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Physical Aspects of Hurricane Hugo in Puerto Rico[1]

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ABSTRACT

On 18 September 1989 the western part of Hurricane Hugo crossed eastern Puerto Rico and the Luquillo Experimental Forest (LEF). Storm-facing slopes on the northeastern part of the island that were within 15 km of the eye and received greater than 200 mm of rain were most affected by the storm. In the LEF and nearby area, recurrence intervals associated with Hurricane Hugo were 50 yr for wind velocity, 10 to 31 yr for stream discharge, and 5 yr for rainfall intensity. To compare the magnitudes of the six hurricanes to pass over Puerto Rico since 1899, 3 indices were developed using the standardized values of the product of: the maximum sustained wind speed at San Juan squared and storm duration; the square of the product of the maximum sustained wind velocity at San Juan and the ratio of the distance between the hurricane eye and San Juan to the distance between the eye and percentage of average annual rainfall delivered by the storm. Based on these indices, Hurricane Hugo was of moderate intensity. However, because of the path of Hurricane Hugo, only one of these six storms (the 1932 storm) caused more damage to the LEF than Hurricane Hugo. Hurricanes of Hugo's magnitude are estimated to pass over the LEF once every 50–60 yr, on average.

RESUMEN

El 18 de septiembre de 1989, la esquina noroeste del huracan Hugo paso sobre la parte este de Puerto Rico y el Bosque Experimental de Luquillo (BEL). Las pendientes de barlovento a 15 km desde el ojo y que recibieron mas que 200 mm de lluvia, sufrieron el mayor impacto. En el BEL, los intervalos medios de ocurrencia asociados al huracan Hugo fueron 50 años para velocidades de vientos, 10–31 años para descargos de quebradas y 5 años para intensidades de precipitacion. En el proposito de comparar las magnitudes de seis huracanes que han pasado recientemente sobre Puerto Rico se desarrollaron indices que utilizan los valores estandarizados de: (1) el producto del cuadrado de la velocidad maxima sostenida del viento en San Juan por la duracion de la tormenta: (2) el cuadrado del producto de la velocidad maxima sostenida del viento en San Juan y la razon de las distancias desde el ojo del huracan a San Juan y al BEL; y (3) el porcentaje con respecto al del promedio anual de la lluvia traida por la tormenta. En ralacion a huracanes historicos, Hugo fue una tormenta de tamaño mediano. Sin embargo, debido a su trayectoria, fue el segundo mayor impacto al BEL. Huracanes de la magnitud de Hugo pasan sobre el BEL cada 30–60 años.

Path and wind velocities.—Hurricane Hugo originated off the coast of Africa and developed into a hurricane on 15 September 1989, three days before it entered the Caribbean. On 18 September 1989 the western part of the hurricane crossed Puerto Rico near the town of Fajardo (Fig. 1), while the central and eastern parts of the storm remained over water (U.S. National Weather Service 1989). Although the shape of the hurricane was variable, the eye generally was about 30 km in diameter.

Wind gusts of tropical storm force were first recorded in Puerto Rico at the U.S. Naval Base near Ceiba at 1600 hr on 17 September 1989. Sustained tropical storm force winds began at 0200 hr the next day. Before U.S. National Weather Service anemometers were damaged, maximum sustained winds of 166 km/hr, with gusts to 194 km/hr, were recorded (U.S. National Weather Service 1989). Unofficial measurements of sustained winds on Puerto Rico were as high as 227 km/hr (J. Francis, pers. comm.). In the affected areas of eastern Puerto Rico, hurricane-force winds lasted about 4 hr. The average time interval between occurrences (recurrence interval) of 166 km/hr sustained winds at the U.S. Naval Base at Ceiba (Fig. 1) was estimated at 50 yr (Marshall 1990). For the small islands east of Puerto Rico, where sustained winds of 194 km/hr and gusts to 240 km/hr were recorded, Marshall (1990) estimated a recurrence interval of 200 yr.

