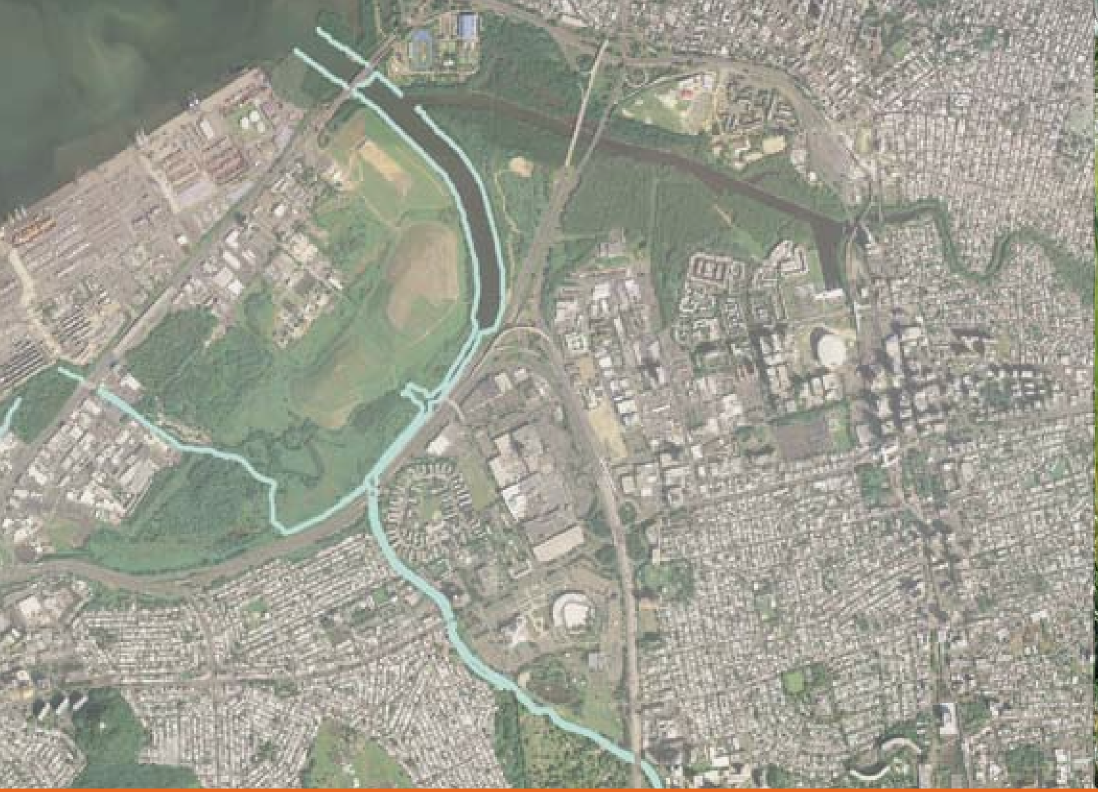

THE RÍO PIEDRAS WATERSHED
and Its Surrounding Environment

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U.S. Department
of Agriculture

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THE RÍO PIEDRAS WATERSHED
and Its Surrounding Environment

CONTENTS

Errata

Error in figure 33 on page 35. The Río Piedras Watershed and Its Surrounding Environment. FS-980. June 2011.

Please substitute this figure for the first map on page 35.

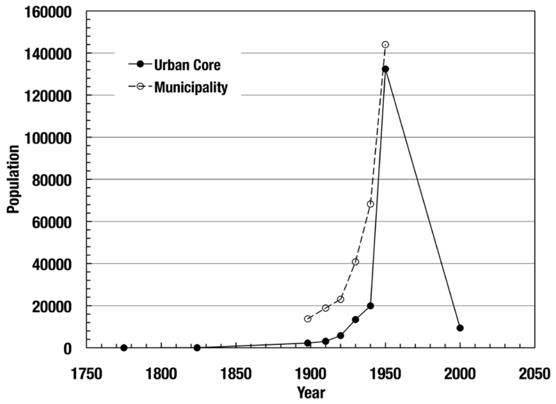

Figure 33. Population changes in the urban core and municipality of Río Piedras between 1774 and 2000 (from Sepúlveda Rivera 2004a).

Introduction

Today, more people live in cities than in rural environments. In Puerto Rico, the proportion of the population that lives in cities passed the 50-percent threshold in the late 1960s and was 94 percent in 2000 (López Marrero and Villanueva Colón 2006). Such a high concentration of human activity raises numerous conservation challenges. On the one hand, concentrating people in cities has positive outcomes to rural landscapes, which benefit from reduced human presence (Lugo 1991). On the other hand, natural and artificial ecological systems of cities are exposed to greater human influence, and it is not clear whether their resilience mechanisms will cope with anthropogenic effects or if the level of disturbance causes them to change states. Regardless of how particular urban ecosystems respond to human population activity, it is clear that quality of life in the city will benefit from healthy environments within and around the city.

The need to understand the functioning of urban environments has led to a new science focus on social ecological systems (SES) (Redman et al. 2004). Studying, understanding, and managing SES require access and synthesis of information from both natural and social sciences. New interdisciplinary and transdisciplinary alliances between these fields, in collaboration with urban communities, government agencies, and nongovernment organizations, will benefit from the compilation of information that is usually dispersed and possessed according to discipline among fragmented technical groups that seldom interact. This publication is such a compilation of biophysical information for the Río Piedras Watershed and its environment, developed in support of the establishment of a new scientific alliance intended to study and understand the SES of the San Juan Metropolitan Area (metropolitan area) (see box 1 for a description of the terminology of geographic locations used in this document and the use of units of measure).

Box 1. Identification of overlapping geographic locations used in this publication (fig. 1).

The San Juan Metropolitan Area (metropolitan area) includes the municipalities of Carolina, San Juan, Trujillo Alto, Guaynabo, Cataño, and Bayamón (fig. 1). Some consider Caguas (to the south) and other municipalities to the east and west as part of the metropolitan area, but we do not. We use only the name of the municipality when referring to the municipalities in the metropolitan area. The Río Piedras Watershed is part of the metropolitan area and includes parts of the municipalities of San Juan, Guaynabo, and Trujillo Alto. The Río Piedras mainstream flows through the following sectors of the municipality of San Juan: Caimito, Cupey, Monacillo, El Cinco, Puerto Nuevo, and Hato Rey. The watershed includes sectors of the municipality of Guaynabo: San Patricio (officially known as Barrio Pueblo Viejo) and Frailes. It also includes sectors from Trujillo Alto: Sabana Llana Sur, Cuevas, and Carraízo. Fifteen traditional barrios or neighborhoods occur within the Río Piedras Watershed (fig. B1-1). Río Piedras was an independent municipality until it was incorporated into the municipality of San Juan and became a sector of the city. We use Río Piedras when referring to the original municipality or current barrio, Río Piedras River when referring to the river, and Río Piedras Watershed when referring to the river's watershed. There is also a Río Piedras U.S. Geological Survey gaging station (50049000). Old San Juan is used to identify the 500-year-old urban sector of the municipality north of San Juan Bay. San Juan Bay Estuary Watershed is a Federal designation that is mostly located within the metropolitan area. Hydrologically, this watershed extends beyond the metropolitan area. We address only those aspects of the San Juan Bay Estuary Watershed of relevance to the Río Piedras Watershed.

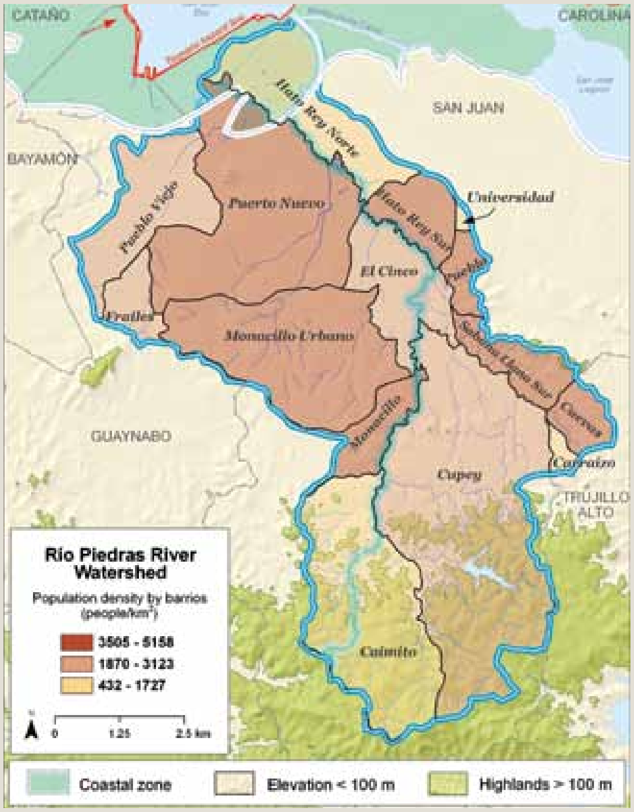

Figure B1-1. Map of the barrios within the Río Piedras Watershed.

We report units of measurement in the metric system, except when the original reference used other systems of measurement. In these situations we use the original unit and convert the value to metric in parentheses or provide a conversion factor.

Figure 1. Map of the San Juan Metropolitan Area showing its municipalities (outlined in black), the Río Piedras Watershed (outlined in blue), many of the geographic locations mentioned in the text, and environmental monitoring stations in the region. The appendix contains more information on each monitoring station. The map also shows the division of the city into three socioecological regions: the coastal zone, as defined by the National Oceanographic and Atmospheric Administration; the builtup matrix; and the rural areas to the south and above the 100-m elevation contour.

Figure 2. Delimitation of the geographic regions of the San Juan Metropolitan Area, according to Picó (1950). Numbers 1B and 7A represent the following categories: 1. northern coastal lowlands (B- Humid alluvial section); 7. humid northern foot hills (A- Northeastern Cretaceous section).

Geography

The Río Piedras Watershed is an urban watershed fully contained within the metropolitan area of San Juan (fig. 1). The watershed has an area of 49 km^2 (Haire 1971) and is located within two geographic regions of Puerto Rico (Picó 1950): the Northern Coastal Lowlands Humid Alluvial Section and the Humid Northern Foot Hills Northeastern Cretaceous Section (fig. 2). The Río Piedras is the only river in San Juan, and it originates at about a 150 m elevation and flows north for 16 km (fig. 3). Its headwaters are located in the Caimito district (or barrio) of San Juan, and as it flows to the Martín Peña Canal (where it enters Bahía de San Juan), the river passes through the Río Piedras, Hato Rey, and Puerto Nuevo districts of the metropolitan area. Two other rivers delimit the metropolitan area (fig. 1): the Río[1] Bayamón to the west, and the Río Grande de Loíza to the east. An additional river, the Río Puerto Nuevo, originates between the Río Piedras and Río Bayamón. Río Puerto Nuevo joins the Río Piedras (box 2) and, with the Río Bayamón, all are heavily influenced by urban development and have had their channels significantly modified (box 2).

The lowlands of the Río Piedras Watershed contain a coastal plain that is about 8 km wide. Anderson (1976, p. 3) described this coastal plain thusly: "…[it] slopes gently from the sea to the foothills. The plain has been built up by surficial deposits consisting of sand, silt, clay, and muck overlying a dissected older surface, the remnants of which stand above the plain as isolated mogotes or hills. Many of the mogotes rise more than 90 m above sea level and 60 m or more above the coastal plain." Marshes, mangroves, and lagoons lie inland offshore. The foot-

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[1] The use of either lowercase or uppercase for río (river) in Spanish is determined by whether the name describes the river—for example, Río Grande, which describes its size, as opposed to río Mameyes, which is a nondescriptive name. To avoid confusion, this document will use uppercase at all times.

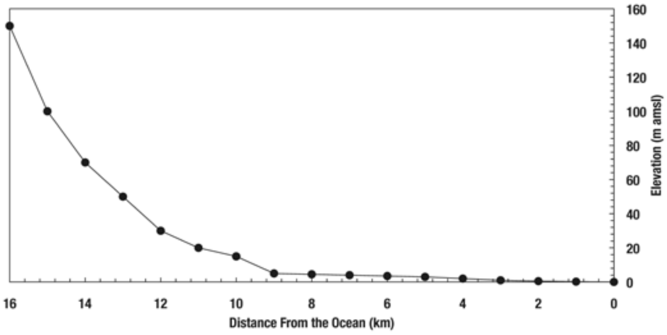

Figure 3. Elevation above mean sea level of the Río Piedras River as a function of distance from the ocean. Data were obtained from the Sand Juan Topographic Quadrangle of the U.S. Geological Survey.

Box 2. Historical maps show different modifications of the channels and different perceptions and cartographic delineations for the location of the main channels of the Río Piedras and Río Puerto Nuevo Rivers (based in part on Sepúlveda Rivera 2004a and 2004c).

The 1950 San Juan Quadrangle (fig. B2-1) shows the Río Piedras River merging as the same streambed into the Río Puerto Nuevo River about 1.6 km after its confluence with the Quebrada Doña Ana in Barrio Puerto Nuevo northwest of the Roosevelt Avenue midsection. The Río Puerto Nuevo then flows into San Juan Bay. At present, the two rivers come together to discharge into San Juan Bay but do so at their engineered confluence with the Caño Martín Peña, east of the historical point of discharge to the bay (fig. B2-2). Río Puerto Nuevo River is identified in some maps as the river reach between the confluence of the Río Piedras River with Canal Margarita and the confluence with the Caño Martín Peña. Over decades and centuries, many alterations have been made to the channels of these two rivers, initially because the channels passed through extensive mangrove forests before discharging into the bay and, more recently, because of dramatic urban development on filled wetlands and outright burial of stream channels. The dramatic alteration of river channels is illustrated in fig. B2-3, which compares the surface channels in 1949 with those in 1998. Figure B2-4 shows the network of potable water pipes and sewer lines that now constitute an artificial hydrologic network below the surface of the city. This network carries more water annually than does the natural hydrologic network (table 1).

More changes are in progress for the Río Piedras River channel and tributaries in the watershed (fig. 17) as part of the channelization works of the Río Puerto Nuevo River, which is the designation of the U.S. Army Corps of Engineers (USACE) that includes both the Río Puerto Nuevo and Río Piedras Rivers. The USACE reported an area of 62.8 km^2 for the basin of the Río Puerto Nuevo, with a population of 250,000 people in the 1980s (Colón 1984).

Table 1. Annual water budget for the Río Piedras Watershed (Departamento de Recursos Naturales y Ambientales 2004).

	Item	**Acre-feet of water**
INPUTS	Rainfall	106,076
	Transfer from other watersheds	174,892
FLUXES	Evapotranspiration	66,963
	Storage in aquifer	8,000
	Aquifer extraction	448
	Discharge of used water to the ocean	64,726
	Net flow to the ocean	61,920
	Aquifer discharge to the ocean	1,000
	Unaccounted water	88,410

One acre-foot is 325,872 gallons or 1,233.4 cubic meter.

Figure B2-1. Detail of San Juan U.S. Geological Survey 7.5 min Topographic Quadrangle (1950) [1:25,000 scale].

Figure B2-2. Detail of San Juan Bay, orthophoto 2007. The Río Piedras-Río Puerto Nuevo stream channel is highlighted in light blue.

Box 2. Historical maps, continued

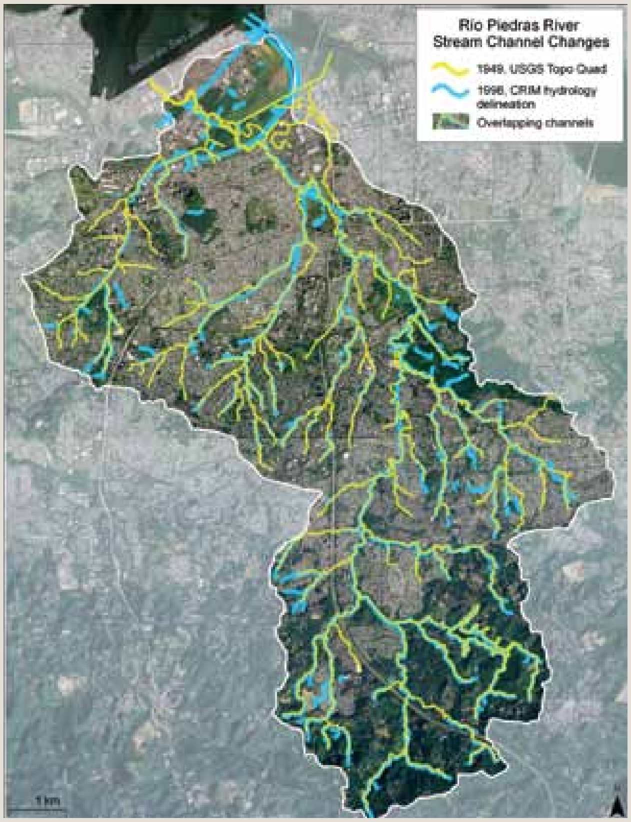

Figure B2-3. Stream and river channels in the Río Piedras Watershed as they appeared in the 1949 US. Geological Survey Topographic Map and in the 1998 Centro de Recaudaciones de Ingresos Municipales hydrology delineation.

Figure B2-4. Network of pipes (potable water in white and sewer lines in red; stormwater not shown) in the Río Piedras River Watershed. The watershed is delineated with a black line; the surface river channels are in blue. Data are for 2006. The infrastructure is managed by the Puerto Rico Authority of Sewers and Acueducts. The Geographic Information System layer data set was obtained from the Puerto Rico Highway Authority.

Figure B2-5. Detail of a 1660 map of the San Juan Bay, depicting the Río Piedras River, the settlement of Río Piedras, and the Caño Martín Peña (Sepúlveda Rivera 2004a).

Figure B2-6. Detail of the 1776 map of San Juan Bay and its environment by Thomas O'Daly (Sepúlveda Rivera 2004a).

Box 2. Historical maps, continued

The natural hydrologic connection between the Río Piedras and Río Puerto Nuevo Rivers, the historical changes to their channels, and the historical uses of these rivers for commerce and other purposes cause confusion, because different maps over the past 300 years show different alignments and connections between them. Here, we present a comparison of historical maps to illustrate how the perception of the location of these rivers has changed.

The Río Piedras River, depicted in a 1660 map of the San Juan Bay, is shown discharging directly into the bay (fig. B2-5). The map also shows the Caño Martín Peña; unlike today, these two channels were not connected to each other. The 1776 map of San Juan Bay and its environment (today's metropolitan area) by Thomas O'Daly (reproduced in Sepúlveda Rivera 2004a) shows the natural features of this region before any development took place (Old San Juan being the exception). In that map (fig. B2-6), which includes lagoons and extensive mangrove and wetland areas, the mouth of the Río Puerto Nuevo River is labeled and shown to be discharging directly into the San Juan Bay. Although the Río Piedras River is not named, a continuous channel from the mouth is shown with a similar alignment to the 1950 river location, leading us to believe it is the same Río Piedras riverbed. Large areas of mangroves and wetlands fringe the lowland reaches of the river. A Spanish Army Corps of Engineers map for 1887 (fig. B2-7) shows these tributaries and canals as being part of the drainage of a fringe mangrove forest, including several tidal channels. All canals drained independently into the bay, however. Yet, an 1884 map by the same Spanish Army Corps of Engineers (fig. B2-8) identifies the Río Puerto Nuevo River as merging with Quebrada Las Margaritas and then flowing into the bay. That map does not show the Río Piedras River.

Both rivers remain as separate canals draining into San Juan Bay in a regional map of San Juan, dated 1898 (fig. B2-9). This map shows a small creek to the east of the Río Piedras River as a tributary to the Río Piedras River and its apparent connection at its inland origin with another canal that drained into the bay between the Río Piedras River and the Caño Martín Peña.

Figure B2-7. 1887 Spanish Army Corps of Engineers map for San Juan Bay area (Sepúlveda Rivera 2004a).

Figure B2-8. 1884 Spanish Army Corps of Engineers map for San Juan Bay area (Sepúlveda Rivera 2004a).

Figure B2-9. 1898 U.S. Military map for San Juan Bay area (Sepúlveda Rivera 2004a).

hills are rounded with elevations of 300 m and up to 600 m. They are composed chiefly of sandstone and siltstone, associated volcanic and intrusive rocks, and some limestone (Anderson 1976). Streams and rivers, such as the Río Piedras, pass through these foothills through narrow valleys whose flood plains are flanked by alluvial terraces.

Climate[2]

San Juan is in Holdridge's subtropical moist forest life zone (1967). Mean annual rainfall (fig. 4) in the basin increases from the coast (1,509 mm) to the uplands (1,755 mm at 8 km inland), and the ratio of pan evaporation to rainfall changes in the same distance from 1.37 to 0.98. Rainfall is seasonal (fig. 4), with the rainy season coinciding with the hurricane season (July through October) and a dry season (January to April). May has a secondary wet period. Severe droughts are recurrent in San Juan and have been recorded in the 1920s, 1930s, 1960s, 1970s, and 1990s (fig. 5a). Anderson (1976) reported 209 days with measurable rainfall during an average year in Old San Juan. The long-term rainfall record for Old San Juan (fig. 5a) reflects a decreasing trend over a 107-year period. Picó (1969) reports six hurricanes and storms with significant effects on Puerto Rico between 1893 and 1956. Since then, several other hurricane events have affected the island, with Hurricanes Hugo and Georges being the most severe in terms of wind effects. Two hurricanes, San Nicolás, in 1931, and San Ciprián, in 1932, passed directly over the metropolitan area. Hurricane San Felipe crossed the island diagonally and San Juan was protected by the Cordillera Central; however, the strongest winds recorded in San Juan were those of Hurricane San Felipe in 1928, with 150 mi/h (240 km/h or 66.7 m/s) winds.

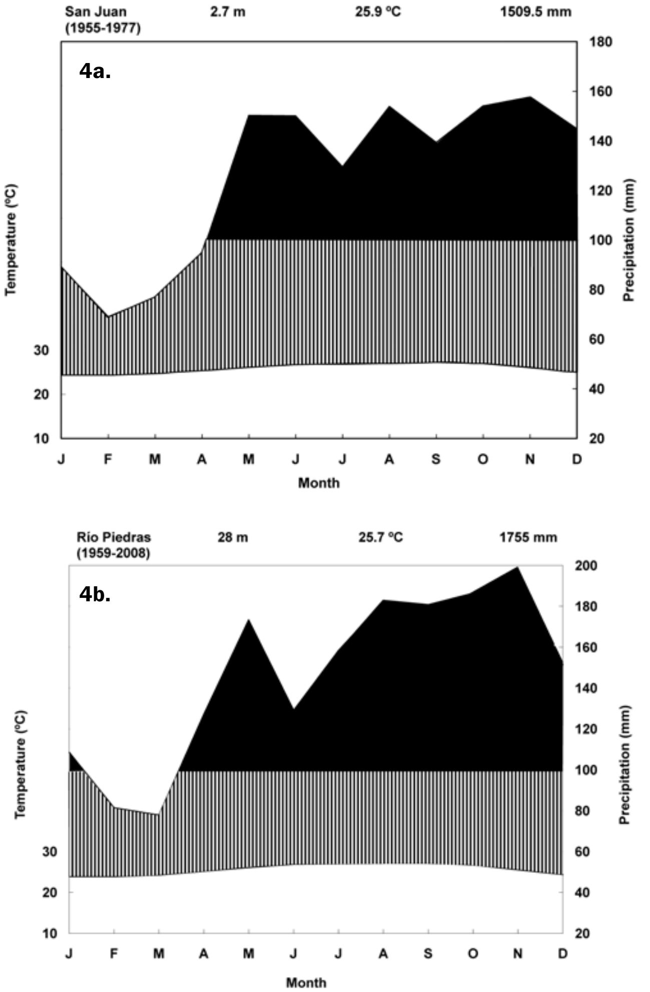

Figure 4. Walter (1971) climate diagram for Old San Juan (a) and Río Piedras (b), Puerto Rico. Solid black represents wet conditions with > 100 mm per month; vertical lines represent moist conditions where the rainfall exceeds potential evapotranspiration. The information on top of each graph shows the location, length of record, and elevation of the station and the annual means for temperature and precipitation.

