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Landslides Triggered by Hurricane Hugo in Eastern Puerto Rico, September 1989

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ABSTRACT. – On the morning of September 18, 1989, a category-four hurricane struck eastern Puerto Rico with a sustained wind speed in excess of 46 m/sec. The 24-h rainfall accumulation from the hurricane ranged from 100 to 339 mm. Average rainfall intensities ranging from 34 to 39 mm/h were calculated for 4 and 6 h periods, respectively, at a rain gage equipped with satellite telemetry, and at an observer station. The hurricane rainfall triggered more than 400 landslides in the steeply sloping, highly dissected mountains of eastern Puerto Rico. Of these landslides, 285 were mapped from aerial photography which covered 6474 ha. Many of the mapped landslides were on northeast- and northwest-facing slopes at the eastern terminus of the mountains, nearest the hurricane path. The surface area of individual landslides ranged from 18 m^2 to 4500 m^2, with a median size of 148 m^2. The 285 landslides disturbed 0.11% of the land surface in the area covered by aerial photographs. An approximate denudation rate of 164 mm/1000 yr was calculated from the volume of material eroded by landsliding and the 10-yr rainfall recurrence interval.

RESUMEN. — En la mañana del 18 de septiembre de 1989, un huracán de categoría cuatro paso por el sector este de Puerto Rico con vientos sostenidos de más de 46 metros por segundo. La acumulación de lluvia en 24 horas fue de 100 y 339 mm. La intensidades promedio de lluvia alcanzaron entre 34 a 39 mm por hora en periodos de 4 y 6 horas respectivamente, en un pluviómetro con telemétria de satélite y otro en una estación de observación. El huracán causó más de 400 deslizamientos en las montañas del sector este de Puerto Rico, cuyas pendientes son muy escarpadas y de alto relieve. De estos deslizamientos, 285 fueron localizados usando fotos aéreas que cubren un área de 6474 ha. Muchos de los deslizamientos están ubicados en las pendientes que miran al noreste y noroeste en el extremo este de las montañas, más cerca del paso del huracán. El área de la superficie de los deslizamientos midió entre 18 y 4500 m^2 y el tamaño mediano fue de 148 m^2. Los 285 deslizamientos afectaron 0.11% de la superficie representada en las fotos aéreas. Una tasa de denudación aproximada de 164 mm por 1000 años fue calculada usando el volumen del material erodado por los deslizamientos y el intérvalo de recurrencia de 10 años de lluvia.

INTRODUCTION

High-magnitude formative events are frequent (5 to 10 years) in humid-tropical regions and attest to the effectiveness of climate in watershed geomorphology of these regions (Wolman and Gerson, 1978). The importance of these episodic events is underscored by the denudation caused by a major storm, which may approach the mean annual rate of erosion in montane wet tropics, (Wolman and Gerson, 1978). The high frequency of these events allows little time for recovery, which should yield slopes that reveal abundant evidence of the effects of these storms. Recent or historic landslide scars are apparent on virtually all hillslopes in the humid eastern mountains of Puerto Rico.

Hurricanes have caused some of the heaviest rainfall in the world, particularly when forward motion is less than 4 m/sec or when the hurricane is affected by orographic barriers. As such, high magnitude rainfall occurs regularly (5 to 10 years) in mountainous Caribbean islands, including Puerto Rico. Hurricane Hugo provides an example of a high-magnitude event that resulted in locally significant denudation of hillslopes by landsliding.

On the morning of September 18, 1989, Hurricane Hugo struck eastern Puerto Rico with sustained winds of 46 m/sec and gusts to 54 m/sec (Fig. 1). The minimum sea level barometric pressure recorded was 946 hPa (709.6 mm of Hg) (NOAA, 1989a). Property damage was estimated at 2.5 billion dollars, and more than 13,000 people were left homeless. Electric power and public water-

