A RAINFALL INTENSITY-DURATION THRESHOLD FOR LANDSLIDES IN A HUMID-TROPICAL ENVIRONMENT, PUERTO RICO

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ABSTRACT. Landslides are triggered by factors such as heavy rainfall, seismic activity, and construction on hillslopes. The leading cause of landslides in Puerto Rico is intense and/or prolonged rainfall. A rainfall threshold for rainfall-triggered landsliding is delimited by 256 storms that occurred between 1959 and 1991 in the central mountains of Puerto Rico, where mean annual rainfall is close to or in excess of 2,000 mm. Forty one of the 256 storms produced intense and/or prolonged rainfall that resulted in tens to hundreds of landslides. A threshold fitted to the lower boundary of the field defined by landslide-triggering storms is expressed as

$$I = 91.46\, D^{-0.82}$$

where I is rainfall intensity in millimeters per hour, and D is duration in hours. Landslide-producing storms occurred at an average rate of 1.2 per year. In general the landslides triggered by short-duration, high-intensity rainfall events were mainly shallow soil slips and debris flows, while the long-duration, low-intensity rainfall produced larger, deeper debris avalanches and slumps. For storms that had durations of up to 10 h, landsliding did not occur until rainfall intensity was as much as three times as high as the rainfall intensity reported as sufficient to trigger landsliding in temperate regions. As storm durations approach 100 h, the rainfall conditions necessary to initiate landsliding in Puerto Rico converge with those defined for temperate regions. A comparison of the Puerto Rico threshold with rainfall data from other humid-tropical regions suggests that the threshold developed for Puerto Rico may be applicable to other similar environments throughout the world.

Key words: *landslides, humid tropics, rainfall threshold.*

Introduction

Landslides are a common and recurring problem for much of the mountainous island of Puerto Rico. A major earthquake in 1918 caused numerous landslides and rockfalls throughout western Puerto Rico where the earthquake was above VII on the modified Mercalli intensity scale (Reid and Taber, 1919). Hillslope modification for highway construction and urbanization has also resulted in numerous landslides (Sowers, 1971; Molinelli, 1984; Jibson, 1989). However, rainfall-triggered landslides on both modified and unmodified slopes are most common and occur frequently throughout the central mountains and foothills of the island (Monroe, 1979; U.S. Weather Service, 1959-1990). Landslides referred to in this paper include shallow soil slips, debris flows, debris slides, debris avalanches, and slumps (classification after Varnes, 1978; Campbell, 1975).

Rainfall-induced landslides have resulted in substantial property damage as well as loss of human life. In 1960, eight deaths were caused by landslides triggered by rainfall associated with Hurricane Donna (U.S. Weather Service, 1959-1990). Landslides in 1970 resulted in 10 deaths, and in 1985, the worst landslide disaster in the history of the United States, in terms of loss of life, occurred when a tropical storm triggered a landslide that killed 129 people (Jibson, 1989).

A characterization of landslide-triggering storms by rainfall duration and intensity has been used to establish a relation between storms and landslides in temperate areas of the world (Campbell, 1975; Cannon and Ellen, 1985; Cannon, 1988) and in humid-tropical areas (Wentworth, 1943; Haldemann, 1956; de Meis and Silva, 1968; Starkel, 1970; So, 1971; Temple and Rapp, 1972; Jones, 1973; Guidicini and Iwasa, 1977; Li Jian and Wang Jingrung, 1984; DeGraff, 1990; Wilson *et al.* 1992). A worldwide threshold has been developed by Caine (1980) using 73 storms. With the use of 256 storms this paper develops a similar rainfall intensity-duration threshold for triggering of landslides in a humid-tropical climate. The threshold is developed by comparing rainfall records of storms that resulted in landslides with those that did not.