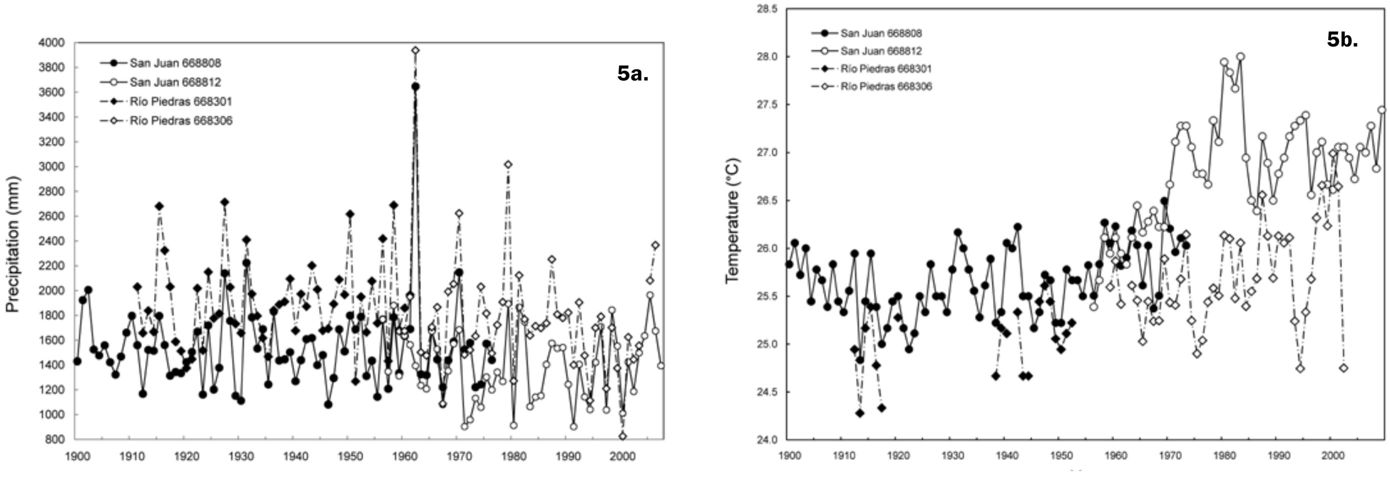

Figure 5. Long-term annual precipitation (a) and air temperature (b) for Old San Juan and Río Piedras, Puerto Rico. Lines represent a 5-year running average. Data are from the National Oceanographic and Atmospheric Administration.

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[2] A list of official climatic, hydrologic, and air quality stations in the metropolitan area is shown in the appendix.

Maximum winds in San Juan for San Ciprián reached 120 mi/h (192 km/h or 53.3 m/s).

Mean annual temperature for Old San Juan and Río Piedras is 25.9 °C and 25.7 °C, respectively (fig. 4). The average temperature ranges from 27.2 °C in August to 23.9 °C in January. Old San Juan Climate Station (2002399) was in service from 1898 until 1977. Temperature data are available until 1973. A new station (2002398) was established in 1955 at the San Juan International Airport (now Luis Muñoz Marín International Airport). Data from this station are available from 1955 to the present. Only 16 years of coincidental temperature data exist between these two stations in San Juan. Both stations show similar temperature records until 1964. The new station shows an increase of temperature from 1965 and a rapid increase after the 1970s (fig. 5b). If the data are plotted monthly for representative years, every month shows temperature increases between 1952 and 1981 (fig. 6). After 1981, the monthly means are higher than before 1981 but tend not to exceed 1981 values. These temperature increases are not reflected in the National Oceanographic and Atmospheric Administration (NOAA) Río Piedras Climate Station (20023985) nearby. This difference suggests a heat island effect in Old San Juan rather than global warming. González et al. (2005) and Velázquez Lozada et al. (2006) reported heat island effects for the metropolitan area, and Velázquez Lozada et al. (2006) found that air temperature has been increasing at a rate of 0.06 °C/yr over the past 40 years. Murphy et al. (in press) found a 1.54 °C heat island effect in the metropolitan area and related it to land cover. This effect may be reflected in urban climate stations, such as the one in Old San Juan in its last 8 years of service, where the surroundings have been urbanized. The sharp increase of temperature after 1964 in the newest San Juan station might be explained similarly, given that the surroundings have been urbanized over the past 100 years.

The prevailing daytime winds in the city are from the northeast at 4.3 to 6.1 meters per second (m/s) and they prevail from the southeast at 2.2 to 4.8 m/s during nighttime (fig. 7). For the region, the prevailing winds are from the east and northeast, but, from September to November, wind currents alternate from the south and southwest. City climate is moderated by diurnal sea breezes that result from differential land/sea heating. These offshore breezes reverse direction at night.

At the onset of the 20th century, a group of scientists sponsored by The United States Fish Commission Steamer Fish Hawk (U.S. Fish Commission 1900) recorded climate parameters in San Juan for a complete year between May 1899 and April 1900. Their observations in figures 8 to 10 are presented in the original units of measurement as a historical curiosity. The long-term rainfall pattern was visible that year (fig. 8), with dry months in February to March and peak monthly rainfall in September. A 5-inch (125 mm), 24-hour rainfall event took place in August. Minimum temperatures dipped in December and maximum temperatures were high in April (fig. 9). Clear days prevailed during the dry season, and June had the greatest number of rainy days (fig. 10).

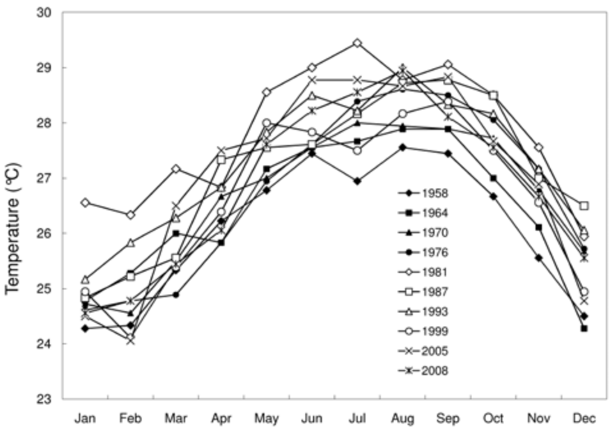


Figure 6. Mean monthly air temperature for a variety of years using data from the Old San Juan Climate Station. The original analysis from Seguinot Barbosa (1983) was updated.

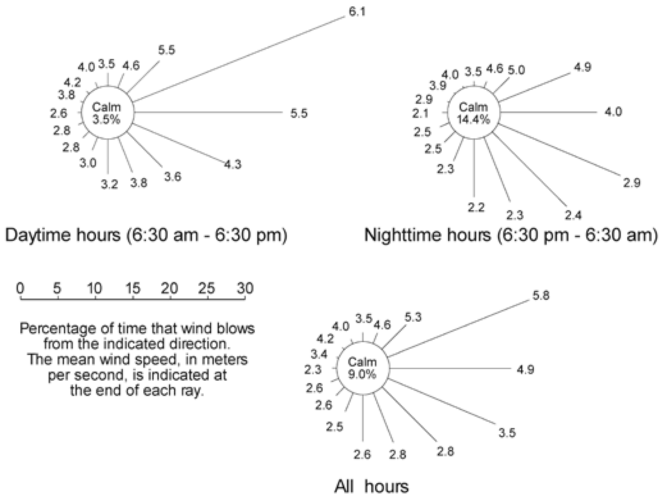


Figure 7. Wind speed and direction for daytime, nighttime, and all hours in San Juan (Webb and Gómez Gómez 1998). Wind speed is in meter per second and is indicated at the end of each ray. The length of the ray is the percentage of time the wind blows in the indicated direction.

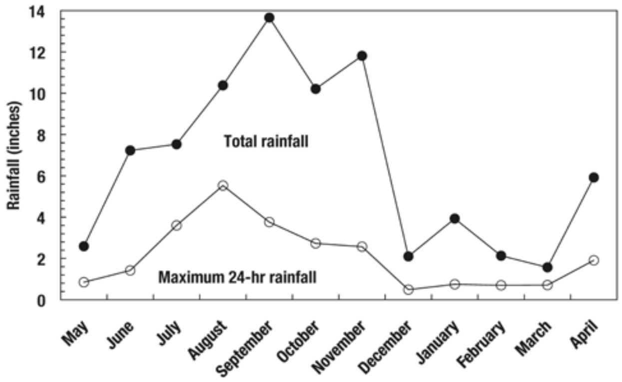


Figure 8. Total rainfall and maximum 24-hour rainfall in Old San Juan in 1900 (U.S. Fish Commission 1900). To convert to millimeters, multiply inches by 2.54.

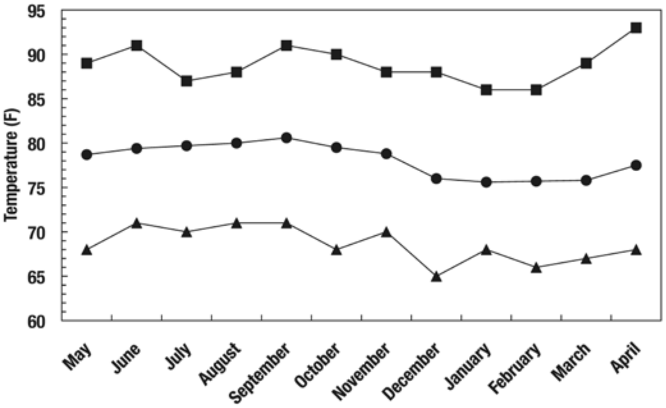


Figure 9. Maximum (squares), minimum (triangles), and mean (circles) air temperature in Old San Juan in 1900 (U.S. Fish Commission 1900). To convert to °C, subtract 32 from °F and multiply by 5/9.

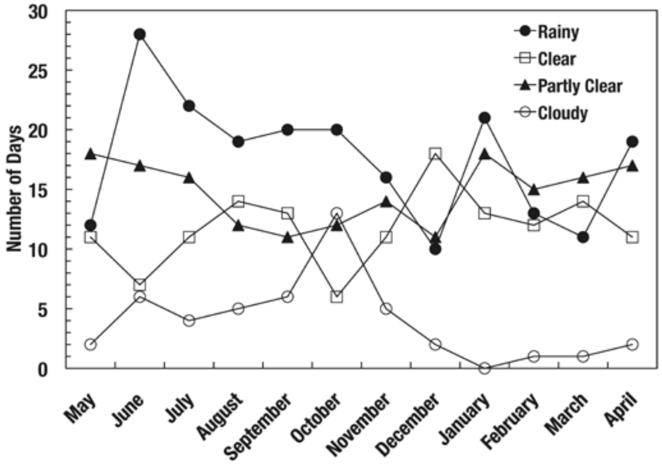


Figure 10. Sky condition in Old San Juan during 1900 (U.S. Fish Commission 1900).

Geology

The Río Piedras River flows over surficial deposits (alluvial, terrace, blanket sand, beach, and dune deposits) ranging in age from Miocene (about 23.5 million years [Ma] ago) to Holocene (about .01 Ma) (Anderson 1976). These surficial deposits mantle the bedrock over the length of the channel (fig. 11). They are less than 15 m deep above the contact between the volcanic and sedimentary rocks and 15 to 30 m deep below the contact point in the lowlands (Anderson 1976). The sequence of underlying rocks from the uplands to the coastal zone described by Anderson includes (in order): volcanic, San Sebastián, Cibao, Aguada, and Aymamón (the last three are sedimentary rocks).

The volcanic rocks occur in the northern foothills south of the metropolitan area and include volcanic tuff, breccia, and lava (Anderson 1976). These rocks are of Cretaceous (about 89 Ma) and Tertiary (about 65 Ma) age and generally lack permeability, except in a weathered and fractured surficial zone that follows the general topography. Pease and Monroe (1977) mapped to a depth of 400 m the geology of the San Juan quadrangle, which includes the Río Piedras Watershed. They mapped 22 stratified rock types and one intrusive rock type. The oldest types are the Guaynabo and Monacillos formations. The Río Piedras formation is from the Eocene Epoch and is about 1,000 m thick.

Pease and Monroe described the stratigraphy of the quadrangle as follows: "...consists of Cretaceous and lower Tertiary clastic and volcaniclastic stratified rocks and thin lavas that are unconformably onlapped by unconsolidated to poorly consolidated sand, silt, and gravel of middle Tertiary to Holocene age along the southern border of the quadrangle [inland towards the origin of the Río Piedras]. Reef limestone, also of middle Tertiary age, occurs in sporadic outcrops, mostly forming prominent hills and ridges that have been deeply excavated by quarrying. Quaternary [about 1.64 Ma] and possibly upper Tertiary [about 5.2 Ma] beech, eolian, swamp, and alluvial deposits form most of the land area in the northern half of the quadrangle [towards the coastal zone], except that large parts of Bahía de San Juan and Laguna San José have been artificially filled." (Pease and Monroe 1977)

The following descriptions of the geologic formations that constitute the sedimentary rocks within the Río Piedras Watershed are from Anderson (1976, pp. 9–11); consult Lugo et al. (2001) for more detail on these formations.

- San Sebastián Formation. The San Sebastián Formation of Oligocene age is composed of crossbedded to massive beds of sand, sand and gravel, and sandy clay, with some thin beds of sandstone and sandy limestone. The formation can be considered consolidated but is essentially uncemented. The formation attains its maximum thickness of about 500 ft (150 m) in the western part of the metropolitan area, but Pease (1968) attributes 150 ft (45 m) of this thickness to the Mucarabones Sand, a formation overlying the San Sebastián and grading into the Cibao. Work in the Bayamón quadrangle by Monroe (1973) indicates that the Mucarabones Sand intertongues eastward with the entire lower part of the overlying Cibao Formation, so that the age of the Mucarabones Sand is Oligocene and Miocene. The San Sebastián Formation commonly is 165 to 330 ft (50 to 100 m) thick, becoming progressively thinner to the east.

- Cibao Formation. The Cibao Formation is of Oligocene and Miocene age and conformably overlies the San Sebastián Formation. The Cibao is composed of interbedded marl, limestone, clay, sand, and gravel. It attains its maximum thickness of 380 ft (115 m) in the westernmost part of the metropolitan area, thinning eastward to about 130 ft (40 m) thick in the vicinity of Carolina. In the westernmost part of the metropolitan area, the Cibao has been divided into five Members (Monroe and Pease 1962): (1) *Upper Member*—chalk, sandy limestone, and sandy marl; 100 to 160 ft (30 to 50 m) thick. (2) *Miranda Sand Member*—sand and gravel, filling channels cut into the underlying limestone; 0 to 60 ft (0 to 20 m) thick. (3) *Quebrada Arenas Limestone Member*—consists of alternating beds less than 3 ft (1 m) thick, of dense crystalline limestone and soft marly limestone; 0 to 70 ft (0 to 20 m) thick. (4) *Río Indio Limestone Member*—a yellowish-orange earthly limestone that grades into a sandy marl toward the east; reported to be 230 ft (70 m) maximum thickness. (5) *Lowermost member* (unnamed)—consists of sandy limestone and marl facies transitional with the San Sebastián; 100 to 230 ft (30 to 70 m) thick.

The three middle members apparently crop out only in the Bucarabones Valley. The upper and lowermost members are identifiable in the vicinity of the Río de Bayamón.

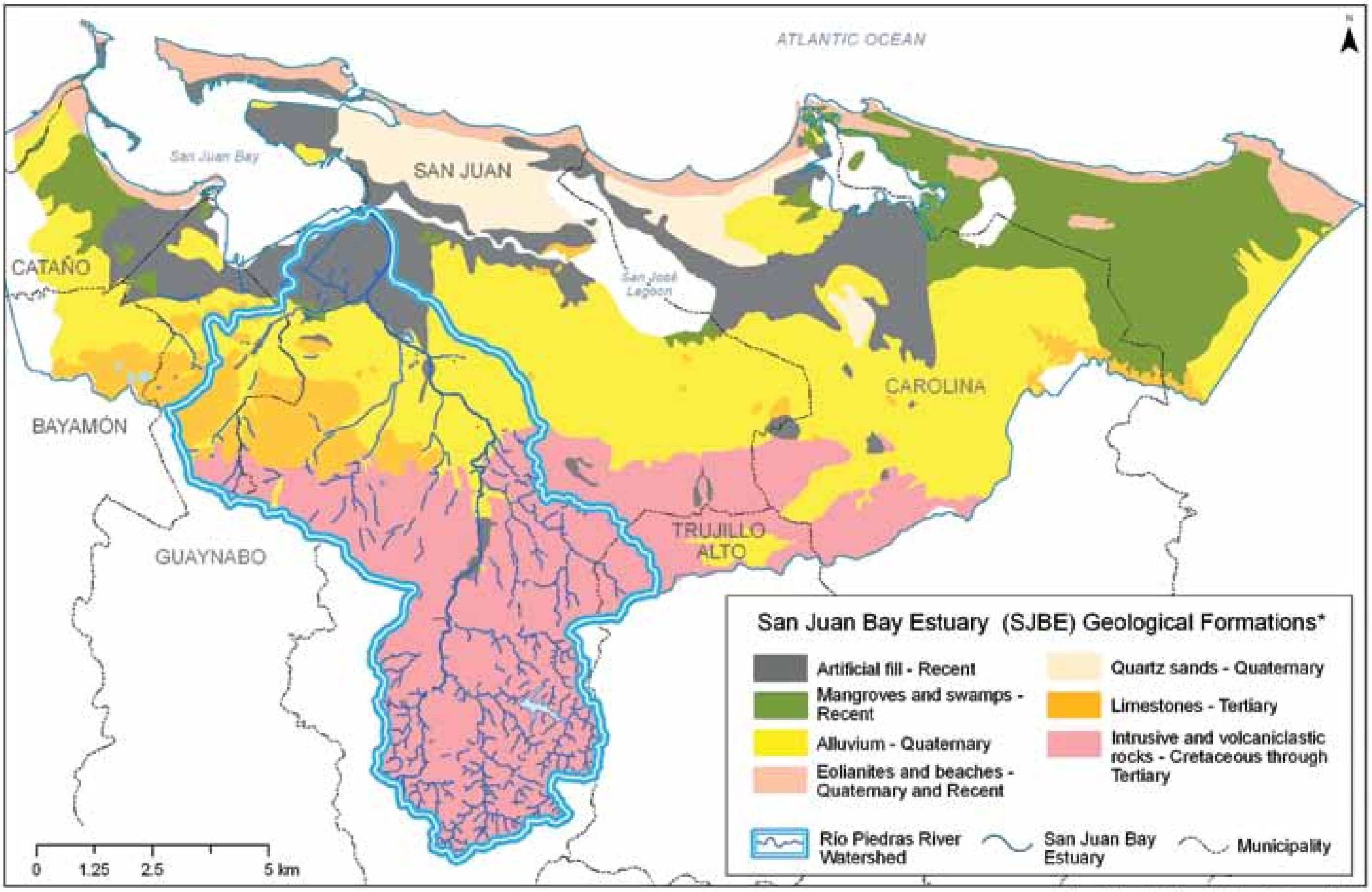
In the Carolina area, the Cibao overlaps the San Sebastián and is believed to rest directly on the bedrock formations of tuff and volcanic rocks. Here the formation is about 130 ft (40 m) thick.

In places, the Cibao forms topographic ridges but more commonly makes up the lower slopes of hills and mogotes capped by the more resistant Aguada and Aymamón Limestones. In the San Juan area, exposures of the Cibao are evident at the base of Montes San Patricio, Montes de Canejas, and the smaller hills south of the San José Lagoon.

- Aguada Limestone. The Aguada Limestone of Miocene age is a transitional formation between the Cibao marl and the relatively pure crystalline limestone of the overlying Aymamón Limestone. Briggs and Akers (1965) described the Aguada on the north coast as "hard, thick-bedded to massive calcarenite and dense limestone interbedded with chalky limestone and marl; commonly containing some quartz grains and locally thin-bedded near top." It ranges in thickness from 100 to 250 ft (30 to 75 m) in outcrop in the study area. South of the Bahía de San Juan, the hard crystalline beds occur in the upper part while the softer and marly beds predominate in the lower part (Gelabert 1964).

  The Aguada is a ridge former and, together with the Aymamón Limestone, makes up most of the mogotes in the San Juan area. Except for these last remaining vestiges of the great karst region to the west, the limestones in San Juan have been largely eroded away and covered with alluvial clay, sand, and beach deposits.

- Aymamón Limestone. The uppermost limestone, the Aymamón of Miocene age, is exposed as case-hardened caps on a few hilltops in Montes de Canejas and in the small hills around the juncture of Caño Martín Peña and the Laguna



* Adapted from Webb and Gómez-Gómez, 1998

Figure 11. Generalized surficial geology for the San Juan Bay Estuary Watershed (from Webb and Gómez Gómez 1998). The Río Piedras Watershed is delineated with a blue line.

San José. Elsewhere it lies beneath a mantel of alluvium and other surficial deposits. The following description of the formation is given by Zapp, Berquist, and Thomas (1948): "It consists almost entirely of very dense conchoidally fracturing limestone of white, light gray, buff and rose colors; unit is quite uniform over its entire outcrop and throughout its entire thickness." The map by Monroe and Pease (1962) of the Bayamón quadrangle shows the limestone outcrops, both of the Aguada and Aymamón to be quite extensive, forming the tops of many of the haystack hills. In the Bayamón area, the Aymamón is either pink or white, well indurated, usually dense limestone; 215 ft (65 m) thick were exposed. Kaye (1959) estimates the thickness of the Aymamón to be as much as 2,000 ft (600 m) at the coastline. Geophysical studies at Palo Seco indicate an aggregate thickness of middle Tertiary limestones (Aguada and Aymamón) to be about 3,000 ft (900 m).

Pease and Monroe (1977) mapped four faults in the San Juan quadrangle, including one on the southern part of the quadrangle, which is part of the Leprocomio fault, one of the principal faults of the great northern Puerto Rico fault zone. This fault is the eastern of two wrench faults, with the western fault moving left lateral and the Leprocomio fault moving right lateral. The entire block between the two faults appears to have moved several kilometers to the west relative to rocks on the other side.

Hydrology

Ground Water

Ground water is mostly stored in the Tertiary sand and limestone aquifers. These aquifers recharge mostly by rainfall in their outcrop areas, from infiltration of streamflow, and from infiltration in the volcanic zone. Leaky water and sewer lines in the urban area are a secondary source of aquifer recharge (Anderson 1976). The aquifers discharge to the large wetlands and lagoons along the coastline.

In the volcanic zone of the watershed, most drainage is converted to streamflow. In some areas, volcanic rocks can discharge into sedimentary rocks. Most ground water discharge is to streams (Anderson 1976). Ground water recharge is cyclic and occurs during the rainy season and also during large storms that can occur at anytime. Urbanization and paving of surfaces is reducing the recharge areas in the metropolitan area, but leakage from sewer and water mains makes up part of the loss. At the time of Anderson's report (1976), that leakage was 1.2 m^3/s.

The Aymamón Limestone contains saltwater throughout most of the metropolitan area, yielding as much as 130 L/s of saltwater (Anderson 1976). The artesian aquifer has not encountered seawater intrusion, however. The upper part of the Cibao Formation and the Aguada and Aymamón Limestones form a prolific unconfined aquifer with the freshwater part, ranging from 3 to 1 km in width between Bayamón and Carolina. The yields of this water-table aquifer range from 2 to 160 L/s and an average of 32 L/s. This aquifer is a high-conductivity aquifer, with an average transmissivity of 1,200 m^2/day (range from 650 to 12,500 m^2/day). Ground water is mostly a calcium bicarbonate type, and some water is a sodium sulfate type (Anderson 1976).

Surface Water

Most of the runoff in the Río Piedras Watershed originates over the volcanic rocks and the impervious urban surfaces. Infiltration occurs largely through the weathered zone from which it flows into stream valleys. The Río Piedras River has a steep gradient within its first 8 km before it reaches the lowlands (fig. 3). This topography causes rapid stage increases after intense rainfall events and flashy streamflows (Osterkamp 2000). For example, a 26-year record at the U.S. Geological Survey (USGS) Río Piedras River at Hato Rey Gaging Station (50049100; see appendix for location and other data) shows that peak discharge is 170 times the mean discharge. In addition to the steep gradient in the uplands, other factors contribute to high-velocity flows and flash foods. One factor is the channelization of most of the tributaries nearly to their headwaters, including concrete-lined channels. A second factor is the large fraction of impermeable surfaces in the city. Osterkamp (2000) estimated that the mean discharge of the Río Piedras River at the Hato Rey Gaging Station was 1.7 m^3/s before urbanization and now averages 2.3 m^3/s after urbanization.

