THE RAINFALL-TRIGGERED LANDSLIDE AND FLASH FLOOD DISASTER IN NORTHERN VENEZUELA, DECEMBER 1999

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Abstract: Rainstorms in December 1999 induced thousands of landslides along the northern slopes of the Cordillera de la Costa mountain range principally in the state of Vargas, Venezuela. Rainfall accumulation of 293 millimeters during the first 2 weeks of December was followed by an additional 911 millimeters of rainfall on December 14 through 16. The landslides and floods inundated coastal communities resulting in a catastrophic death toll estimated at between 15,000 and 30,000 people. Debris flow damage to houses, buildings, and infrastructure in the narrow coastal zone was severe. Flash floods on alluvial fans at the mouths of rivers draining the coastal mountain range also contributed to the general destruction.

In time scales spanning decades to centuries, the alluvial fans along this Caribbean coastline are areas of high geomorphic activity. Because most of the coastal zone in Vargas consists of steep mountain fronts that rise directly from the Caribbean Sea, the alluvial fans provide the only relatively flat areas upon which to build. Rebuilding and reoccupation of these areas requires careful determination of hazard zones to avoid future loss of life and property. A limited assessment of the distribution and character of landslides is currently in progress by the U.S. Geological Survey in cooperation with the Venezuelan Ministry of Environment and Natural Resources.

INTRODUCTION

Several hundred thousand people reside in a narrow coastal zone north of Caracas, Venezuela, in the state of Vargas. Located at the base of steep mountains, the population is highly vulnerable to episodic rainfall-induced landsliding. In December 1999, the interaction of a cold front with moist southwesterly flow from the Pacific Ocean towards the Caribbean Sea resulted in an usually wet period over northern Venezuela. Rainfall accumulation at sea level on the Caribbean coast at the Maiquetía airport for the first 2 weeks of December was 293 mm, more than five times the average (MARN, 2000). An additional 911 mm of rainfall was recorded from December 14-16. On December 15-16, 1999, landslides (mostly debris flows) and flash floods along the northern coastal zone of the Cordillera de la Costa in the state of Vargas and neighboring states in northern Venezuela (fig. 1) killed thousands of people, caused extensive property damage, and changed hillslope, stream channel and alluvial fan morphology. Because no census data are available for many of the affected areas, and because many of the dead were either buried under meters of rocky debris or washed out to sea, the death toll will never be known precisely. Current estimates indicate that as many as 30,000 lives were lost (USAID, 2000).

LANDSLIDE CHARACTERISTICS

Landslides caused by the rainstorm numbered in the thousands in the Cordillera de la Costa, which parallels the north coast. The landslides were mainly debris flows of a few meters or less in depth but 100's of meters in length, and shallow soil slips, which were generally a few meters or less in thickness but, in many cases, 100's of meters in width. The majority of debris flows began as either shallow debris slides or soil slides (slips). As such, many landslides affected the entire length of the hillslope from crest to toe. Hillslopes measured in a sample of 26 landslides had a mean slope angle of 42º (standard deviation of 7.6º). Coalescing debris flows moved rapidly down steep narrow canyons with step-pool morphology. The canyon floor gradients average 5º to 10º in reaches 3 to 6 kilometers upstream of their alluvial fans. Further upstream, steep waterfalls in bedrock prevented additional reconnaissance. In the last several km south of their alluvial fans, channel slopes average 4º to 6º and decrease to 2º to 4º across the fans before reaching the Caribbean Sea.

Most of the landslide scars are on the north side of the mountain range including large areas in El Avila National Park. Although several small communities, San José de Galipán and San Francisco de Galipán, are located within the Park boundary, most of the Park is undeveloped forest. As such, deaths attributed directly to landslides in steeply sloping areas comprised only a small fraction of the total loss of life estimated in the disaster. Landslides also destroyed or damaged many kilometers of the two-lane highway that links coastal communities east of Maiquetía.