As Hurricane Hugo crossed Puerto Rico, a min-

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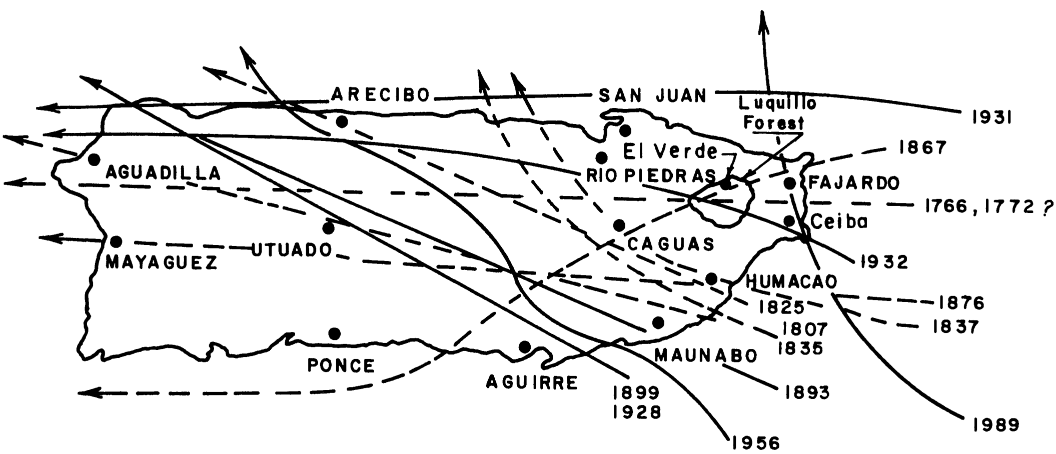

FIGURE 1. Paths of hurricanes that have crossed Puerto Rico since 1700 (adapted from Salivia 1972, Weaver 1986, and U.S. National Weather Service 1990).

imum sea level barometric pressure (MSLBP) of 946.2 mbs was measured at the U.S. Naval base at Ceiba (U.S. National Weather Service 1989). In San Juan, the MSLBP was 972.6 mbs. Storm waves along the coastline of eastern and northeastern Puerto Rico were between 2.1 and 3.9 m. Storm waves of 3.4 to 3.8 m occurred on nearby islands (H. Torres-Sierra, pers. comm.).

Residents on the eastern part of Puerto Rico reported that the storm intensity peaked between 0800 and 0900 hr on 18 September 1989. At Ceiba wind velocities decreased rapidly about 0850 hr, and wind direction shifted from north to southwest (U.S. National Weather Service 1989). A similar wind shift was reported by residents living in Fajardo, and in areas adjacent to the LEF.

Rainfall and stream discharge.—During the 2 wk period prior to Hurricane Hugo, rainfall in eastern Puerto Rico was 80–85 percent below normal (U.S. National Weather Service 1990). During the storm, however, rainfall totals ranged from 100 to 339 mm and precipitation intensities ranged from 34 to 39 mm/hr (U.S. Department of Commerce 1990). Maximum intensities for 1-, 2-, and 3-hr intervals generally had recurrence intervals of 5 yr or less (U.S. Weather Bureau 1961).

During the weeks after the hurricane, large areas of Puerto Rico experienced below average rainfall (Fig. 3). Monthly rainfall totals were below long-term means at Fajardo (U.S. National Weather Service 1990) and within the LEF at El Verde (Luquillo Forest Long-Term Ecological Research Project 1989) until the end of the calendar year. Of the 28 long-term weather stations located throughout Puerto Rico, 21 or more stations reported below normal rainfall for the months of October, November, and December 1989. Peak stream discharges (instantaneous maximums) for drainages in and near the LEF had recurrence intervals of 10–31 yr (Table 1). Within 12 to 24 hr after storm rainfall ended, all of the streams returned to prestorm discharges.

Geomorphic effects.—Examination of two groups of aerial photographs that covered 57 percent (6474 ha) of the LEF revealed 285 Hurricane Hugo related landslides (Fig. 2, Table 2). These landslides affected 0.14 percent of the area photographed. However, 230 of these landslides were concentrated in a 1031 ha area. Field measurements in 13 ha of the Bisley watersheds, which is located on storm-facing slopes within the 1031 ha area of concentrated damage (Fig. 2), indicated that 1.25 percent of the land surface in that area had been disturbed by landslides or uprooted trees (Table 2). Landslides alone affected 0.6 percent of the Bisley watersheds. Multiple uprooted trees accounted for the remaining 0.65 percent of disturbed area.

