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The frequency and distribution of recent landslides in three montane tropical regions of Puerto Rico

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Abstract

Landslides are common in steep mountainous areas of Puerto Rico where mean annual rainfall and the frequency of intense storms are high. Each year, landslides cause extensive damage to property and occasionally result in loss of life. Average population density is high, 422 people/km^2, and is increasing. This increase in population density is accompanied by growing stress on the natural environment and physical infrastructure. As a result, human populations are more vulnerable to landslide hazards. The Blanco, Cibuco, and Coamo study areas range in surface area from 276 to 350 km^2 and represent the climatologic, geographic, and geologic conditions that typify Puerto Rico. Maps of recent landslides developed from 1:20,000-scale aerial photographs, in combination with a computerized geographic information system, were used to evaluate the frequency and distribution of shallow landslides in these areas. Several types of landslides were documented—rainfall-triggered debris flows, shallow soil slips, and slumps were most abundant. Hillslopes in the study area that have been anthropogenically modified, exceed 12° in gradient, are greater than 300 m in elevation, and face the east-northeast, are most prone to landsliding. 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. This approach is an example of an analysis of the frequency of landslides that is computationally simple, and therefore, may be easily transferable to other settings. © 1998 Elsevier Science B.V. All rights reserved.

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1. Introduction

Landslides are a common, natural mass-wasting phenomenon in mountainous areas throughout the world. The term landslide means the downward and outward movement of hillslope-forming materials—natural rock, soils, artificial fills or combinations of these materials (Schuster, 1978). Landslides can include falls, topples, slides, spreads, and flows (Varnes, 1978). Shallow landslides occur in material defined as engineering soils: unconsolidated, inorganic mineral, residual, or transported material (colluvium or alluvium), including rock fragments. Landslides are part of the process of hillslope erosion that is responsible for the introduction of sediment into streams, rivers, lakes, reservoirs, and finally the ocean. In populated areas landslides pose serious problems for public safety. Human-made structures on, or near hillslopes may be in jeopardy if

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geologic, hydrologic, and climatologic conditions are appropriate for landsliding.

Landslides are a recurrent problem throughout most of Puerto Rico. Various factors contribute to the occurrence of landslides. A major earthquake in 1918 caused many rockfalls and slumps along stream and river banks in western Puerto Rico, where the modified Mercalli scale of earthquake intensity (MMI) exceeded VII (Reid and Taber, 1919). Landsliding triggered by earthquakes may be the most significant type of major landslide hazard in Puerto Rico in the long term (Keefer, 1984). Hillslope modification for construction of highways and other structures, however, has also resulted in frequent landsliding (Dames and Moore, 1980; Molinelli, 1984). Landsliding along road corridors has caused major delays and increased costs for highway construction on the island (Sowers, 1971).

Rainfall-triggered landslides are the most common type of landslide, occurring throughout the central mountains and foothills of the island. Forty-one storms triggered abundant landslides about 1–2 imes per year during the last 3 decades (Larsen and Simon, 1993). In 1985, a tropical wave which later became Tropical Storm Isabel caused intense and prolonged rainfall that lasted 2 days in southern Puerto Rico. A hillslope in Barrio Mameyes, Ponce, saturated by this rainfall, failed and resulted in the worst landslide disaster in terms of loss of life in the history of the United States (Jibson, 1989). More than 120 people died as an entire hillside covered with homes slid downslope.

Storm rainfall from individual storms has triggered tens to hundreds of landslides in a wide variety of geographic settings in the central mountains of Puerto Rico. The intensity and duration of rainfall in these storms define the temporal characteristics of landslide occurrence (Larsen and Simon, 1993). The location of any particular storm likely to trigger numerous landslides, however, cannot be predicted. Geographic (spatial) factors must, therefore, be considered in estimating the likelihood of the occurrence of landslides for a given area. The frequency of landslides, as used herein, is the number of landslide scars per km^2 of surface area. No single geographic attribute (land use, slope angle, elevation, and aspect) adequately explains frequency or distribution of landslides. What is needed is a method by which geographic attributes can be integrated to determine where landslides are most likely to occur. A key assumption using this approach is that the potential frequency of landslides will be comparable to the actual (recent) frequency of landslides.

The Blanco, Cibuco, and Coamo study areas were selected to evaluate the frequency and distribution of landslides in Puerto Rico (Fig. 1). These areas, named for the principal river draining each region, vary in surface area from 276 to 350 km^2 and represent a broad range of the climatologic, geographic, and geologic conditions that occur in Puerto Rico. Landslide maps, developed from 1:20,000-scale aerial photographs, in combination with a computerized geographic information system (GIS), were used to determine where landslides were common and to devise a method assessing the frequency of landslides that could be used in other areas of Puerto Rico or elsewhere in the world. Because the method outlined herein is not computationally complex, it is an example of an approach that can be adopted for use in other settings.

1.1. Previous studies

Studies of the distribution of landslides include those of Simonett (1967), Garwood et al. (1979), Harp et al. (1981), Keefer (1984), and Jibson (1988) in which seismically triggered landslides were examined in relation to topographic and geologic variables. Haigh et al. (1988) and Carrara et al. (1991) related the distribution of landslides to land use practices, particularly highway construction and maintenance.

Previous studies of landsliding in Puerto Rico include work on mitigation and repair of areas damaged by landslides in the Blanco area (Dames and Moore, 1980). This work focused on possible remediation of the effects of several large debris avalanches that filled a small reservoir and severed a penstock in the Luquillo Experimental Forest (LEF). Landslide mechanisms and weathering of bedrock and saprolite in the LEF were examined in detail by Deere and Patton (1971). Landslide problems associated with highway construction in the LEF were studied by Sowers (1971) after construction of 4 km of mountain-top highway, Route 930, triggered dozens of small slumps and greatly increased the

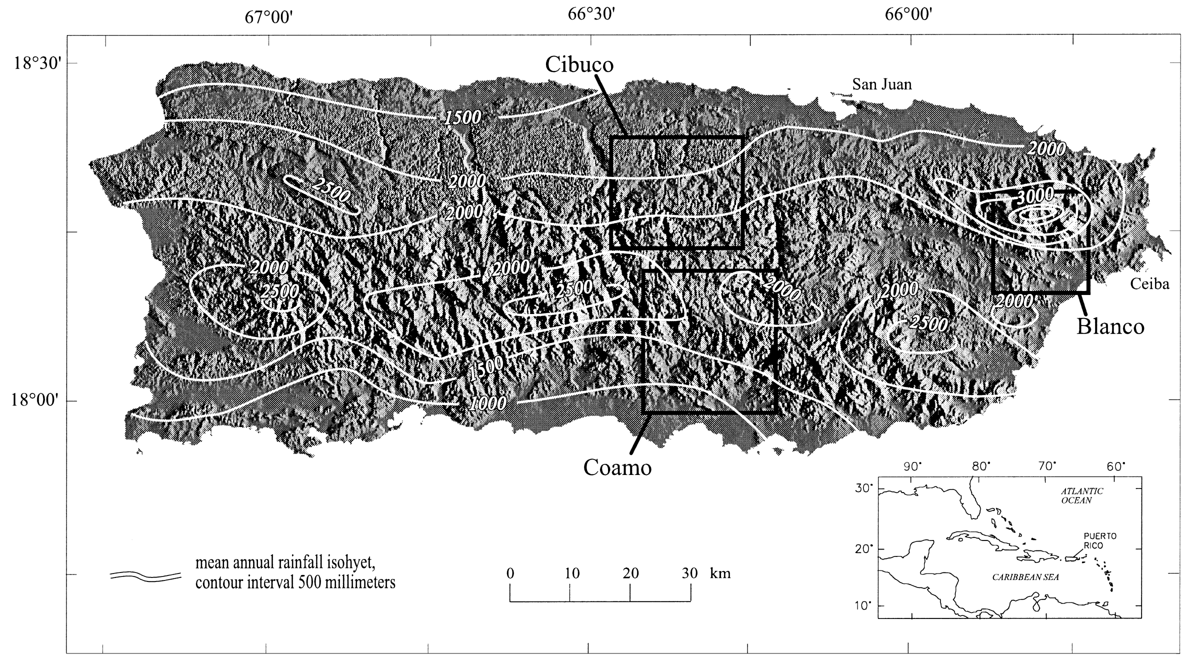

Fig. 1. Shaded relief map of Puerto Rico showing the location of the Blanco, Cibuco, and Coamo study areas, and mean annual rainfall isohyets. Rainfall data from Calvesbert (1970).

cost and time needed for completion of the road. Molinelli (1984) examined the impacts of landslides associated with the construction of a major trans-island highway, Route 52, constructed in the 1970s. Larsen and Parks (1997) determined that within 85 m on either side of roads in the Luquillo mountains, the rate of mass-wasting was 5–8 times higher than that in forested areas.

In 1989, the relatively fast moving Hurricane Hugo triggered more than 400 landslides in northeastern Puerto Rico (Scatena and Larsen, 1991; Larsen and Torres-Sánchez, 1992). The landslides were mainly shallow soil slips (Campbell, 1975) and debris flows that occurred during or shortly after a 6-h period of high intensity rainfall. A preliminary map of landslide locations in the LEF was prepared by Guariguata and Larsen (1990). Guariguata (1990) determined that forest regeneration required about 60 years after landslide disturbance in the uplands of the LEF.

