fig. 7).

The firm yield of a reservoir is the mean annual withdrawal rate that would lower the reservoir to a minimum allowable level during the critical drought of record (Chow et al., 1988). The ratio of the firm yield to the present rate of water withdrawal from the Guajataca reservoir, is 0.30 (Canino et al., 1998). However, at the La Plata and Loíza reservoirs, this ratio is 0.92 and 1.78, respectively (Table 10).

DISCUSSION

Precipitation in the tropics has been in decline since the 1970s (Diaz, 1996). Decreased rainfall in the Caribbean is a possible manifestation of this trend. Annual rainfall accumulation from 1990 to 1997 averaged 87% of normal at 19 of 20 stations on eight islands in the Lesser and Greater Antilles from Barbados to Cuba. Drought conditions were severe to extreme for two episodes during the 1990s according to data from selected stations in Puerto Rico. The distribution and intensity of drought was temporally and spatially heterogeneous on the island, characteristic of weather in the tropics in general but especially in mountainous tropical areas (Hastenrath, 1978). Including the two droughts of the 1990s that are discussed in this paper, a total of five droughts have been documented for Puerto Rico during the 20th century (Colon-Dieppa and Torres-Sierra, 1991). According to the

Table 10. Geographic and Hydrologic Characteristics of Three Public Supply Reservoirs in Puerto Rico[a]

	Guajataca	La Plata	Loiza
Usable pool volume, m^3, 1997	38,855,000	35,460,000	14,190,000
Drainage area, km^2	78	469	539
Year completed	1928	1974	1954
Reservoir area, ha	342	295	267
Mean depth, m	11	12	5
Mean daily withdrawals, m^3	51,000	265,000	371,500
Firm yield, m^3 day^{-1}	170,300	287,700	208,200
Ratio of withdrawals to firm yield	0.30	0.92	1.78
Daily evaporation loss, m^3	12	6	8

[a] Mean daily withdrawal data are unpublished, from Puerto Rico Aqueduct and Sewer Authority. Drainage area of Guajataca reservoir is approximate, karst limestone terrain prevents exact calculation.

Source: Data from USGS (1998), Molina (1998), Webb and Soler-López (1997), and Soler-López et al. (1999a, 1999b). Firm yield data from Canino et al. (1998) and F. Gómez (USGS, pers. comm.).

classification of rainfall records into deciles at four Puerto Rican stations, the 1993–1995 drought was no worse than the droughts of the 1966–1968, 1971–1974, and 1976–1978. During the droughts of 1966–1968, 1971–1974, and 1993–1995, below-normal rainfall occurred 47% to 48% of the time. During the 1976–1978 drought, below-normal rainfall occurred 55% of the time. However, the 1976–1978 drought was of shorter duration than the others. Although the rainfall deficit was large in 1976, deficits were small in 1977 and 1978. Short, intense droughts, while significant for rain-fed agriculture, may not be as important for water-supply reservoirs as are longer duration droughts (Morris and Vázquez, 1990). The 1997–1998 drought, which mainly affected western Puerto Rico, was relatively brief but intense. The very small reservoir contributing area was a major factor affecting the reduction of water levels in the principal reservoir that supplies water to northwestern Puerto Rico.

Mandatory water rationing was implemented six times during the 1990s for periods of up to six months. Rationing of water was implemented during the 1966–1968 drought, but to a lesser degree. However, close comparison of water management during these two droughts is not possible because of large differences in population, reservoir storage capacity, and per capita water consumption. Furthermore, direct comparison of hydrologic conditions during the droughts of the 1960s and 1970s to those of the 1990s is hampered by the instream effects of increased extraction by water filtration plants and increased effluent introduced sewage-treatment plants constructed since the 1970s.

Based on the comparison of rainfall and streamflow recorded during the droughts documented during the 20th century, the Puerto Rican droughts of the 1990s were not unusual from a meteorologic or hydrologic perspective. Nonetheless, the significance of a drought is strongly controlled by socioeconomic conditions. The island population served by public supply water was 2.38 million during the drought in the 1965 but had increased to 3.54 million in 1995. The 49% increase in population occurred while public supply withdrawal increased by 210%, from 526,000 to 1,631,000 m^3 day^{-1} (Fig. 1). This translates to a per capita consumption increase of 108%, from 221 L day^{-1} to 461 L day^{-1}. Public supply withdrawal increased while reservoir capacity decreased from 12% to 47% at the three reservoirs included in this study.

