HYDROLOGIC AND GEOMORPHOLOGIC EVALUATION OF THE 1999 DEBRIS FLOW EVENT IN VENEZUELA

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Abstract

In this paper a general hydrologic and morphological evaluation of the debris flows that took place in December 1999 in Venezuela is presented. First, the major debris flow events that have occurred in Venezuela and other Latin-American countries are summarized, and then the hydrological and geomorphologic processes, associated with the 1999 disaster, are described. An estimation of the maximum flow discharges and sediment accumulation volumes in some basins are made based on field observations. The results indicate that the torrential flows that took place in Venezuela were a unique event in the sense that multiple basins generated hyperconcentrated flows in the morning of December 16, 1999, creating a new coast line and depositing more than 20 millions of cubic meters of sediment on the alluvial fans and beach zones of the north central Venezuelan region.

Key words: debris flows, disaster, Venezuela

Introduction

The extreme rainfalls that occurred in the north central Venezuelan coast on December 99 caused the worst disaster in Venezuela and perhaps one of the worst in Latin America. On December 16 simultaneous extreme debris flows occurred in about twenty streams along fifty kilometers of a narrow coastal strip in the State of Vargas, causing extensive damage in the urban developments located on the valleys. In a few hours complete towns were washed away by the avalanches of mud and debris flows coming down from the mountains. About 15000 people were killed, 23000 houses were destroyed and 65000 houses suffered severe damages. Economical losses has been estimated in more than two billion dollars

Debris-Flow Events in Latin America

Torrential flows, mud flows, and debris flows have happened frequently in Latin America, and more often in the cities developed near the Andes Mountains. Among recent events can be mentioned the landslide disaster in the Paute River in 1993, near the city of Cuenca, Ecuador, better know as the disaster of La Josefina (Zevallos et al., 1993). Ayala et al. (1994) report four large events related to debris flows in Chile in a period between 1987 and 1993, which caused hundreds of victims and tens of million dollars in losses. The most dramatic event was caused by the eruption of Nevado Ruiz Volcano, which in November 14, 1985 produced mud flows that totally destroyed the town of Armero, Colombia, leaving a toll of 25000 people dead. The most recent event occurred when the Mitch Hurricane passed through Central America, generating debris flows that destroyed the town of Casita Volcano in Nicaragua, with 2.000 victims (Must, V. 1999). Other minor-scale mud flows events have also been reported recently in some states of Mexico in 1999 (Caldino and Bonola, 2000). In Venezuela a few debris flow events events have been reported. The oldest written testimony refers to the storm of February 1798 in the region of La Guaira, reported by Alexander Von Humboldt who described the 70-hour duration rainfall that produced a large flood carrying wood trunks and boulders of considerable size. Another more catastrophic storm occurred in the same region (north central coast) in February 1951, with a similar geographic extension as the 1999 storm, affecting also the capital city of Caracas (Sardi, 1959). The town of La Guaira was reported to have been buried to a depth of as much as 4 m. The most dramatic event in Venezuela occurred near the city of Maracay in September 1987, where heavy rainfalls produced flash floods and debris flows in the Rio Limon, causing a death toll of 300 people. However, geological evidence have shown that large-scales debris flows have occurred in the Rio Limon basin, and also in the valley of Caracas (capital city), in pre-Colombian ages between 1100 and 1500 AD (Singer et al., 1983).

Geographic Characteristics of the Area of Disaster

Venezuela is located on the top of South America near the Equator between 1° and 12° of north latitude. The north coastal range of Venezuela lies adjacent to the Caribbean Sea attaining elevations of up to 2,800 m over sea level. The northern slope is very steep descending to sea level in a horizontal distance between 6 and 10 km. The southern slope descends to a valley at 1000 m above sea level, where the capital city of Caracas is located, 15 km south of Maiquetia International Airport (Figure 1). In the coastal plains, urban and tourist developments have taken place along the State of Vargas, a very narrow land strip whose width varies between 200 and 2,000 m. The main populated areas have settled on alluvial fans, canyons and also on the steep slopes of the mountain range. Population was estimated in 300,000 people before December 99 disaster. Most of the basins are well protected by vegetation and belong to the Avila National Park. The slopes support tropical rain forest at higher elevations including large trees of more than thirty meters high, and arid regions near the sea level with scarce vegetation. Basin areas range from 2 km^2 to 70 km^2 with stream bed slopes of up to 90% in the upper reaches and 3% to 6% in the lower reaches. Most of the streams are ephemeral showing some discharge only during the rainy season. The mean annual rainfall is about 500 mm near sea level and 1200 mm in areas of maximum elevations. The mean annual temperature in the coastal zone is 26 degrees.