Most landslides (71 percent), occurred on northeast- (37 percent) or northwest-facing (34 percent) slopes. Of the remaining landslides, 55 percent were at or immediately below the east-west trending ridges that had numerous treefalls (Angel Torres-Sánchez, pers. comm.). The largest failure was a debris avalanche measuring 153 m long, 23–33 m wide, and 3–10 m deep. This landslide occurred 3 d after the hurricane and moved approximately

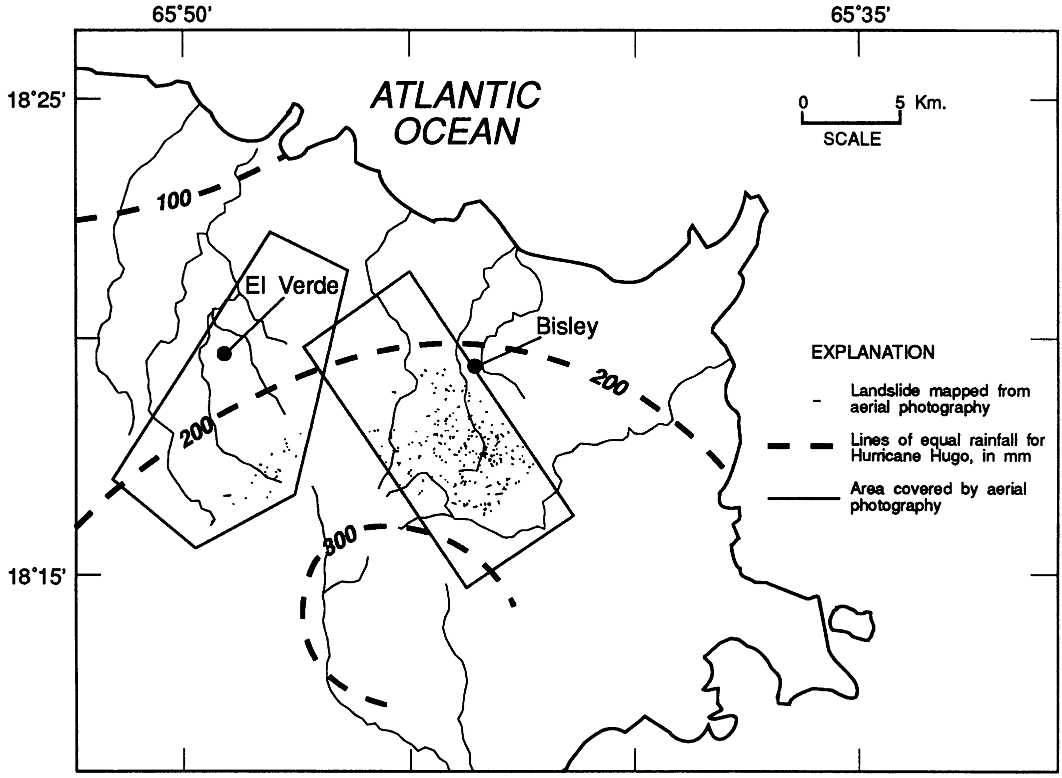

FIGURE 2. Map of eastern Puerto Rico showing research sites at El Verde and Bisley, area covered by aerial photography, location of mapped landslides, and rainfall isohyets for Hurricane Hugo.

30,000 m³ of material more than 600 m into a nearby river.

The majority (77 percent) of landslides were not related to roads, pasture, or cropland and occurred on forest-covered slopes. Fifty-five percent of all landslides were on concave slopes. Shallow soil slips (0.5–1.5 m deep) and debris flows (1–2 m deep) accounted for 91 percent of all landslides surveyed (A. Torres-Sánchez, pers. comm.).

Almost all of the mapped landslides occurred in areas with land-surface elevations of 100–640 m above mean sea level and in areas that received 200 mm or more rainfall (Fig. 2). The rainfall apparently saturated the upper 1–2 m of the relatively impermeable regolith before increases in pore pressure occurred at depth (Larsen & Torres-Sánchez 1990, Larsen 1990). The elevated pore pressures in the saturated shallow regolith were sufficient to trigger the numerous shallow landslides during the short-duration, high-intensity storm. Because almost all of the landslides were in the area that received more than 200 mm of rainfall, this rainfall amount appears to be a threshold for landslides associated with Hurricane Hugo.