Rescue and initial relief efforts were severely hampered because of the lack of ground access. Much of the road was opened to traffic by March 2000; however, along the road corridor east of Naiguata, landslide damage to the highway was extreme and rehabilitation will require extensive reconstruction.

Proceedings of the Seventh Federal Interagency Sedimentation Conference, March 25 through 29, 2001, Reno, NV, p. IV-9 to IV-16.

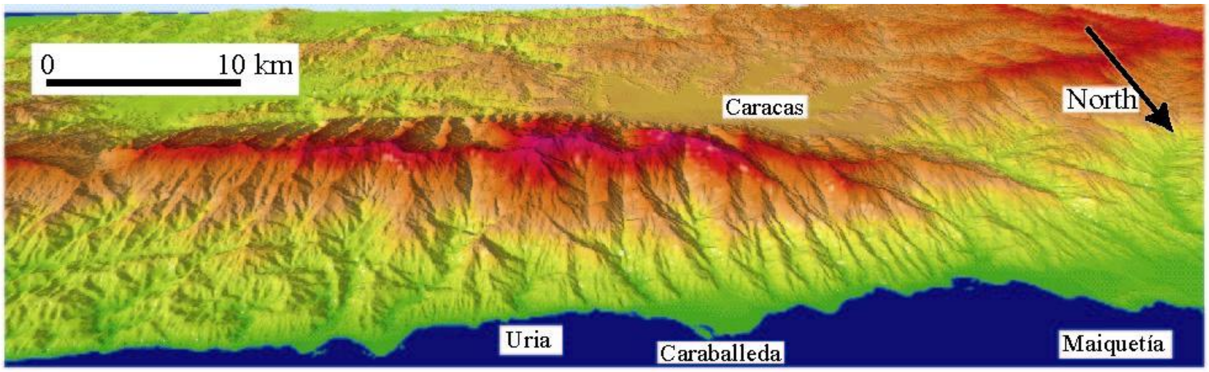

Figure 1. Oblique view looking south at the Cordillera de la Costa, northern Venezuela, showing watershed locations. Image courtesy of F. Urbani, Universidad Central de Venezuela.