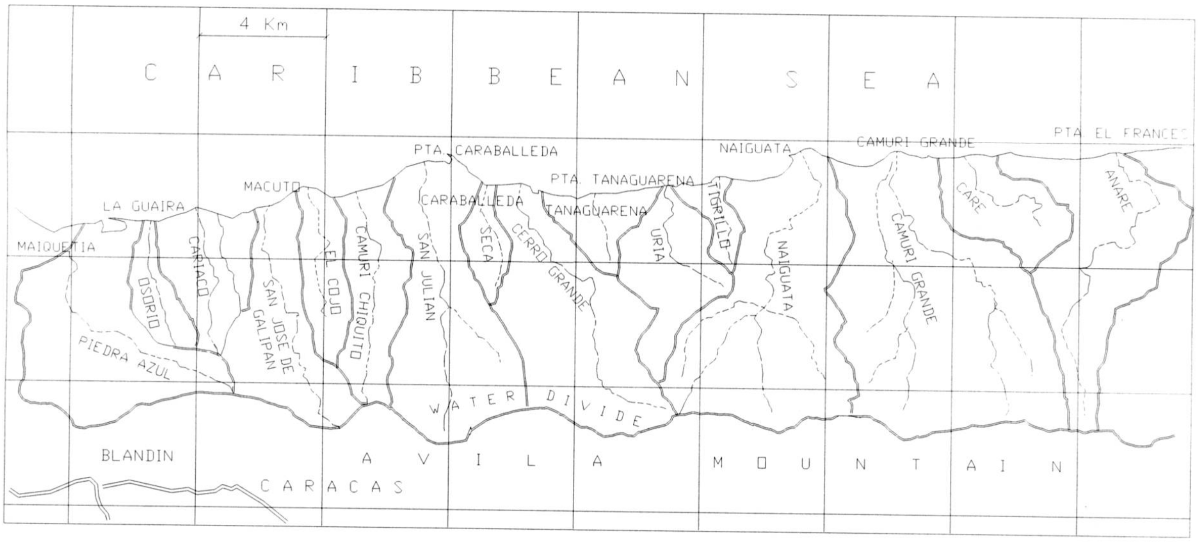


Figure 2. Location map of the main basins in the area of disaster (State of Vargas).

The December 99 Storm

The rainy season in Venezuela extends typically between May and September. However some of the large storms, flash floods and inundations, in the State of Vargas have occurred between November and February, due to cold fronts coming from the North Atlantic. Large humid air masses coming from Colombia and the Pacific Ocean with the jet streams were blocked by the cloud wave which stayed in the Caribbean Sea for about 20 days. By the middle of December, satellite images indicated that the cloudy front in the Caribbean region was covering an area of 20,000 km^2 and extending for about 900 km along the north central coastal line of Venezuela. Rainfall started by the end of November 99. Unfortunately, only two stations were operating in the State of Vargas by the time of the storm. Figure 2 shows rainfall data recorded in the Stations of Maiquetia (43 meters above sea level) and Mamo (81 meters above sea level) for the month of December, 1999 A low intensity but continuous rainfall occurred between December 1 and December 13, amounting to 293 mm in Maiquetia. Then a heavy rainfall took place during the following three days. Maiquetia station reported 911 mm from 14^{th} to 16^{th} and a total precipitation of 1207 mm for the first 17 days of December. This station measured 72 mm of rain between 6 am and 7 am of the morning of December 16. In Mamo, however, the cumulative value for the same period was 438 mm. Other stations located in the upper part of the basins were not operating, but usually the ascent of air masses from the Caribbean Sea to the slopes of the mountain results in higher precipitations. Past observations of preceding events have shown that the amount of rainfall in the mountain could be twice the amount at sea level. For instance, an abandoned station (Infiernito) located at 1000 m above sea level reported a total precipitation of 529 mm for the 1951 storm (60 hours), while Maiquetia reported 282 mm.

For a period of 52 years (excluding 1999), Maiquetia station shows the following figures: annual average of 523 mm; annual maximum of 961 mm (1951); and annual minimum of 205 mm. If we compare these values with the 1999 storm, an evident conclusion is that an extraordinary amount of precipitation fell in the mountains of the State of Vargas in December 1999. The long period of nearly continuous rainfall, between December 1 and December 13, contributed to soil saturation reducing soil resistance and triggered the occurrence of landslides in most of the basins. Then, debris flows were generated almost simultaneously, with difference of several minutes or few hours, in the morning of December 16 in about twenty streams of the State of Vargas.

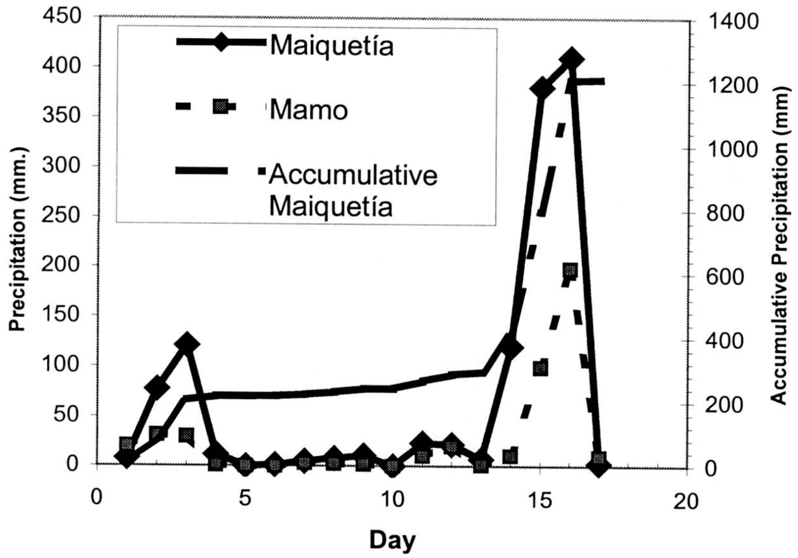


Figure 3. Rainfall data registered during December 99 in the area of disaster.

