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Volcanic debris flows in developing countries – the extreme need for public education and awareness of debris-flow hazards

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ABSTRACT: In many developing countries, volcanic debris flows pose a significant societal risk owing to the distribution of dense populations that commonly live on or near a volcano. At many volcanoes, modest volume (up to 500,000 m^3) debris flows are relatively common (multiple times per century) and typically flow at least 5 km along established drainages. Owing to typical debris-flow velocities there is little time for authorities to provide effective warning of the occurrence of a debris flow to populations within 10 km of a source area. Therefore, people living, working, or recreating along channels that drain volcanoes must learn to recognize potentially hazardous conditions, be aware of the extent of debris-flow hazard zones, and be prepared to evacuate to safer ground when hazardous conditions develop rather than await official warnings or intervention. Debris-flow-modeling and hazard-assessment studies must be augmented with public education programs that emphasize recognizing conditions favorable for triggering landslides and debris flows if effective hazard mitigation is to succeed.

1 INTRODUCTION

Disasters caused by volcanic debris flows disproportionately affect populations in developing countries. Population pressures, fertile agricultural land, and economic realities commonly converge in volcanically active developing countries and result in distributions of dense populations (hundreds of people per km^2) that encroach on or near volcanoes. The proximity of dense populations to volcanoes in these countries increases the likelihood of disastrous consequences from volcano-related events. Populations situated on or close to volcanoes are at risk not only from future eruptions but also from events unrelated to eruptions, such as landslides and debris flows triggered by heavy rainfalls, earthquakes, or releases of stored water (from lakes or reservoirs). The catastrophe that occurred in 1998 at Casita volcano, Nicaragua, where torrential rainfall from Hurricane Mitch triggered a landslide that transformed into a rapidly moving debris flow that destroyed two villages and killed more than 2000 people (Scott 2000), highlights the risk posed by noneruption events to the populace near volcanoes.

Debris-flow-hazard mitigation involves the participation of several parties. Traditionally, debris-flow-hazard mitigation has involved the collaboration of scientists, engineers, and emergency management officials. Scientists usually identify areas inundated by previous debris flows, assess the extents of runout and inundation of flows of varying magnitudes, and estimate frequencies of debris-flow occurrence (e.g. Pierson 1989, Chen 1997, Iverson et al. 1998, Scott 2000, papers in Wieczorek & Naeser 2000). They typically perform hazard assessments using some manner of modeling (e.g. Iverson et al. 1998, Denlinger & Iverson 2001) or field analysis (e.g. Scott et al. 1995). Once the nature and extent of the hazard are defined, defensive strategies commonly developed by engineers and emergency management planners are employed to reduce negative interactions between human and natural systems if the consequences of an event and probability of occurrence are sufficiently great (e.g. Pierson 1989, Davies 1997).

Defensive strategies to mitigate debris-flow hazards have ranged from no action at all to some combination of protective devices, warning systems, general evacuations, and exclusionary zoning (e.g. Pierson 1989). Traditional defensive strategies commonly involve modification of natural systems (Davies 1997). In developed countries that have substantial economic resources, mitigation measures typically include structures engineered to contain, convey, or deflect debris flows to prevent them from inundating populated areas or damaging critical infrastructure (e.g. papers in Chen 1997, Wieczorek & Naeser 2000). In developing countries, costs of such structures usually are overwhelming unless supported by aid from other nations. Even then resources are limited and engineered structures are few. Thus, measures other than, or in addition to, engineered structures must be considered to prevent unnecessary disasters in developing countries.

Warning systems have been utilized in some debris-flow-prone regions (e.g. Marcial et al. 1996). They can be useful for mitigating debris-flow disasters, but they are subject to significant pitfalls. The utility of warning systems depends upon their reliability as well as their ability to provide sufficient advance warning that a debris flow has occurred and is moving toward a populated area. Volcanic debris flows, however, can move rapidly once they are triggered, and near their sources they may move too quickly for authorities to provide effective warning. Statistical analysis of travel times of many volcanic debris flows as a function of distance reveals that flows of widely ranging magnitudes can travel 10 km or more from source within a few to a few tens of minutes (Pierson 1998). Such travel times make effective warnings of debris-flow occurrence close to a volcano nearly impossible.