A threshold of rainfall intensity–duration described the types of 41 storms that triggered recent landslides in the central mountains of Puerto Rico (Larsen and Simon, 1993). Based on data for 256 storms, a relation between rainfall accumulation–duration and landsliding was established. The relation, described by a line fitted visually to the lower boundary of those points representing storms that triggered landslides, is expressed as

$$I = 91.46 D^{-0.82} \tag{1}$$

where I is rainfall intensity in mm/h, and D is duration in hours. This line reflects the approximate minimal rainfall conditions necessary to trigger landsliding. Converting I to R, rainfall accumulation in mm is equal to:

$$R = 91.46 D^{0.18} \tag{2}$$

The exponent is relatively small so over the range of durations of the 41 storms known to have triggered landslides, only a 2.5-fold variation occurs in the rainfall threshold. The rainfall required ranges from 102 to 257 mm and the median storm is 193 mm (Larsen and Simon, 1993). None of the 41 storms that triggered landslides occurred during the dry-season months of February and March.

Deep bedrock weathering is common in most areas of the study areas, so that many hillslopes are covered with as much as 5–10 m of saprolite and soil (Deere and Patton, 1971; Simon et al., 1990). As has been shown in a number of humid-tropical settings, lithology is often of only marginal importance because of the geotechnical similarities among weathered bedrock types (Pitts, 1992). This degree of weathering may reduce the geotechnical effects of the original rock structure. In a study of physical mechanisms of landslide failure in saprolite in the LEF, St. John et al. (1969) concluded that relict joint surfaces in saprolite that weathered from intrusive bedrock may provide failure surfaces for shallow landslides when sufficient moisture is present.

In the Cibuco study area, and elsewhere along the north coast where limestone bedrock outcrops, large retrogressive landslides occurred during the Holocene (Monroe, 1964). These landslides, some of which are still active, are mapped along river valleys with steep cliffs of 50 to more than 200 m in height, and are composed of massive limestone blocks resting on marl or clay. The massive limestone was described as having high to highest susceptibility to landsliding and can be seen as rectilinear areas of high landslide susceptibility in Fig. 2 in northwestern Puerto Rico. According to Monroe (1964), these limestone blocks move slowly down slopes of 5–12° during rainy seasons when the underlying clay and marl layers are saturated.

In contrast, the rate of shallow, rainfall-triggered landsliding in the regions of the Cibuco area underlain by limestone is extremely low (Larsen and Torres-Sánchez, 1996). In the northern one half of this area, where karst haystack hills are a common landscape feature, soil is usually thin (less than 1 m) on the limestone slopes, and limits the amount of material available for mass wasting. Additionally, the high porosity of limestone in this humid environment generally precludes any significant increase in pore pressure during storms, because the rock is so well drained (Monroe, 1980).

Larsen and Torres-Sánchez (1996) noted that soils, mainly Ultisols and Inceptisols, that are mapped on steep slide slopes and ridgetops in the upland, wetter parts of the three study areas, have generally higher landslide frequencies than those soils mapped on flat-lying or low gradient hillslopes. These trends show the difficulty in separating soil classifications (as well as geologic map units) from topographic characteristics and areas of high mean annual rainfall when attempting to determine the major controls on

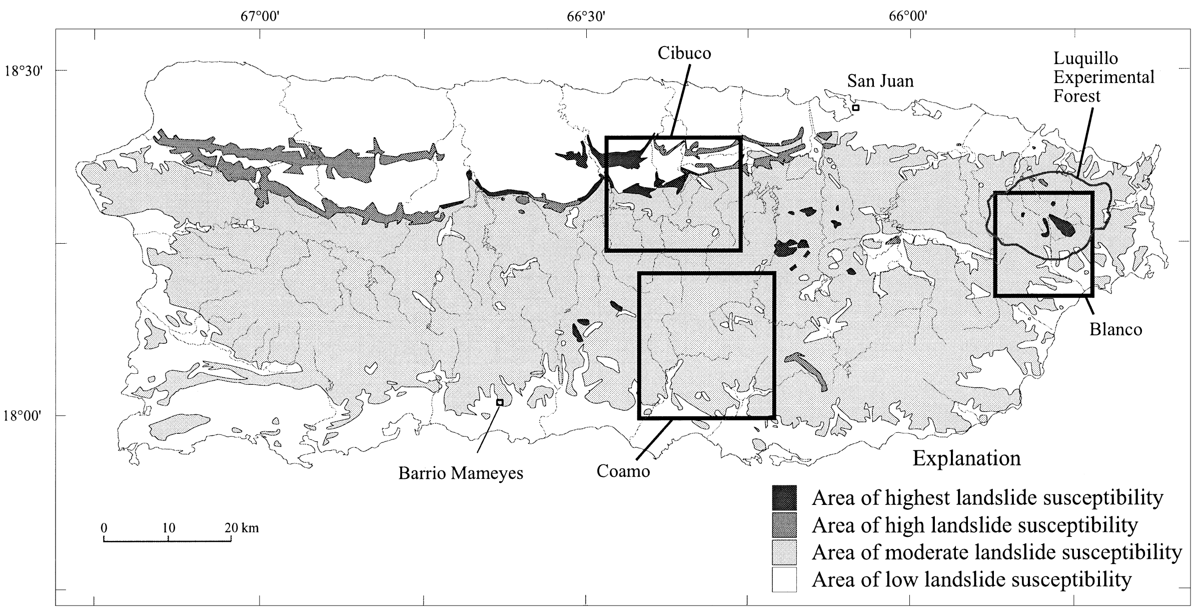

Fig. 2. Areas of susceptibility to landsliding in Puerto Rico (modified from Monroe, 1979).

the frequency of landslides. Topography and the characteristics of rain storms presented by Larsen and Simon (1993) may, therefore, provide most of the information needed to estimate where landslides are likely to be numerous in this environment of deeply weathered regolith.

A generalized map of landslide hazards developed at 1:240,000-scale by Monroe (1979), classified most of Puerto Rico as moderately susceptible to landsliding (Fig. 2). According to Monroe (1979), landslides are relatively common in a variety of rocks in Puerto Rico. Because of the 1:240,000-scale at which Monroe's map was published, much detail is lost and the usefulness of this type of map for planners or civil defense agencies is relatively low. For example, Barrio Mameyes, the site of the worst landslide disaster in the history of the United States, described above, is located in an area mapped only as moderately susceptible to landsliding (Fig. 2). More information is needed by the Commonwealth of Puerto Rico and local governments if hazardous areas are to be adequately delineated.

2. Setting and description of study areas

Puerto Rico, the smallest island of the Greater Antilles, is located about 1700 km southeast of Miami, FL. The island is in the trade-wind belt at the boundary between the Caribbean Sea and the Atlantic Ocean. Because of tectonically-controlled geologic complexity and strong orographic affects on the distribution of rainfall, a variety of land use, topographic, and soil characteristics exist in the relatively small (9000 km^2) area of Puerto Rico. Several major types of bedrock typical of island arc systems throughout the world, have been mapped in Puerto Rico (Donnelly, 1989). This degree of geographic and geologic variability required that at least three different study areas be selected for this study to represent conditions that are typical of the island.

2.1. Topography and land use

Puerto Rico is an island of high relief with a maximum elevation in the central mountain range of 1338 m. Topography is moderately steep to rugged and mountain slopes are dissected with perennial and ephemeral streams. The central mountain range is fringed by a relatively flat coastal plain 8–16 km wide. Gradual forest removal began in the 1600s as land was cleared for agriculture by European settlers. After 3 centuries of extensive agricultural land use, most (94%) of Puerto Rico had been deforested by the late 1940s (Picó, 1974; Birdsey and Weaver, 1987). A shift away from agriculture towards industry began in the 1950s and has resulted in much abandoned pasture and farmland. By 1985, total forest area had increased to 300,000 ha, or 34% of the total land area of the island.

The Blanco study area lies in eastern Puerto Rico and encompasses an area of 275 km^2 (Figs. 1 and 3). It has the greatest relief of the three study areas and rivers there drain to the south and east, into the Caribbean Sea. Elevation of the land surface ranges from sea level to 1074 m above mean sea level. Topography is rugged and stream channels are deeply incised. Much of the area falls within the boundaries of the LEF, an 11,300-ha preserve that is completely forested (Waide and Lugo, 1992). The Blanco study area is largely uninhabited except in the foothills and coastal plain. Land surrounding the LEF is used for small farms and pasture and has been extensively deforested. Human land use for most of the area has historically been limited because of extremely high annual rainfall (García-Montiel and Scatena, 1994). Since the arrival of Europeans, minor cutting of trees for charcoal and small subsistence farms have been the major land use. By the late 1800s much of the Blanco area had become a protected forest preserve, which later came under the jurisdiction of the U.S. Forest Service.

Topography in the 306-km^2 Cibuco study area is rolling to moderately rugged with elevations ranging from near sea level to 670 m. Rivers in the study area drain toward the north and empty into the Atlantic Ocean. Upland slopes are moderate to steep and covered with second growth forest, abandoned pasture, and farmland (Fig. 3). Two large towns, Morovis and Corozal, are in valley bottoms in the uplands. Conversion of forest to crop land was widespread in this area and is comparable to the description of the island-wide land use history noted above.

