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Debris-flow impact, vulnerability, and response

P. M. Santi · K. Hewitt · D. F. VanDine · E. Barillas Cruz

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Abstract This paper calls attention to vulnerable groups that are disproportionately affected by smaller, less-publicized debris flow events and do not always receive the advantages of recent technical advances. The most vulnerable groups tend to be economically restricted to live in relatively inexpensive and more dangerous locations, are often forced to live in topographically cramped areas due to expansion and development, and have limited influence and power needed to bring about mitigative efforts. Technical issues have long been the focus for debris-flow hazard reduction, but the collective judgment of many of those working toward natural hazards reduction, especially in developing countries, is that socio-cultural issues are at least as important as technical choices on the effectiveness of hazard and risk-reduction efforts. This awareness may result in (1) selecting simple designs that use local materials, local construction techniques and skills, and that recognize limited financial means; (2) selecting mitigative methods that require minimal maintenance, can withstand exposure to vandalism and scavenging, and will minimize misappropriation of resources; and (3) capitalizing on local techniques of dealing with other hazards, such as flooding, earthquakes, and landslides. Because of the difficulty in predicting and controlling debris flows, it is useful if mitigative systems can employ multiple elements to enhance the chance of success. These can include: education of the local populace, avoidance and warning to the degree possible, and some combination of channelization and interception of debris. For watersheds disturbed by fire, logging, mining, or construction, hillside treatment can be added to the mitigative methods to reduce water flow and sediment transport. Examples provided in this paper show that these
mitigative systems can be tailored to fit widely varying socio-cultural settings, with different geological characteristics and different debris flow–triggering events.

Keywords Debris flow · Socio-cultural · Mitigation · Vulnerability

1 Introduction

Debris flows, regardless of whether they occur in developed or developing countries, typically strike quickly and without warning, and therefore can have severe consequences. They encompass a wide range of slope movement hazards, including mudflows, mudslides, rapid earth flows, hyperconcentrated flows, lahars, and debris torrents. Debris flows include some of the most destructive events associated with volcanic eruptions, hurricanes and earthquakes.

Those most vulnerable to debris flows tend to be subject to one or more of the following:

- economic restriction—those who are obliged to occupy dangerous sites because the sites are relatively inexpensive and they do not have the resources to relocate (Maskrey 1989; UNDP 2004);
- space restriction—those who live in topographically confined areas, especially as population or development activities demand expansion into more hazardous areas (Bankoff et al. 2004); and
- influence/power restriction—those too weak in socio-political power, or too small in numbers to influence mitigation and obtain protections (Enarson and Morrow 1998; Pelling 2003).

Hewitt (1997) found similar results from a review of worldwide earthquake impacts: those hardest hit by the hazards were the least wealthy and influential, living in unsafe houses, engaged in more dangerous activities, with limited options, and neglected in the crisis itself. He termed this situation a “disaster of social vulnerability”. For earthquakes, event magnitude tends to be a poor predictor of damage, because small earthquakes that affect vulnerable populations have greater consequences than large events in better-protected communities (Ozerdem and Jacoby 2006).

For the past several decades, the per capita wealth in both developed and developing countries has increased. At the same time, losses from natural disasters are reported to have increased rather dramatically, even though there is little evidence that natural hazards have changed substantially in rate of occurrence or magnitude (Etkin 1999; UNDP 2004; United Nations 2005; Munich Re 2009; EM-DAT 2010). During the same time period, the options for, and effectiveness of, natural hazard mitigation have increased. There is good reason to believe that modern planning, land use controls, environmental monitoring, structural and other safety measures have made life safer from natural hazards in many places. In other places, however, these controls are not as available or are not keeping pace with growing endangerment. In the areas where disasters actually occur, it is generally found that available mitigative and protective measures were absent. Furthermore, there is often a failure to meet established codes for the safe siting and structural safety of buildings; most obviously in the schools that have collapsed in a rash of recent earthquakes, or in the run-out zones of landslides (Degg 1992; Schuster et al. 2002; Hewitt 2007).

