Map Showing Susceptibility to Rainfall-Triggered Landslides in the Municipality of Ponce, Puerto Rico

Scientific Investigations Map I-2818

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Abstract

The risk of landslides during intense or prolonged rainfall is high in steeply sloping areas such as the municipality of Ponce, where 56 percent of the 301-square-kilometer municipality has slopes 10 degrees or greater. These are areas where the possibility of landsliding increases when triggering conditions such as heavy rainfall or excavation and construction occur.

Using a 30-meter digital elevation model to classify hillslope angle, a digital map of bedrock geology, and maps showing the locations of landslides associated with a severe storm in October 1985, the municipality was classified into areas of low, moderate, and high susceptibility to landslides triggered by heavy rainfall. Areas defined by geology as having 0-0.1 landslides per square kilometer were mapped as having low landslide susceptibility, areas having 0.1-0.5 landslides per square kilometer were mapped as having moderate susceptibility, and areas having more than 0.5 landslides per square kilometer were mapped as having high landslide susceptibility. Areas with hillslope angles of 5 degrees or less were not classified as they are considered too flat for significant landslide susceptibility. The result of this classification indicates that 34 percent of the municipality has high susceptibility to rainfall-triggered landsliding, 24 percent has moderate susceptibility, and 9 percent has low susceptibility. Approximately 34 percent of the municipality, mainly areas with slopes of 5 degrees or less and water bodies, was not classified.

Because of the uncertainties inherent in the susceptibility classification of extensive landscape areas as well as timing of landslide triggers, landslide susceptibility maps should be used with caution. The results of this study are valid for generalized planning and assessment purposes, but may be less useful at the site-specific scale where local geologic and geographic heterogeneities may occur. Construction in areas of moderate to high landslide susceptibility should proceed only after site evaluation by engineering geologists. Large magnitude earthquakes, which occur rarely in Puerto Rico, are the other major trigger of landslides for Caribbean islands; however, this factor was not considered in the development of this map.

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Introduction

The worst landslide disaster in the history of the United States, in terms of lives lost, occurred at Barrio Mameyes, Ponce, in October 1985, when at least 129 people were killed (Jibson, 1989). This and more recent damaging rainfall-induced landslides have drawn public and government attention to the recurring problem of landslide hazards in Puerto Rico (Larsen and Torres, 1996; Larsen, 1997). The mountainous topography of the island, in combination with a humid climate, frequent intense rainfall, and high population density result in widespread landslide hazards for people and structures located on or near steep slopes (Turner and Schuster, 1996). Earthquakes also periodically cause landsliding in Puerto Rico (Reid and Taber, 1919), and are likely to cause landslides in many of the same areas that are susceptible to rainfall-triggered landslides. However, rainstorms capable of triggering tens's to hundred's of landslides in the central mountains of Puerto Rico are relatively common. For example, storms of this magnitude occurred an average of 1.2 times per year between 1959 and 1991 (Larsen and Simon, 1993). A rainfall threshold published by Larsen and Simon (1993) provides a method for estimating of the accumulation and duration of rainfall likely to trigger landslides in the central mountains. On average, the number of rainfall-triggered landslides increases substantially at a rainfall accumulation of 200 millimeters (mm) or more in a 24-hour period. This threshold indicates when landslides are likely to occur, but not where. Debris flows, the most common type of landslide in Puerto Rico, are recurrent phenomena. Preliminary carbon-14 dating by Jibson (1989) of old debris-flow deposits in the Ponce area indicates that recurrence intervals for debris flows at a given site may range from several decades to several centuries. Without good planning tools and maps delineating landslide-prone areas, the people of Ponce are subject to risks to life and damage to property from landslide hazards.

