EVALUATION OF TEMPORAL AND SPATIAL FACTORS THAT CONTROL THE SUSCEPTIBILITY TO RAINFALL-TRIGGERED LANDSLIDES

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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 [37]. Landslides can include falls, topples, slides, spreads, and flows [9]. Shallow landslides usually 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 natural 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 and their inhabitants on or near hillslopes may be in jeopardy if geologic, hydrologic, and climatologic conditions are conducive to landsliding.

Landslides frequently occur in association with the same types of intense or prolonged rainstorms that cause flash flooding. Debris flows are one of the most common types of landslides and they tend to occur during or immediately after the same rainstorms that result in flash flooding [19]. Unlike flash floods, whose hazard zone is usually in or near perennial and ephemeral stream channels, landslides have less predictable hazard zones. The sites of debris-flow initiation depend upon hillslope characteristics such as bedrock geology, soil thickness, strength, and permeability, antecedent soil moisture, slope angle, and slope curvature. The runout or travel distance of debris flows depends mainly on volume and velocity of the debris flow and the topography of the hillslope. Thus, delineation of hazard zones for debris flows is therefore a complex task and includes a higher degree of spatial uncertainty than that of flood or flash-flood hazard zones.

Determination of landslide susceptibility has taken a variety of approaches, some of which are outlined below. In addition, a description of methods that were used by the author in Puerto Rico to estimate the temporal and spatial controls on landsliding is presented. The purpose of this chapter is to summarize some basic approaches to

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assessment of landslide susceptibility and to provide the reader with the appropriate references for further investigation of this topic.

2. Example Approaches to the Assessment of Landslide Susceptibility

A variety of methods have been used to evaluate landslide susceptibility [1,2,8,11,17, 18,22,27,29,30,32,36]. Some of these are reviewed here. In almost every case, the first step is to map landslide locations on topographic maps using ground surveys, stereo aerial photographs, or, if the landslide features are large enough, satellite imagery [13,19,44]. Recent landslides can be observed on aerial photographs as a break in the forest canopy, bare soil, or other geomorphic characteristics typical of landslide scars, *ie.* head and side scarps, flow tracks, and soil and debris deposits below the scar [44]. Many areas of the world have aerial photograph coverage that dates to the first few decades of the 20th century. If multiple photograph sets are available, the number of landslides per unit time (or the percent area involved in landsliding) can be estimated by determination of the presence or absence of landslide scars in a series of photographs.

An overview of landslide hazard and risk assessment by Wu *et al.*, [47] noted that when there is uncertainty in the assessment of landslide hazard, the conventional approach is to make conservative estimates of design parameters. The common sources of uncertainty are the environmental, i.e. a particular storm, and site, or local geotechnical conditions. An initial requirement of landslide hazard assessment is the knowledge of where landslides have previously occurred [24]. Taylor and Brabb [40] published a map showing California landslides that caused fatalities or at least $1 million in damages between 1906 and 1984. Their objective was to help determine priorities for landslide mapping, mitigation measures, and preparedness planning. Once the basic information of landslide location is determined, the factors that contribute to landslide occurrence can be assessed. In a study of debris flows triggered by intense rainfall in Madison County, Virginia, Morgan *et al.* [33] determined that slope, pre-existing low-order stream channels, and the amount and intensity of precipitation were the critical factors controlling landslide hazard. Their work indicated that because of the extremely high rainfall, as much as 750 mm in 16 h, within a uniform bedrock geology, slope aspect, and land use had little or no influence on the sites of debris flows. Brunori *et al.* [3], working in Tuscany, Italy, evaluated the relative influence of land use, slope gradient, and lithology and developed a statistically-based approach for ranking the factors that contribute to landsliding. A method was proposed for the Cincinnati, Ohio area by Bernknopf *et al.* [1], which used regional geologic, and topographic information, mainly slope angle and property values, for evaluating the economic cost-benefit ratio of landslide mitigation.