The Coamo study area covers 353 km^2 in south-central Puerto Rico, lies in an orographic rain

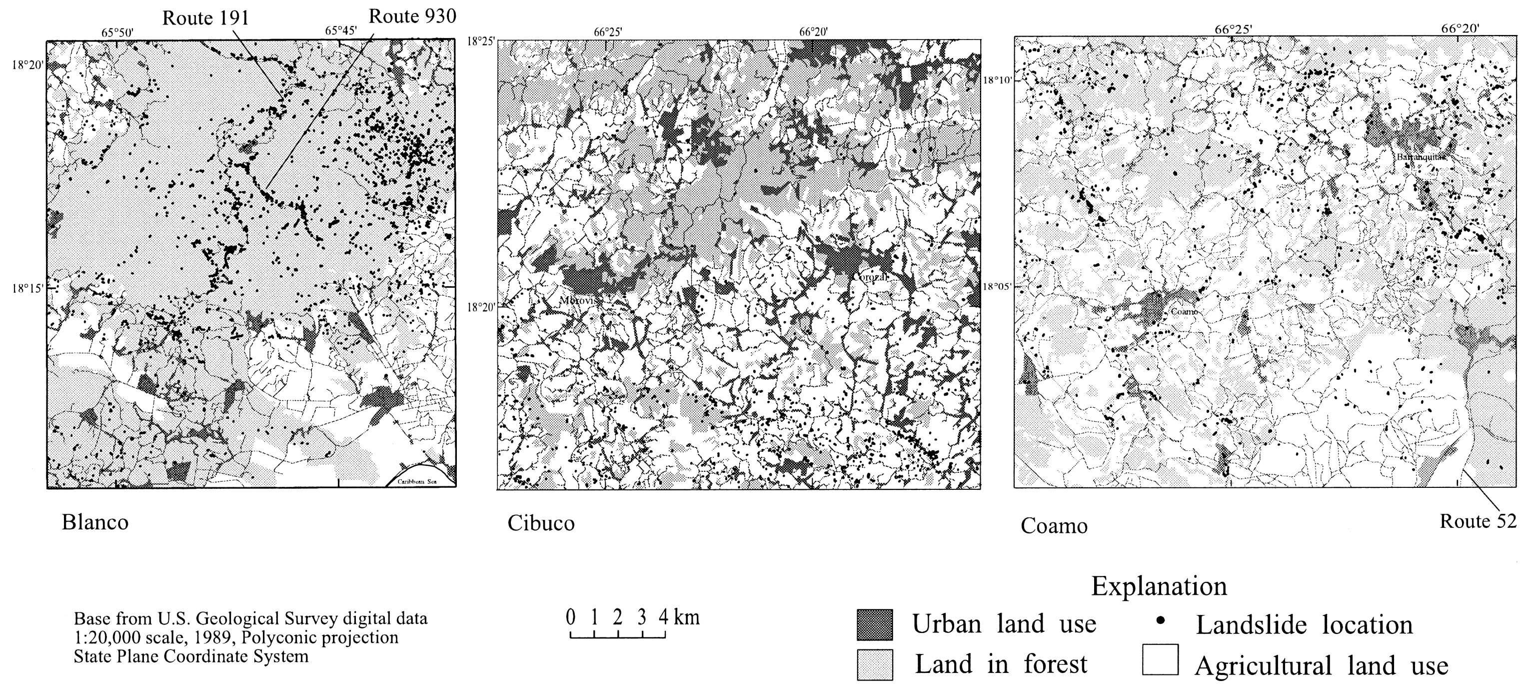

Fig. 3. Locations of landslides, highways, and generalized land use characteristics in the Blanco, Cibuco, and Coamo study areas, Puerto Rico. Land use data from unpublished maps, 1977, Puerto Rico Department of Natural and Environmental Resources.

shadow, and is relatively dry in the southern one-half. Rivers in the study area drain towards the south and west, into the Caribbean Sea. Topography is rolling to moderate and ranges in elevation from near sea level to 860 m. Upland slopes are moderate to steep and covered with second growth forest, abandoned pasture, and small farms. A large town, Coamo, is located in the southern part of the study area. Land use history is comparable to the island-wide pattern.

2.2. Climate and hydrology

The climate of Puerto Rico is dominated by the easterly trade winds (Fig. 4) which control 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 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 in Puerto Rico ranges from 760 mm to more than 5000 mm and varies across the island because of the strong orographic effects of an

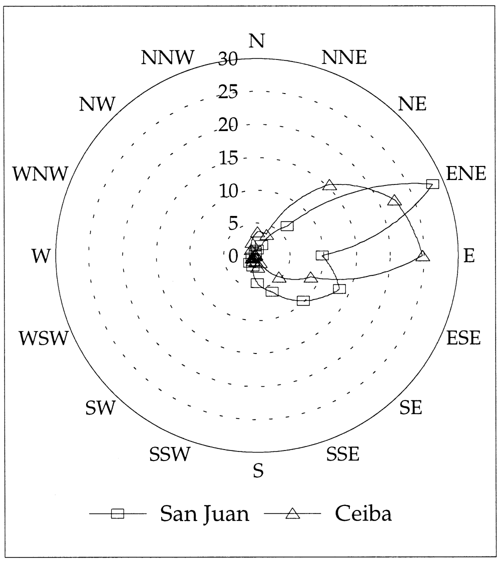

Fig. 4. Mean daily wind direction expressed as a percentage of days per year at San Juan and Ceiba, Puerto Rico. Calm conditions, not shown, are 13.5 and 7.1%, respectively, at San Juan and Ceiba. Data from Calvesbert (1970).

east–west trending central mountain range (Fig. 1). The climate of Puerto Rico ranges from humid-tropical non-seasonal throughout the 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, and ranges from 19° at the highest peaks (1000 to 1300 m) to 27°C along the coastal plains. The average number of rainy days ranges from about 300 in the northeastern mountains, to less than 100 along the south coast.

On average, 8–11 hurricanes occur in the Atlantic Ocean each year (Riehl, 1979; Gray, 1990). The annual occurrence of hurricanes throughout the Caribbean has averaged between 1 and 2 in recent decades. Approximately once every 21 years, Puerto Rico is hit directly by a hurricane.

The Blanco study area, where mean monthly rainfall in any month of the year is about 5–10% of mean annual rainfall, is the wettest of the three study sites (1500 to as much as 5000 mm per year). Runoff ranges from 50 to 90% of annual rainfall, with runoff percentage increasing with elevation.

The Cibuco study area, in north-central Puerto Rico, is characterized by moderate mean-annual rainfall accumulation. The average is 1900 mm per year in the southern uplands and 1500 mm per year in the northern part of the study area.

Rainfall in the Coamo study area has the lowest mean annual total of the three study areas. Annual average rainfall is 1400 mm in the uplands and 800 mm in the southern part of the study area. Many streams are ephemeral because of the low mean annual rainfall.

2.3. Geology and soils

The uplands of Puerto Rico are underlain by predominately Cretaceous, largely marine-deposited, volcaniclastic rock composed of tuffaceous sandstone, siltstone, breccia, conglomerate, lava and tuff (Briggs and Akers, 1965). These rocks are common in the uplands of all three study areas. Several Late Cretaceous, Paleocene, and Eocene plutonic intrusions (granodiorite and quartz diorite) have been mapped in the eastern and central mountains. Extensive middle Oligocene to middle Miocene limestones occur along the northern and southern coasts, covering more than one-fifth of the island (Giusti, 1971). These deposits are common in the lower elevation areas of the Cibuco and Coamo areas. A Tertiary quartz–diorite intrusion was mapped by Seiders (1971) and covers an area of approximately 20 km^2 in the uplands of the Blanco area. In addition, the upland part of the Blanco study area is underlain by Cretaceous marine-deposited volcaniclastic breccia, lavas and tuff (Seiders, 1971). The major bedrock types located in the northern half of the Cibuco study area include extensive middle Oligocene to middle Miocene limestone deposits containing sandstone, dolomite, marl and chalk. Upper Cretaceous marine and subaerially deposited volcaniclastic rock dominate the southern half of the study area and include tuffaceous sandstone, siltstone, breccia, conglomerate, lava, and tuff (Briggs and Akers, 1965). The major bedrock type in the Coamo study area is Cretaceous and Tertiary volcaniclastic rock composed of tuffaceous sandstone, siltstone, breccia and conglomerate, lava and tuff.

Soils throughout Puerto Rico have been mapped by the U.S. Department of Agriculture—Soil Conservation Service (Acevedo, 1982; Boccheciamp, 1977, 1978; Gierbolini, 1975, 1979). Most of the soil orders of the world occur in Puerto Rico, and most occur within the three study areas discussed in this article. Upland areas of high annual rainfall are dominated by Inceptisols and Ultisols. In areas of moderate annual rainfall, Alfisols, Mollisols, Ultisols and Oxisols are common. Vertisols occur in areas adjacent to the dry southern coastal plain.

3. Methods

Aerial photographic, topographic, and land use data from the three study areas were collected, processed, and digitized for use with a GIS. These spatial data were evaluated using a matrix of geographic land surface types to normalize the frequency of landslides in each study area.

