# Map showing susceptibility to earthquake-induced landsliding, San Juan Metropolitan Area, Puerto Rico

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## ABSTRACT
Analysis of slope angle and rock type using a geographic information system indicates that about 68 percent of the San Juan metropolitan area has low to no susceptibility to earthquake-induced landslides. This is at least partly due to the fact that 45 percent of the San Juan metropolitan area is constructed on slopes of 3 degrees or less, which are too gentle for landslides to occur. The areas with the highest susceptibility to earthquake-induced landslides account for 6 percent of the surface area. Almost one-quarter (24 percent) of the San Juan metropolitan area is moderately susceptible to earthquake-induced landslides. These areas are mainly in the southern portions of the San Juan metropolitan area, where housing development pressures are currently high because of land availability and the esthetics of greenery and hillside views. The combination of new development and moderate earthquake-induced landslide susceptibility indicate that the southern portions of the San Juan metropolitan area are be at greatest risk.

## INTRODUCTION
Landslides caused by earthquakes result in significant damage and loss of life in the United States and elsewhere (Keefer, 1984; Jibson, 1988; Jibson and Keefer, 1993; Jibson and others, 1998). Puerto Rico lies in a zone of active seismicity (von Hillebrandt-Andrade, 1994; Dolan and Mann, 1998; Dolan and Wald, 1998; von Hillebrandt-Andrade and Huérfano, 1999) and small earthquakes, generally registering less than 4.0 on the Richter scale are, on average, a daily occurrence. In 1999, for example, 586 earthquakes, the largest of which measured 4.7 on the Richter scale, were recorded by the Puerto Rico Seismic Network (2000). A large earthquake, with an epicenter off the west coast of the island, was recorded on October 11, 1918, and was estimated to have measured 7.2 on the Richter scale. The earthquake and associated tsunami killed 116 people and caused an estimated $4 million in damage (Reid and Taber, 1919). Extensive damage to buildings (mainly in Mayagüez) and a number of landslides and rockfalls were documented. Rockfalls were most abundant in western Puerto Rico, specially in Arecibo, Quebradillas, and Mayagüez.

Most of the island of Puerto Rico is characterized as being moderately to highly susceptible to landsliding (Monroe, 1979). The majority of landslides documented during the 20th century have been triggered by intense or prolonged rainfall (Monroe, 1964, 1979; Jibson, 1989 Larsen and Torres-Sánchez, 1996, 1998). Although rainfall-induced landslides are relatively common, a large earthquake is likely to cause hundreds of landslides in the steeply sloping southern regions of the San Juan metropolitan area. Most secondary (two-lane) roads are likely to be blocked and access to communities will be extremely limited as occurred after the 1976 earthquake in Guatemala (Harp and others, 1981). Hence, a map showing susceptibility to earthquake-induced landsliding serves as an important planning tool for government agencies.

The National Institute of Building Science (NIBS) in cooperation with the Federal Emergency Management Agency (FEMA) has developed the HAZUS (Hazards in the United States) software, a standardized methodology that uses a geographic information system (GIS) to estimate losses from earthquakes (National Institute of Building Science, 1997). HAZUS uses mathematical formulas and information about building stock, local geology and the location and size of potential earthquakes, economic data, and other information to generate earthquake damage estimates. These estimates can provide the basis for developing mitigation policy, for developing and testing emergency preparedness and response plans, and for planning for post disaster relief and recovery. HAZUS methodology can produce three levels of accuracy to estimate damage, based on the detail of available data. Level one (Default Data Analysis) uses default data (general information from national databases) included in the HAZUS software to produce a rough estimate of damage and losses. Levels two (User-Supplied Data Analysis) and three (Advanced Data and Models Analysis) require more extensive inventory information to produce more accurate levels of estimated damage and losses.