An alternative to engineered defensive structures and warning systems is the modification of human behavior and human systems. Modification of human systems involves restricting, or limiting, development in hazardous areas, or relocating populations already established in hazardous areas (Pierson 1989, Davies 1997). Although limiting future development in hazardous areas may be possible in some cases, population pressures and economic realities in many developing countries commonly preclude relocation of existing populations. Given the limitations of traditional mitigation measures in many developing countries, additional strategies must be employed if debris-flow-hazard mitigation in developing countries is to succeed.

Successful mitigation of debris-flow hazards must involve active participation of the populace at risk—perhaps to a greater degree than has been realized previously—and not just governmental authorities, scientists, and engineers. For populations inhabiting potentially hazardous areas, especially those within 10 km of likely source areas of volcanic debris flows, the most effective mitigation measures will rely on inhabitants themselves recognizing conditions that are favorable for generating landslides and debris flows and taking the initiative to evacuate to safer ground. This can be accomplished only if the public has an accurate perception of the nature of the hazard, the extent of the hazardous zone, and some education in recognizing hazardous conditions. Such awareness of debris-flow hazards can happen only through targeted public education. Scott (2000) espouses a similar theme with regard to seismically triggered debris flows, but he focuses on the recognition of an event already in progress. Here we expand the concept of public awareness to *pre-event* recognition of potentially hazardous conditions. We illustrate the need for public education and awareness of debris-flow hazards with a study of debris-flow hazards at volcanoes in El Salvador.

2 VOLCANIC DEBRIS-FLOW HAZARDS IN EL SALVADOR

Volcanic debris flows in El Salvador pose a significant risk to tens of thousands of people as well as to property and substantial infrastructure. At least three of the country's largest cities are located near the bases of active volcanoes (Fig. 1). Nearly 850,000 people reside within 10 km of the summits of San Salvador, San Vicente, and San Miguel volcanoes (J.W. Ewert, U.S. Geological Survey, written comm. 2003). In addition to the cities, several small towns and coffee plantations are located on or around the flanks of the volcanoes, and the Pan-American highway and other major transportation routes cross the lowermost slopes of at least two of the volcanoes. Owing to the population densities of the major metropolitan areas (several hundred people per km^2) and their proximities to those volcanoes, debris flows traveling as little as 2 to 4 km from source put hundreds to thousands of lives, as well as property and infrastructure, at risk.

2.1 *Target volcanoes for debris-flow hazard analysis*

Populations at greatest risk from future volcanic debris flows are located near San Salvador, San Vicente, and San Miguel volcanoes. San Salvador volcano rises above El Salvador's capital and largest city, San Salvador (Fig. 2). The volcano has not erupted for more than 80 years, but it has a long geologic history of repeated, and sometimes violent, eruptions (Sofield in press). Eruptive episodes, however, are not the only times when the populace near this volcano is at risk. Lethal debris flows unrelated to eruptive activity have occurred at least twice in the past 70 years (Fig. 3, Finnson et al. 1996, Major et al. in press). San Vicente volcano is located about 50 km east of the capital city (Fig. 1), and towers above the city of San Vicente as well as smaller villages. Major transportation routes are located near the volcano's lowermost southern and eastern flanks. The last major eruption of the volcano occurred more than 1600 years ago (Rotolo et al. 1998). However, volcanic debris flows have occurred several times in the past few centuries; heavy rainfalls triggered damaging debris flows most recently in 2001 (Fig. 4; Crone et al. 2001, Major et al. in press). San Miguel volcano, in eastern El Salvador (Fig. 1), stands above the city of San Miguel and neighboring villages, and is one of the country's most active volcanoes. Quiescent emplacement of lava flows and minor explosions that deposited modest tephra falls characterize its historical eruptions (Chesner et al. in press). The history of debris flows at San Miguel is poorly known, but modest-volume flows damaged local transportation routes several times in the past six decades (Blanco et al. 2002, Smithsonian Institution 2002).

