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MAP SHOWING LANDSLIDE SUSCEPTIBILITY
IN THE COMERÍO MUNICIPALITY, PUERTO RICO
By Matthew C. Larsen and John E. Parks

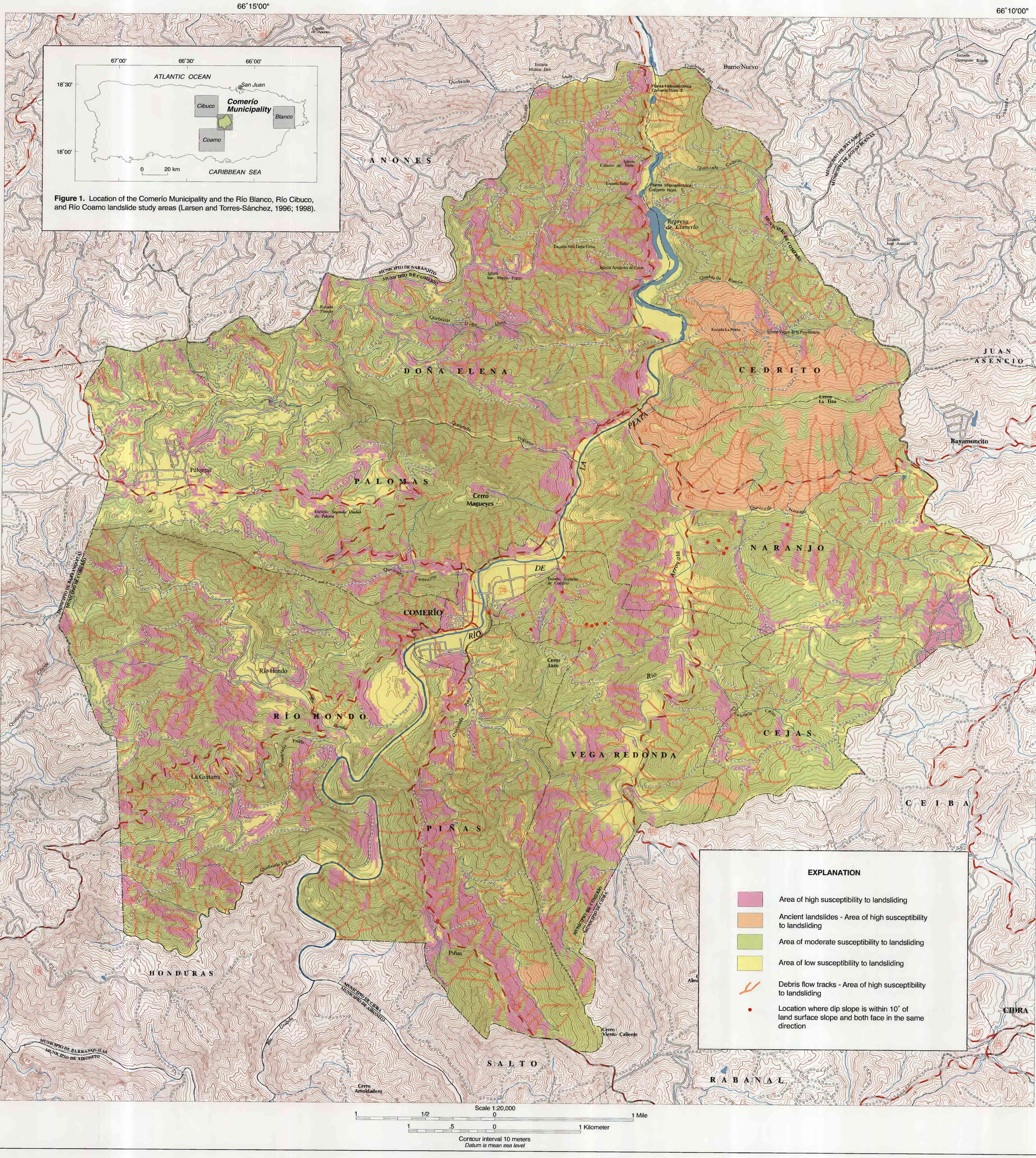

Figure 1. Location of the Comerío Municipality and the Río Blanco, Río Cibuco, and Río Coamo landslide study areas (Larsen and Torres-Sánchez, 1996; 1998).