In steeply sloping areas where the potential for landsliding is high, knowledge of the rainfall conditions that are likely to trigger widespread landslide activity is critical for public safety. This information enables emergency managers to know where landslides are most probable. The common approach has been to quantify the accumulation (or intensity) and duration of each rainstorm associated with documented landslides, which are usually debris flows [19,45]. If enough landslide-triggering storms have been recorded, a rainfall threshold (see below) can be defined [4,21,25,34,45]. A rainfall threshold is a simple empirical model that describes the rainfall conditions that are likely to trigger landsliding. Keefer *et al.*, [21] report on the development of a real-time alert system in the San Francisco Bay area, California. This system combined a rainfall threshold, a real-time network of rain gages, and National Weather Service (NWS) estimates of rainfall in approaching storms to provide public warnings when abundant landsliding (presumed to be predominantly debris flows) was imminent. A generalized worldwide threshold was developed by Caine [4] using 73 storms for a variety of landslide types. This threshold describes the rainfall conditions in a variety of land uses and environments from alpine, to temperate, mediterranean and tropical. A number of researchers have characterized landslide-triggering storms by rainfall duration and intensity has been used to establish a relation between storms and landslides in temperate areas of the world [5,6,7] and in humid-tropical areas [10,14,15,20,31,38,39, 41,43,46]. Using a data set of 256 storms Larsen and Simon [25] developed a rainfall intensity-duration threshold for triggering of landslides in a humid-tropical climate in Puerto Rico. This work is described below.

3. Assessment of Temporal Controls on Landsliding

The temporal controls on landsliding are defined by the accumulation and duration of the rainfall that induced the landslide activity as well as the antecedent soil moisture conditions in the area where the landslides occurred. In humid regions, particularly in the tropics where the frequency of landslide-triggering storms is high, the average rainfall conditions required for the initiation of landsliding can be determined by using records that represent a period of years or perhaps a few decades. In arid to semi-arid regions where landslides may be a less common phenomena, a longer record may be required. In all but the most humid environments, the antecedent soil moisture is an integral element in the development of a rainfall threshold for landsliding [46]. Because the cost of monitoring soil moisture is prohibitive in many areas, daily or weekly rainfall accumulation is often substituted as a surrogate. An alternative measure of ambient moisture conditions is streamflow. Streamflow in small to moderately sized watersheds responds relatively quickly to soil and ground water conditions.

A threshold of rainfall intensity-duration was developed using the characteristics of 41 storms that triggered recent landslides in the central mountains of Puerto Rico [25] and additional storms (215) that did not cause landsliding. A relation between rainfall accumulation-duration and landsliding was established which is described by a line fitted visually to the lower boundary of those points representing storms that triggered landslides, is expressed as:

$$I = 91.46\ D^{-0.82} \qquad (1)$$

where I is rainfall intensity in millimeters per hour, and D is duration in hours. This line reflects the approximate minimal rainfall conditions necessary to trigger landsliding (Figure 1). Converting I to R, rainfall accumulation in mm (1) is equal to:

$$R = 91.46\ D^{0.18} \qquad (2)$$

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 accumulated rainfall required ranges from 102 to 257 mm and the median storm is 193 mm [25]. The duration of landslide-triggering storms ranged from 2 and 312 h, and average rainfall intensities between 1 and 110 mm/h. The threshold relation indicates that for storms of short duration (10 h or less), rainfall intensities higher than 14 mm/h are required to trigger landslides. Low average rainfall intensities of 2 to 3 mm/h appear to be sufficient to cause landslides such as earth flows and rotational slumps as storm durations approach approximately 100 h.