The majority of landslides and debris flows at volcanoes in El Salvador are of modest volume ($<500{,}000\ m^3$) and are not associated directly with eruptions. Those associated directly with magmatic processes and eruptions can range widely in volume. Large debris avalanches (to about 10 km^3 in volume) have occurred at a few of the volcanoes (Major et al. in press, Siebert et al. in press), perhaps triggered by magmatic intrusion or by hydrothermal weakening of an edifice, and small debris flows ($\leq 100{,}000\ m^3$) originating from failure and erosion of tephra deposits following eruptions have occurred locally (Blanco et al. 2002, Smithsonian Institution 2002). Large volcanic debris avalanches represent extremely hazardous, but low-probability, events at many of El Salvador's volcanoes, whereas tephra falls are deposited frequently and provide a ready source of sediment that can be mobilized into small debris flows.

2.2 *Debris-flow inundation zones*

We used a semi-empirical model (Iverson et al. 1998) to estimate potential areas of debris-flow inundation from flows having magnitudes most likely to be triggered by heavy rainfalls or earthquakes (Major et al. in press). The model relies on scaling and statistical relationships among debris-flow volume, area of inundated channel cross-section, and planimetric inundation area. For

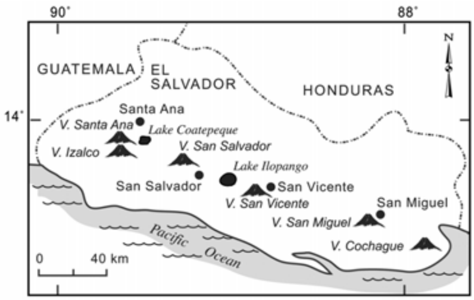


Figure 1. Location of major cities and significant volcanoes in El Salvador. Circles indicate major cities, triangles indicate major volcanoes. Lake Coatepeque and Lake Ilopango are large calderas.

Figure 2. San Salvador volcano viewed from the southeast. The volcano is composed of two prominent peaks—Boquerón (left) and Picacho (right). San Salvador city is in the foreground.

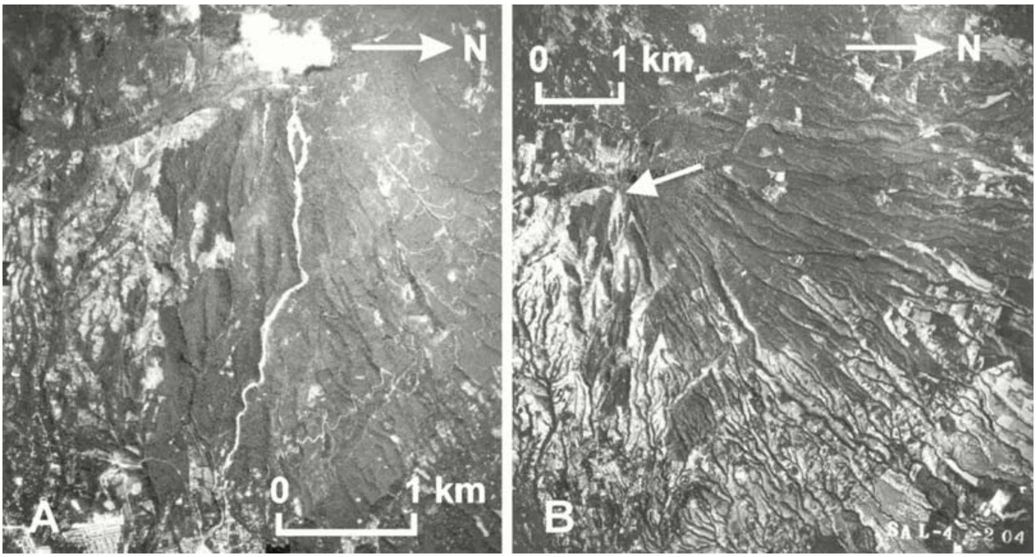


Figure 3. Aerial views of source areas of rainfall-triggered debris flows on east flank of Picacho (San Salvador volcano; cf. Fig. 2). A. Source area, flow track, and depositional area of 1982 debris flow (photo taken November 1982). B. Source area (arrow) of debris flow that occurred in 1934 (photo taken in 1949).

