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Venezuela debris-flow and flash-flood disaster of 1999 studied

Alluvial fans in urban and rural areas are sites of episodic, rainfall-induced natural hazards [*Garner*, 1959; *Campbell*, 1975; *Wieczorek et al*., 2001;]. Debris flows, hyper-concentrated flows, and flash floods that occur episodically in these alluvial fan environments place many communities at high risk during intense and prolonged rainfall. Although scientists have become better able to define areas of high natural hazard, population expansion and development pressures in such areas have put more people at risk than ever before. Recognition of the magnitude and distribution of debris-flow and flash-flood hazards is therefore a critically important area of natural hazard research.

In December 1999, rainstorms induced thousands of landslides in such an area along the Cordillera de la Costa, Vargas, located north of Caracas, Venezuela; an area of dense human settlement located at the base of steep mountains. Flash floods and debris flows caused severe property destruction on alluvial fans at the mouths of the coastal mountain drainage network. Rainfall accumulation on December 2 and 3 totaled 293 mm and was followed by a major storm that dropped 911 mm of rain from December 14 through 16. More than 8000 individual residences and 700 apartment buildings were destroyed or damaged and roads, telephone, electricity, water, and sewage systems were severely disrupted [*Salcedo*, 2000]. Total economic losses are estimated at US$1.79 billion [*Salcedo*, 2000]. The debris flows and floods inundated coastal communities and resulted in a catastrophic death toll of as many as 19,000 people [USAID, 2000]. The landslides and flash floods also changed hill slopes, stream channels, and alluvial fan morphology.

The alluvial fans along this Caribbean coastline are dynamic zones of high geomorphic activity. Because most of the coastal zone in Vargas consists of steep mountain fronts that rise abruptly from the Caribbean Sea—rising to elevations in excess of 2,600 m--the alluvial fans provide practically the only 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.

Natural Hazards on Alluvial Fans

Alluvial fans are defined as gently sloping, cone- to fan-shaped landforms created over thousands to millions of years by deposition of eroded sediment at the base of mountain ranges [*NRC*, 1997]. They are typically associated with arid to semi-arid environments such as that of the western United States; however, alluvial fans also occur in more humid environments as the Venezuelan example illustrates (Figure 1).

Figure 1. This aerial view shows the canyon and alluvial fan at Carmen de Uria, Vargas, Venezuela. Hundreds of buildings in the center of the alluvial fan were obliterated by debris flows on December 16-17, 1999, and the fan prograded seaward as much as 100 m.

The natural hazards described in this article are waterborne floods, hyper-concentrated flows, and debris flows that are induced mainly by intense and prolonged rainfall. Floods on alluvial fans are commonly flash floods: they occur with little to no warning, usually have high velocities and sediment-transporting capability, and are of relatively short duration. Debris flows are a type of landslide that has been defined as a spatially continuous, rapidly moving mass of water and solid material composed mainly of coarse debris; typically 20-80% of the particles are greater than 2 mm in diameter [*Cruden and Varnes*, 1996; *Iverson*, 1997]. A debris flow is about the consistency of wet concrete as it is poured. Hyper-concentrated flows occupy the boundary between debris flows and water flows and are a mixture of water and sediment defined by a sediment concentration of less than 80% but greater than about 40% by weight.

Hyper-concentrated flows can develop as flood waters entrain large amounts of sediment, or as debris flows are diluted by water. Alluvial fans may be highly active, where floods, hyper-concentrated flows, and debris flows can episodically occur at any location on the fan surface; some fans are less active, where tectonic uplift, incision, or both have channeled flows so that much of the fan is not affected during high-runoff events.

Water-generated natural hazards on alluvial fans typically are relatively shallow, can arrive with little warning, travel at high speeds, and carry massive amounts of sediment and debris [*NRC*, 1997]. As defined by the National Research Council Committee on Alluvial Fan Flooding [*NRC*, 1997], alluvial fan flooding typically begins at the hydrographic apex, which is the highest point where flow is last confined by mountain valleys, and it then spreads as sheet flood or debris slurries, or divides into multiple channels. Flooding is characterized by sufficient energy to carry coarse sediment even at shallow flow depths. The abrupt deposition of this sediment or debris strongly influences hydraulic conditions during the event and may allow higher flows to initiate new, distinct flow paths of uncertain direction [*NRC*, 1997].

The great uncertainty can be heightened by sediment deposition in an alluvial fan channel, resulting in rapid overbank flooding of a channel that was perceived as too large to ever overflow. It is this flow path uncertainty that makes debris flow and flood hazard on alluvial fans extremely dangerous. The two principal mitigation strategies are commonly too expensive for the economic resources of developing countries: large structural flood control measures, such as check dams, or complete avoidance of development in these areas [*Hollingsworth and Kovacs*, 1981; *Hungr et al*., 1987; *NRC*, 1997]. As can be seen by the extensive alluvial fan development in Vargas, where no check dams exist, neither strategy has been used, contributing to the tragedy of December 1999.

Geologic, Geographic, and Hydrologic Setting, Venezuelan Cordillera de la Costa

The Cordillera de la Costa is composed mainly of metamorphic rocks dissected by channels that drain northward to the Caribbean Sea across coastal alluvial fans mantled with Quaternary sediment. Although bedrock is exposed in some channel reaches, most channels contain extensive Quaternary sediment deposits up to several meters thick. Exposures of the Tacagua Formation (Mesozoic) consist of graphitic, epidote schists parallel the coast and extend about 1 km inland. The soils developed over these schists are relatively thin, 0.5-3.0 m thick [*Salcedo*, 2000]. Further 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 Cordillera de la Costa. Soils developed over these two formations are thin, sandy, and a light tan-gray in color over shallow, weathered bedrock. The soils developed over these metamorphic rock units are believed to be thin because of the higher rates of erosion induced by the steep topography.

