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Reducing risk from lahar hazards: concepts, case studies, and roles for scientists

Thomas C Pierson[1*], Nathan J Wood[2] and Carolyn L Driedger[1]

Abstract

Lahars are rapid flows of mud–rock slurries that can occur without warning and catastrophically impact areas more than 100 km downstream of source volcanoes. Strategies to mitigate the potential for damage or loss from lahars fall into four basic categories: (1) avoidance of lahar hazards through land-use planning; (2) modification of lahar hazards through engineered protection structures; (3) lahar warning systems to enable evacuations; and (4) effective response to and recovery from lahars when they do occur. Successful application of any of these strategies requires an accurate understanding and assessment of the hazard, an understanding of the applicability and limitations of the strategy, and thorough planning. The human and institutional components leading to successful application can be even more important: engagement of all stakeholders in hazard education and risk-reduction planning; good communication of hazard and risk information among scientists, emergency managers, elected officials, and the at-risk public during crisis and non-crisis periods; sustained response training; and adequate funding for risk-reduction efforts. This paper reviews a number of methods for lahar-hazard risk reduction, examines the limitations and tradeoffs, and provides real-world examples of their application in the U.S. Pacific Northwest and in other volcanic regions of the world. An overriding theme is that lahar-hazard risk reduction cannot be effectively accomplished without the active, impartial involvement of volcano scientists, who are willing to assume educational, interpretive, and advisory roles to work in partnership with elected officials, emergency managers, and vulnerable communities.

Keywords: Lahar; Hazard mitigation; Evacuation; Hazard warning; Risk reduction; Hazard education

Background

Lahars are discrete, rapid, gravity-driven flows of saturated, high-concentration mixtures containing water and solid particles of rock, ice, wood, and other debris that originate from volcanoes (Vallance 2000). *Primary* lahars are triggered during eruptions by various eruption-related mechanisms; between AD 1600 and 2010 such lahars killed 37,451 people worldwide, including 23,080 in the 1985 Nevado del Ruiz disaster alone (Witham 2005; Aucker et al. 2013). During the same period *secondary* lahars, most commonly triggered by post-eruption erosion and entrainment of tephra during heavy rainfall, killed an additional 6,801 (Aucker et al. 2013). Just in the past several decades, staggering losses from widely publicized lahar-related disasters at Mount St. Helens, USA; Nevado del Ruiz, Colombia; Mount Pinatubo, Philippines; and Mount Ruapehu, New Zealand, have demonstrated how lahars of both types significantly threaten the safety, economic well-being, and resources of communities downstream of volcanoes. Lahars can range in consistency from thick viscous slurries resembling wet concrete (termed *debris flows*) to more fluid slurries of mostly mud and sand that resemble motor oil in consistency (termed *hyperconcentrated flows*). These two types of flows commonly occur in all types of mountainous terrain throughout the world, but the largest and most far-reaching originate from volcanoes, where extraordinarily large volumes of both unstable rock debris and water can be mobilized (Vallance and Scott 1997; Mothes et al. 1998).

The destructive nature of lahars derives from their speed, reach, and composition—and our difficulty in predicting (in the absence of warning systems) when they may occur. Large lahars commonly achieve speeds in excess of 20 m/s on the lower flanks of volcanoes and can maintain velocities in excess of 10 m/s for more than 50 km from their source when confined to narrow

* Correspondence: tpierson@usgs.gov
[1]U.S. Geological Survey, Volcano Science Center, Cascades Volcano Observatory, 1300 S.E. Cardinal Court, Suite 100, Vancouver, WA 98683, USA
Full list of author information is available at the end of the article

canyons (Cummans 1981; Pierson 1985; Pierson et al. 1990) (Table 1). Impact forces from multi-ton solid objects commonly suspended in debris-flow lahars (such as large boulders, logs, and other debris) and drag forces exerted by the viscous fluid phase can destroy almost any structure (Figure 1a). Hyperconcentrated-flow lahars damage structures primarily through vigorous lateral erosion of channels that results in bank collapse (Figure 1b). Both flow types commonly occur during a single lahar event as the highly concentrated head of a lahar typically transitions to a more dilute tail. On flow margins or at the downstream ends of depositional zones where velocities are much slower, lahars can encase buildings, roads, towers, and farm land in mud-rock slurries that can dry out to near concrete-like hardness. Yet fresh lahar deposits, commonly many meters deep, can remain fluidized like quicksand for days to weeks, complicating search and rescue efforts. Although most lahars are triggered during or shortly after volcanic eruptions, they can also be initiated without warning by noneruptive events, such as the gravitational collapse of structurally weakened volcanic edifices, large earthquakes, lake outbreaks, or extreme rainfall.

Various approaches to reduce and manage societal risks associated with lahar hazards have been applied over the years (Neumann van Padang 1960; Smart 1981; Suryo and Clarke 1985; Pierson 1989). These approaches fall into four basic categories of mitigation, including hazard avoidance, hazard modification, hazard warning, and hazard response and recovery (Figure 2). The goal of this paper is to provide an overview of each of these risk-reduction strategies and to highlight case studies of how (and how effectively) they have been applied at volcanoes around the world. The timing and magnitude of future lahars is uncertain and risk reduction efforts can be financially and politically costly; therefore economic, political, and social factors can compromise the implementation and long-term effectiveness of any strategy (Voight 1990, 1996; Newhall and Punongbayan 1996; Peterson 1996; Prater and Lindell 2000). We begin by discussing the importance of hazard and risk education for affected populations, elected officials, and emergency managers. We end by reemphasizing the call for committed involvement by volcano scientists in developing and executing these strategies. Scientist involvement improves the credibility and the efficacy of risk-

Table 1 Examples of lahar travel times from lahar source areas (points of initiation) to selected locations in downstream river valleys

Lahar date	Specified locations	Lahar trigger	Distance of specified location from lahar source (km)	Travel time from lahar source to specified location (min)	Average speed (meters per second)[1]
1926	Points along Hurano River, downstream of vent at Tokachidake volcano, Japan	Eruption (pyroclastic density current on snow and ice)	2.4	1	42
			6.4	4	26
			20.0	17	16
			23.2	29	5
1980	Points along Pine Creek, downstream of vent at Mount St. Helens, USA	Eruption (pyroclastic density current on snow and ice)	10.1	7	24
			14.1	11	16
			16.8	13	18
			20.9	19	14
1985	Point along Denjo River, downstream of landslide at Mount Ontake volcano, Japan	Earthquake-triggered slope failure	11.4	10	19
1985	Points along Río Chinchiná, downstream of vent at Nevado del Ruiz volcano, Colombia	Eruption (pyroclastic density current on snow and ice)	11.3	20	10
			33.0	70	7
			68.6	172	6
1990	Points along Drift River, downstream of vent at Redoubt Volcano, Alaska	Eruption (pyroclastic density current on snow and ice)	7.6	8	16
			18.5	27	10
1994	Points along Río Páez, downstream of vent at Nevado del Huila volcano, Colombia	Earthquake-triggered slope failures	4	2 to 3	22 - 33
			9	6 to 9[2]	17 - 25
			30	20 to 30[2]	17 - 25

Travel times are partly a function of lahar magnitude and are determined from eyewitness accounts, instrument recordings, and back-calculations of flow velocity based on physical evidence. Data from Pierson (1998) and Scott et al. (2001).
[1]Average speed is computed from the closest upstream point where timing information was available; not all timing points shown in this table. Localized lahar velocities tend to decrease as channel slopes decrease with distance downstream.
[2]Lahar could be heard or felt about 5 minutes before its arrival at this point.

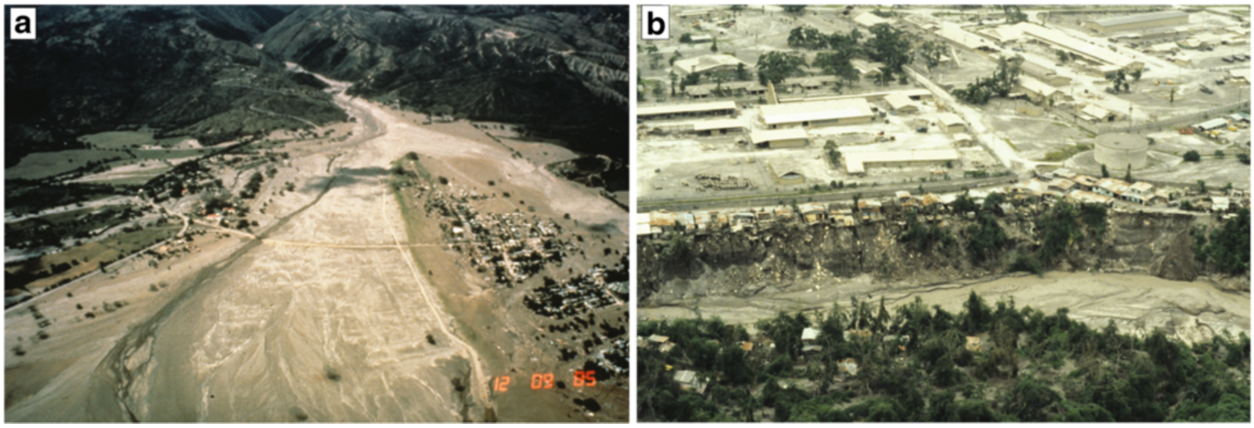

Figure 1 Destructive effects of lahars. (a) Aerial view of Armero, Colombia, following destruction by a lahar on November 13, 1985, that killed approximately 21,000 people at this site alone (see Pierson et al. 1990; USGS photo by R.J. Janda, 9 Dec 1985). Patterns of streets and building foundations are visible in the debris field at center of photo. **(b)** Aerial view of part of Angeles City, downstream of Mount Pinatubo, Philippines, along the Abacan River, showing consequences of vigorous bank erosion by repeated post-eruption hyperconcentrated-flow lahars that were triggered by heavy monsoon rains (see Major et al. 1996; USGS photo by TCP, 15 Aug 1991).

reduction efforts. When the risks are perceived as credible and risk-reduction strategies are understood, tragic losses from future lahars on the scale of 20th-century lahar disasters can be avoided or at least minimized.