A third factor altering the urban hydrology is the paving over ephemeral and intermittent streams that form the drainage network of this watershed. In some cases, permanent streams are buried under thick layers of fill accompanied by considerable land movements involving reshaping of the local topography (box 2). An example is Quebrada Chiclana (photo 1a–d), where a gigantic French drain was constructed over the stream with rocks and soil fill. Concerns for erosion and safety led to litigation and the stream channel was ordered restored in 2003 at a cost of millions of dollars.

USGS Gaging Station at Río Piedras 50049000, which drains 39.4 km^2, is located at a 5 m elevation, averages about 26 Mm^3/yr (million cubic meters per year) (15-year record), equivalent to 810 mm of runoff. With an average rainfall of 2,000 mm, this runoff results in a runoff-to-rainfall ratio of 0.40 for the less urbanized area of the basin (Webb and Gómez Gómez 1998). A ratio of 0.60 was used for the urbanized areas of the basin to raise the input to San Juan Bay from the Río Piedras River to 185 Mm^3/yr. Ortiz Zayas et al. (2006) used a 29-year record for the same station (updated to 2002) to estimate an annual runoff of 1,200 mm and reported a 63-percent urban cover in the watershed.

The discharge record shows wide fluctuation in two stations along the river (fig. 12). The USGS Río Piedras River at El Señorial Gaging Station (50048770) (fig. 12a) shows a decrease discharge during the dry season months of February and the drought of 1994. The trend line for the USGS gaging station at Río Piedras (fig. 12b) reflects annual discharge variation and

Photo 1. The Quebrada Chiclana (a) is a small rocky stream in the uplands of the Río Piedras Watershed that flows through deep valleys covered with vegetation (b). As is customary in Puerto Rico, a developer filled the steep valleys (c) to level the terrain and construct expensive housing over Quebrada Chiclana (d). Photos by A.E. Lugo.

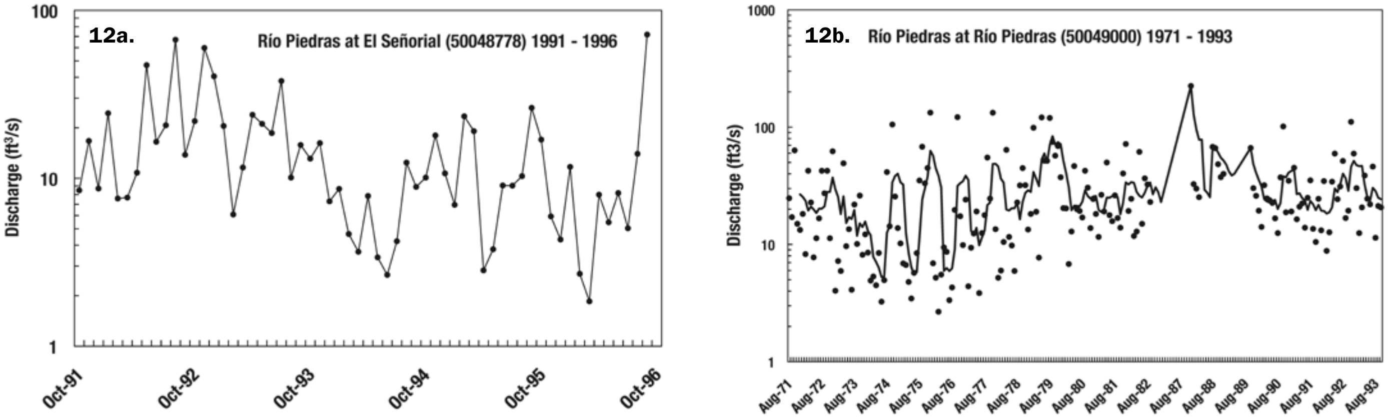


Figure 12. Water discharge for two U.S. Geological Survey gaging stations (station numbers in parentheses) along the Río Piedras River. Monthly values for the station at El Señorial (a) are connected, while a 5-year running average is shown for the monthly data from the Río Piedras station (b). To convert to cubic meter per second, multiply cubic feet per second by 0.02832.

apparent longer trends with periods of decline (1971 to 1974), followed by a period with variable but increasing annual discharge values (1974 to 1988) and another period of decline (1988 to 1993). Unfortunately, data collection at these stations has stopped. The USGS gaging station at Hato Rey drains an area of 15.2 mi^2 (39 km^2) and has a mean flow of 51.21 ft^3/s (1.45 m^3/s), a Q_{99} of 1.5 ft^3/s (0.04 m^3/s), and minimum and maximum flows of 28.7 (0.81 m^3/s) and 10,500 ft^3/s (297.4 m^3/s), respectively.

Periods of high discharge are common in the available record (fig. 13) with peak discharges at about or higher than 10,000 ft^3/s (283.2 m^3/s) during hurricanes and events associated with stationary fronts. The peak flows are considered part of the mean daily flow computation and are reflected in the mean daily flows used to generate the flow duration curve as in the one for the period 1971 to 1982 (fig. 14). In contrast with mean annual discharges of about 55 ft^3/s (1.56 m^3/s) during years of high discharge, the mean annual discharge during the drought years of 1974 and 1994 was about 10 ft^3/s (0.28 m^3/s) and less than 10 ft^3/s (0.28 m^3/s) (fig.15). These droughts resulted in water rationing in the metropolitan area.

The relative flows of tidal and freshwater runoff to the coastal lagoons and to the San Juan Bay favor the marine fluxes, but, during dry weather, the Río Piedras River is a main source of freshwater to the San Juan Bay (fig. 16). During intense rainfall events, river and stormwater discharges dominate the tidal flow patterns of the lagoons. For example, a 70 mm rainfall over a 12-hour period (a common event) generated sufficient storm runoff

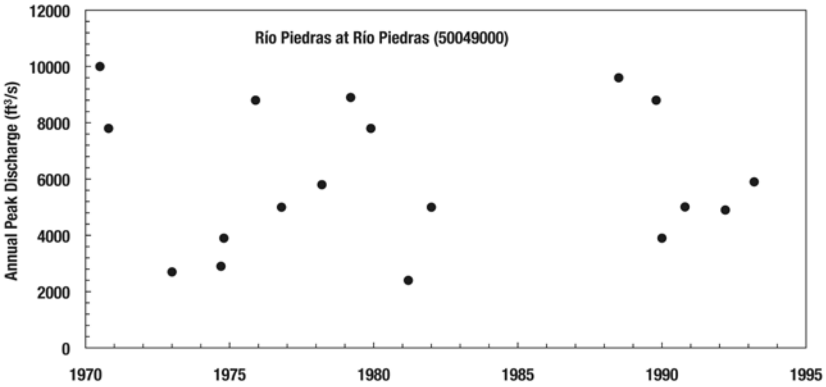


Figure 13. Annual peak discharge rates for the U.S. Geological Survey (USGS) Gaging Station at Río Piedras (station number in parentheses). The two data points before 1973 are from Haire. Data are from the USGS. To convert to cubic meter per second, multiply cubic feet per second by 0.02832.

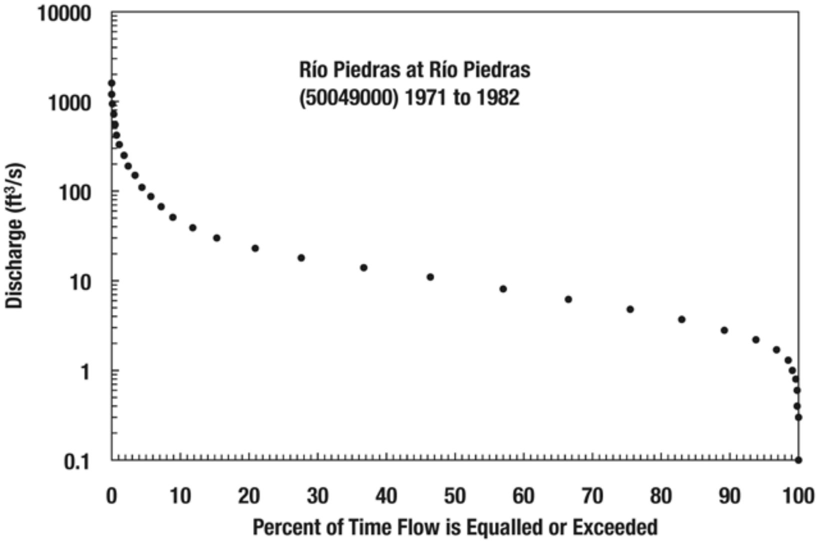


Figure 14. Flow duration curve for U.S. Geological Survey (USGS) Gaging Station at Río Piedras (station number in parentheses). Data are from the USGS. To convert to cubic meter per second, multiply cubic feet per second by 0.02832.

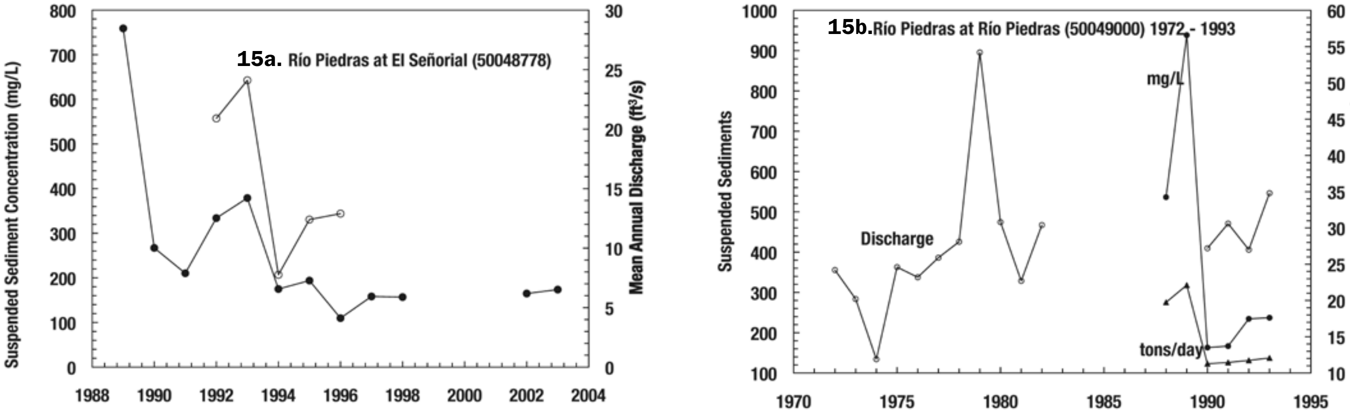


Figure 15. Mean annual discharge (open circles) and suspended sediment concentration (solid circles) in U.S. Geological Survey (USGS) gaging stations at (a) Río Piedras at El Señorial (station number in parentheses), and mean annual discharge, suspended sediment concentration, and suspended sediment export (solid triangles) at (b) Río Piedras at Río Piedras. Data are from the USGS. To convert discharge to cubic meter per second, multiply cubic feet per second by 0.02832, and to convert export to megagram per day, multiply tons per day by 0.9072.

(3.6 Mm^3 or 20 percent of the total volume of Laguna San José, Laguna La Torrecilla, and Laguna de Piñones) to change tidal flows within these lagoons (Webb and Gómez Gómez 1998).

The Departamento de Recursos Naturales y Ambientales (2004) delineated the Río Piedras Watershed and developed a water budget for the watershed (table 1). The budget shows a larger transfer of water to the watershed (for human consumption) than the annual rainfall on the watershed. The water budget is not balanced because a large proportion of the water is unaccounted for. This unaccountability is probably the result of leaky water pipes, which is estimated at about 50 percent at the present (Departamento de Recursos Naturales y Ambientales 2004).

Floods and Flood Control

Haire (1971) reported floods in the Río Piedras watershed for May 23, 1958; November 12, 1961; October 12, 1963; September 16, 1966; June 15 through 17, 1970; and October 5 through 7, 1970. He reported flooding depths of up to 2 m in the last kilometer reach of the Río Piedras. Peak discharges at the Jesús T. Piñero Avenue (4.55 mi [7.3 km] from the mouth) during the flood of June 17, 1970, were 10,000 ft^3/s (283.2 m^3/s) or 650 ft^3/mi^2 (7.11 m^3/km^2). The corresponding discharges for the October 1970 flood were 7,800 ft^3/s (221 m^3/s) and 506 ft^3/mi^2 (6.63 m^3/km^2). These peak discharges had a recurrence interval of 8 and 5 years, respectively, based on data available in the 1970s. Figure 13 substantiates the assumption. A recent flood occurred in November 2009 when the discharge at the USGS Río Piedras Gaging Station (50049000 exceeded 11,000 ft^3/s (>312 m^3/s).

Floods in the Río Piedras Watershed affected some 5,700 families in the 1980s, 325,000 m^2 of commercial space, large land and sea-oriented transportation facilities, and numerous public buildings and facilities (Colón 1984). The value of property in the flood plain was estimated at $3 billion, with quantifiable average annual damages of $20 million and $38.9 million when future conditions are considered (Colón 1984). This increase was expected to occur because of higher stages in flooding and the affluency factor rather than new construction in the flood plain. These calculations were used to justify a proposal for the channelization of the river (fig. 17). The channelization involves 10.4 km of the Río Puerto Nuevo River (lower reach of the Río Piedras, see box 2), 6 km of two of its principal tributaries, and diverting 1.3 km of a third tributary to protect against the 100-year flood. The plan requires eliminating 13.5 ha of mangroves and replacing 22 bridges (15 of them are major highways and avenues). In 1984, the estimated cost of the project was $235.5 million (Colón 1984). The channelization activities began by channelizing the lower reaches of the river, and plans continue to channelize upstream as initially planned. The validity, however, of assumptions made 30 to 40 years ago to justify the channelization of the river have been questioned by the University of Puerto Rico and the Conservation Trust of Puerto Rico, which have developed alternative concepts of water management for the watershed (see Discussion).

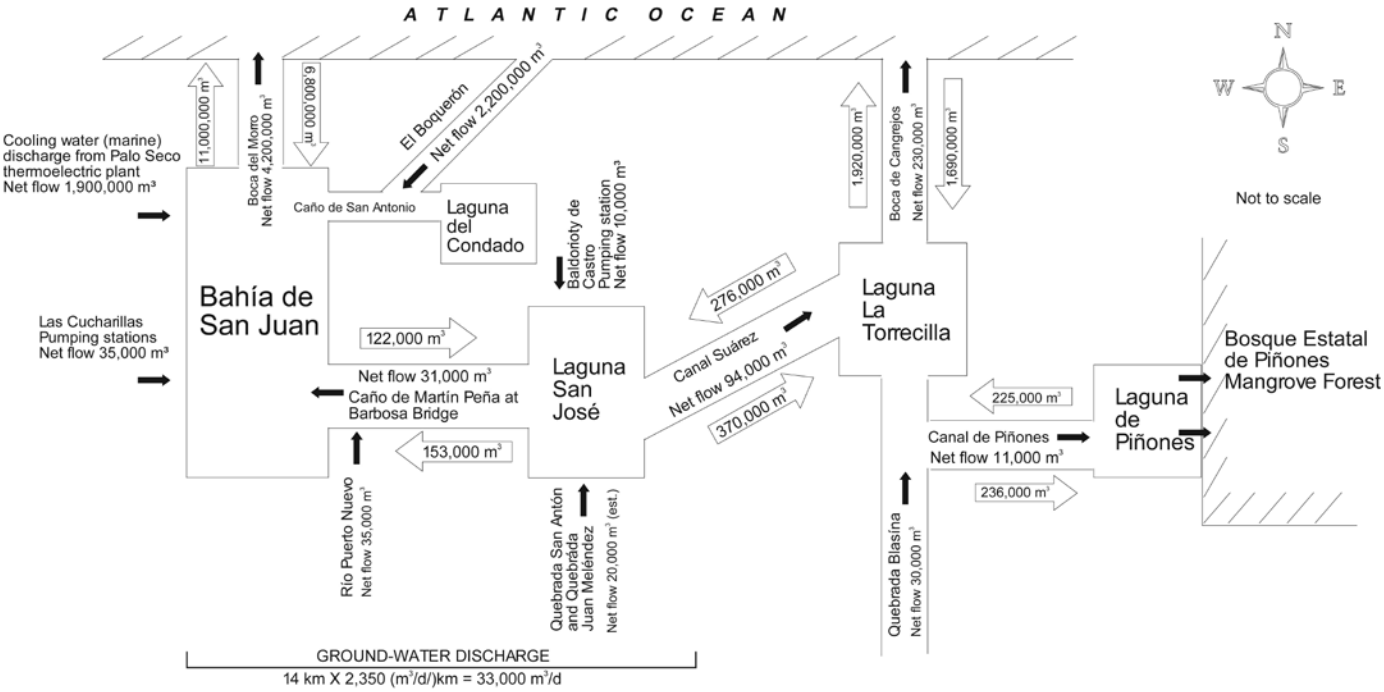


Figure 16. Average daily net flows in dry weather for canals, streams, rivers, pumping stations, tidal creeks, and aquifer discharge that interconnect San Juan Bay with the lagoons of the San Juan Metropolitan Area (Webb and Gómez Gómez 1998).

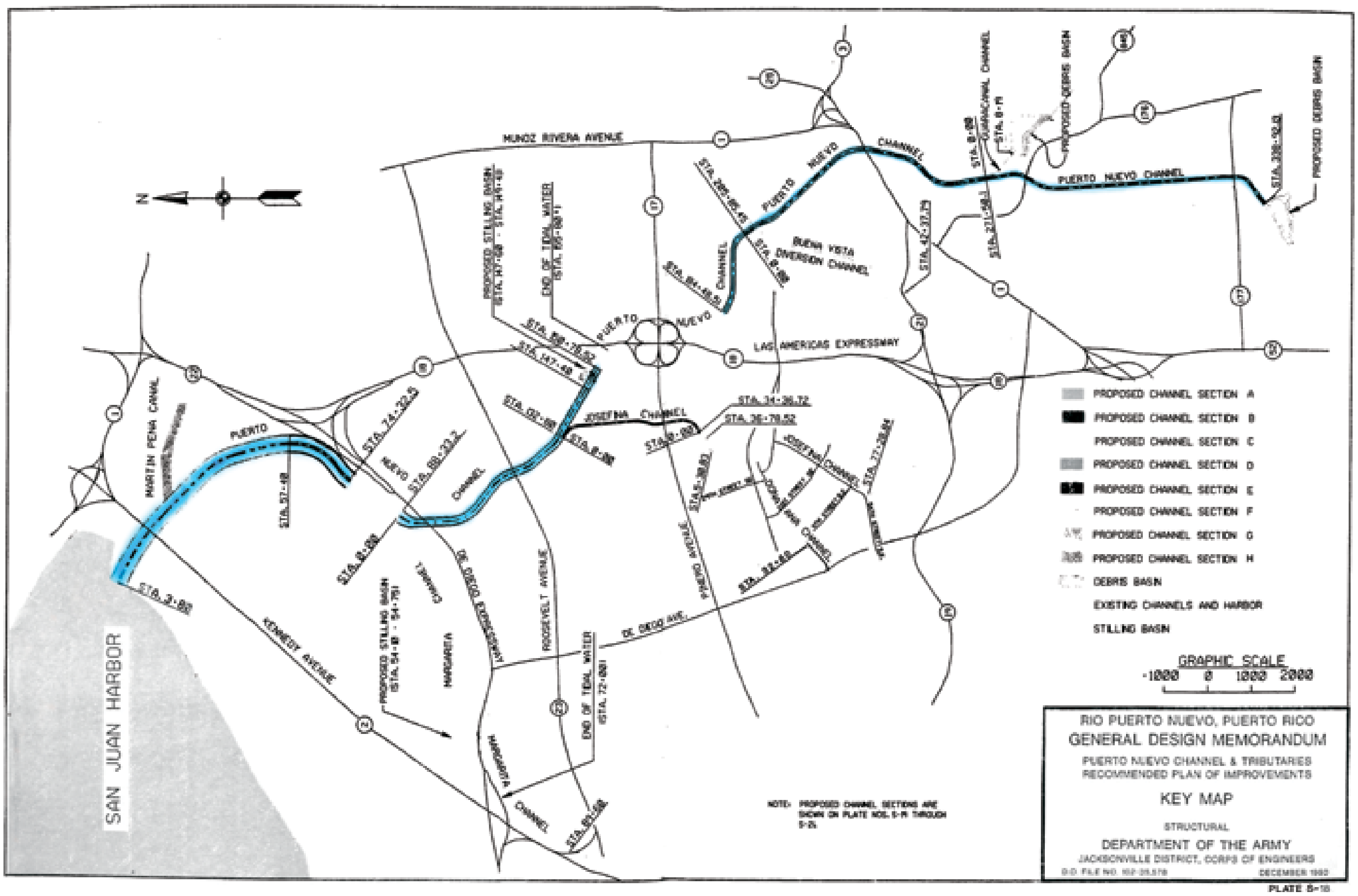


Figure 17. U.S. Army Corps of Engineers channelization plan for the Río Piedras River. The proposed channelization (blue line) continues inland (south) past the Botanical Gardens of the University of Puerto Rico and past highway PR-177 toward Caimito.

Table 2. Area of San Juan Bay geological formations and subsystems.

Formation or subsystem	Area (km²)
Land in the basin	215
Water in the basin	25
Volcaniclastic and intrusive rocks	55
Limestone	13
Quaternary deposits (marine and riverine, alluvium, beach and swamp)	147
Mangrove and swamp deposits	27
Beach deposits	10
Quartz-sand deposits underlie Santurce, and San José and Torrecilla lagoons	11
Urban fill	29*

*12 percent of the watershed.

Source: Webb and Gómez Gómez (1998).

San Juan Bay and Coastal Lagoons

The San Juan Bay has a 240-km² drainage basin (table 2) that includes the Río Piedras Watershed, five coastal lagoons, the Torrecillas-Piñones-Vacía Talega mangroves, and, during flood periods, even the Río Grande de Loíza River. Most of the drainage area of the bay is in the metropolitan area, with the exception of the drainage from the Río Grande de Loíza River, which originates as far as the Luquillo Mountains.

The hydrology of San Juan's five coastal lagoons, all eurihaline and estuarine, is summarized by Ellis and Gómez Gómez (1976). These coastal lagoons are shallow and lined with mangrove forests (table 3). The lagoons are interconnected with channels and export sediments and nutrients to the ocean (table 4). Laguna San José is the coastal lagoon most closely connected to the Río Piedras Watershed as it drains into Caño Martín Peña, as does the Río Piedras River. This lagoon is fed by urban runoff and upwelling of ground water from an aquifer that is recharged in part within the Río Piedras Watershed (fig. 16).

Dredging activities in the coastal lagoons of San Juan have modified their volume and affected their hydrology, tidal oscillations, and water turnover (Ellis 1976). The increase in water volume in the lagoons (fig. 18) has been the result of an increase in water depth due to dredging, despite a decrease in area due to filling and construction (fig. 19). In their original state, these lagoons were shallow, flushed by tides, and had a well-mixed water column. When the lagoons were under tidal control, dissolved oxygen levels in the water column were usually high. After heavy rains, the lagoons received pulses of organic matter from mangroves and their bottom sediments were resuspended. Both effects caused sudden reductions in dissolved oxygen and occasionally massive fish mortalities. Among the coastal lagoons in the metropolitan area, only the Piñones Lagoon continues

Table 3. General characteristics of the San Juan Metropolitan Area's coastal lagoons.

Parameter	La Torrecilla	Piñones	San José	Condado
Area (ha)	26	105	547	31
Average volume (10^6 m^3)	5.91	0.87	13.2	1.42
Maximum depth (m)	18	1.3	11	11
Average depth (m)	2.4	0.8	2.4	4.5
Maximum length (km)	2.5	1.58	5.52	1.2
Width (km)	1.65	0.82	2.2	0.31
Shoreline (km)	19.1	4.91	13.5	2.7
Mangrove cover (km)	14.8	4.66	6.35	0

Source: Ellis and Gómez Gómez (1976).