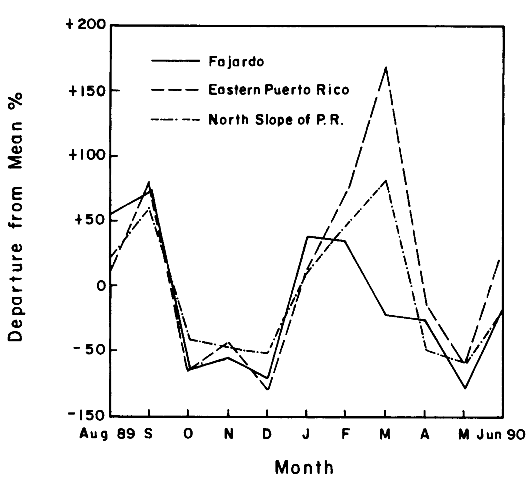

FIGURE 3. Departure from mean monthly rainfall for long-term rainfall stations at Fajardo, eastern Puerto Rico, and the northern slopes of Puerto Rico (from U.S. National Weather Service 1990).

TABLE 1. *Summary of streamflow characteristics and peak discharges during Hurricane Hugo and other large storms at selected streamflow stations in eastern Puerto Rico (Curtis* et al. *1990, López* et al. *1979)*

Streamflow station	Drainage area (km^2)	Average discharge and (years of record) (m^3/s)	Peak discharge (m^3/s) and (recurrence interval in years) Historical maximums	Hurricane Hugo	Hurricane Hugo peak basin runoff (mm/hr)
Espiritu Santo	22.3	1.69 (24)	566 (42)	427 (10)	69
Fajardo	38.6	1.98 (29)	555 (15)	666 (31)	58
Icacos	3.3	0.42 (18)	81 (20)	70 (12)	76
Mameyes	17.8	1.67 (13)	561 (10)	580 (14)	138
Bisley	0.07	0.005 (2)	1.6 (unk)	1.9 (unk)	98
Sabana	10.3	0.57 (10)	255 (12)	231 (10)	81

Although Hurricane Hugo caused extensive defoliation and landsliding on hill slopes, extensive channel or valley floor modification (*sensu* Gupta 1988) was not observed within or near the LEF. Locally, however, boulders were moved, high flow channels and flood plain margins were modified, and small debris dams impounded water in active channels and at culverts. All of the culverts on streams draining north-facing slopes were clogged with debris but none had structural damage. Only one of the eight bridges in the LEF suffered structural damage.

WIND-DAMAGE AND RAINFALL INDICES.—Since 1930 the number of hurricanes in the Caribbean basin has averaged between 0.5 and 1.5 annually (Gray 1990). On average, one of these storms passes over Puerto Rico once every 21 yr (Salivia 1972). The effects of a storm at any location depend on the magnitude and path of the storm, and on the complex interaction of climatic, topographic, lithologic, and biologic factors. In general, the magnitudes of individual storms or the time intervals between storms do not provide satisfactory measures of the effectiveness of extreme events in shaping the landscape (Wolman & Gerson 1978). To compare the relative importance of hurricanes that have passed over Puerto Rico since 1899, wind damage and precipitation indices were developed (Table 3). These indices represent the relative potential of a hurricane to affect changes in the landscape. The indices were computed using the following equations: island-wide wind-damage index = $V_{sj}^2 * D$; LEF wind-damage index = $(V_{sj} * R_{sj}/R_{Lef})^2$; rainfall index = P_h/P_m where V_{sj} = maximum sustained wind velocity at San Juan; R_{sj} = shortest distance between hurricane and San Juan; R_{lef} = shortest distance between hurricane and the LEF; P_h = maximum storm precipitation; P_m = mean annual precipitation at station where the maximum storm precipitation was measured; and D = duration of storm over island.

Both wind damage indices were standardized by dividing each value by the largest value of all the storms and multiplying by 100. The square of the wind velocity was used because both fluid pressure (Streeter & Wylie 1979) and wind damage increase with the square of velocity (Gray 1990). Wind velocity in San Juan was used because it is the only reliable long-term data set. The ratios of the distances account for differences in the paths of hurricanes and the decrease in tangential wind speed from the center of the storm (Anthes 1982).