Geological Aspects
The Avila Mountain is a part of the North Coastal Range of Venezuela which covers a surface of 30,000 km2 and extends in an east-west direction on the north boundary of the South-American continent. The greatest elevations are reached north of the capital city of Caracas with maximum values of 2,765 m (Naiguata peak) and 2,640 (La Silla of Caracas peak). Alluvial fills, like the Caracas Valley, are found in the south of the coastal range. As pointed out by Garner (1959) these mountains are considered to be tectonically and physiographically similar to the Andes Mountains. The rocks of the coastal mountains are composed mainly by metamorphosed and intruded sedimentary rocks. Table 1 show the

most important lithological units within the area affected by the December 1999 disaster. Rocks outcrops are primarily from Pre-Cambrian and Mesozoic ages. Dominant groups are Complejo de la Costa (Mesozoic), Caracas Group (Mesozoic) and Complejo Avila (Pre-Cambrian). Topographic relief differences in Avila Mountain are controlled by differences in rock strength. The oldest Pre-Cambric unit is represented by Meta-granite of Naiguata, Meta-igneous rocks of Tocome, San Julian Schists (gneises and feldespathic schists) and Augen-gneiss of Pena de Mora (quartz micaceous gneiss). The Caracas group is composed by Las Mercedes Formation (calcareous and graphitic schists, and graphitic marbles), and Las Brisas Formation (quartz and feldespatic schists and meta-sandstones). The Complejo de la Costa Group is mainly represented by the Tacagua Phase (marbles, calcareous and epidotic schists). Most of the large rocks and boulders found in the alluvial valleys belong to the upper lithologic units (San Julian schists and Pena de Mora gneisses). However some of them seem to have been transported by past events and moved again by the 1999 flood, as suggested by the red and dark colors observed in the surface of some rocks indicating long-time exposure to the atmosphere. Large proportions of fine material transported by the debris flows were originated from the Tacagua Phase, which can be found in the lower elevations of the basins and is characterized by a brick red color.

Erosion and Weathering

The most frequent geodynamic processes occurring during the storm were translational landslides which developed long scars from the top of the ridges to the toes of natural slopes (Figure 6). Probably, a combination of rotational and translational failures were present in the Avila Mountain during the 1999 storm, exposing the rock underneath. Some scars of considerable size, as large as 500 m long and 200 m wide, have been observed in the Camuri Chico Basin. The evolution of some slide scars in San Jose de Galipan basin indicates that two years after the event, the upstream migration of knick points had almost reached the top of the basin divide (Figure 4). Similar behavior has been observed for the scars located on the north flank of the Avila Mountain. The material involved in the landslides is mainly formed by residual or colluvial soils saturated by the intense rainfall, sliding down with the vegetation cover lying on the top. Observation of aerial photos shows that in the zones most heavily damaged by landslides, the area of denudation could be about 30% of the total area. Considering the whole basins, estimates of the total areas affected by denudation and landslides are in the order of 10 to 20% of the total area exposed to rainstorm.

The thickness of the soil layer in the Avila Mountain varies between 1 and 5 m depending of the gradient slopes and ground elevation. Residual soils have developed by weathering of the rock mass lying below the plant cover (Figure 4). The weathered zone, with variable thickness estimated between 80 and 100 m deep, is due to mechanical and chemical alteration of the rock in the presence of high moisture, organic acids and temperature effects. The maximum depths are found along the river courses that coincides with geologic faults, where the chemical alteration is greater due to water percolation transporting minerals and organic acids through joints and rock fractures.

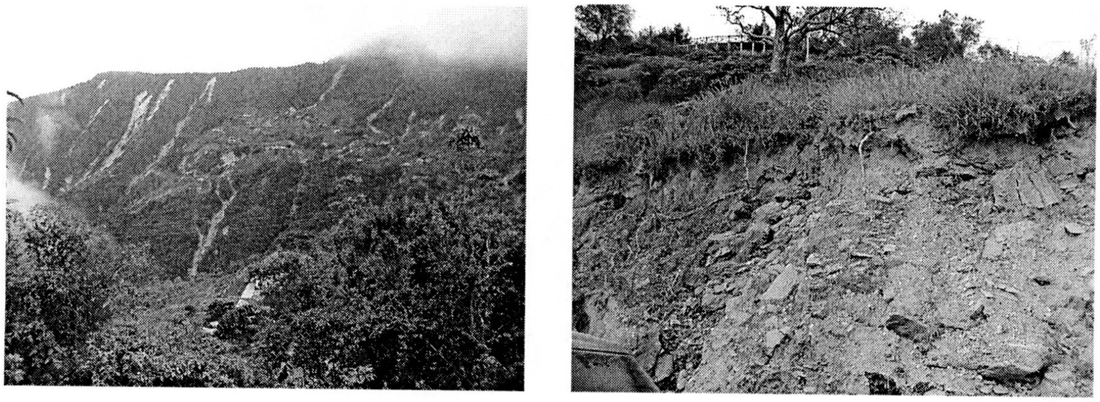


Figure 4. Left: slide scars of the 1999 storm in the upper part of San Jose de Galipan river basin (Picture taken in January, 2001). Right: soil layer and weathered bedrock in the upper basin of San Jose de Galipan river.