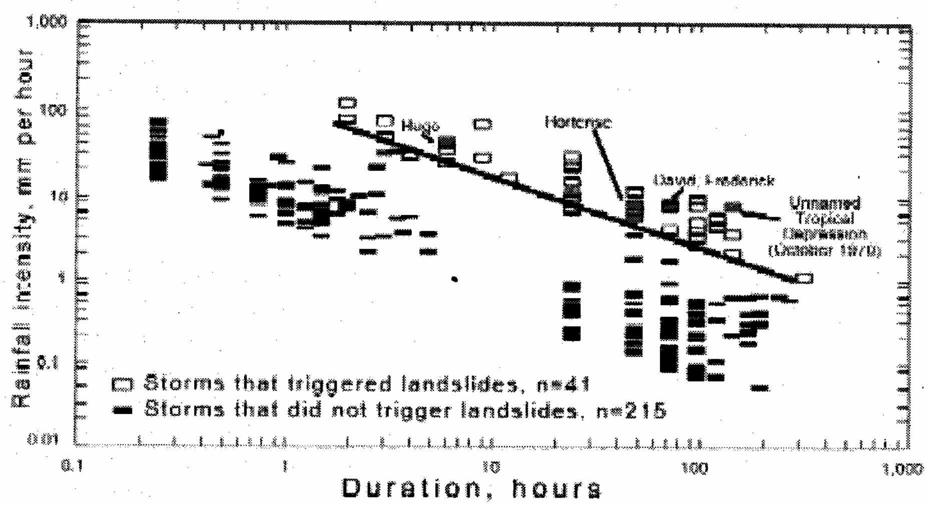

Figure 1. Relation between average rainfall intensity in millimeters and duration in hours for 256 storms dating from 1959 to 1991 in Puerto Rico. The line represents an intensity-duration threshold (lower bound) for storm rainfall that triggered 10's to 100's of landslides. The equation for the line is $I = 91.46D^{-0.82}$ where I is rainfall intensity and D is rainfall duration (figure modified from Larsen and Simon [25].

Rainfall records from governmental archives (i.e., the U.S. National Weather Service) of hourly and daily precipitation were the most dependable source of data for use in developing the rainfall threshold. Storms were selected from this data source only if total rainfall accumulation and duration, and the occurrence or non-occurrence of landslides could be established. Landslide occurrence for selected storms was verified in some cases by using archival newspaper accounts of storm damage when no other data source was available. This is not an unreasonable approach if the timing and location of the landslides is accurate.

4. Assessment of Spatial Controls on Landsliding

If emergency managers can determine when landslides are likely to occur by using a rainfall intensity-duration threshold, they also must know where the landslides are most probable. As noted above, hillslope angle is often the most important geographic factor controlling whether or not landslides will occur. In some cases, slope angle and knowledge of rainfall intensity may be all that is necessary to adequately predict where landslides are most probable [33]. Bedrock geology is important in some areas, particularly with regard to the geotechnical characteristics of the soil and rock types. Geotechnical discontinuities such as joint planes, foliations, bedding planes, weathering planes, and shale/slate cleavage can provide slip surfaces in rock or weathered rock [16]. In humid-tropical regions, the effects of bedrock may be muted or eliminated if weathering is deep and advanced; lithology is often of only marginal importance because of the geotechnical similarities among weathered bedrock types [35]. This degree of weathering may reduce the geotechnical effects of the original rock structure. In these environments, many rainfall-triggered landslides affect only the weathered material, such as saprolite or regolith.

In Puerto Rico, Larsen and Torres-Sánchez [28] used a combination of the angle, aspect, and elevation of a hillslope as well as the generalized land use type to categorize landslide frequency. Hillslope aspect was determined to be important because of the abundance of rainfall delivered by trade winds that are dominantly from the east and north east. The increase in the frequency of landslides with increasing elevation results from the greater mean annual rainfall recorded at higher elevations throughout the island [32]. In addition, mean monthly soil moisture is generally greater at higher elevations in part because evapotranspiration losses and temperature are lower and average cloud cover is greater. The generally wetter soil conditions at high elevation sites in Puerto Rico may mean that not much additional soil water is required to increase soil pore pressure sufficiently to trigger landslides. Finally, the influence of land use has been documented in a number of studies [20,26,29]. In Puerto Rico, land use was simplified into three categories: forest, agriculture, and developed (roads, structures) [28]. 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, and diversion or concentration of drainage. Both practices tend to increase shear stress in the ground beneath the slope [42]. This results in increased landslide probability, other factors being equal. In contrast, areas in forest generally have the lowest landslide frequency. Nonetheless, if rainfall intensity is extreme, the effects of land use may be negligible, as noted by Morgan *et al.* [33].