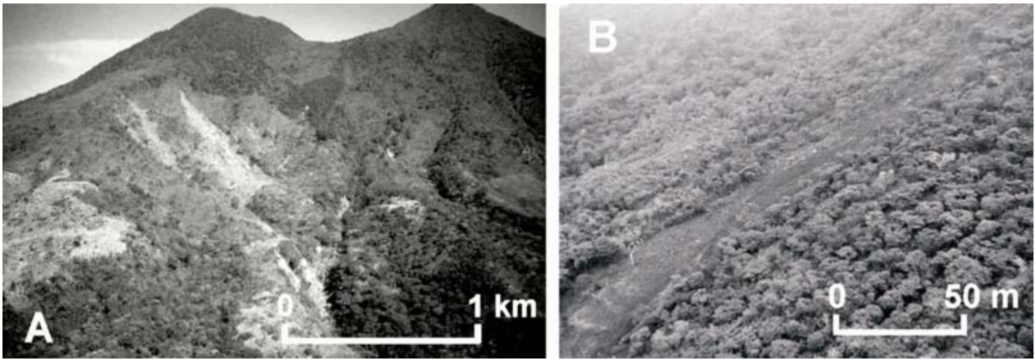


Figure 4. Landslides and debris flows at San Vicente volcano. A. Shallow landslides on the south flank, triggered by rainfall in 1995, transformed into debris flows that traveled 8-10 km. B. Oblique aerial view of source area of a debris flow triggered by rainfall in September 2001 (photograph courtesy of A.J. Crone, U.S. Geological Survey).

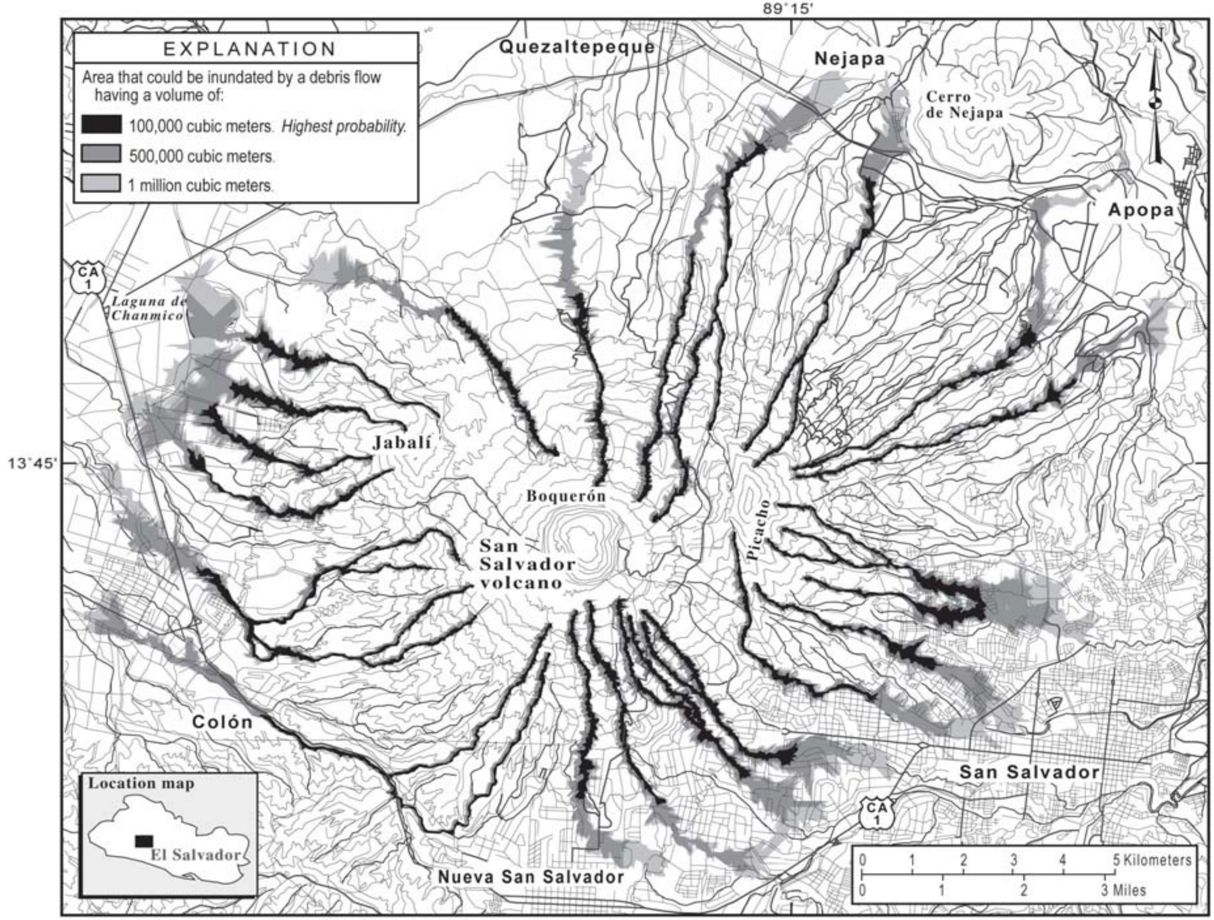
each volcano, we determined nested hazard zones that depict anticipated inundation by debris flows having volumes that ranged from 100,000 m^3 to as much as 2 million m^3.

