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# Geomorphic effects of large debris flows and flash floods, northern Venezuela, 1999

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with 10 figures and 2 tables

**Summary.** A rare, high-magnitude storm in northern Venezuela in December 1999 triggered debris flows and flash floods, and caused one of the worst natural disasters in the recorded history of the Americas. Some 15,000 people were killed. The debris flows and floods inundated coastal communities on alluvial fans at the mouths of a coastal mountain drainage network and destroyed property estimated at more than $2 billion. Landslides were abundant and widespread on steep slopes within areas underlain by schist and gneiss from near the coast to slightly over the crest of the mountain range. Some hillsides were entirely denuded by single or coalescing failures, which formed massive debris flows in river channels flowing out onto densely populated alluvial fans at the coast. The massive amount of sediment derived from 24 watersheds along 50 km of the coast during the storm and deposited on alluvial fans and beaches has been estimated at 15 to 20 million $m^3$. Sediment yield for the 1999 storm from the approximately 200 $km^2$ drainage area of watersheds upstream of the alluvial fans was as much as 100,000 $m^3/km^2$. Rapid economic development in this dynamic geomorphic environment close to the capital city of Caracas, in combination with a severe rain storm, resulted in the death of approximately 5% of the population (300,000 total prior to the storm) in the northern Venezuelan state of Vargas.

**Sommaire.** En Décembre 1999, une tempête d'une rare intensité causa des inondations soudaines et des coulées de débris dans le nord du Venezuela et engendra un des pires désastres de causes naturelles dans l'histoire connue du continent américain. Environ 15,000 personnes périrent. Les coulées de débris et les crues inondèrent les agglomérations côtières situées sur des dépôts d'alluvions aux sorties d'un réseau de drainage de montagne. Le coût des destructions fut estimé à plus de $2 milliards. La tempête provoqua de nombreux et importants glissements de terrain, depuis les côtes jusqu'à la crête des montagnes, sur les pentes raides composées de schistes et de gneiss. Plusieures collines furent completèment dénudées soit par des glissements uniques soit par une juxtaposition de glissements multiples. Les glissements de terrain causèrent des coulées de débris immenses dans les lits des revières, se déversant dans les dépôts d'alluvions en éventail dans les régions côtières avec de forte densités de population. A peu près 15 à 20 millions $m^3$ de sédiments furent déposés sur 50 km de côtes pendant la tempête provenant de 24 bassins versants. Le rendement de sédiments mobilisés par la tempête de 1999 fût au moins de l'ordre de 100000 $m^3/km^2$ pour une surface contribuante d'à peu pres 200 $km^2$ dans les bassins versants en amont des éventails d'alluvions sur les côtes. A cause du dévelopment économique rapide de cette région proche de la capitale de Caracas, à cause d'un environment très dynamique sur le plan géomorphologique, cette tempête soudaine, de très forte intensité, provoqua la mort de 5% de la population d'environ 300000 âmes (avant la tempête) dans l'Etat de Vargas au nord du Venezuela.

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## 1 *Introduction*

A rare, high-magnitude storm following several decades of rapid development and population expansion into a hazardous geomorphic environment resulted in one of the worst natural disasters in the recorded history of the Americas. Alluvial fans located along the northern coast of Venezuela (12° N, 67° W) had become the home and/or workplace of approximately 300,000 people through the second half of the 20th century during a period of few floods or debris flows (fig. 1). In December 1999, rainstorms induced large-magnitude debris flows and flash floods along the Sierra de Avila, Vargas, Venezuela, with spectacular geomorphic results. Cumulative rainfall of 293 mm during the first 2 weeks of December was followed by an additional 911 mm on December 14 through 16. Debris flows and floods inundated coastal communities and caused severe property destruction on alluvial fans at the mouths of the mountain drainage network, resulting in a catastrophic death toll of approximately 15,000 people (LÓPEZ et al. 2003a). The number of deaths was difficult to estimate accurately. Many people were buried or carried out to sea by the debris flows and flooding, and only about 1,000 bodies were recovered. The death toll was equivalent to approximately 5% of the local population, a further indication of the severity of this event.

Damage to communities and infrastructure was extensive. In Vargas, along a 50-km coastal strip north of Caracas, more than 23,000 residences and apartment buildings were destroyed and 65,000 were damaged (LÓPEZ et al. 2003a). Roads, telephone, electricity, water and sewage systems were severely disrupted. Total economic losses were estimated at more than $2 billion (LÓPEZ et al. 2003a).

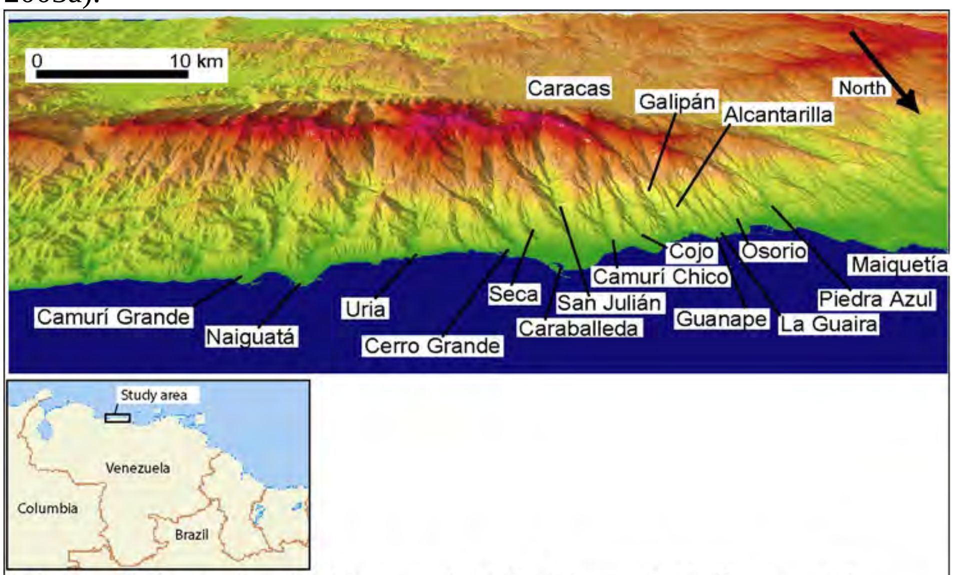


Fig. 1. Oblique view looking south at the Sierra de Avila--coastal mountains, northern Venezuela. This region of steep, highly dissected slopes and narrow coastal plain comprises the state of Vargas. Watershed size is on the order of a few tens of square kilometers and relief is extreme, >2,000 meters. Image courtesy of F. Urbani, Universidad Central de Venezuela.

This paper summarizes some of the geomorphic characteristics of landslides and flooding produced during the storm of December 1999 in northern Venezuela. Data are presented from work conducted on the hillslopes, channels, and alluvial fans of watersheds that were severely affected by the storm. Estimates of the geomorphic effects of the storm are summarized. Structural and non-structural methods that could be useful for hazards mitigation in this region are reviewed.

## 2 *Setting*

The topography of this region of coastal Venezuela is extremely steep and rugged. The crest of the Sierra de Avila rises 2,700 m above sea level within 6-10 km of the coast. The rivers and streams of this mountainous region drain to the north and emerge from steep canyons onto alluvial fans before emptying into the Caribbean Sea. Relatively little flat area is available in Vargas for development with the exception of the alluvial fans.

Alluvial fans are among the most active of geomorphic environments. They are dynamic mountain-front settings subjected to episodic large-magnitude hydrologic and geomorphologic processes such as debris flows, hyperconcentrated flows, and flash floods. Floods and debris flows commonly transport large amounts of sediment from upland watersheds onto fans where the material is distributed across the broad, relatively low-gradient fan surface. Subsequent flood and debris-flow events episodically shift stream channels and the fan deposits, scouring in some areas, and depositing sediment in others as the fan is gradually constructed from material eroded from the mountains. In spite of the obvious natural hazards, humans have favored alluvial-fan environments for millennia because of their proximity to water and soil resources and the relatively low-gradient surfaces, which are suitable for construction. Examples of large cities constructed on or partially on alluvial fans include Los Angeles, Denver, and Salt Lake City, United States and Mexico City, Mexico.

The alluvial fans in Vargas are not deeply incised. Typically, they are slightly higher in elevation (about 5 m) towards the axis of the fan than on the flanks, with only relatively shallow incision of 2 m by the active stream channels. The minimal stream entrenchment indicates that the long-term rate of delivery of material from the upper watersheds to the fans equals or exceeds the rate of removal of material by the stream. The steep mountainous topography with basal accreting fans is consistent with a youthful geomorphic stage of alluvial-fan development in this region.

### 3.1 *Geology and soil*

The geology of Caracas and the northern coastal region of Venezuela has been mapped and described by DENGO (1953), WEHRMANN (1969), URBANI & OSTOS (1989), and SALCEDO (2000). The Sierra de Avila consists mainly of metamorphic rocks with Quaternary channel and alluvial fan deposits extending from a deeply incised channel network on the north side of the mountains. Exposures of the Tacagua Formation (Mesozoic) consist of graphitic epidote schists parallel to the coast and extend about 1 km inland. Soils that have developed over these schists are relatively thin, 0.5- to 3.0-m thick (SALCEDO, 2000), red (Munsell Color 10R), and fine-grained. Generally, they are clayey colluvial deposits overlying partially to deeply weathered, strongly foliated bedrock. The A-horizon is generally less than 0.3 m thick; however, bedrock is commonly weathered to depths of 2 m or more (MERIFIELD 2001). Physical properties of these soils, including grain-size distribution, plasticity, specific gravity, and water content were reported by SALCEDO (2000) for several drainages.

Farther inland of the Tacagua Formation, quartz-plagioclase-mica gneiss and feldspar schist of the San Julián Formation (Paleozoic), and augen (quartz-mica) gneiss of the Peña de Mora Formation (Precambrian) extend to the crest of the Sierra de Avila. Soils developed over these two formations are sandy and light (tan-grey) in color over shallow weathered bedrock. Thicknesses of soils developed over these metamorphic rock units range between 1 to 5 m, depending on local gradient and topography (LÓPEZ et al. 2003a).