4.1. ASSESSING LANDSLIDE SUSCEPTIBILITY

The development of geographic information system (GIS) software during the past several decades has enhanced the making of landslide susceptibility maps [12]. GIS software allows for spatial delineation and analysis of the geographic categories that are associated with landslides mapped from aerial photographs. A detailed description of the technique described below and used in study areas in Puerto Rico is found in [28]. This approach is typical of many in that it assumes that areas that have been susceptible to landslides in the past will continue to be so. This is a reasonable assumption except in the most extreme cases where an episode of landsliding fundamentally alters important topographic characteristics such as hillslope angle, drainage patterns, or soil thickness over a large area.

Most GIS analyses of landslide locations result in a large number of categories (i.e. subdivisions of slope angle, slope aspect, elevation, slope form, land use, bedrock geology, soil type, etc.) for each topographic or geographic element. Given the number of landslides usually mapped in a study area, the large number of categories is too many to permit a meaningful determination of the control that geographic categories exert on the frequency of landslides over time. A simplification or grouping of categories is necessary.

Each topographic or geographic category can be simplified into two or three subdivisions for analysis. In Puerto Rico, for example, the simplification of hillslope angle was accomplished by combining slope angle into low (12 degrees or less) and high (greater than 12 degrees). Hillslopes of greater than 12 degrees had, on average, double the frequency of landslides that was calculated for hillslopes of 12 degrees or less [28]. The simplification of geographic categories results in a more manageable number of combinations of hillslope types.

Using GIS software, a grid with a point spacing on the order of 50 to 300 m (depending on the size and scale of the mapping of the study area and the number of mapped landslides) can be overlain with each geographic coverage for each study area (Figure 2). This permits the determination of which of the possible categories of hillslope types exist at each grid point. Each grid point is assumed to represent the center of a cell with an area of several hundred to a few thousand square meters. Using the geographic coverage showing land use, for example, the cells are designated as forest or agricultural land use if the GIS software determined that the cell coincided with an area that was predominantly in forest or agriculture. 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. However, the trends of the frequency of landslides for the Puerto Rico study area were consistent with the pre-simplification analysis, and indicate that this land use reclassification was reasonable [28]. Larsen and Parks [26] determined that within 85 m on either side of roads in the Luquillo mountains, Puerto Rico, the rate of mass-wasting was 5 to 8 times higher than that in forested areas.

Cells with the same combination of categories were added together to determine the approximate total area for each of the several dozen combinations, or hillslope types. The number of landslides in each of the hillslope types was then divided by the total area, in square kilometers, for that same type of hillslope. This normalized the frequency of landslides for each type of hillslope, resulting in the number of landslides per square kilometer. If sets of aerial photographs for multiple years were used in the analysis, the number of landslides per square kilometer per year or decade can be estimated.

4.2. MAKING A LANDSLIDE SUSCEPTIBILITY MAP

After a methodology for assessing landslide susceptibility, such as that described above has been developed, the results can be used to classify mountainous areas on a map (Figure 3). Using a grid, or raster GIS approach, each grid cell in the area in question can be classified into the hillslope types described above (Figure 2). Landslide susceptibility can be quantified by listing the average number of landslides per square kilometer per decade for each hillslope type [27]. In some instances this may be too confusing for the map user and a more qualitative display of landslide susceptibility may be adopted. Typical approaches have used two or three degrees of susceptibility, such as low and high, or low, moderate, and high, ranked according to the number of landslides per square kilometer per decade (Figure 4).

5. Summary

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

A relatively simple approach to estimating the frequency and distribution of landslides using aerial photography and a GIS is a useful first step in characterizing landslide susceptibility. The approach described above is an example of a technique for the analysis of landslide hazards that is easily transferable to other settings. The advantages of the method include its computational simplicity and the ability to integrate important controls on the frequency of landslides in a heterogeneous environment.