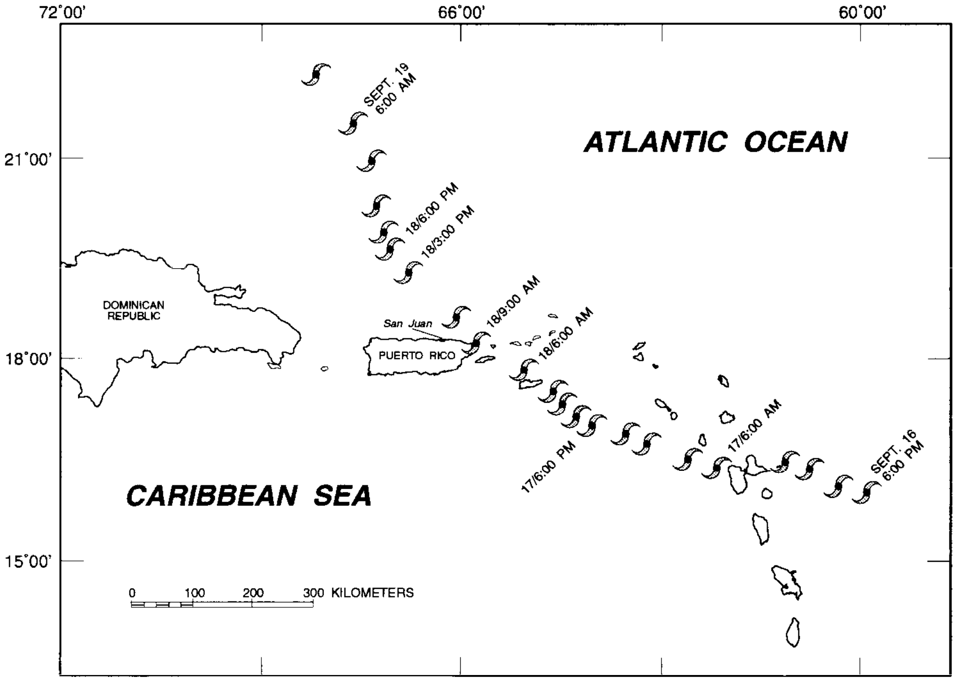

FIG. 1. Puerto Rico. the Antilles. and the track of Hurricane Hugo across the northeastern Caribbean Sea between September 16 and 19, 1989.

supply distribution networks suffered major damage. Although rainfall totals were relatively low compared to previous hurricanes that have affected Puerto Rico, rivers experienced peak discharge recurrence intervals as high as 31 years (Curtis et al., 1990). Because the hurricane eye passed along the northeast corner of Puerto Rico, the northeastern, wettest quadrant of the storm remained. offshore, and the winds in eastern Puerto Rico were predominately northerly.

Forest vegetation was heavily damaged by high winds (46 to 54 m/sec). In parts of the drainage basins of Río Mameyes and Río Sabana, 97% of the canopy trees were defoliated. In these same heavily impacted areas, 31% of the trees were killed, with basal area (sum of the areas of all trees greater than 2.5 cm diameter at breast height – 1.3 m) decreasing from 36.7 m^2/ha to 25.3 m^2/ha (Scatena and Larsen, 1991). Treefalls numbering approximately 40/ha to 60/ha resulted in shallow depressions on the forest floor. These depressions were typically roughly circular, 2 to 3 m in diameter, and as much as 1 m deep.

More than 400 landslides occurred in the mountains of eastern Puerto Rico, as a result of as much as 339 mm of rainfall (U. S. Dept. of Commerce, 1990) (Fig. 2). This paper describes some of the hydrologic characteristics of Hurricane Hugo and the spatial and temporal characteristics of the hurricane-triggered landslides. Additionally, a denudation rate is estimated from the erosion caused by the landslides.

Setting, Topography and Land Use

Eastern Puerto Rico is an area of high topographic relief: mountains are up to 1074 m in elevation, topography is rugged, and slopes are highly dissected by perennial and ephemeral streams. Slopes range from 10 to 100% (Boccheciamp, 1977). Fifteen percent of eastern Puerto Rico falls within the boundaries of the Luquillo Experimental Forest (LEF), a U.S. Forest Service-administered 11,300 ha preserve of mature forest vegetation. Land surround-

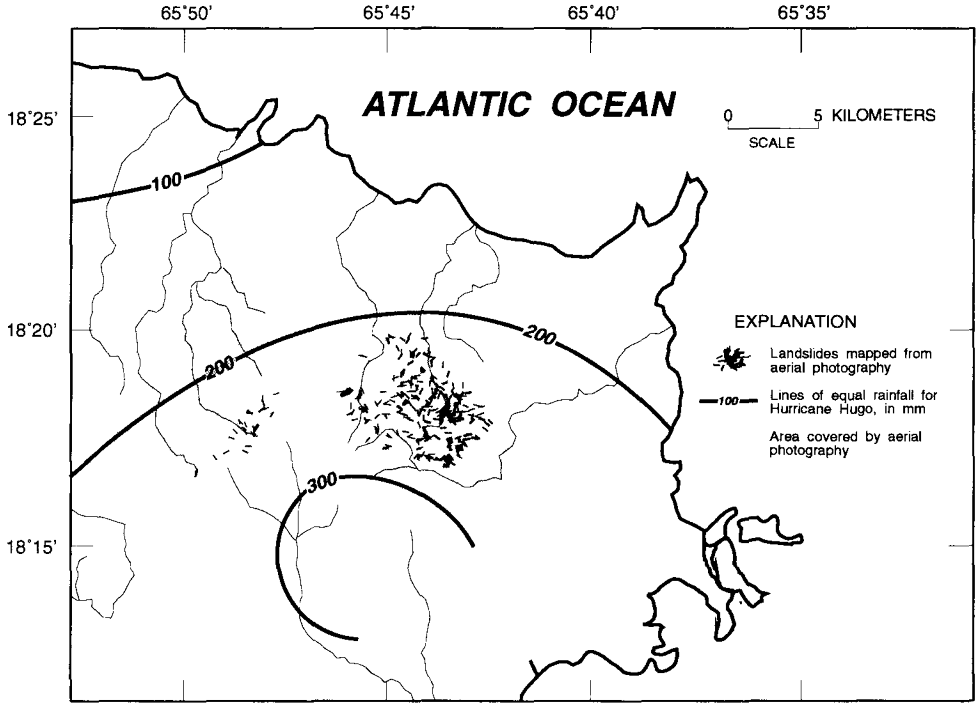

FIG. 2. Landslides triggered by Hurricane Hugo in eastern Puerto Rico with 24-h rainfall contoured in 100 mm intervals and outiine of area covered by aerial photography.

ing the LEF is used for small-scale farming and pasture and has been extensively deforested. Most of the mountains of eastern Puerto Rico are moderately to highly susceptible to landsliding (Monroe, 1979).