3.1. Aerial photograph and geographic information system analysis

Approximately 300 sets of stereo aerial photographs were used to map recent landslides and to assemble a data base to assess the surface area and number of landslides in each of three study areas. For the Blanco study area, photographs for the years 1951, 1962–1967, 1971–1977, and 1990 were used. For the Cibuco and Coamo study areas, the photographs used were from 1987 and 1951, respectively. Because more sets of photographs were examined for the Blanco study area, more landslides were mapped compared to the number observed in the Cibuco and Coamo study areas.

Recent landslides were observed on aerial photographs as a break in the forest canopy, bare soil, or other geomorphic characteristics typical of landslide scars, i.e., head and side scarps, flow tracks, and soil and debris deposits below the scar (Wieczorek, 1984). Each landslide was assigned an identification number, the type of landslide (debris flow, slump, shallow soil slip, and debris avalanche) was determined, and land use for the hillslope was noted. Multiple photograph sets bracketed most landslide scars in the Blanco study area allowing minimum and maximum ages to be determined. Land owners also provided age estimates for some landslide scars.

Analysis of aerial photographs allowed for examination of extensive areas. The technique is limited, however, by the poor quality of some black and white photographs taken between the 1930s and 1950s. Additionally, forest canopy and shadows on steep hillslopes mask landslide features and reduce the total number of landslides identified in such areas. Finally, many of the observed landslide scars were relatively small, near the limit of observation (about 10×10 m on 1:20,000-scale photographs). Regular field reconnaissance (from 1987 to 1997) along highways, foot trails, ridge tops, and river channels, indicates that some small recent landslide scars (less than 10 m in length or width) along very steep slopes and under closed forest canopy were not seen on the photographs. The small landslide scars were not abundant, however, and their absence is not expected to markedly alter the data for forested areas or hillslopes otherwise masked from view.

A vector-based GIS software (ESRI, 1993) was used to relate the locations of landslides to various geographic factors. The locations of landslides in each study area were compared to digitized topography (slope angle, slope elevation, and slope aspect) and land use. GIS software was used to determine the identification number of each landslide falling into each sub-category defined for each geographic attribute. GIS software was then used to determine the area, in square meters, that each attribute covered in each study area.

3.2. Characterization of topography and land use

Topography was taken from a USGS GIS data base which includes topographic contours scanned at 1200 dots/in. from 1:20,000-scale maps. Topographic analysis involved categorizing the slope angle, slope aspect, and land surface elevation for each study area.

Categories of land-use (forest, pasture, crop land, and developed areas such as roads and structures) for each study area were digitized from 1:20,000-scale maps and compared to the location of landslides mapped from aerial photographs. The land use attributes in each study area were determined from unpublished Puerto Rico Department of Natural and Environmental Resources maps made in 1977. Because of the gradual reforestation of abandoned agricultural areas in the central mountains that has occurred at the same time as increased urbanization of other areas, land use categories are considered to be only estimates. Finally, these categories, as well as those discussed below, may contain some inconsistencies as some degree of spatial distortion may be incorporated into a GIS data base when spatial data are digitized from paper maps.

Roads in the study area occupy a 10-m wide swath, either from cutting into the upper side of the road embankment, placement of fill on the lower side of the road embankment, or both. Wide paved roads occupy a broader swath but most roads in the study areas are narrow two-lane highways or dirt and gravel tracks. Developed areas included all roads and clusters of houses as well as small towns. Extensively urbanized regions with low slope ranged from 0.5 to 2 km^2 in area and were not included in the study.

3.3. Simplification of geographic attributes

GIS software allows for detailed description and analysis of the various geographic attributes that are associated with landslides mapped from aerial photographs. The total number of categories initially defined for each geographic attribute amounted to between 75 and 102 for each study area (Larsen and Torres-Sánchez, 1996). Given the number of landslides mapped in each study area (1019 to 1859), even 75 categories is too many to permit a meaningful determination of the control that geographic attributes exert on the frequency of landslides over time. A simplification or grouping of categories was, therefore, necessary.

Each topographic attribute (hillslope angle, elevation, and aspect) was simplified into two or three categories for analysis. Land use was simplified to three categories by combining pasture and cropland into a single agricultural category. In the Coamo study area, the category of forest land use was combined with agricultural land use because: (1) only 22% of the study area is forested and (2) much of the forested area is in coffee shade forest, an agricultural land use, and (3) most forest shown on the land use maps has only very recently (10–20 years) recovered from former pasture or cropland. Forest recovery in former pasture sites has been shown to be slow, compared to recovery following natural disturbance, with grasses, herbs, vines, and ferns persisting for 20 or more years (Aide et al., 1995).

The simplification of topographic attributes was achieved by combining slope angle into low (12° or less) and high (greater than 12°) angles for each study area. Twelve degrees was chosen because it was, on average, the angle above or below which the frequency of landslides changed in each of the three study areas (Fig. 5A). Elevation categories were similarly combined into low and high subdivisions because in two of the three study areas, higher elevation hillslopes had greater frequency of landslides (Fig. 5B). A 300- to 400-m break in elevation was chosen because this elevation divides each study area into relatively drier (less than approximately 1750 mm mean annual rainfall) and wetter (more than approximately 1750 mm mean annual rainfall) regions, respectively (Fig. 1). The eight slope aspect categories for each study area were grouped according to whether the slope faced the prevailing wind direction for the island (northeast and east), or did not face the prevailing wind direction (in the lee— southwest and west, or normal to the prevailing wind

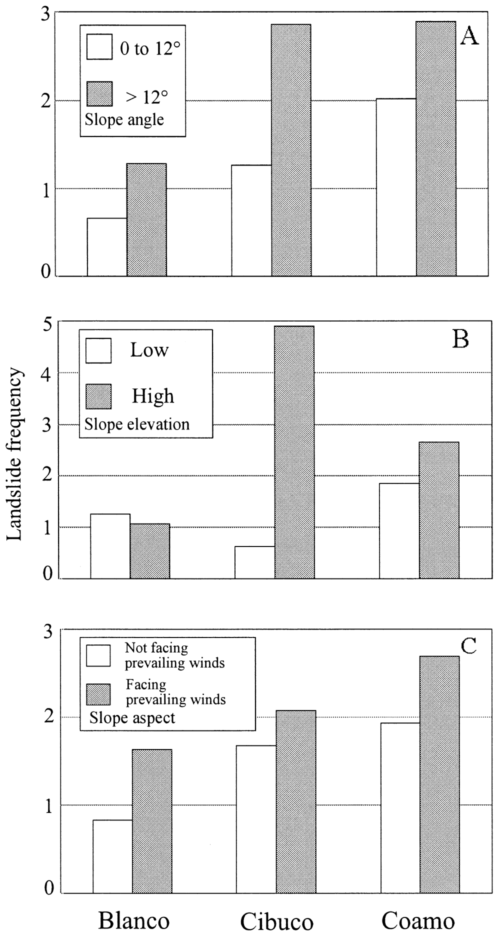

Fig. 5. The frequency of landslides (landslide scars per km^2 per decade) as a function of hillslope angle, elevation, and aspect in forest, pasture, and agricultural areas of the Blanco, Cibuco, and Coamo study areas, Puerto Rico. Landslides associated with roads and housing were excluded to reduce possible bias resulting from the location of road corridors and construction sites. Hillslopes, low elevation are ≤ 300 m in the Cibuco and Coamo study areas and ≤ 400 m in the Blanco study area; hillslopes facing prevailing wind are those hillslopes that face east and northeast; hillslopes not facing prevailing wind face the remaining six octants.

—southeast, south, northwest and north) (Figs. 4 and 5C).

3.4. Matrix of geographic attributes of the frequency of landslides

The simplification of geographic attributes resulted in 24 combinations of hillslope attributes for the Coamo study area, and 36 combinations for the Blanco and Cibuco study areas. Using the previously determined categories of geographic attributes for each landslide, the number of landslides for each of the 24–36 hillslope types was determined (Tables 1–3).

Using GIS software an 8075- to 8170-point grid (95 rows and 85 or 86 columns) with a point spacing of approximately 180 m was overlain with each geographic coverage for each study area. This permitted determination of which of the 24 to 36 possible categories of hillslope attributes existed at each grid point. After eliminating as much as 9% of the points (because some of them were over ocean, wetlands, and other areas that were so flat that GIS software could not determine a slope aspect) the remaining 7300 to 7400 points were then assumed to represent the center of a cell with an area of approximately 3.4, 3.8, and 4.4 ha, respectively, in the Blanco, Cibuco, and Coamo study areas.

Cells were designated as forest or agricultural land use if the GIS software determined that the cell coincided with a forest or agricultural polygon. If the GIS determined that the cell contained roads or structures, land use was reclassified to that category. This may have resulted in a slight over-estimation of total area in roads and structures. The trends of the frequency of landslide for each study area are consistent with the pre-simplification analysis, and indicate that this land use reclassification was reasonable (Larsen and Torres-Sánchez, 1996).

Cells with the same combination of attributes were added together to determine the approximate total area for each of the 24 to 36 combinations (Tables 4–6). The number of landslides on each of the 24 to 36 types of hillslope was then divided by the total area, in km^2, for that same type of hillslope. This normalized the frequency of landslides for each type of hillslope, resulting in the number of landslides per km^2.