The Puerto Rico Planning Board (PRPB) is a local agency cooperating with FEMA to compile and develop the GIS database for Puerto Rico, so that HAZUS software can produce levels two and three analysis for Puerto Rico. One of the data layers needed by the PRPB is a map showing earthquake-induced landslide susceptibility.


**Figure 1.** Location of the San Juan metropolitan area, Puerto Rico.

### Purpose and Scope
The objectives of this report are to contribute to the development of a GIS database for Puerto Rico and to provide the PRPB with one of the digital data layers needed to accurately estimate losses from potential earthquakes, essential for good decision making at the local, regional, and national levels of government. A map showing earthquake-induced landslide susceptibility for the San Juan metropolitan area (fig. 1), which include the municipios of Bayamón, Carolina, Cataño, Guaynabo, San Juan, Toa Baja, and Trujillo Alto, was developed following the standardized methodology presented in NIBS (1997).

Damage and loss estimates are not precise predictions, but are rather estimates based on generalized scientific and engineering information. The use of the resulting data set is limited to applications where the methodology established by the NIBS (for defining areas of equal susceptibility to landslides) is appropriate.

The map is appropriate to use as (1) a comparative guide to seismically-induced landslide susceptibility for different areas of the San Juan metropolitan area; (2) a regional planning tool for evaluation of susceptibility of transportation corridors, recreational areas, emergency vehicle access routes, etc.; (3) preparation of emergency response plans for earthquakes that will occur in the future; and (4) a guide for earthquake-induced landslide damage and loss estimates.

The map serves as a general planning and regional evaluation tool and should not be used to determine site specific, absolute risk of an earthquake-induced landslide. The map is not meant for detailed planning of transportation corridors or other routes, for estimating property insurance, or for zoning of specific parcels of land (Wieczorek and others, 1985). This map does not show areas susceptible to earthquake damage caused solely by liquefaction or other seismic movement associated with non-sloping terrain.

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## METHODOLOGY
The methodology presented in NIBS (1997) was used to characterize landslide susceptibility based on the bedrock type, slope angle, and ground-water condition. Studies by Wilson and Keefer (1985), and by Wieczoreck and others (1985) were the foundation of this methodology, which categorizes landslide susceptibility from lowest to highest. The digital and paper map (plate 2) were developed in the vector GIS software, Arc/Info (Environmental Systems Research Institute, 1993).

Bedrock geology (table 1; appendix) was derived from 1:20,000 scale USGS geologic maps (Seiders, 1971; Monroe, 1963, 1973, 1977; Pease, 1968a, 1968b; Pease and Monroe, 1977). Each rock type was classified into three geologic groups using the HAZUS method, which was derived from Wieczorek and others (1985) (table 2). Slope angle was generated from USGS digital line graph topographic data, using the Arc/Info subsystem GRID, and was grouped into six slope classes: 3-10, 10-15, 15-20, 20-30, 30-40, >40 degrees (table 3). All areas with slopes of less than 3 degrees were omitted from consideration as they are too flat for the HAZUS model.

**Table 1.** Bedrock types in the San Juan metropolitan area, Puerto Rico. *Data from Seiders (1971), Monroe (1963, 1973, 1977), Pease (1968a, 1968b), and Pease and Monroe, (1977).*

| Geologic group | Bedrock type |
|---|---|
| A | Strongly cemented rocks, including Cretaceous and Tertiary marine-deposited sandstone, siltstone, and mudstone of volcanic origin, lavas, tuffs, breccias and conglomerates, intrusive rock (granodiorite, quartz diorite) and massive limestone without clay interbeds or extensive fracturing. |
| B | Weakly cemented rocks, including sandstone and gravel. |
| C | Shale, clayey limestone and marl, artificial fill, unconsolidated bay and lagoon fill, old landslides, Quaternary alluvium and terraces. |