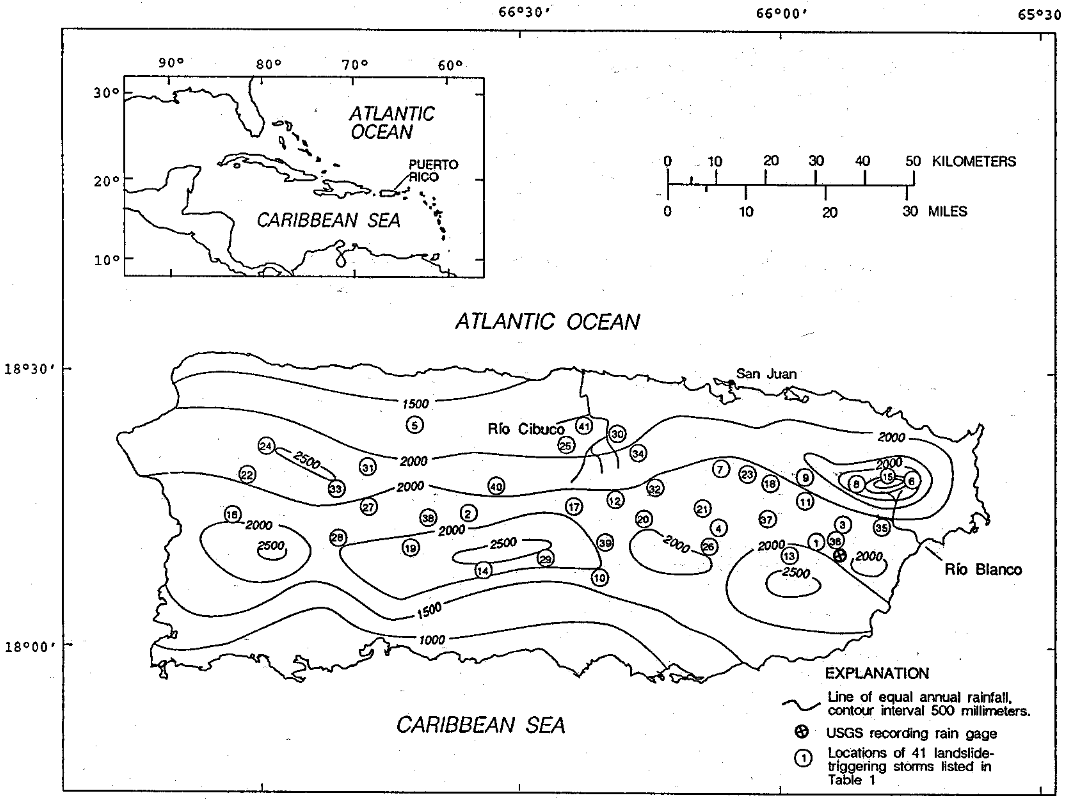

Fig. 1. Location of Puerto Rico, distribution of mean annual rainfall in millimeters (data from Calvesbert, 1970), location of 41 storms that triggered landslides (listed in Table 1) and location of the USGS recording rain gage.

Climate and setting

The island of Puerto Rico is situated at the eastern end of the Greater Antilles, and is located in the path of the easterly tradewinds (Fig. 1). These winds dominate regional climate and are strongest during the wet season months of May through December (Calvesbert, 1970). Much of the yearly rainfall is delivered by tropical waves, depressions, storms, and hurricanes imbedded in the easterly trade winds. Northerly cold fronts bring about one quarter to one third of the total annual rainfall during the winter months (Calvesbert, 1970). Annual rainfall ranges from 760 to more than 5,000 mm and varies because of the orographic effects of an east-west trending central mountain range (Fig. 1). The climate of Puerto Rico ranges from humid-tropical weakly-seasonal throughout the investigated central mountains and northern coast, to seasonal dry tropical (dry winters, wet summers) along the southern coastal plain. Mean annual temperature also varies with elevation, increasing from 19° Celsius (C) at the highest peaks (1,000 to 1,300 m) to 27° C along the coastal plains.

Topography, land use, and geology

Topography in the study area, the central mountains of Puerto Rico, is typified by moderate to steep slopes that are dissected by perennial and ephemeral streams. The central mountain range, with peak elevations of up to 1,340 m above sea level, is fringed by a relatively flat coastal plain, which is 8 to 16 km wide.

Following three centuries of extensive agricultural land use, more than 90 percent of the island was deforested by 1935 (Birdsey and Weaver, 1987). However, because of a more recent shift away from agriculture towards industry, large areas of former farmland and pasture have been abandoned and reforested, so that in 1987 only 60 percent of the island remained deforested (Birdsey and Weaver, 1987).