Mechanical weathering and fractures in the rock mass could also be caused by solar radiation, thermal differential changes and tectonic activity. Monthly fluctuations of temperature ranges between 10 and 15°. At Maiquetia station, located at 40 m above sea level, the mean annual is 26,5°, with a maximum range of 9,5° between the hottest and the coldest month. At Los Castillitos station (1600 m) the thermal fluctuation is 13° with a mean annual of 17°. It is noted that the rates of many chemical reactions increase exponentially with rising temperatures. Commonly, a 10° increase in temperature doubles or triples the reaction rate (Leopold et al., 1964). Solar radiation also contributes to increase the temperature in surface of soils and rocks. Mean annual values of solar radiation for Maiquetia station and Los Castillitos station are equal to 431 cal/cm^2 and 464 cal/cm^2, respectively. The presence of salinity in the air masses coming from the Caribbean Sea, in addition to changes in ground elevation, could also contribute to the chemical alteration of the rock mass, and is an important factor in the distribution and type of vegetation found in the Avila Mountain.

Geologic Fault System

Two geologic fault systems are present in the area affected by the debris flows. One of them is parallel to the coastal range and the second one is transversal to it. Some of the streams, like San Julian, Quebrada Seca, and Cerro Grande, have developed their channels along transverse faults. Rocks in these faults are sensitive to develop structural fissures. Rocks are fractured, smashed and cut into wedges, rhombus and various shapes by the weathering processes in the structural fissures. The resulting blocks, when fall and slip down to the gullies at the trigger of earth vibration, are important mass sources for debris flows. Slope instability is enhanced by the high earthquake potentiality due to the vicinity of a seismic zone where intensive earthquakes have often taken place in the past. Regionally, some of the faults are important from a seismic point of view. The most important one is the San Sebastian Fault, which is considered responsible for the linear trace of the Central Coast. This fault is considered part of the meridian limit of the Caribbean Tectonic Plate.

Longitudinal Profiles

One of the most striking aspects of the Avila Mountain is its abrupt relief and steep profiles of valley sides and channels. River courses descend steeply from near 3.000 meters elevations into sea level in a horizontal distance not greater that 10 km. Channel slopes up to 90% are common in the upper part of the basins. Near vertical face slopes can be found very often in the sides of the mountain. Table 2 presents some geometric characteristics for the main basins located in the area of interest. The longitudinal profiles of the streams are shown in Figure 8. The greatest channel lengths correspond to the streams of Cerro Grande, San Julian, Naiguata and Camuri Grande, which have deeply incised the bottom of the valleys. Significant changes of slopes are observed above the 400 m elevation, in the transition between the gorge and the upper basin. The values of the channel slopes in this zone are shown inside a rectangle in Figure 8. In the upper part of the basin, the channel slopes vary between 28.4% and 65.4%. In the alluvial fans, the slopes vary between 1.6% and 6.7%. The maximum average slope corresponds to Guanape stream with a value of 32.7%. San Jose de Galipan and Cerro Grande streams present inflexion points in the profiles, due to existence of terraces of probably tectonic origin.

These high values of channel slopes and side slopes in the upper reaches of the basins, whose waters drain zones conformed by weathered material (gneisses and schists), were important factors that contributed to the large amount of sediment loads transported by the streams during the 1999 storm.

Changes in Bed Profiles

A closer view at the longitudinal profile in the lower reach of Cerro Grande stream is presented in Figure 9, showing the conditions before (March, 1999) and after (January, 2000) the debris flow event of December 1999. The bed profile depicted in Figure 9 indicates that accumulation of sediment occurred in the canyon and alluvial fan of Cerro Grande river. The slope of the channel bed did not significantly changed after the storm, keeping an average value of 4% in the canyon and a value of 2,5% in the fan. The alluvial fan was extended about 140 m into the sea and sediment deposition along the river course amounted to 4 to 5 m in the valley and to 2 to 3 m in the canyon.

Sediment deposition in the canyons and alluvial valleys seem to have been the general trend for the majority of the streams. However not all the streams behaved in the same way. In San Julian stream a large amount of sediment, in the order of 0.5 millions of cubic meters, was eroded from the canyon (average slope 8%) and transported downstream to be deposited on the alluvial fan (average slope 5%). On the contrary, the alluvial fan of Uria stream was subjected to extreme erosion that opened a channel 30 m wide and 7 m deep along a heavy urbanized area, destroying and dragging many houses down to the sea. This particular event is also associated with the collapse of a sediment trap dam, 15 m high, that was totally destroyed by the debris flows in the first hours of December 16, 1999.

