2001, in E. Gruntfest and J. Handmer, eds., Coping with Flash floods, Kluwer Academic Publishers, p. 259-275.

LANDSLIDE HAZARDS ASSOCIATED WITH FLASH-FLOODS, WITH EXAMPLES FROM THE DECEMBER, 1999 DISASTER IN VENEZUELA

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Introduction

Throughout history, landslides and flash floods have episodically affected human settlements in or near steeply sloping areas susceptible to heavy rainfall. These two types of natural hazard are closely related and are commonly triggered simultaneously by intense or prolonged rainfall at or near steep mountain fronts. As global population has increased, economic losses and the loss of life have risen because of occupation and development of areas vulnerable to landslides and flash floods [1, 38]. Recent examples have been documented in the Campania region of Italy (1998), Acapulco, Mexico (1997), Honduras and Nicaragua (1998), eastern Mexico (1999), and northern Venezuela (1999).

Intense rainfall can cause sudden and often unexpected flash flooding that sometimes affects urban and rural communities. At the same time, rainfall may trigger mass movements that damage structures on or near hillslopes and contribute to hyperconcentrated flows and water floods with high sediment loads (fig. 1). The combined result heightens risk to inhabitants, increases property damage, and may increase the number of fatalities. Mass-movement events associated with flash floods are usually of brief duration and occur during or immediately after heavy rainfall. The magnitude and frequency of landslides is dependent on the intensity and duration of the triggering rainfall, antecedent soil moisture, and the geographic and geologic setting. Factors such as topography, soil type, hydrography and land use play an important role in determining where landslides are likely to be most numerous. Heavy and prolonged rainfall associated with hurricanes or other types of tropical disturbances, thunderstorms, or other types of convective storms, are common triggers. In many cases, there is little advanced warning of rapidly forming storms.

A number of approaches are used to reduce fatalities and property damage associated with flash flood and landslide events. These approaches consist of identifying and assessing mass-movement-prone areas, developing hazard or susceptibility maps for land-use zoning, and implementing warning systems based on rainfall accumulation, rainfall intensity-duration thresholds, and measurements of soil moisture. The importance of understanding the processes that control mass wasting and flash floods is indicated by the fact that in small basins, peak-discharge values calculated by using evidence from debris flows often lead to high estimates for major floods [12].

In this chapter, mass-movement types and processes and the geographic and geologic settings in which mass movements commonly occur are described. Some of the physical properties of debris flows and flash floods and the mechanisms by which rainfall-triggered mass movements occur are discussed. Finally, a brief description of the December 1999 landslide and flash-flood disaster in Venezuela is presented.

Landslide Types

Several descriptions and classifications of landslide types and processes have been published [4, 13, 15, 17, 20, 29, 48, 54]. Varnes [48] and more recently, Cruden and Varnes [17] are widely cited and provide a standard set of terminology for describing landslides. The principal types of landslides and the processes by which they occur are described below. Readers are referred to Cruden and Varnes [17] for an in-depth presentation of this information.

In the simplest terms, a landslide is the movement of a mass of rock, debris, or earth down a slope [16]. Two basic criteria are used to classify landslides: the type of material and the type of movement. Materials are divided into rock, debris and earth [17]. Rock is simply defined as an intact, firm or hard mass that was in its natural place before movement began. Debris is composed mainly of coarse material; 20 to 80 percent of the particles are greater than 2 mm in diameter. Earth is material that is predominantly fine; 80 percent or more of the particles are less than 2 mm in diameter. (The value of 2 mm is used by geologists to define the boundary between sand- and gravel-sized material [47]). All three of these terms, earth, debris, and rock, describe landslide material at its place of origin, *i.e.*, before displacement on the hillside.