Hazard and risk education

The foundation for all risk-reduction strategies is a public that is well informed about the nature of hazards to their community, informed about how to lessen societal risk related to these hazards, and motivated to take risk-reducing actions. This knowledge base and accompanying appreciation of volcano hazards are needed to increase the interest and ability of public officials to implement risk-reduction measures and create a supportive and responsive at-risk population that will react appropriately when an extreme event occurs. Volcano scientists play a critical role in effective hazard education by informing officials and the public about realistic hazard probabilities and scenarios (including potential magnitude, timing, and impacts); by helping evaluate the effectiveness of proposed risk-reduction strategies; by helping promote acceptance of (and confidence in) hazards information through participatory engagement with officials and vulnerable communities as partners in risk reduction efforts; and by communicating with emergency managers during extreme events (Peterson 1988, 1996; Cronin et al. 2004b; McGuire et al. 2009). But before successful use of hazard information can occur, the scientists' first and main role is to make technical data, hypotheses, and uncertainties understandable to non-technical users of hazard information. Serious misunderstandings can arise, sometimes with tragic consequences,

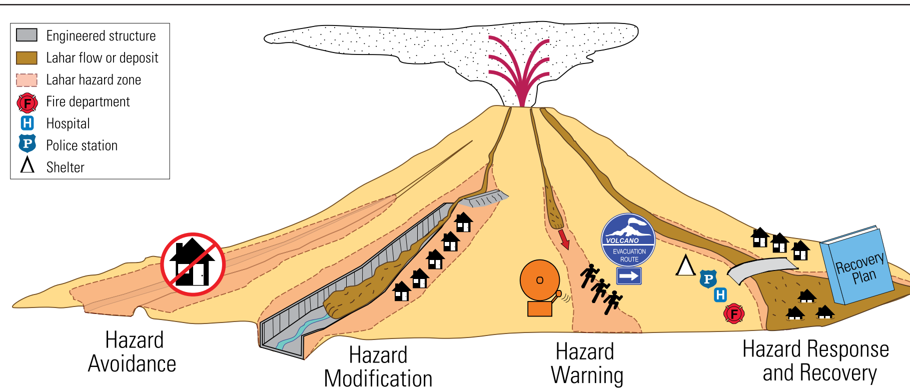

Figure 2 Schematic representation of the four basic strategies to reduce lahar-hazard risk within lahar hazard zones. Strategies include (1) hazard avoidance with land-use planning and zonation; (2) hazard modification with engineered protection structures (bypass channel and deflection berm); (3) hazard warning to allow for timely evacuation; and (4) hazard response and recovery, which minimize long-term impacts after a lahar has occurred.

when scientists do not perform this role effectively (Voight 1990; Hall 1992).

An effective hazard education program begins when scientists inform people in vulnerable communities about past hazardous events and current threats—information necessary for preparedness for future events. Scientists need to be involved in hazard-education efforts, because they provide the needed hazard expertise, and the public tends to imbue them with a high level of trust (Ronan et al. 2000; Haynes et al. 2008; Mei et al. 2013). But the straightforward presentation of information that may seem logical to many scientists may not be effective; hazards information must be transmitted in ways that are not only understandable but also emotionally palatable and culturally relevant to the target audience (Cronin et al. 2004b). People are more likely to implement risk-reduction strategies before an event or evacuate during an event if they comprehend that past events have impacted their communities, if they believe that future events could do so again and that viable mitigation options exist, and if they themselves have been involved in determining their community's risk-reduction strategies (Mileti 1999). Community adoption of mitigation strategies is also more likely if hazard education is integrated into existing development programs and if it includes discussion of tangible actions that can be taken to protect lives and livelihoods, instead of just discussing uncontrollable threats (Paton et al. 2001). The types of educational products, activities, and tasks that benefit from the active participation of scientists are varied (Figure 3):

- Informative, jargon-free, general-interest publications and multi-media information products about potential hazards in digital and print formats (e.g., IAVCEI 1995, 1996; USGS 1996, 1998, 2010; Gardner et al. 2000; Gardner and Guffanti 2006; Driedger and Scott 2008; Dzurisin et al. 2013).
- Technical information products to summarize scientific information about potential or ongoing volcanic activity or potential hazards, such as hazard-assessment reports, alerts and information statements on the status of current volcanic activity, volcanic-activity notification services, response plans developed in partnership with other agencies and stakeholders, and specific guidance based on the latest research (Guffanti et al. 2007). Such products can be made available through print, fax, email, web-site, and social media outlets (e.g., Scott et al. 1997; Hoblitt et al. 1998; Pierce County 2008; Wood and Soulard 2009a).
- Accessible and understandable spatial depictions of hazardous areas and evacuation routes to safe areas that are tailored to a target audience (Figure 3a,b), such as traditional hazard maps, evacuation route maps, explanations of the volcanic origins of familiar landscape features, labeled aerial photographs with vertical and oblique perspectives, and simple perspective maps keyed on cultural features and boundaries (Haynes et al. 2007; Némath and Cronin 2009). Web sites developed by local agencies can be good outlets for this type of information (e.g., http://www.piercecountywa.org/activevolcano).
- Hazards information presentations and training for the media (Figure 3c), emergency management officials (Figure 3d), first responders, land managers, public safety officials, search-and-rescue (SAR) teams, community-based monitoring teams, and public information officers before and during volcano crises (Driedger et al. 2008; Frenzen and Matarrese 2008; Peterson 1988, 1996; Driedger et al. 2008; Driedger and Scott 2010; de Bélizal et al. 2013; Stone et al. 2014).
- Teacher trainings (Figure 3e) and special school curricula for children in order to provide a foundation of knowledge at a young age, as well as to educate and motivate their families (e.g., Driedger et al. 2014).
- Presentations to and dialogues with community groups and councils, volunteer organizations, local government bodies, and schools about existing hazards (Figure 3f), while seeking opportunities to engage vulnerable populations in devising potential options for risk reduction (Peterson 1988, 1996; Driedger et al. 1998; Cronin et al. 2004a,b).
- Relationship-building with communities and community leaders (official and unofficial) to establish trust and credibility, to encourage community-based risk-reduction solutions, and to maintain an ongoing dialogue with officials and at-risk community members (Peterson 1988, 1996; Cronin et al. 2004b; Haynes et al. 2008; McGuire et al. 2009; Mileti 1999; Stone et al. 2014).
- Collaboration with emergency managers in the design and message content of signs for hazard awareness, locations of hazard zones, and evacuation procedures and routes (Figure 3g) (Schelling et al. 2014; Driedger et al. 1998, 2002, 2010; Myers and Driedger 2008a, b) and for disaster commemorations (such as monuments or memorials) that remind the public that extreme events are possible (Figure 3h).
- Collaboration in the development of accurate and consistent warning messages to be sent out when a lahar triggers a warning system alert (Mileti and Sorenson 1990).

Hazard education materials should be tailored to address the demographics and socioeconomic context of

Figure 3 Examples of some approaches for communicating hazards information to emergency managers, public officials, and at-risk populations. (a) *Non-traditional hazard maps*: An oblique perspective map showing potential lahar zones (brown) emanating from Mount Rainier volcano, with City of Tacoma, Washington (79 km downstream of Mount Rainier), in lower center of image along Puget Sound shoreline. Many people find it easier to visualize spatial information on such maps than on vertical plan-view maps. Satellite ground-surface image from Google Earth® modified by NJW, with Case 1 lahar hazard zones from Hoblitt et al. (1998) overlaid. **(b)** *Signs and posters*: A trail sign for hikers, using words and pictures, to convey lahar hazard information and instructions on what to do if they hear an approaching lahar (Mount Rainier National Park, USA). **(c)** *Working with media*: A USGS-hosted press conference to inform the media about the reawakening of Mount St. Helens (USA) in 2004 (USGS photo by D. Wieprecht). **(d)** *Training*: A training class on volcano hazards for emergency managers and given by scientists to provide an opportunity for relationship-building, as well as education (USGS photo by CLD). **(e)** *Working with teachers*: A scientist-led teacher workshop where simple physical models of lahars were used to help teachers grasp (and later teach) fundamental concepts about lahars (USGS photo by CLD). **(f)** *Involving vulnerable populations in hazard-mitigation decisions*: A 3-dimensional participatory mapping exercise for residents of a threatened village at Merapi volcano, Indonesia (photo by F. Lavigne, used with permission). **(g)** *Practice drills*: A lahar evacuation drill in 2002 at a school in Orting, Washington, which is downstream of Mount Rainier (USGS photo by CLD). **(h)** *Monuments and memorials*: A simple disaster memorial commemorating 22 people killed by lahars in the town of Coñaripe on the lower flank of Villarrica volcano, Chile, in 1964 (USGS photo by TCP).

at-risk populations (e.g., Wood and Soulard 2009b). This may include providing information in multiple languages on signs, pamphlets, and warning messages where appropriate, or conveying information in pictures or cartoons to reach children and nonliterate adults (Ronan and Johnston 2005; Tobin and Whiteford 2002; Dominey-Howes and Minos-Minopoulos 2004; Gavilanes-Ruiz et al. 2009). Educational outreach should also include efforts to reach tourists and tourism-related businesses, because these groups may lack hazard awareness and knowledge of evacuation procedures (Bird et al. 2010).

A hazards and risk education program can increase its effectiveness by focusing outreach on those individuals and groups who can further spread information throughout a community. Such outreach can target institutions such as social organizations, service clubs, schools, and businesses, as well as trusted social networks (Paton et al. 2008, Haynes et al. 2008). The key to sustaining hazard education is to identify and train community members with a vested interest in preparedness, such as emergency managers, educators, health advocates, park rangers, community and business leaders, and interested residents and other stakeholders. Training community members to integrate hazard information into existing social networks is especially crucial for hard-to-reach, potentially marginalized community groups, such as recent immigrants, daily workers coming from outside of hazard zones, or neighborhoods with people who don't speak the primary language (Cronin et al. 2004a).

Direct involvement in training community members and elected officials extends a scientist's capacity to educate a community. It also provides opportunities for scientists to gain insight on how people conceptualize and perceive the hazards and the associated risks (for example, the role traditional knowledge and local experience), strengths and weaknesses of communication lines within a community, and any context-appropriate measures that might be used to increase local capacity for risk reduction (Cronin et al. 2004b). Several studies have shown that people's behavior towards volcano risks is influenced not only by hazards information but also by the time since the last hazardous event and the interaction of their perceptions with religious beliefs, cultural biases, and socioeconomic constraints (Lane et al. 2003; Gregg et al. 2004; Chester 2005; Lavigne et al. 2008). Understanding these influences and the socio-cultural context of risk is important if scientists are to successfully change behaviors and not simply raise hazard awareness. Participatory methods such as three-dimensional mapping (Gaillard and Maceda 2009) (Figure 3f), scenario planning (Hicks et al. 2014), participatory rural appraisals (Cronin et al. 2004a 2004b), and focus group discussions (Chenet et al. 2014) can be used to understand the societal context of volcanic risk, to integrate local and technical knowledge, and to promote greater accessibility to information. These "bottom-up" efforts, as opposed to government-driven efforts that are perceived as "top-down", promote local ownership of the information (Cronin et al. 2004b), empower at-risk individuals to implement change in their communities (Cronin et al. 2004a), and can result in risk-reduction efforts becoming an accepted part of community thinking and daily life.