Purpose and Scope

A map showing susceptibility to rainfall-induced landslides is a useful tool for planning and development in Ponce (plate 1). Prior to publication of the map described herein, the only map showing landslide susceptibility in the Ponce area has been a map covering the entire island of Puerto Rico (Monroe, 1979). This 1979 map, published at a scale of 1:240,000, designates most of Ponce with low to moderate landslide susceptibility, but is too generalized for use at local scale by planners and civil-defense officials (fig. 1). Accordingly, a landslide susceptibility map was developed at 1:30,000 scale in cooperation with the Ponce municipal government to provide a means for land-use managers to interpret susceptibility to rainfall-triggered landslides in their effort to develop the municipality in a sustainable manner. The map shows all areas with hillslopes greater than 5 degrees according to an estimated high, medium, or low susceptibility to the initiation of rainfall-triggered landslides.

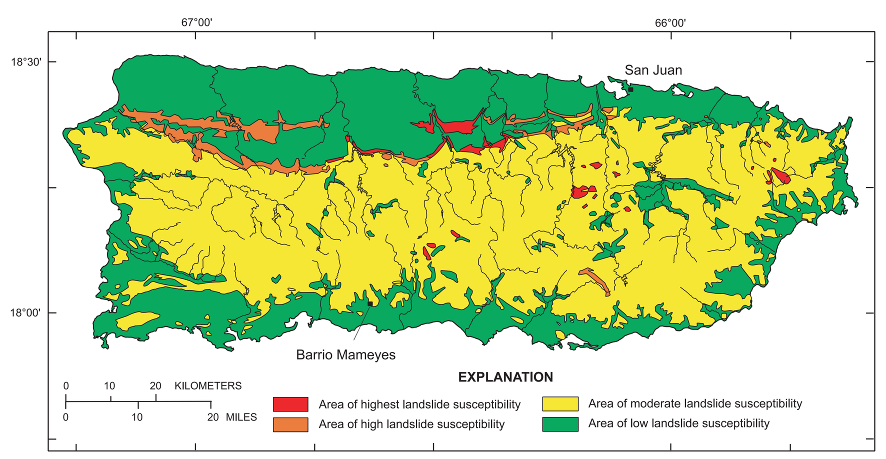

Figure 1. Map showing landslides susceptibility in Puerto Rico (simplifed from Monroe, 1979).

Methods

Landslide susceptibility in the municipality of Ponce was categorized using a combination of factors that includes landslide locations (from the October 1985 storm) and associated bedrock geology and hillslope angle (Varnes, 1978; Wieczorek, 1984, 1996). Landslides, mainly debris flows, were mapped by Jibson (1989) in the Ponce area in 1985 using field and aerial photographic techniques. The landslides occurred during or immediately following heavy rainfall associated with Tropical Storm Isabel, which devastated the southern region of Puerto Rico on October 5-8, 1985. Using Jibson's (1989) landslide locations, which were mapped on 1:20,000-scale topographic quadrangles, the U.S. Geological Survey (USGS) delineated 560 landslide initiation points on a digital map covering a 361.4 square kilometer (km^2) area in and around the municipality of Ponce (fig. 2). Although this landslide data set is large (560 points), it is derived from a single storm rather than a large number of storms where average conditions would prevail. As such, unique factors associated with the October 1985 storm, for example, spatial factors such as the location of an intense rain cell or local heterogeneities in bedrock and regolith, can affect the distribution of landslide locations and therefore the overall accuracy of the susceptibility map.