Five terms define the type of movement: fall, topple, slide, spread, and flow [17]. Each of these terms can be combined with the three types of materials to describe a landslide using terms that are commonly accepted. A fall describes the detachment of material from a steep slope with virtually no shearing, in which the material moves rapidly by falling, bouncing, or rolling (fig. 2). A topple is defined as the forward rotation of a mass from a slope in which the point of rotation is below the center of gravity of the mass. A slide is the downslope movement of material that occurs on a rupture surface or zone of shear strain. The term spread is defined as the extension of a cohesive mass of earth, debris, or rock. The mass generally subsides into softer underlying material. Finally, a flow is a spatially continuous movement in which the shear surfaces are short-lived, closely spaced, and usually not preserved (fig. 3). Debris flows are commonly called mudflows by the popular media. A lahar is a debris flow on a volcano where loose volcanic debris such as ash or tephra is mobilized [17, 38]. Additional terminology to refine the landslide type according to factors such as the landslide water content, rate of movement, and the present condition of the landslide is listed in Cruden and Varnes [17].

Physical properties of water and sediment mixtures

Most researchers who study landslide processes do not study flash floods, with the opposite also being true. Although this division of study seems reasonable, the physical boundaries that separate mass movements, such as debris flows from stream flow are not so clear cut, and are better defined using a continuum [12].

Water is a Newtonian fluid that transports sediment by turbulent suspension, rolling, and saltation (bouncing) of particles along the channel bed. Very fine sediment may be held in suspension by electrostatic charges in slow-moving water [12]. Turbulent flows of floodwaters transport sediment loads of up to about 40 percent by weight. As the sediment concentration increases into the range of hyperconcentrated flow, fluid density and viscosity increase and particle fall velocity decreases. The fluid is non-Newtonian and has a finite shear strength, unlike water. This strength means that sediment transport rates can be much higher [40]. Debris flows occupy the highest range of sediment concentration in which water and sediment move together with a range of consistencies in which steep bouldery fronts may be followed by liquified slurry tails [36]. Massive boulders can be transported by debris flows. The sediment mixture is supported by a combination of cohesive strength, buoyant forces, increased pore pressure, and grain-to-grain contact. High quasi-static pore-water pressure gradients are commonly thought to explain the mobility of wet rocky debris. High pore pressure can be sustained by the presence of silt and clay, even in small amounts (about 2 percent by weight), which reduces the hydraulic diffusivity of the debris [24]. Although pore pressure dissipates quickly in coarse-grained debris flow snouts, pore pressure in the finer-grained trailing debris can persist allowing the tail to flow freely pushing the coarse-grained snout from behind [36].

Debris flows have a consistency similar to wet concrete. They are composed of material with a sediment concentration of 80 percent or more by weight, and a bulk density in excess of 2.0 tonnes/m^3 (fig. 4) [22]. Debris flow values reported by Costa [12] are slightly lower with sediment concentration by weight of 70 to 90 percent, and bulk density of 1.8 to 2.3 tonnes/m^3. Pure water has a density of 1.0 tonnes/m^3 [19]; the average density of silicate minerals in the Earth's crust is 2.65 tonnes/m^3 [41]. In the relation expressed by Hutchison [22], debris flows have bulk densities that may exceed 2.0 tonnes/m^3, and a maximum sediment concentration that approaches 99 percent by weight. Hyperconcentrated flows occupy the boundary between debris flows and water flows, and are a mixture of water and sediment defined by a sediment concentration of less than 80 percent but greater than about 40 percent by weight, according to Hutchison [22]. The unit weight of hyperconcentrated flows ranges from 1.3 tonnes/m^3 to 2.0 tonnes/m^3. Costa [12] uses an upper limit of 70 percent by weight and bulk density between 1.33 and 1.8 tonnes/m^3 to describe hyperconcentrated flows. Finally, fluid flows with a sediment concentration and unit weight below that of a hyperconcentrated flow are defined as streamflow.