Finally, scientists should understand that effective hazard and risk education is a long-term investment of time and resources and will not be a one-time effort. One issue is that people may show great enthusiasm in hazards and risk information at public forums, but their interest and participation in risk-reduction activities may diminish over time as other day-to-day issues become higher priorities. Another issue is unavoidable turnover among users of hazards information. Elected officials may retire or be voted out of office. Emergency managers, first responders, and teachers may transfer to other positions or retire. People move in and out of vulnerable communities. So, just as scientists continually monitor changing physical conditions at volcanoes, they should also appreciate the dynamic nature of the perceptions and knowledge of hazards within communities, agencies, and bureaucracies—and plan for sustained education and outreach efforts.

Strategies for lahar-hazard risk reduction

Each of the four basic risk-reduction strategies of hazard avoidance, hazard modification, hazard warning, and hazard response and recovery (Figure 2) has basic underlying requirements for successful application. These requirements include an accurate assessment of the hazard; a realistic understanding by elected officials, emergency managers, and at-risk populations of the hazards, risks, and limitations of any implemented strategy; thorough planning; adequate funding; practice exercises and drills, where appropriate; and effective communication among stakeholders during actual lahar occurrence (Mileti 1999; Leonard et al. 2008). Scientists have important roles to play in all of these underlying requirements.

Hazard avoidance

A range of approaches can either regulate or encourage hazard avoidance—the strategy seeking to expose as few lives and societal assets as possible to potential loss. Land-use zoning regulations or development of parks and preserves that ban or limit occupation of hazard zones are ways to keep people, developed property, and infrastructure out of harm's way. Another way is for local government policies to allow occupation of hazard zones but to also impose disincentives for those who choose to live there. A third way is to educate the public about the hazard, the risks, and the probabilities of hazardous event occurrence, and then to trust that people will choose to minimize the hazard exposure of their homes and businesses.

A complete ban on development in a hazard zone is probably the most effective way to avoid the hazard. This may be easiest immediately following a disaster and if the ban aligns with cultural values, such as when the entire town site of Armero, Colombia, was made into a cemetary after about 21,000 people were killed there by a lahar in 1985 (Pierson et al. 1990; Voight 1990). However, it is commonly challenging to implement development bans based on hazard zonation prior to a disaster due to people's strong attachment to a place, cultural beliefs, political push-back from business and real-estate interests, the lack of alternative locations for new development, attitudes of individuals who don't want to be told where they can or cannot live, or needed access to livelihoods that exist in volcano hazard zones (Prater and Lindell 2000; Lavigne et al. 2008). Indeed, lahar hazard zones can be attractive for transportation and other infrastructure and for residential development, because these areas typically encompass deposits of previous lahars that offer flat topography, commonly above flood hazard zones, and they may offer scenic views of a nearby volcano (Figure 4). Lahar and related deposits also may be attractive for resource extraction. In the Gendol valley at Mount Merapi (Indonesia) for example, thousands of people work daily as miners in high-hazard zones, excavating sand and gravel to sell. Most, if not all, are aware of the risk but are willing to accept it because of the financial reward (de Bélizal et al. 2013). In other cases such hazard zones may already be occupied by well-established communities—a reality that makes development bans problematic. A

Figure 4 Mount Rainier volcano and dense residential housing in downstream community of Orting, Washington. The town is built on the flat upper surface of a lahar deposit from Mount Rainier that was emplaced about 500 years ago. Orting is one of several communities that are in lahar hazard zones downstream of Mount Rainier. A warning system in this valley would give residents about 40 minutes to evacuate to high ground (USGS 2013). USGS photograph by E. Ruttledge, 18 Jan 2014.

strong cultural attachment to the land and the lack of available safe land elsewhere may lead communities to accept lahar risks and even continue to rebuild homes after multiple lahar burials (Crittenden 2001; Crittenden and Rodolfo 2002).

A more realistic land-use planning approach may be to restrict the kind or amount of development allowed to occur in lahar hazard zones. For example, vulnerable valley floors could be limited to agricultural use only, with homes built on higher ground. Downstream of Mount Rainier in Pierce County (Washington, USA), comprehensive land use plans include urban growth boundaries that prohibit tourist facilities larger than a certain size and limit other high-density land uses in lahar hazard zones (Pierce County 2014). Downstream of Soufriére Hills volcano in Montserrat (British West Indies), only daylight entry into certain hazard zones for farming was allowed in the 1990s, due to pyroclastic-flow and lahar hazards associated with the actively erupting volcano (Loughlin et al. 2002). The goal of such restrictions is to minimize population exposure and to only allow land uses in which people could be evacuated quickly, yet such measures are not always foolproof (Loughlin et al. 2002). Ordinances can also limit the placement of critical facilities (hospitals, police stations, schools, and fire stations) in hazard zones, so that basic community services would be available for rescue, relief, sheltering, and recovery efforts in the event of a lahar (Pierce County 2014).

Where no restrictions are imposed on development of lahar hazard zones, it may be possible to discourage development through the use of various disincentives. These could include higher property tax rates, higher insurance rates, and limitation of public services or infrastructure in designated hazard zones. For example in the United States, the National Flood Insurance Program requires that people living in designated flood zones purchase flood insurance (Michel-Kerjan 2010). As premiums for such types of insurance increase, purchase of a home in a hazard zone should become less attractive.

Hazard education alone could, theoretically, also achieve some hazard avoidance, but evidence suggests that many residents already living in hazard-prone areas rarely undertake voluntary loss-prevention measures to protect their property, despite increased hazard awareness (Michel-Kerjan 2010). Discouraging new residents from moving into hazard zones may be more realistic. Focused public education campaigns are one way to raise hazard awareness. Another is to require that hazard information be disclosed to people buying property or building structures in a hazard zone. Such disclosures are required on building-permit applications in Orting, Washington in the lahar hazard zone downstream of Mount Rainier. Some individuals may use increased hazard awareness to assess whether the risk is acceptable, others may not, and still other may object to increased hazard awareness. In fact, just the dissemination of hazards information to people living in hazard zones can engender fierce political opposition, particularly from some business and real-estate interests (Prater and Lindell 2000).

Volcano scientists play important supporting roles throughout any land-use planning process aimed at reducing risk from lahar hazards. First, land-use decisions require hazard-zonation maps that are scientifically defensible, accurate, and understandable, given the potential for political, social, or legal push-back from various constituents. Second, good planning needs input from predictive models that estimate lahar runout distances, inundation areas, and travel times to populated areas. In addition, scientists are needed to help explain the uncertainties inherent in the maps and models, to estimate the likelihood of occurrence, and to evaluate the effectiveness of proposed risk-reduction strategies as land-use planners balance public safety against economic pressures to develop.

Hazard modification

Some communities predate recognition that they are situated in a lahar hazard zone. Others may expand or be developed in hazard zones because of social and economic pressures, inadequate understanding of the risks, or acceptance and tolerance of the risks. When societal assets are already in lahar hazard zones, construction of engineered protection structures can reduce risk by (a) preventing some lahars from occurring, (b) weakening the force or reach of lahars, (c) blocking or trapping lahars before they can reach critical areas, or (d) diverting lahars away from critical areas—all methods of hazard modification (Smart 1981; Baldwin et al. 1987; Hungr et al. 1987; Chanson 2004; Huebl and Fiebiger 2005). Engineered protection works, sometimes referred to as sabo works (*sabō* = "sand protection" in Japanese), and slope stabilization engineering methods have been widely used for centuries in volcanic areas in Japan and Indonesia, as well as in the Alps in Europe for protection from nonvolcanic debris flows.

Engineered structures designed for lahar protection downstream of volcanoes have many of the same advantages and disadvantages of river levees in flood-prone areas, sea walls in coastal areas, or engineered retrofits to buildings and bridges in seismic areas. The main advantages of this approach are that communities can survive small- to moderate-size events with little economic impact, and communities, if they choose to, can gradually relocate assets out of hazard zones. However, protection structures are expensive to build and maintain, which may overly burden communities financially or lead to increased vulnerability if funding priorities shift and maintenance is neglected. Another important disadvantage is that protection structures tend to lull populations into a false sense of security. People commonly assume that all risk has been eliminated, and this perception may result in fewer individuals taking precautionary steps to prepare for future events. This view may also result in increased development of areas now perceived to be safe because of the protective structure. The reality is that risk is eliminated or reduced only for events smaller than the 'design event' that served as the basis for construction. Events larger than the design event can occur and when they do, losses can be even larger because of the increased development that occurred after construction of the protection structure—also referred to as the 'levee effect' in floodplain management (Tobin 1995; Pielke 1999). This was the case near Mayon Volcano (Philippines) where lahar dikes built in the 1980s led to increased development behind the structures. When they failed because of overtopping by lahars during Typhoon Reming in 2006, approximately 1,266 people were killed (Paguican et al. 2009). The effectiveness and integrity of engineered structures can also be compromised by the selection of cheap but inappropriate construction materials (Paguican et al. 2009) and by ill-informed human activities, such as illegal sand mining at the foot of structures or dikes occasionally being opened to allow for easier road access into communities. Therefore, although protection structures may reduce the number of damaging events, losses may be greater for the less frequent events that overwhelm the structures. In addition, engineered channels and some other structures can have negative ecological effects on watersheds.

The potential for large losses is exacerbated if public officials choose to build the structure that is affordable, rather than the structure a community may need. Economics and politics may play a bigger role than science in deciding the type, size, and location of protection structures, because of the high financial costs and land-use decisions associated with building the structures and with relocating populations that occupy construction areas (Tayag and Punongbayan 1994; Rodolfo 1995) (Case study 1). Because decision makers will have to balance risk against cost, scientists have a significant role in helping public officials by (a) estimating the maximum probable lahar (the design event); (b) predicting probable flow routes, inundation areas, and possible composition and flow-velocity ranges; (c) estimating probabilities of occurrence; and (d) evaluating the effectiveness of proposed mitigation plans and structures.