Climate

Puerto Rico is in the path of easterly trade winds, which dominate the climate for much of the year. Average annual rainfall in the LEF ranges from 2500 to more than 5000 mm, varying because of the orographic effects of an east-west trending central mountain range (Calvesbert, 1970). The wet season is generally from May through November, however, average monthly rainfall is relatively evenly distributed throughout the year and ranges from 5 to 10% of the annual total (Riehl, 1979).

An average of 8 to 11 hurricanes occur in the Atlantic Ocean each year (Riehl, 1979; Gray, 1990). The annual occurrence of Caribbean basin hurricanes has ranged from 0.5 to 1.5 in recent decades. Approximately once every 21 years, Puerto Rico experiences the direct pass of a hurricane (Salívia, 1972). The direct pass of a hurricane over the LEF is estimated to occur approximately once every 60 years (Scatena, 1989).

Geology, Soils, and Hydrology

The geology of the LEF is predominantly marine volcaniclastic sandstone, mudstone, breccia and conglomerate of Cretaceous age (Seiders, 1971). A Tertiary quartz-diorite intrusion, the Río Blanco stock, covers about 20 km^2 of the LEF. Bedrock is overlain by saprolite which averages 11 m deep on hillslopes (Dames and Moore, 1980; Simon et al., 1990). The highly leached soils overlying the saprolite are Ultisols and Inceptisols that are moderately-plastic, moderately-drained, highly-weathered, clayey-silty loams, averaging 1.5 m thick (Boccheciamp, 1977). At a depth of one meter, median soil bulk density and cohesive strength average 1.28 g/cm3 (*n* = 24) and

TABLE 1. Accumulation and duration of rainfall resulting from Hurricane Hugo, September 19, 1989, eastern Puerto Rico, at U.S. Geological Survey, U.S. Forest Service, and NOAA operated rain gages. OB = observer; RE = recording; ST = satellite transmitting; gage locations shown in Fig. 3.

Station	Gage type	Duration in hours	Accumulation in mm	Comment
1	OB	6-9?	339	unknown duration less than 24 h
2	OB	6-9?	269	unknown duration less than 24 h
3	OB	10?	165	unknown duration less than 24 h
4	OB	6	234	gage checked at 0600 and 1200 hrs
5	RE	1.5	47	stopped recording at 0030 hrs
6	OB	6-9?	225	gage damaged
7	ST	7	170	stopped transmitting at 0900 hrs
8	ST	10	174	
9	ST	7.5	124	
10	ST	10	124	

6.6 kPa (n = 14) respectively and median field moisture content is 36% of dry weight (n = 29). Surficial soils are at or near saturation most of the year (Weaver, 1986).

Stream hydrography data indicate that high intensity rainfall in the LEF results in rapid runoff. Deep infiltration of water is limited because of relatively low permeability at depth (Jordan, 1970). Two soil samples taken on a hillslope in soil overlying volcaniclastic bedrock at 38 cm and 84 cm depth, had saturated hydraulic conductivities of 2.8 x 10^{-8} cm/sec, and 2.9 x 10^{-8} cm/sec, respectively. Although this silty-clay matrix conductivity is extremely low, blocky soil structure, abundant macropores from 1 to 2 cm diameter root casts, and 2 mm diameter worm burrows increase the bulk soil permeability. Accordingly, average surficial (0 to 20 cm) soil infiltration rates for the Ultisols in the LEF range from 0.42 x 10^{-3} to 1.4 x 10^{-3} cm/sec (Boccheciamp, 1977). Although the soils contain a high percentage of clay (38 to 57%) it is well aggregated in the upper soil layers, which results in a bulk density that increases 32% from a depth of 3 to 43 cm, and ranges from 0.75 to 0.99 g/cm3 (Jordan, 1970). Soil water drains by near-surface interflow; the water infiltrates almost vertically, and flows laterally downslope upon reaching denser soil (Jordan, 1970). Stream hydrography show rapid peaks (minutes to hours) followed by a return to base flow within 5 to 10 h for storms lasting less than 24 h.

TABLE 2. Characteristics[1] of streams draining the Luquillo Experimental Forest, showing Hurricane Hugo related peak discharge, recurrence intervals, peak mean runoff, and landslides per km.[2]

Name of stream	Years of record	Drainage area in km^2	Average discharge in m^3/s	Hurricane Hugo peak discharge in m^3/s (and recurrence interval in years)[2]	Hurricane Hugo peak mean runoff in mm/h	Hurricane Hugo triggered landslides per km^2
Río Espíritu Santo	24	22.3	1.69	427 (10)	69	0.8
Río Fajardo	29	38.6	1.98	666 (31)	58	10
Río Icacos	18	3.3	0.42	70 (13)	76	unknown
Río Mameyes	13	17.8	1.67	580 (14)	138	3
Río Sabana	11	10.3	0.57	231 (10)	81	15

[1] Curtis et al., 1990 and López et al., 1979.
[2] Based on log Pearson type III flood frequency analysis.