The potential for rainfall-related effects associated with the hurricanes were compared using the ratio of the maximum storm rainfall to the average annual rainfall at the location where the maximum storm rainfall was measured, *i.e.*, the percentage of average annual rainfall produced by the hurricane (Table 3). This index takes into account inherent differences associated with precipitation falling in different climatic regions and is analogous to scaling the geomorphic work of individual events by the

TABLE 2. *Summary of Hurricane Hugo landslide characteristics in areas of the Luquillo Experimental Forest covered by aerial photography and field measurements in the Bisley Experimental Watersheds (Fig. 2).*

	Area covered by aerial photographs	Bisley Experimental Watersheds
Number of landslides	285	5
Median size, m^2	161	370
Minimum size, m^2	20	75
Maximum size, m^2	4821	600
Area of survey, ha	6474	13
Area affected by landslides, ha	9.1	0.16

TABLE 3. *Characteristics of hurricanes that have passed over Puerto Rico since 1899. The island-wide wind damage index is the standardized product of sustained wind speed (at San Juan) squared and storm duration. The LEF wind damage index is the standardized product "the square of" of sustained wind speed (at San Juan) hand the ratio of the distance between the hurricane eye and San Juan (and) the distance between the eye and the LEF. The rainfall index is the ratio of maximum storm rainfall to average annual rainfall at the location of measurement. Data from Salivia 1972, Pico 1974, and U.S. Department of Commerce 1990.*

Year	Maximum sustained winds in San Juan (km/hr)	Storm duration over island (hr)	Maximum storm rainfall (mm)	Island-wide wind damage index (scale 0–100)	Island-wide rainfall index (percent of annual rainfall)	LEF wind damage index (scale 0–100)
1989	148	4	339	19	15	63
1956	144	3	215	13	11	4
1932	194	7	415	57	17	100
1931	144	6	135	27	5	3
1928	241	8	725	100	40	20
1899	122	6	575	19	23	5

ratio of storm erosion to mean annual erosion (Wolman & Gerson 1978).

DISCUSSION

RAINFALL.—Storm rainfall totals of 500 mm are common for hurricanes (Riehl 1979) and some Caribbean storms have reportedly produced more than 2000 mm (Gupta 1988). Compared to these storms, Hurricane Hugo was relatively dry with a maximum rainfall of 339 mm (Table 3). However, compared to other large hurricanes that have crossed Puerto Rico since 1899, Hugo was a moderate storm in terms of the combined effects of wind and rain.

Hurricane-induced rainfall at any location depends on many factors, including proximity to the storm's center, the horizontal velocity of the storm, and local topographic effects (Anthes 1982). The relatively low total rainfall associated with Hurricane Hugo was apparently influenced by both the path and diameter of the storm. Moisture and energy balances within hurricanes dictate that rainfall intensity is inversely related to the radius of the hurricane (Riehl 1979) and that the northwestern part of the storm typically has the least precipitation (Riehl 1979, Anthes 1982).

Because Hugo was a relatively large-diameter hurricane, that passed rapidly over the island, total storm rainfall associated with this storm was less than that of many other hurricanes. However, when spatial variations in annual rainfall are accounted for by calculating the percentage of the mean annual rainfall that occurred during the hurricane, the relative importance of Hugo and that of other hurricanes is similar (Table 3). Furthermore, the magnitude and intensity of the rainfall associated with Hugo was sufficient to trigger numerous landslides.

The temporary decrease in rainfall following Hurricane Hugo was apparently caused by both microclimate changes induced by the hurricane and meso-scale weather patterns. At the regional level, below-average rainfall was associated with a series of high pressure atmospheric systems that passed over the island and was not limited to either hurricane-damaged or montane areas.

During much of the 3 mo period following the storm, the cloud base over the LEF was not at the usual 500–600 m level but was at an elevation of

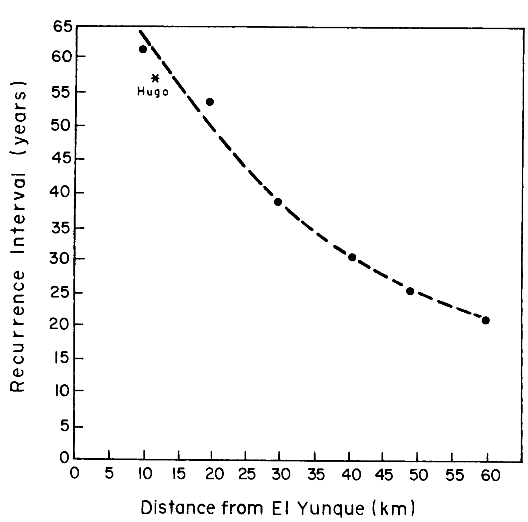

FIGURE 4. Estimated recurrence intervals of hurricanes passing within a given distance from El Yunque peak at the center of the Luquillo Experimental Forest, Puerto Rico. Based on the cumulative frequency distribution of distances of hurricanes relative to the LEF using the trajectories of hurricanes in Figure 1 (adapted from Scatena 1989).