Case study 1. When economics and politics trump science

Following the June 15, 1991, eruption of Mount Pinatubo (Philippines), lahars and volcanic fluvial sedimentation threatened many downstream communities. Geologists from a number of institutions met with officials at local, provincial, and national levels to explain the threats and to evaluate and discuss proposed countermeasures. Due to political pressures (Rodolfo 1995), officials ultimately adopted a lahar mitigation strategy that was based on the construction of parallel containment dikes close to the existing river channels, using easily erodible fresh sand and gravel deposits of earlier lahars as the construction material. Appropriation of the private land needed for lahar containment areas of adequate size was viewed by officials as too politically costly. Officials hoped the dikes would divert lahars and floods past vulnerable communities. However, nearly all the geologists involved in the discussions expressed the opinion that this was a poor strategy because (a) channel gradients were too low for effective sediment conveyance and deposition would occur in the wrong places, (b) dike placement did not provide adequate storage capacity and dikes would be overtopped or breached, (c) most of the dikes were not revetted and would be easily eroded by future lahars, and (d) people would be lured back to live in still-dangerous hazard zones. The advice of the scientists was not heeded, and over the next several years many of these predictions came true, including breached dikes due to lahar erosion and overtopped dikes due to sediment infill. Lahars breaking through the levees caused fatalities and destroyed many homes. A government official later explained (to TCP) that political considerations prompted the decisions to minimize the area of condemned land and build lahar catch basins that were too small. He felt that the plan recommended by the geologists would have angered too many people and that it was better for officials to be seen doing something rather than nothing, even if the chance of success was low. Indeed, political and economic forces can override scientific recommendations (Tayag and Punongbayan 1994*; Rodolfo* 1995*; Janda et al.* 1996*; Newhall and Punongbayan* 1996*; Crittenden* 2001*).*

Slope stabilization and erosion control

Volcanic ash mantling hillslopes is extremely vulnerable to rapid surface erosion and shallow landsliding, and it is easily mobilized as lahars by heavy rain (e.g., Collins and Dunne 1986; Pierson et al. 2013). Even after long periods of consolidation and revegetation, ash-covered slopes can fail on massive scales and result in catastrophic lahars (Scott et al. 2001; Guadagno and Revellino 2005). Various methods of slope stabilization, slope protection, and erosion control can limit shallow landsliding or surface erosion in disturbed landscapes that could produce extreme sediment inputs to rivers (Figure 5), although most of these approaches are intensive, costly, and generally limited to hillside-scale problem areas (see overviews in Theissen 1992; Morgan and Rickson 1995; Gray and

Figure 5 Example of slope stabilization. Timber retaining walls used to stabilize a steep slope in a volcanic area in Japan (USGS photo by TCP).

Sotir 1996; Holtz and Schuster 1996; Schiechtl and Stern 1996; Beyers 2004; Valentin et al. 2005). These are only briefly summarized here. Options for drainage-basin-scale slope stabilization and erosion control are more limited, have been tested mostly in basins disturbed by wildfire rather than by volcanic eruptions, and are not always effective (Beyers 2004; deWolfe et al. 2008).

Regardless of scale of application, slope stabilization and erosion control techniques attempt to either (a) prevent shallow landsliding by mechanically increasing the internal or external forces resisting downslope movement, decreasing the forces tending to drive downslope movement, or both; or (b) prevent rapid surface erosion and sediment mobilization on slope surfaces and in rills, gullies, and stream channels (Gray and Sotir 1996; Holtz and Schuster 1996). Inert materials used to stabilize slopes and control erosion include steel, reinforced concrete (pre-cast elements or poured-in-place), masonry, rock, synthetic polymers, and wood, although many of these degrade and weaken with time. Biotechnical stabilization (Morgan and Rickson 1995; Gray and Sotir 1996) uses live vegetation to enhance and extend the effectiveness of many engineered structures.

Forces resisting slope failure or erosion can be maintained or augmented by a variety of approaches (Morgan and Rickson 1995; Gray and Sotir 1996; Holtz and Schuster 1996). Counterweight fills, toe berms, retaining walls, and reinforced earth structures can buttress toes of slopes. To maintain buttressing at a toe slope, revetments using riprap, gabion mattresses, concrete facings, and articulated block systems can prevent toe-slope erosion. Anchors, geogrids (typically wire-mesh mats buried at vertical intervals in a slope face), cellular confinement systems consisting of backfilled three-dimensional structural frameworks; micro-piles, deeply rooted woody vegetation, chemical soil binders, and drains to decrease internal pore pressures can increase the shear strength of natural or artificial slopes. To reduce the driving forces, proven methods include regrading to lower slope angles, and weight reduction of structures or materials placed on slopes. Surface erosion of slopes can be controlled by protecting bare soil surfaces and by slowing or diverting surface runoff through the application of reinforced turf mats, geotextile and mulch blankets, hydro-seeded grass cover, and surface drains. Channelized surface erosion can be retarded with gully fills or plugs of cut brush or rock debris, or small check dams.

Intensive slope-stabilization and erosion-control techniques such as many of those listed above may be too costly for large areas of volcanically disturbed drainage basins, but they may be cost-effective in specific problem areas. Over large areas, economically feasible approaches may include tree planting, grass seeding, and grazing management to limit further destruction of slope-stabilizing vegetation. However, much post-disturbance erosion is likely to occur before grass seed can germinate or tree seedlings can grow to effective size, and a number of studies have shown that large-scale aerial grass seeding is no more effective for erosion control than the regrowth of natural vegetation (deWolfe et al. 2008).

Lake stabilization or drainage

Stabilizing or draining lakes that could breach catastrophically without warning is another way to prevent lahars from reaching vulnerable downstream areas. Crater lakes, debris-dammed lakes (dammed by pyroclastic-flow, debris-avalanche, or lahar deposits), and glacial moraine-dammed lakes all can become unstable if their impounding natural dams are overtopped or structurally fail. Historic rapid lake outbreaks in several countries have triggered catastrophic lahars that resulted in loss of life (O'Shea 1954; Neumann van Padang 1960; Umbal and Rodolfo 1996; Manville 2004). Very large prehistoric outbreaks of a volcanically dammed lake have been documented having peak flows comparable to the world's largest floods (Scott 1988; Manville et al. 1999). Stabilization methods include armoring of existing spillways on natural dams, construction of engineered spillways, and rerouting lake outflow by pumping or drainage through tunnels (Sager and Chambers 1986; Willingham 2005) (Figure 6; Case study 2). Preemptive drainage of dangerous lakes can be fraught with difficulties and may not be successful (Lagmay et al. 2007).

Case study 2. Examples of lake stabilization

Since AD 1000, 27 eruptions of Mount Kelud (Java, Indonesia) have catastrophically expelled lake water from the volcano's crater lake and created several deadly lahars, including a lahar in 1919 that killed more than 5000 people (Neumann van Padang 1960*). In an attempt*

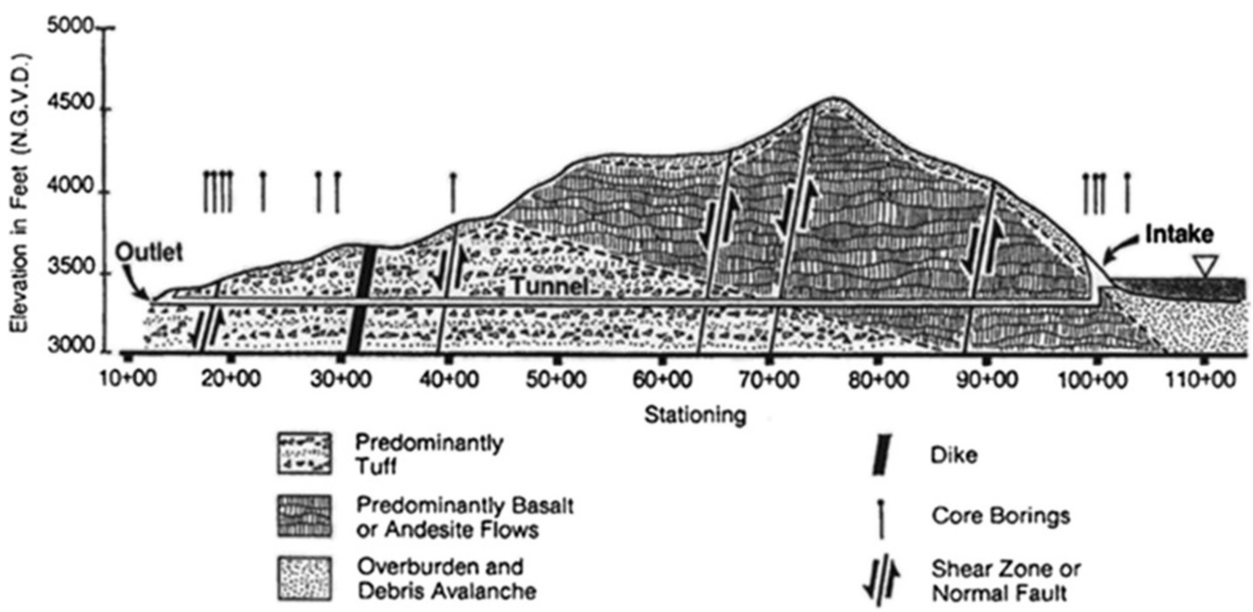

Figure 6 Lake-level stabilization to prevent failure of a natural debris dam and a subsequent lahar. At Mount St. Helens (USA) a tunnel was bored through a mountain ridge to divert water from Spirit Lake into an adjacent drainage basin. In this case debris-avalanche and pyroclastic-flow deposits formed the potentially unstable natural dam. This geologic cross section shows the 2.5-km-long outlet tunnel, which stabilizes the lake by keeping the water surface at a safe level below the dam crest (from Sager and Budai 1989).

to drain this lake, engineers in 1920 dug a drain tunnel over 955 m in length from the outer flank of the cone into the crater but eventually abandoned the project because of ongoing volcanic activity and other technical difficulties. Thereafter, siphons were constructed to control the lake level, and these were responsible for partial drainage of the crater lake and for a reduced number of lahars during the 1951 eruption (Neumann van Padang 1960*).*

More recently, debris-avalanche and pyroclastic-flow deposits from the 1980 eruption of Mount St. Helens (Washington, USA) blocked tributary drainages of the North Fork Toutle River and enlarged several preexisting lakes. The largest and potentially most dangerous of these was Spirit Lake, which, when mitigation efforts began, was impounding 339 million m^3 *of water—enough to form a lahar that could have destroyed major parts of several cities located approximately 90 km downstream. To prevent the Spirit Lake blockage from ever being breached by overflow, the level of the lake surface was stabilized by the U.S. Army Corps of Engineers (USACE) at a safe level, first by pumping water over the potentially unstable natural dam in pipes using diesel pumps mounted on barges, and thereafter by draining lake water through a 3.3-m-diameter outlet tunnel that was bored 2.5 km through an adjacent bedrock ridge to form a permanent gravity drain that was completed in 1985 (Figure 6). The USACE stabilized the outlets from two other debris-dammed lakes at Mount St. Helens (Coldwater and Castle Lakes) by constructing engineered outlet channels. The Spirit Lake drainage tunnel continues to function well, although periodic inspection and maintenance of the tunnel are necessary. None of the stabilized lakes at Mount St. Helens have had outbreaks (Sager and Budai* 1989*; Willingham* 2005*).*

Lahar diversion

Lahars can be prevented from spreading out and depositing in critical areas by keeping them channelized in modified natural channels or by engineering new channels. Such artificial channels (Figure 7a) must be sufficiently smooth, steep, and narrow (to maintain sufficient flow depth) in order to prevent in-channel deposition. The goal of such channelization is to keep lahars flowing so that they bypass critical areas. The effectiveness of this approach depends on lahar size and composition, channel dimensions, and construction techniques. Highly concentrated lahars (debris flows) can transport large boulders at high velocity and are extremely erosive, so channel bottoms and sides must be lined with concrete or stone masonry surfaces. Even so, hardened diversion channels may require frequent maintenance. Without hardening, lahars in diversion channels can easily erode channel boundaries and establish new flow paths. Channelization of lahar-prone streams draining volcanoes is relatively common in Japan and Indonesia (Smart 1981; Japan Sabo Assoc. 1988; Chanson 2004).

