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NATURAL HAZARDS ON ALLUVIAL FANS: THE DEBRIS FLOW AND FLASH FLOOD DISASTER OF DECEMBER 1999, VARGAS STATE, VENEZUELA

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ABSTRACT: Large populations live on or near alluvial fans in locations such as Los Angeles, California, Salt Lake City, Utah, Denver, Colorado, and lesser known areas such as Sarno, Italy, and Vargas, Venezuela. Debris flows and flash floods occur episodically in these alluvial fan environments, and place many communities at high risk during intense and prolonged rainfall. In December 1999, rainstorms induced thousands of landslides along the Cordillera de la Costa, Vargas, Venezuela. Rainfall accumulation of 293 mm during the first 2 weeks of December was followed by an additional 911 mm of rainfall on December 14 through 16. Debris flows and floods inundated coastal communities resulting in a catastrophic death toll of as many as 30,000 people. Flash floods and debris flows caused severe property destruction on alluvial fans at the mouths of the coastal mountain drainage network.

In time scales spanning thousands of years, 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, 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.

KEY TERMS: Debris flows, flash floods, alluvial fans, natural hazards, landslides, Venezuela

INTRODUCTION

Alluvial fans in Los Angeles, California, Salt Lake City, Utah, Denver, Colorado, and lesser known areas such as Sarno, Italy, and Vargas, Venezuela are sites of episodic, rainfall-induced natural hazards (Garner, 1959; Campbell, 1975; Audemard and others, 1988; Wieczorek and others, 1989; Cacini and others, 1998; Runyan and others, 1997; Larsen and others, 2001). Debris flows, hyperconcentrated 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 pressure have put more people at risk than ever before (Burton and others, 1993). Recognition of the degree and distribution of debris flow, and flash flood hazard is therefore a critically important area of natural hazard research and description. This paper briefly describes the alluvial fan environment and associated hazards, and provides examples from the state of Vargas, Venezuela.

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NATURAL HAZARDS ON ALLUVIAL FANS

The natural hazards described herein are waterborne floods, hyperconcentrated 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 (several hours) duration. Debris flows are a type of landslide that has been defined as a spatially continuous, rapidly moving mass of water and material that is composed mainly of coarse debris; typically 20 to 80 percent of the particles are greater than 2 mm in diameter (Cruden and Varnes, 1996). The simplest example of the consistency of a debris flow is that of wet concrete as it is poured. Hyperconcentrated flows occupy the boundary between debris flows and water flows, and are a mixture of water and sediment defined by a sediment concentration of less than 80 percent but greater than about 40 percent by weight (Hutchison, 1988). Hyperconcentrated flows can develop as flood waters entrain large amounts of sediment, or conversely, as a debris flow is diluted by water (Wieczorek and others, 1989).

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 described below indicates (fig. 1). Alluvial fans may be highly active, where floods, hyperconcentrated 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 channelized flows so that much of the fan is not affected during high-runoff events.