Table 4. Sediment and nutrient fluxes through two channels from San José Lagoon in San Juan.

	Inflow		Outflow		Net load	
Parameter	Canal Suárez	Caño Martín Peña	Canal Suárez	Caño Martín Peña	Canal Suárez	Caño Martín Peña
TOC	4.77	2.52	8.70	3.08	– 3.93	– 0.56
TOP as P	0.19	0.13	0.31	0.13	– 0.12	0
TP as P	0.26	0.21	0.39	0.20	– 0.13	0.01
Suspended Sediment	4.32		4.22		0.10	

Note: All data are in Mg based on one tidal cycle (25 hours) from January 24 through January 25, 1974. Negative numbers indicate a net export. Canal Suárez data were taken at the Highway 26 bridge and the Caño Martín Peña data were taken at the Barbosa bridge (Ellis and Gómez Gómez 1976). Total organic phosphorus (P) is TOP, total P is TP, and total organic carbon is TOC. Empty cells mean no data are available.

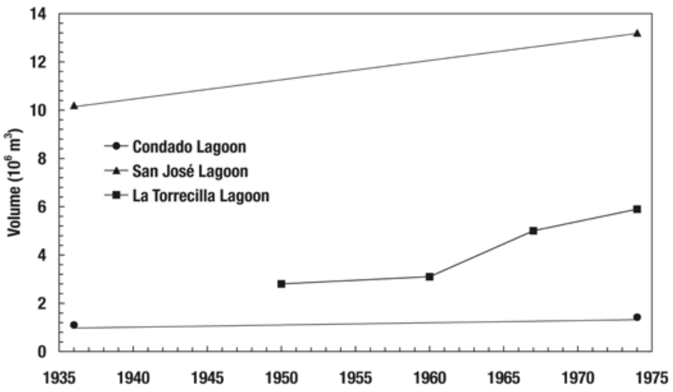


Figure 18. Historical change in the water volume of three lagoons of the San Juan Metropolitan Area (Ellis 1976).

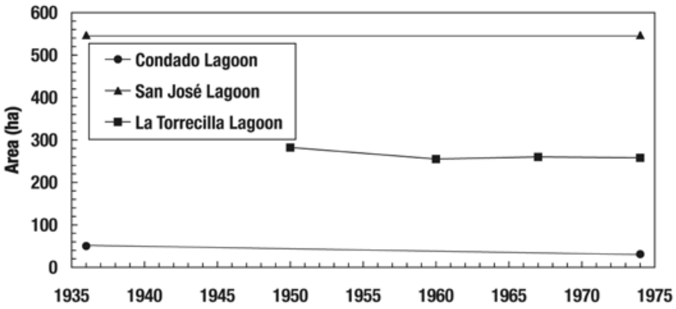


Figure 19. Historical change in the area of three lagoons of the San Juan Metropolitan Area (Ellis 1976).

to function as it did before the anthropogenic transformation of the past 500 years. All others have been modified by changes in area and depth as a result of human activities. Ellis (1976) reports depths of up to 18 m in La Torrecilla Lagoon and up to 11 m in Condado and San José Lagoons.

A consequence of the increase lagoon volume is the reduction in water turnover, because the same tidal flux encounters a greater amount of water in the lagoons. Thus, water quality deteriorates due to the accumulation of pollutants and the development of anaerobic conditions in the water column, which becomes stratified. The anaerobic layer forms at depths that exceed the original average depth of 2 m for the lagoons; in fact, all dredged areas below 2.5 m depth turn anaerobic (Ellis 1976).

The largest storm surge (still-water elevation above the predicted astronomical tide) in Bahía de San Juan was 73 cm in November 1982 (Webb and Gómez Gómez 1998). This surge was caused by a storm in the North Atlantic. Hurricane Hugo in 1989 generated a surge of 70 cm. In the past, sand dunes from El Boquerón (by Laguna del Condado) to Punta Vacía Talega absorbed the energy of such surges. In the Piñones area, however, 10-meter-high dunes were removed to construct the Luis Muñoz Marín International Airport, and now these areas are overtopped frequently by moderate surge events. A large portion of the coastal zone of the metropolitan area is subject to tsunami inundation (fig. 20).

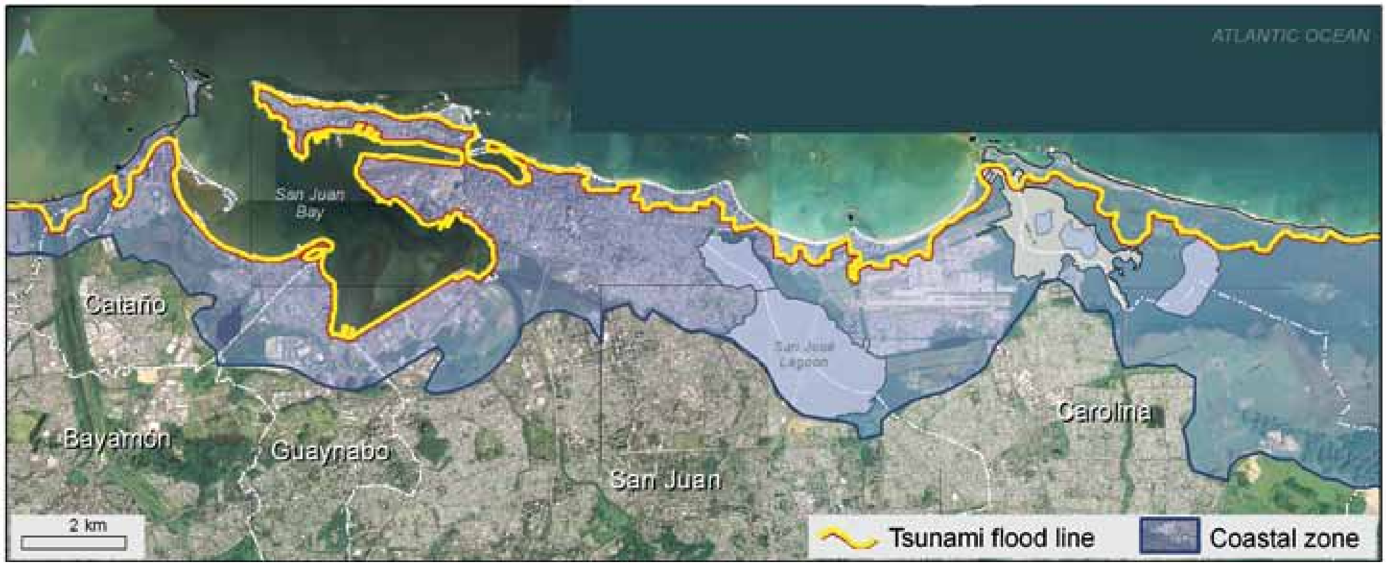


Figure 20. Trace of the expected inland penetration of a tsunami in the San Juan Metropolitan Area. The maximum runup wave level was estimated at 8.99 m. This information was provided by a Federal Emergency Management Agency/University of Puerto Rico Mayagüez Campus study sponsored through Sea Grant.

Table 5. Rainfall quality (mg/L) in Río Piedras at 15.2 m elevation.

Parameter	Mean	Standard deviation	Maximum	Minimum
Calcium	1.8	1.4	6.5	0.3
Magnesium	0.8	0.6	4.6	0.1
Bicarbonate	11	4.5	27	2
Sulfate	1.5	1.3	5.2	0
Chloride	4.9	4.6	9.8	0.2
Nitrate	0.2	0.8	1.2	0
Dissolved solids	21	12	81	7
Hardness as $CaCO_3$ (calcium, magnesium)	8.5	5.4	29	2
Hardness as $CaCO_3$ (noncarbonate)	1	2.2	13	0
pH	6.8	0.4	7.6	5.7

Note: Analyses are based on a monthly collection between 1963 and 1967.

Source: Quiñones Márquez (1975).

Water Quality

In Relation to Rainfall

Quiñones Márquez (1975) found a low correlation (r = 0.2) between rainfall intensity and its specific conductance in Río Piedras. The concentrations of calcium (Ca), magnesium (Mg), and dissolved solids in Río Piedras rainfall (table 5) tended to be higher, however, than in other locations in the island. Dissolved solids in rainfall varied seasonally. During dry months (December through March), concentrations increased and then decreased as the rainy season progressed.

In Relation to Surface Water

Kwak et al. (2007) analyzed the waters of the Río Piedras River at the bridge of PR 176 and found that, in comparison with the mean of 46 insular rivers, the waters of the Río Piedras River had higher dissolved solids, conductivity, ammonia (NH4), alkalinity, and hardness and lower phosphorus (P), nitrate (NO3), and nitrite (NO2) (table 6). The Environmental Quality Board and the U.S. Environmental Protection Agency classify the waters of the Río Piedras River as highly polluted. Figure 21 shows that the fecal bacteria counts in USGS Río Piedras River at Hato Rey Gaging Station (50049100) are normally above the Puerto Rico sanitary quality goals for class SD waters, which, by definition, are waters with unacceptable quality (http://www.ct.gov/dep/cwp/view.asp?a=2719&q=325620).

W. McDowell, University of New Hampshire (McDowell 2010), found that the level of urbanization in the Río Piedras Watershed was linearly related to the concentration of NH_4 and phosphate (PO_4) but not with the concentration of NO_3 in riverine waters. The following mean, maximum (max.), minimum (min.), and standard deviation (SD) concentration values represent data that McDowell collected between January 15 and July 30, 2009, at the Río Piedras Puente Parque Station. All data are in mg/L, except for PO_4 and NH_4, which are in μ/L. NH_4 and PO_4 are generally high and variable. In the table, DOC, TDN, and DON are dissolved organic carbon, total dissolved nitrogen, and dissolved organic nitrogen, respectively.

	DOC	TDN	Cl	NO_3	SO_4	PO_4	Na	K	Mg	Ca	NH_4	DON
Mean	4.6	1.40	29.77	0.88	4.56	63	23.20	3.26	10.25	24.43	288	0.23
Max.	45.51	1.84	34.91	1.24	5.87	284	27.75	4.54	11.94	32.90	686	0.39
Min.	1.70	0.92	21.19	0.60	3.57	19	17.96	2.48	7.19	15.89	75	0.09
SD	8.97	0.28	4.23	0.18	0.56	58	2.79	0.46	1.31	4.54	197	0.08

Cl = chlorine. K = potassium. Na = sodium. SO_4 = sulfate.

Table 6. Water quality measures of Río Piedras River water at the bridge off highway PR-176.

Parameter	Río Piedras	Mean of 46 rivers
Water temperature (°C)	23.85	24.32
Total dissolved solids (g/L)	0.294	0.209
Conductivity (μS/cm)	452	322
Salinity (ppt)	0.22	0.15
Nitrate (mg/L as NO_3^-)	0.2	3.7
Nitrite (mg/L as NO_2^-)	0.062	0.076
Ammonia (mg/L as NH_3)	0.12	0.08
Phosphorus (mg/L as PO_4^-)	0.49	0.65
Alkalinity (mg/L as $CaCO_3$)	169	130
Hardness (mg/L as $CaCO_3$)	168	135
Turbidity (FAU)	6	6.6
pH	7.50	8.29
Dissolved oxygen (mg/L)	7.49	8.19

μS/cm = microsiemens per centimeter, ppt = parts per thousand, FAU = Formazin Attenuation Units

Note: Data correspond to the spring of 2007 by Kwak et al. (2007).

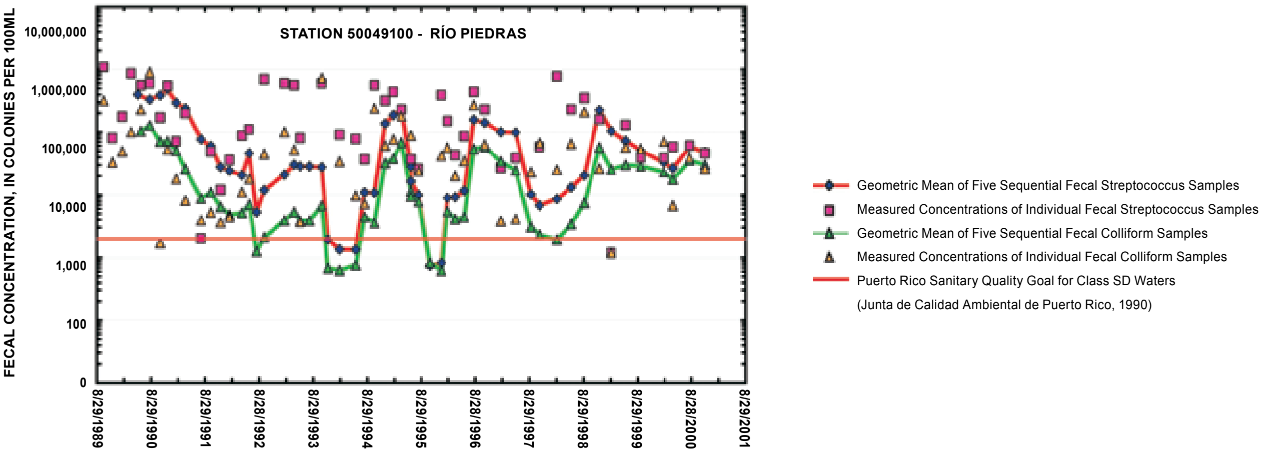


Figure 21. Long-term fecal bacteria concentrations in waters of the U.S. Geological Survey Río Piedras Gaging Station. Notice the logarithmic Y-scale. The horizontal red line is the sanitary quality goal for class SD waters (Larsen and Webb 2009). Waters classified as SD are waters with unacceptable conditions.

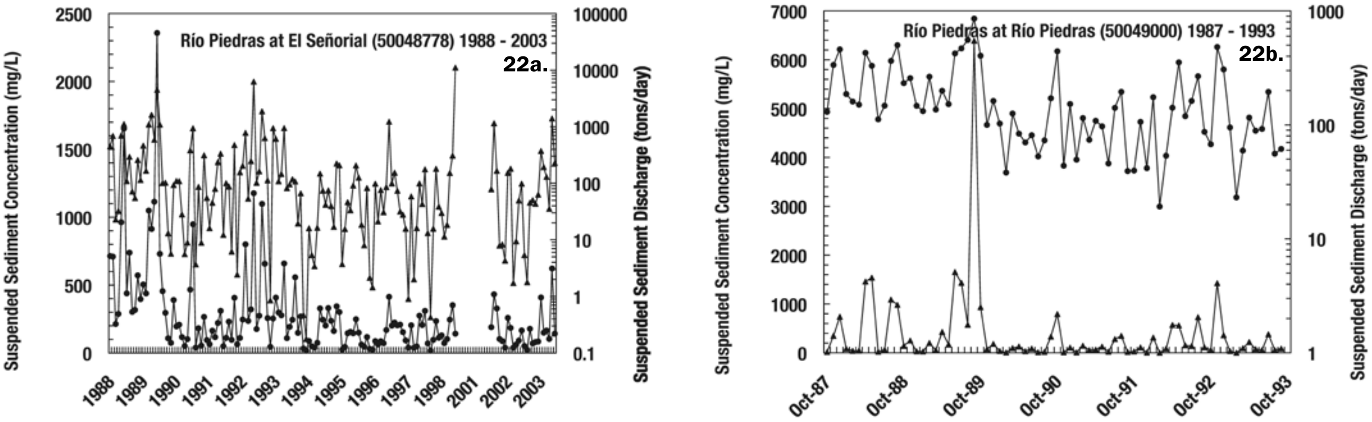


Figure 22. Monthly suspended sediment concentration (circles) and suspended sediment export (triangles) in two U.S. Geological Survey gaging stations in the Río Piedras River (number of stations in parentheses). The stations are Río Piedras at El Señorial (a) and Río Piedras at Río Piedras (b). Monthly data begin on April of each year. To convert export to megagram per day, multiply tons per day by 0.9072.

Ortiz Zayas et al. (2006) found that nitrogen (N) export by the Río Piedras River was 32.9 kg/ha.yr (SE = 3.0), the highest among urban and agricultural watersheds they studied in Puerto Rico. Annual runoff explained most of the variation in fluvial N yield. Nitrogen concentration in the Río Piedras River was not sensitive to streamflow and averaged 2.7 mgN/L (SD = 1.97). Larsen and Webb (2009) plotted the available temporal record of N and P concentration data for USGS Río Piedras at Hato Rey Gaging Station (50049100) and found that these N-rich discharges reach export values of about 140 kg/ha.yr. They surmised that urban centers generate nitrogen oxide NO_x and nitrous oxide (N_2O) that contribute to greater N deposition on natural forests on the island.

The Río Piedras River also carries large sediment loads, as illustrated in fig. 22 and photo 2. At the upstream USGS Río Piedras at El Señorial Gaging Station (50048770) (fig. 22a), suspended sediment concentrations and daily sediment discharge are lower than at the Río Piedras USGS Gaging Station (50049000) (fig. 22b). In both stations, however, peak water discharge events can transport thousands of tons of sediment per day to San Juan Bay. These high-sediment discharge events are due to both increases in water discharge and suspended sediment concentrations. For example, during events associated with Hurricane Hugo in September 1989 and Hurricane Georges in September 1998, the USGS gaging station at El Señorial (50048778) exhibited suspended sediment discharges of 4,477 and 11,110 tons (short) per day, respectively (or 4,064 and 10,079 Mg/day [megagrams per day]). The concentration of suspended sediments in this station during Hurricane Hugo was 2,357 mg/L. The suspended sediment discharge at the Río Piedras USGS Gaging Station (50049000) was 6,390 tons (5,800 Mg) per day. It is clear that events such as hurricanes dominate the hydrological year for the Río Piedras River. These events are shown for 1989, a hurricane year for which we have annual discharge data (fig. 15). Table 7 shows that the annual export of suspended sediments from the Río Piedras River is generally high, even in nonhurricane years, in comparison with other island rivers for which we have data.

Guevara González (1996) related the production of sediments in the Río Piedras Watershed with the construction activity in the basin. He noted that rapid construction of housing units between 1970 and 1990, coupled with poor control of soil erosion and sediment retention at construction sites, contributed to high rates of soil losses. For example, the number of housing units in 1970, 1980, and 1990 were 134,000, 156,000, and 167,000 units, respectively. He noted that, during the years from 1987 to 1993, soil losses in the watershed were as extreme as 12,254 tons/mi^2.yr (4,295 Mg/km^2.yr) in 1988 and 27,406 tons/mi^2.yr (9,606 Mg/km^2.yr) in 1989. Hall and Taylor (1997) developed a nonpoint model to estimate the sediment and nutrient discharges of the Río Piedras River. Their report, which covers the years 1989 to 1994, used sediment yields to estimate the average N and P yields for the river at the Hato Rey, Río Piedras, and El Señorial USGS gaging stations. The range of values for the Hato Rey Gaging Station was 427 to 760 lbs/day (194 to 345 kg/day), and 851 to 1,518 lbs/day (386 to 689 kg/day) for N and P, respectively.

Urban-influenced discharges to the San Juan Bay and associated estuaries and lagoons have an effect on the surface water and sediment quality (Webb and Gómez Gómez 1998). For example, ammonia-nitrogen (N-NH_3) concentration at the Caño Martín Peña averaged 2.3 mg/L and fecal-coliform bacterial counts ranged from 270,000 to 610,000 colonies/100 ml between 1994 and 1995. This station was the most polluted station in the San Juan Bay estuary. Sedimentation rates ranged from 0.2 cm/yr in the Piñones Lagoon to 0.61 in San Juan Bay and 3.9 cm/yr in the Caño Martín Peña. During storm events, these rates potentially reach 10 cm/yr in shallow San Juan Bay waters.

Webb and Gómez Gómez (1998) also described temporal trends in surface water quality in the Río Piedras River and San Juan Bay estuarine waters. Overall, the water quality in the

Table 7. Suspended sediment export for the Río Piedras River at Río Piedras.

Water year	Mg/km^2.yr	Mg/yr
1988	5,486	268,814
1989	9,600	470,400
1990	1,669	81,781
1991	1,705	83,545
1992	2,398	117,502
1993	2,425	118,825

Notes: Data are from the USGS Gaging Station 50049000 at Río Piedras. Seven rivers reported by Lugo et al. (1980) averaged 2,158 with a maximum and minimum of 5,150 and 511 Mg/km^2.yr, respectively.

Photo 2. The Río Piedras River at flood stage with its typical chocolate-colored waters due to the sediment load it carries. Photo by A.E. Lugo.

region has improved since the 1970s in most stations, but some parameters reflected a reduction in water quality. For example, the total P and Lead concentrations and dissolved oxygen saturation in the upper reaches of the Río Piedras River (USGS Hato Rey Gaging Station 50049100) decreased, while pH and N concentrations showed no trend. The sediments of Caño Martín Peña had the following trends, suggesting a reduction in DDT (dichloro-diphenyl-trichloroethane) and accumulation of heavy metals and other chemicals used heavily in the modern city:

Parameter	Pre 1950	1950 to 1974	1975 to 1995
PCB	38 µg/kg		12 µg/kg
DDT		62 µg/kg	27 µg/kg
Lead	0 µg/g		750 µg/g
Hg	0.16 µg/g		4.7 µg/g

Bis (2-ethylhext) phthalate, a common plasticizing agent, exceeded concentrations of 20,000 µ/kg and, together with the mercury (Hg) and Polychlorinated biphenyl (PBC) concentrations exceeded values considered hazardous to humans (Webb and Gómez Gómez 1998).

Figure 23. Cartoon of the shrimp *Palaemon pandaliformis*, which appeared in the editorial page (p. 58) of *El Vocero* on November 26, 2008, when the species was rediscovered in the Río Piedras River. Cartoonist is Yépez. 2008.

In Relation to Ground Water

Ground water becomes progressively mineralized from the mountain region to the coast where both limestone and sea water contribute to the mineralization (Anderson 1976). The Aguada Limestone waters have good quality, an alkaline pH of 7.7 to 8.3, moderate dissolved solids concentrations of 293 to 4,550 mg/L, and are very hard (110 to 1,100 mg/L). Ground water from the Cibao and San Sebastián Formations are less mineralized. In San Juan, ground water is used for public consumption (table 1) mostly during emergencies or extreme drought.

Aquatic Organisms and Other Wildlife

Despite the high level of water pollution and human activity, the Río Piedras River and its riparian zone support diverse levels of biological richness. For example, the richness of aquatic organisms living in the Río Piedras River is surprisingly high (table 8). The river recently became front-page news in Puerto Rico when Omar Pérez Reyes reported a new record for a shrimp species for this watershed and for Puerto Rico (fig. 23). The small shrimp *Palaemon pandaliformis* was found to be common in the river, but despite its abundance it had escaped scientific discovery for almost a century. He also found a freshwater sponge in the Río Piedras River, *Spongilla alba*, the first time a freshwater sponge is reported for Puerto Rico. Further study revealed two species of freshwater sponges in the samples.

Kwak et al. (2007) found 10 freshwater fish species in one reach of the Río Piedras, 6 of which were native (table 9). Native fish species are all migratory (diadromous). Table 8 has 12 fish species reported for the river. Although the native fish species were more abundant than ones introduced in the study by Kwak et al. (2007), the introduced species accumulated as much biomass as did the native species. Despite the differences, native fish in the Río Piedras River were found to be lacking in external abnormalities such as deformities, lesions, ulcers, or tumors, while introduced fish did exhibit these deformities including tumors in anal fins (N. Martínez Rivera et al. 2010). N. Martínez Rivera and A. Ramírez also found large numbers of macro consumers in the Río Piedras River, but they could not find a significant role for these organisms (relative to controls) in the breakdown of leaf litter. Apparently abiotic controls in lowland urban rivers play more important roles in litter breakdown then they do in montane streams. Their study showed that water temperature in the Río Piedras River ranged between 24 and 29 °C, while in nonurban streams it ranged from 22 to 25 °C. Such temperature differences influence microbial respiration and could accelerate processes in stream waters.

Marine fish are not included in the species list in tables 8 and 9. They enter the estuary at the point of contact between fresh and seawater. There, in places like the Caño Martín Peña where

Table 8. Species list for aquatic organisms found in the Río Piedras River.