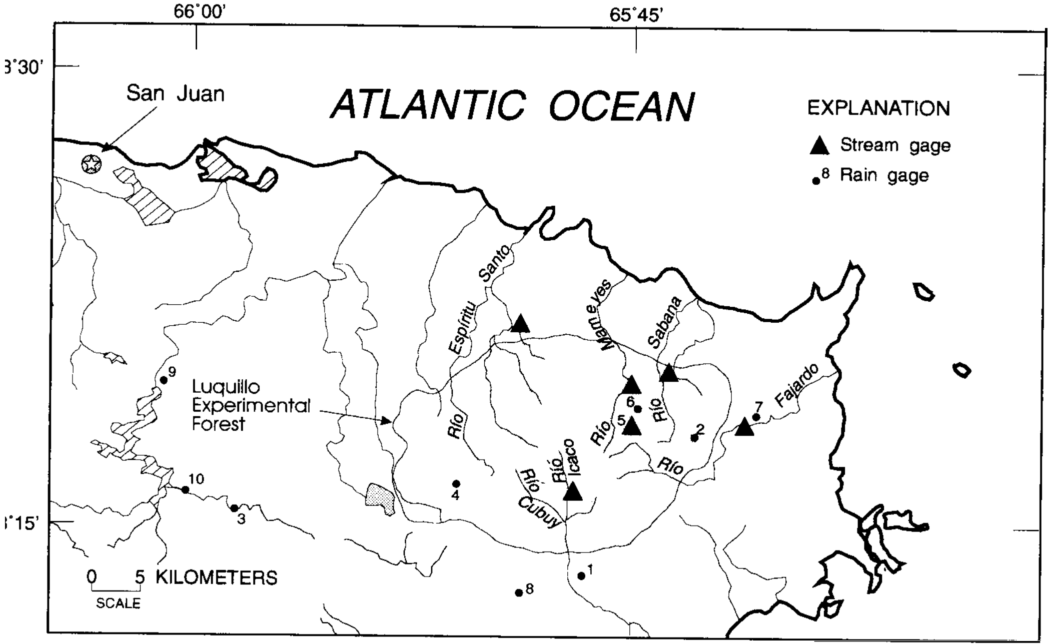

FIG. 3. Eastern Puerto Rico showing the principal rivers draining the Luquillo Experimental Forest, surface water gaging stations and rain gages.

METHODS

Rainfall data for Hurricane Hugo were collected from five observer, one recording, and four satellite-transmitting rain gages in and near the LEF (Table 1; Fig. 3). Antecedent rainfall was determined from gages 2 and 7 (Fig. 3). High winds associated with the hurricane damaged three gages, and may have caused some gages to under measure actual rainfall accumulation (Table 1). Streamflow data for eastern Puerto Rico was collected from five recording and satellite-transmitting stream gages (Table 2; Fig. 3). To confirm recorded peak discharge data, field measurements were made at each gage site after the passage of the hurricane.

Landslides were mapped on 1:20,000 scale topographic quadrangles. Areal extent, slope aspect, landslide type, and land use was noted. Terminology used to classify the landslides caused by Hurricane Hugo follows Varnes (1978), and Campbell (1975). Ground access to affected areas was limited during the week after the hurricane because of downed trees and utility poles. Field reconnaissance began 2 days after the hurricane and an aerial survey was conducted within 2 weeks after the hurricane. Color aerial photography from an overflight 5 months after the hurricane covered 6474 ha, or 57% of the LEF. The initial aerial survey indicated that the LEF sustained most of the rainfall-triggered landslides. All the area covered by aerial photography was within the part of the LEF underlain by volcaniclastic bedrock.

RESULTS

Rainfall and Streamflow Resulting from Hurricane Hugo

Hurricane Hugo rainfall accumulation was low relative to previous tropical disturbances affecting Puerto Rico (Table 3). The maximum recorded accumulation was 339 mm (Table 1). However, the 24 h Hurricane Hugo rainfall regional accumulation in the LEF may be best represented by rain gages 1, 2, 4, and 6 (Table 1; Fig. 3). The average rainfall accumulation for those gages is 267 mm, which represents a 10-yr recurrence interval (U.S. Weather Bureau,

TABLE 3. Tropical disturbance-caused rainfall in Puerto Rico.[1]

Rainfall accumulation (mm)	Storm	Year	Storm duration (days)
976	Tropical depression	1970	5
752	Hurricane San Felipe	1928	2
635	Upper level trough	1985	2
625	Tropical storm Isabel	1985	2
508	Hurricane San Ciriaco	1899	1
502	Hurricane David	1979	2
477	Hurricane Donna	1960	2
459	Tropical wave	1978	5
382	Tropical storm Frederick	1979	1
339	Hurricane Hugo	1989	1

[1] Data from U.S. Weather Service, 1959-1988; Tannehill, 1956.

1961). High-intensity rainfall (approximately 34 mm/h), measured at a transmitting rain gage in the LEF, began 3 h prior to the passage of the hurricane eye and continued for at least 4 h (Table 1, gage number 7). High intensity bursts of as much as 20 mm in 5 minutes were recorded as the hurricane eye passed gage number 7 (Fig. 3). At an observer rain gage in the LEF, rainfall intensity for Hurricane Hugo averaged 39 mm/h during a 6 h period.