Deflection and diversion structures also can be employed to reroute or redirect lahars away from critical infrastructure or communities. Structures include (a) tunnels or ramps to direct flows under or over roads, railroads, and pipelines; (b) training dikes (also termed levees or bunds) oriented sub-parallel to flow paths to guide lahars past critical areas; and (c) deflection berms oriented at sharper angles to flow paths to force a major course alteration in a lahar (Baldwin et al. 1987; Hungr et al. 1987; Huebl and Fiebiger 2005; Willingham 2005). However, lahar diversion may cause additional problems (and political resistance) if the diversion requires the sacrifice of only marginally less valuable land. Diversion ramps and tunnels are more practical for relatively small flows,

Figure 7 Types of lahar diversion structures. (A) Engineered channel reach in small river draining Sakurajima volcano in southern Japan, where channel is revetted with reinforced concrete and engineered to be as steep, narrow, and smooth as possible, in order to divert lahars away from a developed area. **(B)** Training dike revetted with steel sheet piles on the lower flank of Usu volcano, Japan and designed to deflect lahars away from buildings and other infrastructure. USGS photos by TCP.

whereas training dikes and deflection berms can be scaled to address a range of lahar magnitudes.

Dikes and berms are constructed typically of locally derived earthen material, but to be effective, these structures must be revetted (armored) on surfaces exposed to highly erosive lahars (Figure 7b). Revetment can be accomplished with thick layers of poured-in-place reinforced concrete, heavy concrete blocks or forms, heavy stone masonry faces or walls, stacked gabions, or steel sheet piles; layers of unreinforced concrete only centimeters thick cannot withstand erosion by large lahars (e.g., Paguican et al. 2009). However, if a well-revetted dike is overtopped, rapid erosion of the unarmored back side of the dike can quickly cause dike failure and breaching nontheless (Paguican et al. 2009) (Case study 3). In Japan, where probably more of these structures are constructed than anywhere else in the world, a major design criterion is that their orientation should ideally be less than 45° to the expected attack angle of a lahar to minimize overtopping and erosional damage (Ohsumi Works Office 1995). Sometimes emergency levees are constructed without revetments, but this usually results in unsatisfactory performance, sometimes with disastrous results (Case study 1).

Case study 3. Lahar and sediment containment and exclusion structures

In the months following the May 18, 1980 eruption of Mount St. Helens (Washington, USA), the U.S. Army Corps of Engineers (USACE) built a rock-cored earthen sediment-retention structure (N-1 sediment dam) as a short-term emergency measure to try to hold back lahars and some of the volcanic sediment expected to wash downstream (Willingham 2005*). The structure had two spillways made of rock-filled gabions covered with concrete mortar; it was 1,860 m long and 13 m high, and was located approximately 28 km downstream of the volcano. Neither the upstream nor downstream face of the dam was revetted. Within a month of completion, one of the spillways was damaged by high flow. That spillway was repaired and resurfaced with roller-compacted concrete. In slightly more than a year, the N-1 debris basin filled with about 17 million m*^{3} *of sediment, and the bed of the river aggraded nearly 10 meters. During the summer of 1981, the USACE excavated 7.4 million m*^{3} *from the debris basin, but the river replaced that amount and added more during the following winter. The dam was overtopped and breached in quick succession by two events in early 1982—a major winter flood in February and an eruption-triggered, 10-million-m*^{3} *lahar in March. Overtopping caused deep erosion of the downstream face of the dam at several points, which led to breaching. Even the reinforced, roller-compacted concrete spillways were scoured tens of centimeters, exposing ends of steel reinforcing bars that were abraded to dagger-like sharpness. The extensive damage to the dam and the limited capacity of the catch basin resulted in abandonment of the project (Pierson and Scott* 1985*; Willingham* 2005*).*

Several years later, the USACE started construction of another larger sediment-containment dam (the Sediment Retention Structure or SRS), which was completed in 1989 and further modified in 2012 (Figure 8a). It was built 9 km downstream of the original N-1 structure. In addition to trapping fluvial sediment, it was also designed to intercept and contain a possible future lahar (estimated peak discharge up to 6000 m^3*/s) from a potential breakout from Castle Lake. The SRS is a concrete-faced (upstream face), rock-cored, earthen dam about 550 m long, 56 m high, 21 m wide at the crest, and has a 122-m-wide armored spillway; its upstream catch basin is 13 km*^{2} *in area and was designed to hold back about 200 million m*^{3} *of sediment (USACE—Portland District,*

Figure 8 Examples of large-scale lahar containment and exclusion structures. (a) The Sediment Retention Structure (SRS) downstream of Mount St. Helens, USA, built specifically to contain potential lahars and eroded sediment (USGS photo by Adam Mosbrucker, 11 Nov 2012); the volcano is visible on the horizon on the left side of the image. **(b)** Mud Mountain Dam with a large concrete overflow spillway on the White River downstream of Mount Rainier (USA), (Stein 2001). It was built as a flood-control structure but it also may function as a trap for at least part of future lahars because little water is normally impounded behind the dam (photo courtesy of U.S. Army Corps of Engineers). **(c)** Exclusion levees surrounding the Drift River oil terminal on an alluvial plain approximately 40 km downstream of Redoubt Volcano, Alaska (USGS photo by Chris Waythomas, 4 Apr 2009).

unpublished data). By 2005, infilled sediment reached the level of the spillway, and river bed-load sediment began to pass through the spillway, even though the catch basin was filled only to 40% of estimated capacity. After 2005, only a fraction of the river's sediment load was being intercepted, so raising of the spillway by an additional 2.1 m was completed in 2012 and experiments are continuing to induce greater sediment deposition in the upstream basin. The SRS has performed an important function in preventing large amounts of sediment from reaching and filling a reach of the Cowlitz River farther downstream and thus preventing serious seasonal flooding in communities along that river. No attempt has yet been made to excavate and remove sediment from behind the SRS.

An example of a lahar exclusion structure is the levee system enclosing the Drift River Oil Terminal (DROT) in Alaska (USA), which is a cluster of seven oil storage tanks that receive crude oil from Cook Inlet oil wells via a pipeline, plus some buildings and an air strip (Dorava and Meyer 1994*; Waythomas et al.* 2013*). The DROT is located on the broad, low-gradient flood plain at the mouth of the Drift River, about 40 km downstream of Redoubt Volcano (Figure 8c). Oil is pumped from these tanks to tankers anchored about 1.5 km offshore at a pumping-station platform. A U-shaped levee enclosure (built around the DROT but open at the downstream end) was raised to a height of 8 m following the 1989–1990 eruption, in order to increase protection of the facility from lahars and flooding. During both the 1989–1990 and 2009 eruptions of Redoubt, lahars were generated that flowed (at low velocity) up against the levees. Minor overtopping of the levees and backflow up from the open end caused some damage and periodic closure of the facility. The river bed aggraded to within 0.5 m of the levee crest in 2009, and the levees were thereafter reinforced and raised higher. The levee enclosure basically did its job, though it would have been more effective if the enclosure had been complete (on four sides).*

Lahar containment or exclusion

Various structures can prevent lahars from reaching farther downstream, or seal off and protect critical areas while surrounding terrain is inundated. Sediment retention dams (Figure 8a) or containment dikes are used hold back as much sediment as possible but not necessarily water. To contain lahars, they must be constructed to withstand erosion and possible undercutting along their lateral margins and be tall enough to avoid overtopping. Under-design of these structures or inadequate removal of trapped sediment behind them can result in eventual overtopping and failure of the structure (e.g., Paguican et al. 2009; Case study 3). The area upstream of a barrier where sediment is intended to accumulate is usually termed the catch basin or debris basin. Small excavated catch basins are also termed sand pockets. Such accumulation zones are typically designed to accommodate sediment from multiple flow events, and large tracts of land may be needed for this purpose. However, acquisition of land for this purpose can be problematic (Case study 1). If the design capacity is not large enough to accommodate all of the sediment expected to wash into a catch basin, provisions must be made to regularly excavate and remove accumulated sediment.

In addition to specially built lahar-related structures, pre-existing dams can sometimes be useful in containing all or most of the debris in a lahar (Figure 8b). Dams built for flood control or for impoundment of water for hydroelectric power generation or water supply can contain lahars and prevent them from reaching downstream areas, as long as (a) sufficient excess storage capacity exists behind the dam to accommodate the lahar volume, and (b) there is no danger of lahar-induced spillover at the dam in a way that could compromise dam integrity and lead to dam failure. Reservoir drawdown during volcanic activity might be necessary to ensure sufficient storage capacity to trap a lahar. This was done at Swift Reservoir on the south side of Mount St. Helens prior to the 1980 eruption, allowing it to successfully contain two lahars totaling about 14 million m^3 (Pierson 1985).

Exclusion dikes can enclose and protect valuable infrastructure, as was done in 1989–1990 and 2009 to protect oil storage tanks at the mouth of the Drift River, Alaska, from lahars and volcanic floods originating from Redoubt Volcano (Dorava and Meyer 1994; Waythomas et al. 2013) (Case study 3; Figure 8c). Diked enclosures may be a more appropriate strategy than channelization, diversion, or deflection in areas with low relief where low channel gradients encourage lahar deposition and where areas to be protected are small relative to the amount of channelization or diking that otherwise would be required.