ABSTRACT

In Puerto Rico, the combination of mountainous terrain and frequent intense rainstorms results in a landscape where landslide features are commonplace. The risk of landslides occurring during intense or prolonged rainfall is high in steeply-sloping interior municipalities such as Comerío, where 77 percent of the 74-square-kilometer municipality has slopes of 21 percent (12°) or more. A set of simplified matrices representing geographic conditions was developed from earlier studies in three other regions of the central mountains of Puerto Rico and provides a basis for the estimation of the spatial controls on the frequency of rainfall-triggered landslides. Four geographic characteristics were used to categorize hillslope types: elevation, slope, aspect, and land use. The frequency of landslides is higher in the wetter regions of the island, or generally at elevations greater than 300 meters. In general, hillslopes with a slope angle of 12 percent (7°) or less have a relatively low landslide frequency. A slope angle in excess of 21 percent (12°) is a threshold above which the frequency of landslides is relatively high. In Puerto Rico, slope aspect is also relevant because hillslopes that generally face the prevailing winds, which deliver much of the rainfall to the island, have the highest frequency of landslides. Conversely, hillslopes facing away from the prevailing winds have the lowest frequency of landslides in the study areas. Hillslopes in the remaining quadrants generally have an intermediate landslide frequency. The greatest variation in the frequency of landslides exists among land use categories. A map showing landslide susceptibility in the Comerío municipality was developed by dividing the municipality into generalized regions of low, moderate, and high landslide susceptibility. These susceptibility zones were amended by including additional areas defined by the locations of ancient landslide deposits taken from geologic maps and recent and historic debris-flow tracks and runout zones.

INTRODUCTION

The combination of mountainous terrain and frequent intense rainstorms in Puerto Rico results in abundant rainfall-triggered landslides (Jibson, 1989; Larsen and Torres-Sánchez, 1998). Although earthquakes periodically cause landsliding in Puerto Rico, rainstorms capable of triggering 10's to 100's of landslides in the central mountains of Puerto Rico occurred an average of 1.2 times per year between 1959 and 1991 (Reid and Taber, 1919; Larsen and Simon, 1993). In 1985, a hillslope in Barrio Mameyes, Ponce, saturated by heavy rainfall, failed and resulted in the worst landslide disaster—in terms of loss of life—in the history of the United States (Jibson, 1989). Rockfalls along highway 167 near Comerío have destroyed cars and killed drivers (Monroe, 1979).

In the 74-square-kilometer municipality of Comerío, located in the east-central mountains of Puerto Rico, the risk of landslides occurring during intense or prolonged rainfall is high because steep slopes are common in this region—77 percent of the municipality has slopes of 21 percent (12°) or more. A map published by Monroe (1979) shows most of the municipality of Comerío as being moderately susceptible to landslides. However, because the Monroe map was published at 1:240,000 scale, it lacks local detail. Accordingly, the U.S. Geological Survey (USGS), in cooperation with the Comerío municipal government, prepared a landslide susceptibility map at 1:20,000 scale. This map provides a means for land-use managers to interpret susceptibility to rainfall-triggered landslides in their effort to develop the municipality in a sustainable manner.

METHODS

A rainfall threshold published by Larsen and Simon (1993) provides a method for estimation 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 or more in a 24-hour period. This relation between rainfall and landsliding was expanded by Larsen and Torres-Sánchez (1996; 1998) by evaluating which hillslope types are prone to failure. This methodology is summarized below and was used to create the map showing landslide susceptibility in the municipality of Comerío. More detail on the procedures used can be found in the Larsen and Torres-Sánchez reports.