Native Fish

Anguilla rostrata, Anguillidae (American eel, Anguila)
Agonostomus monticola, Mugilidae (Mountain mullet, Lisa de río, Dajao)
Awaous banana, Gobiidae (River goby, Saga, Olivo)
Eleotris perniger, Eleotridae (Smallscale spinycheek sleeper, Morón)
Gobiomorus dormitor, Eleotridae (Big mouth sleeper, Guavina)

Introduced Fish

Tilapia sp. Cichlidae (Tilapias)
Oreochromis mossambicus, Chichlidae (Mozambique tilapia, Tilapia mosambica)
Pterygoplicthys pardalis, Loricariidae (Sailfin catfish, Amazon or Armored catfish, Chupapiedras, Pleco, Corroncho de América del Sur)
Gambusia affinis, Poeciliidae (Mosquito fish)
Poecilia reticulata, Poeciliidae (Guppy)
Xiphophorus hellerii, Poeciliidae (Green swordtail, Pez de cola de espada)
Sicydium plumieri, Gobiidae (Sirajo goby, Olivo, Chupapiedra)

Aquatic Insects

Order: Ephemeroptera	Families: Leptophlebidae, Baetidae, Caenidae
Order: Odonata	Families: Libellulidae, Coenagrionidae
Order: Hemiptera	Family: Veliidae
Order: Trichoptera	Families: Hydroptilidae, Philopotamidae
Order: Coleoptera	Family: Elmidae
Order: Diptera	Families: Chironomidae, Simuliidae, Tipulidae

Arthropoda-Crustacea Shrimp (Decapoda)

Atya lanipes
Xyphocaris elongata (Salpiches or Piquines)
Macrobrachium faustinum (Camarón zurdo)
M. carcinus[1] (Camarón bocu)
M. crenulatum
Palaemon pandaliformis
Atya innocuous[1] (Gata, Guabara, Chagara)
A. scabra[1] (Gata, Guabara, Chagara)
Epilobocera sinuatifrons (Buruquena)

Other Aquatic Invertebrates

Mollusca-Gastropoda *Marisa cornuarietis*
Tarebia granifera
Platyhelminthes-Turbellaria *Dugesia antillarum* (Planaria de Puerto Rico)
Acari, Hydracarina, water mites (Acaros)
Annelida, Hirudinea, leeches (Sanguijuelas)
Clitellata, Tubificida and others, aquatic worms (Lombrices)
Hexapoda, Collembola, springtails (Colémbolos)
Crustacea, Peracarida, amphipods (Anfípodos)
Porifera, *Spongilla alba,* freshwater sponge

Reptilia

Trachemys stejnegeri stejnegeri (Jicotea)

[1] Based on biological collections.

Notes: This list is based on information provided by Alonso Ramírez (Tropical Limnology Laboratory of the University of Puerto Rico, Río Piedras) and Omar Pérez Reyes (Utah State University). Kwak et al. (2007) was used to supplement the fish list.

Table 9. Species richness, diversity (H'), density, and biomass of fishes in the Río Piedras River at the bridge off highway PR-177

Parameter	Native fish	Introduced fish	All species
Richness	6	4	10
Diversity	1.27		1.69
Density (fish/ha, SE)	1,638 (106)	270 (15)	1,908 (107)
Biomass (kg/ha, SE)	56 (6)	57 (12)	113 (13)

Note: Data correspond to the spring of 2007 and SE is the standard error of the mean (n is unknown). Empty cell means data are not available.

Source: Kwak et al. (2007).

the Río Piedras River discharges, sport and artisan fisherman harvest large tarpon and other marine fish species.

The riparian vegetation is also used by a large number of organisms. Over a few weeks of casual observations, S. Lugo et al. (2001) recorded 22 bird species, 3 species of mammal, 2 species of fish, 1 species of amphibian, 4 species of reptile, 1 species of snail, and 1 species of decapods (table 10). The section on Forests contains more information on birds.

Vegetation

The vegetation of the metropolitan area consists of forests (including salt and freshwater forested wetlands), pastures, freshwater herbaceous wetlands, riparian vegetation, and ephemeral and/or dispersed vegetation that emerges in abandoned lots and throughout the city. The urban forest was described as consisting of four types based on their presence on the landscape (Lugo 2002). These types are: (1) a natural matrix of forests composed of closed mature forest stands that either escaped deforestation or were allowed to mature naturally after abandonment of agricultural or urban land cover; (2) natural corridors such as those along riparian zones; (3) green oases, which are small planted or naturally regenerating forest fragments scattered over the built-up urban landscape; and (4) artificial corridors such as those along streets and avenues. Examples of these stands exhibit different structural and compositional characteristics as will be illustrated below. The section on the land cover of the metropolitan area contains information on the area and types of vegetation in the metropolitan area.

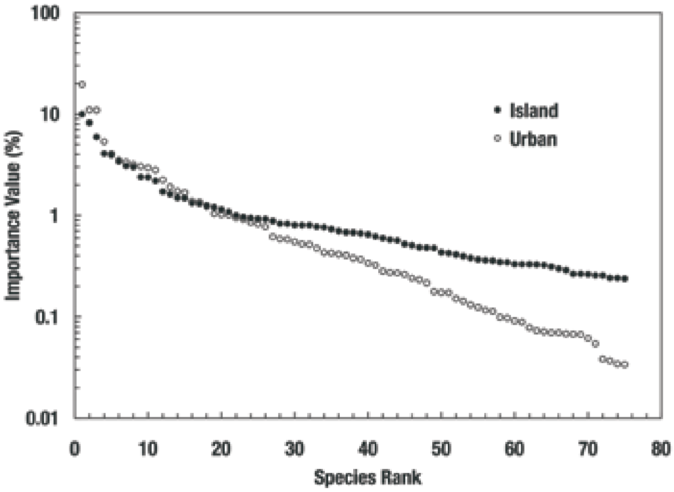


Figure 24. Importance Value curve for tree species from the San Juan urban forest and a combined data set for islandwide forests. The Importance Value is the sum of relative basal area and relative density of a species expressed in percent. Species are ranked from the highest to the lowest in Importance Value. The islandwide forest species list is truncated at the number of species in the urban forest. Data are from the USDA Forest Service Forest Inventory and Analysis program.

Forests

Natural matrix of forests. Natural forest stands within the metropolitan area include the mangrove forests lining San Juan Bay and Lagoons, the karst forests on the tops and slopes of mogotes, and the tall evergreen forest within the Botanical Gardens and in the vicinity of the University of Puerto Rico, in the Commonwealth Forest of the New Millennium in Río Piedras. A large area of mangrove forests occurs in the Torrecilla, Piñones, and Vacía Talega sectors of the metropolitan area. The mangroves of this region are described elsewhere (Lugo and Cintrón 1975) and will not be addressed in this overview.

The USDA Forest Service inventoried the forests of the San Juan Bay Estuary Watershed using 108 systematically located points, where 6 plots covering 0.42 ha were sampled (Lugo and Brandeis 2005). They found high species dominance and a high proportion of introduced species in the urban forest. The three top-ranked species of urban forests had higher importance values than the corresponding species in dry, moist, and wet forests elsewhere in the island (fig. 24). Introduced species attain their highest importance and abundance in urban forests (fig. 24). For example, *Albizia procera*, an introduced species, was the second most important urban tree species that invades vacant barren and institutional lands with highly compacted soils (Chinea 2002). In contrast, endemic species attained their lower presence in urban forests compared to other forest types inventoried (table 11).

Table 10. Common diurnal animal species along the Río Piedras River.

Site	Species	Common name
RP1	*Ardea herodias*	Great egret
	Egretta thula	Snowy egret
	Butorides virescens	Green heron
	Buteo jamaicensis	Red-tailed hawk
	Rattus rattus	Rat
	Iguana iguana	Green iguana
	Trachemys stejnegeri	Hicotea (water turtle)
	Lepidodactylus albilabris	White-lipped coqui (frog)
	Anolis sp.	Lizard
RP2	*Zenaida aurita*	Zenaida dove
	Z. asiatica	White-winged dove
	Butorides virescens	Green heron
	Margarops fuscatus	Pearly-eyed thrasher
	Sicydium plumieri	Sirajo goby
	Rattus rattus	Rat
	Tilapia mossambica	Tilapia
	Anolis sp.	Lizard
	Gastropoda	Turret snail
RP3	*Ardea herodias*	Great blue heron
	Nycticorax nycticorax	Black-crowned night heron
	A. herodias	Great egret
	Tyrannus savana	Grey kingbird
	Tiaris bicolor	Black-faced grassquit
	Columbina passerina	Ground dove
	Tilapia mossambica	Tilapia
	Canis sp.	Stray dogs
	Anolis sp.	Lizard
RP4	*Ardea herodias*	Great egret
	Egretta thula	Snowy egret
	Charadrius vociferus	Kildeer
	Tringa melanoleuca	Greater yellowlegs
	Lonchura punctulata	Nutmeg mannikin
	Tiaris bicolor	Black-faced grassquit
	Buteo jamaicensis	Red-tailed hawk
	A. herodias	Tilapia
	Actitis macularia	Spotted sandpiper
	Anolis sp.	Lizard
	Tilapia mossambica	Tilapia
	Trachemys stejnegeri	Hicotea (water turtle)
	Herpestes javanicus	Mongoose
RP5	*Ardea herodias*	Great egret
	Egretta thula	Snowy egret
	E. tricolor	Tricolored heron
	Nycticorax nycticorax	Black-crowned night heron
	Crotophaga ani	Smooth-billed ani
	Tyrannus savana	Grey kingbird
	Zenaida aurita	Zenaida dove
	Rattus rattus	Rat
	Iguana iguana	Iguana
	Decapoda	Crab

Source: S. Lugo et al. (2001).

Table 11. Introduced and endemic tree species found in the inventory of the San Juan Bay Estuary Watershed.

Parameter	Urban forest	Mature moist forest
Endemic species (% of total species)	0	10
Introduced species (% of total species)	47.9	6.3
IV of introduced species	76.5	41.4
Number of sapling species	20	28
Number of tree species	19 (76)	38
Total number of species	33	80*

IV = Importance Value.

* Includes seedlings (58 species)

Notes: Data for mature moist forest are included for comparison. The area sampled for urban and mature forests was 0.42 and 0.49 ha, respectively.

Source: Lugo and Brandeis (2005).

The prevalence of introduced species in the urban forest is the result of two processes: tree planting (discussed below under green oases and artificial corridors) and natural regeneration. The natural regeneration of species like *Albizia procera*, *Spathodea campanulata*, *Melaleuca quinquenervia*, and others, is resulting in the formation of novel forest types within the city. Notable examples of novel natural forests dominated by introduced species is a stand in the San Patricio forest growing after the abandonment and demolition of houses of a Naval Station, the *Melaleuca* stand in the San Juan Bay Estuary, and the Commonwealth Forest of the New Millennium in the center of the Río Piedras Watershed. The establishment and growth of introduced species in novel forests is a natural process of forest regeneration that is also common in the rest of the island on abandoned agricultural lands (Lugo and Helmer 2004).

Table 12. Distribution of tree species along an elevation gradient in the San Patricio *mogote* in Guaynabo.

	Elevation (m)				
Species	**32**	**26**	**31**	**56**	**92**
Tabebuia heterophylla	9				
Roystonea borinquena	1				
Calophyllum calaba	1				
*Terminalia catappa**	12				
*Delonix regia**	10	59	25		
*Albizia procera**	26	10	41		
*Spathodea campalulata**	30	18	1		
Citharexylum fructicosum	9	5	4	9	
Eugenia monticola	1	2		2	
Casearia guianensi	1				
Malpighia infestissima		1			
Bourreria succulenta		4		1	2
*Carapa guianensis**		1	1		1
Coccoloba diversifolia		1		32	52
Leucaena leucocephala			28		
E. rondicollia				8	3
*Eucalyptus robusta**				2	
E. lancea				3	
Exostema caribaeum				5	
Guapira fragans				3	
Guatterria caribaea				4	
Krugiodendron ferreum				5	
Maitenus eliptica				1	
Ficus laevigata				2	14
Bursera simaruba				6	9
Bucida buceras				16	12
Sideroxylon foetidissimu					1
S. salicifolium					2
*Adenanthera pavonina**					4

* Identifies introduced species.

Note: Numbers correspond to the Importance Value of the species.

Source: Suárez et al. (2005).

Albizia and *Spathodea* dominated the San Patricio stand. Other introduced species were present in these stands; however, some like *Delonix regia* were preexisting during the Naval Station's operation (table 12). Physiognomically and structurally, little difference exists between the novel forest stand and the natural matrix that survived the deforestation of the mogote at San Patricio (table 13). The species density (richness) is higher at the top of the mogote, however, where only native species occur, than in the novel forest dominated by introduced species (tables 12 and 13). Similarly, Súarez et al. (2005) found that most of the regeneration in the San Patricio forest was attributed to native species, with very few introduced species showing regeneration in the most disturbed stands.

At San Patricio, the top of the mogote that constitutes most of the area of this public forest contains a full complement of native tree species forming a closed forest (elevations 56 and 92 in tables 12 and 13) with no regeneration of introduced species (Súarez et al. 2005). The dominant species in the mogote top was *Coccoloba diversifolia* followed by *Bucida buceras*. The dominance of *Coccoloba* was high (Importance Value was 52 percent), as is typical of other mogotes to the west of San Patricio (Aukema et al. 2007).

Mangroves and karst forests represent forest types on soils with severe limitations for plant growth (salinity and flooding in mangroves and shallow nutrient-poor soils in karst). Those on volcanic substrates, however, develop on deeper and nutrient-rich soils, with the consequence that forests are taller with a larger basal area. The Commonwealth Forest of the New Millennium in Río Piedras, a public forest, is an example. This forest developed naturally after the abandonment of agricultural activity in the rural zone of Río Piedras (compare images in photos 3 and 4). The changes in land use that led to the development of this forest are discussed below in the section on land cover. Despiau Batista (1997) and Lugo et al. (2005) studied the forest when it was 60 and 68 years old, respectively. Because the forest developed on agricultural soils and a moist climate, its growth was rapid and it is one of our best examples of what forests on the lowlands looked like before these lands were deforested for agricultural use.

The species with the highest Importance Value in this forest was *Spathodea campanulata*. This species was dominant in most topographic positions and in two instances was second to the natives *Tabebuia heterophylla* and *Hymenaea courbaril* (on slopes). Other species with high Importance Values in this forest were *Hura crepitans*, *Terminalia catappa,* and *Guarea guidonia*. Overall the forest had 53 to 55 species per hectare, a value comparable to most mature forests in Puerto Rico (Lugo 2005). The species density changed with topographic position, with the highest values on slopes (table 14). The highest basal areas were in river valleys, where the Importance Value of the most dominant species was high and tree density was low.

Table 13. Structural indices for individual trees and plots along an elevation gradient in the San Patricio *mogote* in Guaynabo.

		Elevation (m)				
	Parameter	**32**	**26**	**31**	**56**	**92**
Trees ≥ 5 cm dbh	Average diameter (cm)	11.2	13.6	10.1	12.7	12.8
	Average height (m)	8.1	8.6	8.5	9.6	9.0
	Density (trees/ha)	1,422	1,395	1,763	1,763	1,790
	Basal area (m^2/ha)	18.4	38.6	20.8	29.1	30.8
	Number of species	10	9	6	16	10
Trees ≥ 2.5 < 5 cm dbh	Average diameter (cm)	3.2	4.0	4.1	0.9	3.5
	Average height (m)	3.1	2.3	4.8	1.1	5.8
	Density (trees/ha)	3,567	510	3,568	3,057	1,529
	Basal area (m^2/ha)	3.0	0.6	0.7	2.5	0.5
	Number of species	3	1	2	4	2

dbh = diameter at breast height.

Note: The sampling area was 380 y 19.63 m^2, respectively, for tree with a dbh of ≥ 5 cm and ≥ 2.5 < 5.0 cm.

Source: Súarez et al. (2005).

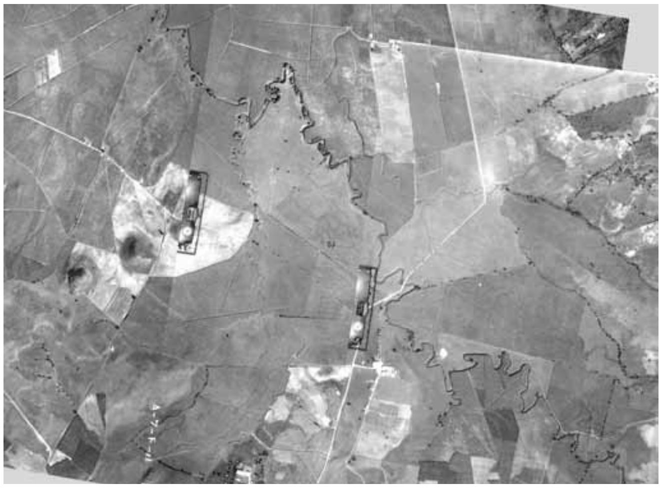


Photo 3. Aerial photograph of the Río Piedras region in 1931. Photo by Philadelphia Aerial Surveying. Sponsored by the U.S. Department of Defense.

Photo 4. Aerial photograph of the Río Piedras region in 2006. Photo by Puerto Rico Department of Natural Resources and the Environment.

Table 14. Stem density, basal area, number of species, and Importance Value of the most dominant tree species in 1997 and 2005 at the Commonwealth Forest of the New Millennium in Río Piedras.

Topographic position	**Density (stems/ha)**		**Basal area (m^2/ha)**		**Species/plot**		**Number of species**		**Importance Value (%)**	
Year	**1997**	**2005**	**1997**	**2005**	**1997**	**2005**	**1997**	**2005**	**1997**	**2005**
Riverine valley	1,316	1,246	38.1	38.1	6.8	7.1	26	26	44.4	38.3
Slope	2,208	1,819	33.4	26.8	10.6	10.9	34	28	28.6	14.2
Ridge	2,330	1,961	25.8	26.8	8.5	9.3	32	33	25.9	21.8
Draw	1,393	1,362	27.4	25.1	7.8	7.4	29	25	37.2	38.9
All forest	1,808	1,562	30.8	28.6	—	—	56	53	32.9	26.7

Notes: Data are for trees with a diameter at breast height ≥ 4 cm. The sampling area in ha was 0.2545, 0.2290, 0.2545, 0.2799 y 1.0 for riverine valley, slope, ridge, draw, and all forest, respectively. Each plot had an area of 254 m^2.

Source: Lugo et al. (2005).

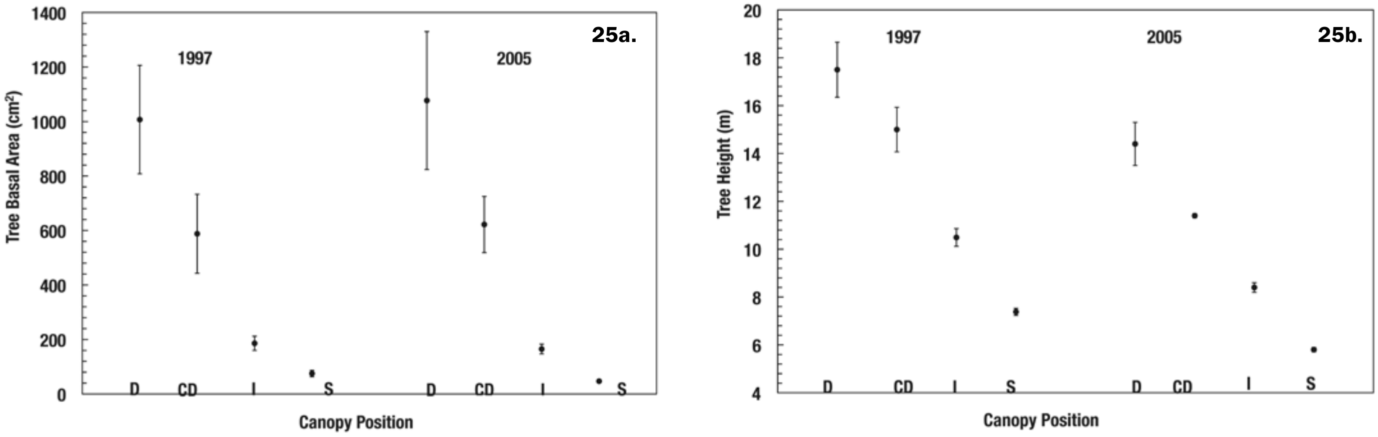


Figure 25. Tree basal area (a) and height (b) as a function of canopy position in the Commonwealth Forest of the New Millennium in Río Piedras. Crown positions are dominant (D), codominant (CD), intermediate (I), and suppressed (S), which receive full sunlight on all sides, from the top only, through gaps, or not at all, respectively. Mean and 95 percent confidence level are shown (Lugo et al. 2005).

Tree dimensions varied with the position of the crown (fig. 25). The largest trees were those with their canopy exposed to full sunlight on all sides, identified as dominant crowns in fig. 25. These large trees were followed by codominant canopies with full sun exposure only from the top, intermediate canopies shaded by dominant and codominant crowns, and suppressed canopies, which were exposed to shade all the time. Trees with suppressed canopies had the smallest dimensions. Tree growth was faster in the dominant canopy class, particularly in the riverine valley and least in suppressed canopy trees, regardless of topographic position (table 15).

Hurricane Georges affected the forest in 1998 between the study of Despiau Batista (1997) and Lugo et al. (2005). The effects of the hurricane were slight given the distance to the center of the hurricane (Lugo et al. 2005), but they were most significant on ridges, which had trees exposed to winds (fig. 26). There, tree mortality exceeded tree ingrowth, but in other topographic positions the two processes were balanced. Another measure of hurricane effects was tree growth, particularly height growth (tables 15 and 16). The hurricane reduced the height of the forest, and trees exhibited negative height growth. Consult Lugo et al. (2005) for a detailed analysis of hurricane effects. A critical finding was that the species composition, including the dominance of the introduced species *S. campanulata,* did not change significantly after the hurricane. This finding suggests that the introduced species can survive moderate hurricane winds and maintain dominance in these novel forests.

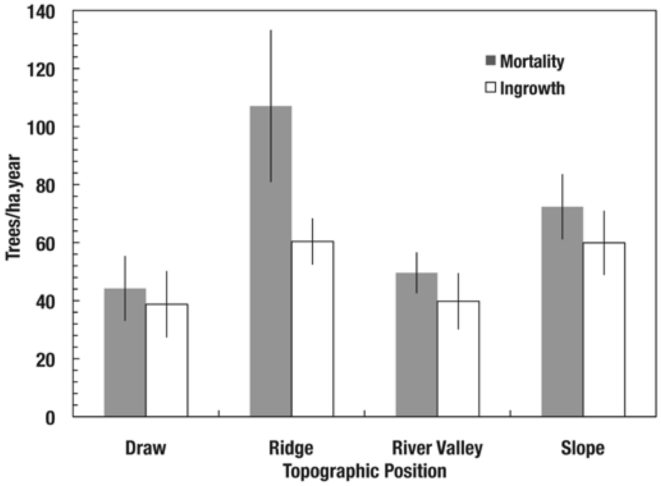


Figure 26. Tree mortality and ingrowth according to topographic position in the Commonwealth Forest of the New Millennium in Río Piedras 7 years after Hurricane Georges passed south of the forest. Mean and standard errors are shown (n = 10, except for draw = 9) (Lugo et al. 2005).

Natural corridors. S. Lugo et al. (2001, p. 74) discussed the riparian vegetations of the Río Piedras River thusly:

> The vegetation along the Río Piedras tends to be patchy. Within an urban environment, land use can change in very short distances. With these changes, the riparian vegetation also changes, which may contribute to the high species diversity along the river. Such diversity of habitats provides a wide range of niches, which allow for a large number of species. When undisturbed, the riparian zone may become a forested habitat. Although a few patches of forest habitat were found at most sites, this was not possible because the urban environment influenced and disturbed the riparian zone. The average distance to the first urban structure (fences, yards, roads, sidewalks, etc.) was only 20 m from the edge of the channel. The diversity of landscapes along this urban river is due to the different stages of regrowth after constant disturbance, different land uses, and topography. In an urban habitat, change is inevitable, always altering this dynamic community. The species found in this habitat are well adapted to, and thrive in this ever-changing environment.