Check dams to control lahar discharge and erosion

Some structures are built to slow down or weaken lahars as they flow down a channel. Check dams are low, ruggedly built dams that act as flow impediments in relatively steep stream channels (Figures 9 and 10). They have four functional roles: (a) to prevent or inhibit downcutting of the channel, which in turn inhibits erosion and entrainment of additional sediment; (b) to trap and retain some of a lahar's sediment, thereby decreasing its volume; (c) to add drop structures to the channel profile in order to dissipate energy and slow downstream progress of the lahar; and (d) to induce deposition in lower-gradient reaches between dams (Smart 1981; Baldwin et al. 1987; Hungr et al. 1987; Johnson and McCuen 1989;

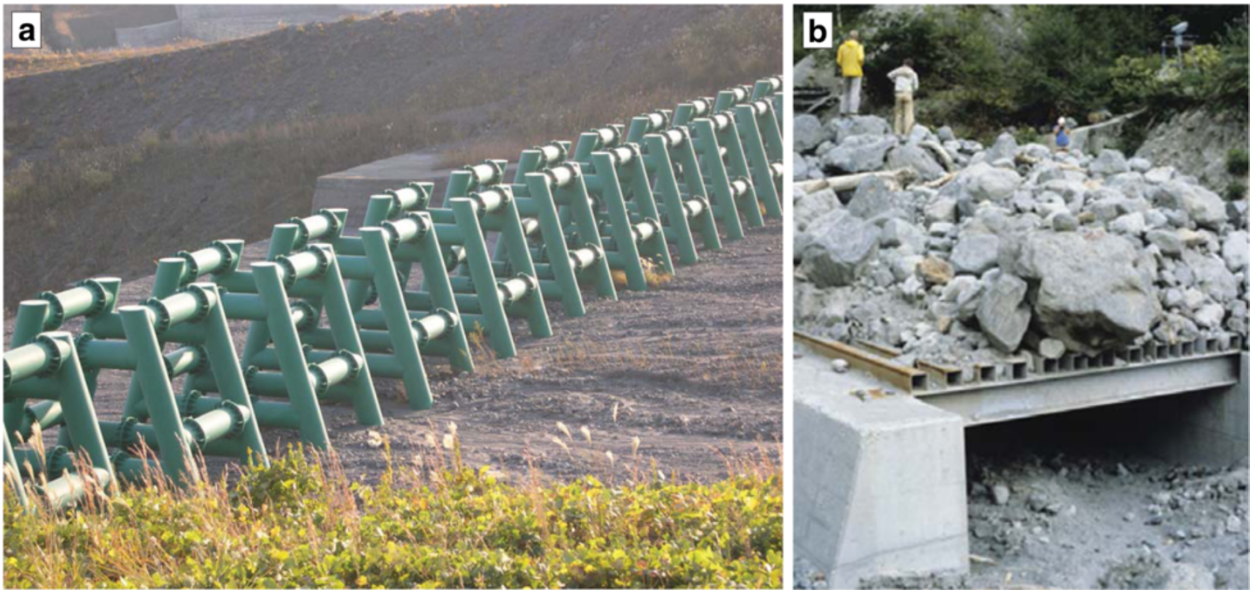

Figure 9 Examples of permeable lahar flow-control structures. (a) Steel-pipe slit dam at Mount Unzen, Japan. **(b)** Drain-board screen at Mount Yakedake, Japan, after having stopped the bouldery head of a small debris-flow lahar. USGS photos by TCP.

Armanini and Larcher 2001; Chanson 2004; Huebl and Fiebiger 2005; deWolfe et al. 2008).

Check dams are commonly built in arrays of tens to hundreds of closely spaced dams that give a channel a stair-step longitudinal profile. Very low check dams are also called stepped weirs and are commonly constructed between larger check dams to act as hydraulic roughness elements for large flows (Chanson 2004). A variety of styles and sizes of check dams have been developed, but fall into two basic categories: permeable or impermeable.

Permeable slit dams, debris racks, and open-grid dams (Figure 9a) are constructed of heavy tubular steel or structural steel beams, commonly with masonry bases and wing walls. Such structures are designed to act as coarse sieves, catching and retaining boulder-size sediment in a lahar but allowing finer material and water to pass through with depleted energy and mass. In addition to reducing the velocity of flows as they pass through, these dams also attenuate peak discharge. The effect is most pronounced on granular (clay-poor) debris-flow lahars that typically have steep, boulder-laden flow fronts. A variation on these vertically oriented structures is the drain-board screen (Azakami 1989) (Figure 9b), which is a horizontally oriented steel grate or grill that performs the same sieving function for boulders as permeable dams when a lahar passes over the top of the grate, retaining coarse clasts while water and finer sediment drop down through the grate. Because of their orientation, these structures do

Figure 10 Examples of impermeable lahar flow- and erosion-control structures. (a) Series of sheet-pile check dams with masonry aprons at Mount Usu, Japan. **(b)** Dam of rock-filled steel cribs at Mount Ontake, Japan. USGS photos by TCP.

not have to withstand the same high lateral forces as the upright permeable dams.

Impermeable check dams are composed of solid concrete, concrete with a packed earthen core, or steel cribs or gabion baskets filled with rocks and gravel (Figure 10). They may have small slits or pipes to allow exfiltration of water through the dam, in order to minimize impoundment of water. Gabions are used widely in the developing world because of their low construction costs—gravel fill often can be excavated locally from the channel bed, their permeability, and their flexibility, which can allow a dam to sag without complete failure if undermined by erosion. The crests of impermeable check dams commonly slope toward the center of the dam, where a notch or spillway is constructed, in order to direct streamflow or lahars over the dam onto a thick concrete apron extending downstream to protect the toe of the dam from erosion. Concrete sills or roughness elements commonly are placed at the downstream ends of aprons to further slow the flow that passes over the main dam. If upstream catch basins fill to capacity with sediment, check-dam functions are then limited to *a*, *c*, and *d* noted above, but full functionality can be restored if catch basins are regularly excavated.

Hazard warning

Where communities already occupy lahar hazard zones or where transient populations move in and out, a lahar warning system can be an option that would allow an at-risk population to safely evacuate prior to lahar arrival, whether or not used in conjunction with engineered protection structures. Lahar warning systems can minimize fatalities, but they are not practical in every situation. In cases where populations are situated close to a lahar source area, there simply may be little or no time for a timely warning to be issued and for people to receive it in time to evacuate (Cardona 1997; Pierson 1998; Leonard et al. 2008). Timing is even more challenging at volcanoes where lahars unrelated to ongoing or recent volcanic activity can occur—where volcanic edifices are weakened by hydrothermal alteration, for example, because lahar occurrence generally would not be anticipated. The decision of whether or not to install a warning system should also consider the long-term and ongoing needs for sustaining coordination and communication among the many organizations and individuals involved, regularly maintaining and testing the instrumentation, and keeping at-risk populations informed and prepared, especially where populations are transient.

Lahar warning systems have three basic components: (1) sensors or observers to detect an approaching lahar; (2) data acquisition, transmission, and evaluation systems to transfer and evaluate data to determine if there really is an approaching lahar; and (3) alert-notification systems to inform people that a lahar is coming. The spectrum of ways to accomplish these functions can range from simple 'low-tech' approaches largely involving human observers to more sophisticated 'high-tech' systems (Figure 11). In addition to these basic components that warn of an approaching lahar, integrated (often called "end-to-end") warning systems also include components that not only warn people but prepare them and lead them to respond proactively and to assume personal responsibility for evacuating. These additional components include pre-event planning and preparation; mechanisms to formulate and target appropriate warning messages; effective outreach to at-risk populations so that they understand what to do when a warning is received; establishment of evacuation routes and safe

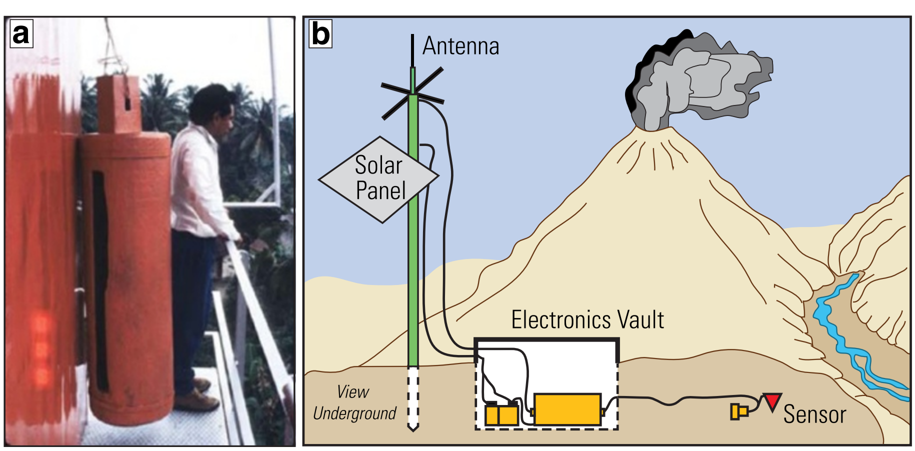

Figure 11 Examples of "low-tech" and "high-tech" lahar detection systems. (a) Human observer in lahar observation tower along a river that originates on Merapi volcano, Indonesia; observer strikes the large hanging steel drum ("tong-tong") with a steel bar after seeing or hearing an approaching lahar. USGS photo by TCP. **(b)** Schematic diagram of an acoustic flow monitor (AFM)—a sensor that detects ground vibrations generated by an approaching lahar, then telemeters that information in real time to a base station, where the signal is evaluated and a decision is made on whether or not to issue an alarm (see LaHusen 2005).

refuges that can be reached (generally on foot) before lahar arrival; and evacuation exercises with follow-up evaluation (Mileti and Sorenson 1990; Basher 2006; Leonard et al. 2008).

Once a warning system becomes operational and depended upon, there must be sufficient ongoing funding and institutional commitment to continue operation indefinitely and to regularly educate and train the at-risk population. This is important because termination of a warning system while the hazard still exists may involve liability and ethical issues. Long-term operation costs include not only those for the normal maintenance of warning-system components, but also replacement costs if components are vandalized or stolen and, where necessary, costs for providing instrument-site security.

Volcano scientists play important roles, not only in developing or deploying warning system instrumentation, but also in training emergency managers to confidently interpret scientific and technical information from the monitoring systems. Scientists also can help to develop clear warning messages that are appropriate and understandable by affected populations (Mileti and Sorenson 1990). Although lahar warning systems can issue false alarms, research shows that the "cry wolf" syndrome does not develop within affected populations as long as people understand the hazard and are later told about the possible reasons why a false warning was issued (Mileti and Sorenson 1990; Haynes et al. 2008).