Geographic controls of land use and topography were evaluated in three study areas (areas in and near the Río Blanco, Río Cibuco, and Río Coamo watersheds shown in fig. 1) representing about 10 percent of the land surface of Puerto Rico (Larsen and Torres-Sánchez, 1996; 1998). Maps of recent landslides were developed from 1:20,000-scale aerial photographs and were used to evaluate the frequency and distribution of shallow, rainfall-triggered landslides—the most common type of hillslope failure in Puerto Rico. A set of simplified matrices representing geographic conditions in the three study areas was developed and provides a basis for the estimation of the spatial controls on the frequency of landslides in Puerto Rico (table 1).

Table 1. Classification of land surface types for determination of mapping of landslide susceptibility in the municipality of Comerío, Puerto Rico
[Each set of topographic characteristics and land use combine to determine the degree of landslide susceptibility.]

Topographic characteristic			Landslide susceptibility 1=low, 2=moderate, 3=high		
			Land use		
Elevation	Slope angle	Aspect	Forest	Agriculture	Developed
all	gentle	all	1	1	1
low	moderate	lee	1	1	1
low	moderate	normal	1	1	1
low	moderate	facing	1	1	2
low	steep	lee	1	2	2
low	steep	normal	2	2	3
low	steep	facing	2	3	3
high	moderate	lee	2	2	2
high	moderate	normal	2	2	3
high	moderate	facing	2	2	3
high	steep	lee	2	2	3
high	steep	normal	2	2	3
high	steep	facing	2	3	3

Note: Low elevations are less than or equal to 300 meters; high elevations are those greater than 300 meters. Gentle slopes are 7° or less; moderate slopes are greater than 7° but less than 12°; and steep slopes equal or exceed 12°. Hillslopes with facing aspect are those that face prevailing winds (between 22.5° and 112.5°); lee aspect hillslopes face opposite to prevailing winds (between 202.5° and 292.5°); hillslopes not within these two groups are classified as normal aspect hillslopes.

The matrices used four geographic characteristics to categorize hillslope types: elevation, slope angle, aspect, and land use. The frequency of landslides was higher at elevations greater than 300 meters (where greater mean annual rainfall is recorded than at lower elevations). In general, hillslopes with a slope angle of 12 percent (7°) or less have a relatively low landslide frequency (Larsen and Torres-Sánchez, 1996; 1998). A slope angle in excess of 21 percent (12°) was a threshold above which the frequency of landslides was relatively high. Slope aspect is most relevant in relation to prevailing winds and resulting rainfall and soil moisture conditions. Hillslopes in the Río Blanco, Río Cibuco, and Río Coamo study areas generally had the highest frequency of landslides on hillslopes which face the prevailing winds (between 22.5° and 112.5°), which deliver much of the rainfall to the island. Conversely, hillslopes facing away from the prevailing winds (between 202.5° and 292.5°) had the lowest frequency of landslides in the study areas. Hillslopes in the remaining quadrants (between 112.5° and 202.5°, between 292.5° and 360°, and between 0° and 22.5°) had intermediate landslide frequency. The greatest variation in the frequency of landslides exists between land-use categories. Landslide frequency on hillslopes modified for roads or structures is 2 to 8 times higher than landslide frequency on hillslopes in forested land use. The topographic factors of elevation, hillslope gradient, and aspect are almost as important as land use. The ratio calculated between high and low categories of hillslope gradient and elevation, and for hillslopes categorized into those facing and those not facing prevailing winds ranged from 1.3:1 to 7.5:1 (Larsen and Torres-Sánchez, 1998).