These generalized approaches permit the evaluation of the temporal and spatial factors that control the susceptibility to rainfall-triggered landslides. Landslides, and debris flows in particular, are common in areas susceptible to flash flooding. Integrated planning tools such as susceptibility maps showing areas vulnerable to flash flooding and landslides are essential for effective disaster mitigation. It is hoped that the methods outlined herein will be useful for emergency managers and planners in both the developed and developing world.

1. Map landslide locations from aerial photographs and field surveys.
2. Create grid of 'cells' over map showing landslide locations in study area.
3. Use GIS to classify the topographic, geographic, geologic characteristics, and the presence or absence of landslide scars in each 'cell' in a grid.
4. Sort the resulting cell groups to determine which types of cells have the greatest, average, and least number of landslide scars. (example of cell type in Puerto Rico with highest number of landslide scars: steep slope angle, high elevation, windward aspect, anthropogenically altered landscape)
5. Assumption: past landslide frequency equates with future susceptibility. Use GIS to classify each cell in study area into high, medium, and low landslide

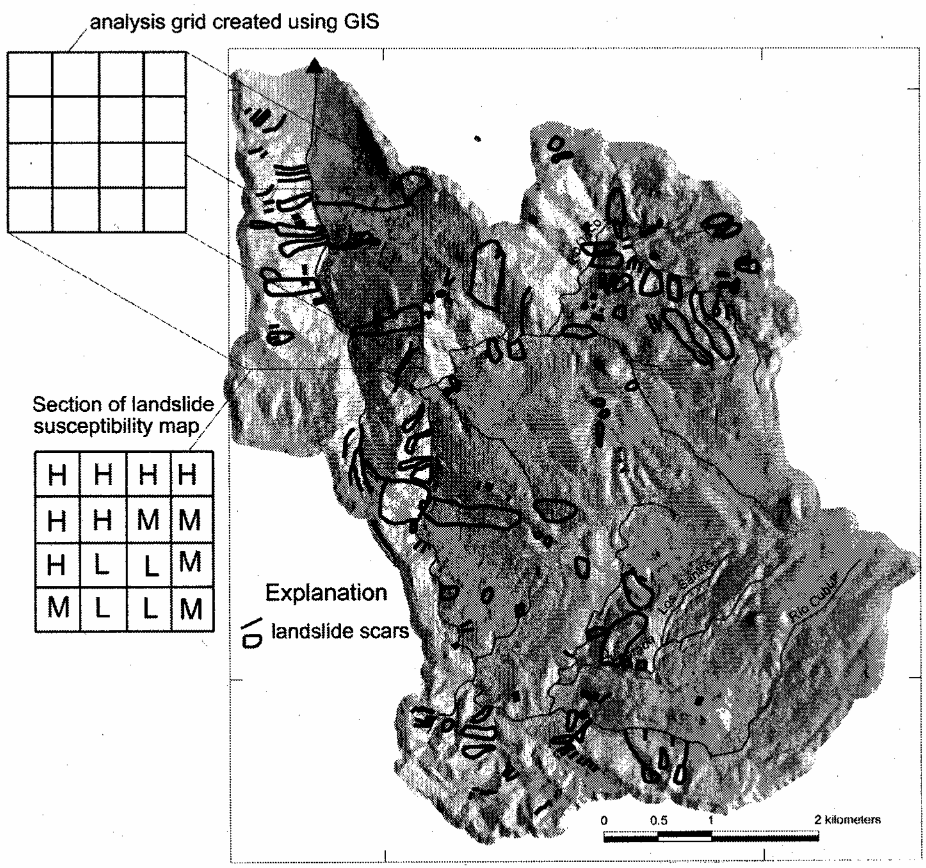

Figure 2. Method for creation of a landslide susceptibility map using landslides mapped from aerial photographs (example using shaded relief map of Canóvanas watershed, eastern Puerto Rico, showing roads, rivers, and the location of 216 landslide scars mapped from 1937 and 1995 aerial photographs).

Figure 3. Aerial photograph of Comerio, Puerto Rico, 1991, with site of landslide susceptibility map shown in Figure 4.