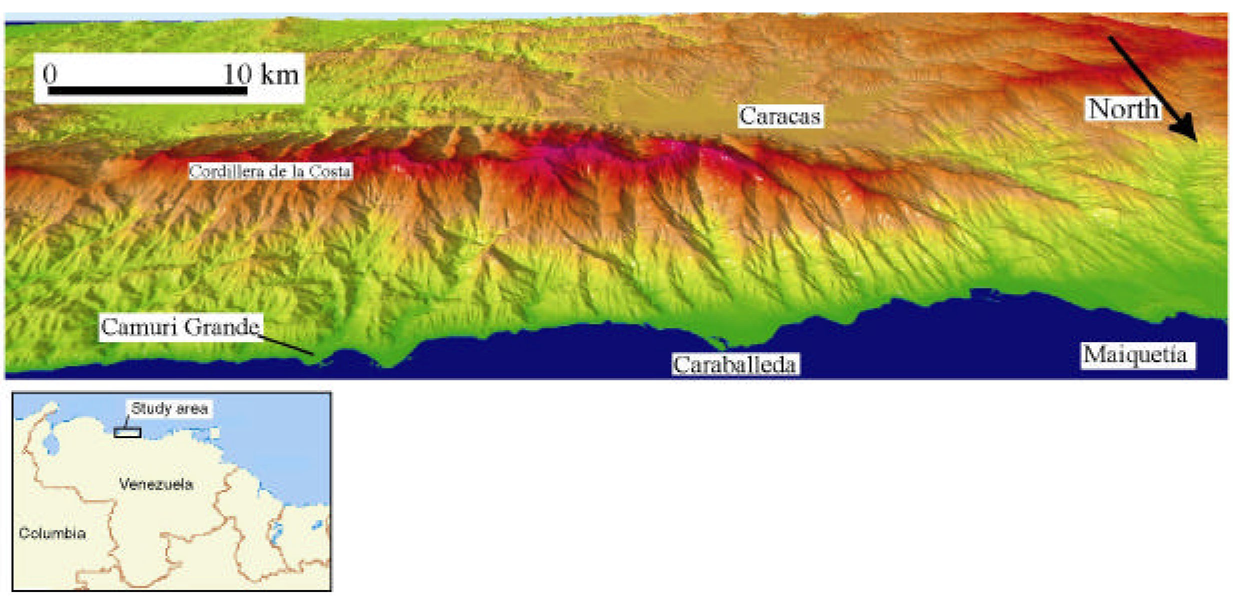

FIGURE 1. Oblique view looking south at the Cordillera de la Costa, northern Venezuela, showing alluvial fans along coast. Image courtesy of F. Urbani, Universidad Central de Venezuela.

Water-generated natural hazards on alluvial fans are typically relatively shallow but can strike with little warning, travel at high speeds, and carry massive amounts of sediment and debris (NRC, 1997; Wieczorek and others, 2000). 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 then spreads out as sheetflood, debris slurries, or in 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. There are only two mitigation strategies and both are commonly too expensive for local economic resources: large structural flood control measures, such as check dams, or complete avoidance of the affected area (Hollingsworth and Kovacs, 1981; Hungr and others, 1987; NRC, 1997). As can be seen by the extensive alluvial fan development in Caraballeda, Venezuela, where no check dams exist, neither strategy has been used, contributing to the tragedy of December 1999 (fig. 2).