Geographic and geologic controls on landslides

Natural and human factors influence the frequency and magnitude of mass movements. Some of the principal human activities that contribute to or influence mass movements in vulnerable areas include cut-and-fill construction for highways and railroads, construction of buildings, and mining operations. Disasters and human development of the environment are closely related [5]. Human use and manipulation of the environment and natural resources can substantially alter natural processes and aggravate the impact of extreme natural phenomena by changing natural drainage paths and reducing soil infiltration. Typical examples include deforestation, urbanization, and industrialization of landscapes, which increase the vulnerability of populations and infrastructure in the areas at risk. A particularly serious problem in developing countries is increased settlement of vulnerable areas such as on or near steep hillslopes. Economically marginalized populations are often left with no alternative but to construct simple dwellings in settings where risks from flash floods, landslides, or other hazards are dangerously high (fig. 1). For example, more than 100 people were killed when their ‘squatter’ community in Ponce, Puerto Rico, was destroyed by a massive rainfall-triggered rock slide in 1985 (fig. 5) [27, 28].

The principal natural factors that control landslide activity are topography, geology, and precipitation (discussed in the following section). Topography responds to and influences hillslope and fluvial erosion and sediment transport. The steeper the slope, the greater the role that gravity plays in mass movements. Bedrock strength, type, and structure, faulting, and rock resistance to weathering are some of the fundamental geologic factors that control mass movement processes. As a result, some bedrock formations or rock types are more susceptible than others to landslide activity. For example, shale is a weakly cemented clay-rich rock type that is prone to landslide failures [14]. Rock types with bedding planes that are oriented parallel to a hillslope are particularly susceptible to failure (fig. 5).

Rainfall and soil moisture controls on landslides

Synoptic weather systems such as hurricanes, tropical storms and cold fronts, as well as localized weather systems (convective systems and intense thunderstorms), can cause intense and prolonged rainfall, which are common triggering mechanisms for landslide activity. The intensity and duration of precipitation that is necessary before landsliding begins is strongly controlled by local geologic and geographic conditions, as discussed previously. In general, the likelihood of a landslide occurrence becomes high when hourly rainfall intensity exceeds about 20 to 30 mm, and the total daily amount of rainfall exceeds a value of 100 to 200 mm [6, 8, 33, 50]. Common hydrologic triggering mechanisms include a reduction in shear strength of rocks and soil through the infiltration of precipitation or during periods of ground-water recharge [7, 25, 51]. These processes increase pore-water pressure (ground saturation), reduce soil cohesion, and decrease soil or rock shear strength.

In all but the most humid environments, the triggering of landslides by rainfall requires that a soil moisture deficit be met [7, 30, 51]. In environments where rainfall is highly seasonal, soil moisture is low at the onset of the rainy season and several precipitation events may be necessary before soil moisture approaches a maximum [30]. This soil moisture deficit may be eliminated, however, during a single storm. Once the soil is at or near saturation, a subsequent storm can trigger landslide activity. The amount of precipitation necessary varies with the local geography, geology, and climatology.

Application of warning (ALERT) Systems

The concept of ALERT (automated local evaluation in real time) systems was developed during the 1970s in California for basins less than 260 km^2 in area to provide early warning to communities subject to potential hazards from flash floods [11]. These systems of automated precipitation and stream gages relay rainfall and flood stage information continuously to weather service, civil defense, or other emergency-warning centers [11]. In the 1980s, an ALERT system was used for landslide warning purposes in the San Francisco Bay area, California [30]. Two remote sensing systems, radar and satellites, also have been developed and implemented by many countries [43]. These systems provide almost continuous monitoring in many areas of the world subject to catastrophic events, and can be used to estimate rainfall for areas devoid of ground-measured data. When these estimates are coupled with algorithms that incorporate rainfall into soil moisture accounting procedures, forecasts can be made of critical flood stages and landslide probablity to alert emergency response and relief agencies.

Once hazardous areas have been identified, the expense of developing an ALERT-type system may not be very high. Although sophisticated systems use radio or satellite telemetry, ALERT systems have been implemented using simple telephone relay technology and algorithms that do not require computer technology, *i.e.*, only simple mathematical solutions [52]. Rainfall-intensity thresholds for landslides have been developed for various areas of the United States [8, 9, 30, 33, 39, 53]. These thresholds are simple, empirically based models that can be used in conjunction with flash-flood warning systems to define minimum rainfall conditions that may trigger landslides.