This paper calls attention to vulnerable populations who are disproportionately affected by smaller events and do not always receive the advantages of recent technical advances.
It reviews the socio-cultural aspects of natural hazards and identifies some appropriate debris-flow mitigative methods for both developed and developing countries. The paper is aimed at scientists and engineers that specialize in debris-flow studies and mitigation, natural hazard managers in both developed and developing countries, and those professionals from developed countries who apply their knowledge to developing countries. The paper seeks to provide a base of socio-cultural awareness for those who already have technical expertise and provides technical direction to those who already are socio-culturally aware.

2 Extent of the hazard

Debris flows are among the most frequently occurring of natural hazards, especially in mountainous, volcanic, semi-arid and sub-polar regions. Schuster et al. (2002) concluded that most casualties in catastrophic landslides in Latin America were due to “... high velocity debris avalanches and high-, to medium-velocity long-runout debris flows and mud flows.” Li (2004) reported many lethal and destructive debris flows in the mountains of China and placed them among the most severe sources of damage. Damage to the economy of the former USSR by “mudflows”, according to Gerasimov and Zvonkova (1974), “occupied” first place. Debris flows are rated among the most commonly reported hazards in the highland areas of New Zealand (Selby 1993). Nakano (1974) ranked “mudflows and rocky mudflows” high among the more damaging mass movements in the mountainous and hilly areas of Japan. Hewitt (2004) concluded that debris flows are the most widespread and frequent of destructive earth surface processes in the mountainous upper Indus Basin of Pakistan, Afghanistan and India. In the United States (USA) alone, landslides and debris flows annually cause 25–50 deaths and over $2 billion in damage (National Research Council 2004). Worldwide, reports range up to nearly 1,000 deaths per year due to landslides and debris flows (Dilley et al. 2005). Two of the most dangerous aspects of debris flows are their rapid onset and the significant distances between where they initiate and where they may eventually cause damage.

An important point to stress is that the greatest numbers of destructive debris flows worldwide are triggered as secondary hazards caused by other events. These other events include tropical cyclones and other severe storms, floods, earthquakes, volcanic eruptions, large landslides of which debris flows are an offshoot, rapid snow or ice melt, and sudden releases of water that has been ponded by vegetation, landslides and glacial processes. In exceptional cases, the losses may be directly attributed to debris flows, but more often they are lumped in with impacts of the primary natural hazard that triggered the event. In part, this explains why the overall toll and significance of debris flows tend to be underestimated and under-reported. For example, the UNDP (2004) global report found that losses attributed to four natural hazards were of overwhelming importance: earthquake, tropical cyclone, flood and drought. However, Hewitt (1997) showed that slope instability and landslides were identified with a large part of damages in at least half of some 250 earthquake disasters between 1959 and 1990. As a result, affected communities may be focused on other natural hazards when debris flows occur, or relief efforts may be directed elsewhere or over-stretched.

The case should not be overstated, but clearly landslides and debris flows are much greater sources of damage than reported in disaster news and statistics. Perhaps the important point is that, while little or nothing can be done to prevent the larger triggering events, much can be done to identify, avoid, mitigate or engineer the debris flow environment.
With respect to the scale of debris flow damages, including loss of life, a distinction must be made between relatively few events that are listed as ‘catastrophic losses’, and the vastly greater number of smaller, more localized events. The large events attract special attention, since they usually involve exceptional death tolls and destructiveness, and generally occur in larger communities. In the world’s mountain environments, however, frequent debris flows may be cumulatively just as devastating, but rarely get reported in the international press or disaster inventories.

The risks from debris flows for human activity are closely tied to landforms, surface and near-surface hydrology, and sediment availability. For example, long runout debris flows tend to follow well-defined paths and impact particular parts of the landscape, and in more arid lands, debris flows are closely associated with sediment fans (sometimes called alluvial fans).