'Low-Tech' warning systems

In some developing countries, effective low-tech warning systems employ human observers to alert threatened populations. Observers can be positioned at safe vantage points within view of lahar-prone river channels at times when flows have a high likelihood of occurring, such as during ongoing eruptions and during and following intense rainfall, particularly within the first few years after eruptions (de Bélizal et al. 2013; Stone et al. 2014). Observers stationed near lahar source areas are in a position to see or hear localized convection-cell rain storms that can trigger lahars, and human hearing can be very effective in detecting the approaching lahars themselves, often minutes before they come into view. The low-frequency rumbling sound caused by large boulders grinding against the river bed can carry hundreds or thousands of meters through the air and through the ground—a sound that is unmistakable to a trained observer. For example, a relatively small lahar occurring recently at Mount Shasta, California, sounded "like a freight train barreling down the canyon" and at times "like a thunder rumble" to a U.S. Forest Service climbing ranger (Barboza 2014).

Once a lahar is detected, an observer can quickly issue an alert directly (by drum, siren, cellular phone, handheld radio, etc.) to people living nearby (Figure 11a). This basic approach to lahar detection may be preferable where there is limited technical or financial capacity for maintaining sensors and other electronic equipment, where there are safe and accessible observation points, where there is high likelihood of expensive instruments being damaged or stolen without someone to guard them, where environmental conditions are challenging, or where electrical power and telecommunications are unreliable. Lahar detection by human observers is not immune to failure, however. Reliability is a function of the trustworthiness and alertness of the observers, their level of training, and the effectiveness of the alert notification method.

Automated telemetered warning systems

Automated electronic warning systems can be used to detect approaching lahars and telemeter alerts in areas where electrical power, technical support capabilities, and funding are more assured. Systems also can be designed to detect anomalous rainfall or rapid snowmelt that could trigger lahars, sense incipient motion of an unstable rock mass or lake-impounding natural dam, or detect an eruption that could trigger a lahar (Marcial et al. 1996; Sherburn and Bryan 1999; LaHusen 2005; Manville and Cronin 2007; Leonard et al. 2008; USGS 2013) (Figure 11b). In order for data from any of these various sensors to be useful for alert notification, they must be transmitted from remote sites in real time to a receiving station. Transmission can be accomplished by either ground-based or satellite-based radio telemetry (LaHusen 2005) or cellular phone (Liu and Chen 2003). Alert notifications can occur either automatically when some threshold in the level of the detection signal is exceeded, or an intermediate step can involve emergency management personnel, who verify and validate the detection signal before an alert is issued. Coordination among multiple agencies is critical to the success of an automated system, because hardware and software development of the sensor and the data acquisition/transmission systems are typically handled by physical scientists and engineers, whereas the development, operation, and maintenance of warning systems are typically managed by emergency managers and law-enforcement personnel (Case study 4).

Case study 4. The Mount Rainier lahar warning system

A significant volume of rock on the upper west flank of Mount Rainier (USA) has been extensively weakened (60–80% loss in unconfined strength) by hydrothermal alteration and is unstable (Watters et al. 2000*; Finn et al.* 2001*; John et al.* 2008*). A lahar warning system was developed by the U.S. Geological Survey and Pierce County (Washington) to detect potential lahar initiation from this sector, and it was installed in 1995 by USGS and Pierce County personnel in the Carbon and Puyallup River valleys downstream of the weak and oversteepened rock mass (USGS* 2013*). The system is designed to warn tens* *of thousands of people who live in the downstream lahar hazard zone of an approaching lahar. Affected communities are situated from 40 to 80 km downstream of the volcano and could have from 12 minutes to 2 hours, depending on location, to evacuate after receiving a warning message. Since installation, the warning system has been maintained and operated by the Pierce County Department of Emergency Management, in collaboration with the Washington State Emergency Management Division.*

The system comprises specialized seismic sensors capable of detecting ground vibrations within a frequency range typical of lahars (30–80 Hz), a ground-based radio telemetry system for detection-signal transmission, and a combination of sirens, direct notification, and the Emergency Alert System (EAS) that utilizes NOAA weather radios for warning message dissemination (LaHusen 2005*; USGS* 2013*). County and state emergency-management agencies and city and county law-enforcement agencies collectively have responsibility for verifying and validating alerts from the sensors, activating warning sirens, and sending warning messages.*

Collaboration between all the agencies involved in lahar hazard warning and risk reduction at Mount Rainier is fostered by regular meetings of the "Mount Rainier Work Group". Such lahar warning systems require ongoing collaboration between scientists and emergency management officials, as well as regular maintenance and testing. Members of the at-risk population (including schools) have been assigned evacuation routes, have been informed about what to do when a warning message is received, and regularly participate in evacuation drills (Figure 3g).

Warning message development and delivery

In the simplest warning systems, warning messages are delivered only as simple audible signals (drums, sirens, whistles, etc.), and the affected population must be informed beforehand about what the signals mean and what the appropriate response should be. In more sophisticated systems, incident-specific alert messages can be delivered to large populations simultaneously by cellular phone, the Internet, radio, or television. In these cases, the alert must convey a definitive and unambiguous message that effectively prompts individuals to take protective actions. Several factors influence the effectiveness of a warning message, including the content and style of the message, the type and number of dissemination channels, the number and pattern of warning statements, and the credibility of the warning source (Mileti and Sorenson 1990).

Warning messages should be specific, consistent, certain, clear, and accurate (Mileti and Sorenson 1990). To ensure credibility, message content should include a description of the hazard and how it poses a threat to people, guidance on what to do to maximize personal safety in the face of impending danger, location of the hazard, the amount of time people have to take action, and the source of the warning. The more specific a warning message is, the more likely the receiver is to accept the warning (Cola 1996; Greene et al. 1981). Emergency warnings without sufficient detail create information voids, and the affected population may then rely on ill-informed media commentators, friends, neighbors, or personal bias and perceptions to fill this void (Mileti and Sorenson 1990). Input from volcano scientists is critical for some of this detail and specificity.

Both credibility and consistency of the warning message are important. At-risk populations commonly receive information from informal sources (for example, the media, friends, social media), sometimes more quickly than through various official channels during a crisis (Mileti 1999; Leonard et al. 2008; Dillman et al. 1982; Mileti and Sorenson 1990; Parker and Handmer 1998; Mei et al. 2013). For example, 40–60% of people in the vicinity of Mount St. Helens first received informal notification of the 1980 eruption (Perry and Greene 1983; Perry 1985). The proliferation of informal information channels today with the Internet and social media can benefit the warning dissemination process, because individuals are more likely to respond to a warning if it is confirmed by multiple sources (Cola 1996; Mileti and Sorenson 1990). But multiple sources become problematic if they advance conflicting information, causing individuals to become confused. Therefore, challenges for emergency managers and scientists are to keep reliable information flowing quickly and to maintain consistent messages, both during and after an emergency. Joint information centers can ensure that (a) there is consistency in official warning statements among multiple scientific and emergency-management agencies, (b) easy access is provided for the media to the official information and to experts who can explain it, and (c) the effectiveness of warning messages is monitored (Mileti and Sorenson 1990; Driedger et al. 2008).

Evacuation training

Warnings are given so that people in a lahar flow path can move quickly out of harm's way. Sheltering in place is generally not a viable option. The lives of at-risk individuals may depend on understanding that they are living in, working in, driving through, or visiting a lahar hazard zone, as well as understanding what to do when they receive a warning (Mileti and Sorenson 1990; Leonard, et al. 2008). As the world witnessed in the 1985 Nevado del Ruiz disaster (Voight 1990) (Case study 5), warnings that a lahar was bearing down on their town were not able to prevent catastrophic loss of life, because the warnings were issued without the population's understanding of the risk or how they should respond. To increase the likelihood of successful evacuations, scientists should encourage and help lead hazard-response exercises and evacuation drills, especially in areas with short time windows for evacuating hazard zones. These exercises and drills provide emergency managers the opportunity to identify weaknesses in the warning–evacuation process and to minimize potential delays that could result from confusion, insufficient information, or lack of understanding on what to do. They also provide scientists with a platform for discussing past catastrophes and the potential for future events. Holding an annual table-top exercise or community-wide evacuation drill on the anniversary of a past disaster can help to institutionalize and personalize the memory of past events, an important step if new community members are to take these threats seriously. A well-educated and trained community that possesses information about where they will get information and what emergency actions to take is less likely to be confused by warning messages, to resist evacuation orders, or to blame officials for ordering an evacuation when a catastrophic event fails to occur (e.g., Cardona 1997). The goal for scientists and emergency managers is to create a "culture of safety" (cf., Wisner et al. 2004, p. 372) where at-risk individuals understand potential hazards, take personal responsibility for reducing their risks, understand how to respond to an event, and realize that lessening of risks requires actions from all levels of a community and government.

Case study 5. The Nevado del Ruiz disaster

The 1985 Nevado del Ruiz lahar disaster, which cost approximately 21,000 lives in the town of Armero, Colombia (Figure 1a), is an excellent case study of the complexities that can lead to ineffective evacuation after warning messages are broadcast, poor emergency response, and a haphazard disaster recovery (Voight 1990*; Hall* 1992*). In post-event analyses, it was generally concluded that the Ruiz catastrophe was the result of cumulative human and bureaucratic errors, including lack of knowledge, misunderstanding and misjudgment of the hazard, indecision, and even political barriers to effective communication, rather than inadequate science or technical difficulties. Other factors contributing to the catastrophe included evacuation plans that had been prepared but not shared with the public, poorly equipped emergency management authorities, the absence of agreed-upon decision-making processes, and uncertainty about the pre-event hazard assessments that made public officials reluctant to issue an early evacuation order because of the potential economic and political costs. The hazard maps produced by scientists for Nevado del Ruiz prior to the eruption were highly accurate in their predictions of where lahars could go, but they were published only about a month before the disaster, giving little time for assimilation and responsive action by the emergency managers. Furthermore, production of the maps did not lead to effective risk communication, because the scientists who made the maps generally did not engage in conveying that risk information in understandable terms to officials and the public. Scientists may prepare excellent hazard assessments and maps, but unless they participate fully in conveying hazard information to officials and the public in ways that are understandable, disasters can still happen (Voight* 1990*; Hall* 1992*).*

Hazard response and recovery planning

The first three risk-reduction strategies focus on minimizing losses through actions taken before a lahar occurs, but this fourth strategy determines the effectiveness of the immediate emergency response and the longer-term course of recovery after a lahar has occurred, which together define a community's resilience. Hazard response includes the rescue, emergency care, sheltering, and feeding of displaced persons, which is facilitated by a robust incident command system. Such a system could range from coordinated communication in a small village to a structured multi-agency protocol, such as NIMS (National Incident Management System) in the United States (FEMA 2014). Recovery involves the reestablishment of permanent housing, infrastructure, essential services, and economic viability in the community.