Landslide susceptibility and mitigation: planning and zoning decisions

Although one of the most effective means of reducing loss of life in floods and landslide disasters is to install forecast and warning systems, substantial reduction in both the loss of life and property damage is also achieved through zoning, or the delineation of susceptible areas. Activities associated with zoning include identification of 100-year flood or hazard zones (areas with a one-percent probablity of flooding in any given year) and evaluation of potential insurance alternatives. Delineation of 100-year flood zones has become the standard for determining flood risk in the United States [5]. Unfortunately, determination of landslide hazard-zones is not quite as simple. Nonetheless, with the use of aerial photography, the development of remote sensing through satellite technology, and advances in geographic information systems (GIS), a variety of theoretical and empirical hydrogeologic models have been developed for landslide-hazard prediction and susceptibility mapping [10, 18, 34, 49]. Geologic and geomorphic heterogeneity at the local scale, however, has reduced the widespread application of the models. Nevertheless, the use of simple algorithms and rules can assist in identifying areas where landslides are most likely to occur. Most landslide-susceptibility models use, at a minimum, a combination of hillslope angle and precipitation quantity to delineate hazard zones. Areas susceptible to landslides can then be identified using GIS techniques that offer innovative ways to provide hazard and risk information to decision-makers [18]. Some recent examples of the assessment and mapping of landslide susceptibility are provided in Irigaray *et al*. [23], Jager and Wieczorek [26], Larsen and Parks [32], Maharaj [35] , and Pomeroy [42].

Combined flash-flood and landslide disaster: Venezuela example

On December 15-16, 1999, flash floods and landslides killed thousands of people, caused extensive property damage, and changed hillslope, stream channel and alluvial fan morphology in coastal and near-coastal areas in the state of Vargas and neighboring states in northern Venezuela (fig. 6). Because no census data are available for many of the affected areas, and because many of the dead were either buried under meters of rock and debris or washed out to sea, the death toll will never be precisely known. Current estimates indicate that 30,000 lives were lost [46].

In December 1999, the interaction of a cold front with the moist, southwesterly flow of air from the Pacific Ocean towards the Caribbean Sea resulted in an usually wet period over northern Venezuela. Rainfall accumulation at sea level on the Caribbean coast at the Maiquetia airport for the first 2 weeks of December was 293 mm, more than five times the average [37]. An additional 911 mm of rainfall were recorded on December 14-16. Landslides that resulted from the rainstorms number in the thousands in the El Avila mountain range, which parallels the north coast. The landslides are mainly debris flows that are a few meters or less in depth, but 100’s of meters in length, and shallow soil slips, which are generally a few meters or less in thickness, but in many cases, 100’s of meters wide (fig. 7). Many of the landslides affected the entire length of the hillslope, from crest to toe. Most of the landslide scars are on the north side of the mountain range (the city of Caracas is on the south side of the range). Land use in the mountain range is dominated by El Avila National Park. Although several small communities, San José de Galipán, San Francisco de Galipán, are located within the Park boundaries, most of the area is undeveloped forest. As a result, deaths attributed directly to landslides in these steeply sloping areas comprised only a small fraction of the total number of estimated dead from this disaster.

Landslide damage to the two-lane highway that links coastal communities east of Maiquetia was severe. Many kilometers of road surface and road bed were destroyed or damaged (fig. 8). Some sections were re-opened to emergency and military traffic by January 2000, however, along the road corridor east of Naiguata, landslide damage to the highway was extreme and rehabilitation will require extensive reconstruction.