Their study led them to six generalizations about these plant communities. (1) The dominance of grasses in the riparian zone of the river is associated with frequent flooding. (2) Most riparian areas had little to no tree cover due to flooding and human activities. (3) Community structure includes high species dominance in both tree and nontree communities. (4) Geometric rank-abundance curves were found for tree species, while nontree species followed a lognormal curve (fig. 27). (5) Species richness (table 17, fig. 28) and species diversity of the nontree component were high and exceeded those of the tree component. (6) Most species found in the riparian forest are nonnative and/or invasive. The introduced species all had some connection with human use such as food, ornamental, or timber species. Tree height was variable among sites, but average between 6 and 7 m at the best locations (fig. 29).

Table 15. Tree growth rate in the Commonwealth Forest of the New Millennium in Río Piedras.

		Annual growth		
	Analysis criteria	**Diameter (cm)**	**Basal area (cm^2)**	**Height (m)**
Topographic position	River valley	0.41 (0.04, 232)	14.3 (2.8, 232)	– 0.26 (0.03, 230)
	Slope	0.20 (0.02, 318)	5.0 (0.8, 318)	– 0.05 (0.02, 308)
	Ridge	0.24 (0.02, 352)	5.4 (0.6, 352)	– 0.12 (0.02, 351)
	Draw	0.25 (0.02, 237)	6.3 (0.8, 237)	– 0.21 (0.03, 236)
Crown position	Dominant	0.48 (0.12, 60)	29.0 (9.1, 60)	– 0.43 (0.08, 58)
	Codominant	0.36 (0.05, 292)	16.5 (2.9, 67)	– 0.35 (0.08, 64)
	Intermediate	0.30 (0.02, 712)	8.3 (1.0, 292)	– 0.21 (0.03, 289)
	Suppressed	0.22 (0.01, 712)	3.9 (0.4, 712)	– 0.08 (0.01, 712)
By plot	Plots	0.30 (0.02, 39)	8.4 (1.0, 39)	– 0.15 (0.03, 39)
All trees	All trees	0.27 (0.01, 1,139)	7.3 (0.7, 1,139)	– 0.15 (0.01, 1,125)

Notes: Results are given for different analysis criteria. The standard error followed by the number of samples is given in parentheses.

Source: Lugo et al. (2005).

Table 16. Mean, median, and mode of tree dbh, BA, height, and their respective annual rates of change and descriptive statistics.

	Tree dimensions						Growth		
	dbh (cm)		BA (cm^2)		Height (m)		dbh (cm)	BA (cm^2)	Height (m)
Statistical parameter	**1997**	**2005**	**1997**	**2005**	**1997**	**2005**			
Mean	11.4	13.6	176.5	234.8	9.2	8.1	0.27	7.3	– 0.15
Standard error	0.3	0.3	11.4	13.8	0.1	0.1	0.01	0.7	0.01
Median	7.7	9.7	46.5	73.9	8	7	0.14	1.8	– 0.12
Mode	4.9	6.3	13.8	31.2	7	7	0	0	– 0.13
Range	78	81	5,305	5,659	29	20	8.2	590	4
Sample size (n)	1,139	1,139	1,139	1,139	1,131	1,130	1,139	1,139	1,125
Highest value	82.3	85	5,317	5,672	30.7	22	6.6	527	2.5
Lowest value	4	4	12.6	12.6	1.7	2	– 1.6	– 63.0	– 1.9
Coefficient of variation (%)	84	79	218	198	47	40	165	306	257
Confidence level (95.0%)	0.56	0.62	22.3	27.0	0.3	0.19	0.03	1.3	0.02

BA = basal area. dbh = diameter at breast height.

Notes: Data are for live trees in the Commonwealth Forest of the New Millennium in Río Piedras. Some values were rounded.

Source: Lugo et al. (2005).

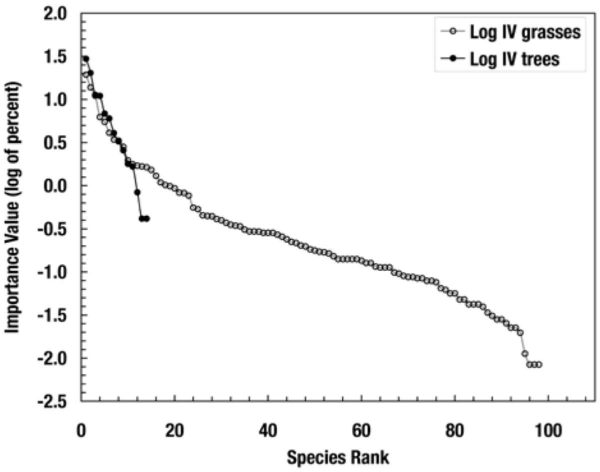


Figure 27. Log-transformed Importance Value curves for riparian vegetation in the Río Piedras River (S. Lugo et al. 2001). The tree curve is logarithmic, while the grass curve is lognormal.

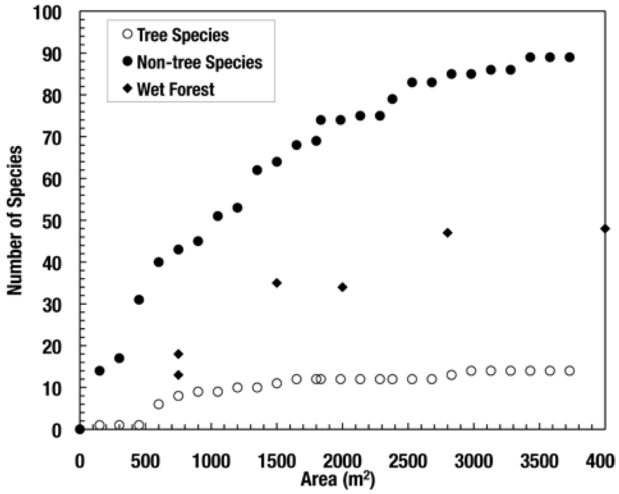


Figure 28. Species/Area curve for tree and nontree riparian vegetation in the Río Piedras River (S. Lugo et al. 2001). A wet karst forest known for its high tree species richness is shown for comparison.

The grassy riparian vegetation was not only diverse in species but also tall, with average heights of 2 to 3 m. The most abundant grass was *Paspalum paniculatum*, a native grass. In the forest stands, the most abundant tree was *Albizia procera*, a nitrogen-fixing tree capable of growing on compacted soils and competing with the grasses. Few tree species grew at 0 to 5 m from the riverbank (table 17). Only three species in this region were found close to the riverbank (S. Lugo et al. 2001): *Musa sp.*, *Terminalia catappa*, and *Ricinus communis*. All are fast-growing, flexible species and one (*Musa*) is an herb with a tree habit. Most of the trees (49 percent) grew between 10 and 20 m from the water, while 22 percent of the trees grew between 20 and 30 m from the water's edge (table 18).

Flooding frequency appears to be the main driver of vegetation distribution in the Río Piedras riparian zone (S. Lugo et al. 2001). The grass-dominated zone is frequently flooded, and most trees grow in higher topographic positions away from these flood-risk zones. Because of the steepness of the slopes next to the river, this reduces the flooding frequency and trees can grow closer to the water at higher elevations in the watershed. In the Caimito region, with steep topography, a forest of *Cecropia schreberiana*, a native pioneer species, grows on the

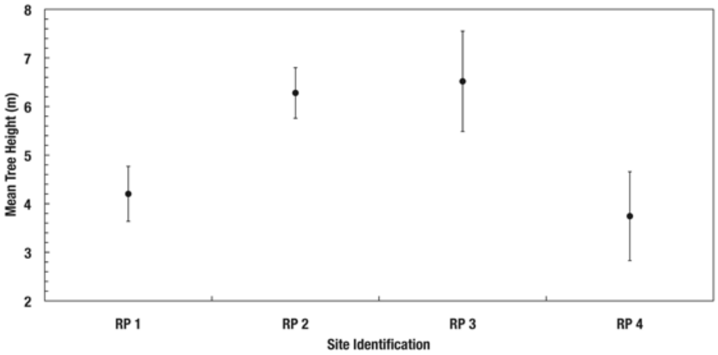


Figure 29. Mean tree height in four riparian-forest stands in the Río Piedras River (new plot based on the study of S. Lugo et al. 2001). Mean and standard errors are shown; n = 42, 69, 18, and 10, respectively, for sites RP 1 to RP 4.

Table 17. Number of tree and nontree species in five sites along the Río Piedras River.

Site	Area (m^2)	Tree species	Nontree species	Land use
RP1	750	5	35	Undeveloped, one riverbank flood plain
RP2	648	10	48	Undeveloped, some construction near
RP3	900	8	34	Neighborhood, groomed vegetation
RP4	900	1	28	City park
RP5	450	1	28	Roadside
All sites	3,648	14	92	

Note: The sampling area and land use at the site are also shown.

Source: S. Lugo et al. (2001).

Table 18. Characteristics of tree population in relation to distance from the river at five sites along the Río Piedras River.

Distance (m)	Basal area (m²/ha)	Species (no)	Mean height (m)	Density (trees/ha)
0 to 5	1.37	3	3.2	246
5 to 10	3.03	7	4.9	315
10 to 15	6.00	6	4.8	578
15 to 20	8.00	6	5.6	458
20 to 25	0.77	3	5.5	104
25 to 30	16.00	6	8.1	383

Source: S. Lugo et al. (2001).

riparian zone, and few grasses are present. The domination of grasses occurs downstream over low-elevation flood plains. This habitat was at one time dominated by *Pterocarpus officinale*, which formed floodplain forests, but this species has almost been completely extirpated from the flood plain of the Río Piedras River. The largest tree measured by Lugo et al. (2001) was a 19 m tall *Pterocarpus macrocarpus*, an introduced species not known to grow well in saturated soils (Francis 2000).

Green oases. Forest fragments, or patches, are abundant in the metropolitan area, many times in abandoned lots (photo 5a–c). These urban forests, which are usually embedded in the urban built-up land, moderate air temperature, provide substantial recreational opportunities, attract significant numbers and variety of wildlife, and influence the hydrological cycle through evapotranspiration and reduction of urban runoff.

An example of this type of forest is a 1.1-ha forest planted in 1988 by a neighborhood association at Urbanización El Paraíso in Río Piedras (Román Nunci et al. 2005). By 2007, the forest had 37 tree species (9 native and 28 introduced) including two endemic species, species representative of primary forests from dry, moist, and wet forests (table 19). The species combination of these urban forests reflects the preferences of those who planted the trees, and this explains the novel aspect of the species list. One species, *Cecropia schreberiana,* regenerated naturally after the flowering of the individual that was planted at the site. Also, because of the heavy use by residents and safety concerns, the understory of this forest is poorly developed and mostly absent, however, the forest has a closed canopy. Litterfall accumulation on the forest floor is also low, as the government periodically removes leaves and dead wood. The respective mean diameter at breast height (dbh) and height of trees are 26.8 cm and 9.8 m. The forest as a whole had a basal area of 17.3 m^2/ha and a tree density of 127 trees/ha (215 stems/ha due to multiple stems in some trees). Román Nunci et al. (2005) found that about one-half of the trees were growing very slowly but the remaining trees grew at better than a 20 cm^2/yr clip, including 15 percent that grew at better than 100 cm^2/yr (fig. 30). Annual tree mortality was 1.4 to 1.5 percent.

5a.

5b.

5c.

Photo 5. Development of forest fragments in abandoned lots of Río Piedras, Puerto Rico. Construction in the lot was halted due to violations of zoning regulations in 2006 (a). Since then, vegetation removal has taken place periodically, but, in 2010, *Albizia procera* trees can be seen growing among the weeds (b and c). If left unchecked, they will form a tall forest despite site modification. Photos by A.E. Lugo.

Table 19. Tree species composition, structural attributes, and Importance Value in *Parque Central* of the El Paraíso urbanization in Río Piedras.

	dbh	**Height**	**Density**		**BA**	**IV**
Species	**(cm)**	**(m)**	**(stems/ha)**	**(trees/ha)**	**(m^2/ha)**	**(%)**
Swietenia macrophylla x mahagoni	46.1	11.8	27	24	5.1	24.3
Peltophorum pterocarpum	31.6	12.6	19	6	1.9	7.7
Ficus benjamina	91.6	10.3	3	2	2.3	7.4
Melaleuca quinquenervia	17.2	8.7	24	12	0.7	6.7
*Tabebuia heterophylla**	21.1	9.2	19	11	0.7	6.4
Lagerstroemia speciosa	25.0	8.4	19	6	1.1	5.3
Cordia sebestens	16.2	5.8	9	9	0.2	4.2
Terminalia catappa	23.1	8.4	7	7	0.3	3.9
Swietenia mahagoni	37.0	12.2	6	5	0.6	3.6
Tabebuia rosea	35.3	13.0	6	5	0.6	3.6
*Roystonea borinquena**	4.5	10.3	4	4	0.5	3.0
Callistemon citrinus	17.0	7.5	11	5	0.3	2.7
Swietenia macrophylla	31.1	11.9	5	4	0.4	2.6
Delonix regia	36.1	10.5	6	2	0.6	2.5
Eucalyptus robusta	28.5	14.1	5	3	0.3	2.1
Pterocarpus indicus	70.0	12.0	1	1	0.4	1.4
Cassia fistula	18.5	12.7	6	2	0.2	1.2
*Thespesia grandiflora**	18.5	11.6	5	2	0.1	1.1
*Ceiba pentandra**	48.0	10.0	1	1	0.2	0.9
*Cecropia schreberiana**	13.5	8.0	2	2	0.0	0.8
Schefflera actinophylla	12.4	6.5	2	2	0.0	0.8
Tamarindus indica	16.8	8.5	5	1	0.1	0.7
Cassia javanica	18.2	11.6	4	1	0.1	0.6
Cananga odorata	29.2	10.5	1	1	0.1	0.5
Chrysophyllum cainito	12.9	7.0	4	1	0.1	0.5
Tabebuia capitata	11.6	7.5	5	1	0.1	0.5
Syzygium malaccense	25.5	11.0	1	1	0.0	0.5
Mangifera indica	25.2	8.0	1	1	0.0	0.5
Melicoccus bijugatus	23.8	8.0	1	1	0.0	0.5
Tabebuia aurea	23.2	12.0	1	1	0.0	0.5
*Petitia domingensis**	22.7	11.0	1	1	0.0	0.5
Grevillea robusta	19.8	7.5	1	1	0.0	0.4
*Pimenta racemosa**	9.8	8.0	3	1	0.0	0.4
Cocos nucifera	16.5	5.0	1	1	0.0	0.4
Crescentia cujete	12.1	6.0	1	1	0.0	0.4
*Guaiacum officinale**	7.3	3.0	2	1	0.0	0.4
*Manilkara bidentata**	9.6	4.4	1	1	0.0	0.4

* Indicates native species; the rest are introduced.

BA = basal area. dbh = diameter at breast height for all trees with dbh $\geq$ 4 cm. IV = Importance Value.

Note: Species are arranged in the order of IV.

Source: Román Nunci et al. (2005).

Another example of a green oasis is the urban forest in the campus of the University of Puerto Rico at Río Piedras. This campus was established in 1903 and contains an approximate area of 279 cuerdas (110 ha) and a large diversity of planted trees and lawns. Otero Vázquez (1995) established a route through campus and systematically observed birds twice a week between 6:30 and 7:30 a.m. between 1987 and the 1990s. His paper contains a list of 47 bird species, including 8 endemic species. In addition to the endemic species, his list includes resident species known to reproduce or not known to reproduce in Puerto Rico, introduced species, naturalized species, migratory species, migratory species that reproduce in Puerto Rico, and resident and migratory species. This list is a conservative estimate of the number of avian species in this urban forest, because he included only those species that he observed more than once and ignored reports of other species present in campus.

Artificial corridors. The streets and avenues of San Juan are lined with trees of many species, including native and introduced species. These artificial corridors are known to attract wildlife and they are valued in the city for the shade they provide (photo 6). The management of these corridors

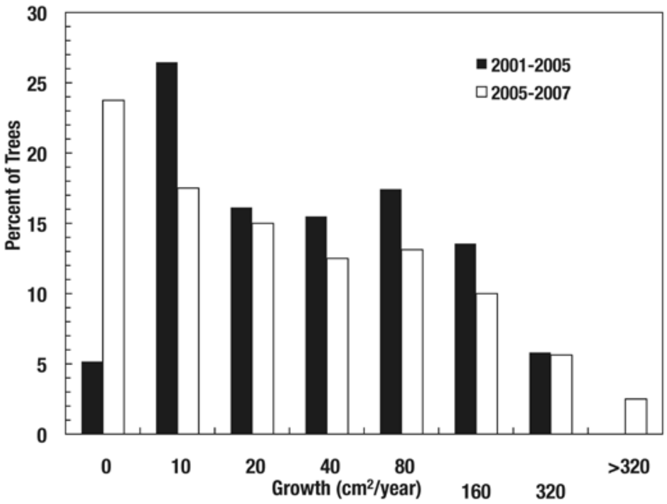


Figure 30. Histogram of basal area tree growth rates for trees in the Parque Central at the El Paraíso urbanization, Río Piedras. The 2001-to-2005 values are based on 155 individual rates; the 2005-to-2007 values are based on 160 individual rates (Román Nunci et al. 2005).

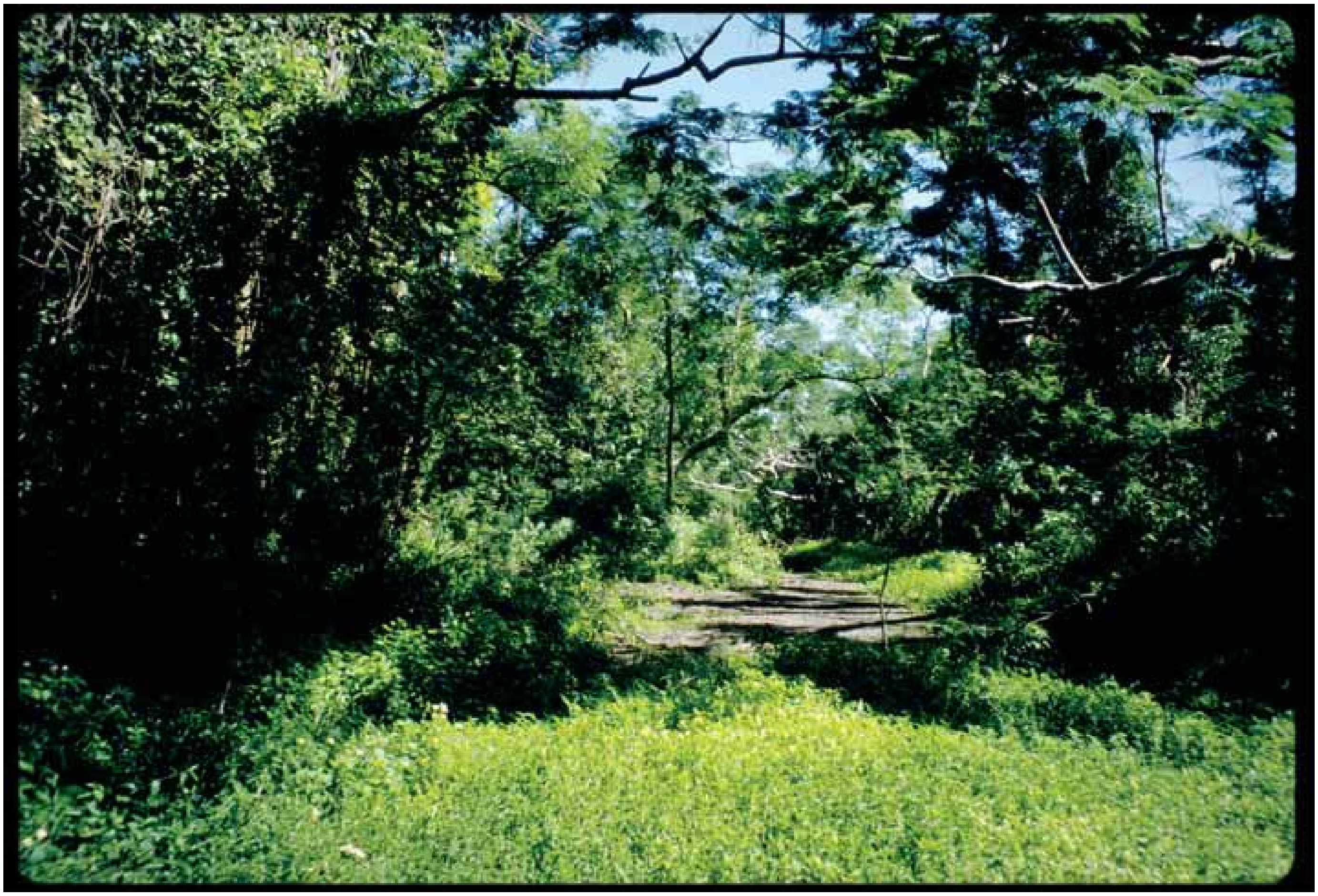


Photo 6. A forested urban corridor at San Patricio, Río Piedras, Puerto Rico. The pavement in the photo is an abandoned street of a former Naval Station, now an urban Commonwealth forest. Photo by A.E. Lugo.

7a.

7b.

is problematic because little attention is paid to the species to be planted and less so to the space needed for the tree to grow its root system and canopy. The result involves many types of conflict, such as the following:

- Trees overtopping power lines and then interrupting service during periods of high winds.
- Tree roots breaking sidewalks, cracking building walls, and clogging drainage systems and water lines.
- Trees growing to excessive heights and then causing hazards to vehicles and pedestrians due to falling limbs.

In the absence of professional management, these problems are addressed without proper plans or technical knowledge, which explains the decapitation and injury of trees (photo 7a–c), with the resulting loss in city aesthetics and public conflict by those who disapprove of any cutting of trees in the city. The artificial corridors present the greatest vegetation management challenge to municipal and State governments.

Wetlands

Wetlands, other than forested wetlands discussed above, are common in the urban setting of Río Piedras. Some wetlands emerge as a result of broken pipes or accumulation of water due to changes in drainage patterns throughout the city (photo 8a-c). One of the largest remaining natural wetland areas in the metropolitan area is Ciénaga Las Cucharillas, a large swamp dominated by freshwater herbaceous vegetation with eurihaline transition to mangroves and saline vegetation (fig. 1). This large swampy area is a remnant of what would have been a more extensive wetland region behind the mangroves in the lowlands of the Río Piedras River at its confluence with San Juan Bay.

7c.

Photo 7. Examples of excessive pruning of trees along urban corridors in Río Piedras, Puerto Rico. Pruning is often done to protect power lines (a and b) but sometimes to convert large trees into shrubs (c). Photos by A.E. Lugo.

8a.

Human Activity

Río Piedras appeared depicted for the first time as a settlement in a map of Puerto Rico prepared by Miguel de Muesas in 1775 (Sepúlveda Rivera 2004a). In 1777, Río Piedras had three houses and a population of 15 people. The town had been founded in 1714. In 1828, Pedro Tomás de Córdova reported that Río Piedras had 41 artisans, 77 naturalized aliens, 16 *pulperias* and *ventorrillos*, and more than 100 houses (Sepúlveda Rivera 2004a). The *parroquia* San Pilar was built in 1714. This church was the main structure in the first urban map of Río Piedras reproduced in Sepúlveda Rivera (2004 b). A more elaborate expansion plan for the town, including streets, appeared in 1880 (fig. 31).

By 1878, Manuel Úbeda y Delgado reported the following: an agricultural richness of 40,677 pesos and 20 cents, 12,092.20 in urban, and 6,823.20 in livestock; 7 schools; 9,612 people belonging to 1,660 families; 373 houses, and 1,275 *ranchos* and *bohíos*. In the town itself were 140 houses, 50 *bohíos*, 190 families, 3 general stores, 2 *fondas*, a café, a *botica*, and 14 *pulperías*. The main transportation venues were to San Juan (11 km) and Caguas (24 km), secondary roads to Carolina (11 km), and one in construction to Trujillo Alto (7 km). The Río Piedras aqueduct was built by 1890, as was the bridge over the river on the Caguas road (Sepúlveda Rivera 2004c). That bridge

8b.

8c.