Sets of aerial photographs, covering a 39-year period, were used to map landslides in the Blanco study area. Because a time series of aerial photographs was used, the maximum age of many of the landslide scars could be constrained by the dates of the photographs. The recovery of vegetation gradually masks the visibility of landslide scars on the photographs. It was determined that, in general,

Table 1
Matrix showing the number of landslides associated with 36 geographic categories in the Blanco study area, Puerto Rico

Elevation	Slope orientation	Slope angle	Number of landslides		
			Forest land use	Agricultural land use	Roads and structures
> 400 m	Lee of prevailing wind	> 12°	47	6	24
		≤ 12°	34	6	13
	Normal to prevailing wind	> 12°	143	20	72
		≤ 12°	48	7	40
	Facing prevailing wind	> 12°	128	41	74
		≤ 12°	38	3	37
≤ 400 m	Lee of prevailing wind	> 12°	35	66	31
		≤ 12°	11	52	13
	Normal to prevailing wind	> 12°	84	157	68
		≤ 12°	32	111	16
	Facing prevailing wind	> 12°	83	128	58
		≤ 12°	23	91	19
Totals			706	688	465

landslides as old as 10 years could be recognized in the aerial photographs, indicating that the total period of time represented is approximately 50 years (Guariguata, 1990). The frequency of landslides for the Blanco study area was divided by five, which results in the approximate number of landslides that have occurred per km^2 per decade. Only one set of aerial photographs was used for the Cibuco and Coamo study areas. Judging from the regrowth of vegetation on scars and the ages (estimated by local landowners) of landslide scars that were field checked, the frequency of landslides per km^2 was assumed to represent a minimum of 10 years.

4. Results and discussion

Landslides, mapped as part of this study totaled 1859 in the Blanco study area, 1019 in the Coamo study area, and 1161 in the Cibuco study area (Figs. 6–8). Landslides in the Blanco study area were

Table 2
Matrix showing the number of landslides associated with 36 geographic categories in the Cibuco study area, Puerto Rico

Elevation	Slope orientation	Slope angle	Number of landslides		
			Forest land use	Agricultural land use	Roads and structures
> 300 m	Lee of prevailing wind	> 12°	18	33	58
		≤ 12°	10	28	41
	Normal to prevailing wind	> 12°	17	42	89
		≤ 12°	9	58	61
	Facing prevailing wind	> 12°	16	68	80
		≤ 12°	6	56	48
≤ 300 m	Lee of prevailing wind	> 12°	4	5	17
		≤ 12°	7	21	31
	Normal to prevailing wind	> 12°	11	8	42
		≤ 12°	15	41	84
	Facing prevailing wind	> 12°	4	14	40
		≤ 12°	5	24	50
Totals			122	398	641

Table 3
Matrix showing the number of landslides associated with 24 geographic categories in the Coamo study area, Puerto Rico

Elevation	Slope orientation	Slope angle	Number of landslides	
			Agricultural and forest land use	Roads and structures
> 300 m	Lee of prevailing wind	> 12°	98	43
		≤ 12°	40	7
	Normal to prevailing wind	> 12°	136	55
		≤ 12°	61	11
	Facing prevailing wind	> 12°	143	89
		≤ 12°	46	10
≤ 300 m	Lee of prevailing wind	> 12°	37	5
		≤ 12°	47	7
	Normal to prevailing wind	> 12°	42	10
		≤ 12°	50	7
	Facing prevailing wind	> 12°	27	8
		≤ 12°	39	1
Totals			766	253

relatively evenly distributed between shallow soil slips, debris flows, and slumps, with only a few debris avalanches present (Table 7). Slumps were most common in the Blanco study area, where wetter conditions prevail. Most of the landslides in the Cibuco and Coamo study areas were shallow soil slips and debris flows. The Coamo study area, with some of the driest conditions and thinnest soils among the three study areas, had the greatest percentage of debris flows.

In general, each study area displayed similar geomorphic trends with respect to elevation, slope angle, and slope aspect, although the Blanco study area, where mean annual rainfall is high throughout the range of elevation, did not show the increase in the frequency of landslides with elevation that is seen in the other two study areas (Fig. 5B). The frequency of landslides, however, is complicated by the interaction of multiple topographic variables and land use. If single topographic variables are used to examine the frequency of landslides, the patterns of distribution are not necessarily distinct and an integrated approach is required. Furthermore, land use is one of the most important controls on the frequency of landslides, and geomorphic effects must be considered with this in mind. For example, although the

Table 4
Matrix showing the estimated area in ha for 36 geographic categories in the Blanco study area, Puerto Rico

Elevation	Slope orientation	Slope angle	Number of ha		
			Forest land use	Agricultural land use	Roads and structures
> 400 m	Lee of prevailing wind	> 12°	1816	124	89
		≤ 12°	791	76	86
	Normal to prevailing wind	> 12°	4355	175	227
		≤ 12°	1317	103	144
	Facing prevailing wind	> 12°	2119	93	96
		≤ 12°	709	24	83
≤ 400 m	Lee of prevailing wind	> 12°	850	399	103
		≤ 12°	760	998	440
	Normal to prevailing wind	> 12°	1655	698	306
		≤ 12°	1706	1720	839
	Facing prevailing wind	> 12°	977	306	131
		≤ 12°	1004	695	341
Totals			18,059	5411	2886

Table 5
Matrix showing estimated area in ha for 36 geographic categories in the Cibuco study area, Puerto Rico

Elevation	Slope orientation	Slope angle	Number of ha		
			Forest land use	Agricultural land use	Roads and structures
> 300 m	Lee of prevailing wind	> 12°	261	291	72
		≤ 12°	94	397	98
	Normal to prevailing wind	> 12°	623	922	321
		≤ 12°	280	1043	253
	Facing prevailing wind	> 12°	215	521	110
		≤ 12°	185	529	196
≤ 300 m	Lee of prevailing wind	> 12°	400	306	110
		≤ 12°	975	1862	703
	Normal to prevailing wind	> 12°	695	880	317
		≤ 12°	3139	5564	2297
	Facing prevailing wind	> 12°	423	442	140
		≤ 12°	1322	2731	835
Totals			8612	15,487	5451

frequency of landslides is generally lower in forested areas, much of the existing forest in the three study areas is on steep slopes where agriculture is less advantageous. Conversely, agricultural practices increase the frequency of landslides, but, because gentler slopes are more likely to be under cultivation than steeper ones, the landslide–frequency relation is sometimes obscured.

4.1. Land use

Categories of land use have the greatest variability in the frequency of landslides in the study areas indicating that human modification fundamentally alters hillslope stability in these areas. The most common construction-related activities involve undercutting the foot of a slope or deposition of soil and rock along the upper edge of a slope. Both practices tend to increase shear stress in the ground beneath the slope (Terzaghi, 1950). If the average shear stress of the hillslope material then becomes equal to the average shear resistance, a landslide can occur. In agricultural areas, Aide et al. (1995) have shown that soils in pasture and former pasture have high compaction and have lost soil structure. These

Table 6
Matrix showing estimated area in ha for 24 geographic categories in the Coamo study area, Puerto Rico

Elevation	Slope orientation	Slope angle	Number of ha	
			Agricultural and forest land use	Roads and structures
> 300 m	Lee of prevailing wind	> 12°	2597	243
		≤ 12°	1930	494
	Normal to prevailing wind	> 12°	4540	356
		≤ 12°	3621	872
	Facing prevailing wind	> 12°	1999	169
		≤ 12°	1860	455
≤ 300 m	Lee of prevailing wind	> 12°	759	82
		≤ 12°	3087	494
	Normal to prevailing wind	> 12°	1427	143
		≤ 12°	5221	702
	Facing prevailing wind	> 12°	655	56
		≤ 12°	1908	234
Totals			29,603	4301