Terraces consisting of prehistoric debris-flow and flood deposits are elevated 10-20 m above the current stream channels, suggesting contemporaneous tectonic uplift of the coastal range combined with channel incision (fig. 2). An arid period associated with the late Pleistocene has been correlated with elevated terraces having similar deposits of bouldery debris over bedrock located about 100 km west of the Vargas region (SCHUBERT 1985). Scouring of channels and removal of alluvium during December 1999 exposed eroded bedrock benches above the apices of the fans, with apparent vertical steps ranging from about 0.5 to 2 m above the current levels of the channels. These benches are indicative of tectonic uplift and bedrock channel incision in this region. STALLARD (1988) has suggested an uplift rate of 2-5 m/1000 years for terraces at the northern terminus of the Andes in northwestern Venezuela. Most of the Quaternary faults in this region, however, are described as having right lateral, rather than vertical displacements, such as the San Sebastian fault (AUDEMARD et al. 2000), although the offshore Quaternary faults could have a substantial vertical component of movement. Near the International Airport at Maiquetia, the fault-scarp contact between the Pliocene Cabo Blanco Formation and the Mesozoic Tacagua Formation shows vertical offset (AUDEMARD et al. 2000).

Fig. 2.Prehistoric terrace of flood and debris-flow deposits about 20 m thick above current channel of Quebrada San Julián near Caraballeda. Channel is filled with car-size boulders deposited by December 1999 debris flows and floods. Note person for scale on left side of photograph.

4 *Historic storms*

Although the severity of damage to structures and roads was extreme, the landslides and flooding that were triggered by the intense rainfall in 1999 were not unique in this region or elsewhere in Venezuela. Historical records indicate that similar hydrologic events led to severe flooding and/or landslides in this region in 1740, 1780, 1797, 1798, 1909, 1912, 1914; 1938, May and November 1944, 1948, 1951, and 1954 (RÖHL 1950, SINGER et al. 1983, AUDEMARD et al. 1988, LÓPEZ et al. 2003b). On average, four high-magnitude flash floods or landslides per century have been recorded in this region since the 17$^{th}$ century. In addition, large debris flows occurred in the Caracas valley and Limón watershed between 1100 A.D. and 1500 A.D., according to geologic evidence described by SINGER et al. (1983). More recent storms, such as those described below, can be characterized and described from published information.

4.1 *La Guaira 1798*

Using Spanish archives, RÖHL (1950) provided a detailed summary of flash floods and debris flows in La Guaira in February 1798 that extensively damaged (219) homes and government buildings, and destroyed all bridges. A 70-hour rainstorm resulted in high-magnitude flood and debris flows, which forced Spanish soldiers to place cannons cross-wise in front of the upstream-facing entrance of a fort, located near the Osorio stream channel, to prevent debris from pouring into the structure. Deposits exposed on terraces and along the banks of river channels reveal a record of prehistoric floods and debris flows as well.

## 4.2 *La Guaira 1951*

Examination of selected aerial photographs along the coastal region in the state of Vargas allows comparison of the extent of damage caused by a February 1951 storm with that of the December 1999 storm (LÓPEZ et al. 2003a). The 1951 storm was smaller with respect to the amount of rainfall, number of landslides on hillslopes, and the relative scale of debris flows and flooding occurring in the main channels and deposition on the fans. During the February 1951 storm, rainfall of 282 mm was recorded at Maiquetia (43 m mean sea level (msl)), whereas at the higher elevation of El Infiernito (1,750 m msl) rainfall of 529 mm was recorded; rainfall at higher elevations of the Sierra de Avila were about double the amounts recorded along the coast. The town of La Guaira was buried with as much as 4 m of sediment (LÓPEZ et al. 2003a).

## 4.3 *Río Limon 1987*

On September 9, 1987, the Limón drainage, located in the State of Aragua approximately 100 km west of Caracas, received 174 mm of rainfall in less than 5 hours. The intense storms triggered shallow landslides that quickly transformed into debris flows. About 20,000 people returning from a weekend at the beach were isolated by the debris flows that damaged or destroyed approximately 1,500 homes, 500 cars, 3 bridges, and 25 km of roads (AUDEMARD et al. 1988). About 300 people were killed, 400 injured, and more than 30,000 temporarily isolated by the event (AUDEMARD et al. 1988, SCHUSTER et al. 2002, LÓPEZ et al. 2003a).

# 5 *Storm of December 1999*

In early December 1999, the interaction of a cold front with moist southwesterly flow from the Pacific Ocean towards the Caribbean Sea resulted in an unusually wet period over coastal northern Venezuela. Moderately heavy amounts of rainfall (less than 300 mm) during the first week of December were followed by extremely heavy rainfall (more than 900 mm) that began on December 14 and lasted through December 16 (MARN, 2000). The timing and intensity of the rainfall were unusual because the rainy season in coastal Venezuela normally lasts from May through October. The total 3-day rainfall along the coast at the International Airport at Maiquetia (43 m above msl) for a 52-hour span on December 14-16 totaled 911 mm (from 1945 hours on Dec. 15 to 2345 hours on Dec. 17, UTC). Hourly rainfall from 0600 to 0700 hours on December 16 measured 72 mm. These amounts and intensities of rainfall were exceptional for this region; the daily totals (381 and 410 mm) for both December 15 and 16 at Maiquetia may have exceeded the 1,000-year probability for this location (MARTINEZ 2000). Because few recording rain gages were operating in this region during this storm, however, probabilities were difficult to quantify. Furthermore, no rainfall gages were operational in the upper elevation areas of the Sierra de Avila, the source areas for flooding and debris flows. LEÓN (2003) notes that because of the short record and extreme magnitude of this rare event, precise probability is difficult to estimate. Nonetheless, PERICCHI and COLES (2003) argue that, using extreme value theory and a Bayesian approach, the 1999 event could have been probabilistically anticipated. They calculated that the single highest daily rainfall total, 410 mm, recorded on December 15, 1999, has a recurrence interval of 150 years. BELLO et al. (2003) argue that daily annual maximum rainfall data show a better fit with the Log Pearson III frequency distribution than with the Extreme Value Distribution. They state that the Log Pearson III frequency distribution indicates that the December 1999 storm had a >1,000-year recurrence interval if the 1999 storm is not included in the data set. If the 1999 storm is included in the analysis, then the recurrence interval is 270 years. Another approach to rainfall estimation used satellite data, described by WIECZOREK et al. (2003). A spatial and temporal representation of distribution of rainfall was based on the GOES 8 satellite

NOAA/NESDIS rainfall estimator. The GOES data spans 52 hours, from 1945 hours on Dec. 15 to 2345 hours on Dec. 17, UTC. There are 104 half-hour data sets, with the 0145, Dec. 15, data set missing. Rainfall estimates were computed using a relation between rainfall rate and cloud-top temperature determined from infrared sensors on the GOES 8 satellite (VICENTE et al. 1998, WIECZOREK et al. 2003). In previous storms, ground-based rainfall measurements in this region indicated that the higher elevations towards the crest of the Sierra de Avila received about twice as much rainfall as the regions along the coast (SALCEDO, 2000). Rainfall distribution contoured from the GOES 8 data, with a cell size of 4 x 4 km, indicates that the heaviest rains fell within 8 km of the coast and at the higher elevations of the Sierra de Avila roughly centered over the mid to upper part of the San Julián watershed, upstream of Caraballeda. Rainfall decreased towards Caracas on the southern side of the crest of the Sierra de Avila and to the east of Naiguata and to the west towards Maiquetia along the coast. These areas of heavy rainfall centered over the San Julián and adjacent watersheds roughly correspond to the areas of most abundant landslides and most severe flooding and debris-flow damage. Limited comparison of the ground-based measurements revealed that the rainfall totals from remotely sensed data were inconsistent with ground-based values. The factors that influenced the accuracy of remotely sensed rainfall data include spatial registration and map projection, as well as prevailing wind direction, cloud orientation, and topography.

## 6 *Field analysis*

Nine watersheds along the northern slope of the Sierra de Avila were examined in the field in April and July of 2000 (Camurí Chico, San Julián, Cerro Grande, Camurí Grande, Alcantarilla, Seca, El Cojo, San José de Galipán, and Osorio (fig. 1, also see WIECZOREK et al. 2001, Plate 1). Emphasis was given to hillsides where landslides initiated and to channels that experienced flooding and/or debris flows. The details of field measurements and observations, values of measurements from these sites, and additional photographs illustrating features at these sites are available on the web from WIECZOREK et al. (2001, http://pubs.usgs.gov/of/2001/ofr-01-0144/).

### 6.1 *Landslides and debris flows*

Landslides were abundant and widespread on steep slopes within areas underlain by schist and gneiss, from near the coast to slightly over the crest of the Sierra de Avila. Some hillsides were entirely denuded by single or coalescing failures (fig. 3A). Most landslides were initiated as thin earth (soil) slides or debris slides (soil with pieces of rock), as indicated by shallow sliding surfaces within soil or weathered, foliated, and jointed rock (classification according to VARNES, 1978). With the addition of more water from either the hillslopes or the channels, these slides of loose soil and rock liquefied into debris flows. A few isolated larger rock slides, and rotational or block slides of earth or rock, also were observed. In most cases, debris-flows entrained additional colluvium while traveling down steep hillside paths. Upon entering main channels, the debris flows incorporated stream alluvium from the channel and colluvium from channel banks, ranging in size from fine-grained material to extremely large boulders (fig. 3B).