The Vargas coastal areas are home to highly urbanized neighborhoods with buildings ranging in size from single-story, un-reinforced masonry and concrete homes to multi-story, modern apartment buildings (Figures 1 and 2). Almost all of the structures are built on alluvial fans. Prior to the 1950s, the alluvial fans on which these neighborhoods are constructed were used for agriculture and population density was low. The Cordillera de la Costa uplands are part of El Avila National Park, a forested preserve with minimal human disturbance, although a few unpaved roads parallel the ridgeline of the mountains. The north boundary of the park is marked by the slope break at the seaward base of the mountains.

Rainfall records for Vargas are sparse, as development of the area was minimal prior to 1950. Mean annual precipitation at the International Airport at Maiquetia, which is 43 m above mean sea level, is 750 mm [*MARN*, 2000]. The total 3-day rainfall for a 52-h span on December 14-16 totaled 911 mm at this location. Hourly rainfall from 6 a.m. to 7 a.m. on December 16 measured 72 mm; such rainfall at this location has a 50-yr return interval. These amounts and intensities of rainfall were highly exceptional for this region; the daily totals (381 and 410 mm) for December 15 and 16, respectively, at Maiquetia approximately equaled the 1000-yr probability rainfall event for this location.

Historical records indicate that similar hydrologic events leading to severe flooding or landslides occurred in this region in 1798, 1912, 1914, 1938, 1944, 1948, and 1951 [*Salcedo*, 2000]. On average, at least one or two high-magnitude flash-flood or landslide events per century have been recorded in this region since the 17th century. Spanish archivesindicate that flash floods and debris flows in La Guaira in February 1798 caused extensive damage to 219 homes and government buildings and destroyed all bridges. The high magnitude of this 2-day event forced Spanish soldiers to place cannons cross-wise in front of the upstream-facing entrance of a fort, located near the stream channel, to prevent debris from pouring into the structure. Examination of deposits exposed on terraces and along the banks of river channels in Vargas reveals a record of prehistoric floods and debris flows as well.

Figure 2. Debris flow damage to an apartment building in Caraballeda, Vargas, Venezuela, occurred in December 1999. Debris flows passed through the first two stories of this building.

The Vargas Debris Flow-Flash Flood Disaster

Most of the December 1999 landslides initiated as thin soil slides or debris slides--soil with pieces of rock--as indicated by shallow sliding surfaces within soil or weathered, foliated, and jointed rock. With the addition of more water from either the hill slopes or the channels, these slides of loose soil and rock liquefied into debris flows. Most landslides occurred within the top 0.5-2.0 m of soil or weathered schist or gneiss [*Wieczorek et al*., 2001]. Some smaller slides coalesced to denude larger sections of hillsides. Stratigraphic sequences exposed in main scarps indicated some reactivation of previous landslides. Debris flows and other types of landslides numbered in the thousands on steep hill slopes in the coastal mountain range and coalesced into massive debris flows that moved rapidly down steep narrow canyons. Stream-channel gradients in these catchments range from 20% to 50% percent (11° to 27°); on the canyon floor, gradients average 5° to 10° in reaches 3-6 km upstream of their alluvial fans. In the several kilometers south, or upstream of the alluvial fans, channel slopes average 4° to 6° and decrease to 2° to 4° across the fans before reaching the Caribbean Sea.

Flash floods, hyper-concentrated flows, and debris flows occurred in the canyons and alluvial fans of most of the several dozen small catchments (watershed areas on the order of 10-30 km^2) that drain the coastal mountain range. Residents with homes on the alluvial fans described multiple high stream flows and debris flows that began late on the night of December 15 and continued until the afternoon of December 16. Although the alluvial fans showed evidence of massive debris flows, most also contained well-stratified flood deposits, indicating that both flood and debris flow processes were common. 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 the Vargas 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. Sediment size ranged from clay and sand to numerous boulders as large as 10 m in diameter (Figure 2). Sediment and debris, including massive boulders, were deposited up to several meters thick across large sections of alluvial fans.

A combination of climatologic and geologic factors make alluvial fans highly susceptible to episodic debris flows and flash floods. In Vargas, the extremely steep, tectonically active Cordillera de la Costa forms the boundary with a tropical sea. Easterly trade winds and storms can force moist air masses upslope and precipitate large rainfall volumes, creating conditions for high-magnitude debris flows and flash floods.

The example discussed in this article demonstrates the potential for extreme loss of life and property damage where a large population occupies an alluvial fan. The possibility for an event of comparable magnitude exists in other parts of the world where extensive development has encroached on alluvial fans. Without careful planning of human settlements, the impacts of these types of disasters are likely to increase in the future.

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Authors
Matthew C. Larsen, Gerald F. Wieczorek, L. Scott Eaton, Benjamin A. Morgan, and Heriberto Torres-Sierra

For additional information, contact Matthew C. Larsen, U.S. Geological Survey, Caribbean District, GSA Center, 651 Federal Drive, Ste. 400-15, Guaynabo, Puerto Rico 00965, USA; E-mail: mclarsen@usgs.gov

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