The uplands of Puerto Rico are underlain predominantly by Cretaceous-age, largely marine-deposited volcaniclastic rock which includes tuffaceous sandstone, siltstone, breccia, conglomerate, lava, and tuff (Briggs and Akers, 1965). Several late Cretaceous, Paleocene, and Eocene-age plutonic intrusions (granodiorite and quartz diorite) occur in the eastern and central mountains. Because of high annual rainfall and temperature, chemical weathering of rock is rapid. Bedrock in the central mountains is highly weathered and overlain with an average of 5 to 10 m of saprolite (St. John *et al.* 1969; Deere and Patton, 1971).

Data collection

Rainfall records from three sources were examined and the rainfall intensities and durations of a total of 256 storms were used. The U.S. Weather Service Storm Data series (U.S. Weather Service, 1959-1990) provided a 32-year record of storm rainfall data that included text comments on the occurrence of landsliding. Storms were selected only if total rainfall accumulation and duration, and the occurrence or non-occurrence of landslides could be established. Landslide occurrence for selected storms was verified in some cases by using archival newspaper accounts of storm damage when no other data source was available (San Juan Star, 1959-1991). The landslide type (debris flow, slump, etc.) was not noted in the U.S. Weather Service Storm Data series (U.S. Weather Service, 1959-1990). This data source yielded 42 storms that occurred between 1959 and 1990 in the central mountains and/or adjoining foothills of Puerto Rico where mean annual precipitation (MAP) is close to, or in excess of 2,000 mm (Fig. 1). Forty of these storms were documented as triggering tens to hundreds of landslides (Table 1) and 2 caused no landslides.

The monthly summaries of U.S. Weather Service data were examined for indications of storms not yet published in the U.S. Weather Service Storm Data series. A single multi-day storm that began on October 5, 1990, was reported to have triggered landslides and was documented from this source (Table 1; U.S. Dept. of Commerce, 1990).

A U.S. Geological Survey (USGS) recording rain gage in the central mountains was selected for further sampling of rainfall duration and intensity (Fig. 1). Although from only a two-year period, this data sample was assumed to be derived from the same population as the sample from the U.S. Weather Service Storm Data series because:

1) it is located in an area of the central mountains which receives MAP of 2,000 mm, and MAP at this site can be considered as equivalent to the average MAP of 2,040 mm reported by Calvesbert (1970) for the central mountains;
2) topography and land use in this area are comparable to that throughout much of the central mountains: moderate to steep slopes in pasture, pasture recovering to forest, and forest (Quiñones-Máquez *et al.* 1989);
3) the area is underlain by bedrock comparable to most of the central mountains: marine-deposited volcaniclastic rock and plutonic intrusions (Briggs and Akers, 1965);
4) soils in the area are mainly Inceptisols, common throughout the central mountains (Acevedo, 1982; Boccheciamp, 1977, 1978; Gierbolini, 1975, 1979);
5) the site is within a 20 km radius of 12 of the 41 landslide-triggering storms, and;
6) the rain gage was visited weekly to biweekly between April 1989 and April 1991, as part of a study of erosion and sedimentation (Gellis, 1991). This allowed the confirmation of the occurrence or non-occurrence of landslides during the two-year period.

Daily rainfall was calculated from the rain gage recordings for two years. No rainfall-triggered landslides were noted in the 40 km^2 area near the rain gage during this period.

Data for 213 rainfall events recorded by this rain gage and 2 storms documented by the U.S. Weather Service (1959-1990) that did not trigger landsliding are listed in a table that is available from the authors. A summary of those data is shown in Table 2.

Bursts of higher-intensity rainfall that may have occurred during storms are not reflected in the long-duration rainfall data. These bursts may be important as discrete events that trigger landsliding during long-duration storms (Jibson, 1989). In addition, the rainfall data presented in Table 1 and used in Figure 3 reflect maximum rainfall at a single location, which is often greater than regionally distributed rainfall.

Table 1. Date of occurrence and rainfall characteristics of 41 storms that triggered landslides in Puerto Rico. Number refers to storm location shown on Figure 1 (data sources: U.S. Weather Service, Storm Data, 1960-1990; U.S. Department of Commerce, 1990).