**Table 2.** Landslide susceptibility of geologic groups (Wieczorek and others, 1985)
*[>, more than]*

| Geologic group | Slope angle (degrees) | | | | | |
|---|---|---|---|---|---|---|
| | 3-10 | 10-15 | 15-20 | 20-30 | 30-40 | >40 |
| A | None | III | VI | VII | VIII | VIII |
| B | V | VIII | IX | IX | IX | X |
| C | VII | IX | X | X | X | X |

**Table 3.** Distribution of hillslope angle in the San Juan metropolitan area, Puerto Rico
*[areas do not include water bodies; >, more than]*

| Hillslope angle (degrees) | Area (square kilometers) | Percent of land area |
|---|---|---|
| 0-3 | 255 | 45 |
| 3-10 | 118 | 21 |
| 10-15 | 60 | 11 |
| 15-20 | 55 | 10 |
| 20-30 | 59 | 11 |
| 30-40 | 16 | 3 |
| > 40 | 2 | 0 |
| Total area | 565 | 100 |

Ground-water conditions were considered as wet for all the metropolitan area quadrangles. This approach results in a relatively high level of susceptibility for the various combinations of bedrock and slope angle. It is appropriate, however, because of the relatively high annual rainfall in the San Juan metropolitan area, which ranges from 1,500 to 2,000 millimeters per year (U.S. Department of Commerce, 2000). In addition, the rainfall is well distributed at 4 to 11 percent of the annual total in any given month. Eight months out of the year, rainfall totals are 8 percent or more, and only 2 months, February and March, (5 and 4 percent, respectively) have less than 7 percent of annual rainfall. This means that most of the time, soil moisture conditions tend to be primed for failure in the event of an earthquake.

A spatial overlay of these data layers (geologic group and slope angle) was performed using Arc/Info software. The resulting polygons were then attributed with the corresponding susceptibility category (I to X). Quality control checks and verification plots were performed, and corrections were made as necessary. Metadata files were generated for a digital version of the map.

## RESULTS
Almost one-half (45 percent) of the San Juan metropolitan area is constructed on coastal plain and former wetlands, an extensive area with low relief and slopes of 0 to 3 degrees (table 3, fig. 2). These areas are not susceptible to earthquake-induced landsliding. These unconsolidated sediments, however, are highly susceptible to liquefaction or other seismic movement associated with non-sloping terrain (Santiago and Rodríguez, 1999).

The remaining 55 percent of the San Juan metropolitan area (mainly in the southern portion of the area) is on moderate to steep hillslopes (fig. 2), which are susceptible to earthquake-induced landsliding. Bedrock geology in the San Juan metropolitan area is classified predominately (57 percent) into the A group, which is considered to be less susceptible to earthquake-induced landsliding. In general, the A geologic group includes massive, strongly cemented sedimentary, volcanic, and intrusive rock types (tables 1, 4; appendix). The weakest rock types, classified into group C, are poorly consolidated clays, shales, alluvium, old landslides, and artificial fill and account for 40 percent of the San Juan metropolitan area. Bedrock in 6 percent of the San Juan metropolitan area is classified into group B, weakly cemented rocks including sandstones and gravels.

**Table 4.** Surface area of geologic groups in the San Juan metropolitan area, Puerto Rico
*[numbers do not add to 100 because of rounding]*

| Geologic group | Area (square kilometers) | Percent of land area |
|---|---|---|
| A | 288 | 51 |
| B | 36 | 6 |
| C | 228 | 40 |
| Water | 12 | 2 |
| Total | 565 | 100 |