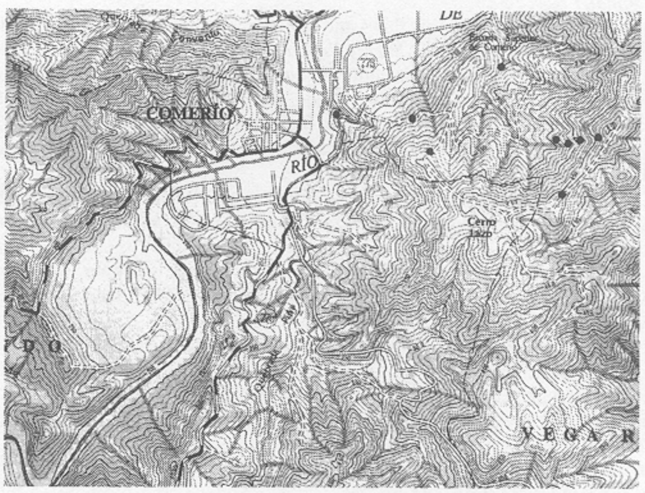

Figure 4. Example of a landslide susceptibility map, Comerio, Puerto Rico, excerpted from Larsen and Parks [27]. Dark gray areas show zones of high landslide susceptibility, medium gray areas are zones of moderate landslide susceptibility, and light gray areas are zones of low landslide susceptibility. Short dark lines indicate ephemeral drainages where debris flows are probable. Black dots are dip slopes: areas where bedrock bedding planes and hillslope angles are approximately parallel.

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7. References

1. Bernknopf, R.L., Campbell, R.H., Brookshire, D.S., and Shapiro, C.D. (1988) A probabilistic approach to landslide hazard mapping in Cincinnati, Ohio, with applications for economic evaluation, *Bulletin of the Association of Engineering Geologists* 25 39-56.
2. Brabb, E.E., Pampeyan, E.H., and Bonilla, M.G. (1972) Landslide susceptibility in San Mateo County, California, *U.S. Geological Survey*, 4 p.
3. Brunori, F., Casagli, N., Fiaschi, S., Garzonio, C.A., and Moretti, S. (1996) Landslide hazard mapping in Tuscany, Italy: an example of automatic evaluation *in* Slaymaker, Olaf, ed., Geomorphic Hazards, J.Wiley and Sons, New York, p. 55-67.
4. Caine, N. (1980) The rainfall intensity-duration control of shallow landslides and debris flows, *Geografiska Annaler* 62A 23-27.
5. Campbell, R. H. (1975) Soil slips, debris flows and rainstorms in the Santa Monica Mountains and vicinity, southern California, *U.S. Geol. Survey Prof. Paper* 851 51 pp.
6. Cannon, S. H. (1988) Regional rainfall-threshold conditions for abundant debris-flow activity, in S.D. Ellen and Wieczorek, G. F., (eds.) Landslides, floods, and marine effects of the storm of January 3-5, 1982, in the San Francisco Bay region, California, *U.S. Geol. Survey Prof. Paper* 1434 35-42.
7. Cannon, S. H. and Ellen, S. D. (1985) Rainfall conditions for abundant debris avalanches, San Francisco Bay region, California, *California Geology* 38 267-272.
8. Carrara, A., Cardinali, M., Detti, R., Guzzetti, F., Pasqui, V., and Reichenbach, P. (1991) GIS techniques and statistical models in evaluating landslide hazard, *Earth Surface Processes and Landforms* 16 427-445.
9. Cruden, D.M. and Varnes, D.J. (1996) Landslide types and processes in Turner, A.K., and Schuster, R.L, eds., *Landslides, investigation and mitigation*: Special Report 247, Transportation Research Board, National Academy Press, Washington, D.C. 36-75.
10. DeGraff, J. V. (1990) Landslide dams from the November 1988 storm event in southern Thailand, *Landslide News*, Japan Landslide Society, Tokyo 4 12-15.
11. Ellen, S., Peterson, D.M., and Reid, G.O. (1982) Map showing areas susceptible to different hazards from shallow landsliding, Marin County and adjacent parts of Sonoma County, California, *U.S. Geological Survey map* MF 1406.
12. ESRI (1993) *Understanding GIS-- The ARC/INFO method*: Environmental Systems Research Institute, Inc., J. Wiley and Sons, New York, 535 p.
13. Guariguata, M.R and Larsen, M.C. (1990) Preliminary map showing landslides in El Yunque quadrangle, Puerto Rico, *U.S. Geological Survey Open-file report* 89-257.
14. Guidicini, G. and Iwasa, O.Y. (1977) Tentative correlation between rainfall and landslides in a humid tropical environment, *Bull. of the International Assoc. of Eng. Geol.* 16 13-20.