Hazards from the most likely magnitudes of debris flows at San Salvador, San Vicente, and San Miguel volcanoes are greatest within about 15 km of their summits, and are focused along major channels that drain the volcanoes (Figs. 5-7). The location and size of an inundated area that could be affected by future debris flows will depend on the location and nature of the triggering mechanism, the volume and character of the rock and sediment involved, and the shape of the channel in which a debris flow occurs.

Despite the relatively short extents of the estimated hazard zones, even the smallest debris flows could have devastating consequences. The city of San Salvador and surrounding communities have encroached onto the lower flanks of San Salvador volcano, all major towns near San Vicente volcano are located within 10 km of its summit, and although the major towns that surround San Miguel volcano lie beyond 10 km from the summit, smaller villages, coffee plantations, and important transportation routes are located on the lower flanks of the volcano and lie within 10 km of its summit. At each volcano, the hazard zones of even the smallest debris flows extend well into areas that are now densely settled or used for agriculture (e.g. Fig. 5).

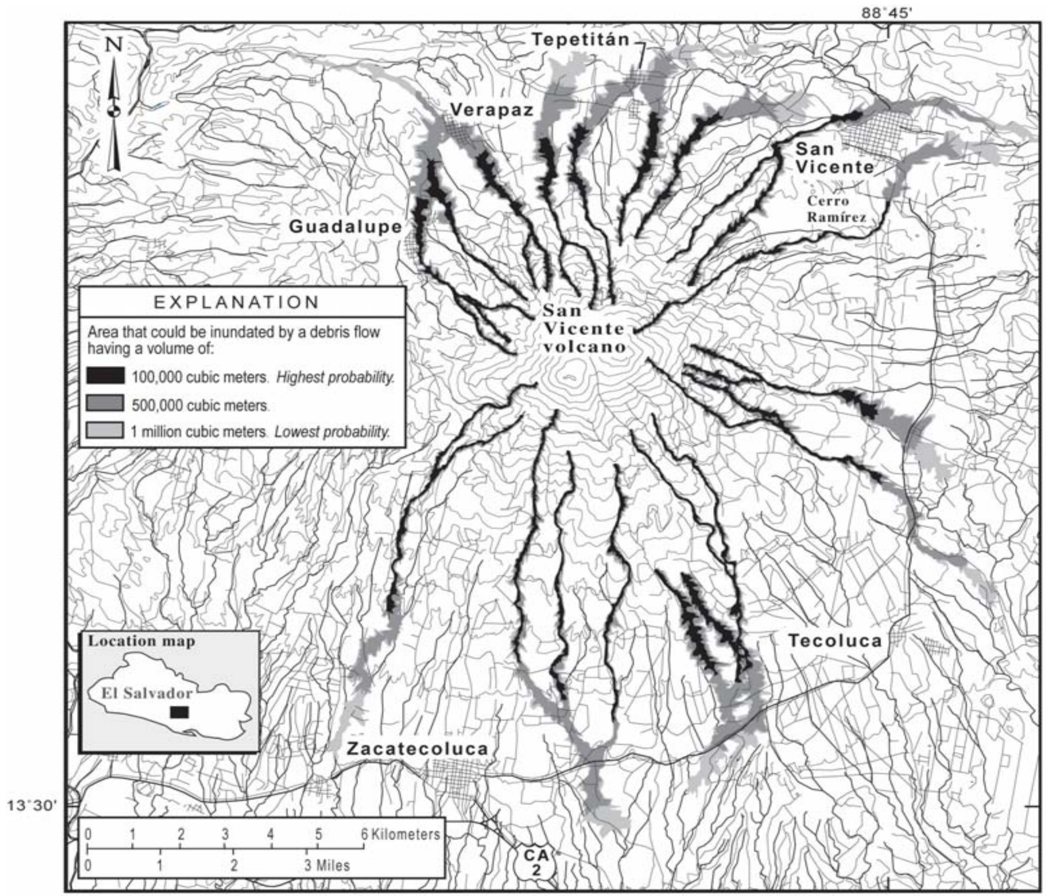
2.3 *Frequency of volcanic debris flows*