[CF= cold front; H= hurricane; HR= heavy rains; LLT= lower level trough; SF= stationary front; TD= tropical depression; TS= tropical storm; TRS= thunderstorm; TW= tropical wave; ULT= upper level trough; MAP = mean annual precipitation]

Number	Date	Year	Storm type	Accumulation, mm	Duration, h	Intensity, mm/h	Percent MAP
1	Oct 14	1976	TRS	142	2	71.12	7%
2	Sep 27	1980	TRS	221	2	110.50	11%
3	Dec 10	1975	HR	203	3	67.73	10%
4	Nov 15	1977	HR	127	3	42.33	6%
5	Oct 30	1976	CF	102	4	25.48	5%
6	Sep 18	1989	H Hugo	225	6	37.50	11%
7	May 9	1982	ULT	203	6	33.87	10%
8	Nov 9	1969	HR	178	6	29.66	9%
9	Jan 26	1969	HR	127	6	21.16	6%
10	Aug 27	1970	HR	225	9	25.00	11%
11	Jan 13	1965	LLT	544	9	60.44	27%
12	Apr 16	1988	ULT	168	12	14.00	8%
13	Aug 23	1988	TD	312	24	13.00	15%
14	Oct 14	1962	TW	216	24	9.00	11%
15	May 4	1965	HR	144	24	6.00	7%
16	Aug 27	1961	TW	456	24	19.00	22%
17	Nov 3	1984	ULT	192	24	8.00	9%
18	Dec 6	1987	CF	493	24	20.54	24%
19	Oct 6	1985	TS	625	24	26.04	31%
20	Sep 12	1982	TW	330	48	6.88	16%
21	Sep 6	1960	H	477	48	9.94	23%
22	May 27	1980	TRS	288	48	6.00	14%
23	Aug 23	1971	TD	232	48	4.83	11%
24	May 12	1986	ULT	279	48	5.81	14%
25	Nov 9	1970	CF	254	48	5.29	12%
26	Aug 29	1979	H David	502	72	6.97	25%
27	Dec 9	1965	CF	474	72	6.58	23%
28	May 8	1970	HR	254	72	3.53	12%
29	Sep 4	1979	TS Frederick	459	72	6.38	23%
30	Dec 8	1970	CF	419	96	4.36	21%
31	Nov 26	1968	CF	329	96	3.43	16%
32	Apr 22	1969	TRS	268	96	2.79	13%
33	May 15	1985	ULT	635	96	6.62	31%
34	Dec 11	1981	CF	740	96	7.71	36%
35	May 18	1987	ULT	453	120	3.78	22%
36	Oct 22	1978	TW	459	120	3.83	23%
37	Nov 24	1987	ULT	583	120	4.86	29%
38	Nov 29	1960	CF	438	144	3.04	21%
39	Oct 4	1970	TD Unnamed	976	144	6.78	48%
40	May 20	1981	ULT	254	144	1.76	12%
41	Oct 5	1990	TW	303	312	0.97	15%

Data treatment

Rainfall-intensity data derived from storm durations greater than 9 h were lumped by the U.S. Weather Service (1959-1990) into 24, 48, and 72 h (and so on) categories. The data in the monthly summaries of the U.S. Weather Service (U.S. Dept. of Commerce, 1990) is in the form of daily rainfall totals. Rainfall data for the USGS rain gage are generally recorded in 15-minute increments. The data are listed as 24 h totals for one-

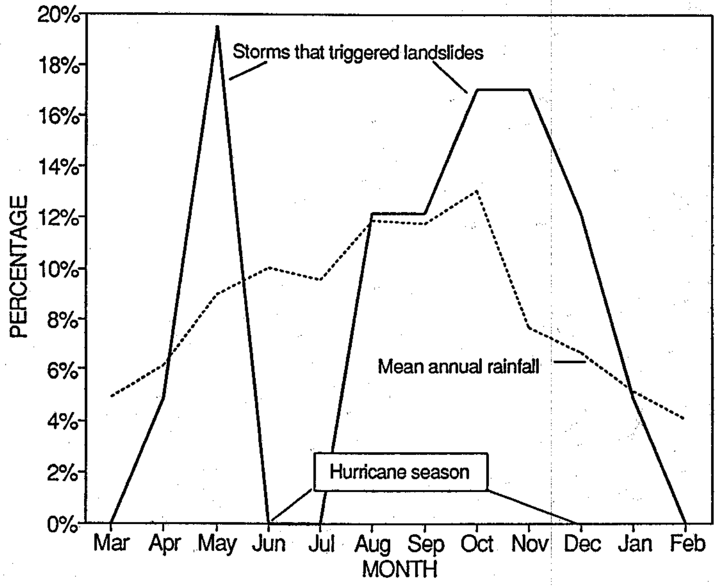

Fig. 2. Plot of monthly percentage of landslide-triggering storms and monthly percentage of mean annual rainfall in the central mountains of Puerto Rico.