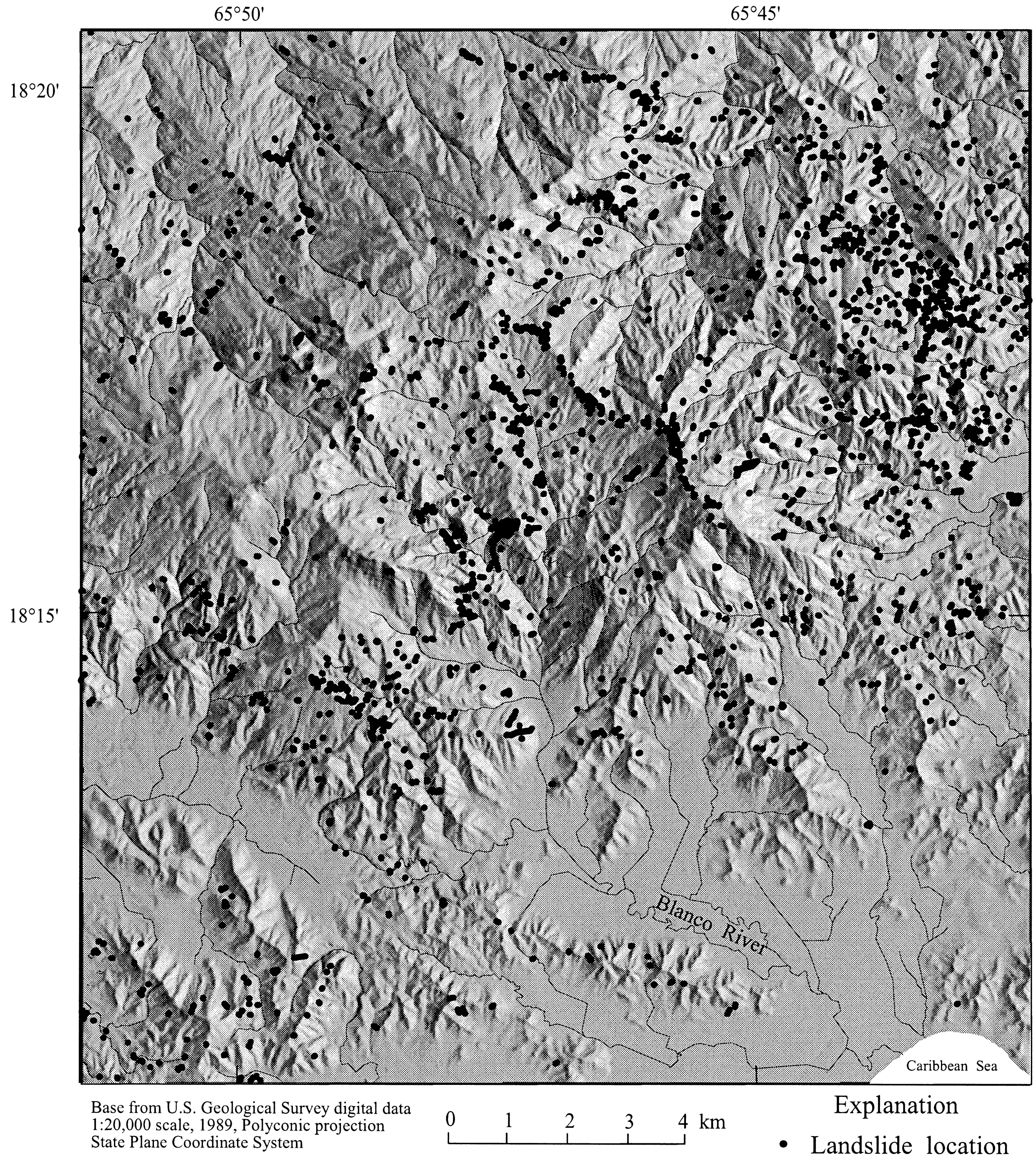

Fig. 6. Shaded relief map of the Blanco study area, Puerto Rico, showing locations of landslides and rivers.

conditions lead to greater runoff and increased erosion and may contribute to an increased frequency of landslides. In addition, overgrazing by cattle is common in pastures in the study areas. The greatest effects of cattle on the landscape are on upland slopes where they reshape and compact soil by tram-

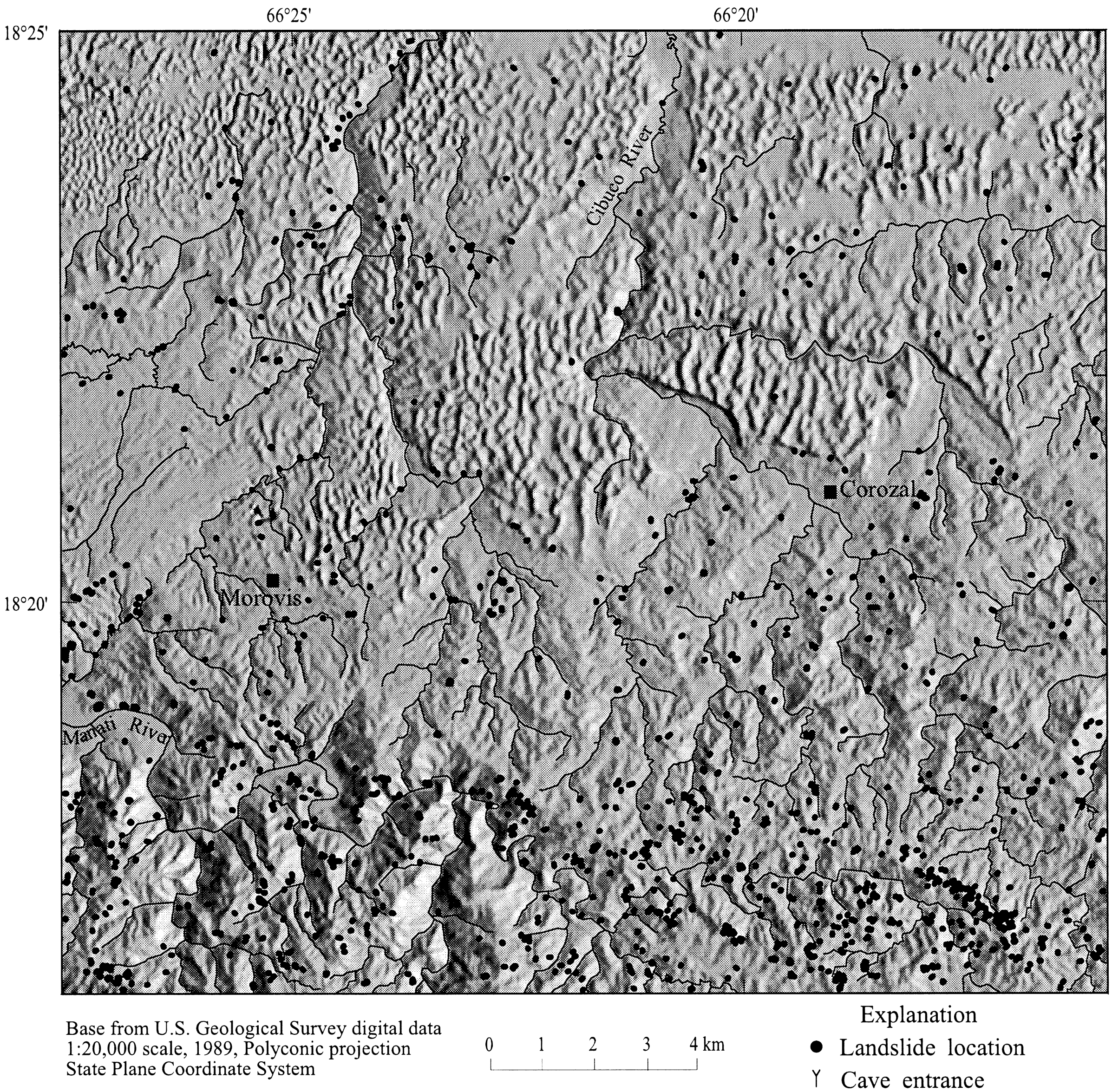

Fig. 7. Shaded relief map of the Cibuco study area, Puerto Rico, showing locations of landslides and rivers.

pling which can cause increased runoff (Trimble and Mendel, 1995). The concentration of runoff along cow terracettes—the contour-parallel trails made by cattle—is thought to increase gully development and may lead to decreased slope stability.

In each study area, the average frequency of landslides increased markedly as landscape disturbance increased from forest to agriculture to roads and structures. This can be easily seen by reading across any row in the matrices of the frequency landslides starting with the forest land-use category and ending with the roads and structures land-use category (Tables 8–10). This trend is apparent for almost every type of hillslope noted for all three study areas and illustrates the distinct effects of land use on landslide disturbance.