STREAM	AREA (Km^2)	MAX. ELEV. IN BASIN (m)	TOTAL LENGTH (Km)	AVERAGE SLOPE (%)	ALLUVIAL FAN LENGTH (m)	ALLUVIAL FAN SLOPE (%)	CANYON SLOPE (%)	CHANNEL SLOPE ABOVE 400 M
Piedra Azul	24,8	1950	9,0	17,3	1500,0	4,8	6,0	27,3
Osorio	4,6	1700	5,0	32,0	500,0	4,4	11,0	52,4
Guanape	5,7	1960	5,5	32,7	450,0	6,7	10,0	65,4
Galipan	14,0	2300	8,0	21,5	700,0	6,3	6,5	37,8
El Cojo	6,8	1550	5,5	19,6	600,0	4,0	7,0	43,0
Camuri Chico	11,2	2350	7,5	16,0	600,0	5,7	8,5	33,0
San Julián	23,6	2490	9,8	21,6	2000,0	5,0	8,0	33,8
Seca	5,3	1240	3,8	25,3	800,0	6,2	10,0	54,0
Cerro Grande	26,6	2750	10,5	20,2	950,0	2,5	6,0	38,3
Uria	11,6	2150	7,5	29,3	750,0	6,3	7,0	56,7
Naiguatá	33,4	2000	12,0	12,3	1200,0	1,6	4,0	28,4
Camurí Grande	42,90	2190	10,2	19,6	1100,0	2,5	5,0	33,4
Mamo	141,00	2100	38,5	5,5	3,4	1,5	2,0	6,0
La Zorra	6,20	900	6,1	15,0	1,0	3,0	6,0	27,8
Tacagua	93,50	1900	22,4	7,6	3,1	1,3	2,0	11,0

Table 3. Geometric and phisiographic characteristics of main basins in the area of disaster.

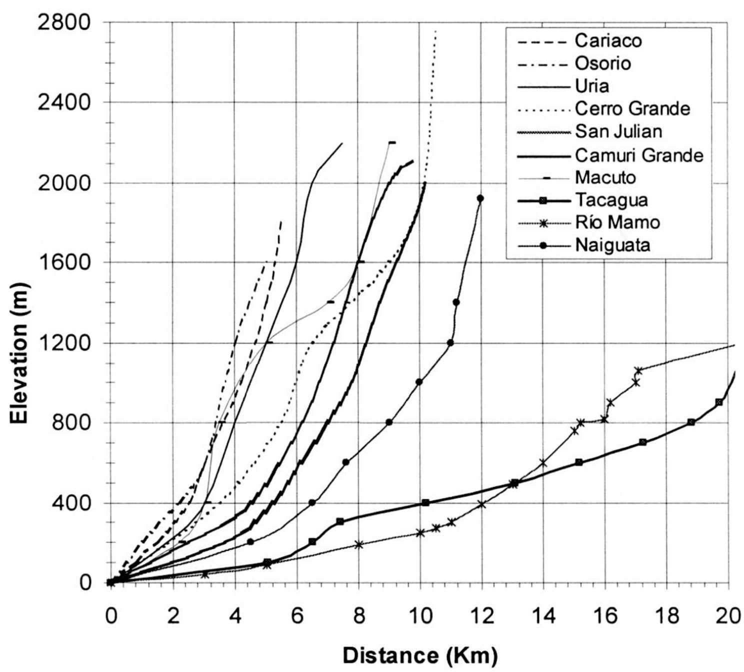
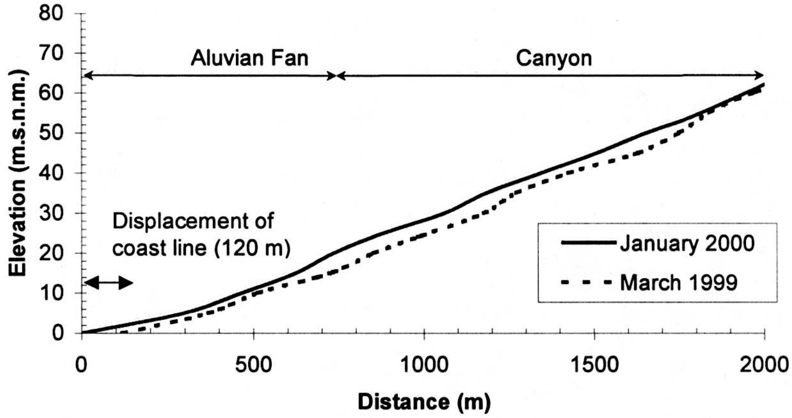
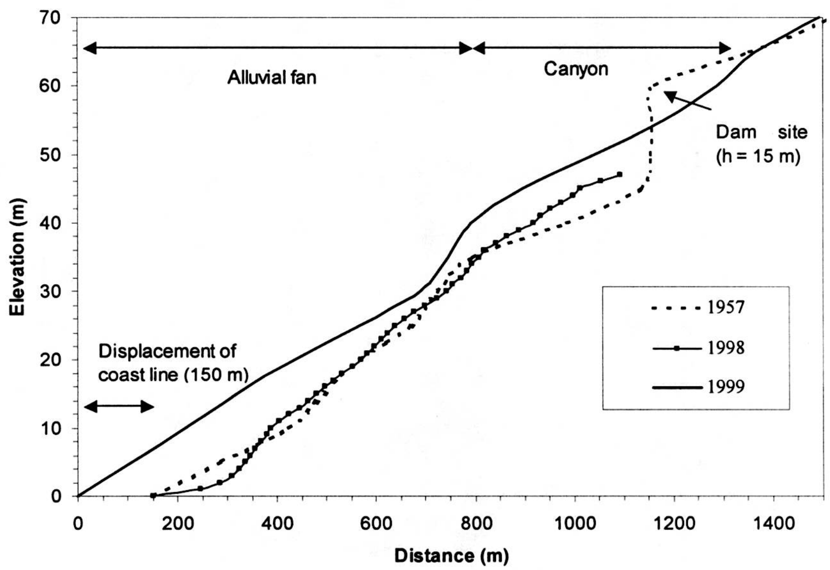