Photo 8. Closeup of an herbaceous wetland in Río Piedras, Puerto Rico (a). The plants are reproducing. A wider view of the wetland uncovers its location along a street (b). The water supply for this wetland is from broken water pipes due to construction (c). Photos by A.E. Lugo.

was completed in 1853 (Pumarada O'Neill 1991) and spanned 21.5 m. Today, it is the only surviving bridge from the original central road between San Juan and Caguas. When it was recently restored, the span of the bridge increased due to erosion of the channel as a result of urban growth and high river discharge. The construction of the University of Puerto Rico campus' buildings and facilities began between 1900 and 1910.

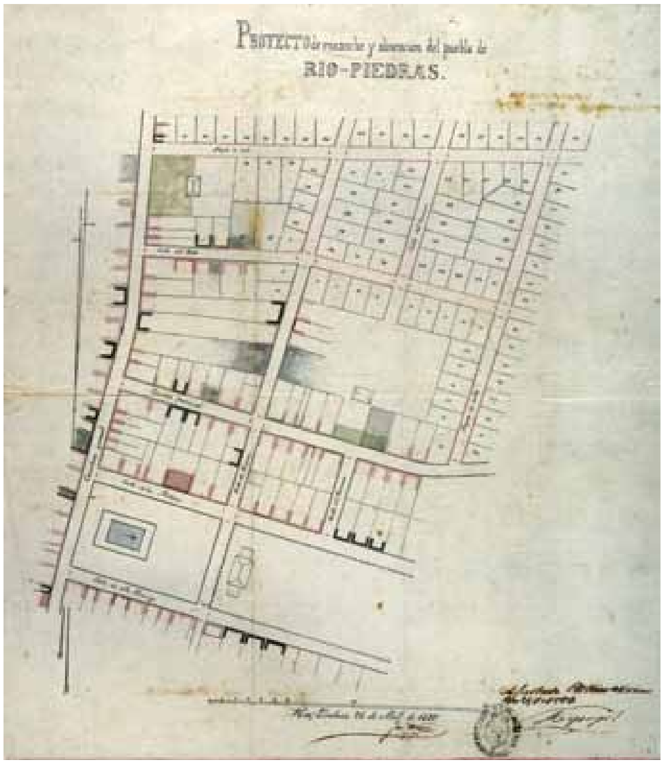


Figure 31. The 1880 expansion plan for the urban core of Río Piedras (Sepúlveda Rivera 2004b).

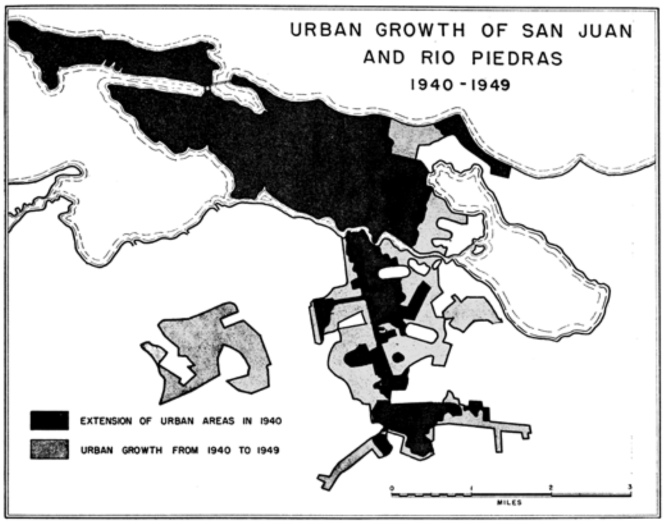


Figure 32. Urban growth in San Juan and Río Piedras between 1940 and 1949 (Picó 1950). This map depicts the early stages of urban sprawl in the San Juan Metropolitan Area.

Picó (1950, p. 52) described the development of Río Piedras (at the heart of the Río Piedras Watershed) thusly: "…Río Piedras, a small rural village which had been selected in 1903 as the site for the main branch of the University of Puerto Rico, was also beginning to attract the attention of the metropolitan dwellers and its population increased from 2,249 in 1899 to 5,820 in 1920." By 1940, Río Piedras had a population of 19,935 and some 20,000 people were living in new urban developments, mostly in the Hato Rey sector, that marked the beginning of urban sprawl in Puerto Rico (fig. 32). The metropolitan area comprising Old San Juan, Santurce, Hato Rey, and Río Piedras coalesced as a continuous urbanized zone by 1948 (Picó 1950). In 1951, the municipality of Río Piedras was incorporated into the municipality of San Juan (Picó 1969). In 1950, the population of Río Piedras was 143,989 or 39 percent that of San Juan. Afterwards, the population of Río Piedras declined sharply (fig. 33) as a result of urban sprawl. By the 1990 census, urban population density in the San Juan Bay basin ranges from 94/km^2 in Piñones to 8,300/km^2 in the business district of Río Piedras (Hato Rey; Webb and Gómez Gómez 1998).

The initial rapid increase in population of Río Piedras was attributed to public transportation and the connection of the city to San Juan via a train (Sepúlveda Rivera 2004b). The decline was the result of sprawl caused by increasing dependence on private cars. The dramatic flow of vehicles in and out of the metropolitan area during the 1960s is illustrated in fig. 34. Today, this high level of connectivity is more pronounced and much higher than it was in the 1960s. A large proportion of the approximately 2.5 million vehicles in Puerto Rico enters and exits the metropolitan area daily.

Saez (1988) gives a vivid and detailed account of the development of Río Piedras and the activities of its habitants. His accounts cover between 1898 and 1945, and he provides street-by-street information and covers all aspects of the daily lives of people. Picó (1950) reported that the hills of the Río Piedras region, including Trujillo Alto, Carolina, and Gurabo, are prime locations for vegetable production, where in 1935 one-half of the island production was harvested in this region.

The history of water supply for San Juan includes a period of time before 1953 when the city obtained water from the Río Piedras aqueduct (fed by the Río Piedras River) and the Río Bayamón River, supplemented with ground water from several high-yield wells (Anderson 1976). Before that, people used rainwater, carried water from streams, or depended on public faucets to satisfy their water needs (Saez 1988). The Río Piedras River was used for swimming, washing clothes, water supply, and to deposit wastes. Seepage from latrines and agriculture runoff reached the river.

In 1953, the Loíza Reservoir was built, and surface water replaced ground water as the major water supply for the metropolitan area. Ground water pumpage declined from 0.22 m^3/s in 1945 to 0.13 m^3/s in 1960 (Anderson 1976). In 1971, the now historic water purification plant in the University of Puerto Rico Botanical Gardens had a capacity of 0.11 m^3/s and a production of 0.10 m^3/s. The plant got its water from the Lago

Las Curias, also in the Río Piedras Watershed. This reservoir stored 1.39 hm^3 of water (367 million gallons). Anderson (1976) estimated that the 1971 output of municipal water supply in the metropolitan area averaged 4.7 m^3/s, double the 1959 output of 2.4 m^3/s. This water consumption originated mostly outside the Río Piedras Watershed (table 20), however. In 1971, the loss of water through leaky mains was 25 percent. By the 2000s, the leakage was more than 50 percent, and a water balance developed by the Department of Natural and Environmental Resources could not be balanced (table 1). A severe drought in the mid-1960s uncovered the vulnerability of the reservoir system, and this led to increased drilling for ground water as a supplement for the city water supply.

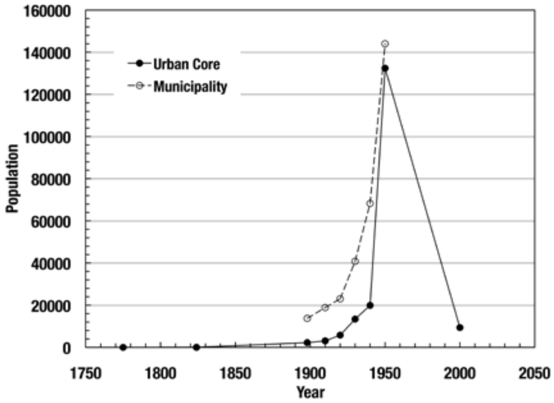


Figure 33. Population changes in the urban core and municipality of Río Piedras between 1774 and 2000 (from Sepúlveda Rivera 2004a).

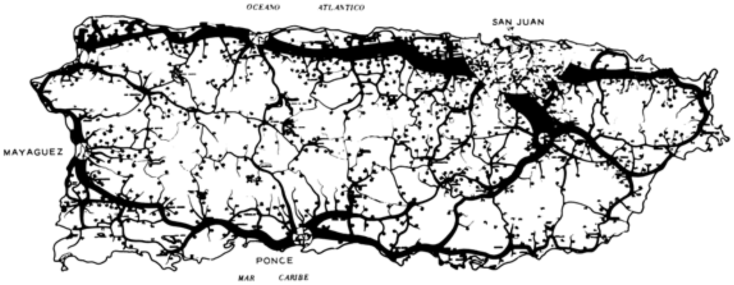


Figure 34. Traffic flow in Puerto Rico (Picó 1969). The width of the lines is proportional to the number of vehicles using the particular route. The San Juan Metropolitan Area is connected to the rest of the island by three main roads, one each from the west, east, and south.

Land Cover for the Metropolitan Area

The metropolitan area has rapidly increased its urban land cover since 1900 (fig. 35). Ramos González et al. (2005) updated this cover using satellite images corresponding to November 27, 1999 (box 3). The most extensive individual land cover class in the metropolitan area (fig. 36, table 21) was high-density urban or built-up (35 percent) followed by forested vegetation (26 percent). Nonforest vegetation also comprised about 26 percent of the metropolitan area and barren land was 2 percent. They found that 53 percent of the study area was classified as vegetation. The largest coverage of vegetation and forests was on the southern limit or the uplands of the various municipalities (fig. 36). Bayamón had the highest forest area, while Carolina had the largest area of agricultural systems, wetlands, and barren land. San Juan had the largest area of high-density urban or built-up land in the region (table 21).

In terms of the percent coverage of each municipality, San Juan had 56 percent of its area as urban built-up and 17 percent forest cover (fig. 37). In contrast, Trujillo Alto was the least urban and most rural municipality with 35 percent forest cover and 80 percent vegetation. Guaynabo was the only other municipality with a larger percentage of forest than urban

Table 20. Water sources for the San Juan Metropolitan Area in 1971 and their capacity and production in cubic meter per second and million gallons per day in parentheses.

Plant	Capacity	Production	Source	Distribution area
Sergio Cuevas	2.6 (60)	3.0 (67.5)	Lago Loíza	Carolina-San Juan
Guaynabo	1.1 (26)	1.3 (29.7)	Lago de Cidra, Río de Bayamón, Río Guaynabo	Guaynabo-Bayamón
Botanical Gardens	0.11 (2.5)	0.10 (2.2)	Lago Las Curias	Río Piedras-San Juan
San Juan	0.47 (10.7)	0.01 (0.2)	18 wells	San Juan
Campanilla-Sabana Seca	0.68 (15.6)	0.39 (8.88)	16 wells	Levittown

Source: Modified from Anderson (1976).

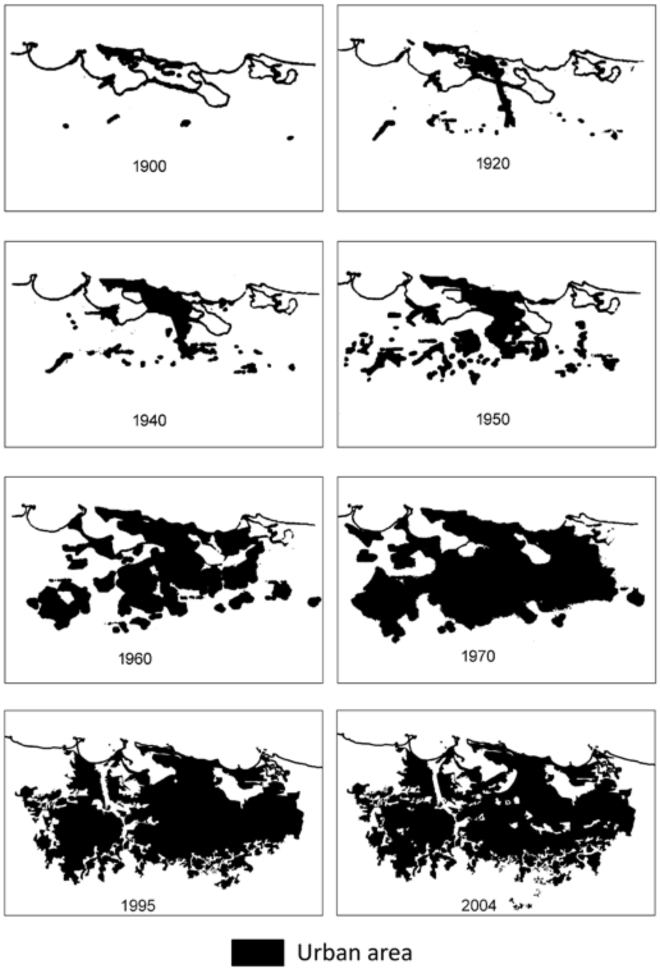


Figure 35. Historic changes in land cover for the San Juan Metropolitan Area. Covers between 1900 and 1970 are from Webb and Gómez Gómez (1998). Post-1970 covers are from Universidad Metropolitana and Estudios Técnicos, Inc. (2001).

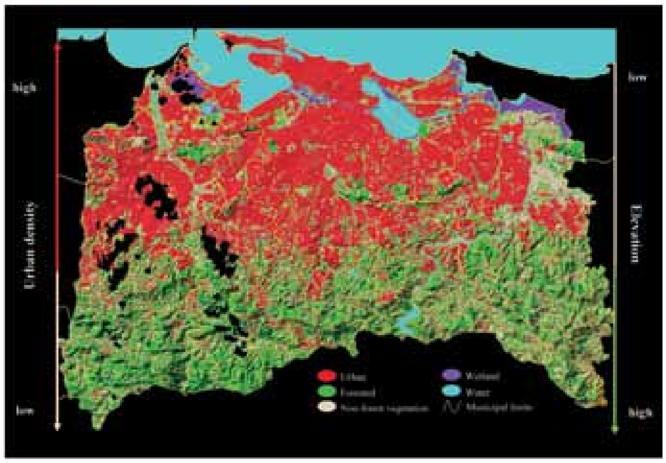


Figure 36. Land cover for the San Juan Metropolitan Area in November 1999 (Ramos González et al. 2005).

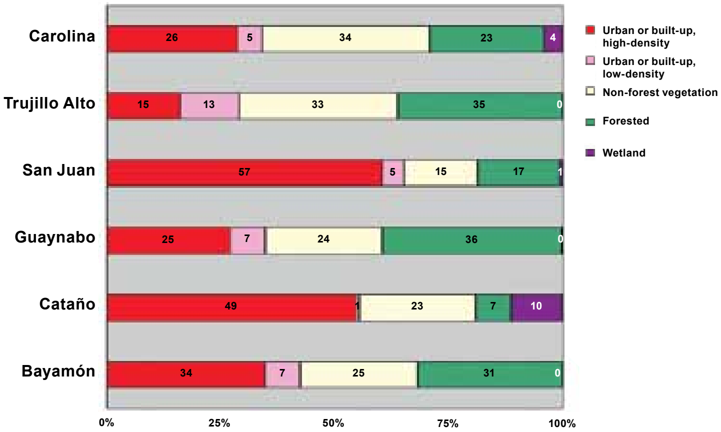


Figure 37. Percent of land cover for the municipalities of the San Juan Metropolitan Area in November 1999 (Ramos González et al. 2005).

Table 21. Land cover-class area (hectare) for each municipality of the San Juan Metropolitan Area.

Land cover	Bayamón	Cataño	Guaynabo	San Juan	Trujillo Alto	Carolina	Total
Urban, high density	3,911	656	1,771	7,298	857	3,281	17,775
Urban, low density	863	10	508	588	698	634	3,300
Barren, artificial	202	11	163	225	53	286	940
Barren, natural	26	8	16	21	12	36	118
Nonforest vegetation	2,902	307	1,673	1,961	1,850	4,209	12,902
Forested vegetation	3,567	92	2,554	2,147	1,934	2,882	13,176
Wetlands	2	136	18	95	0	462	713
Water	71	89	29	339	141	567	1,237
Total area	11,545	1,308	6,731	12,674	5,544	12,357	50,160
Total urban	4,774	666	2,279	7,885	1,555	3,915	21,075
Total vegetation	6,472	535	4,245	4,203	3,784	7,553	26,791

Notes: The unaccounted area corresponds to cloud cover. Data are rounded to the nearest hectare.

Box 3. Methods for Land Cover Analysis of the San Juan Metropolitan Area

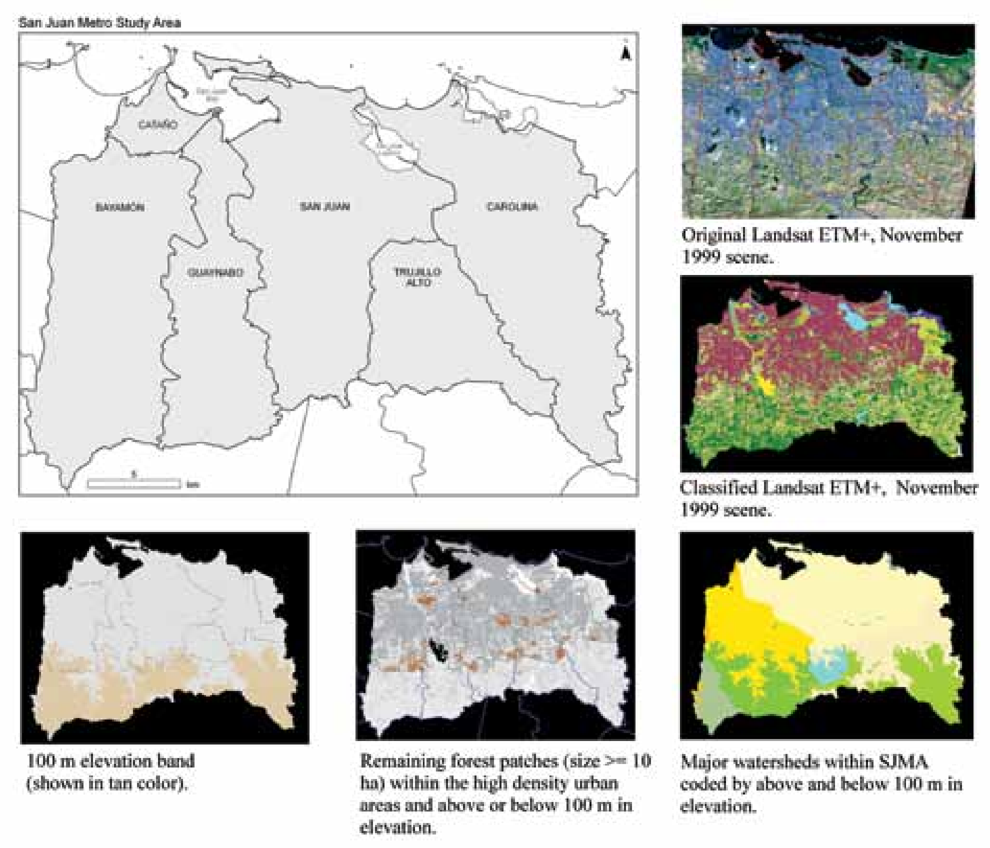
A Landsat ETM+ scene dated November 27, 1999, with less than 10 percent cloud coverage was acquired, terrain-corrected, and georeferenced through the U.S. Geological Survey EROS Data Center in Sioux Falls, SD (fig. B3-1). We used six of the 30 m resolution spectral bands (bands 1 to 5 and 7) and the 15 m panchromatic band (band 8) from this satellite sensor. The scene was subset to the study region, preprocessed for clouds and cloud-shadows, and pan-sharpened with the panchromatic band. A 6-band composite image resulted, incorporating the 15 m spatial resolution and the spectral information (visible to near infrared spectra) from the original scene.

The image was further segmented using a first-cut, unsupervised ISODATA clustering procedure into vegetation, nonvegetation, and water. This split reduced confusion among spectral classes and provided the benefit of running further clustering routines individually by general land cover element in separate images. Each of these images was iteratively processed using both unsupervised and supervised clustering procedures until separation of clear land cover was achieved, most specifically for the vegetation segment. Ancillary data such as aerial photographs (1:48,000 NOAA, 1999 and 1:20,000 DTOP, 1997–2000) and other available Geographic Information System (GIS) data sets (U.S. Fish and Wildlife Service National Wetland Inventory and San Juan Bay Estuary) were used as reference information to manually edit and refine the resulting classified image.

The following land cover classification scheme was used for the assessment: (1) high-density urban or built-up (more than 80-percent built-up land), (2) low-density urban or built-up, (3) natural barren (sand, gravel, bare rock, or sediment), (4) artificial barren (artificially exposed soil), (5) nonforest vegetation (pasture, grassy areas, pasture with shrub), (6) forested (closed forest canopy), (7) wetland (forested and herbaceous), (8) water (inland water bodies or ocean), (9) clouds, and (10) no data (outside satellite coverage).

The minimum mapping unit chosen for the analysis was 0.5 ha. Total land area classified in the San Juan Metropolitan Area (SJMA) was 50,588 ha. When estimating the percentage of each land cover class, however, we did not include cloud cover or areas with no satellite coverage. This exclusion reduced the total area assessed to 50,160 ha. All images were processed using ERDAS Imagine 8.4, whereas map output was generated using ESRI Arc View 3.2a GIS software or ArcGIS 9.3. We conducted an initial accuracy assessment by comparing results with aerial photography. The labeling is correct to within 80 to 90 percent accuracy. The map date corresponds to November 27, 1999.

The following analysis perspectives were used to uncover the spatial distribution patterns of forest fragments in the SJMA (fig. B3-1): Total land cover area in SJMA and percent land cover within each municipality, land cover within 50 and 100 m elevation ranges, land cover within high-density vs. low-density urban areas, and number and characterizations by size and location of forest fragment classes. In addition, area and percent land cover were calculated by major watersheds above and below 100 m elevation bands for the entire study area.



Original Landsat ETM+, November 1999 scene.

Classified Landsat ETM+, November 1999 scene.

100 m elevation band (shown in tan color).

Remaining forest patches (size >= 10 ha) within the high density urban areas and above or below 100 m in elevation.

Major watersheds within SJMA coded by above and below 100 m in elevation.

Fig. B3-1. Original Landsat ETM+ satellite image and stages of interpretation of the image were used to study land cover for the San Juan Metropolitan Area.

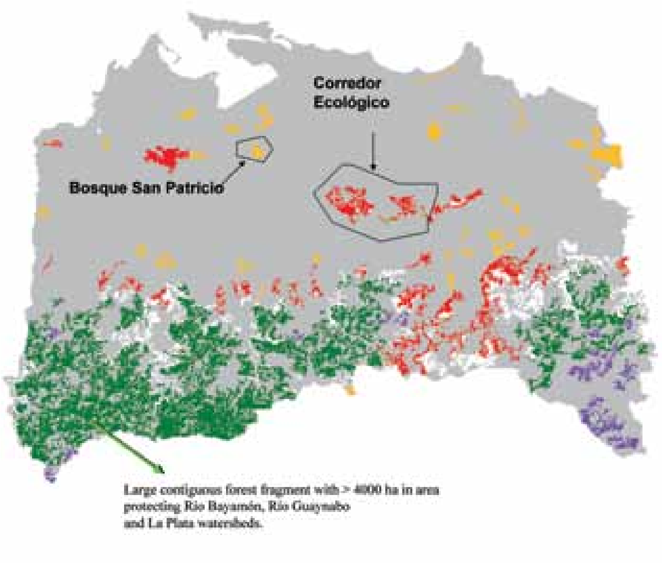


Figure 38. Forest cover in the San Juan Metropolitan Area in November 1999 (Ramos González et al. 2005). Dark green represents the largest forest fragments, which are concentrated and contiguous only above 100 m in elevation. Below 100 m, forest patches tend to be more isolated and much smaller in extension. All are less than 200 ha in area and are displayed in red and orange. Some of these patches are currently in protected status. Bosque San Patricio (approx. 25 ha) and the University of Puerto Rico Botanical Gardens within the newly designated San Juan Ecological Corridor (approx. 200 ha) are examples.

cover. Cataño had the largest percentage of wetlands and the lowest of forest cover than any municipality. Cataño was the second most urbanized municipality in the metropolitan area. The percentage of barren land was similar in all municipalities.