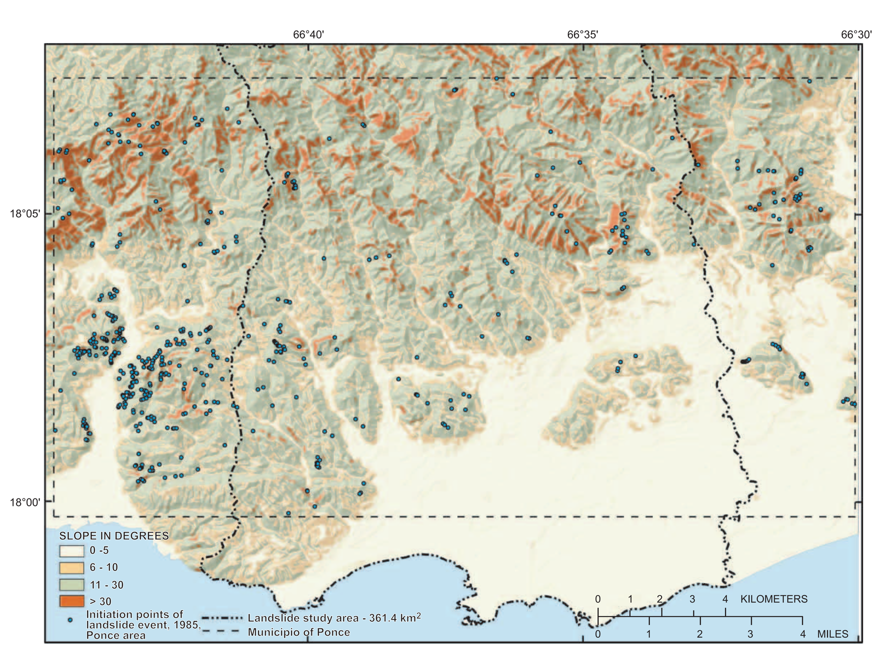

Figure 2. Map of Ponce study area showing location of 560 landslide triggered by rainfall associated with the Tropical Storm Isabel, October, 1985.

Using geographic information system (GIS) software, the location of each of the 560 landslide initiation points was compared to bedrock geology and hillslope angle. Bedrock geology was determined using a digital geologic map of Puerto Rico published by Bawiec (2001) (table 1). Hillslope angle was estimated from a 30-meter (m) digital elevation model (DEM) developed by the USGS for the island of Puerto Rico with GIS (table 2). To analyze the combined effect of bedrock geology and hillslope angle on landslide occurrence, the digital map of the 560 landslide initiation points was digitally overlaid (intersected) with the geologic map and DEM to calculate the bedrock type and hillslope angle for each landslide point.

Table 1. Landslide frequency and bedrock types in the Ponce area, Puerto Rico.

[Group A has low susceptibility, group B has moderate susceptibility, and group C has high susceptibility. ** These formations or bedrock types do not exist in the Ponce study area but occur within the municipality of Ponce. The determination of landslide susceptibilty for each is explained in the text of the report.]

Name of formation or bedrock type	Geologic formation code	Area underlain by formation, square kilometers	Percent of study area	Number of landslides	Percent of landslides	Landslides per square kilometer	Landslide susceptibilty group
Cotui Limestone	Kcot	0.5	0.1	4	0.7	8.0	C
Juana Diaz Formation	Tjd	62	17	321	57	5.1	C
Augite-hornblende porphyry	TKahp	0.6	0.2	2	0.4	3.2	C
Anon-Monserrate Formations, undivided	TKamo	2	0.6	6	1	3.0	C
Ponce Limestone	Tpo	21	6	54	10	2.6	C
Guayo Formation	Tg	4	1	6	1	1.6	C
Yauco Formation	TKy	43	12	66	12	1.5	C
Monserrate Formation	Tm	43	12	50	9	1.2	C
Lago Garzas Formation	TKl	34	9	29	5	0.9	C
Amygdaloidal dacite	TKda	11	3	6	1	0.5	C
Lago Garzas and Yauco Formations, undivided	TKly	18	5	8	1	0.4	B
Anon Formation	TKa	8	2	3	0.5	0.4	B
Maravillas Formation	Kmar	3	1	1	0.2	0.3	B
Augite andesite porphyry	TKap	5	1	1	0.2	0.2	B
Robles Formation **	Kr						B
Alluvium	Qa	93	26	3	0.03	0.1	A
Coamo Formation	Kcoa	4	1	0	-	-	A
Quartz diorite-granodiorite	TKqd	2	0.7	0	-	-	A
Porphyritic dacite	Td	2	0.5	0	-	-	A
Anon Formations and Lago Garzas, undivided	TKal	2	0.5	0	-	-	A
Unclass	unclass	0.8	0.2	0	-	-	A
Hornblende dacite	TKhda	0.6	0.2	0	-	-	A
Cuevas Limestone	Tc	0.5	0.1	0	-	-	A
Landslide deposits	Ql	0.4	0.1	0	-	-	A
Fault breccia	Tfb	0.4	0.1	0	-	-	A
Swamp deposits	Qs	0.2	0.1	0	-	-	A
Cotorra Tuff	Kctt	0.1	0.0	0	-	-	A
Achiote Conglomerate	Kac	0.1	0.0	0	-	-	A
Hornblende quartz diorite porphyry	Thp	0.04	0.0	0	-	-	A
Augite trachybasalt	TKat	0.03	0.0	0	-	-	A
Maricao Formation	TKm	0.00	0.0	0	-	-	A
Jayuya Tuff **	Kja						A
Granodiorite-quartz diorite and Hornblende quartz-diorite porphyry **	Tkh, Ku						A
Artificial Fill, Beach deposits **	Af, Qb						A
Total		**361**		**560**			