Rainfall accumulation and degree of soil saturation on north-facing slopes was greater than on south-facing slopes, because of the almost horizontal delivery of rainfall from the north. No soil moisture measurements are available to confirm this, however the aerial photographs show severe wind damage to vegetation on north-facing slopes. Less vegetation damage was noted on most lee slopes. Additionally, continuous horizontal rainfall movement was observed by the authors for several hours during the hurricane, even at locations 40 km west of the hurricane eye track, where wind speeds were 34 m/sec (NOAA, 1989a).

Rainfall in and near the LEF was 100% and 70% above normal for the months of July and August, respectively (NOAA, 1989b). However, for two weeks before the hurricane, rainfall was 80% below normal.

Streamflow magnitudes and recurrence intervals provide another check of the magnitude and recurrence intervals of rainfall resulting from the storm. In addition, peak mean basin runoff calculated from peak stream discharge indicates maximum rainfall intensity in each drainage basin (Table 2). Peak discharge recurrence intervals for five streams draining the LEF range from 10 to 31 yr, and compare well to the 10-yr recurrence interval calculated from rainfall data (Table 2; Fig. 3). The Espiritu Sante, Icacos, Mameyes and Sabana stream gages, with flood recurrence inter-

TABLE 4. Summary of Hurricane Hugo landslide characteristics based on analysis of aerial photography.

	All landslides n = 285	Landslides on forested hillslopes only n = 215	Landslides associated with roads /structures n = 35	Landslides on pasture and cropland n = 35
	Area, m^2	Area, m^2	Area, m^2	Area, m^2
Median	148	161	99	142
Mean	299	308	305	233
Minimum	18	18	20	25
Maximum	4502	4502	2399	1115

TABLE 5. Landslide disturbance in the Luquillo Experimental Forest.

	All landslides	Landslides in forested areas	Landslides associated with roads and structures	Landslides on pasture and cropland
Total affected by landslides, in hectares	8.52	6.63	1.07	0.82
Total area, in hectares	6474	5883	194	388
Percent study area	100	91	3	6
Percent area disturbed by landslides	0.13	0.11	0.55	0.21
Percent landslides	100	75.4	12.3	12.3

vals of 10, 13, 14, and 10 yr, respectively, are in the middle to upper reaches of the rivers and therefore reflect rainfall conditions at upper elevations in the LEF (Table 2). The Fajardo gage is located where the lower reach of the river crosses a coastal plain and urbanized areas, in an area close to the hurricane track. The peak discharge recorded at the Río Fajardo gage corresponds to a 31-yr recurrence interval and may reflect the runoff associated with extreme rainfall that occurs along hurricane tracks (Anthes, 1982). After the passage of Hurricane Hugo, stream hydrographs showed only a 12 to 24 h lag from the time that rainfall ended until pre-storm base flow was recorded.

Landslides Resulting from Hurricane Hugo

Aerial photographs revealed 285 landslides that occurred in 57% (6474 ha) of the LEF during or after the passage of Hurricane Hugo (Fig. 2; Table 4). Another 121 landslides were mapped from ground-based observations made along highways in sections of the LEF not covered by aerial photography. These landslides had a median size of 113 m^2, and 72% were shallow soil slips. Seventy-one percent of the landslides observed from ground-based observations were associated with highway construction, 17% were in abandoned pasture, and 12% were on forested hillslopes.

The 285 landslides mapped from aerial photographs had a density of 4.4 landslides/ km^2, and affected 0.13% of the land area surveyed (Table 5). Seventy-five percent of the landslides occurred on forested hillslopes (3.7 landslides/km^2), and of these, 61% occurred on northeast-, north- and northwest-facing hillslopes (Fig. 4). Landslides on forested hillslopes affected 0.11% of the 5883 ha of forested land area (Table 5). However, 187 (66%) landslides occurred in a 1031 ha area (16% of the area mapped) closest to the hurricane's eye, in the drainage basins of Ríos Fajardo, Mameyes and Sabana (Figs. 2, 3). In this region, landslides (18.2 landslides/km^2) affected 0.65% of the land surface. Seventy-one percent of these landslides occurred on northeast, north, and northwest-facing slopes. The surface area of the individual landslides that occurred on forested hillslopes has a log-normal distribution (Fig. 5). These landslides had a median surface area of 161 m^2 (Table 4).

Shallow soil slips (0.5 to 1.5 m deep) and debris flows (1.5 to 2 m deep) were the predominant forms of slope failure and together accounted for 91% of the landslides. The remaining 9% were slumps. Seventy percent of the shallow soil slips that were field checked had failure planes that were at the boundary between soil and saprolite. The 20 debris flows that were field checked apparently originated as shallow soil slips with similar failure planes near the head scarp.