Volcanic debris flows in El Salvador are relatively common events that are triggered mainly by heavy rainfalls or earthquakes rather than by volcanic eruptions. In 1982, a rainfall-triggered debris flow having a volume of about 200,000 m^3 originated at San Salvador volcano (Fig. 3), flowed into the outskirts of San Salvador city more than 4 km from its source, and killed 300 to 500 people (Finnson et al. 1996); a similar event occurred in 1934 (Fig. 3, Major et al. in press). At San Vicente volcano earthquake and rainfall-triggered landslides and debris flows up to about 200,000 m^3 are reported in 1774, 1934, 1936, 1995, and 2001 (Major et al. in press). These flows damaged or destroyed nearby towns (Fig. 4), buried local transportation routes, and killed several people. Others may have occurred in historical time but are not recorded. At San Miguel volcano rainfall-triggered debris flows damaged local roads at least 11 times from 1945-2001 (Blanco et al. 2002, Smithsonian Institution 2002). These events, as well as other landslides and debris flows triggered



Base maps from El Salvador 1:50,000 scale series: San Salvador quadrangle, 1984 (2357II); Nueva San Salvador quadrangle, 1983 (2357III); from best available source. Digital Base Maps from Titan Averstar, Inc. Universal Transverse Mercator projection, Zone 16, Horizontal Datum North American 1927, Vertical Datum Mean Sea Level, Spheroid Clarke 1866.

Figure 5. Debris-flow hazard zonation for San Salvador volcano. The hazard zones are subdivided on the basis of hypothetical debris-flow volumes. Note the large areas of high population density that may be affected by future debris flows.



Base maps from El Salvador 1:50,000 scale series: Puente Cuscatlán quadrangle, 1985 (modified) (2456I); Berlín quadrangle, 1985 (2456II); La Herradura quadrangle, 1983 (2456III); San Vicente quadrangle, 1983 (2456IV); from best available source. Digital Base Maps from Titan Averstar, Inc. Universal Transverse Mercator projection, Zone 16, Horizontal Datum North American 1927, Vertical Datum Mean Sea Level, Spheroid Clarke 1866.

Figure 6. Debris-flow hazard zonation for San Vicente volcano.