Landslide frequency (number of landslides per square kilometer) was categorized across the classes of hillslope angles and types of bedrock geology represented in the Ponce study area by separating the values of landslide frequency into three continuous groupings from lowest to highest frequency across the range of values that were calculated using GIS. This simplification into three groupings was necessary, because a total of 29 geologic units are present in the Ponce study area (tables 1, 2). Additionally, 10 categories of hillslope angle were used to analyze the relation between landslide frequency and slope. Rock units having more than 0.5 landslides per square kilometer (average of 3 landslides per square kilometer) were classified as having high susceptibility to landslides. Rock types having 0.1-0.5 landslides per square kilometer (average of 0.4 landslides per square kilometer) were classified as having moderate susceptibility to landslides, and areas having less than 0.1 landslides per square kilometer were classified as having low susceptibility to landslides.

Table 2. Landslide frequency (landslides per square kilometer) and hillslope angle, Ponce area, Puerto Rico.

[>, more than; km^2, square kilometer]

Slope angle, degrees	Number of landslides	Percentage of landslides	Area, km^2	Percentage of study area	Landslides per km^2
0-5	8	1.4	112	31	0.1
6-10	38	6.8	46	13	0.8
11-15	90	16.0	49	14	1.8
16-20	87	15.5	50	14	1.7
21-25	110	19.6	44	12	2.5
26-30	92	16.4	33	9	2.8
31-35	74	13.2	18	5	4.1
36-40	46	8.2	6	2	7.3
41-45	13	2.3	1	0.4	9.3
>45	2	0.4	0.3	0.1	7.6
	560		361.4		

Average landslide frequency calculated using only slope angle resulted in a range between 0.1 and 9.3 landslides per square kilometer, using 10 groupings. Slope angle categories were simplified from 10 groups into 3, based on the range of landslide frequency (tables 1, 3). Areas with slopes of 6-10 degrees had relatively low landslide frequency, less than one landslide per square kilometer. Areas with slopes of 11-30 degrees had moderate landslide frequency, more than one but less than four landslides per square kilometer, and areas with slopes of 30 degrees or more had high landslide frequency, greater than four landslides per square kilometer. Areas with slopes of 5 degrees or less were not included in the simplified analysis, because they are considered too flat for significant landslide susceptibility. The combination of rock type and hillslope angle were then ranked into high, moderate, and low susceptibility, according to the relative influence of slope angle on bedrock geology. Because the geologic units are exposed across a range of hillslope angles, their susceptibility to landslide varies with the degree of slope. Rock types that are prone to failure on steep slopes may be less so on low-gradient hillslopes (table 3). The distribution of high, moderate, and low landslide susceptibility used to classify the municipality of Ponce was based on classification shown in table 3.