Fans can be attractive places for human settlement because they contain aquifers and have relatively good soils and gentler slopes than the surrounding terrain. They tend to support population concentrations in the drier Eurasian lands, from the Atlas mountains of Morocco to the Hindu Kush, and in the arid southwest of the USA. Hazard levels are related to the nature of debris flow emergence from the watersheds above the fans, and channelization or shifting of channels. Thus, where fans are growing and aggrading, debris flows are likely to continually alter their paths across the fan—the natural process of fan-form development. Where stream incision and fan trenching are taking place, many debris flows will be channelized in gullies below the fan surface. These can be critical sites for protective measures.

Finally, it is important to recognize that the triggering mechanisms, incidence, and scale of debris flow events change over time. The controlling factors can include episodic events such as forest fires, severe storms, cold, droughts, and infestations. Major volcanic eruptions can re-set the conditions for debris flow initiation for decades or centuries. Climate changes can alter vegetation cover, hydrologic conditions in surficial materials, and the incidence of the extreme weather events that trigger debris flows. In mountains and at higher latitudes, changes in glacier cover, snowfall and permafrost can further alter meltwater events that can result in debris flows.

3 Socio-cultural conditions and natural hazards

Culture refers to that which creates, informs, sustains, and defines collective life. In one way or another, people engage, or fail to engage, with natural disasters through learned and shared perspectives and beliefs.

The process of understanding and responding to natural hazards depends upon socially defined perspectives, priorities, goals, economics and politics. Almost all important risk-reducing or enhancing actions are undertaken by, or depend upon, human institutions and the social order (Maskrey 1989). Furthermore, society’s concerns and expectations with respect to danger, including natural hazards, reflect and are integral to socio-cultural norms. If natural hazard response fails to recognize socio-cultural norms, it is likely the success of the response will be jeopardized. This concept has already entered natural hazard studies through the awareness that cultures treat persons differently according to age, gender, occupation, ethnic or some other status (Douglas and Wildavsky 1982; Oliver-Smith and Hoffman 2003). In this context, natural hazard prevention, emergency response and mitigation can be more challenging and less effective when professionals and agencies from one culture work in another that is quite different. It has been suggested that the
community itself, and not the scientists or the sociologists, is the most effective group at deciding which actions to take (Davies, in press).

In 2008, a global online conference was held on the topic of socio-cultural effects of natural hazards. Approximately 450 participants from over 70 countries participated. The conference resulted in a comprehensive overview of a broad range of socio-cultural issues associated with many types of natural hazards. Much of the summary report (ICIMOD 2009) related to debris flows.

Perhaps the most revealing consensus issue was that, regardless of how traditional cultures can create impediments, “the negative impact of interveners … who fail to behave appropriately toward communities at risk” can be more significant (ICIMOD 2009).

Other key points from the conference were:

- knowledge of natural hazards and methods of hazard and risk assessment and reduction is generally adequate; however, there can be unequal, inconsiderate, repressive or exploitative relations between those assisting and those being assisted;
- ties to the land and loyalty to ancestral history of residents can be more important than the risks from remaining in a hazardous location;
- trust in authorities is often lacking, for example, police can be brutal and government can be greedy or corrupt and mitigative tools, even tools such as maps, can be diverted to assist those in power; therefore, earning respect and trust of vulnerable residents is crucial;
- fatalism is frequently misconstrued as a helpless response to “acts of God,” as opposed to a coping mechanism;
- ethnocentrism and arrogance widen the gap between outside assistance and local residents;
- analytical, scientific approaches may not take into account much stronger socio-cultural values;
- outside assistance is typically concerned with macro-threats, while residents are concerned more about everyday micro-threats, such as livelihood, welfare and health;
- working through a translator can impede socio-cultural connection and, therefore, it is useful to team with someone from a socio-cultural background similar to those being assisted, and
- ethics and rights are paramount, but can be ignored by common natural hazard mitigation (Roussel 2003).

From this online conference, it appears that success stories shared several common themes:

- the best practical results are usually achieved when residents are given every opportunity to influence their safety priorities; and
- a socio-culturally sensitive approach is time consuming, but when the time is taken to understand another culture the results are more positive.