900–1000 m. During this period there was a noticeable decline in the number of brief episodes of orographic rainfall that occurs throughout the day in the lower elevations of the LEF. These local changes were apparently caused by a rise in the cloud base, which resulted from increased temperatures and albedo in defoliated areas. The lack of rainfall following the storm appears to have affected animal populations (Woolbright 1991) and fine root mortality (Parrotta & Lodge 1991).

PATH, WIND VELOCITIES, AND DAMAGE.—Neither the path of Hurricane Hugo through the Caribbean, nor the location of landfall on Puerto Rico was unique. All 15 of the severe hurricanes that have passed over the island since 1700 have landed on the eastern part of the island, and most (9 hurricanes) have landed along the coast between Maunabo and Fajardo (Fig. 1). However, no historical hurricane has crossed the island of Puerto Rico with a path similar to the path of Hurricane Hugo.

Once over land, hurricanes follow irregular paths and diminish in intensity because of decreased evaporation, increased surface friction, and changes in ground level air temperature (Anthes 1982). Consequently, both internal coriolis and centritugal forces decline and radial pressure gradients weaken. When large differences in surface conditions exist, like those developed when part of a hurricane intersects mountainous terrain, asymmetric radial pressure gradients develop and the hurricane may move away from these mountainous areas. This mechanism may explain why only 4 of the last 15 hurricanes to pass across Puerto Rico have crossed directly over the LEF (Fig. 1). Most hurricanes have crossed the island along the intermountain region to the south and west of the LEF.

The island-wide wind damage index indicates that Hurricane Hugo was about the fourth largest of the six hurricanes to affect the island of Puerto Rico since 1899 (Table 3). However, because of its path across the eastern part of the island, Hurricane Hugo was the second most important storm to affect the LEF. The largest of the six hurricanes to hit Puerto Rico since 1899 occurred in 1928 but that storm had relatively little effect on the LEF (Crow 1980).

During Hurricane Hugo, extensive damage to vegetation was limited to areas within 30 km of the path of the storm. Landslides and other geomorphic modifications were most common in areas receiving 200 mm or more rainfall and within 15–25 km of the eye of the storm. Although some damage occurred 100 km from the storm, beyond 40–50 km, the damage from the storm was isolated and strongly dependent on local conditions. Wadsworth and Englerth (1959) reported similar findings for the 1956 hurricane. They found no appreciable biologic or geomorphic damage beyond 40 km of the center of the storm.

The average recurrence interval for a hurricane to pass within a given distance of the LEF was derived from the cumulative frequency of distances of hurricanes relative to the center of the LEF (Scatena 1989; Fig. 4). Each point defining the curve shown in Figure 4 represents a radius from the center of the LEF, except for the point labeled "Hugo." This figure was based on the paths of hurricanes shown in Figure 1, and reflects the higher frequency of hurricanes when a larger distance from the LEF is considered (Scatena 1989).

Both the 1956 and 1989 hurricanes caused extensive damage to forest vegetation within 40–50 km of the center of the storm. Because most hurricanes have a 40-km wide zone of maximum winds (Anthes 1982) and hurricanes have passed within 40 km of the LEF with an average recurrence interval of about 25–30 yr, it is likely that the LEF will be affected by a hurricane once every 25–30 yr on average (Fig. 4). However, the average recurrence interval for a hurricane to pass as close to the LEF as Hurricane Hugo did and affect as large an area of the forest as that affected by Hugo, is about 50–60 yr (Fig. 4).

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LITERATURE CITED

ANTHES, R. A. 1982. Tropical cyclones, their evolution, structure and effects. Meteorological Monographs, 19.
CROW, T. R. 1980. A rain forest chronicle: a 30 year record of change in structure and composition at El Verde, Puerto Rico. Biotropica 12(1): 42–55.