Virtually all mapped landslides were bounded by the 200 mm rainfall isohyet (Fig. 2). Landslides were more concentrated in the drainage basins closest to the hurricane eye track (Fajardo had 10/km^2 and Sabana had 15/km^2), while basins further to the west had fewer landslides per unit area (Espiritu Santo had 0.8/km^2 and Mameyes had 3/km^2). The Río Icacos drainage basin was not covered by aerial photography. The median size of landslides as-

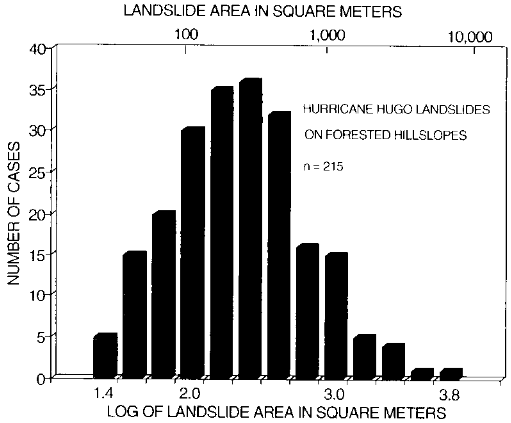

FIG. 4. Distribution of Hurricane Hugo-triggered landslides on forested hillslopes by surface area in square meters.

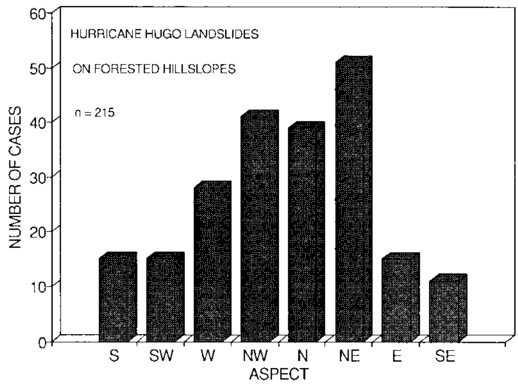

FIG. 5. Topographic characteristics of Hurricane Hugo-triggered landslides mapped from aerial photography showing relation to hillslope aspect.

sociated with road structure was smaller than that of landslides on forested hillslopes. However, 12% of the landslides occurred on land used for roads or structures, while only 3% of the area covered by aerial photography (6474 ha) falls into this category (Table 5). Additionally, the percent area disturbed by road- and structure-related landslides was five times greater than the percent area disturbed by landslides on forested hillslopes (Table 5). Twelve percent of the landslides were observed on land used for pasture or crops. The combined pasture and crop area covered by aerial photography amounts to 6% of the total area, indicating that these land uses also increase the number of landslides per km^2 but not to the same extent as road- and structure-related land use (Table 5).

The largest observed Hurricane Hugo-triggered landslide was a debris avalanche measuring 153 m long, 23 to 33 m wide, and 3 to 10 m deep. It moved approximately 30,000 m^3 of soil and rock 600 m downslope into Río Cubuy, and exposed unweathered bedrock along the erosional scar (Fig. 6). The avalanche followed the runout of a 1970 debris avalanche. The incised 1970 runout may have been a contributing factor in the Hurricane Hugo debris avalanche, because the runout undercut the slope flank on which the Hurricane Hugo debris avalanche occurred.

This debris avalanche occurred three days after the hurricane, when infiltration of rainfall probably caused increased pore pressure at depth. Lag times of days to weeks were associated with all of six large (10,000's to 100,000's m^3) debris avalanches that have occurred since 1970, after major rainstorms in eastern Puerto Rico (Deere and Patton, 1971; Dames and Moore, 1980; Simon et al., 1990). Interviews with residents near the LEF indicate that the shallow soil slips, debris flows, and slumps probably occurred during or immediately after the passage of Hurricane Hugo.

DISCUSSION

Rainfall-triggered landslides are a common result of hurricanes and other tropical disturbances. On average, 1.2 storms per year with sufficient rainfall intensity and/or duration to cause tens to hundreds of landslides in the central mountains of Puerto Rico have occurred during the last 31 years. The relatively shallow landsliding (0.5 to 2 m) triggered by Hurricane Hugo is typical of short-duration high-intensity storms in which surface infiltration of rain water rapidly exceeds the combined amounts of downslope throughflow and percolation beneath the slide plane (Wilson, 1989). Rainfall from this storm rapidly saturated the upper 1 to 2 m of soil and regolith, elevating pore pressures sufficiently to trigger shallow landsliding be-