In light of the previous observations, several recommendations for progress in dealing with natural hazards were described in the summary report of the online conference (ICIMOD 2009), and are paraphrased as follows:

- natural hazards are not solely environmental and technical issues, but also socio-cultural issues;
- partnerships are needed to develop innovative solutions and to allow improved natural hazard reduction;
empowerment involves finding ways to increase power, resources, and participation of residents; and
involvement supports effective and sensitive socio-cultural respect and dialog to better understand the needs and priorities of residents.

4 General socio-cultural approaches to debris-flow mitigation

Based on existing debris-flow literature and practices, two general points regarding socio-cultural approaches to debris-flow mitigation are relevant. First, debris-flow studies seldom address how debris flows enter the lives and activities of residents. For instance, debris-flow studies and technical literature in the Himalayas focus on roads, especially highways, built in recent decades, primarily for military, commercial, and tourist traffic. Yet, debris-flow disasters in the region affect huge numbers of people in mountain communities nowhere near these roads.

Second, most debris-flow studies do not consider the knowledge and experience of non-geoscientists and local residents in places of concern. Looking again to the Himalayas, some villagers have a very good knowledge of how and where debris flows originate, how they behave, and have very practical ideas how to mitigate the associated hazards and risks. Regrettably, residents often accept outside assistance even when they know it is misinformed and misguided, because it can bring much-needed cash and jobs, albeit in some cases only to some. What these points indicate is that, even sound and well-intentioned initiatives to apply geotechnical knowledge are unlikely to lead to successful responses unless they recognize socio-cultural knowledge, norms, and conditions in the places of application.

In mountainous areas, debris flows are often secondary natural hazards, associated with or triggered by other natural hazards, for example, snow avalanches, glacial lake outburst floods, rain storms and natural dam breaks. Therefore, debris-flow studies should address all natural hazards, and the associated relative risks and socio-cultural issues. Indeed, natural hazards are often not the only hazards with which residents live.

For the livelihoods, communities and property of residents, debris-flow hazards and risk involve a series of conditions:

- exposure—location relative to the runout path;
- vulnerability—the extent and ways in which harm can occur to residents, property, and activities;
- resilience—response capacities and arrangements to warn, avoid, limit or recover from debris-flow hazards and risks;
- existing and possible active and passive mitigative measures (refer to Sect. 7); and
- the broader hazards and risks—how debris flows rank among the range of other hazards and risks, priorities in the society and the ways in which mitigation of other hazards and risks can reduce or aggravate debris-flow hazards and risks.

Each of these conditions helps define the overall debris-flow hazard and risk. Socially, they are interdependent, and their relative significance and mix can vary greatly within, as well as between, communities. Some or all of these conditions can be governed by conditions unrelated to natural hazards and/or the physical environment.

Exposure, for example, can be carefully managed by land-use constraints, but may be affected by socio-cultural issues that are dependent on employment, real estate values
(dangerous sites may be cheaper), forced migration and resettlement, and development schemes.

Vulnerability and resilience may depend more upon human factors, such as unenforced building codes or socio-cultural issues, than on geological factors. In rating vulnerability and resilience, it is usually better to base practical and ethical standards on who and what is safer in the same society, rather than preconceptions in the minds of disaster managers, or the potential benefits from outside assistance (Batista and Baas 2004). There may be useful measures of vulnerability and resilience, say, per capita income or a collection of variables like those used to measure poverty or economic disadvantage. However, it is a mistake to focus on monitoring or managing such indicators of vulnerability, rather than on improving the range of social conditions that create or magnify vulnerability (Sen 1981; Bohle 1993; Boetzen and Van den Bergh 2009). In both developed and developing countries, vulnerability may be trumped by political pressures to keep debris flow hazards from constraining economic development.

Mitigation can also depend upon other conditions having little or nothing to do with debris flows, such as

- state of knowledge of natural hazards or environmental change that can alter the severity of the hazards and risks;
- available and affordable technologies;
- choices among land uses driven by socio-cultural needs; and
- above all, institutional arrangements through which mitigation is accepted or rejected.