Figure 8. Longitudinal profiles of main streams in the area of disaster.


80
70
60
50
40
30
20
10
0
Elevation (m.s.n.m.)
Aluvian Fan
Canyon
Displacement of
coast line (120 m)
January 2000
March 1999
0
500
1000
1500
2000
Distance (m)


70
60
50
40
30
20
10
0
Elevation (m)
Alluvial fan
Canyon
Dam site
(h = 15 m)
Displacement of
coast line (150 m)
1957
1998
1999
0
200
400
600
800
1000
1200
1400
Distance (m)

Sediment Accumulation

Based on field observations and aerial photos taken in December 21,1999, the amount of sediment accumulation in the alluvial fans has been estimated for the most important basins in the study area. The volumes of sediment deposition are listed in Table 4 and refers only to the accumulation of sediment in the alluvial fans. It dos not include the sub-aqueous deposition in the sea. A total volume of sediment deposition for all basins in the study area has been estimated in the order of 20.000 millions of cubic meters. Obviously, most of the sediment conveyed by the flood was washed away into the ocean, and is unaccounted for in these deposition estimates. The deposition of debris flows created a new coastline in the State of Vargas, generating new beaches and areas that could be used for recreational purposes (Figure 10). The amount of land gained to the sea by the 1999 event has been estimated to be approximately equal to 1000 Ha. **(*OJO*: parece muy alto) (EFECTIVAMENTE CREO QUE UNA CIFRA MAS RAZONABLE ES 50 ó 100 Ha)**

Figure 9. Comparison of Cerro Grande bed profiles.

STREAM	AREA OF SEDIMENT DEPOSITION (Has)	VOLUME OF SEDIMENT DEPOSITION (10^6 m^3)
Piedra Azul	55,0	1,37
Osorio	17,8	0,45
Guanape	18,1	0,40
San Jose de Galipan	25,4	0,64
El Cojo	45,0	1,10
Camuri Chico	30,0	0,75
San Julián	127,0	2,60
Seca	74,1	1,48
Cerro Grande	36,6	1,60
Uria	37,2	1,50
Naiguatá	66,7	1,00
Camurí Grande	79,0	1,90

Table 4. Volume of sediment depositions in alluvial fans of main streams.

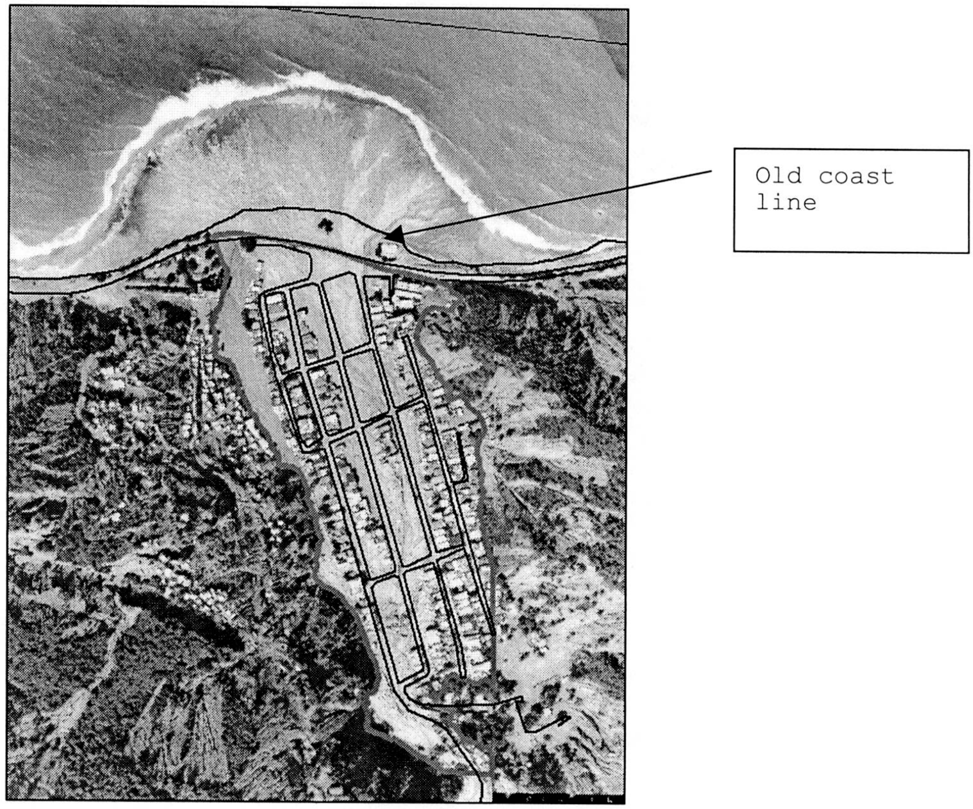


Figure 10. Modification of the coastline in Uria.