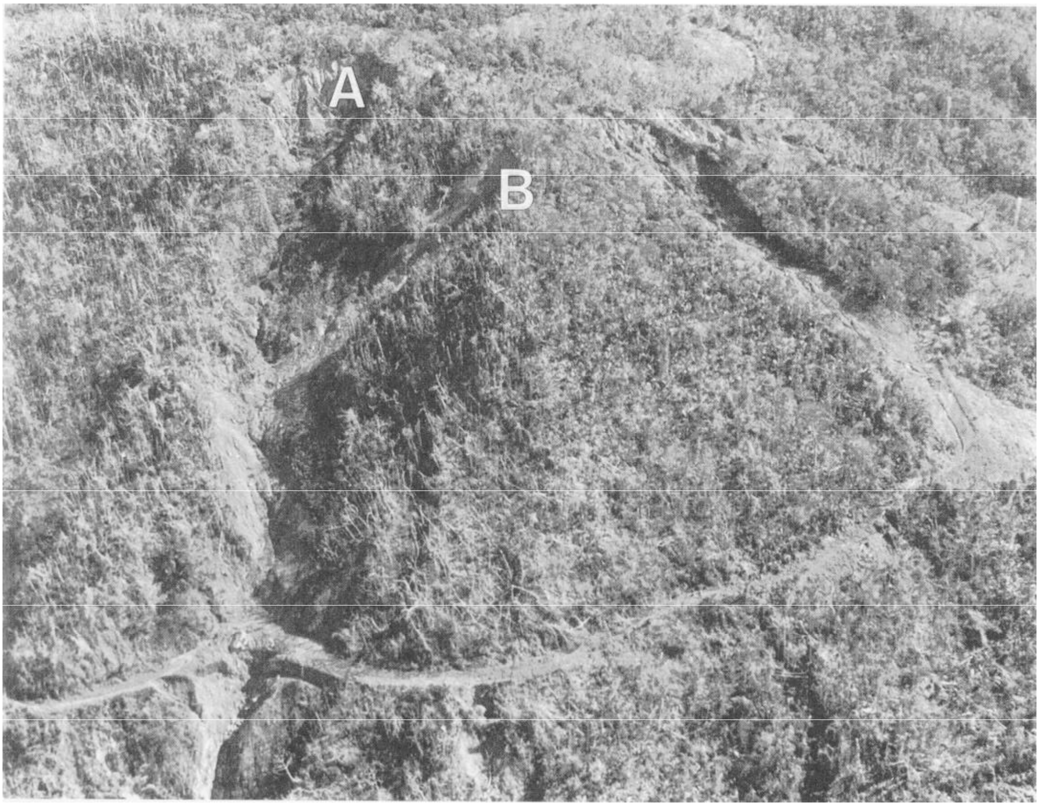

FIG. 6. The largest landslide (B) triggered by Hurricane Hugo, a 30,000 m^3 debris avalanche. The longer scar (A) at left resulted from a debris avalanche that was triggered by a 1970 tropical depression in which 976 mm of rain fell in 5 days. Visible in the center of the photograph are numerous tree trunks stripped of branches and tipped to the left (south) by the northerly hurricane winds. Note 2-lane vegetation-covered road in lower part of photograph for scale.

fore increases in pore pressure occurred at greater depth.

All mapped Hurricane Hugo-related landslides were within the area bounded by the 200 mm rainfall isohyet. This rainfall accumulation may be the minimum necessary to trigger landslides in the LEF following a 2-week period of below-normal rainfall. However, the log normal distribution of landslide surface areas exceeded two orders of magnitude for the landslides that occurred on forested hillslopes which indicates that 200 to 300 mm of rainfall in 24 h or less is sufficient to trigger landslides in a variety of geomorphic settings in the LEF.

Most of the Río Grande de Loiza drainage basin (adjacent to the LEF on the west) experienced rainfall accumulation of only 100 to 200 mm (Fig. 3). Although the bedrock, topographic and soil characteristics are similar to those of the LEF, air and ground reconnaissance of this basin revealed virtually no landslide activity caused by the storm. Only 23% of the Río Grande de Loiza basin is forested (Quiñones et al., 1989). The remainder is used for pasture (66%), crops (3%), and urbanization (8%). In the LEF, these land use categories doubled to quadrupled the density of landslides triggered by Hurricane Hugo (Table 5). However, these anthropogenic effects in the Río Grande de Loiza basin did not contribute to triggering of landslides after less than 200 mm of rainfall accumulation. In addition to rainfall accumulation and intensity, factors such as slope aspect and treefall apparently were important for landslide occurrence in the LEF.

Landslides are common along all highways in the LEF (Guariguata and Larsen, 1989). The five times higher percentage of disturbed area caused by Hurricane Hugo road- and structure-associated landsliding attests to the significance of hillslope modification by man. The proportionately higher number of landslides in anthropogenically disturbed areas is generally common along road cuts in humid-tropical regions, including other Caribbean islands (Cooper, 1977; Anderson and Kneale, 1980).

Extensive rainfall intensity data were not available for the hurricane because of damage to rain gages and the uncertainty associated with rainfall collection during high winds. Peak mean basin runoff, calculated from peak stream discharge, gives an indication of the maximum rainfall intensity in each drainage basin (Table 2). However, peak mean basin runoff does not correlate well with landslide density, perhaps because of the uneven distribution of high-intensity rainfall bursts associated with hurricanes (Anthes, 1982). The highest peak mean basin runoff was associated with the Río Mameyes basin, which drains the northern side of the LEF, but landslides in the Río Mameyes basin numbered only 3/km ^{2}. The 10 to 31 year peak discharge recurrence intervals for the streams draining the LEF indicate the variable effects of topography on rainfall accumulation and runoff. Topographically-controlled rainfall accumulation may be one of the most important factors affecting landslide occurrence.

Slope aspect was important in influencing landslide distribution. Of the 215 landslides mapped on forested hillslopes, most occurred on hillslopes with a north component (Fig. 4). In the 1031 ha area of greatest landslide occurrence, 71% of the hurricane-triggered landslides occurred on hillslopes with a north component. Of the remaining landslides in this area, half were at or immediately below ridge tops trending generally east-west, where treefalls were numerous. The basins near the eye track and with the greatest percentage of north-facing slopes experienced the highest number of landslides per unit area; Sabana had 15/ km^{2}and Fajardo had 10/ km^2 The Espiritu Santo basin, in the area where aerial photography was available, drains to the west and northwest and had a much lower incidence of landsliding (0.8 /km^2). The close association between landsliding and slope aspect reflects the synergistic effects of wind-driven rainfall and wind-toppled trees. The horizontal delivery of rainfall from a predominantly north direction resulted in higher soil saturation on north-facing slopes compared to south-facing slopes. Additionally, numerous depressions in the soil caused by overturned tree root systems contributed to rapid infiltration of rainfall on these slopes.