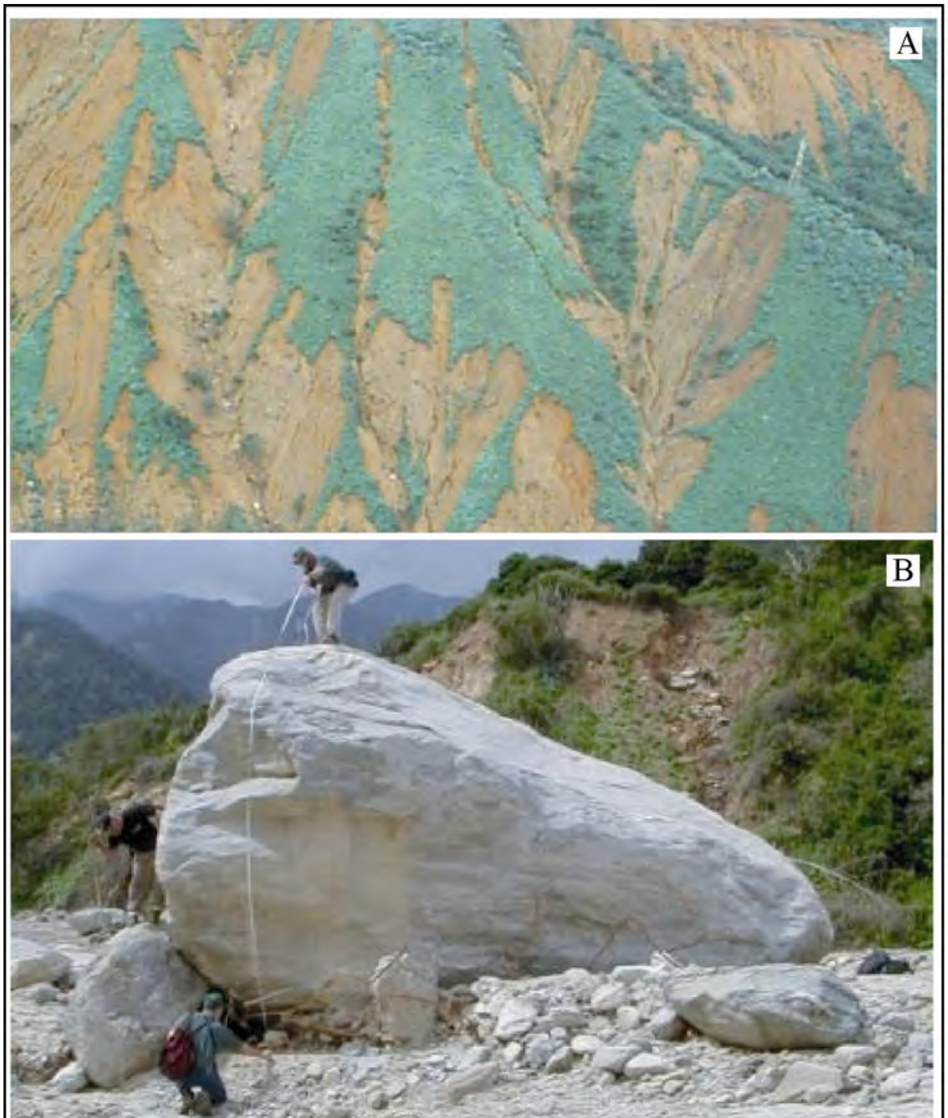


Fig. 3A. Coalescing shallow landslides initiated on steep hillsides in soils developed over bedrock of Tacagua Formation. Shallow slides initiated on steep hillslopes coalesced with other slides as they traveled into channels. Transmission tower, 30 m high, (upper right) for scale. 3B. Large (11.3 x 5.0 x 3.5 m) sub-rounded gneissic boulder deposited in center of channel of Quebrada Camurí Chiquito. Boulder was deposited atop former house foundation; strands of steel rebar are visible along base of boulder.

The undermining and collapse of prehistoric debris-flow deposits along the banks of channels was one mechanism by which large boulders became incorporated into the 1999 flows. Sub-rounded to sub-angular large gneissic boulders derived from the Peña de Mora Formation, which crops out at higher elevations within the Sierra de Avila, were abundant in channels and alluvial fan deposits near the coast in areas underlain by the Tacagua Formation (figs. 3, 4). The underlying geology and in situ weathering characteristics indicate that these boulders have been transported at least several kilometers, probably by multiple episodes of flood/debris flow over many thousands of years. According to URBANI (2002), the presence of large (>10 m diameter) boulders far from their sources has been described by a number of early geologists working in northern Venezuela. Morphologic measurements included hillside inclination, and dimensions of initial slides including thickness, width, and length. Noted were the composition of materials involved in sliding, and whether the site showed evidence of previous sliding. Most slides were limited to the top 0.5-2.0 m of soil and/or weathered schist or gneiss, although rare deeper earth slumps or rock-block slides were noted. The width of slides varied greatly, with a mean of 19.5 m and standard deviation of +/- 20 m (landslide source data are given by WIECZOREK et al., 2002, Appendix A). Some smaller slides coalesced to denude large sections of hillsides. Stratigraphic sequences exposed in main scarps indicated some reactivation of previous landslides. According to LÓPEZ et al. (2003a), some landslide scars in the San José de Galipán watershed had eroded headward to almost the top of the basin divide by 2001.

Fig. 4. Remnant of 1999 bouldery debris-flow deposit (~ 2 m thick) incised by later flooding with subsequent fine-grained flood deposits in foreground in the channel of Río Camurí Chiquito. Grain-to-grain, partially matrix-supported randomly oriented boulders indicative of transitional flow (KEATON et al. 1988).

Measurements indicated that landslides had initiated on slopes ranging from 30 to greater than 60 degrees, and the slopes that failed had a mean inclination of 42 degrees with a standard deviation of +/- 7.7 degrees (N=26). SALCEDO (2000) reported a mean initial slope of 38.5 degrees with a standard deviation of +/- 5.1 degrees (N=15). These comparable mean values of original slope inclination before failure might actually be slightly low because a sampling bias in this steep terrain limited the measurements to slopes that could be safely ascended for measurement without climbing equipment. Bedrock structure in this region strongly influences slope stability. In locations where the direction of steeply dipping foliation of the schist and gneiss is towards an open slope face, conditions are favorable for sliding. The steeply dipping foliation in many part of this region (DENGO, 1953) in combination with exceptional storm events has inhibited the development of thick soils. The steep inclination of the slopes commonly exceeds the frictional resistance (angle of internal friction) of the sandy soils in this region, indicating that other sources of strength, such as internal cohesion, soil suction (negative pore pressure), soil structure, or contribution of vegetative root strength, must contribute to the apparent stability of steep slopes.

Hillside soils involved in landsliding were predominantly silty sands and silty gravelly sands (SM), or clayey sands and clayey gravelly sands (SC), according to the Unified Soil Classification System (SALCEDO, 2000). Using an infinite slope analysis, SALCEDO (2000) showed that for similar sandy soils with a typical effective angle of friction between 30 and 40 degrees, an effective cohesion of 1 $t/m^2$ (1.29 psi or 8.9 kPa) would be required for stability on slopes equal to or greater than 40 degrees. For these types of sandy cohesionless soils, such values of cohesion would be unusually high and such soils would be unstable, unless additional resistance to sliding was added by the strength of tree roots or capillary soil suction. In his observations of landslide failure scars in this region, MERIFIELD (2001) found that root penetration generally was confined to the thin topsoil layer, except in a few cases where roots penetrated along open fractures of joints or foliation. Roots made up less than an estimated 5 % of the slip surface, a low value compared to slopes elsewhere (MERIFIELD, 2001), so root strength alone was not sufficient to account for the apparent stability of soil on steep slopes in this region. In light of the probable low cohesive strength available from soil and roots in this setting and marginal stability dependent on soil suction under dry conditions, it is not surprising that during the extremely heavy rainfall in December 1999, the strength of thin soils on steep slopes was insufficient to resist sliding.

### 6.2 *Channels and Fans*

The main channels and fans of the nine watersheds we examined displayed a complex sequence of sediment deposition. The layering exposed in most channels was evidence of both flooding and debris-flow processes; however, the types of flow processes, stratigraphy, and thickness of deposits typically varied along the length of a channel and onto the fan. Deposits in most channels and fans showed that flooding had preceded debris-flow activity. Multiple pulses of debris flows, some of them highly destructive, deposited large boulders and tree trunks amidst a sandy matrix on nearly all the fans. Flooding in the later stages of the storm subsequently incised these fluvial and debris-flow deposits (fig. 4). Measurements of the range of thickness of deposits and depths of flow are summarized for each watershed in Table 1 (see also WIECZOREK et al. 2002, Appendix B).

The degree of matrix support of coarser clasts observed in deposits varied from fully matrix-supported to fully clast-supported deposits. The association between flow processes and depositional texture was gradational with debris-flow deposits having fully matrix-supported, unsorted, unstratified clasts, transitional flow with partially matrix-supported clasts, and hyperconcentrated sediment flow with a fully clast-supported texture. The surface of some deposits was matrix-free as a result of winnowing of debris-flow deposits by recessional and/or secondary overland water flows.

The confluence of debris flows from lower-order tributaries into the main channels contributed additional sediment to maintain the debris flows in the main channels. We noted that the thickness of debris-flow deposits was increased below many tributary junctions. In some drainages we found evidence of a few isolated temporary blockages of the main channel with remnants of large boulders and large woody debris, caused by a debris flow from a tributary entering a main channel. There was no evidence, however, of sediment deposition upstream of these blockages, indicating that the blockages were short-lived and that the volume of flow in the main channels was sufficiently great to quickly overwhelm any blockage. Reports that channel blockages (SANCIO and BARRIOS 2000) were the source of the destructive debris-flow surges or pulses observed on the fans were not confirmed by our field evidence. Based on the evidence we saw for the short duration of the few blockages and the several kilometer length of the channels before reaching the fans, we ascertained that these reports had probably noted the characteristic front or snout of a debris-flow pulse that was not necessarily the consequence of the collapse of a blockage.

In most of the drainages, the sequence of flooding and debris-flow deposition during the storm was confirmed by eyewitness accounts. Flooding generally was observed beginning after 8 p.m. local time (Atlantic Standard Time (AST)) on the evening of December 15. Some residents fled from the vicinity of rivers overtopping their banks and remained atop nearby houses, watching the events unfold. The first eyewitness accounts of debris-flow events with descriptions of crashing rocks were reported about 8:30 pm on December 15 on the San Julián River. Other possible debris flows, e.g. “rumbling noise and vibration of rocks”, were reported between 2 and 3 a.m. on December 16. Another series of debris flows was observed between 5 and 7 a.m.; the last series of debris flows was reported between 8 and 9 a.m. on December 16. Flooding was noted in a few channels between 7 and 9 a.m. on December 16 and lasted until late in the afternoon of December 16, and eroded many of the debris-flow deposits within channels (figs. 4). LÓPEZ et al. (2003b) described the effects of flooding and debris flows on the Uria fan (fig. 5). In addition, they described river channelization, which contributed to extensive development of housing on the fan during the 1980s and 1990s.