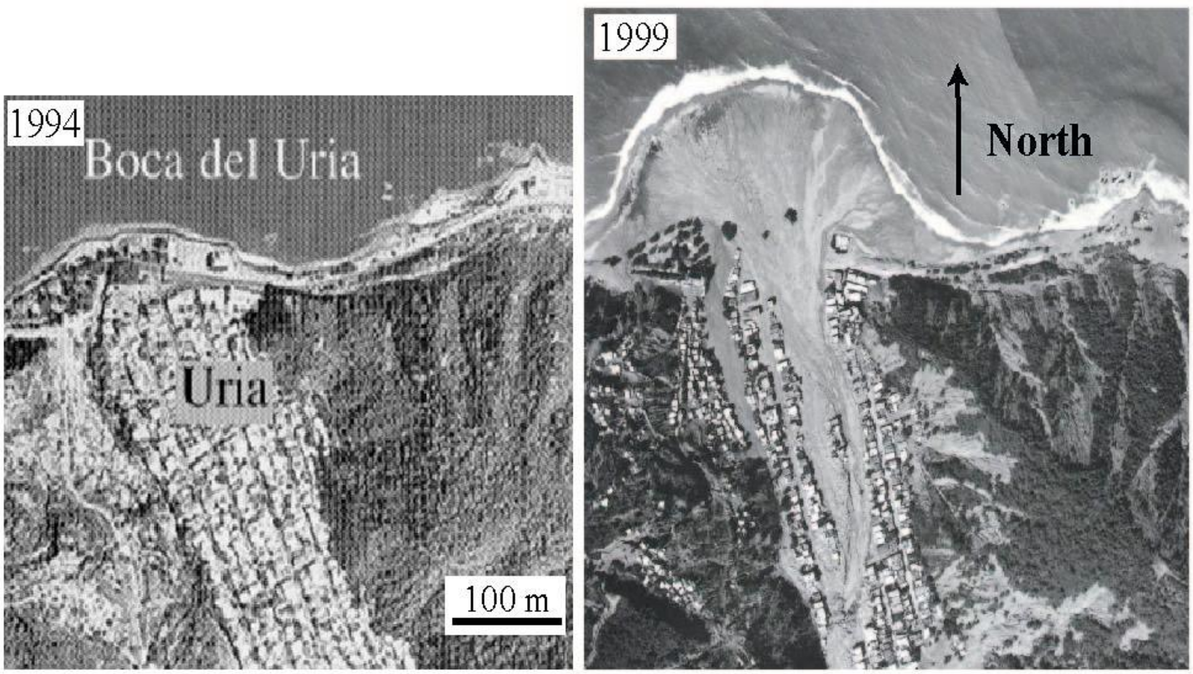

Figure 2. Aerial photographs taken in 1994 and after the December 1999 event showing destruction of the Carmen de Uria community and shoreline progradation (MARN-SAGECAN, 2000). Photograph (1999) courtesy of F. Urbani, Universidad Central de Venezuela (1999).

FLASH FLOODS

Flash floods and debris flows occurred in most of the several dozen small catchments (watershed areas on the order of 10 to 30 km^2) that drain the Cordillera de la Costa mountain range north to the Caribbean Sea. The stream-channel gradients in these catchments range from 20 to 50 percent (11 to 27 degrees); headwater elevations range from 2,000 to 2,700 meters and drop to sea level across a distance of 6 to 12 km (MARN, 2000). After passing through narrow canyons, streams emerging at the mountain front only a few tens of meters above sea level drain onto low-gradient (2 to 4 degrees) alluvial fans. High water marks left by flash floods were noted in the downstream canyons of 10 watersheds. Peak flow depths were as great as 8 to 10 m in canyon reaches that were on the order of 50 m wide. Channel slopes in these reaches were between 4 and 6 degrees. Residents with homes at the mouths of the 10 watersheds generally reported episodic high stream flows that began late on the night of December 15 and continued until the afternoon of December 16. Although each of the watersheds showed evidence of massive debris flows, most also contained laminar, well stratified flood deposits, indicating that both flood and debris flow processes were common.

VULNERABILITY OF POPULATION AND INFRASTRUCTURE

Because most of the coastal zone in the Vargas state consists of steep mountain fronts that rise directly from the Caribbean Sea, the alluvial fans provide the only flat areas upon which to build. A major airport at Maiquetía and seaport facilities have been constructed on these fans and a few available stretches of narrow coastal plain. In addition, housing that ranges from unregulated shanty towns, to middle- and upper-income single-family dwellings, to multi-story apartment buildings and condominiums, to hotels has been concentrated in communities along the coast east of Maiquetía (fig. 1). These residential and vacation communities are where most of the damage and loss of life occurred (figs. 2,3,4).

A combination of debris flows that transported massive boulders, and flash floods carrying extremely high sediment loads were the principal agents of destruction. On virtually every alluvial fan along 50 km of coastline, rivers incised new channels into fan surfaces to depths of several meters, and massive amounts of new sediment were disgorged upon fan surfaces in quantities of up to 15 metric tonnes per square meter (fig. 5). Sediment size ranged from clay and sand to boulders as large as 10 meters in diameter (figs. 5,6). Hundreds of houses, bridges and other structures were damaged or obliterated. Because residents had little warning in advance of the debris flows and flash floods that struck during in the early hours of December 16, many were caught in their homes and their bodies were carried out to sea or buried in the flood debris.

Carmen de Uria and Caraballeda are two of the many communities impacted by debris flows and flash floods. These two well-known areas provide insight into the types of damage that the coastal region incurred.