Disturbance and Denudation

Although landsliding is an important erosive process on steep slopes in all climates, the combination of steep slopes, intense rainfall and thick regolith in the humid tropics leads to high rates of denudation through mass wasting (Carson and Kirkby, 1972). An approximate denudation rate can be calculated from the 0.11% of forest area disturbed by hurricane rainfall-triggered landslides (Table 5). The 0.11% disturbance of forested area for storm rainfall with a 10-yr recurrence interval is equivalent to 1.l%/100 yr. Using the total areas of each landslide type (shallow soil slips, debris flows, and slumps) and the thickness of each (1 m, 1.75 m, and 3 m, respectively), a volume of 111,767 m^{3}was eroded by Hurricane Hugo. The entire 5883 ha of forested area mapped would be lowered 1.45 m after 8871 yr. This corresponds to 164 mm/1000 yr or 1 m/6110 yr.

The 164 mm/1000 yr denudation rate does not account for the fact that landslide erosion is not uniform throughout the mapped area, and that some sediment is not transported out of the basin, but remains on the hillslope or in the stream channel. Additionally, hillslope erosion based on the 10-yr rainfall-recurrence interval is slightly overestimated since it ignores the effects of hurricane-induced treefall. A direct pass of a hurricane over the

LEF occurs about every 60 yr. However, 8 of the 10 storms shown in Table 3 caused tens to hundreds of landslides in the LEF during a 90 year period, indicating that a 10-yr recurrence interval for similar landslide-triggering events is appropriate (Haire, 1972; Dames and Moore, 1980). The two 1985 storms in table 3 were centered over western Puerto Rico.

The 164 mm/1000 yr rate is close to a denudation rate based on stream sediment export for the LEF. The landslide denudation rate corresponds to erosion of 243 $t/km^2/yr$ from LEF forested-hillslopes by rainfall-triggered landsliding, given the median soil density of 1.28 g/cm^3 and the given volume of eroded material. The soil density value (1.28 g/cm^3) underestimates the density of rock, but overestimates the density of soils in the upper meter. Combined suspended sediment and bedload exported from two small (combined area of 13 ha) volcaniclastic terrain watersheds in the Río Mameyes basin amounts to approximately 300 $t/km^2/yr$ (F. Scatena, USFS, pers. comm.) and a denudation rate of 230 mm/1000 yr. The estimated mass-wasting denudation rate of 243 $t/km^3/yr$ is equal to 81% of the stream sediment export of 300 $t/km^2/yr$, indicating that mass-wasting is a major agent of hillslope erosion in the LEF.

The only other landslide disturbance rates for forested hillslopes in the LEF are up to an order of magnitude lower than the rate estimated from Hurricane Hugo landslides. Guariguata (1990) published landslide disturbance rates for the LEF of 0.08 and 0.3%/100 yr for the upper Luquillo Mountains at an elevation range of 530 to 850 m, in volcaniclastic and quartz-diorite bedrock terrains, respectively. These rates, based on 46 landslides in an area of 4400 ha, were probably underestimated because of the poor quality of aerial photographs used and low number of landslides mapped in that study.

The 1.1%/100 yr disturbance rate based on Hurricane Hugo landslides is lower, but comparable to the 2%/100 yr rate in Panama for erosional landsliding (defined by Garwood et al., 1979, as non-seismically triggered landsliding). A 3%/100 yr rate was determined for non-seismic landsliding in New Guinea (Simonett, 1967; Garwood et al., 1979).

CONCLUSIONS

High-intensity, short-duration rainfall associated with Hurricane Hugo triggered numerous landslides in the LEF. These landslides were mostly shallow, of limited areal extent, and occurred in the area of the LEF closest to the hurricane track. The surface areas of the landslides on forested hillslopes were log-normally distributed, extending over two orders of magnitude. Because all the landslides were bounded by the 200 mm isohyet, this rainfall accumulation may represent a 24 h threshold for the triggering of numerous landslides in the LEF. Mass wasting is a dominant agent of hillslope erosion in the LEF, as the mass wasting triggered by Hurricane Hugo is equal to 81% of the sediment exported from several small monitored watersheds. Presence of highways in the LEF increased landslide disturbance by a factor of five over disturbance documented on unmodified, forested hillslopes. Construction and maintenance of highways is one of the most important elements affecting hillslope erosion in the LEF.

To determine a watershed erosion rate, the major processes controlling sediment generation and transport (which are usually spatially and temporally highly variable) must be quantified (Dietrich and Dunne, 1978). The disturbance and denudation rates presented here are based on small watershed-scale measurements from a single event and therefore provide only an estimate of long-term erosional processes. However, they offer insight into watershed-scale processes resulting from a formative event which is frequent and of high magnitude in mountainous humid-tropical environments. Hurricanes and other large storms regularly affect Puerto Rico and other Caribbean islands. The landslides triggered by Hurricane Hugo in the Luquillo Experimental Forest are representative of a commonly occurring geomorphic event affecting hillslopes in Puerto Rico.

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