Table 1. Characterization of flood and debris-flow deposition in study watersheds. Velocity estimates are calculated from evidence of superelevation. Flow depth (*) reported where evidence of deposit had been removed. Modified from WIECZOREK et al. (2001, 2002).

| Drainage | Sequence and type of deposition (top to bottom) | Deposit thickness, m | Max. boulder diameter, m | Velocity (m/s) | Fabric |
|---|---|---|---|---|---|
| Camuri Chico | Coarse Debris-flow/Fine Debris-flow/Flood incision | 3.0-4.0 | 5.1-12.0 | 5.8 | Matrix supported-grain to grain support |
| San Julian | Coarse Debris-flow /Flood/Fine Debris-flow /Flood incision | 4.0 | 1.0-5.6 | N/A | Grain to grain support |
| Cerro Grande | Flood/Flood incision | 2.0 | 0.2-0.4 | 4.2-7.0 | Graded |
| Camuri Grande | Coarse Debris-flow /Hypcon. Flow/Flood incision | 3.0-6.0 | 2.7-4.1 | N/A | Grain to grain support |
| Alcantarilla | Coarse Debris-flow /Sandy Flood/Flood incision | 3.2-4.5 | 1.7-2.7 | 3.5-13.6 | Matrix supported |
| Seca | Coarse Debris-flow /Flood incision | 2.5-4.0 | 1.8-7.5 | 3.3 | Grain to grain support, partially imbricated |
| El Cojo | Debris-flow/Flood incision | 2.0-3.6 | 2.5-9.5 | 3.2-5.2 | Matrix supported |
| San Jose de Galipan | Debris-flow/Flood incision | 1.0-4.0 | 3.2-5.3 | 4.4 | Grain to grain support |
| Osorio | Debris-flow/Flood incision | 3.0-6.0* | 3.2-7.1 | 4.1-5.8 | No Data |

Fig. 5A. Aerial photograph showing Uria alluvial fan progradation seaward and extensive areas of destroyed housing and landslide scars on adjacent hillslopes, December 1999. 5B. Oblique aerial view to south showing Uria alluvial fan during initial road-rebuilding effort, January 2000. 5C. Photograph taken by resident, Emilio Peñaranda, during floods of December 16, 1999, view to east [courtesy of Prof. José Luis López, Universidad Central de Venzuela]. Prior to the 1999 storm, the flooded area in the center of the fan was occupied by 2-story homes such as those in the foreground.

Important factors influencing the variation of flood/debris-flow depositional processes along the channels included the location of the junctions with tributaries and whether these tributaries were themselves subjected to debris flows or flooding. In the highest parts of the drainages that were easily accessible, about 4 km inland, bedrock channels had been severely scoured and had been left almost devoid of sediment. Although vegetation trim lines were identified on the channel sides, we were unable to determine whether the channel sediments had been removed by flood, debris flow, or an intermediate variety of flow. The inflow from a flooding tributary also could have diluted a debris flow into a transitional flow or hyperconcentrated flows in the higher parts of drainages. In almost all drainages, debris-flow deposits were traced from the distal ends of the fans upstream to about 2-3 km from the coast (fig. 5A, 5B). Additionally, the deposition extended laterally beyond the shorelines as subaqueous fans for some tens of meters (LARSEN et al. 2001, LÓPEZ et al. 2003b). Shorelines of some alluvial fans prograded by more than 100 m (LÓPEZ et al. 2003a,b, BELLO et al. 2003). The thickness of subaqueous deposition from the 1999 event could not be determined because of the lack of pre-event bathymetric surveys. The subaqueous deposits were probably less than 1m thick, reasoned from observations of subaerial, thin-bedded, dominantly fine-grained deposits grading into the coast. Most of the fine-grained deposits examined at the coastline were of fluvial origin. Sediment-laden flood flows that are the likely source of some of these deposits were observed by residents on the morning of December 16, 1999 (fig. 5C). BELLO et al. (2003) estimate that Cerro Grande River flood flows had an average sediment concentration of 35-40% by volume. Maximum debris-flow discharges for the Cerro Grande and Uria Rivers were estimated at 1,230 $m^3/s$ and 1,670 $m^3/s$, respectively, by LÓPEZ et al. (2003a). NAKAGAWA et al. (2003) reported peak debris-flow discharge of 900 $m^3/s$ for the Camuri Grande River, with maximum sediment concentration of 65% by volume. A characterization of the type(s), sequence and thickness of deposition, and maximum boulder size within each drainage and on fans is given in Table 1.

Velocities during flooding were estimated by measuring the maximum sizes of transported boulders (WIECZOREK et al. 2002, Appendix B). COSTA (1983) and CLARKE (1996) developed empirical relations dependent on boulder diameter for estimating the average velocity accompanying flood discharge. These methods determine the critical (competent bed) velocity required to initiate boulder movement. Because they used different measures of boulder diameter, Costa's equation results in a velocity estimate about 40% greater than that of CLARKE. We also estimated velocities from superelevation on channel bends, where flows reached higher elevations on the outsides of channel bends than on the insides. Based on the cross-channel flow surface angle, radius of curvature of the channel bend, and channel slope, the approximate mean velocity of flow can be calculated (COSTA, 1984).

The average velocities of the flows ranged from 4 to 14.5 m/s using methods of COSTA (1983) and CLARKE (1996), and that were based on measurements of the largest transported boulders. A slightly lower range of velocities from 3.3 to 13.6 m/s was determined at several dozen sites from measurements of superelevation on channel bends. Direct comparison between these two methods was possible at only six sites. Assuming the superelevation method as that most applicable to debris flows, the methods by CLARKE (1996) and COSTA (1983) based on boulder size overestimated the velocity by about 28% and 68%, respectively. The velocity based on superelevation probably better represents the actual flow velocity of a debris flow or flood because the calculation is independent of fluid density (COSTA, 1984, p. 304). The methods of COSTA (1983) and CLARKE (1996) are based on average velocity necessary for initial movement of a boulder along the channel bed in a clear water flood. This technique probably overestimates the velocity because a debris flow suspends boulders within a matrix that has a density greater than clear water making it capable of transporting boulders with a slightly lower velocity.

Prehistoric debris-flow deposits were exposed in the channels and banks of most of the channel reaches that we examined, and provided a plentiful supply and wide range of boulder sizes available for transport during the 1999 storm (figs. 2, 3, 6, 10). The prehistoric deposits were not only thicker, but contained boulders larger than those known to have been moved during December 1999. In terms of hazard assessment, the magnitude of the December 1999 event should not be assumed to be the highest possible for a storm in this region.

Fig. 6. Prehistoric debris-flow deposit (7.7 m thick) undermined in channel bank of Quebrada San José de Galipán. Fully matrix-supported texture with randomly oriented sub-angular large gneissic boulders from the Peña de Mora Formation gneiss deposited in a sandy matrix. Top of deposit, which is matrix-free, produced by winnowing of debris flow by recessional and/or secondary overland water flows.

6.2.1 *Caraballeda Fan*

The large fan of the San Julián River at Caraballeda was one of the areas most heavily damaged in December 1999 (fig. 7). The volume and thickness of deposition, maximum size of transported boulders, and size of inundated area were all notably larger in this drainage than in other watersheds (Table 2). The Caraballeda fan was one of the more intensively developed communities with many high-rise buildings and large individual multi-story houses. At the fan apex, the peak volume of flow, probably during a debris-flow surge, exceeded the channel capacity. As a result, multiple stream avulsions and subsequent flows spread bouldery debris throughout the community. The flow overwhelmed the channel in several places, notably wherever sections or lineaments of the channel changed direction. Pre-1951 topographic maps show the channel of the San Julián River taking a more or less straight path across the western part of the fan. Photographs taken following the February 1951 storm show deposition limited to the channel through the eastern part of the fan. During December 1999, the channel avulsed high on the fan and followed the pre-1951 course. Whereas the 1951 flows were adequately contained within the eastern channel, the flows of 1999 roughly followed the channel that existed prior to 1951.

Outside the main channel, flows inundated the second stories of several apartment buildings, causing their partial collapse (figs. 7B, 7C), and also buried or completely destroyed many 2-story residential structures. Farther down the fan, flows followed the paths of streets and openings between houses; the deposition of debris thinned, but still exceeded 1 m in thickness at several locations (figs. 8, 9). About one third of the original area of the Caraballeda fan was inundated by debris flows in this event; however, buildings on the entire fan are built upon previous debris-flow deposits (fig. 10).

Table 2 Estimated alluvial fan deposition, upstream watershed erosion, and surface lowering. Data from LÓPEZ et al. 2003a and CÓRDOVA & GONZÁLEZ SANABRIA 2003.

| Watershed name, area of deposition on alluvial fan, ha | Watershed drainage area, upstream of fan, $km^2$ | Deposition, volume, million $m^3$ | | Sediment thickness on alluvial fan | Erosion, $t/km^2$ [calculated using average deposit density of 1.7 t/ $m^3$] | | Watershed surface lowering, mm | |
|---|---|---|---|---|---|---|---|---|
| | | [data from LÓPEZ et al. 2003a] | [data from CORDOVA & GONZALEZ SANABRIA 2003] | [data from LÓPEZ et al. 2003a] | [data from LÓPEZ et al. 2003a] | [data from CORDOVA & GONZALEZ SANABRIA 2003] | [data from LÓPEZ et al. 2003a] | [data from CORDOVA & GONZALEZ SANABRIA 2003] |
| Piedra Azul, 25.6 | 24.8 | 1.37 | 2.22 | 5.4 | 90,000 | 150,000 | 55 | 90 |
| Osorio, 17.8 | 4.6 | 0.45 | 0.84 | 2.5 | 170,000 | 310,000 | 98 | 183 |
| Guanape, 18.1 | 4.8 | 0.40 | 1.00 | 2.2 | 140,000 | 350,000 | 83 | 208 |
| Galipan, 25.4 | 14.8 | 0.64 | 1.62 | 2.5 | 70,000 | 190,000 | 43 | 109 |
| El Cojo, 16.4 | 6.1 | 1.10 | 1.14 | 6.7 | 310,000 | 320,000 | 180 | 187 |
| Camuri Chico, 82.7 | 9.6 | 0.75 | 1.79 | 0.9 | 130,000 | 320,000 | 78 | 186 |
| San Julian, 127 | 21.5 | 2.60 | 2.64 | 2.0 | 210,000 | 210,000 | 121 | 123 |
| Quebrada Seca, 74.1 | 3.1 | 1.48 | 1.62 | 2.0 | 810,000 | 890,000 | 477 | 523 |
| Cerro Grande, 36.6 | 26.4 | 1.60 | 1.68 | 4.4 | 100,000 | 110,000 | 61 | 64 |
| Uria, 37.2 | 12.2 | 1.50 | 1.40 | 4.0 | 210,000 | 200,000 | 123 | 115 |
| Naigauta, 66.7 | 31 | 1.05 | 2.07 | 1.6 | 60,000 | 110,000 | 34 | 67 |
| Camuri Grande, 79 | 40 | 1.90 | 2.23 | 2.4 | 80,000 | 90,000 | 48 | 56 |
| Totals | 198.9 | 14.84 | 20.25 | | | | | |
| Averages | | | | 3.1 | 198,000 | 271,000 | 117 | 159 |