day storms, and grouped into multiples of 24 h if rainfall on successive days exceeded 3 mm on any single day. Days with rainfall totals of less than 3 mm were disregarded. In addition, 15-minute increments of rainfall accumulation were examined for all days on which rainfall accumulation exceeded 3 mm. Events of less than 24 h were included if one or more consecutive 15-minute increment exceeded 3 mm of rainfall accumulation.

Characteristics of storms that triggered landslides

Examination of the storm-rainfall data for 1959-1990 indicates that the number of storms of sufficient magnitude to trigger moderate to extensive landsliding in Puerto Rico averaged 1.2 per year. More than one half of these landslide-triggering storms were tropical disturbances (hurricanes, tropical storms, tropical depressions, tropical waves, and troughs) (Table 1). The remainder were localized heavy rains and convective thunderstorms (27 percent) and storms associated with winter cold fronts (20 percent). The majority (25 out of 41 storms) of the landslide-triggering storms occurred during the hurricane season (June through November) (Fig. 2). Most of these 25 storms occurred during the peak months of the hurricane season (August through October) (Fig. 2). A relatively large number of landslide-triggering storms also occurs in May when the last cold fronts of the season and the first tropical waves of the summer begin to affect the island.

Rainfall intensity-duration threshold

Using data for 256 storms, a threshold relation be-

Table 2. Rainfall accumulation and duration for 215 storms that did not trigger landslides in the vicinity of a USGS index station or elsewhere in the central mountains of Puerto Rico (data from U.S. Weather Service, 1959-1990; USGS unpublished data, 1988-1991).

	Rainfall accumulation, mm	Rainfall duration, hours
Minimum	3.3	0.3
Maximum	192	264
Mean	20	41.1
Median	10	3.8

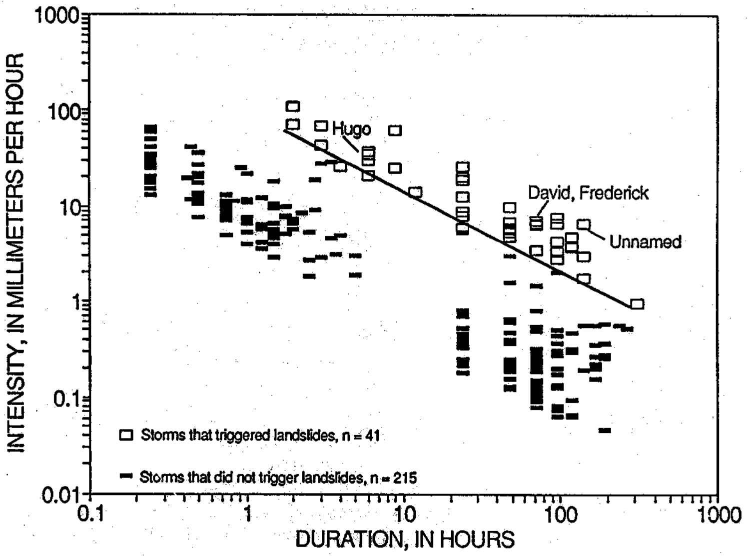

Fig. 3. Relation between average rainfall intensity in millimeters and duration in hours for 256 storms dating from 1959 to 1991 in Puerto Rico. The line represents intensity-duration threshold (lower bound) for storm rainfall that triggered landslides.

tween rainfall intensity-duration and landsliding was established (Fig. 3). The threshold, fitted by inspection to the lower boundary of those points representing landslide-triggering storms, is expressed as

$$I = 91.46\,D^{-0.82}$$

where I is rainfall intensity in millimeters per hour, and D is duration in hours. A threshold fitted to the lower boundary of data points reflects the approximate minimal rainfall conditions necessary to trigger landsliding. This rainfall threshold relation is defined for storms that had durations between 2 and 312 h, and average rainfall intensities between 1 and 110 mm/h. The threshold relation indicates that for storms of short duration (10 h or less), rainfall intensities higher than 13.8 mm/h are required to trigger landslides. Low average rainfall intensities of 2 to 3 mm/h appear to be sufficient to cause landsliding as storm durations approach approximately 100 h.