Table 3. Landslide susceptibility of geologic groups in relation to hillslope angle, based on landslide frequency data shown in tables 1 and 2.

[>, more than. Areas with hillslope angles of 5 degrees of less were not rated.]

Geologic group	Landslide susceptibility, by combination of hillslope angle and geologic group		
	Hillslope angle, degrees		
	6-10	11-30	>30
A	Low	Low	Moderate
B	Low	Moderate	High
C	Moderate	High	High

Sites where debris flows are likely, such as pre-existing gullies (ephemeral streamflow channels) and areas directly downslope from likely debris-flow tracks, are areas of high landslide hazard. Debris flows are slurries of soil, rock, and water that can move rapidly downslope (Cruden and Varnes, 1996). Because of the high velocity of debris flows, the runout zones on flatter surfaces at the base of slopes prone to debris flows are at great risk (Campbell, 1975). The locations of potential debris flow tracks are too numerous to be shown on the landslide susceptibility map, however, all ephemeral channels and hillslope gullies may be affected by debris flows.

Over time scales of centuries to millennia, debris flows form fans at the bases of hillslopes, known as debris fans. These fans typically widen where debris flows emerge from steep, narrow canyons at the hillslope base onto broader areas where slopes are flatter. Because the fans have relatively low gradients and are generally higher in elevation than downstream flood plains, they are commonly used for building homes and businesses. However, structures on debris fans are at risk from episodic damage from debris flows. Identification of debris fans was beyond the scope of this study, but in general, debris-fan locations can be identified wherever ephemeral channels and gullies intersect low-gradient surfaces.

In many areas, the angle of inclination of the bedrock layers (dip angle) is an important geologic characteristic for assessing landslide hazard. Where the bedrock dip angle is roughly parallel to the slope surface, the hillslope is known as a dip slope. Dip slopes may be particularly unstable, with the most tragic example being the Mameyes landslide of 1985, which occurred on a dip slope. In the municipality of Ponce, localized small rock falls may be the most common landslide hazard that occur on these slopes, but larger failures such as rock slides, debris slides, and earth slides may also be possible at such sites. Dip-slope locations were determined using USGS 1:20,000 scale geologic maps (Bawiec, 2001). Dip slopes are shown on the landslide susceptibility map where the dip angle and slope angle are within 10 degrees of each other. These locations are shown on the landslide susceptibility map and highlighted because slope failure potential may be enhanced by the presence of dip slopes.

The effect of roads on landslide susceptibility was studied by Larsen and Parks (1997). The investigation was conducted in forested sections of the Luquillo mountains—located in eastern Puerto Rico, across a broad range of elevation and aspect conditions and where hillslope angles were equal to or greater than 4 degrees. In general, at distances of up to 85 meters (m) from either side of roads, landslide frequency, which is defined as the number of landslides per square kilometer of land surface, was 5 to 8 times higher than that in forested areas without roads. Although not shown on this map of Ponce, this 85-m distance may be an appropriate estimate of a zone of increased landslide susceptibility along road corridors in the municipality. Road construction and maintenance in mountainous terrain can keep a highway corridor in a constant state of dynamic instability. For example, each time road crews clear landslide debris, they create potential instabilities on the upslope side of the road by undercutting steep slopes and on the downslope side of the road by overloading the hillslope with cleared landslide debris.

Results

According to Jibson (1989, 1992), the distribution of landslides associated with the 1985 storm indicates that bedrock geology, slope, and intense rainfall were the most important factors controlling landslide locations. In general, landslide susceptibility is proportional to hillslope angle (table 2). Landslide frequency increased in proportion to slope angle, with the highest frequency (9.3 landslides per square kilometer) on hillslopes of 41 to 45 degrees. The landslide frequency decreased on slopes greater than 45 degrees, presumably because slopes this steep have limited soil development and consequently little material available for failure during storms, and because there were few hillslopes with such steep angles. A large number of landslides occurred on the west side of the study area. Because hillslope angles are not consistently high in this region, this may result from a combination of two additional factors: bedrock geology and storm rainfall concentration.