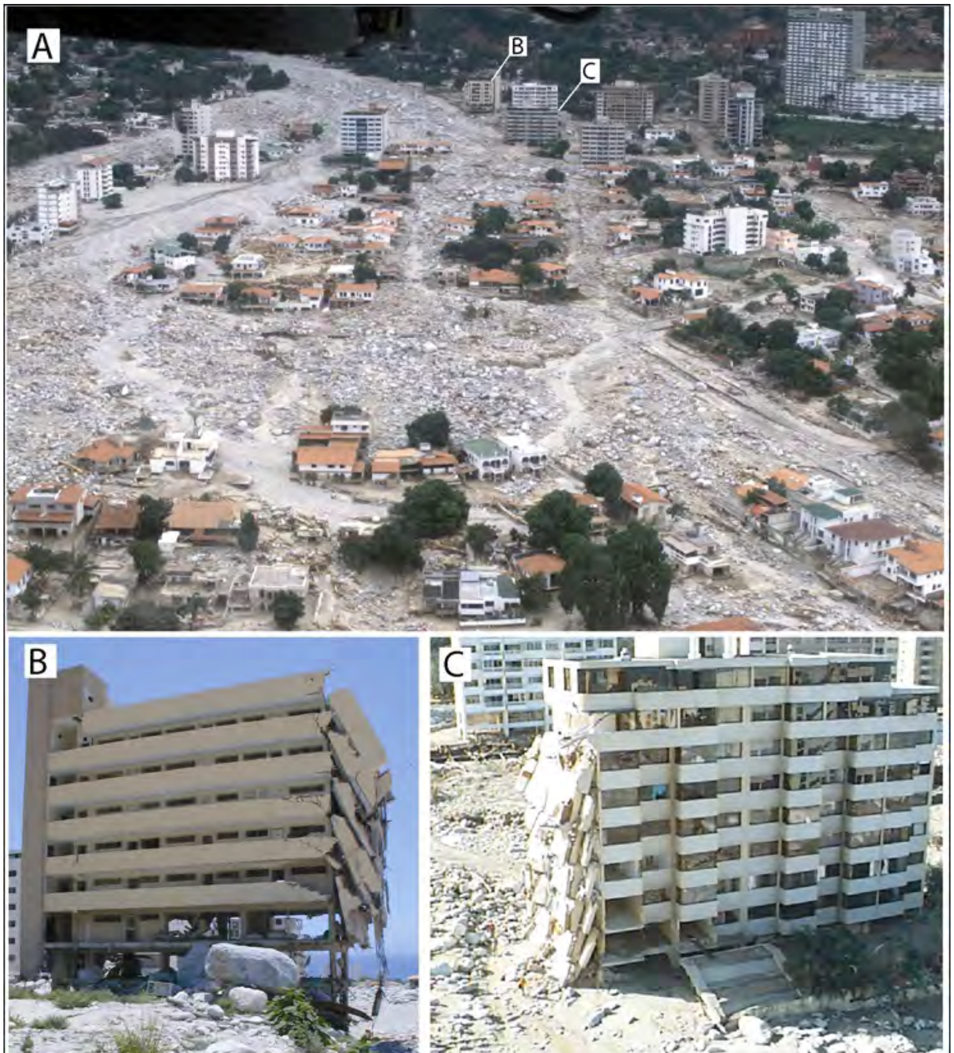

Fig. 7A. Aerial view of debris-flow deposition resulting in widespread destruction on the Caraballeda fan. Avulsion of the main channel (left side of photo) resulted in deposits up to 6 m thick and totaling about 1.8 million cubic meters of bouldery debris. Secondary new flood channels are visible through center of fan to the lower right of photo (Photo by Lawson Smith, USACE). 7B, C. Apartment buildings with extensive damage from passage of debris-flow front at least 3.5 m in height, leaving boulders (> 1 m) on second floor of building B. Location of buildings noted on photo A by letters.

We measured degree of slope, depositional thickness, and boulder size from the fan apex to the distal edge of the fan near the coastline (fig. 8, see also WIECZOREK et al. 2002, Appendix B). We mapped the distribution and thickness of deposits and estimated the total volume of deposits on the fan (fig. 9). Total deposition on the subaerial fan was calculated using two different methods. In the field we measured deposit thickness, or if necessary, estimated the depth of flow where material had been removed from cleanup. Where material had been removed, mudlines on houses and other structures were used as an approximate measure of deposit thickness. Total depositional volume of 1.9 million $m^3$ was determined from field measurements using 3-dimensional modeling software (WIECZOREK et al. 2003). This volume is a minimum because it neglects the amount of material that remained in the main channel after the event, but was removed by the time of our visits. The same software also was used for comparison of pre-and post-event digital topography on the fan, and the results show a 1999 depositional volume of 1.8 million $m^3$ (fig. 9). The determination of volume by comparison of pre- and post-event digital topography is the preferred method because of the modifications on the fan by the time of our field work, although the two values differ by less than 10 %.

We measured deposits between 4 and 5 m thick in the center of the fan, located where two major avulsions diverged from the main channel of San Julián River. The thickest deposits

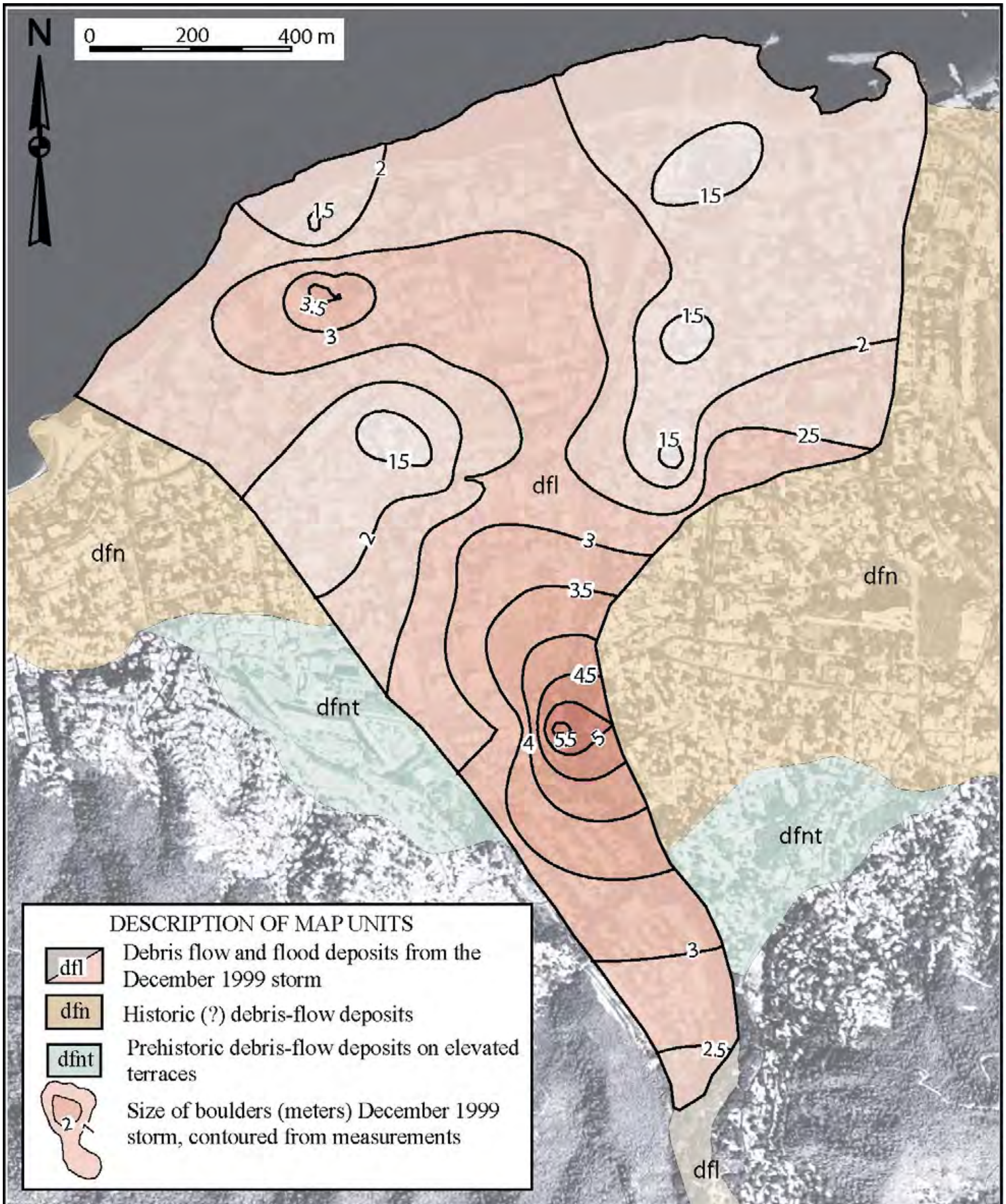


Fig. 8. Debris-flow deposits and contours of maximum boulder size on the Caraballeda Fan, Venezuela, simplified from WIECZOREK et al., (2002).