Using the approach described above, a map showing landslide susceptibility in the Comerío municipality was developed. Topography was categorized for hillslope elevation, hillslope gradient, and hillslope aspect using 30-meter digital elevation models developed by the USGS for the island of Puerto Rico with a geographic information system (ESRI, 1993). Digital land use maps derived from unpublished maps available through the Puerto Rico Department of Natural and Environmental Resources were simplified into the land use types listed in table 1. The municipality then was divided into generalized regions of low, moderate, and high landslide susceptibility, according to the classification shown in table 1.

Areas of low landslide susceptibility may have one landslide or less per square kilometer per decade. Areas of moderate susceptibility may have one to three landslides per square kilometer per decade, and areas of high susceptibility may have more than three landslides per square kilometer per decade. These susceptibility zones were amended by including additional areas defined by the locations of ancient landslide deposits mapped by Pease and Briggs (1960), Briggs and Gelabert (1962), and Pease (1968) and recent and historic debris-flow tracks and runout zones mapped from digital topographic maps and 1:20,000-scale aerial photographs taken in 1995.

Debris flows are rapid mass movements that move as a slurry of soil, rock, and water (Varnes, 1978; Cruden and Varnes, 1996). Movement commonly initiates along ephemeral stream channels or other slope concavities during intense rainfall when soil and regolith are saturated. Because of the high velocity of debris flows, both the hillslope part and runout zones on low gradient surfaces at the base of hillslopes prone to debris flows are at great risk (Campbell, 1975). Debris-flow tracks were mapped in the municipality of Comerío from aerial photographs and from digital topographic maps (Wieczorek, 1984; Larsen and Torres-Sánchez, 1998). The runout zones were mapped by extending the debris-flow paths to the first intersection with a perennial stream channel. Field checking of debris-flow tracks verified the location and approximate lengths determined from the aerial photographs. Debris-flow tracks and areas directly downslope of the scars were designated as areas of high landslide susceptibility. An average width of 10 meters was assigned to all debris-flow tracks, based on the mean width of 2,198 debris flows that were measured in studies elsewhere in Puerto Rico by Larsen (1997) and Larsen and Torres-Sánchez (1998). The width of a debris-flow front typically widens where debris flows emerge from steep, narrow canyons at the hillslope base onto broader areas where slopes are gentler. This increases the potential impact area beyond the 10-meter width shown on the map. Determination and mapping of the potential width of each debris-flow track, where it reaches the valley floor, was beyond the scope of this study. However, structures within 10's of meters of the axis of the debris-flow track, where it reaches the valley floor, are considered to be in a high landslide susceptibility zone.

Pease and Briggs (1960), Briggs and Gelabert (1962), and Pease (1968) mapped several forms of ancient landslide deposits in extensive areas of the municipality of Comerío. Detailed description of the ancient landslide deposits can be found in these reports. In addition, the engineering characteristics of soils in the Barranquitas quadrangle, which includes part of the municipality of Comerío, are listed in Briggs and Gelabert (1962). All of the ancient landslide deposits were designated as high landslide susceptibility zones in the present map. The location of the ancient landslide deposits indicates that local geologic controls (such as the type of bedrock and type and thickness of residuum) are more important than topographic influences in some areas. Except for the use of dip angle data, discussed below, the assessment of local geologic controls on landslide susceptibility was beyond the scope of this study.

The dip angle of a bedrock structural or bedding surface, defined as the inclination of a planar surface, is a geologic characteristic that is important to consider in some locations. When the dip angle is parallel or nearly parallel to the land surface and faces in the same direction downslope on hillslopes where bedrock is exposed at or near the surface, the hillslope is known as a dip slope. These slopes may be unstable, and in the municipality of Comerío, localized small rockfalls are possibly the most common landslide hazard that results. However, translational failures such as rock slides, debris slides, and earth slides are also possible at these sites. Pease and Briggs (1960) mapped dip angle at 894 locations in the Comerío quadrangle. Dip slopes are shown on the map only if the dip angle and slope angle where within 10° of each other. These locations are shown on the landslide susceptibility map and are highlighted because slope failure potential is 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°. In general, at distances of up to 85 meters from either side of roads, landslide frequency was 5 to 8 times higher than that in forested areas without roads. Although not shown on this map of Comerío, this 85-meter distance may be an appropriate estimate of a zone of increased landslide susceptibility along road corridors in the municipality.