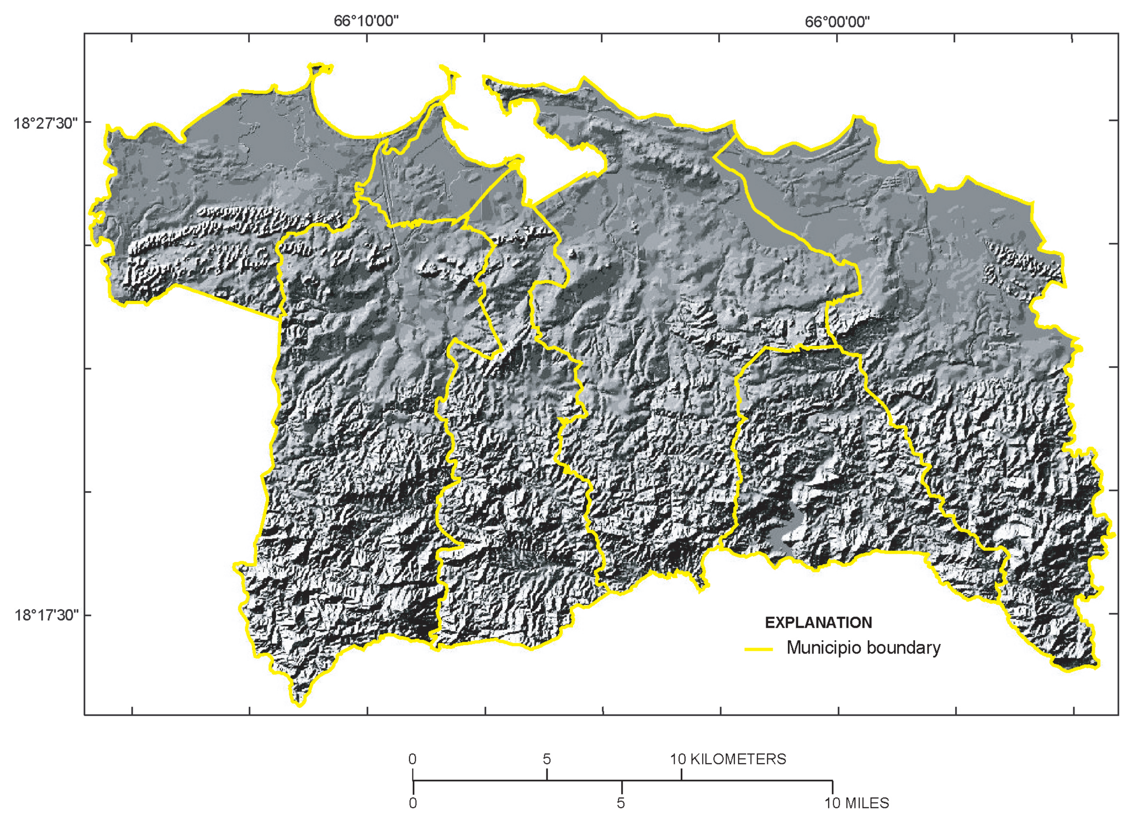


**Figure 2.** Shaded relief of the San Juan metropolitan area, Puerto Rico.
*Relief map was generated from Digital Line Graph data, U.S. Geological Survey, 1989.*

Earthquake-induced landslide susceptibility, classified as none, III, or V, is low to very low for most areas in the San Juan metropolitan area (see plate 2). These areas, shown in yellow, compose 68 percent of the San Juan metropolitan area (table 5). About 24 percent of the San Juan metropolitan area, shown in green, is classified as VI and VII, which can be considered as moderately susceptible to earthquake-induced landsliding. About 6 percent of the San Juan metropolitan area is mapped into the categories (VIII, IX, and X) that are most susceptible to earthquake-induced landslides, shown in tan orange, red and brown on plate 2. Most of the areas with the greatest susceptibility to earthquake-induced landslides are in the northern portions of the San Juan metropolitan area in Toa Baja, Bayamón, Guaynabo, and Carolina, where extensive Tertiary limestone outcrops have formed steep-sided hills known locally as mogotes. In general, the landslide type associated with these rocky, near-vertical sloping mogotes are small localized rockfalls (Larsen and Torres-Sánchez, 1998). As such, a significant portion of the greatest susceptibility is confined to small hazard areas on or directly adjacent to the mogotes.