Debris flows and flash floods occurred in most of the several dozen small catchments (watershed areas on the order of 10 to 30 km^2) that drain the El Avila mountains north to the Caribbean Sea. Stream-channel gradients in these catchments are extreme: headwater elevations range from 2,000 to 2,700 meters and drop to sea level across a distance of 6 to 12 km, resulting in average slopes of 20 to 50 percent [37]. After passing through narrow canyons at the mountain front at only a few 10’s of meters above sea level, streams draining the catchments flow onto low-gradient (2 to 4 degrees) alluvial fans.

Over time scales spanning decades to centuries, these alluvial fans are dynamic zones of high geomorphic activity [2, 45]. On average, at least one or two high-magnitude flash-flood and landslide events per century have been recorded in this region since the 17th century. In the nearby states of Aragua and Carabobo, destructive flash flood and landslide events were recorded in 1693, 1789, 1798, 1804, 1808, 1812, 1890, 1892, 1902, 1912, 1914, 1927, 1933, 1945, 1946, 1951, 1956, 1962 and 1963 [2]. Another 13 such events were recorded during the 1970s. Northern Venezuela lies within a region where an average of 50 thunderstorms per year are documented for any point on the land surface [21]. In this dynamic environment, the alluvial fans prograde seaward and are built upward as episodic large-magnitude storms such as that which occurred in December 1999, erode upstream hillslopes and transport sediment onto the fans (fig. 9). An average of 2 to 3 meters of sediment was deposited on the fans in December 1999.

Because most of the coastal zone in the Vargas state consists of steep mountain fronts that rise directly from the Caribbean Sea, the alluvial fans provide the only flat areas upon which to build. It is upon these fans and a few narrow stretches of coastal plain that the principal airport and seaport facilities are constructed in Maiquetia. In addition, housing that ranges from unregulated shanty towns, known locally as ‘ranchos’, to middle- and upper-income single-family dwellings and multi-story apartment buildings, condominiums, and hotels has been constructed, principally in the communities of Maiquetia, La Guaira, Macuto, Caraballeda, and Naiguata. These are the communities where most of the damage and loss of life occurred.

A combination of debris flows that transported massive boulders and flash floods carrying extremely high sediment loads were the principal agents of destruction. On virtually every alluvial fan between Maiquetia and Camuri Grande, new river channels were cut into fan surfaces to depths of several meters, and massive amounts of new sediment were disgorged upon fan surfaces in quantities of up to 15 metric tonnes per square meter (fig. 9). Sediment sizes ranged from clay and sand to boulders as large as 10 meters in diameter (fig. 10). Hundreds of houses, bridges, and other structures were damaged or completely obliterated (fig. 11). Because residents had little warning in advance of the debris flows and flash floods that struck during the early hours of December 16, many lives were lost when people caught in their homes were either buried in the flood debris or swept out to sea.

Summary

Landslides and flash floods commonly occur together in response to intense and prolonged rainfall. Although these phenomena may be viewed by the popular media as distinct events, rainfall-triggered landslides and flash floods are part of a continuum of processes that includes debris flows, hyperconcentrated flows, and streamflow. This combination of processes has proven to be highly destructive in populated areas. Without careful planning of human settlements, the impacts of these types of disasters are likely to increase in the future. As stated by the Secretary General of the United Nations, Kofi Annan, *“The term ‘natural disaster’ has become an increasingly anachronistic misnomer. In reality, human behavior transforms natural hazards into what should really be called unnatural disasters.”* [44].

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References

1. Askew, A.J. (1997) Water in the international decade for natural disaster reduction, in *Destructive Water: Water-Caused Natural Disasters, their Abatement and Control*, IAHS Publication No. 239, The Netherlands, pp. 3-11.

2. Audemard, F.A., De Santis, F., Montes, L., Lugo, M. and Singer, A. (1988) El alud torrencial del 6-9-1987 del Río Limón, al norte de Maracay, Estado Aragua, *Informe Interno FUNVISIS* (Fundación Venezolana de Investigaciones Sísmicas) 9 pp.

3. Bagnold, R.A. (1956) The flow of cohesionless grains in fluids *Proceedings of the Royal Society of London* **A249** 235-297.

