Rainfall triggered landslides, anthropogenic hazards, and mitigation strategies: examples from Puerto Rico and Venezuela

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Global vulnerability to rainfall-triggered landslides, particularly debris flows, has increased because of population expansion in areas on or adjacent to hillslopes. To reduce loss of life and destruction of property, government agencies are faced with two general approaches: implement rational land use plans and develop landslide warning systems. Effective land use planning requires sustained political will, knowledge of hazards, and possibly, relocation of existing communities. Warning systems are expensive to install, difficult to maintain and operate, and must function effectively during times of severe weather. Furthermore, warning systems in steeply sloping areas must be designed to give sufficient time to allow authorities to evacuate large, dispersed communities.

On October 7, 1985, a hillslope in Ponce, Puerto Rico, saturated by heavy rainfall (560 mm in 24 hours), failed at about 3:00 a.m. and resulted in the worst landslide disaster in terms of loss of life in the history of the United States. Approximately 130 people were killed as a massive limestone rock-block slide destroyed an estimated 120 homes and buried most of the victims.

In December 1999, an unusually severe series of rain storms near the Venezuelan capital of Caracas triggered landslides, flash floods, and debris flows that caused one of the worst natural disasters in the recorded history of the Americas. Much of the loss of life (15,000 killed) and property losses ($\sim$ US$2 billion) occurred where debris flows and floods rapidly inundated coastal communities built on alluvial fans. Sediment and debris carried by these flows originated largely from landslides in steep catchments underlain by schist and gneiss on the north side of a coastal mountain range. Soil from some hillsides was entirely stripped by individual or coalescing failures. The large, rapid delivery of runoff and sediment resulted in floods, debris flows, and hyperconcentrated flows. An approximate sediment budget from 24 watersheds along 50 km of coastline indicates that 15 to 20 million cubic meters of sediment were deposited on alluvial fans and beaches during the storm. The sudden delivery of this material as floods and debris flows onto urbanized alluvial fans killed $\sim$5% of the population in the northern Venezuelan State of Vargas.

These two landslide disasters in the Americas provide examples of basic landslide

processes, as well as mitigation strategies that can be used before, during, and after the landslide-triggering event.