Spatial analysis of the location of the 560 landslide initiation points indicates that four bedrock types were most likely to fail. These four rock types account for 47 percent of the Ponce study area and contain 87 percent of the landslide initiation points (table 1). The majority (321, or 57 percent) of landslide points appear in an area underlain by a single rock type, the Juana Díaz Formation, a conglomerate composed of clayey chalk and chalky limestone (table 1). The second largest group (66, or 12 percent) of landslides, occurred in areas underlain by the Yauco Formation, a rock type that is predominately siltstone and claystone. Two other rock types, the Ponce Limestone, which has clay interbeds that contribute to failure, and the Monserrate Formation, which is siltstone and sandstone with tuff and conglomerate, accounted for an additional 104 landslides (19 percent). Using the combination of the 560 landslide initiation points, bedrock geology, and hillslope angle, approximately 34 percent of the surface area of the Ponce municipality was classified as having high landslide susceptibility. Areas of moderate landslide susceptibility constituted approximately 24 percent of the municipality and about 9 percent was determined to have low landslide susceptibility. Areas not classified, mainly areas with slopes of 5 degrees or less, and water bodies, constituted 34 percent of the municipality.

Spatial analysis of published bedrock dip angles in conjunction with hillslope angle indicates that there are only nine sites with dip slopes, as defined above. These are locations where the possibility of hillslope failures such as rock falls, rock slides, debris slides, and earth slides may be enhanced. There is a total of 986 km of roads in the municipality. The 170-m-wide zone of high landslide susceptibility that may be associated with these highways on hillslopes greater than 5 degrees corresponds to an area of 49 km^2, representing about 16 percent of the municipality. Although the area of the municipality in which landsliding may be associated with highway corridors is substantial, most landslides associated with roadcuts and fill sections are relatively small and loss of life has been historically rare (Jibson, 1989; Larsen and Torres-Sánchez, 1998).

Determination of the frequency with which debris flows are likely to recur along debris flow tracks was beyond the scope of this study. According to Larsen and Simon (1993), however, rainstorms capable of triggering ten's to hundred's of landslides in the central mountains of Puerto Rico occurred an average of 1.2 times per year between 1959 and 1991. This suggests that during the life span of residents, there is a strong potential for structural damage and loss of life in the areas of (or downslope from) the municipality of Ponce mapped as highly susceptible to landslides.

Summary

Most (58 percent) of the Ponce municipality is moderately to highly susceptible to landslide activity. These are areas where the possibility of landsliding increases when triggering conditions such as heavy rainfall or excavation and construction occur. Large magnitude earthquakes, which occur with low frequency in Puerto Rico, are the other major trigger for Caribbean islands and are likely to cause landslides in many of the same areas that are susceptible to rainfall-triggered landslides.

Because of the uncertainties inherent in the susceptibility classification of extensive landscape areas as well as timing of landslide triggers, landslide susceptibility maps should be used with caution. The results of this study are valid for generalized planning and assessment purposes, but may be less useful at the site-specific scale where local geologic and geographic heterogeneities may prevail. Construction in areas of moderate to high landslide susceptibility should proceed only after site evaluation by engineering geologists.

The location of homes and businesses in or near debris flow tracks (commonly ephemeral channels and hillslope gullies) and on debris fans in the municipality of Ponce is of particular concern. Because rainstorms capable of triggering ten's to hundred's of landslides in the central mountains of Puerto Rico occur each year, there is a strong potential for structural damage and loss of life in these zones during the lifetime of residents. Finally, in areas mapped as moderately or highly susceptible to landslides, residents, municipal planners, and civil defense personnel should be vigilant for signs of landslide activity during construction, excavation, and periods of heavy or prolonged rainfall.

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