4. Brunsden D. and Prior, D.B. (1984) *Slope Instability* John Wiley and Sons, New York, 620 pp.

5. Burton, Ian, Kates, R.W, and White, G.F. (1993) *The environment as hazard* Guilford Press, New York, 290 pp.

6. Caine, N. (1980) The rainfall intensity-duration control of shallow landslides and debris flows, *Geografiska Annaler* **62A,** 23-27.

7. 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.

8. 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.

9. Cannon, S. H., and Ellen, S. D. (1985) Rainfall conditions for abundant debris avalanches, San Francisco Bay region, California, *California Geology* **38,** 267-272.

10. 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.

11. Clark, R. A. (1992) Evolution of the national flood forecasting system in the USA, in *Coping with Floods*, NATO ASI Series, Series E: Applied Sciences **257,** 437-444.

12. Costa, J.E. (1988) Rheologic, geomorphic, and sedimentologic differentiation of water floods, hyperconcentrated flows, and debris flows, in V.R. Baker, R.C. Kochel, and P.C. Patton, (eds.), *Flood Geomorphology*, John Wiley and Sons, New York, pp. 113-122.

13. Costa, J.E., and Wieczorek, G.F. (1987) (eds.), *Debris Flows/Avalanches: Processes, Recognition and Mitigation*, Geological Society of America: Reviews in Engineering Geology (7)

14. Crosby, E.J. (1978) Front range urban corridor, Colorado environmental geologic and hydrologic studies, Landforms-Boulder-Fort Collins-Greeley Area, *United States Geological Survey Map* I-855-H.

15. Crozier, M. J. (1986) *Lanslides: Causes, Consequences, and Environment*, Croom Helm, London, 252 pp.

16. Cruden, D.M. (1991) A simple definition of a landslide, Bulletin of the International Association of Engineering Geology **43**, 27-29.

17. 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.

18. DeVantier, B.A. and Feldman, A.D. (1993) Review of GIS applications in hydrologic modeling, *J. Water Resources Planning and Management*, **119**, No 2, 246-261.

19. Dingman, S.L. (1984) *Fluvial hydrology*, W.H. Freeman and Company, San Francisco, 383 p.

20. Gostclow, T.P. (1996) Landslides, in *V.P. Singh (ed), Hydrology of Disasters*, Kluwer Academic Publishers, Water Science and Technology Library, Dordrecht, pp.183-230.

21. Hayden, B.P.(1988) Flood climates, in V.R. Baker, R.C. Kochel, and P.C. Patton, (eds.), *Flood Geomorphology*, John Wiley and Sons, New York, pp. 13-26.

22. Hutchinson, J.N. (1988) General Report: morphological and geotechnical parameters of landslides in relation to geology and hydrogeology, in C. Bonnard, (ed.), Proceedings of the Fifth International Symposium on Landslides, A.A. Balkema, Rottedam, Netherlands, **1**, 3-35.

23. Irigaray Fernandez, 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.

24. Iverson, R.M. (1997) The physics of debris flows, *Reviews of Geophysics*, **35**, 245-296.

25. Iverson, R.M. and Major, J.J. (1986) Groundwater seepage vectors and the potential for hillslope failure and debris flow mobilization, *Water Resources Research*, **22**, 1543-1548.

26. Jager, S., 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**.

27. Jibson, R.W. (1989) Debris flows in southern Puerto Rico, *Geological Society of America* Special paper **236**, 29-55.

28. Jibson, R.W. (1992) Mameyes, Puerto Rico, lanslide disaster of October 7, 1985, *Geological Society of America, Reviews in Engineering Geology*, **9**, 37-54.

29. Johnson, P.A. and McCuen, R.A. (1996) Mud and debris flows, in V.P. Singh (ed.), *Hydrology of Disasters*, Kluwer Academic Publishers, Water Science and Technology Library, Dordrecht, pp 161-181.

30. 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.

31. 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.