**Table 5.** Surface area by landslide susceptibility group in the San Juan metropolitan area, Puerto Rico

| Landslide susceptibility | Landslide susceptibility code | Area (square kilometers) | Percent of land area |
|---|---|---|---|
| None | None | 322 | 57 |
| Lowest | III | 53 | 9 |
| | V | 12 | 2 |
| | VI | 51 | 9 |
| | VII | 82 | 15 |
| | VIII | 17 | 3 |
| | IX | 7 | 1 |
| Highest | X | 9 | 2 |
| | Water | 12 | 2 |
| | Total area | 565 | 100 |

## CONCLUSION
A map showing earthquake-induced landslide susceptibility for the San Juan metropolitan area is essential for good decision making at local, regional, and national levels of government to accurately estimate losses from potential earthquakes. Most of the San Juan metropolitan area is not susceptible to earthquake-induced landslides, according to a simplified analysis of slope angle and rock type. Much of the area that is most susceptible is confined to the immediate vicinity of steep-sided Tertiary limestone hills. Almost one-quarter (24 percent) of the San Juan metropolitan area is moderately susceptible to earthquake-induced landslides. These areas are mainly in the southern portions of the San Juan metropolitan area, where housing development pressures are currently high because of land availability and the esthetics of greenery and hillside views. It is in this region that the combination of new development and earthquake-induced landslide susceptibility may be of greatest concern.

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**Appendix.** Geologic codes, groups, and descriptions from geologic quadrangle maps within the San Juan metropolitan area, Puerto Rico. Data from Seiders (1971); Monroe (1963, 1973, 1977) Pease (1968a, 1968b) and Pease and Monroe (1977).