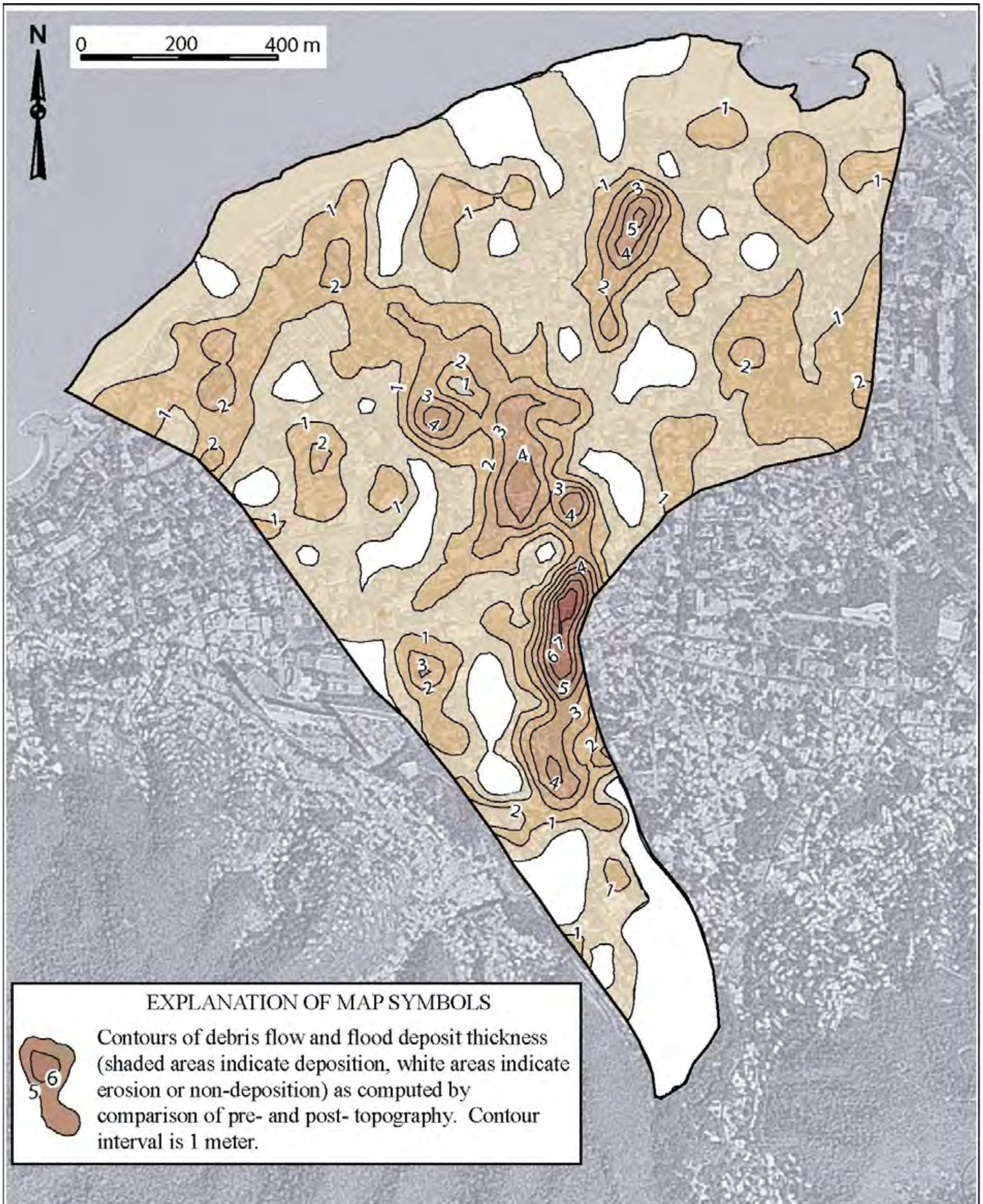


Fig. 9. Debris-flow and flood deposit thickness, December 1999 storm, Caraballeda Fan, Venezuela, simplified from WIECZOREK et al. (2002).

ere near the middle of the fan where 2-story houses were either completely destroyed or partially buried (fig. 7A). At this locale, the fan slopes ranged between 5 and 6 degrees, and the maximum thickness of deposits was 5.3 m, as determined by comparing pre- and post- topography.

The importance of the volume of deposits on the Caraballeda fan can be ascertained from comparison with other large debris flows worldwide. Using a magnitude scale, M, of the log of depositional volume suggested by KEATON et al. (1988), the magnitude of debris-flow deposits on the Caraballeda fan (M=6.3) is amongst the largest on record from rainfall-induced debris flows; however, even the largest of rainfall-induced debris flows are at least an order of magnitude smaller than the largest triggered by volcanic explosions, eruptions, or earthquakes (WIECZOREK et al. 2003).

Fig. 10A. Structure at Plaza de Piedras in the eastern older portion of Caraballeda. This Casa de Piedras (House of Stones) built around 1917, predated the flood and debris-flow events of 1951 on the Caraballeda fan. 10B. Recently built home on western side of Caraballeda fan built on an old debris-flow deposit exposed by the 1999 storm.

## 7 *Sediment deposition and erosion*

A massive amount of sediment derived from 24 watersheds along 50 km of the Vargas coast during the December 1999 storm was deposited on alluvial fans and beaches, and has been estimated at 15 to 20 million $m^3$ (Table 2). The sediment was derived from watersheds with total area of approximately 200 $km^2$, meaning that, on average, sediment yield for the 1999 storm was as much as 100,000 $m^3/km^2$. Sediment mass, approximated as 1.7 tonnes/$m^3$ (using the density of quartz, 2.6 tonnes/$m^3$ and accounting for pore space), would therefore be approximately 170,000 tonnes/$km^2$. This impressive figure places the 1999 event among the highest ever documented for sediment transport by rainfall-triggered geomorphic activity (MILLIMAN & SYVITSKI 1992). For example, high annual fluvial sediment yields in anthropogenically disturbed areas of the montane humid tropics are on the order of 10,000 to 20,000 tonnes/$km^2$ (LARSEN & SANTIAGO-ROMÁN 2001). The sediment deposition elevated alluvial fan surfaces by as much as 7 m in some areas (WIECZOREK et al. 2002) although 1 to 2 m was more common (fig. 8, 9). Additionally, because of seaward progradation of alluvial fans and beaches, new land surface has been estimated at 150 hectares (LÓPEZ et al. 2003a). If the watershed sediment yield summarized in Table 2 is averaged over the source areas, the entire surface of the watersheds upstream of the alluvial fans was lowered (eroded) by 117 to 159 mm during the 1999 storm. Volumetric estimates of sediment deposition on alluvial fans are listed in Table 2. The data cited from CORDOVA & GONZALEZ SANABRIA (2003) were estimated using two methods: The U.S. Army Corps of Engineers, Los Angeles District method for prediction of debris yield and the FLO-2D model (Table 2). Sediment deposition estimates reported by CORDOVA & GONZALEZ SANABRIA (2003) are, on average, 1.6 times higher than those reported by LÓPEZ et al. (2003a). NAKAGAWA et al. (2003) estimated that sediment deposition on the Camuri Grande alluvial fan was 1.62 million $m^3$, which is 1 million $m^3$ less than the values listed in Table 2. WIECZOREK et al. (2002) used two different methods to estimate that sediment deposition on the Caraballeda fan (San Julián watershed) was between 1.8 and 1.9 million $m^3$. Extensive field measurements were used by WIECZOREK et al. (2002) to calculate these data, which are available in appendices to their report. The differences in the sediment deposition estimates reported here highlight the work still necessary to quantify the geomorphic effects of the 1999 storm. Nonetheless, all of the estimates probably are conservative with respect to the total amount of sediment mobilized by the storm because so much of it was transported directly to the Caribbean Sea.

## 8 *Prehistoric Flood/Debris-flow Events*

Prehistoric flood/debris-flow deposits were exposed along channel banks in most of the observed watersheds, and we recorded the dimensions of large boulders in these prehistoric deposits as well as the deposit thicknesses (WIECZOREK et al. 2002, Appendix B). The sizes of boulders and thicknesses of prehistoric deposits are at least as large as those of December 1999, and in several areas, greater, indicating that the event of December 1999 was not necessarily the largest to have occurred in this region.

The ages of previous events and the average recurrences of flood/debris flow events in the San Julián River and other drainages is important for rebuilding and mitigation considerations. Aerial photo interpretation and field examinations indicate that prehistoric and historical debris-flow deposits cover much of the Caraballeda fan with thicknesses and sizes of boulders comparable to those associated with the 1999 storm (fig. 10). Evidence from aerial photographs shows that the debris flows and floods of 1951 on this fan were minor in comparison to the 1999 event. This fan had been extensively developed since 1951, as reflected in the magnitude of loss of life and property damage in 1999.

Prehistoric flood and debris-flow deposits are exposed along the banks of the San Julián River and on the flanks of the Caraballeda fan. At Plaza de Piedras, located high above the active channel on the eastern side of the fan at an elevation of approximately 75 m, a house built in 1917 sits on a boulder terrace with the largest visible boulder of approximately 2.9 $m^3$ (fig. 10A). On the western side of the fan at about the same elevation, a thick (~17 m) sequence of multiple flood/debris flow deposits include gneissic boulders 1.5 m in diameter in a brownish-yellow, slightly cemented sandy matrix. Similarly thick deposits with large boulders in a sandy yellow matrix could be roughly traced upstream from the western side of the fan for about 0.5 km along the western banks of the San Julián River. A home in this area of the Caraballeda fan, built on an

old debris-flow deposit exposed by the 1999 storm, provides an additional example of the extensive debris-flow deposits and vulnerability of structures built on this fan (fig.10B).
In a fresh exposure located on the western channel banks, we found organic carbon in paleosols above and below a thick (10-m) debris-flow deposit, containing large subrounded gneissic boulders (diameters of 2-3 m) suspended in a sandy matrix. The dates from the carbon samples recovered from the paleosols bracketed the debris-flow deposit between the upper dates of 3720 +/- 50 yBP, 3750 +/- 40 yBP and the lower date of 4267 +/- 38 yBP. Closer examination of this exposure and mapping the lateral extent of this deposit might determine whether this sequence of coarse bouldery deposits represents a single episode or several different debris-flow episodes within the span of about 500 years. Although we observed prehistoric debris-flow deposits in other watersheds, we did not explore systematically for dateable materials to bracket their ages.

## 9 *Mitigation Options*

The extensive damage from debris flows and flooding triggered by the intense rainfalls of December 1999 indicates the great need for mitigation to minimize loss of life and property damage from future events of similar or greater magnitude (BELLO et al. 2003, GARCÍA et al. 2003, NAKAGAWA et al. 2003). The selection and design of appropriate mitigation measures depends upon the magnitude and frequency of events, and on the economics, feasibility, and acceptability of preventing damage and casualties (UNITED NATIONS, 1996).