32. 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.

33. Larsen, M.C., and Simon, A. (1993) Rainfall-threshold conditions for landslides in a humid-tropical system, Puerto Rico, *Geografiska Annaler* **75A** 13-23.

34. 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.

35. 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.

36. Major, J.J., and Iverson, R.M. (1999) Debris flow deposition: effects of pore-fluid pressure and friction concentrated at flow margins, *Geological Society of America Bulletin*, **111**, 1424-1434.

37. MARN (2000) Informe preliminar sobre los aspectos ambientales vinculadas al desastre natural ocurrido en Venezuela durante el mes de diciembre de 1999: Ministerio del Ambiente y de los Recursos Naturales, Venezuela, unpublished report.

38. Neall, V.E. (1996) Hydrological disasters associated with volcanoes, in V.P. Singh (ed.), *Hydrology of Disasters*, Kluwer Academic Publishers, Water Science and Technology Library, Dordrecht, pp 395-425.

39. Neary, D. G., and Swift, L. W. (1987) Rainfall thresholds for triggering a debris 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.

40. Nordin, C.F. (1963) A preliminary study of sediment transport parameters, Río Puerco near Bernardo, New Mexico, *U.S. Geological Survey Professional Paper* **462-C**, 1-21.

41. Plummer, C.C., and McGeary, D. (1982) *Physical Geology*, W.C. Brown Co. Publishers, Dubuque, Iowa, 500 pp.

42. Pomeroy, J. S. (1988) Map showing landslide susceptibility in Maryland: *U.S. Geological Survey* **MF-2048**.

43. Showstack, R. (1998) Real-time monitoring and warning for natural hazards can provide real-time benefits, *EOS, Transactions, American Geophysical Union*, **79**, 329-333.

44. Showstack, R. (2000) UN head calls for “culture of prevention” in addressing natural disasters, *EOS, Transactions, American Geophysical Union*, **80**, 438.

45. Singer, A, Rojas, C., and Lugo, M. (1983) Inventario nacional de riesgos geológicos, mapa, glosario y comentarios, *Serie Técnica FUNVISIS*, (Fundación Venezolana de Investigaciones Sísmicas) 03-83, Caracas, 126 p.

46. USAID, 2000, Venezuela Factsheet, February, 2000, USAID-Office of Foreign Disaster Assistance.

47. Vanoni, V.A. (1977) *Sedimentation Engineering*, American Society of Civil Engineers, Manual and Reports on Engineering Practice, no. 54, 745 p.

48. Varnes, D.J. (1978) Slope movement types and processes, in R.L. Schuster, and R.J. Krizek, (eds.), *Landslides, Analysis and Control: Special Report 176*, Transportation Research Board, National Academy of Sciences, Washington, D.C. 12-33.

49. 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.

50. 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.

51. Wilson, R.C. (1989) Rainstorms, pore pressures, and debris flows: a theoretical framework, in P.M. Sadler, and D.M. Morton, (eds.), Landslides in a semi-arid environment, Publication of the Inland Geological Society, *University of California Riverside Press*, 2, 101-117.

52. 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.

53. Wilson, R.C., and Wieczorek, G.F. (1995) Rainfall thresholds for the initiation of debris flows at La Honda, California, *Environmental and Engineering Geoscience*, **1**, 11-27.

54. Zaruba, Q., and Mencl, V. (1982) *Landslides and their control*, Elsevier, Amsterdam, Netherlands, 324 pp.

Figure 1. Homes destroyed by debris flow and flash floods, December 1999, Carmen de Uria, Venezuela.