There is a relation between landslide characteristics and the position of the landslide-triggering storm on the threshold line. Storms near the short-duration/high-intensity end of the threshold line may trigger mostly shallow landslides by causing excess pore pressure in shallow soil zones. Such landslides were typical of those associated with Hurricane Hugo which occurred in 1989 (Table 1; Hugo in Fig. 3). The landslides triggered by Hurricane Hugo averaged 1.5 m in thickness and had a median surface area of 161 m^2 (Scatena and Larsen, 1991; Larsen and Torres Sánchez, 1992). These landslides, which were mainly shallow soil slips and debris flows, had failure planes in saprolite or at the soil-saprolite boundary. In contrast, storms near the long-duration/low-intensity end of the threshold have triggered the largest, deepest landslides in the central mountains. Storms that occurred on August 29, 1979 (Hurricane David), September 4, 1979 (Tropical Storm Frederick), and October 4, 1970 (unnamed tropical depression) (Table 1; Fig. 3) are associated with debris avalanches with an average thickness of 10 m and surface areas ranging from 20,000 to 40,000 m^2 (Dames and Moore, 1980). Failure planes were at the contact between the saprolite and underlying unweathered bedrock. These large, deep-seated debris avalanches are attributed to prolonged storms that allow gradual infiltration of water, which appears to result in excess pore pressure at depth (Simon *et al.* 1990).

Return periods in the central mountains for rainfall accumulations based on the intensity-duration threshold line range from 25 years for a 1 h storm with 92 mm of rainfall to 1 year for a 120 h storm with 222 mm of rainfall (U.S. Weather Bureau, 1961; Miller, 1965). Storms between 2 and 6 h duration have a return period of approximately 10 years, and storms between 7 and 24 h duration have an approximate return period of 5 years. Storms of 48 to 96 h duration are estimated to return approximately each 2 to 5 years.

Table 3. Mean annual precipitation and characteristics of shallow (0.4 to 2 m depth) soil samples collected in two Puerto Rico drainage basins. (modified from Simon and others, 1990). [mm = millimeters; g/cm^3 = grams per cubic centimeter; SD = standard deviation; n = number of samples].

Characteristic	Río Blanco Basin			Río Cibuco Basin		
	Mean	SD	n	Mean	SD	n
Clay (percent)	31.6	2.3	61	42.3	2.4	33
Sand and gravel (percent)	48.0	4.1	51	26.7	3.3	33
Plasticity Index (percent)	15.9	1.5	44	22.3	1.6	33
Moisture content (percent)	34.9	1.7	70	29.3	1.6	33
Degree of saturation (percent)	80.0	2.0	65	70.0	3.0	33
Saturated density (g/cm^3)	1.79	0.02	65	1.8	0.02	33
Mean annual precipitation (mm)	3,500			2,080		

Antecedent soil-moisture conditions

In the mountainous interior of the island, the tradewinds deliver a constant flow of moisture-laden air, and much of the rainfall occurs in frequent, brief, low-intensity orographic showers; there are more than 1,600 rain showers per year in the mountains of eastern Puerto Rico (Brown *et al.* 1983). In a related study, soil samples were collected at various times during both wet and dry seasons in the Blanco and Cibuco drainage basins (Fig. 1) (Simon *et al.* 1990). These data indicate that the average soil moisture content at depths of 2 meters or less, was 23% and 35% in the Cibuco and Blanco basins, respectively (Table 3).

A U.S. Army Corps of Engineers (1960) study of soil structure and moisture in forested areas in the mountains of eastern Puerto Rico found that the average year-long rate of daily soil moisture loss in the upper 305 mm layer was about one-half that of the average summer rate in humid climates of the U.S. Average daily soil-moisture loss in Puerto Rico was 1.8 mm of water per 305 mm of soil during all seasons. The average summer loss rate reported for humid areas of the U.S. was 2.8 mm of water per 305 mm of soil. Moreover, minimum moisture contents in Puerto Rico were considerably higher than those found in comparable U.S. soils. The study noted that central Puerto Rico has almost twice the annual mean number of days (209 days) in which precipitation exceeds 3 mm, as selected humid sites in the U.S. In addition to high annual rainfall characterized by frequent showers, the lower soil-moisture depletion rates in Puerto Rico were attributed to shorter summer days, lower maximum summer temperature, and greater interception of short-wavelength rays by high amounts of water vapor in the micro-climatic zone immediately above the soil surface. The combination of these factors seems to maintain soils in a moist condition throughout the year.