Characteristics of the Bed Material

Figure 11 presents grain-size distribution curves for samples of bed material collected from different streams in the area of interest. All samples were taken in the alluvial fans. Grain-sizes samples smaller that gravel (6.4 cm) were analyzed in the laboratory and distribution curves for greater fractions were obtained directly in the field by a counting procedure similar to Wolman´s technique. The finer fractions show a quite uniform distribution with particle mean diameters between 0.1 and 10 mm. The maximum percentage of clays and silts was obtained in Cerro Grande (12%), suggesting that fine material was available to generate mud flows. A matrix of cobbles, gravel and fine material was observed under the base of large boulders in many streams, indicating the presence of the so-called "inverse grading".

For the coarser fractions analyzed, the mean diameters varies between 1 and 2 m.. Proportions of sediment sizes in the alluvial fan of San Julian stream was estimated to be 50% of boulders, 20% of cobbles, 20% of gravel, and 10 percent of sand and finer material. Similar proportions for Cerro Grande stream are 40% of boulders, 15 % of cobbles, 25% of gravel, and 20% of sand and finer.

Table 4 shows typical sizes, shape factors and weights of large boulders sampled in the canyons and alluvial fans of Camuri Chico and San Julian streams. These large rocks originated from the San Julian Schists and Gneisses of Pena de Mora (Figure 4). The volumes were calculated by assuming an ellipsoidal particle with dimensions equal to *a*, b and *c*, in which they are respectively, the length of the longest, intermediate, and shortest mutually perpendicular axes of the boulder. The shape factors indicate not well rounded material except for the one with a value of SF = 0.81.

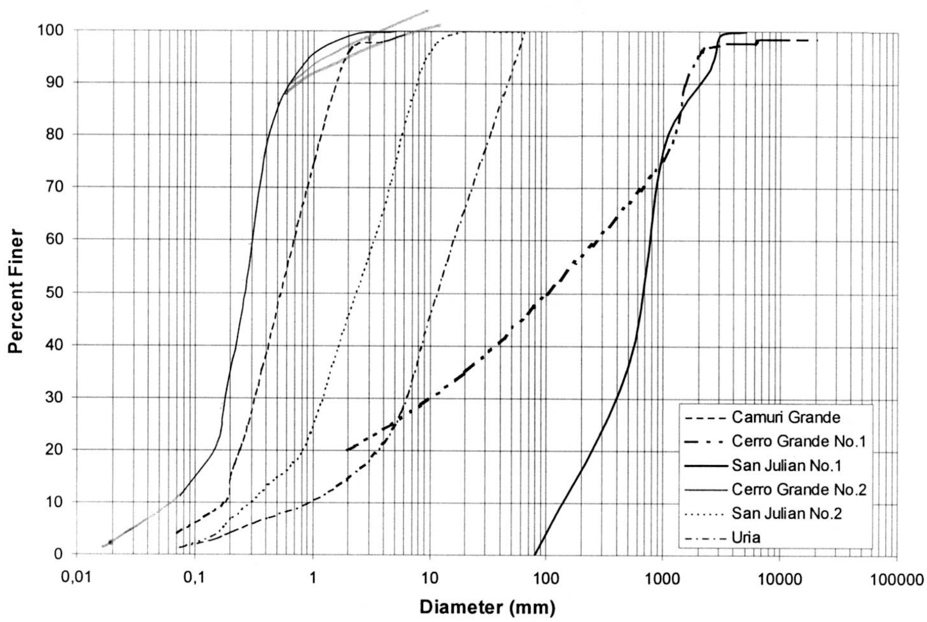


Figure 10. Grain size distribution of bed material at selected streams.

Stream	Axes dimensions			Shape Factor	Volume	Weight	Corrected
	a	b	c	c/sqrt(a b)	V = 1/6 p a b c	(ton)	Weight (ton)
Camuri	5.10	4.10	2.00	0.44	21.90	61.3	49.0
Camuri	7.80	7.60	5.00	0.65	155.19	434.5	347.6
Camuri	11.30	5.00	3.30	0.44	97.62	273.3	218.7
Camuri	15.00	9.00	4.00	0.34	282.74	791.7	633.3
Camuri	5.10	4.10	2.00	0.44	21.90	61.3	49.0
Camuri	12.00	8.20	2.40	0.24	123.65	346.2	277.0
Camuri	10.00	4.70	3.50	0.51	86.13	241.2	192.9
San Julian	8.20	7.50	4.41	0.56	142.01	397.6	318.1
San Julian	5.00	2.60	1.00	0.28	6.81	19.1	15.2
San Julian	5.60	4.30	1.70	0.35	21.43	60.0	48.0
San Julian	4.30	3.20	2.50	0.67	18.01	50.4	40.3
San Julian	6.10	3.50	2.60	0.56	29.06	81.4	65.1
San Julian	7.20	6.10	1.60	0.24	36.79	103.0	82.4