The 1999 land cover results for the municipality of San Juan (fig. 37) match the 17-percent forest cover figure reported for 1995 by J. Molineli of the University of Puerto Rico. Ramos González et al. (2005) found that regionalizing the results improved the description of the spatial distribution of the forest fragments in the region. Forest fragments tend to be sparse and isolated in the lowlands, whereas above 100 m in elevation, forest fragments are larger and more connected (fig. 38). The southern areas in San Juan contain about one-half of the vegetation cover for the whole municipality (fig. 39). The difference in spatial distribution of these fragments is striking, although similar in number of hectares as shown in the table within fig. 39. Most of the municipalities, in general, fall short of healthier tree cover goals such as those proposed by American Forests; that is, 40 percent for general tree cover and 25 percent for urban residential areas. (http://www.americanforests.org/resources/urbanforests/treedeficit.php).

The metropolitan area still contains significant areas of vegetation other than forests. Ramos González et al. (2005) recognized that some of this vegetation (that is, managed grass and pasture) is indicative of urban development. This class includes vegetation in cemeteries, golf courses, grass along roads, and in parks and other recreation areas. Nevertheless, this cover class and other

Below 100 m in elevation		
Class name	*Percent*	*Area (ha)*
Urban or built-up, high density	67.9%	7149.3
Urban or built-up, low density	3.0%	311.2
Artificial barren	1.7%	176.9
Natural barren	0.2%	19.5
Non-forest vegetation	12.7%	1342.5
Forested	10.4%	1095.4
Wetland	0.9%	94.8
Water	3.2%	342.0
No data 1 (outside sat cov)	0.0%	0.0
No data 2 (cloud and unk)	0.0%	0.0
	Total Area	10531.7
Above 100 m in elevation		
Class name	*Percent*	*Area (ha)*
Urban or built-up, high density	7.8%	170.7
Urban or built-up, low density	12.8%	281.4
Artificial barren	2.2%	49.5
Natural barren	0.0%	1.0
Non-forest vegetation	28.7%	631.1
Forested	48.4%	1065.2
Wetland	0.0%	0.0
Water	0.2%	3.6
No data 1 (outside sat cov)	0.0%	0.0
No data 2 (cloud and unk)	0.0%	0.0
	Total Area	2202.5
	Total San Juan area	12734.2

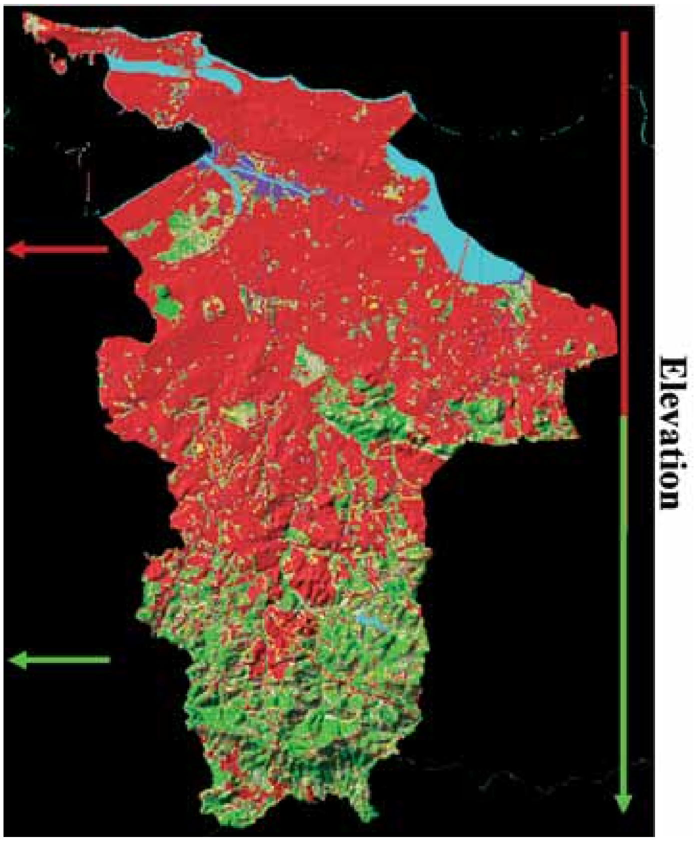


Figure 39. Land cover for the Municipality of San Juan in November 1999 (Ramos González et al. 2005). Cover area and its percentage are reported separately for below and above 100 m elevation.

pasture and shrub classes contribute to the green infrastructure of the city and represent opportunities for restoring forests where appropriate. Inhabitants in the city derive benefits from all the green areas and the built-up land. Only San Juan and Cataño have more land without vegetation than with vegetation, and the metropolitan area as a whole is at 44 percent of the area without vegetation. The distribution of vegetated areas provides options for city planners to maintain a mix of vegetation and nonvegetation zones to optimize the benefits of the green infrastructure.

Land cover data by watershed (fig. 40) show how prevalent forested vegetation is on the upper portions of all watersheds (compare fig. 40a for lowland portions of watersheds with fig. 40b for the corresponding uplands). The Río Piedras Watershed is part of the San Juan Bay Estuary Watershed in these figures. Table 22 contains information on land cover for the Río Piedras Watershed only. It shows that in comparison with other watersheds in the island, the Río Piedras Watershed is heavily urban with equal proportions of nonforest and forest cover. Even near the Río Piedras River channel, the urban cover is significant.

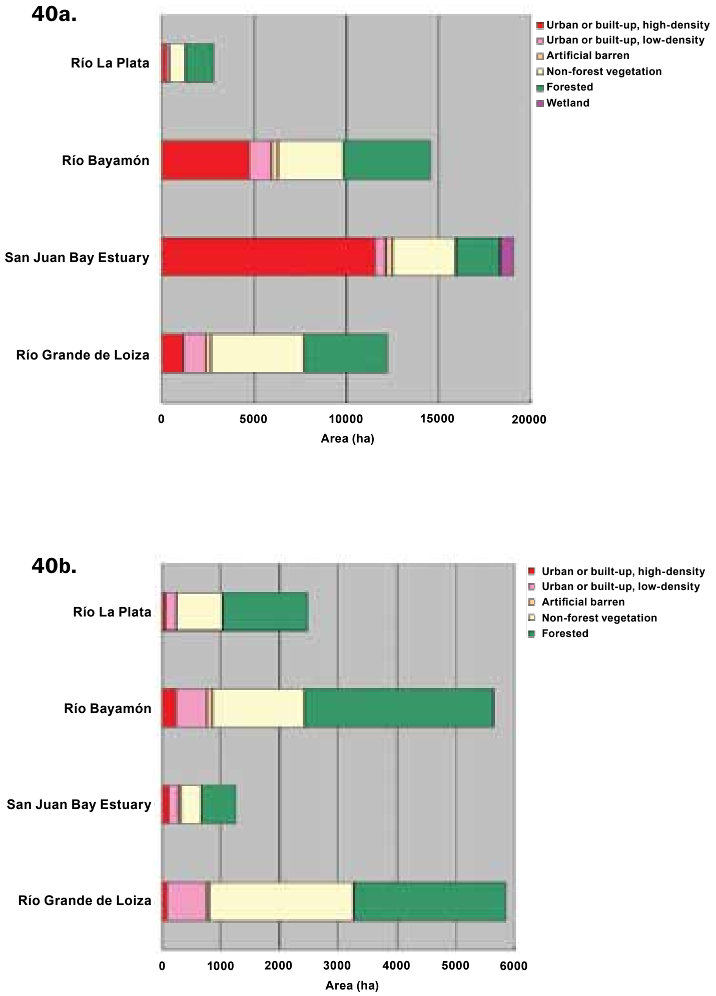


Figure 40. Distribution of land cover classes in (a) the lowlands, below 100 m in elevation, and (b) the uplands, above 100 m in elevation, by major watershed in the San Juan Metropolitan Area (Ramos González et al. 2005).

Overview of the Effects of Human Activity in the San Juan Bay Area

Seguinot Barbosa (1983) conducted a comprehensive analysis of coastal modifications and land transformation in the San Juan Bay Area, which we now summarize for its value as an overview of the effects of human activity in the metropolitan area. The early presence of humans in the region was before 350 AD, and the climax of indigenous activity by the Taíno was in 1200 AD. This activity was followed by 400 years of land transformation by the Spanish colonial period and more than 100 years of accelerated change under the influence of the United States of America.

The port of San Juan became the most significant development nucleus of Puerto Rico that attracted rural populations and the formation of extensive slums throughout the first half of the 20th century. As an industrial model of development progressively substituted the agricultural model, urban sprawl began to take hold, particularly after the 1960s. Deterioration of the urban core accelerated the population shift towards the periphery of the city and adjacent municipalities. Such

Table 22. Land cover (percent) at three spatial scales above a Río Piedras River station located at the intersection of highway PR-176 and the river channel.

	Parameter	Río Piedras	Mean of 46 rivers
30-m riparian buffer	Agriculture	30.1	37.4
	Forest	31.6	43.9
	Shrub and woodland	11.1	14.8
	Urban	24.3	3.5
100-m riparian buffer	Agriculture	27.3	25.3
	Forest	28.8	56.9
	Shrub and woodland	9.3	13.6
	Urban	33.0	4.0
Watershed	Agriculture	24.8	40.1
	Forest	26.3	42.1
	Freshwater	0.7	0.1
	Shrub and woodland	8.8	13.4
	Urban	39.4	4.2

Source: Kwak et al. (2007).

dramatic shifts in human activity and population distribution had considerable effects on the physical environment.

The San Juan Bay experienced few changes between 1518 and 1790. Land reclamation processes of coastal areas were the greatest effects documented up to the turn of the 20th century. Between 1912 and 1980, however, the changes were dramatic. The coastal configuration of the Bay changed with significant effects on ocean currents and wave refraction, reflection, erosion, deposition, and circulation patterns. About 19,158 m^2 of the Bay were filled or dredged. Coastal erosion was evident at rates of 0.6 m/y and 2.9 m/yr in different locations. These erosion rates were associated with hurricanes, other natural events, and synergy with dredging, filling, and channelization of streams and rivers. Humans have constructed artificial beaches; contributed to the formation of the Palo Seco spit; and changed deposition patterns, allowing mangroves to develop where sediments accumulate. High-wave energy areas have been converted to low-energy coastal areas.

Large areas of mangroves on the eastern shore of the Bay were filled and converted to urban built-up land such as the Puerto Nuevo area, which now floods with high frequency. The filled area in the San Juan Bay Watershed was equivalent to 12 percent of the watershed (table 2). Vegetation cover was reduced by 80 percent between 1508 and the 1980s. *Ciénaga Las Cucharillas* lost 50 percent of its 1508 area and 90 percent of its mangroves. In 1888, the average depth of San Juan Bay was about 10 ft (3.1 m); it increased to 12 ft (3.7 m) by 1912, and was 25 ft (7.6 m) in the 1980s. Shoals and benthic communities disappeared. The extension of the flood plains of the Río Bayamón and Río Piedras Rivers was reduced by 95 percent.

Discussion

Our analysis has uncovered a number of issues that deserve additional attention. The Río Piedras Watershed has been heavily modified by human activity, and it is very difficult to establish its hydrologic boundaries (box 2). We found different delineation by different government agencies, some in clear inconsistency with the hydrologic definition of what a watershed is. The connection of the original channel of the Río Piedras River with the Caño Martín Peña and water from the Bayamón River make the mouth of the river a very complex hydrological system that requires further attention.

The proposal of the U.S. Army Corps of Engineers to channelize the Río Piedras and Río Puerto Nuevo Rivers (fig. 17) will further complicate the hydrologic behavior of the Río Piedras River by introducing hypercritical flows to the watershed. These measures were necessary due to the lack of effective implementation of land use planning in the metropolitan area. We found that in the 1940s to the 1960s (Picó 1950, 1969), the Planning Board had made land development plans for the region (fig. 41) by regulating the conversion of rural lands to urban uses. These plans were apparently abandoned after the 1970s as the Planning Board abandoned its efforts to plan the development of rural lands in the island. Instead, the Planning Board simply permitted urban developments and zoned urban areas but did not develop a land use plan for rural lands (see Padín et al. N.d.).

The rapid expansion of urban uses in the metropolitan area negated many of the assumptions that led to the planning of the channelization of the Río Piedras. For example, constructions of large buildings near vital river intersections with main roads limited the width of the proposed canal, thus leading to the need to incorporate hypercritical fluxes into the design of the channelization. This design, in turn, not only made the project more expensive but also demanded more land for water storage in the basin during periods of high rainfall. It also made the project more dangerous, and required the isolation of the channel from human use of the river to avoid fatalities during the periods of critical discharges. When the channelization was conceived, however, the expectations for urban expansion and population density in the metropolitan area were overestimated, as no one could predict in the 1960s and 1970s the movement of population away from urban cores and into the rural areas of Puerto Rico away from the metropolitan area. Thus, the upper portions of the Río Piedras River watershed were not developed as expected, which allows for more flexibility for the design of the proposed concrete channels. Moreover, today the value of the river for uses other than concrete channels is a public concern as alternative technologies exist to reduce storm runoff. There appears to be sufficient cause to revisit the management alternatives for the floodwaters in the Río Piedras Watershed.

As an example of the increased recognition of the value of rivers and riparian zones in Puerto Rico, we quote here a section of the Law of Flood Prevention and Conservation of Streams (*Ley 49, 2003, Art 2*):

> *Se dispone que en cualquier obra de urbanización o cualquier lotificación colindante con un río, quebrada, laguna o cualquier cuerpo de agua se dedicará a uso público, en interés general de la conservación del cuerpo de agua, mediante inscripción en el Registro de Propiedad, una faja de terreno*

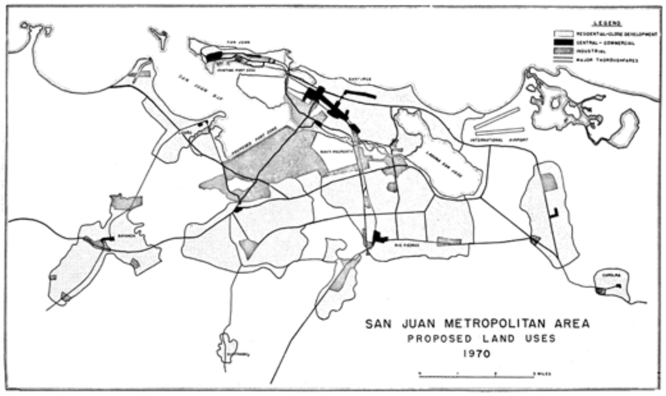


Figure 41. Land use plan for the 1970s in the San Juan Metropolitan Area (Picó 1969). This plan regulated the development and conversion of rural lands to urban uses.

> *con un ancho mínimo de cinco metros lineales a ambos lados del cauce del río, arroyo o quebrada o del lecho de la laguna o lago. Esta faja se mantendrá expedita y no podrá ser utilizada para usos distintos al propósito de conservación. Sólo se permitirán usos recreativos pasivos que no conlleven obstrucción, no conflijan con funciones de conservación y limpieza y estén relacionados con el disfrute del cuerpo de agua. Cuando se trate una quebrada o arroyo, la faja deberá será cedida al Municipio con jurisdicción.*

San Juan Bay is the economic hub of Puerto Rico, as most of the shipping and tourism vessels require use of the Bay. The large sediment and nutrient loads that are transported by the Río Piedras River to San Juan Bay (table 7) deteriorate water quality and sediment the Bay, however, which requires more frequent dredging and maintenance at a high cost to the Federal Government. These costs could be reduced with better regulation of land movement in the Río Piedras Watershed, but such regulations do not exist or are not enforced. Allowing developers to sediment the river is a subsidy from the Federal Government to the construction industry that saves money for developers who do not have to be careful with land movement activities.

We were surprised by the high species richness in the Río Piedras River itself and its surrounding environment (tables 8–10) and the health and species richness (tables 11–19, photos 4, 5, and 7) of urban forests and vegetation throughout the city. This high level of biotic activity reflects a functioning river system and watershed despite the highly polluted conditions of its waters, which are classified as unacceptable to humans in terms of fecal bacterial counts (table 6, fig. 21). This situation appears paradoxical, although the Río Piedras River might be an example of the resilience of riverine systems in urban environments, or the fact that what is poor water quality for humans might be acceptable water quality to wild organisms, or perhaps both. On the other hand, terrestrial vegetation and wetlands in the metropolitan area must be playing important ecological roles that sustain economic activity and life quality, although these ecosystem services are not generally recognized.

We also found a reduction in monitoring activities by U.S. Government agencies in the metropolitan area (see appendix). Many of the studies conducted in the coastal lagoons, aquifers, rivers, and streams of San Juan could not be conducted today because a network of stations gaging these natural systems no longer exists. A system of rainfall, stream gaging, water quality, tidal surges, biological diversity, and aquifer behavior is critically needed for this overcrowded part of Puerto Rico.

Finally, our review only briefly addressed the issue of the large use of energy in the metropolitan area, which leads to the development of a heat island effect, but which also powers the economy. A clear need exists to gain more understanding on the metabolism of the SES of San Juan, with particular focus on the material and energy balances that support such high levels of human activity in such a small area.

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Appendix. Environmental Monitoring Stations Operated by the Government in the San Juan Metropolitan Area.

Note: Empty cells mean that data are not available. For more information on the stations, see the indicated Web pages.

1. U.S. Geological Survey gaging stations (http://waterdata.usgs.gov/nwis/).

Station number	Station name	Latitude (NAD 27)	Longitude (NAD 27)	Drainage area (km^2)	Datum of gage (m asl NGVD 29*)
50048680	Lago Las Curias at Damsite near Río Piedras River	18°20'40"	– 66°03'03"	2.8	99.97
50048690	Quebrada Las Curias BLW Las Curias outflow	18°20'42"	– 66°03'08"	2.85	80.00
50048770	Río Piedras River at El Señorial	18°21'51"	– 66°03'56"	19.40	60.02
50048800	Río Piedras near Río Piedras River	18°22'15"	– 66°03'40"	21.2	29.99
50049000	Río Piedras at Río Piedras	18°23'48"	– 66°03'24"	32.4	50.02
50049100	Río Piedras River at Hato Rey	18°24'34"	– 88°04'10"	39.37	0.98
50999971	Lago Las Curias Raingage Near Cupey	18°20'05"	– 66°02'23"	n/a	47.24

* m asl NGVD 29 = meters above sea level National Geodetic Vertical Datum of 1929

2. National Oceanographic and Atmospheric Administration climate stations (http://www.ncdc.noaa.gov/oa/climate/stationlocator.html).

Station number	Station name	Latitude	Longitude	Elevation (m)	Period of record*
668814**	San Juan WFO (Weather Forecast Office)	18.43	– 66.00	2.59	2006 to 2009
20023983	Río Piedras	18.40000	– 66.06667	29.87	1/1/55 to 1/31/62
20023985	Río Piedras, Experiment Station	18.39056	– 66.05417	28.04	1/1/59 to 2009
20023988	San Juan International Airport	18.43250	– 66.01083	2.74	1/1/55 to 2009
20023989	San Juan Naval Station	18.43333	– 66.08333	13.11	1/1/39 to 12/31/45
20023994	San Juan Isla Grande	18.45000	– 66.10000	18.90	12/1/47 to 5/31/55
20023999	San Juan City	18.46667	– 66.10000	6.10	1/11/1888 to 5/31/77
20024000	San Juan AFF (Autoridad de Fuentes Fluviales)	18.46667	– 66.11667	24.99	6/1/41 to 6/30/43
30001966	San Juan FAA (Federal Aviation Administration)	18.11750	– 66.07861	851.61	7/7/97 to 2009

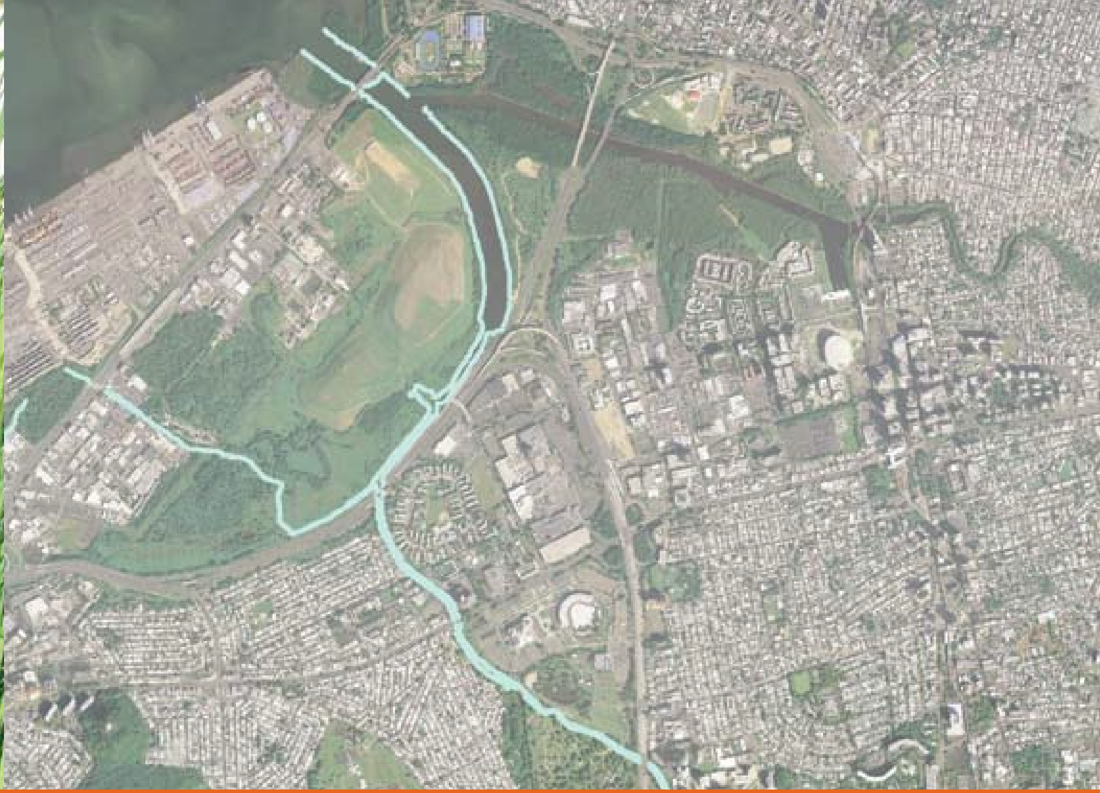
*As of 2009.

** COOP (cooperative agreement) number.

Note: Station numbers correspond to those of the National Climate Data Center.

3. Environmental Protection Agency Air Quality System (http://www.epa.gov/ttn/airs/airsaqs/detaildata/downloadaqsdata.htm).

Site ID (72-127-)	Address	Latitude (WGS84)	Longitude (WGS84)	Period of record
0001	Fire Department, Muñoz Rivera and Manuel Domenech	18.416761	– 66.055011	1/1/62 to 12/31/64
0002	Stop 22, Ponce de León, Santurce	18.447222	– 66.067500	1/1/81 to 2009
0003	Baldorioty de Castro Ave.	18.449814	– 66.052510	10/26/82 to 2009
0004	Gandara Ave., University of Puerto Rico	18.403889	– 66.052778	3/18/81 to 8/30/02
0005	65th Infantry and Verona	18.396667	– 66.026111	1/1/82 to 2009
0006	High School Trina Padilla, Hato Rey	18.408056	– 66.073056	12/8/84 to 5/14/85
0007	Post Office, Juan B. Huyke St.	18.423333	– 66.059722	4/2/86 to 12/19/98
0008	William Jones St., Río Piedras	18.401944	– 66.046389	2/1/95 to 2009
0009	St. 16, NE-5, Puerto Nuevo	18.418889	– 66.087500	2/20/97 to 2009
0010	Covadonga Terminal, Fernández Juncos and Comer	18.466760	– 66.112793	11/29/96 to 2009
0011	Fernández Juncos Ave.	18.449859	– 66.073426	5/14/04 to 2009
1001	Edificio Margarida, 562 Muñoz Rivera Ave.	18.406944	– 66.054167	1/1/74 to 12/31/81
1002	Shopping Center FD Roosevelt and Muñoz Rivera	18.422500	– 66.056667	1/1/76 to 12/31/81
1003	FD Roosevelt Ave., Hato Rey	18.422778	– 66.069722	1/1/78 to 12/31/81



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