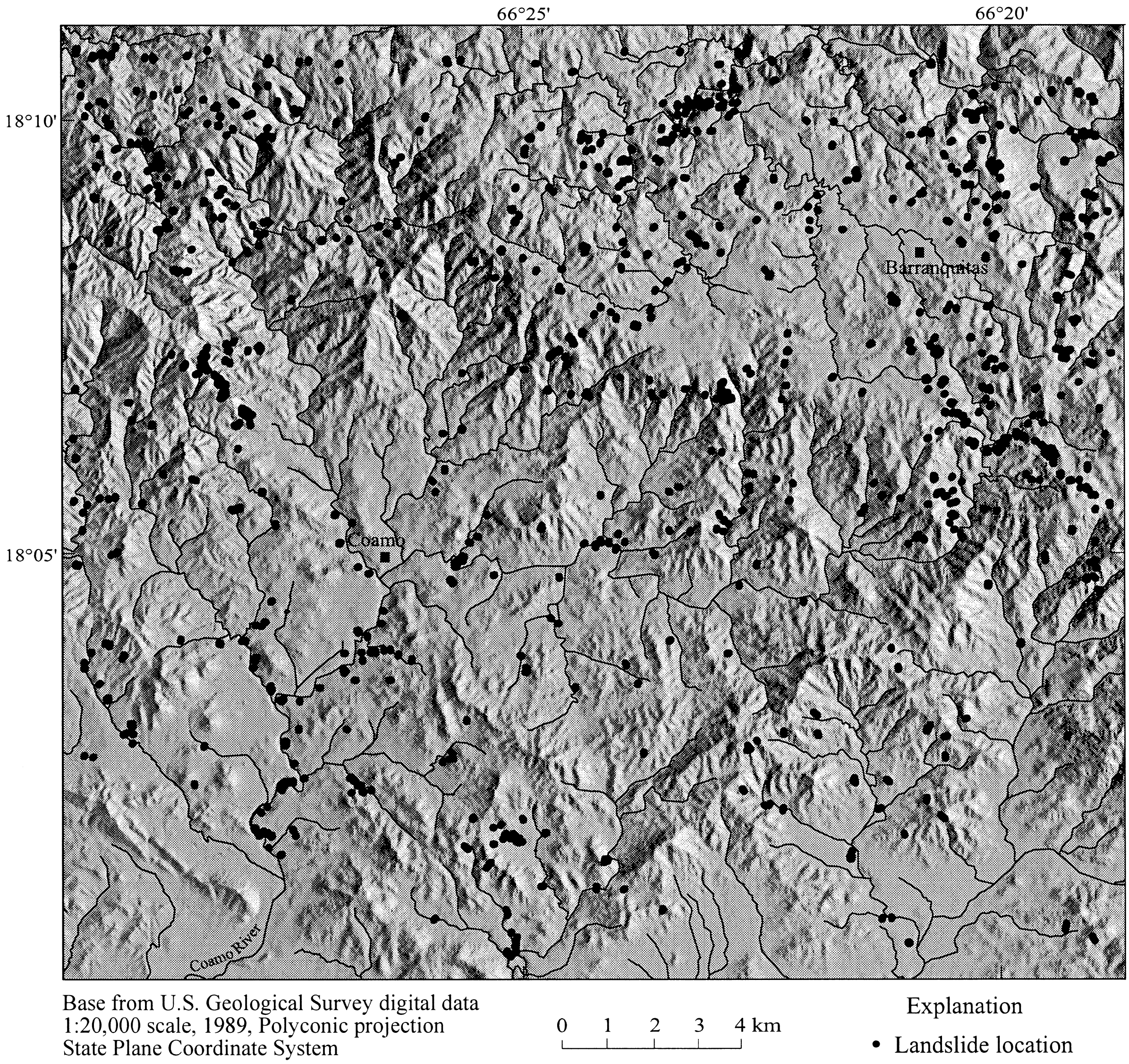

Fig. 8. Shaded relief map of the Coamo study area, Puerto Rico, showing locations of landslides and rivers.

Table 7
Landslide types in the Blanco, Cibuco, and Coamo study areas, Puerto Rico

Landslide type	Percentage of landslides		
	Blanco	Cibuco	Coamo
Shallow soil slip	36	49	30
Debris flow	37	45	51
Slump	26	6	19
Debris avalanche	1	0	0

The average frequency of landslides in the Blanco study area for all types of hillslopes was lower than that for the Cibuco, and Coamo study areas (Tables 8–10). The Blanco study area has been the least modified (García-Montiel and Scatena, 1994), retaining the high percentage of relatively undisturbed forest cover which probably explains its lower frequency of landslides in spite of having the greatest mean annual rainfall. The frequency of landslides on

Table 8
Matrix showing the estimated frequency of landslides (number of landslides per km^2 per decade) in 36 geographic categories in the Blanco study area, Puerto Rico

Elevation	Slope orientation	Slope angle	Landslides per km^2 per decade		
			Forest land use	Agricultural land use	Roads and structures
> 400 m	Lee of prevailing wind	> 12°	*0.5*	*1.0*	5.4
		≤ 12°	*0.9*	*1.6*	*3.0*
	Normal to prevailing wind	> 12°	*0.7*	*2.3*	6.3
		≤ 12°	*0.7*	*1.4*	5.5
	Facing prevailing wind	> 12°	*1.2*	8.8	**15.4**
		≤ 12°	*1.1*	*2.5*	9.0
≤ 400 m	Lee of prevailing wind	> 12°	*0.8*	*3.3*	6.0
		≤ 12°	*0.3*	*1.0*	0.6
	Normal to prevailing wind	> 12°	*1.0*	4.5	4.4
		≤ 12°	*0.4*	*1.3*	*0.4*
	Facing prevailing wind	> 12°	*1.7*	8.4	8.9
		≤ 12°	*0.5*	*2.6*	*1.1*
Averages			*0.8*	*2.5*	*3.2*

Values calculated by first dividing the number of landslides per category by area in km^2 and then dividing by 5 to account for the 5-decade span of data. Averages are based upon totals listed in Tables 1 and 4.
Landslide frequencies in upper quartile are shown in bold text, lower quartile in italics.

Blanco study area hillslopes modified for roads and structures is much higher than that for forested hillslopes in almost every case. The number of landslides per km^2 was, on average, 4 times greater but as much as 13 times greater in some areas, attesting to the dramatic effects of construction in this environment (Table 8). An example of this instability is a two-lane highway (Route 191) in the Blanco study area that has been closed for almost 25 years because of massive debris avalanches that severed the highway in 1970 and 1979 (Dames and Moore, 1980; Fig. 3). In addition, during the 1960s, construction of

Table 9
Matrix showing the estimated frequency of landslides (number of landslides per km^2 per decade) in 36 geographic categories in the Cibuco study area, Puerto Rico

Elevation	Slope orientation	Slope angle	Landslides per km^2 per decade		
			Forest land use	Agricultural land use	Roads and structures
> 300 m	Lee of prevailing wind	> 12°	*6.9*	*11.3*	**80.8**
		≤ 12°	*10.6*	*7.1*	41.7
	Normal to prevailing wind	> 12°	*2.7*	*4.6*	27.7
		≤ 12°	*3.2*	*5.6*	24.1
	Facing prevailing wind	> 12°	*7.4*	*13.0*	**73.0**
		≤ 12°	*3.2*	*10.6*	24.4
≤ 300 m	Lee of prevailing wind	> 12°	*1.0*	*1.6*	*15.5*
		≤ 12°	*0.7*	*1.1*	*4.4*
	Normal to prevailing wind	> 12°	*1.6*	*0.9*	*13.2*
		≤ 12°	*0.5*	*0.7*	*3.7*
	Facing prevailing wind	> 12°	*0.9*	*3.2*	28.6
		≤ 12°	*0.4*	*0.9*	*6.0*
Averages			*1.4*	*2.6*	*11.8*

Values are calculated by first dividing the number of landslides per category by area in km^2. Averages are based upon totals listed in Tables 2 and 5.
Landslide frequencies in upper quartile are shown in bold text, lower quartile in italics.

Table 10
Matrix showing the estimated frequency of landslides (number of landslides per km^2 per decade) in 24 geographic categories in the Coamo study area, Puerto Rico

Elevation	Slope orientation	Slope angle	Landslides per km^2 per decade	
			Agricultural and forest land use	Roads and structures
> 300 m	Lee of prevailing wind	> 12°	*3.8*	17.7
		≤ 12°	*2.1*	*1.4*
	Normal to prevailing wind	> 12°	*3.0*	15.5
		≤ 12°	*1.7*	*1.3*
	Facing prevailing wind	> 12°	*7.2*	**52.6**
		≤ 12°	*2.5*	*2.2*
≤ 300 m	Lee of prevailing wind	> 12°	*4.9*	*6.1*
		≤ 12°	*1.5*	*1.4*
	Normal to prevailing wind	> 12°	*2.9*	*7.0*
		≤ 12°	*1.0*	*1.0*
	Facing prevailing wind	> 12°	*4.1*	*14.2*
		≤ 12°	*2.0*	*0.4*
Averages			*2.6*	*5.9*

Values are calculated by first dividing the number of landslides per category by area in km^2. Averages are based upon totals listed in Tables 3 and 6.
Landslide frequencies in upper quartile are shown in bold text, lower quartile in italics.

another LEF highway (Route 930) was so hampered by landsliding that the cost and time to build were two to three times what was anticipated by the contractor (Sowers, 1971; Fig. 3).

The frequency of landslides in agricultural regions of the Blanco and Cibuco study areas averaged 2 to 3 times the frequency determined for forested areas (Tables 8 and 9). Pasture and crop land uses appear less disturbing to the landscape than the construction of roads and buildings but the frequency of landslides still increases compared to relatively undisturbed forest. The average frequency of landslides in all three study areas for hillslopes modified for roads and structures ranged from 2.3 to 8.4 times the frequency determined for forested hillslopes.

4.2. Hillslope angle

Hillslope angle is an essential component of hillslope stability analysis. As hillslope angle increases, shear stress in soil, saprolite, or other unconsolidated material generally increases as well (Huang, 1983). Gentle hillslopes are expected to have a low frequency of landslides because of generally lower shear stresses associated with low gradients. On average, the frequency of landslides was greater on

Table 11
Frequency of landslides (number of landslides per km^2/decade) averaged for all land use types in the Blanco, Cibuco, and Coamo study areas, Puerto Rico

Study area	Angle		Elevation		Aspect		Ratio of high to low frequencies		
	High	Low	High	Low	High	Low	Angle	Elevation	Aspect
Blanco	4.5	1.9	3.7	2.6	5.1	2.2	2.4	1.4	2.3
Cibuco	16.3	8.3	19.9	4.7	14.3	11.3	2.0	4.2	1.3
Coamo	11.6	1.5	9.3	3.9	10.7	4.5	7.5	2.4	2.4

High angle indicates hillslopes > 12°; low angle indicates hillslopes ≤ 12°; high elevation indicates hillslopes > 400 m in the Blanco study area and > 300 m in the Cibuco and Coamo study areas; high aspect indicates that hillslopes face prevailing wind direction; low aspect indicates that hillslopes do not face prevailing wind direction.
Data summarized and refer to those data listed in Tables 8–10.

steep slopes than on gentle slopes (Table 11; Fig. 5A). Steep natural slopes resulting from outcropping bedrock, however, may not be susceptible to shallow landslides if little regolith is available. This was noted in two cases in the Blanco study area where steep (> 12° gradient) forested hillslopes above 400 m elevation showed equal or slightly lower frequency of landslides than the gentle hillslopes (Table 8). Although not verified with GIS analysis, low frequency of landslides on steep bedrock hillslopes was a common field observation in the three study areas. Nonetheless, in 16 out of 18 possible combinations of land use, hillslope elevation, and hillslope aspect in the Blanco study area, hillslopes where slope angle exceeded 12° had a greater frequency of landslides (Table 8). Generally, the frequency of landslides was greater by a factor of 2.5–3.5 on the steep hillslopes, other factors being equal. The greatest difference between gentle and steep slopes was noted in land below 400 m elevation used for roads and structures. Here, steep slopes were associated with as much as a 10-fold increase in the frequency of landslides.