San Julian	2.30	1.70	1.60	0.81	3.28	9.2	7.3

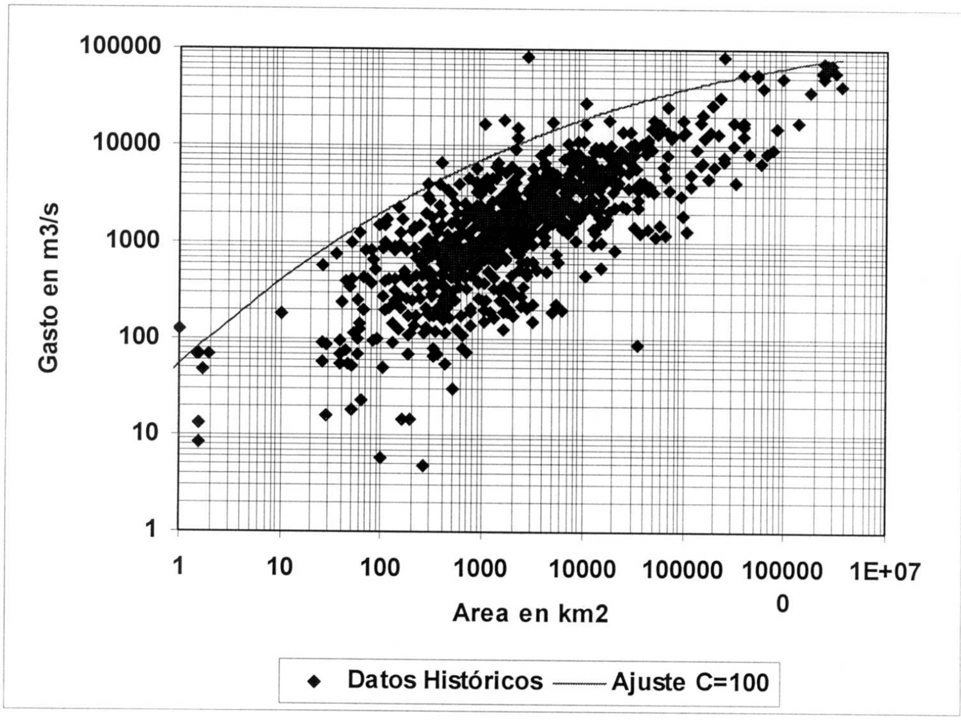
Table 4. Geometric characteristics of boulders in San Julian and Camuri Chico

Some of these boulders were transported into the alluvial fan of San Julian River. One of the largest sizes, up to 8.2 m long, was found at 800 m downstream from the foothill of the mountain. (Figure 5), with a corresponding weight of 318 tons. The maximum size and weight corresponds to a boulder observed in the canyon of Camuri Chico: 15 m long and 633 tons.

Debris Flow Discharges

Reinaldo Garcia*

(HABLAMOS DE ESTO)



Conclusions

Multiple basins generated simultaneous extreme debris flows in the morning of December 16, 1999 in the north coastal range in Venezuela. The main causes for the formation of debris flows are associated to: a) the presence of very steep slopes in the channels and valley sides of the Avila mountain (average channel slope for the upper reach of all basins is 20°); b) the occurrence of a long rainstorm (300 mm in 13 days) that saturated the soils previous to the event: c) the occurrence of huge rainfall rates (911 mm in 72 hours, and 72 mm in one hour) during the event; d) the presence of abundant sediment, sufficient thickness of soil, large plants, and weathered bedrocks.

Collapse of natural dams within the channels is believed to have been responsible for the occurrence of large debris flow discharges that can not be explained by the usual response of rainfall-runoff processes in the basins. The magnitudes of the measured flow discharges in Cerro Grande and San Julian are twice greater that the observed in basins of the world with similar extension area.

Human perturbation was minimal in the middle and upper part of most of the watersheds prior to the 1999 storm because they are part of the Avila National Park, protected by local regulations. Basins were well vegetated with minor damages and no significant landslides or hillslopes failures occurrence in the area. Only in one basin (San Jose de Galipan) crop activities were allowed and roads were built for vehicle transportation. Floods did not occur very often in the valleys (last flood event took place in 1951). Thus, a false sense of security was created in the alluvial fans and houses and buildings were built along both sides of river channels. The high toll of victims is associated to the indiscriminate occupation of these valleys with no particular control works to regulate and transport the water and sediment flows.

Volumes of sediment deposition in the alluvial fans have been estimated in the order of 20 million cubic meters for the towns located along 40 km in the coastal area of the State of Vargas. This accumulation of sediment penetrated deeply into the sea modifying the coastline and creating new lands whose aerial extent has been estimated in approximately 1000 Ha.

Occurrence of different types of debris flows ???

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