| Geologic code | Geologic group | Description from geologic quadrangle map |
|---|---|---|
| af | C | Artificial Fill |
| Kb | A | Barrazas Formation |
| Kc | A | Camarones Sandstone |
| Kcb | A | Cambalache Formation |
| Kcbv | A | Cambalache Formation, Toma de Agua Vitrophyre Member |
| Kcf | A | Camarones Sandstone, Flow beneath the Mamey Lava |
| Kcf | A | Camarones Sandstone, Lava Member |
| Kcg | A | Cerro Gordo Lava |
| Kcgt | A | Cerro Gordo Lava, bedded Tuff Member |
| Kcl | A | Camarones Sandstone Limestone Lens |
| Kcl | A | Celada Formation |
| Kcm | A | Camarones Sandstone, Mamey Lava Member |
| Kcn | A | Cancel Breccia |
| Kco | A | Canóvanas Formation |
| Ke | A | El Ocho Formation |
| Keb | A | El Ocho Formation, Breccia Member |
| Kep | A | El Ocho Formation, Piña Siltstone Member |
| Kes | A | El Ocho Formation, Bedded Calcareous Sandstone Member |
| Kf | A | Frailes Formation |
| Kff | A | Frailes Formation, Lava Flow |
| Kfl | A | Frailes Formation, Leprocomio Mudstone Member |
| Kg | A | Guaynabo Formation, |
| Kgb | A | Guaynabo Formation Basalt |
| Kgf | A | Guaynabo Formation, Andesite Member |
| Kgl | A | Guaynabo Formation, Leprocomio Siltstone |
| Kgl | A | Leprocomio Siltstone Member |
| Kgll | A | Guaynabo Formation Limestone |
| Kgm | A | Guaynabo Formation, Martín González Member |
| Kgm | A | Martín González Lava |
| Khp | A | Hato Puerco Formation |
| Khpb | A | Hato Puerco Formation, Breccia Member |
| Khpl | A | Hato Puerco Formation, Lava Flow |
| Kil | A | Infierno Formation, Lava Member |
| Kim | A | Infierno Formation, Mudstone Member |
| Kiv | A | Infierno Formation, Volcaniclastic rocks |
| Kl | A | La Muda Formation |
| Kl | A | Lomas Formation |
| Klc | A | La Muda Formation, Conglomerate |
| Kll | A | La Muda Formation Limestone |
| Kll | A | Lomas Formation, Lava Flow |
| Km | B | Monacillo Formation |
| Kmg | A | Martín González, Lava |
| Kml | B | Small Limestone Lens |
| Kmt | B | Monacillo Formation, Trujillo Alto Limestone Member |
| Kmt | B | Trujillo Alto Limestone Member |
| Kn | A | Los Negros Formation |
| Kpa | A | Pájaros Tuff, |
| Kr | A | Río de la Plata Sandstone |
| Krc | A | Río de la Plata Sandstone, Conglomerate Member |
| Krf | A | Río de la Plata Sandstone, Lava Member |
| Ks | A | Santa Olaya Lava |
| Ksb | A | Santa Oyala Lava, Breccia Member |
| Ksp | A | Santa Oyala Lava, Pyroxene Lava Member |
| Kss | A | Santa Olaya Lava, Bedded volcanic rocks |
| Kt | A | Tortugas Andesite |
| Ktl | A | Tortugas Andesite, Limestone |
| Kts | A | Tortugas Andesite, Siltstone Member |
| Kz | A | Carraízo Breccia |
| Kzs | A | Carraízo Breccia, Volcanic Wacke Member |
| Qa | C | Alluvium |
| Qa | C | Alluvium and River Terrace Deposits |
| Qal | C | Alluvial Deposits |
| Qat | C | Alluvial and Terrace Deposits |
| Qb | B | Beach deposits |
| Qbq | C | Beach Deposits (Holocene and Pleistocene) |
| Qe | A | Eolianite |
| Qf | C | Alluvial Fan |
| Ql | C | Landslide Deposits |
| Qls | C | Landslide Debris |
| Qr | B | Reef Deposits |
| Qrt | C | River Terrace Deposits |
| Qs | C | Swamp Deposits |
| Qss | C | Silica Sand |
| Qt | C | River - Terrace Deposits |
| Qt | C | Older Terrace Deposits |
| QTb | C | Blanket Deposits |
| QTt | C | High Terrace and Alluvial-Fan Deposits |
| QTt | C | Older Alluvial Deposits |
| Ta | C | Aguada Limestone |
| Tay | A | Aymamón Limestone |
| Tc | B | Cibao Formation |
| Tcq | B | Cibao Formation, Quebrada Arenas Limestone Member |
| Tcr | B | Cibao Formation, Río Indio Limestone Member |
| Tcu | C | Cibao Formation, Upper Member |
| Td | A | Diabase |
| Td | A | Pyroxene Diorite |
| Tg | A | Guaracanal Andesite |
| Tgb | A | Guaracanal Formation, Basalt |
| Tgl | A | Guaracanal Andesite, Limestone |
| Tgl | A | Guaracanal Formation, Limestone Member |
| Tgm | A | Guaracanal Formation, Mudstone Member |
| Tgv | A | Guaracanal Andesite, Vitrophyre |
| TKa | B | Andesite Dike |
| TKd | A | Quartz Diorite |
| TKh | B | Hydrothermally Altered Rocks |
| TKk | A | Keratophyric Dike |
| TKm | A | Monacillo Formation |
| TKmb | A | Monacillo Formation, Basalt |
| TKmi | A | Quartz Diorite Porphyry |
| TKmt | A | Monacillo Formation, Trujillo Alto Limestone Member |
| TKp | A | Hornblende Porphyry |
| Tm | B | Mucarabones Sand |
| Tn | A | Naranjito Formation |
| Tr | A | Río Piedras Siltstone |
| Trc | A | Río Piedras Siltstone, Coarse Grained Member |
| Trl | A | Río Piedras Siltstone, Limestone Member |
| Trs | A | Río Piedras Siltstone, Siltstone Member |
| Tru | A | Río Piedras Siltstone, Upper Member |
| Ts | C | San Sebastián Formation |