Carmen de Uria

Carmen de Uria is a small community dominated by lower-income housing built on a narrow alluvial fan between steep canyon walls at the mouth of an 11.9 km^2 watershed (fig. 2). Dozens of homes in a section of the central fan were obliterated by debris flows that survivors said occurred in two to three episodes between midnight and 9 am on December 16 (fig. 3). Before that date, the large open area, visible in figures 2 and 3 had a housing density comparable to that seen in the southeast section of figure 2.

The mass of debris flow and flood-transported sediment built the shoreline seaward by as much as 100 m and deposited a new subaerial delta of approximately 233,000 m^3, assuming a 20 degree submarine slope. This volume of deposition indicates a minimum erosion depth of 20 mm averaged over the entire watershed. The actual number is likely to be substantially higher as the submarine section of the delta distal to the new shoreline was not included, nor were the portions of the sediment load that were transported offshore.

Caraballeda

On the Caraballeda alluvial fan, 10 km west of Carmen de Uria, extensive property destruction occurred (figs. 4,5). Approximately 1.25 million m^3 of debris flow deposits, which included numerous massive boulders up to 10 m long, were distributed across several square kilometers of fan surface resulting in a deposit thickness of up to 4 m (fig. 5). Small structures were reduced to rubble in many cases and large, multi-story apartment buildings sustained heavy damage (fig. 6). The thickness of debris flow deposits measured at locations within 150 m of the current shoreline averaged 1.5 to 2 m, and the diameter of the largest boulders (D_{90}) at sites near the shoreline was on the order of 1 m. An estimated 450,000 m^3 of sediment was deposited in a 1,000-m wide subaerial delta with an average seaward extent of 50 m, assuming the same 20 degree submarine slope used for the estimate at Carmen de Uria.

PREVIOUS DEBRIS FLOW EVENTS

Exposures of old debris flow deposits were ubiquitous along canyon walls and on dissected alluvial fan surfaces (figs. 7,8). These deposits are strong physical evidence for the episodic recurrence of debris flow events in the Cordillera de la Costa. Deposits from a high-magnitude prehistoric debris flow event were observed in a number of watersheds (fig. 8). The deposits included massive boulders, larger than those moved in the December 1999 event, and indicate that although the 1999 event was rare, a more extreme storm event occurred in prehistoric time.

Over time scales spanning decades to centuries, the alluvial fans are dynamic zones of high geomorphic activity (Audemard and others, 1988; Singer and others, 1983). On average, at least one or two high-magnitude flash-flood and landslide events per century have been recorded in this region since the 17th century. In the nearby states of Aragua and Carabobo, destructive flash

Figure 3. Aerial and ground views showing debris flow and flash flood damage at Carmen de Uria, January 2000.

Figure 4. Aerial image taken after December 1999 event showing the Caraballeda fan and destruction of the Los Corales community. Image courtesy of F. Urbani, Universidad Central de Venezuela.

flood and landslide events were recorded in 1693, 1789, 1798, 1804, 1808, 1812, 1890, 1892, 1902, 1912, 1914, 1927, 1933, 1945, 1946, 1951, 1956, 1962 and 1963 (Röhl, 1950; Garner, 1959; Audemard and others, 1988). Another 13 high-magnitude events were recorded during the 1970's.

Using Spanish archives, Röhl (1950) provided a detailed summary of flash floods and debris flows that caused extensive damage to homes and government buildings and destroyed all bridges in La Guaira in 1798. A series of floods and debris flows occurred over a 2-day period. and were so large that Spanish soldiers placed cannons cross-wise in front of the upstream-facing entrance to a fort constructed near the stream channel to barricade the structure.

Northern Venezuela lies within a region where an average of 50 thunderstorms per year are documented for any point on the land surface (Hayden, 1988). In this region, high-intensity rainfall events with decadal-scale return frequencies erode upstream hillslopes and transport massive amounts of sediment onto aggrading and prograding alluvial fans. In this dynamic environment, population and infrastructure are highly vulnerable by these episodic large-magnitude storms such as that which occurred in December.