The classification of landscapes for degree of landslide susceptibility as shown on this map must be considered an approximation, because of the complexity of slope processes and the variety of factors affecting slope stability. Landslides can have many causes, which include geological, hydrological, and human factors (Wieczorek, 1996). The methods used in the 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.

RESULTS

Approximately 60 percent of the surface area of the Comerío municipality was classified as having moderate landslide susceptibility. Areas of high landslide susceptibility constituted approximately 27 percent of the municipality, and about 12 percent was determined to have low landslide susceptibility. Areas not classified, mainly water bodies, constituted 1 percent of the municipality.

Debris-flow tracks. A total of 695 debris-flow tracks were mapped. Their median length was 329 meters: lengths ranged from 79 to 1,365 meters. The total length was 258,000 meters, which using the average width of 10 meters, represents a surface area of 2.6 square kilometers or about 4 percent of the surface area of the municipality. In many locations, homes and businesses are situated in or at the mouth of the debris-flow tracks (a typical example is located on the south side of Cerro Magueyes, where several debris-flow tracks cross highway 156 and reach the Río de la Plata). Determination of the frequency with which debris flows are likely to recur along each mapped debris-flow track was beyond the scope of this study. According to Larsen and Simon (1993), however, rainstorms capable of triggering 10's to 100'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 lifespan of the occupants, there is a strong potential for structural damage and loss of life in the debris-flow zones in the municipality of Comerío.

Ancient landslides. Areas of ancient landslide deposits mapped by Pease and Briggs (1960), Briggs and Gelabert (1962), and Pease (1968) totaled 4.2 square kilometers or about 6 percent of the municipality. These deposits, such as those shown on Cerro La Tiza, may continue to be unstable because of the bedrock type and its structural characteristics. The surface areas of all debris-flow tracks and ancient landslide deposits were included in the 27 percent of the municipality classified as having high landslide susceptibility. This is an underestimate, because as discussed above, debris-flow tracks normally widen where they emerge onto valley floors.

Dip slopes. Dip slopes are sites where rockfalls, rock slides, debris slides, earthslides, or other translational movements are possible. A total of 21 dip slopes were indicated with red circles in the Comerío quadrangle. More dip slopes are likely to exist but these data were not available from published geologic maps of the area. An example location of dip slopes can be found in Barrio Naranjo, just west of highway 172.

Landslides associated with highways. There is a total of 95 kilometers of secondary and tertiary highways in the municipality. The 170-meter wide zone of high landslide susceptibility that may be associated with these highways on hillslopes of 4° or greater corresponds to an area of 12 square kilometers, representing about 16 percent of the municipality. Although the area of the municipality in which landslides may be associated with highway corridors is substantial, most landslides associated with roadcuts and fill sections are relatively small and loss of life has historically been rare (Jibson, 1989; Larsen and Torres-Sánchez, 1998).

CONCLUSIONS

Most of the Comerío municipality is moderately to highly susceptible to landslide activity. These are areas where the possibility of landslides 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. 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 at the mouth of the debris-flow tracks in the municipality of Comerío is of particular concern. Because rainstorms capable of triggering 10's to 100'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 debris-flow zones during the lifetime of occupants. Finally, in areas mapped as moderately or highly susceptible to landslides, residents, municipal planners, and civil defense personnel should be extremely vigilant for signs of landslide activity during construction, excavation, and periods of heavy or prolonged rainfall.

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Base map from Digital Line Graph data
U.S. Geological Survey, 1989
Supplemental road data from Puerto Rico
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