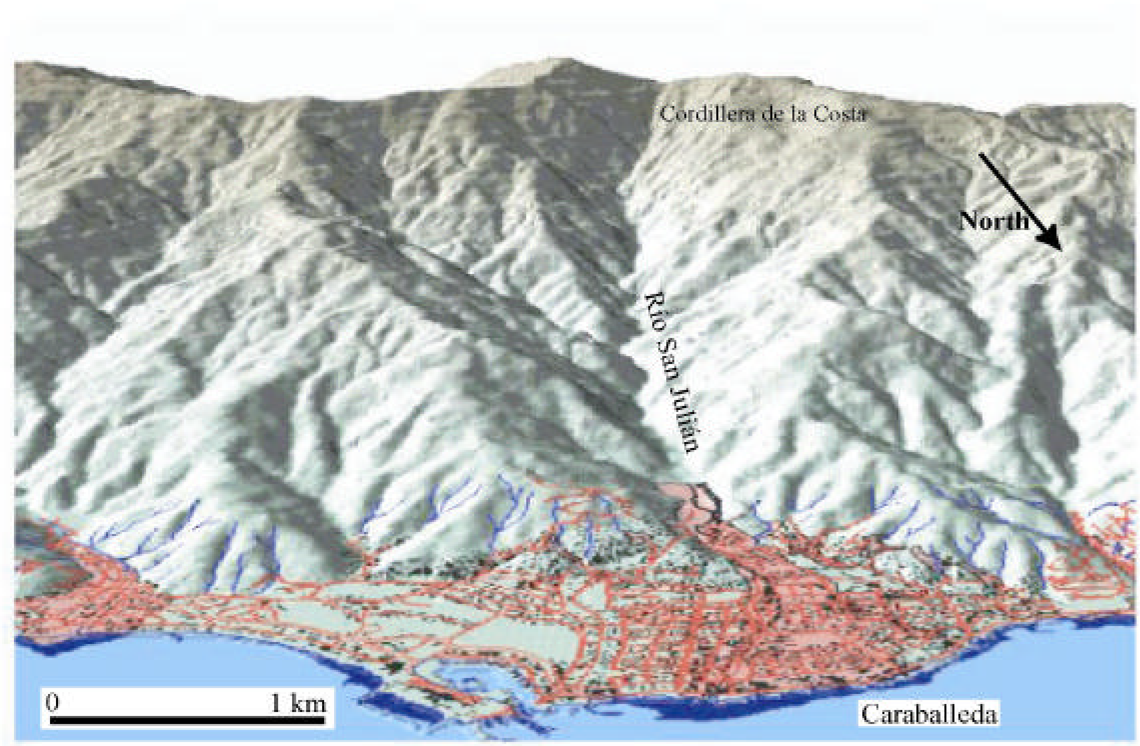

FIGURE 2. Oblique view looking south at the Río San Julián watershed and Caraballeda alluvial fan, Vargas, Venezuela. Image courtesy of P. Delfín, Venezuela Ministry of Environment and Natural Resources.

THE DEBRIS FLOW AND FLASH FLOOD DISASTER, VARGAS STATE, VENEZUELA

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 that rise to elevations in excess of 2,000 m, the population is highly vulnerable to episodic rainfall-induced landsliding. An unusually wet period in 1999 resulted in rainfall accumulation at sea level on the Caribbean coast of 293 mm for the first 2 weeks of December, followed by an additional 911 mm of rainfall from December 14 to 16 (MARN, 2000). On December 15 and 16, 1999, landslides (mostly debris flows) and flash floods along the northern coastal zone of the state of Vargas and neighboring states in northern Venezuela (fig. 1) killed an estimated 30,000 people (USAID, 2000), caused extensive property damage, and changed hillslope, stream channel and alluvial fan morphology.

Debris flows and other types of landslides numbered in the thousands on steep hillslopes in the coastal mountain range and coalesced into massive debris flows that moved rapidly down steep narrow canyons (Larsen and others, 2001). Stream-channel gradients in these catchments range from 20 to 50 percent (11º to 27º); on the canyon floor, gradients average 5º to 10º in reaches 3 to 6 km upstream of their alluvial fans. In the several kilometers south, or upstream of the alluvial fans, channel slopes average 4º to 6º and decrease to 2º to 4º across the fans before reaching the Caribbean Sea (fig. 2).

Flash floods, hyperconcentrated 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 to 30 km^2) that drain the coastal mountain range (figs. 3, 4). 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 laminar, well-stratified flood deposits, indicating that both flood and debris flow processes were common.

FIGURE 3. Aerial view of upstream portion of alluvial fan at Camuri Grande, Vargas, Venezuela, showing buildings damaged by flash floods at regional campus of Universidad Simón Bolívar, January 2000.

FIGURE 4. Debris flow deposits on alluvial fan, Los Corales sector of Caraballeda, Vargas, Venezuela. Structure in foreground is tiled rooftop of one-story house, July 2000.

A combination of debris flows that transported massive boulders, and flash floods carrying extremely high sediment loads were the principal agents of destruction (fig. 4). 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 boulders as large as 10 m in diameter. Sediment and debris including massive boulders were deposited up to several meters thick across large sections of alluvial fans in Camuri Grande and Caraballeda (figs. 3, 4). Hundreds of houses, bridges and other structures were damaged or destroyed. Residents had little advance warning of the debris flows and flash floods that struck in the early hours of December 16, so many were caught in their homes and their bodies were carried out to sea or buried by the flood debris.

SUMMARY

A combination of climatologic and geologic factors make alluvial fans highly susceptible to episodic debris flows and flash floods. In Venezuela, the extremely steep, tectonically active Cordillera de la Costa 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 these

mountains is inevitably vulnerable to hydrologic disasters. This example from Venezuela shows 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. By building communities and other infrastructure on alluvial fans, dramatic natural hydrologic processes have been changed into major lethal events. As stated by the Secretary General of the United Nations, Kofi Annan, *"The term 'natural disaster' has become an increasingly anachronistic misnomer. In reality, human behavior transforms natural hazards into what should really be called unnatural disasters."*

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