Response to a lahar that has impacted a populated area can be difficult. Lahars present first responders, search-and-rescue teams, and disaster-management officials with challenges unlike some other disasters: (a) the area of impact can be extensive and locally covered by debris from crushed buildings and other structures; (b) the degree of impact is generally greatest toward the center of the impact zone and less along the edges; (c) lahars can transport victims and structures long distances from their initial locations; (d) survivors may be difficult to locate; (e) fresh lahar deposits commonly stay liquefied (like quicksand) for days to weeks, and upstream river flow may cut through a debris field, so that access to victims may be limited to hovering helicopters, small boats, or rescuers on the ground being confined to walking on logs or sheet of plywood (Figure 12); (f) once located, victims can be difficult to extract from the mud; and (g) critical facilities (hospitals, police and fire stations, etc.) may be inaccessible, damaged, or destroyed. These challenges can be critical, because the time window is small for getting injured victims to medical care, and uninjured victims trapped in liquefied mud can quickly become hypothermic. To minimize fatalities from a lahar, communities in hazard-prone areas should develop realistic rescue and response plans that are understood by all individuals and responsible agencies. In addition to developing search and rescue tactics, such plans should include identification of refuge zones, logistical resources, emergency social services, and security personnel that will be

Figure 12 Examples of challenges to rescue and recovery where thick liquefied mud and debris have flowed into a populated area—the Highway 530 (Oso, Washington) landslide disaster of 22 March 2014. Soft mud can preclude rescue of victims by responders on the ground, particularly in the first hours or days following a lahar. **(a)** Rescuer being lowered by helicopter to an area where ground is too soft to reach on foot (copyrighted AP photo by Dan Bates, used with permission). **(b)** Rescuer searching for victims using an inflatable boat, because flooding from backed-up river inundated part of the debris field (copyrighted AP photo by Elaine Thompson, used with permission).

needed to establish emergency shelters and for survivors at those shelters, and for site access control and security (see UNDRO 1985, for an emergency plan example). Scientists can support emergency managers and public officials in the aftermath of a catastrophic event by assessing the likelihood of future lahars and floods, the suitability of areas for relief operations, and the evolving stability of lahar deposits.

Proper shelter planning is critical to minimize the potential for additional victims. Poor planning of emergency shelters and camps can create new disaster victims due to disease outbreaks and malnutrition if shelter is inadequate and timely supply of food, clean water, and medicine does not occur. Shelter planning should also take into account the quality of life and livelihoods for displaced populations. For example, 50 to 70% of people displaced by the 2010 eruption of Mt. Merapi (Indonesia) ignored evacuation orders and consistently returned (in some cases daily) to danger zones during the crisis because of the need to care for livestock and to check on possessions (Mei et al. 2013). The lack of activities and work programs in the evacuation camps also can result in people leaving the shelters. In addition, if schools are used as shelters, then public education suffers because school buildings are occupied by evacuees. In countries with limited relief resources, people may be better served if extended families can temporarily house impacted relatives during emergencies. Community leaders, with assistance from scientists, can encourage residents to develop their own evacuation and relocation strategies.

Following an initial disaster response, recovery becomes the next goal. Restoring community functions is typically a top priority in the aftermath of an extreme event such as a lahar, but quick reconstruction may not be possible if key infrastructure, industrial parks, downtown cores of communities, and extensive areas of residential housing are buried or swept away (Tobin and Whiteford 2002). Pre-event recovery planning, however, can allow resilient communities to recover more quickly by prioritizing the building of redundant and diversified back-up systems, services, and infrastructure into their communities beforehand. For transportation networks for example, this could mean having multiple routes to critical or essential facilities, predetermined appropriate sites for helipads or temporary airstrips, and storage sites for heavy equipment—all located outside of the hazard zone. Scientists can assist the development of recovery plans by providing advice on where future commercial, residential, and industrial districts could be located outside of hazard zones. A well thought-out recovery plan also provides an impacted community with opportunities for the established social fabric of a community to be maintained, for relocation to a safer site, and for comprehensive redevelopment that avoids haphazard or fragmented future growth.

Resettlement following a disaster is not simply a matter of rebuilding homes and infrastructure at a safer site. The quality of life, means of making a living, and social needs and networks of displaced populations must be recognized for resettlement to be successful, and residents must be part of the planning process. For example, Usamah and Haynes (2012) document low occupation rates of (and minimal owner investment in) government-provided housing at permanent relocation sites two years after the Mayon volcano (Philippines) eruption in 2006. They attribute this to the lack of community planning participation, lack of appreciation of original house design and function (for example, metal roofs on new houses make them hotter during the day than traditional houses with palm-thatch roofs), delays in utility infrastructure, no public facilities such as religious centers and schools, few livelihood options, and little long-term community development. Although authorities and donors (and residents) were satisfied that the new housing was safer, interviewees felt the long-term objective of facilitating sustainable lives was ignored. A similar reluctance to participate in a resettlement program was found at Colima volcano (Mexico) for many of the same reasons (Gavilanes-Ruiz et al. 2009). Thus, community participation in long-term recovery planning is needed to ensure identification of the community's needs and the community's support.

Development of an effective recovery plan can ensure provision of a number of practical recovery needs. Those needs include: achievement of more appropriate land-use regulations, identification of funding sources for reconstruction, identification of resources and disposal sites for debris clearance, enlistment of economic support for recovering businesses, and adoption of new construction standards. Recovery plans help ensure that reconstruction after the event does not reoccupy a hazard zone or happen in an ad hoc fashion. Scientists can contribute to this planning process by (a) helping public officials visualize the probable physiographic, geologic, and hydrologic realities of a post-event landscape; and (b) identifying what post-event hazards would be relevant for the community.

Scientist roles in lahar risk reduction

All four of the basic strategies for lahar-hazard risk reduction—hazard avoidance, modification, warning, and response/recovery—require the input and judgment of volcano scientists, even though emergency managers and public officials have the responsibility for their planning and implementation. In addition, scientists play a critical role in educating emergency managers, public officials, and at-risk populations about lahar hazards. Specific ways that scientists can participate are discussed in the sections above.

Some scientists are uncomfortable participating in processes that are influenced (if not dominated) by social, economic, and political factors. However, risk managers cannot successfully manage natural threats to communities without involvement by scientists (Peterson 1988, 1996; Hall 1992; Haynes et al. 2008). Peterson (1988) goes as far to say that scientists have an ethical obligation to effectively share their knowledge to benefit society by making their knowledge understandable to non-scientists. Scientists can communicate hazard information to the public through formal and informal face-to-face meetings, through public presentations, and through the media. Qualities exhibited by scientists that enhance their trustworthiness in the eyes of the public are reliability (consistency and dependability in what they say), competence (having the skills and ability to do the job), openness (having a relaxed, straightforward attitude and being able to mix well and become 'part of the community'), and integrity (having an impartial and independent stance) (Pielke 2007; Haynes et al. 2008). Yet there is always a potential for friction and other distractions during the stressful time of a volcano crisis, and scientists should recognize and try to avoid the various problems related to personal and institutional interactions that have plagued the credibility of scientists during past volcanic crisis responses, such as communications breakdowns and disputes among scientists (with different messages coming from different scientists), scientists advocating for particular mitigation strategies, scientists avoiding or "talking down" to the public, poor scientific leadership, failure to recognize cultural differences between themselves and affected populations, and failure to share information and scarce resources (Newhall et al. 1999).

Effective lahar-hazard risk reduction cannot occur unless the hazard and its attendant risks are recognized by authorities and the public, and this recognition is affected by the willingness and ability of scientists to communicate hazards information (Peterson 1988). The contributions of scientists will be effective if they are willing to embrace their educational, interpretive, and advisory roles, to work in partnership with officials and the public, and to be sensitive to the cultural norms of the society in which they are working. Scientists must be willing and able to participate in community events, hone skills related to public speaking, work with the media, and work one-on-one with community leaders. As Newhall et al. (1999) state, the guiding principle for scientists during volcanic crises should be to promote public safety and welfare. This principle extends to non-crisis situations, as well, and scientists can and should work with officials and the public frequently to lessen the risk from future lahars. In short, lahar-hazard risk reduction cannot be effectively accomplished without the active, impartial involvement of qualified scientists.

Consent

Written informed consent was obtained from individuals whose faces are recognizable in photographs appearing in Figure 3. Blanket permission was obtained for the students shown in Figure 3g from the Superintendent of the Orting School District.

Abbreviations

AP: Associated Press; DROT: Drift River Oil Terminal (Alaska); IAVCEI: International Association of Volcanology and Chemistry of Earth's Interior; NOAA: National Oceanic and Atmospheric Administration (USA); OFDA: Office of Foreign Disaster Assistance; SRS: Sediment Retention Structure; UNDRO: United Nations Disaster Relief Organization; USACE: U.S. Army Corps of Engineers; USAID: U.S. Agency for International Development; USGS: U.S. Geological Survey.

Competing interests

The authors declare that they have no competing interests.

Authors' contributions

TCP developed the risk-reduction strategy categorization, evaluated the effectiveness of many of the strategies, and wrote approximately 60% of the manuscript. NJW summarized the ways that community vulnerability and risk reduction can be applied to lahar hazards, and he wrote approximately 40% of the manuscript. CLD edited and revised an early draft of the section on hazard and risk education. This section is in large part a distillation of CLD's findings on how hazards information can be communicated effectively and understandably. All authors read and approved the final manuscript.

Authors' information

TCP is an expert on lahars and lahar hazards with the U.S. Geological Survey Volcano Science Center. He has personally observed and advised on the effectiveness of various lahar risk-reduction strategies in various parts of the world.
NJW is an expert on natural hazard risk and vulnerability reduction and on how hazards information affects responses of officials and at-risk populations. He works extensively with vulnerable communities and is attached to the Western Geographic Science Center of the U.S. Geological Survey.
CLD is a specialist on volcano hazard communication and education for officials, emergency managers, and the public with the U.S. Geological Survey Volcano Science Center. She is extensively involved in developing training curricula and materials on hazards education topics for schools (teachers and students), emergency managers, national park visitors, and the media.

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Author details

[1]U.S. Geological Survey, Volcano Science Center, Cascades Volcano Observatory, 1300 S.E. Cardinal Court, Suite 100, Vancouver, WA 98683, USA. [2]U.S. Geological Survey, Western Geographic Science Center, 2130 SW 5th Ave., Portland, OR 97201, USA.

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