In the Cibuco study area, hillslopes where slope angle exceeded 12° had a greater frequency of landslides in 15 out of 18 possible combinations of land use, hillslope elevation, and hillslope aspect (Table 9). Steep hillslopes in the Coamo study area had consistently greater frequencies of landslides than did gentle hillslopes (Table 10). The greater degree of landscape alteration for agriculture and predominance of debris flows in this study area may explain the higher frequency of landslides on steep hillslopes in this study area, when compared to the Blanco and Cibuco study areas. The generally drier soil-moisture conditions of the Coamo study area make debris flows the dominant landslide type. The initiation debris flows, however, requires a relatively steep slope angle, so the majority of debris flow scars would be expected on slopes exceeding 12°. On average, steep slopes in the Coamo study area had a frequency of landslides that was 7.5 times the frequency on gentle slopes (Table 11).

4.3. Hillslope elevation

In the Blanco study area, the frequency of landslides on high elevation hillslopes was 1.4 times that of low elevation hillslopes (Tables 8 and 11). In all cases in the Cibuco and Coamo study areas, hillslopes above 300 m elevation had frequencies of landslides that were 2.4–4.2 times greater than the frequencies of landslides on hillslopes less than 300 m elevation (Tables 9–11).

The increase in the frequency of landslides with increasing elevation is expected because of the greater mean annual rainfall recorded at higher elevations throughout the island. In addition, mean monthly soil moisture is generally greater at higher elevations in part because evapotranspiration losses are lower and average cloud cover is greater (Odum et al., 1970). The generally wetter soil conditions in the study area uplands may mean that not much additional soil water is required to increase soil pore pressure sufficiently to trigger landslides, at least in hillslopes in unconsolidated material (Simon et al., 1990).

The orientation of the Cibuco study area should yield the simplest pattern of orographically-controlled distribution of rainfall among the three study areas because it is the only predominately north-facing study area. The greatest contrast in the frequency of landslides between high and low elevation hillslopes was in the Cibuco study area, where the frequency of landslides on high-elevation hillslopes was more than four times that determined for low-elevation hillslopes (Table 11). Here, however, a geologic factor provides additional explanation because the lower elevation areas are underlain by limestone which, as discussed above, has a very low frequency of shallow landslides. The Blanco and Coamo study areas, although wetter in the uplands, have more complex patterns of mean annual distribution of rainfall because they face away from prevailing winds.

4.4. Hillslope aspect

Given the low latitude of the tropics, the north or south aspect of hillslopes does not cause the large differences in soil temperature that occur in temperate regions (Van Wambeke, 1992). Instead, diurnal patterns of afternoon cloudiness as well as the prevailing direction of the wind may be more important in controlling soil moisture. Rainfall is delivered much of the year by trade winds that are dominantly from the east and north east (Fig. 4). This results in regional rain shadows across the island and can be observed on a local scale between adjacent watersheds. Those watersheds facing towards the trade winds frequently show greater runoff than those facing the opposite direction (Díaz et al., 1994). In addition, more than half of 41 recent landslide-triggering storms were tropical disturbances which generally approach the island from the east (Calvesbert, 1970; Larsen and Simon, 1993). Finally, a significant part of annual moisture input in tropical montane cloud forests (the highest elevations in the eastern mountains of Puerto Rico) is delivered by condensation and direct contact of cloud droplets (Bruijnzeel and Proctor, 1993). This input of water, known as cloud drip, or horizontal precipitation, is conveyed by clouds moving with the trade winds.

The factors noted above may explain the higher frequency of landslides noted on hillslopes that face prevailing winds. The frequency of landslides in the Blanco study area was highest on northeast- and east-facing slopes (Table 8). In general, the frequency of landslides was 2.3 times greater on hillslopes facing the prevailing winds than the frequency on hillslopes not facing the prevailing winds (Table 11). The frequency of landslides was lowest on those slopes facing to the southwest, west, and northwest.

Landslides were abundant on northeast- and east-facing hillslopes in the Cibuco study area showing the same pattern as in the Blanco study area (Tables 9 and 11; Fig. 5C). The frequency of landslides was lowest on north-, northwest-, and west-facing hillslopes. The north-facing Cibuco study area would not be expected to have many south-facing hillslopes. South- and southwest-facing slopes in the deeply incised Manatí River account for the anomalously high landslide frequencies noted for those two aspect categories (Fig. 7). The inclusion of this area may, therefore, explain the relatively low ratio (1.3) of the frequency of landslides noted between hillslopes facing and not facing prevailing winds (Table 11).

Trends of hillslope aspect in the Coamo study area were similar to the those noted above for the Blanco study area (Tables 10 and 11). Landslides were most abundant on east-facing hillslopes and least so on hillslopes facing the northwest. Because the study area faces southwest, few slopes are northeast-facing. The high frequency of landslides noted for southeast-facing slopes, however, is anticipated as those slopes are close to facing the prevailing direction of the wind. Despite differences in overall orientation of the study areas, trade-wind-facing slopes in all three study areas had the greatest proportion of landslides. This suggests that moisture derived from the trade winds may provide an important explanation for the location of landslides.

5. Summary and conclusions

A relatively simple approach to estimating the frequency and distribution of landslides using aerial photography and a GIS is presented. Geographic controls of land use and topography were evaluated in three study areas representing about 10% of the land surface of the 9000-km^2 island of Puerto Rico. 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.

The marked effects of land use on the occurrence of landslides in the study areas are apparent because, on average, the frequency of landslides was highest in areas modified by humans. The higher average frequency of landslides on hillslopes in agricultural land use as well as in land used for roads and structures provides strong evidence that although mean annual rainfall is high, intense storms are frequent, and hillslopes are steep, forested hillslopes are relatively stable as long as they are not modified by humans. The greater the modification of a hillslope from its original, forested state, the greater the frequency of landslides.

In all three study areas, a slope angle in excess of 12° was a threshold above which the frequency of landslides increased (Table 11). The contrast between steep and gentle slopes was greatest in the Coamo study area where debris flows predominate and weakest in the Cibuco study area where steeply-sloping limestone hills with little soil cover minimize the occurrence of landslides. In addition, the frequency of landslides was higher at elevations greater than 300 m (where greater mean annual rainfall is recorded) in the Cibuco and Coamo study areas. The frequency of landslides in the Blanco study area, where mean annual rainfall is high (> 1500 mm) throughout the range of elevation, was about equal with respect to higher and lower elevation areas.

Slope aspect is most relevant in relation to prevailing winds and resulting rainfall and soil moisture conditions. The dominance of the east-northeasterly trade winds, which deliver much of the rainfall in Puerto Rico, can be easily seen by examination of the frequency of mean annual wind. Single large storms, such as hurricanes, however, may trigger numerous landslides on hillslopes facing the predominant wind-driven rainfall delivered by the storm. Hillslopes in all three study areas generally had the highest frequency of landslides on northeast- and east-facing hillslopes. Conversely, southwest- to northwest-facing hillslopes had the lowest frequency of landslides in all three study areas. Hillslope aspect provided the greatest contrast in the frequency of landslides in the Blanco and Coamo study areas. There, the frequency of landslides was more than two times higher on hillslopes facing the prevailing winds, than the frequency calculated for hillslopes that did not face the direction of the prevailing wind.

The greatest variation in the frequency of landslides exists between land use categories. The average ratio between hillslopes modified for roads or structures and those hillslopes in forested land use ranged from 2.3 to 8.4 for the three study areas. The topographic factors of hillslope angle, elevation, and aspect were almost as important as land use. The three ratios calculated between high and low categories of hillslope angle and elevation, and for hillslopes categorized into those facing and those not facing prevailing winds ranged from 1.3 to 7.5. All of these categories are important geographic factors to consider when estimating the frequency of landslides in the three study areas.

The frequency of landslides on forested hillslopes in the Blanco study area should be the most representative of pristine conditions among the three study areas. Most of this area of about 190 km^2 falls within the boundaries of the LEF and is dominated by slopes that exceed 12°, are higher than about 400 m elevation, and receive in excess of 3500 mm of mean annual rainfall. The low frequency of landslides on forested hillslopes and minimal variability among types of hillslopes within forested areas reinforces the conclusion that landscape disturbance by human modification may be the most important factor controlling the frequency of landslides.

The set of simplified matrices representing geographic conditions in the three study areas provide the means to evaluate spatial controls on the frequency of landslides. This approach is an example of a technique for the analysis of landslide hazards that is easily transferable to other settings. The advantages of the method described above include its computational simplicity and the ability to integrate important controls on the frequency of landslides in a heterogeneous environment.

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