All three reservoirs are relatively shallow (5 to 12 m average depth), making them vulnerable to evaporation but, more importantly, to the effects of sedimentation (Table 10). During the drought of 1994–1995, water levels in the Loíza reservoir dropped so low that water intakes at the dam were nearly cut off from upstream sections of the reservoir. An emergency dredging operation was launched in order to connect these sections and was in progress when rainfall in September 1994 filled the reservoir (Ross, 1994a). The removal of 5 million m^3 of sediment from the Loíza reservoir that was completed in 1999 increased usable pool volume by 35%. The anticipated increase in yield is 19,000 m^3 day^{-1}, equal to 5% of the current production (Table 10). This increased storage capacity at the Loíza reservoir will help mitigate the effects of mild droughts in the future, but will be dependent on a program of continuous dredging, currently planned for 500,000 m^3 of sediment removal biannually (Vega and Terrasa-Soler, 1998). The water withdrawal rates at the La Plata and Loíza reservoirs are close to or above the firm yield calculated for each reservoir. Because the withdrawal rate is nearly double the firm yield of the Loíza reservoir, the recent rationing of water in San Juan was not unexpected and without other sources of water for San Juan, is likely to be repeated in the near term when ever streamflow is at or below the 10th percentile for more than a few months (Table 10).

In addition to the dredging of sediment from the Loíza reservoir, several other infrastructure projects were begun as a result of the drought of 1993–1995. Large-scale expansion of surface water exploitation using in-stream water extraction is in progress at various locations in Puerto Rico (Quiñones et al., 1998; Vélez-Arocho et al., 1998). The construction of numerous small filtration plants for in-stream extraction of surface water avoids the large cost and environmental impact associated with the construction of new reservoirs. However, the rate and timing of withdrawal must be carefully managed to minimize the impact that reduced streamflow has on water quality and aquatic fauna (Pringle and Scatena, 1999). A $500 million, 80-km pipeline project is scheduled to bring water from western Puerto Rico to San Juan at the anticipated rate of 380,000 m^3 day^{-1} (Quiñones et al., 1998). Except in the case of continued drought in western Puerto Rico, this large additional quantity of water should reduce the vulnerability of San Juan to droughts affecting the La Plata and Loíza reservoirs, as long as it is not overly used for new urbanization and development.

Water managers and planners in large urban areas of the United States have been reluctant to invest in expensive new sources of water as a solution to recent droughts (Changnon, 2000). The government of Puerto Rico responded aggressively to the droughts of the 1990s with major development and expansion of water-supply infrastructure as well as the dredging of the Loiza reservoir. The reservoir dredging project was the first ever to be authorized by the U.S. Army Corps of Engineers for a water body simultaneously being used for municipal water supply (Vega and Terrasa-Soler, 1998).

It is possible that, with better management and conservation of existing water supply, much of the development of new sources of public supply water would not have been necessary. Ultimately, however, sustainable management of the island's water resources will require more conservative water use by consumers and industry. In addition, a significant reduction in the amount of water that is lost during production and distribution is necessary. Without such changes, rationing may be commonplace in the future.

CONCLUSIONS

Annual rainfall accumulation averaged 87% of normal at 19 of 20 stations on eight islands in the Lesser and Greater Antilles from Barbados to Cuba from 1990 to 1997. Annual rainfall accumulation and streamflow deficits from 1993 to 1995 caused significant reservoir depletion that resulted in mandatory rationing of public-supply water to more than 1 million people in metropolitan San Juan, Puerto Rico. Analysis of monthly rainfall distribution and streamflow at selected stations in Puerto Rico indicate that the drought of 1993–1995 was not particularly unusual with respect to monthly rainfall and streamflow deficits. Changes in socioeconomic conditions may be the fundamental difference between the droughts of the 1990s and the droughts of the 1960s and 1970s. Between 1965 and 1995, there were large increases in the population served by public supply water (49%), public supply withdrawal (210%), and per capita consumption of water (108%), while reservoir storage capacity declined by 12% to 47% and available water that is lost or unaccounted for rose to 40%. These trends indicate that, even with increased surface and groundwater extraction, water rationing may become more common in the future unless water conservation, management, and distribution is improved.

The 1990s rainfall deficit in Puerto Rico occurred in the context of a regional dry period, indicating that large populations in the West Indies are vulnerable to water shortages. The total population of the 24 island nations in the West Indies is 37 million, equivalent to the state of California in the United States. The critical water shortages that occurred in Puerto Rico, the third most populous island in the West Indies, provide an example of the effect of increased consumption of limited water resources by growing population. The consequences of these extended dry periods of the 1990s on reduced streamflow and water resources are an example of the potential impact of global change on human systems. The rainfall deficits of the 1990s and resulting water-supply dilemmas provide a glimpse into the future for other regions of the earth as the potential impacts of increasing resource consumption and global change are quantified and better understood.

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