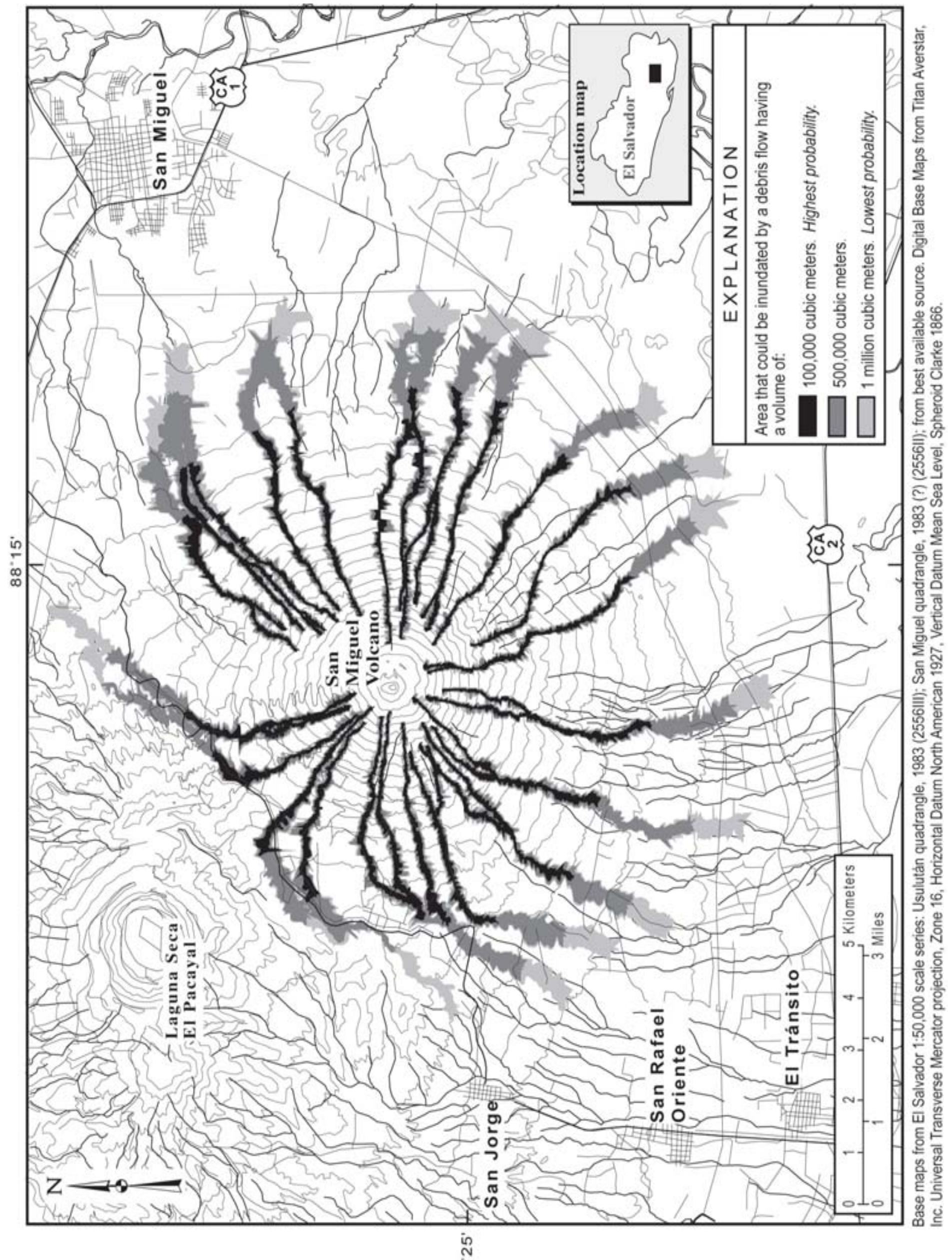


Figure 7. Debris-flow hazard zonation for San Miguel volcano.

regionally (e.g. Rymer & White 1989, Bommer & Rodriguez 2002, Jibson et al. in press), indicate that flows having volumes up to about 500,000 m^3 occur multiple times per century.

3 RECOGNIZING CONDITIONS FAVORABLE FOR LANDSLIDES AND DEBRIS FLOWS

The potential extent of inundation by volcanic debris flows, their probable frequency of occurrence, the speed with which they travel, and the magnitudes of the populace that live within 10 km of the summits of the most highly urbanized volcanoes in El Salvador indicate that traditional mitigation strategies must be augmented to prevent future debris-flow disasters. The extent and costs of traditional engineering structures that would be needed to protect local citizenry at risk from volcanic debris flows preclude extensive engineering intervention. Furthermore, the proximity to source areas of the populace potentially affected by volcanic debris flows precludes effectively warning those at greatest risk of the onset of an event. Thus, traditional mitigation strategies must be augmented with alternative strategies that actively involve those at greatest risk.