Although antecedent soil-moisture conditions have been shown to be important in the determination of if and when rainfall-triggered landslides may occur in temperate regions (Campbell, 1975; Keefer *et al.* 1987; Wieczorek, 1987) they seem to have a negligible effect in Puerto Rico. Antecedent soil-moisture conditions were therefore not determined for the storms used here to define the threshold. However, antecedent soil-moisture conditions merit further investigation as the higher percentage of landslide-triggering storms towards the end of the hurricane season could be attributed to the increased soil moisture that may follow the three wettest months of the year (Fig. 2).

Storms and mean annual precipitation

In the eastern uplands of the United States, Eschner and Patric (1982) determined that storms that triggered debris avalanches had a 24 h accumulation threshold of 125 mm. This accumulation represents 5 to 13 percent of MAP for that region. In the southern Appalachian Mountains of

Table 4. Rainfall accumulation, percentage of mean annual rainfall (MAP)(2,040 mm), and duration of 41 storms that triggered landslides in the central mountains of Puerto Rico between 1960 and 1990.

	Rainfall accumulation, in millimeters	Percent MAP	Storm duration, in hours
Minimum	102	5%	2
Maximum	976	48%	312
Median	284	14%	48
Mean	349	17%	58

the United States, a 1977 storm with a rainfall accumulation of 200 mm (7 percent of MAP), triggered debris avalanches (Neary and Swift, 1987). A few debris flows in a 10 km^2 study area in the Santa Cruz mountains of California were triggered by ten storms with a mean rainfall accumulation of 87 mm (Wieczorek, 1987), 11 percent of MAP.

In Puerto Rico, however, the mean rainfall accumulation for the 41 storms that triggered landslides in Puerto Rico is 362 mm, which represents 17 percent of MAP in the central mountains (Table 4). This higher percentage of MAP is comparable to that reported in other humid-tropical areas as well. Several storms that triggered landslides in Brazil were reported as having 8 to 25 percent MAP by Guidicini and Iwasa (1977). Li Jian and Wang Jingrung (1984) described an area in the Yunnan Province of China where 10 to 17 percent of MAP triggered mudflows.

Rainfall accumulations necessary to trigger landslides in temperate environments are generally lower than the accumulation reported here for Puerto Rico. The percentage of MAP falling in a landslide-triggering storm is also generally less in temperate environments than in Puerto Rico or other humid-tropical areas.

Comparison with other thresholds

A worldwide threshold for rainfall-triggered debris flows developed by Caine (1980) is shown in Figure 4 for comparison with the threshold relation developed here. This worldwide threshold falls below the Puerto Rico threshold for durations of less than 100 h. The worldwide threshold has the form:

$$I = 14.82\,D^{-0.39}$$

A comparison of the Puerto Rico and other thresholds indicates that for durations of 10 h or less, as much as three times as much rainfall is required to trigger landsliding in Puerto Rico than in temperate areas. This higher rainfall threshold for widespread landsliding in the humid tropics has also been suggested by Ruxton and Berry (1957) and Carson and Kirkby (1972). However, this does not suggest that landsliding is less likely in the humid tropics than in temperate settings. The humid tropics by definition receive high annual rainfall (Gupta, 1988) (2,000 to 5,000 mm in the central mountains of Puerto Rico). The regular occurrence of rainfall-triggered landslides in Puerto Rico (an average of 1.2 events per year) indicates that landsliding is an important geomorphic process in humid tropical areas of high relief (Simon and Guzmán-Ríos, 1990). As storm durations approach 100 h, the Puerto Rico threshold converges with the worldwide threshold. This indicates that geomorphological and climatological differences between humid-tropical and temperate environments may not be significant when hillslopes receive large amounts of rainfall over a prolonged period.