### 9.1 *Land use and zoning measures*

Approaches to debris-flow hazard mitigation can be separated generally into structural and non-structural measures. The non-structural measures include removing or converting existing development, discouraging development, and regulating development (ERLEY and KOCKELMAN, 1981). Non-structural measures can be especially cost effective in areas subject to frequent debris flows, such as in the state of Vargas, Venezuela. Land-use regulations can reduce hazards by limiting the type or amount of development in hazardous areas. Hazard-prone areas can be set aside for open space uses, such as parks, grazing, or certain types of agriculture, and the intensity of development can be kept to a minimum. Preventing redevelopment of areas of suspected high susceptibility to future hazards, e.g. Carmen de Uria and Quebrada Seca, may be more cost effective than structural mitigation measures (GARCÍA et al. 2003, LÓPEZ et al. 2003b).

On the Caraballeda fan, several non-structural planning methods can be employed to minimize damage from future debris flows. Employing setbacks of perhaps 30 m beyond the tops of banks along stream channels would limit damage in smaller magnitude events. Likewise, clustering development to avoid building on or near ephemeral channels on fans would also help to minimize future damage. To the extent that most of the large apartment houses withstood the force of the debris flows without collapsing during December, 1999, such structures were safer than individual 1- and 2-story residences and prevented more casualties. Thus, seeking shelter in these large multi-story structures could prevent loss of life. Likewise, even such a small step as orienting a building so that its long dimension is parallel to the direction of flow will minimize the width of the building exposed to a debris flow. Additionally, orienting streets to generally parallel the downslope direction of the fan would help them to serve as overflow channels, limiting potential damage to structures. GARCÍA et al. (2003) proposed a method for the delineation of debris-flow hazard maps in the Caracas and Vargas area using the FLO-2D model.

They report that government planning officials are using these hazard maps to design emergency plans and to update land-use policies.

### 9.2 *Forecast measures*

Monitoring, warning, and evacuation also are non-structural approaches to hazard mitigation. In order to increase the ability of emergency managers to respond to future potential events, early warning systems could be developed based on weather forecasts and rainfall information. Enhanced weather forecasting is needed for the Caribbean and the northern coastal parts of Venezuela. In the San Francisco Bay region of California for example, the U.S. National Weather Service and the U.S.Geological Survey (USGS) developed a real-time landslide warning system that was used to issue the first public, regional warning for debris flows in the United States during the storms of February 12-21, 1986 (KEEFER et al. 1987). These warnings were conveyed to local officials in the San Francisco Bay region responsible for emergency services, who deployed resources in areas likely to be affected.

### 9.3 *Rainfall intensity-duration thresholds*

Rainfall intensity-duration thresholds are simple, empirically based models used for estimation of rainfall conditions likely to trigger landslides. These thresholds have been widely identified in many different climates and geologic settings. For example in Italy, a series of rainfall thresholds have been identified for different regions (CROSTA 1998). Rainfall thresholds have similarly been identified for other regions including the Blue Ridge Mountains of central Virginia (WIECZOREK et al., 2000), Hawaii (WILSON et al., 1992), Puerto Rico (JIBSON, 1989; LARSEN and SIMON, 1993), and the San Francisco Bay region of California (CANNON and ELLEN, 1985). In order to develop rainfall thresholds for the state of Vargas, it would be necessary to document the amount of rainfall necessary to trigger floods and landslides in multiple storms. A real-time network of rainfall monitoring used in conjunction with rainfall intensity-duration threshold curves could serve as a basis for a regional landslide warning system in Venezuela.

### 9.4 *Warning systems*

Several components are necessary for a warning system to be effective in the coastal area of northern Venezuela. Detailed maps depicting areas that are at high risk of debris-flow activity are essential (GARCÍA et al. 2003) along with an automated network of rainfall stations upstream of high-risk areas. Public education on how to respond to warnings and safe means of evacuation are at least as important as the establishment of a prediction and warning system. The lack of sufficient evacuation routes along the coast of Vargas is a paramount problem. The single highway along the coast was extensively blocked during December 1999, making both evacuation and post disaster recovery extremely difficult (fig. 5B). Building additional or alternate roads, along with augmenting heliport and port facilities, could facilitate evacuation and disaster relief.

Some debris-flow warning systems use instruments such as Acoustic Flow Monitors (AFM), which detect the specific frequency of ground motion caused by debris flows; and seismic sensors, which are placed next to channels to detect approaching debris flows. When connected via a telemetry link to downstream sirens and emergency response centers, warnings can be provided (LAHUSEN 1998). Arrays of AFM’s are installed at Mount Rainier, Washington, to provide warnings to cities more than 50 km from the volcano. Flows will be detected at least 30 minutes before they can reach the main populated areas (SCOTT 2000). For most of the communities in Vargas, however, the relatively short distances of less than 4 km from the mid and upper drainages to the fans would leave very little time for warning and practically no time for evacuation.

Tripwire systems also have been widely employed to detect oncoming debris flows, but as with other warning systems the channels of potential debris flow path must be well known and sufficiently long for the advance warning to be practically useful for rapidly moving debris flows. For example, advanced warning of a debris flow traveling at an average mean velocity of 10 m/s would be only 5 minutes for the developed part of Caraballeda if the trip wire was about 3 km upstream on the San Julián River. Because of the steep gradients of the Sierra de Avila, tripwires would not provide adequate time for warning and evacuation in the communities along the coast of Vargas. In addition, vandalism would likely cause false trip wire warnings.

### 9.5 *Structural Measures*

Within channels and on fans, the most common method of entrapment of flowing debris is by check dams or debris basins (NAKAGAWA et al. 2003, CÓRDOVA & GONZÁLEZ SANABRIA 2003). Structures of this nature have a high initial cost and generally require annual or more frequent maintenance. Debris basins surrounded by residential development should be designed with the capability to remove material on a 24-hour basis during storms. These structures could be made compatible with park and recreation areas by creating open space. Debris-flow check dams have been extensively employed in Europe, Japan, China, Indonesia, Canada, and to a lesser extent, in the United States. An assessment of the effectiveness of structural flood and debris-flow control measures on alluvial fans prepared by USACE (1993) presents a number of useful case studies in the United States.

The utility of employing structural measures in this region of Venezuela depends upon the cost and degree of safety that can be provided against a particular magnitude and frequency of anticipated event. TAKAHASHI et al. (2001) have examined some of the drainages and fans in the Vargas region that were strongly affected by flooding and suggested various structural measures. For the largest boulders that were transported by debris flows during December 1999 in most of the drainages, channel modifications, check dams, and other structural measures would be largely impractical. In addition, the large amounts of uprooted trees and other vegetative debris caused avulsions from many channels and would have severely challenged the design and expected performance of structural measures. Further studies are necessary within each watershed to answer specific design questions, particularly for the magnitude of event for which they should be designed.

## 10 *Conclusion*

A steep coastal mountain range that rises to elevations of more than 2,000 m at distances of 5 to 10 km from the Caribbean Sea provides a dramatic backdrop to coastal development that surged during the second half of the 20$^{th}$ century. Located just north of Caracas, the Venezuelan state of Vargas was home to approximately 300,000 people before a severe storm in December 1999 caused floods and debris flows that killed an estimated 15,000 people. During the storm, an estimated 15 to 20 million m$^3$ of sediment, derived from 24 watersheds with a total area of approximately 200 km$^2$, was deposited on alluvial fans and beaches along the Vargas coast. On average, sediment yield for the 1999 storm was as much as 100,000 m$^3$/km$^2$. The sediment mass

approximated from the volume is 170,000 tonnes/km$^2$, which places the 1999 event among the largest ever documented for sediment transport by rainfall-triggered geomorphic activity.
The population that resides at the base of the mountains is inevitably vulnerable to the geomorphic effects of episodic high-magnitude storms. The flash flood-debris flow process combination is highly destructive in populated areas. Without careful planning of human settlements, the impact of these types of events is likely to increase in the future.

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## References

AUDEMARD, F. A., DE SANTIS, F., MONTES, L., LUGO, M. & 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), Caracas, Venezuela; 9 pp.

AUDEMARD, F.A., MACHETTE, M.N., COX, J.W., DENT, R.L. & HALLER, K.M. (2000): Map and database of Quaternary faults in Venezuela and its offshore regions - U.S. Geological Survey Open-File Report **00-018**: 78.

BELLO, M.E., LÓPEZ, J.L., GARCÍA-MARTINEZ, R. & O'BRIAN, J.S. (2003): Simulation of flooding and debris flows in the Cerro Grande River. - Acta Cientifica Venezolana. **54**: 22-32.

CANNON, S.H. & ELLEN, S.D. (1985): Rainfall conditions for abundant debris avalanches in the San Francisco Bay region, California. - California Geology **38(12)**: 267-272.

CLARKE, A.O. (1996): Estimating probable maximum floods in the Upper Santa Ana basin, Southern California, from stream boulder size. - Environmental & Engineering Geoscience. **2**: 165-182.

CÓRDOVA, J.R. & GONZÁLEZ SANABRIA, M.G. (2003): Estimación de los volumes y caudales máximos que produjeron los aludes torrenciales ocurridos en diciembre de 1999 en cuencas del litoral central del Estado Vargas, Venezuela. – Acta Cientifica Venezolana. **54**: 33-48.

COSTA, J.E. (1983) Paleohydraulic reconstruction of flash-flood peaks from boulder deposits in the Colorado Front Range - Geological Society of America Bulletin. **94**: 986-1004.

COSTA, J.E. (1984): Physical geomorphology of debris flows, [*in*] COSTA, J.E. & FLEISHER, P.J., eds., Developments and Applications of Geomorphology, Springer-Verlag, New York, 268-317 pp.

CROSTA, G. (1998): Regionalization of rainfall thresholds: an aid to landslide hazard evaluation. - Environmental Geology, International Journal of Geosciences, Special Issue: Hydrological triggers of diffused landsliding, Springer-Verlag. **35(2-3):** 131-145.

DENGO, G, (1953): Geology of the Caracas Regions, Venezuela. - Bulletin of the Geological Society of America. **64**: 8-37.

ERLEY, D. & KOCKELMAN, W.J. (1981): Reducing landslide hazards: a guide for planners. - American Planning Association, Planning Advisory Service Report Number **359**: 29.