CURTIS, R. E., Z. AQUINO, P. L. DÍAZ, AND R. J. VACHIER. 1990. Water resource data Puerto Rico and the U.S. Virgin Islands. U.S. Geological Survey Water-Data Report PR 89-1.
GRAY, W. M. 1990. Strong association between West African rainfall and the U.S. landfall of intense hurricanes. Science 248: 1251–1256.
GUPTA, A. 1988. Large floods as geomorphic events in the humid tropics. *In* V. R. Baker, R. C. Kochel, and P. C. Patton (Eds.). Flood geomorphology, pp. 301–315. John Wiley & Sons, New York, New York.
LARSEN, M. C. 1990. Landslides and soil moisture increases associated with Hurricane Hugo, September 1989, eastern Puerto Rico. Geological Society of America, Abstracts With Programs: 22 No. 7, A331.
———, AND A. J. TORRES-SANCHEZ. 1990. Rainfall–soil moisture relations in landslide-prone areas of a tropical rain forest, Puerto Rico. *In* J. H. Krishna, Vicente Quiñones-Aponte, Fernando Gómez-Gómez, and G. L. Morris (Eds.). Tropical hydrology and Caribbean water resources, pp. 121–130. Proceedings of the International Symposium on Tropical Hydrology and Fourth Caribbean Islands Water Resources Congress.
LÓPEZ, M. A., E. COLÓN–DIEPPA, AND E. D. COBB. 1979. Floods in Puerto Rico, magnitude and frequency. U.S. Geological Survey Water Resources Investigation 78-141.
LUQUILLO FOREST LONG-TERM ECOLOGICAL RESEARCH PROGRAM. 1989. Daily rainfall at El Verde, Puerto Rico. University of Puerto Rico—Data Archive, Río Piedras, Puerto Rico.
MARSHALL, R. D. 1990. Hurricane Hugo in the Caribbean; assessment of surface wind speeds by the National Institute of Standards and Technology. Gaithersburg, Maryland. Department of Structural Engineering, University of Puerto Rico, Río Piedras, Puerto Rico.
PARROTTA, J. A., AND D. J. LODGE. 1991. Fine root dynamics in a subtropical wet forest following hurricane disturbance in Puerto Rico. Biotropica 23: 343–347.
PICO, R. 1974. The geography of Puerto Rico. Aldine Publishing Company, Chicago, Illinois.
RIEHL, H. 1979. Climate and weather in the Tropics. Academic Press, New York, New York.
SALIVIA, L. A. 1972. Historia de los temporales de Puerto Rico y las Antillas, 1492–1970. Editorial Edil, Inc., University of Puerto Rico, Río Piedras, Puerto Rico.
SCATENA, F. N. 1989. An introduction to the physiography and history of the Bisley Experimental Watersheds in the Luquille Mountains of Puerto Rico. U.S. For. Serv. Gen. Tech. Rep. SO-72.
STREETER, V. L., AND E. B. WYLIE. 1979. Fluid mechanics. McGraw-Hill Book Company, New York, New York.
U.S. DEPARTMENT OF COMMERCE. 1990. National disaster survey report. Hurricane Hugo September 10–22, 1989.
U.S. NATIONAL WEATHER SERVICE. 1989. Forest Office in San Juan, 1989. October 24, 1989 Statement on Hurricane Hugo.
———. 1990. Forecast Office in San Juan, monthly weather reports.
U.S. WEATHER BUREAU. 1961. Generalized estimates of probable maximum precipitation and rainfall frequency data for Puerto Rico and Virgin Islands. Technical Paper No. 42. U.S. Department of Commerce, Washington D.C.
WADSWORTH, F. H., AND G. H. ENGLERTH. 1959. Effect of the 1956 hurricane on forests of Puerto Rico. Caribb. For. 20: 38–51.
WEAVER, P. L. 1986. Hurricane damage and recovery in the montane forests of the Luquillo Mountains of Puerto Rico. Carib. J. Sci. 22 (1–2): 53–70.
WOLMAN M. G., AND R. GERSON. 1978. Relative scales of time and effectiveness of climate in watershed geomorphology. Earth Surface Processes 3: 189–208.
WOOLBRIGHT, L. L. 1991. The impact of Hurricane Hugo on forest frogs in Puerto Rico. Biotropica 23: 462–467.