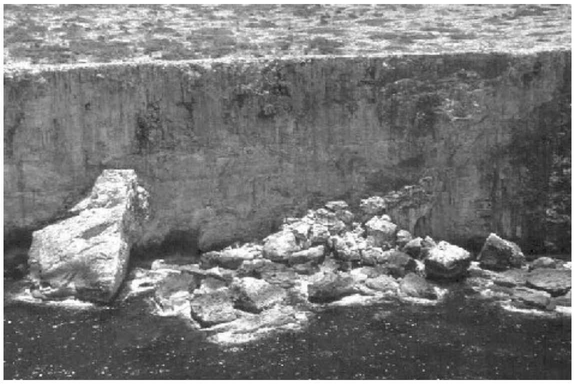

Figure 2. Rockfall deposits at base of 70-m-high limestone and dolomite cliffs, Isla de Mona, Puerto Rico.

Figure 3. Debris flow scars resulting from the December 1999 rainstorm, Caraballeda, Venezuela.

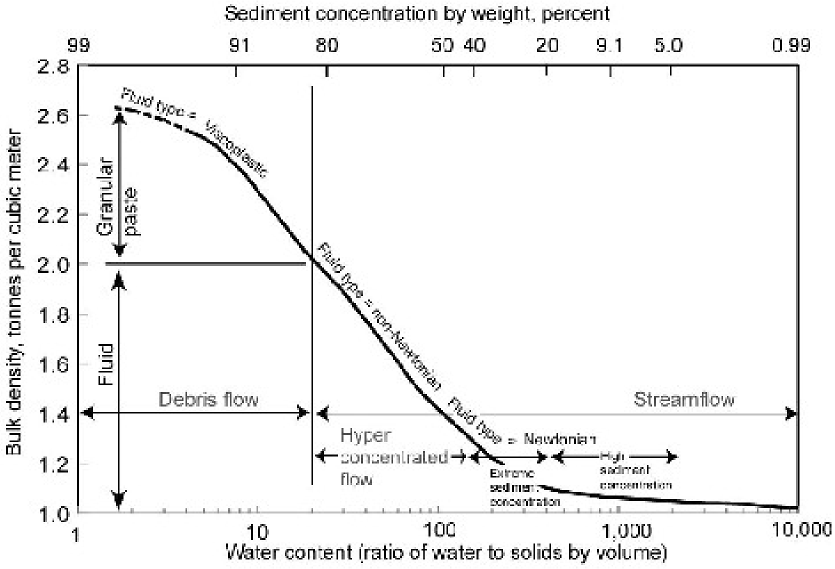

Figure 4. Plot showing an empirically based distribution of the range of sediment concentration from debris flows to rivers carrying high sediment loads (modified from 3, 12, 22].

Figure 5. Rock-block slide, Barrio Mameyes, Ponce, Puerto Rico, October, 1985 [28].

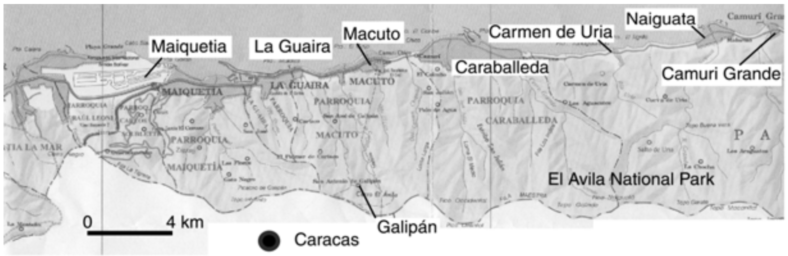

Figure 6. Central part of Vargas state, Venezuela. Map source: Political Territorial Division from the *Gaceta oficial* of the

Republic of Venezuela, no. 36-489, July 3, 1998.

Figure 7. Debris flow scars near San Francisco de Galipán, El Avila National Park, Venezuela.

Figure 8. Landslide damage to two-lane coastal highway, Vargas state, Venezuela.

Figure 9. New stream channels and rocky debris on alluvial fan surface transported by flash floods and debris flows, Caraballeda, Venezuela.

Figure 10. Massive boulder transported by debris flows onto alluvial fan, Caraballeda, Venezuela.

Figure 11. Flash-flood and debris flow damage to apartment building, Caraballeda, Venezuela. Note large boulder at level of second floor.