GARCÍA, R., LÓPEZ, J.L., NOYA, M., BELLO, M.E., BELLO, M.T., GONZÁLEZ, N. PAREDES, G. VIVAS, M.I. & O'BRIEN, J.S. (2003): Hazard mapping for debris-flow events in the alluvial fans of northern Venezuela. – [In:] RICKENMANN, D & CHEN, C. (eds). Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment: Proceedings of the Third International Conference. Davos, Switzerland, Sept. 10-12, 2003, pp. 589-599. Millpress Science Publishers, Rotterdam.

JIBSON, R.W. (1989): Debris flows in southern Puerto Rico, [in] SCHULTZ, A.P. & JIBSON, R.W., eds., Landslide processes of the eastern United States and Puerto Rico. - Geological Society of America Special Paper **236**: 29-55.

KEATON, J.R., ANDERSON, L.R. & MATHEWSON, C.C. (1988): Assessing debris flow hazards on alluvial fans in Davis County, Utah, [in] FRAGASZY, R.J., ed., Twenty-fourth Annual Symposium on Engineering Geology and Soils Engineering: Publications and Printing, Washington State University, Pullman, Washington, 98-108 pp.

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. & ZATKIN, R.S. (1987): Real-time landslide warning during heavy rainfall. – Science. **238**: 921-925.

LAHUSEN, R.G. (1998): Detecting debris flows using ground vibrations - U.S Geological Survey Fact Sheet FS-236-96.

LARSEN, M.C. & SIMON, A. (1993): A rainfall-intensity-duration threshold for landslides in a humid-tropical environment, Puerto Rico. - Geografiska Annaler. **75A(1-2)**: 13-23.

LARSEN, M.C. & SANTIAGO-ROMÁN, A. (2001) Mass wasting and sediment storage in a small montane watershed: an extreme case of anthropogenic disturbance in the humid tropics *in* Dorava, J. M., Palcsak, B.B., Fitzpatrick, F. and Montgomery, D.eds., **American Geophysical Union Water Science & Application Volume 4**, Geomorphic Processes and Riverine Habitat, 119-138.

LARSEN, M.C., WIECZOREK, G.F., EATON, L.S., MORGAN, B.A. & TORRES-SIERRA, H (2001): Natural hazards on alluvial fans: the Venezuela debris-flow and flash-flood disaster. - U.S. Geological Survey Fact Sheet, FS 103-01, 4 p. http://pubs.usgs.gov/fs/fs-0103-01/fs-0103-01.pdf

LEÓN, R.J. R. (2003): Algunas reflexiones estadisticas sobre la tragedia del Estado Vargas de 1999. – Acta Cientifica Venezolana. **54**: 13-16.

LÓPEZ, J.L., PEREZ, D. & GARCÍA, R. (2003a): Hydrologic and geomorphologic evaluation of the 1999 debris-flow event in Venezuela. [In:] RICKENMANN, D & CHEN, C. (eds). Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment: Proceedings of the Third International Conference. Davos, Switzerland, Sept. 10-12, 2003, pp. 989-1000. Millpress Science Publishers, Rotterdam.

LÓPEZ, J.L., BELLO, M.E., GONZÁLEZ, N., TOYO, A., SHUCHENG, Z., PENG, C. & FANGQUIANG, W. (2003b): Lecciones aprendidas de la tragedia de Vargas: el caso de Carmen de Uria. – Acta Cientifica Venezolana **54**: 49-62.

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, 55 pp.

MARTINEZ, E. (2000) Evento meteorológico sobre el Litoral Central en diciembre 1999. unpublished report.

MERIFIELD, P.M. (2001): Observations on the December 1999 catastrophic debris flows and floods in Venezuela, [*in*] LUKE, B., JACOBSON, E., & WERLE, J., eds., Proceedings of 36th Symposium Engineering Geology & Geotechnical Engineering, March 28–30, 2001, University of Nevada, Las Vegas: Pocatello, Idaho, Idaho State University, p.271–280.

MILLIMAN, J.D., and SYVITSKI, J.P.M., (1992) Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers. – Jour. of Geology. **100**, 525-544.

NAKAGAWA, H., TAKAHASHI, T., SATOFUKA, Y. & KAWAIKE, K. (2003): Numerical simulation of sediment disasters caused by heavy rainfall in the Camuri Grande basin, Venezuela 1999. – [In:] RICKENMANN, D & CHEN, C. (eds). Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment: Proceedings of the Third International Conference. Davos, Switzerland, Sept. 10-12, 2003, pp. 671-682. Millpress Science Publishers, Rotterdam.

PERICCHI, L.R. & COLES, S. (2003): ¿Pudo haber Sido Anticipada Probabilisticamente La Lluvia Extrema Que Causó La “Tragedia de Vargas”? – Acta Cientifica Venezolana. **54**: 17-21.

RÖHL, E. (1950): Los diluvios en las montañas de la cordillera de la costa. - Boletín de la Academia de Ciencias Físicas, Matemáticas y Naturales, Venezuela, **38**: 1-28.

SALCEDO, D.A. (2000): Los flujos torrenciales catastróficos de Diciembre de 1999, en el estado Vargas y en Caracas: Características y lecciones apprendidas. - Memorias XVI Seminario Venezolano de Geotecnia, Caracas. 128-175 pp.

SANCIO, R.T. & BARRIOS, R. (2000): Disaster in Venezuela: the floods and landslides of December 1999. - Natural Hazards Observer. **24:** 1-2.

SCHUBERT, C. (1985): Aluviones colgantes en la cordillera de la costa: indicio de aridez durante el quaternario tardio. - Acta Científica Venezolana. **36**: 201-202.

SCHUSTER, R.L., SALCEDO, D.A. & VALENZUELA, L. (2002): Overview of catastrophic landslides of South America in the twentieth century. – [In:] EVANS, S.G. & DEGRAFF, J.V. (eds) Catastrophic landslides: effects, occurrence, and mechanisms: Boulder, Colorado. - Geological Society of America Reviews in Engineering Geology. **15**: 1-34.

SCOTT, K.M. (2000): Precipitation-triggered debris-flow at Casita Volcano, Nicaragua: Implications for mitigation strategies in volcanic and tectonically active steeplands:[ *in* ] WIECZOREK, G.F. & NAESER, N.D., eds., Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment: Proceedings of the Second International Conference, Taipei, Taiwan, August 16-18, 2000, A.A. Balkema, Rótterdam, 3-13 pp.

SINGER, A, ROJAS, C. & LUGO, M. (1983): Inventario nacional de riesgos geológicos, mapa, glosario y comentarios. - Serie Técnica FUNVISIS, (Fundación Venezolana de Investigaciones Sísmicas) **03-83**:126.

STALLARD, R. F. (1988): Weathering and erosion in the humid tropics, in Lerman and Meybeck, eds., Physical and Chemical Weathering in Geochemical Cycles, Kluwer Academic Publishers, Dordrecht, Holland, 225-246 pp.

TAKAHASHI, T., NAKAGAWA, H., MAKI, N., JAUREGUI, E., CHIGIRA, M., ONDA, Y., & AGUIRRE-PE, J. (2001): Flood and sediment disasters caused by the 1999 heavy rainfall in Venezuela: Research Report on Natural Disasters, Sponsored by the Ministry of Education, Science, Sports and Culture (Japan), Grant No. 11800020, CD, February, 2001.

UNITED NATIONS (1996): Mudflows, Experience and Lessons Learned from the Management of Major Disasters, Chapter 4, Mudflow prevention: United Nations Department of Humanitarian Affairs, Geneva, p.21-42.

URBANI, F. & OSTOS, M. (1989): El complejo avila, cordillera de la costa, Venezuela. - Geos, UCV, Caracas, **29**: 205-217.

URBANI, F. (2002): Consideraciones geológicas de la catástrofe del Estado Vargas de Diciembre. – Geos. **35**: 13-22.

USACE, (1993) Assessment of structural flood-control measures on alluvial fans: US Army Corps of Engineers Hydrologic Engineering Center, prepared for Federal Emergency Management Agency, 76 pp.

VARNES, D.J. (1978): Slope movement types and processes: [in] SCHUSTER, R.L. & KRIZEK, R.J., eds., Landslides Analysis and Control, Special Report 176, Transportation Research Board, National Academy of Sciences, Washington, D.C., 11-33 pp.

VICENTE, G.A., SCOFIELD, R.A. & MENZEL, W.P. (1998): The operational GOES Infrared rainfall estimation technique. - Bulletin of American Meteorological Society. **79**: 1883-1898.

WEHRMANN, M. (1969) Mapa Geologico de la Region Colonia Tovar-Guatire: IV Congreso Geologico Venezolano, MinisteRío de Minas e Hidrocarburos, scale 1:100,000.

WIECZOREK, G. F., MORGAN, B. A. & CAMPBELL, R. H. (2000): Debris-flow hazards in the blue ridge of central Virginia. - Environmental & Engineering Geoscience **6(1)**: 3-23.

WIECZOREK, G.F., LARSEN, M.C., EATON, L.S., MORGAN, B.A. & BLAIR, J.L. (2001): Debris-flow and flooding hazards associated with the December 1999 storm in coastal Venezuela and strategies for mitigation - U.S. Geological Survey Open File Report **01-144**: 40, 3 tables, 2 appendices, 3 plates, 1 CD. **(**http://pubs.usgs.gov/of/2001/ofr-01-0144/)

WIECZOREK, G.F., LARSEN, M.C., EATON, L.S., MORGAN, B.A. & BLAIR, J.L. (2002): Debris-flow and flooding deposits in coastal Venezuela associated with the storm of December 14-16, 1999. - U.S. Geological Survey, Geologic Investigation Series Map I-2772. http://pubs.usgs.gov/imap/i-2772/

WIECZOREK, G.F., COE, J.A. & GODT. J.W. (2003): Debris-flow hazard assessment using remote sensing of rainfall. – [In:] RICKENMANN, D & CHEN, C. (eds). Debris-Flow Hazards Mitigation: Mechanics, Prediction, and Assessment: Proceedings of the Third International Conference. Davos, Switzerland, Sept. 10-12, 2003, pp. 1257-1268. Millpress Science Publishers, Rotterdam.

WILSON, R.C., TORIKAI, J.D. & ELLEN, S.D. (1992) Development of rainfall warning thresholds for debris flows in the Honolulu District, Oahu. - U.S. Geological Survey Open-file Report **92-521**: 45.

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