15. Haldemann, E.G. (1956) Recent landslide phenomena in the Rungwe volcanic area, Tanganyika, *Tangányika Notes Records* 43 3-14.
16. Hencher, S.R. (1987) The implications of joints and structures for slope stability, in M.G. Anderson and K.S. Richards, (eds.), *Slope stability*, John Wiley and Sons, New York, 145-186.
17. Irigaray F., C., del Castillo, T., El Hamdouni, R., and Chacon Montero, J. (1999) Verification of landslide susceptibility mapping: a case study, *Earth Surface Processes and Landforms* 24 537-544.
18. Jager, Stefan and Wieczorek, G.F. (1994) Landslide susceptibility in the Tully Valley area, Finger Lakes region, New York, *U.S. Geological Survey Open-file report* 94-615.
19. Jibson, R. W. (1989) Debris flows in southern Puerto Rico, *Geol. Soc. of Amer. Special Paper* 236 29-55.
20. Jones, A. (1973) Landslides of Rio de Janeiro and the Serra da Araras escarpment, Brazil, *U.S. Geol. Survey Prof. Paper* 697 42 pp.
21. Keefer, D. K., Wilson, R. C., Mark, R. K., Brabb, E. E., Brown, W. M. III, Ellen, S. D., Harp, E. L., Wieczorek, G. F., Alger, C. S., and Zatkin, R. S. (1987) Real-time landslide warning during heavy rainfall, *Science* 238 921-925.
22. Kingsbury, P.A., Hastie, W.J., and Harrington, C.D. (1991) Regional landslip hazard assessment using a Geographic Information System in Bell, D.H., (ed.), Landslides, *Proceedings of the Sixth International Symposium*, February 10-14, 1992, Christchurch, New Zealand, Balkema Pub., Rotterdam, 995-999.
23. Larsen, M.C., Collar, P.D., and Stallard, R.F. (1993) Research plan for the investigation of water, energy, and biogeochemical budgets in the Luquillo mountains, Puerto Rico, *U.S. Geological Survey Open-file Report* 92-150 19 p.
24. Larsen, M. C. and Torres-Sánchez, A. J. (1992) Landslides triggered by Hurricane Hugo in eastern Puerto Rico, September 1989, *Caribbean Journal of Science* 28 113-125.
25. Larsen, M.C. and Simon, A. (1993) Rainfall-threshold conditions for landslides in a humid-tropical system, Puerto Rico, *Geografiska Annaler* 75A 13-23.
26. Larsen, M.C. and Parks, J.E. (1997) How wide is a road? The association of roads and mass-wasting disturbance in a forested montane environment, *Earth Surface Processes and Landforms* 22 835-848.
27. Larsen, M.C. and Parks, J.E. (1998) Map showing landslide hazards in the municipality of Comerio, Puerto Rico, *U.S. Geological Survey Open-file Report* 98-566, 1 sheet.
28. Larsen, M.C. and Torres Sanchez, A.J. (1998) The frequency and distribution of recent landslides in three montane tropical regions of Puerto Rico, *Geomorphology* 24 309-331.
29. Maharaj, R.J. (1993) Landslide processes and landslide susceptibility analysis from an upland watershed: a case study from St. Andrew, Jamaica, West Indies, *Engineering Geology* 34 53-79.
30. Mehrotra, G.S., Sarkar, S., and Dharmaraju, R. (1991) Landslide hazard assessment in Rishikesh-Tehri area, Garhwal Himalaya in Bell, D.H., ed. Landslides, *Proceedings of the Sixth International Symposium*, February 10-14, 1992, Christchurch, New Zealand, Balkema Pub., Rotterdam, 1001-1007.
31. de Meis, R.M. and Silva, R. (1968) Mouvements de mass récents a Rio de Janeiro: une étude de géomorphologe dynamique, *Rév. Géomorph. Dynamique* 18 145-151.
32. Monroe, W.H. (1979) Map showing landslides and areas of susceptibility to landsliding in Puerto Rico, *U.S. Geological Survey Miscellaneous Investigations Series Map* I-1148 1 sheet, 1:240,000 scale.
33. Morgan, B.A., Wieczorek, G.F., and Campbell, R.H. (1999) Map of rainfall, debris-flows, and flood effects of the June 27, 1995, storm in Madison County, Virginia, *U. S. Geological Survey Miscellaneous Investigation Series Map* I-2623A, 1:24,000.
34. Neary, D. G. and Swift, L. W. (1987) Rainfall thresholds for triggering a débris avalanching event in the southern Appalachian Mountains, in J. E. Costa and G. F. Wieczorek (eds.), Debris Flows/Avalanches: Processes, Recognition and Mitigation, *Geol. Soc. of America: Reviews in Engineering Geology*, 7 81-92.
35. Pitts, J. (1992) Slope stability in Singapore, in A.Gupta and J. Pitts, (eds.), *Physical adjustments in a changing landscape, The Singapore story*, Singapore University Press, Singapore, 259-300.
36. Pomeroy, J.S. (1988) Map showing landslide susceptibility in Maryland, *U.S. Geological Survey* MF-2048.
37. Schuster, R.L. (1978) Introduction, in Schuster, R. L., and Krizek, R. J., (eds.), *Landslides, analysis and control*: National Research Council, Transportation Research Board Special Report 176, p. 1-10.
38. So, C.L. (1971) Mass movements associated with the rain storm of June 1966 in Hong Kong, *Trans. Inst. Brit. Geographers* 53 55-65.