Debris flows associated with volcanic activity cannot be predicted precisely, but they should be anticipated if a volcano shows signs of unrest. Fortunately, scientists normally can recognize and monitor several indicators of impending volcanic eruptions (e.g. Ewert & Swanson 1992), although they commonly can make only very general statements about the probability, type, and scale of an impending eruption (e.g. Newhall & Hoblitt 2002). As an example of anticipating conditions favorable for generating eruption-related debris flows, consider San Miguel volcano. When San Miguel volcano erupts again, it is likely to deposit tephra on its flanks. Subsequent erosion of that tephra (Fig. 8) may generate debris flows similar to those that have occurred in the past 60 years at that volcano. In this case, the eruption of the volcano can serve as a warning that conditions are favorable for debris-flow formation, and the distribution of tephra can indicate which flanks are most likely to be affected. Volcanic unrest, however, need not culminate in an eruption before triggering landslides and debris flows. Intrusion of magma into a volcano could trigger a landslide before culminating in an eruption. In the rare event of a large volcanic landslide triggered by intrusion of magma into a volcano (e.g. McGuire 1996, Glicken 1998), deformation of the volcano during magmatic intrusion will serve as a warning that conditions are hazardous.

It is difficult, if not impossible, to predict the precise occurrence of landslides and debris flows triggered by earthquakes or torrential rains, although areas susceptible to such events can be recognized (e.g. Parise & Jibson 2000, Baeza & Corominas 2001). Governmental authorities and the public need to realize that potentially lethal events can occur within debris-flow hazard zones, such as depicted in this report, with little or no warning. However, generally hazardous conditions that favor formation of landslides and debris flows can be recognized to some extent. Forecasts for very heavy rainfall, which commonly trigger flood warnings, can serve broadly as indicators that conditions are favorable for landslides and debris flows, especially if previous investigations have examined broad rainfall intensity thresholds responsible for triggering landslides and debris flows (e.g. Keefer et al. 1987). If a volcano watershed experiences a significant wildfire, debris flows should be anticipated at the onset of subsequent rainfall (e.g. Cannon et al. 2001). A primary earthquake shock can serve as a warning that a flow possibly has been triggered, and ground tremor from an approaching flow sometimes can be perceived. Disaster can be averted if those living, working, or recreating within debris-flow hazard zones seek higher ground without delay if any ground tremor is perceived (Scott 2000).

Public recognition of conditions favorable for producing landslides and debris flows requires significant public education. Clearly, individual scientists and engineers cannot educate the entire population at risk from volcanic debris flows. They must, however, actively participate in educating emergency management planners about the potential risk to the populace and the extent of hazardous areas. Scientists as well as emergency management planners should participate in the public education process by holding town meetings to discuss debris-flow hazards, but they should also

Figure 8. San Miguel volcano viewed from the west. Deep erosional scars on the flank of the volcano are source areas for debris flows.

actively educate small groups of people who are perceived to be credible, such as local authorities and non-governmental organizations (NGOs). These small groups can then assume the responsibility for actively educating the broader populace at risk through community meetings and workshops. In this way, local citizens can become active participants in the hazard-mitigation process.

4 CONCLUSIONS

Volcanic debris flows pose significant threats to people that live on or near major volcanoes in developing countries. In El Salvador, for example, more than 700,000 people live within about 10 km of the summits of just three of the country's several active volcanoes, and at those volcanoes debris flows recur with a frequency of several times per century. The population densities around many volcanoes in developing countries combined with the costs of protective structures preclude massive engineering efforts as a viable defensive strategy for protecting all vulnerable areas. Furthermore, the close proximity of many population centers to the source areas of landslides and debris flows, and the typical speeds with which debris flows travel, inhibit warning of the onset of a debris flow as a means of effective hazard mitigation for many vulnerable communities. People inhabiting debris-flow hazard zones, especially within 10 km of source areas, must become active participants in the hazard-mitigation process. Inhabitants living, working, or recreating along channels that drain volcanoes must learn to recognize potentially hazardous conditions, be aware of the extent of debris-flow hazard zones, and be prepared to evacuate to safer ground when hazardous conditions develop rather than await official warnings or intervention. Learning to recognize conditions favorable for debris-flow formation, understanding the consequences of debris flows, and awareness of the extents of hazard zones requires substantial public education. Debris-flow-modeling and hazard-assessment studies must be augmented with public education programs that emphasize recognizing conditions favorable for triggering landslides and debris flows if effective hazard mitigation in developing countries is to succeed.

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