Only seven of the 73 storms used to define the worldwide threshold were from humid-tropical areas, which suggests that the worldwide threshold mainly reflects temperate conditions. The data points from these seven storms, six other storms that caused landslides in the humid tropics, and a debris flow threshold developed for Honolulu, Hawaii by Wilson *et al.* (1992) are also shown in Figure 4. The Hawaii threshold is based on average rainfall values developed for rainfall-warning thresholds for abundant debris flows in two sub-areas of the Honolulu study area. The 13 humid-tropical storms plot above the worldwide threshold line, and fall in the same field as those storms that define the Puerto Rico threshold (Fig. 3, 4). Twelve of the 13 tropical sites plot on or above the Puerto Rico threshold line, and the

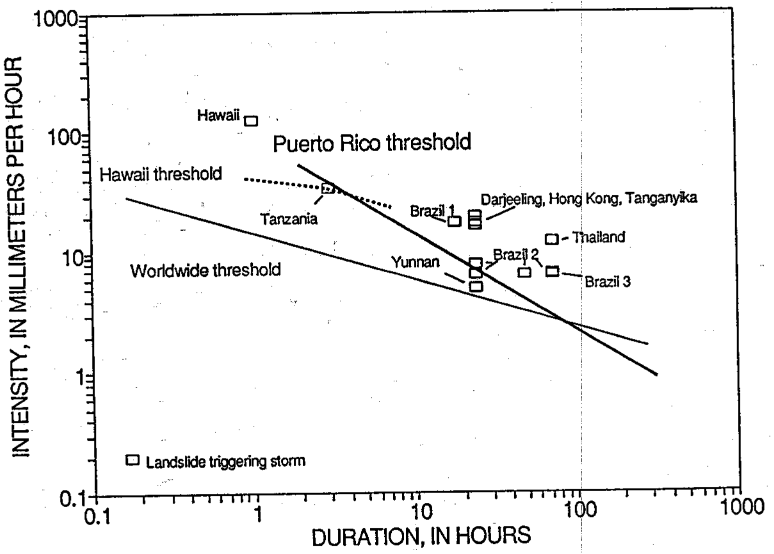

Fig. 4. Puerto Rico rainfall threshold line for storms triggering landslides, worldwide rainfall threshold, Hawaii threshold, and 11 storms that triggered landslides elsewhere in the humid tropics; [data sources: Brazil 1, Jones, 1973; Brazil 2, Guidicini and Iwasa, 1977; Brazil 3, de Meis and da Silva, 1968; Darjeeling, Starkel, 1970; Hawaii, Wentworth, 1943; Hawaii threshold, Wilson *et al.* 1992; Hong Kong, So, 1971; Tanganyika, Haldemann, 1956; Tanzania, Temple and Rapp, 1972; Yunan, Li Jian and Wang Jingrung, 1984; Worldwide threshold, Caine, 1980]

Hawaii threshold is close to and intersects the Puerto Rico threshold. The similarity of the Puerto Rico data with other humid-tropical data provides strong evidence that the threshold relation proposed here may well be applicable to other humid-tropical environments throughout the world.

Conclusions

An analysis of a 33-year record of storm-rainfall data which includes records of landslide occurrence indicates that tens to hundreds of landslides have occurred over a wide range of rainfall intensity-duration conditions. On average, short duration rainfall (10 h or less) requires an intensity in excess of 13.8 mm/h to trigger landslides; but durations of 100 h or more with an average intensity of 2-3 mm/h can trigger landslides. In general, landslides triggered by short-duration, high-intensity rainfall events are shallow soil slips and debris flows. Long-duration, low-intensity rainfall generally produces larger, deeper debris avalanches and slumps. The landslide-threshold relation indicates that in humid-tropical Puerto Rico, as much as three times more rainfall is required to trigger landslides (for rainfall durations less than 10 h) than the rainfall amount that triggers landslides world-wide. In contrast, for rainfall durations approaching 100 h, the differences between humid-tropical and temperate environments may be less significant.

The rainfall intensity-duration threshold presented here for landslides in the central mountains of Puerto Rico is generalized. No differentiation among geologic and topographic settings, failure types, or land use was attempted. A more extensive data set that provided a detailed inventory of failure locations and mechanisms would increase the accuracy of this relation for a given locale in Puerto Rico. Still, the threshold presented is a reasonable first approximation for humid-tropical Puerto Rico and may be applicable to other humid-tropical areas of high relief. In addition, the threshold provides a key element for a potential landslide warning system.

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