39. Starkel, L. (1970) Cause and effects of a heavy rainfall in Darjeeling and in the Sikkim Himalayas, *Jour. Bombay Natural History Soc.* 67:1-6.
40. Taylor, F. and Brabb, E.E. (1986) Map showing landslides in California that have caused fatalities or at least $1,000,000 in damages from 1906 to 1984, *U.S. Geological Survey Miscellaneous Field Studies Map* MF-1867, one sheet.
41. Temple, P. H. and Rapp, A. (1972) Landslides in the Mgeta area, Western Uluguru Mountains, Tanzania, *Geografiska Annaler* 54A 157-193.
42. Terzaghi, K. (1950) Mechanism of landslides, *Geological Society of America, Engineering Geology*, Berkey volume, 83-123.
43. Wentworth, C.K. (1943) Soil avalanches on Oahu, Hawaii, *Bull. Geol. Soc. Amer.* 54 53-64.
44. Wieczorek, G.F. (1984) Preparing a detailed landslide-inventory map for hazard evaluation and reduction, *Bulletin of the Association of Engineering Geologists* 21 337-342.
45. Wieczorek, G. F. (1987) Effect of rainfall intensity and duration on debris flows in central Santa Cruz Mountains, California, in J. E. Costa and G. F. Wieczorek, (eds.), Debris Flows/Avalanches: Processes, Recognition and Mitigation. *Geol. Soc. of America, Reviews in Engineering Geology* 7 93-104.
46. Wilson, R.C., Torikai, J. D., and Ellen, S. D. (1992) Development of rainfall warning thresholds for debris flows in the Honolulu district, Oahu, *U.S. Geol. Survey Open-file report* 92-521 35 pp.
47. Wu, T.H., Tang, W.H., and Einstein, H.H. (1996) Landslide hazard and risk assessment in Turner, A.K., and Schuster, R.L, eds., *Landslides, investigation and mitigation*: Special Report 247, Transportation Research Board, National Academy Press, Washington, D.C. 106-118.