SUMMARY

A combination of climatologic, geologic, and demographic factors makes the Caribbean coast of Venezuela in the state of Vargas highly susceptible to episodic debris flows and flash floods. An extremely steep, tectonically active mountain front forms the boundary with a tropical sea. Easterly tradewinds can force moist air masses upslope and precipitate large rainfall volumes, creating conditions for high-magnitude debris flows and flash floods. The population of several hundred thousand people that reside at the base of the mountains is inevitably vulnerable to hydrologic disasters that seem to recur once or twice per century. The flash flood-debris flow process combination is highly destructive in populated areas. Without careful planning of human settlements, the impacts of these types of disasters are likely to increase in the future.

ACKNOWLEDGEMENTS

This work was supported by the USGS, the Venezuela Ministry of Natural Environment, and the USAID Office of Foreign Disaster Assistance. Special thanks are expressed to Prof. Franco Urbani, Universidad Central de Venezuela, for his enthusiam in the field, geologic insights, and for the extensive data he provided to the authors. Helpful review comments were provided by Joseph W. Troester and Benjamin A. Morgan, USGS. Gratitude is expressed to Colonel Romer Mena Nava, Dr. Alicia Moreau, and Pedro Delfín, Servicio Autónomo de Geografía y Cartografía Nacional, Ministerio del Ambiente y de los Recursos Naturales, Venezuela, for facilitating access to data, support for the helicopter overflights in coastal Venezuela, January 2000 and numerous field trips between January and August 2000.

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Figure 5. Debris flow deposits on the Caraballeda fan. (A) House with 1-m diameter boulders on roof. (B) Concrete house rotated off foundation by debris flow. (C) View across debris fan; tiled surface on right is top of one story home. (D) View up debris fan looking towards San Julián canyon.

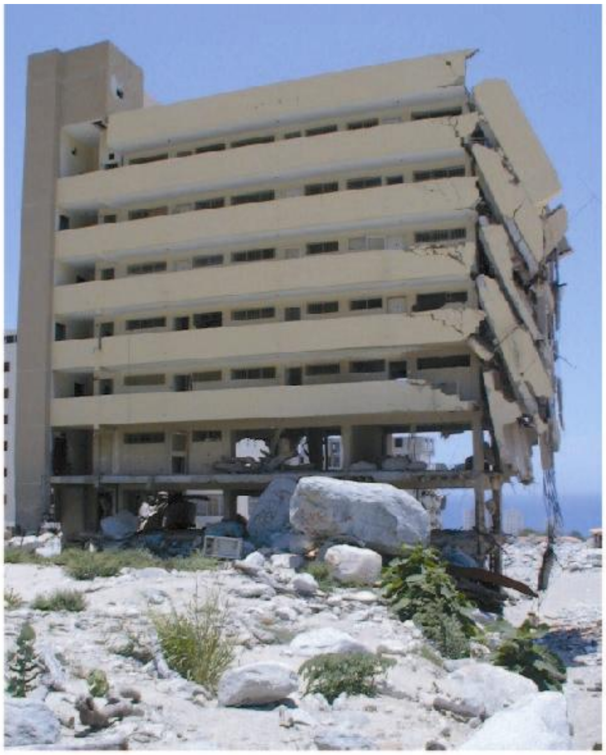

Figure 6. Apartment building damaged by debris flows, Caraballeda. Note collapsed apartments and boulders on floor of second story.

Figure 7. House and garage on Caraballeda fan with exposed foundation showing old debris flow deposit.

Figure 8. Massive boulders deposited by ancient debris flow in the Río San Julian valley, approximately 2 km upstream of Caraballeda. The boulders were exposed by the December 1999 event. Their dimensions exceed that of the largest boulders moved in December 1999. Note person on left for scale.