With these socio-cultural issues in mind, some common elements of debris-flow mitigation exist:

- mitigation can be implemented by local professionals or community leaders who may not be debris-flow specialists, and therefore “one size fits all” or simple designs have the best chance of being implemented appropriately;
- mitigation can be implemented with limited finances and utilizing local construction techniques and skills;
- mitigative elements may be vulnerable to vandalism, scavenging, and misappropriation of resources;
- there may be ranges in the ability to maintain the debris-flow mitigative elements; therefore, in some situations, “build and forget” designs or designs where obvious indications when maintenance is needed may be more successful;
- mountain communities may have a greater awareness of water floods than of debris flows, and their experience with water flood mitigation can be exploited, keeping in mind that debris-flow mitigation has many differences, and the mitigative measures should be viewed differently; and
- mitigation programs should be considered as systems incorporating several elements that will improve the overall success at reducing hazard and risk.

5 Examples of socio-cultural attitudes toward debris flows

Before reviewing debris-flows mitigative methods (Sect. 7) and examples of socio-culturally sensitive mitigative approaches (Sect. 8), it is worthwhile to review six severe debris-flow events (Sect. 6) and three examples of socio-cultural attitudes toward debris
flows (this section). It should be recognized, however, that it is easy to over-generalize attitudes, even within very specific socio-cultural regions.

5.1 Southern California, USA

There is a high level of awareness of debris flows and related hazards and risks in southern California. Events are frequent, press coverage is ample, and physical reminders abound, such as the presence of numerous debris catchment basins. The wildfire-debris flow sequence, in which dry-season wildfires are followed by wet-season debris flows, is common in southern California’s Mediterranean climate and is well recognized by the residents (Bustillo 2003). Scientifically, historical records of debris-flow activity are available for many drainages, hazard maps are common (for example, see Fig. 1), and critical rainfall intensity-duration thresholds have been established and are often referred in the press and used by natural hazard managers (for example, Malibu Surfside News 2008). Evacuation is not uncommon. Debris-flow hazard and risk awareness is also enhanced by general natural hazard awareness because the area also experiences recurrent earthquakes, landslides, and water floods. Safe ground is often nearby and easy to get to, except along constricted mountain roads.

Socio-culturally, the rule of law is quite strong and local law enforcement, National Guard, and governmental authorities are generally trusted and respected. There is an expectation that government will take care of residents during and after disasters (which is why the late and weak response to Hurricane Katrina was so upsetting to many). Science is also typically held in high regard, although sometimes an individual’s unique and

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**Fig. 1** Example debris-flow hazard (probability of occurrence) map published following a wildfire in southern California (from Cannon et al. 2010)
statistically rare personal experiences may trump scientific reason (engendering attitudes such as “I don’t wear a seatbelt because someone I know was killed in a car accident and the highway patrol said they would have lived if they didn’t have their seat belt on”). The area has excellent multiple communication options: very responsive television and radio news, reverse emergency telephone alert systems, and widespread instant electronic communication such as email. Compared to the rest of the world, southern California has an extensive resource network, which improves its ability and willingness to evacuate, to manage the hazards and risks, and to respond to debris-flow events.

The socio-culture also produces some difficulties for natural hazard management and response:

- southern California is a melting pot of numerous ethnic, racial, linguistic, economic, and educational groups, and therefore mitigative approaches must appeal to shared socio-cultural elements, or focus on geographically defined regions with narrower socio-cultural characteristics.
- American “individualism” can complicate natural hazard and risk responses; individual residents may balk at being forced to do things for their own good, and may refuse to evacuate or permanently relocate from high hazard and/or risk areas.
- residents can become complacent with time since the last disaster, or conversely they can reach “evacuation saturation” if too many false alarms are generated.
- confusion can result from blending scientifically supported and politically motivated responses. For example, reseeding of burned hillsides is a highly visible method of debris-flow and erosion-control that can placate residents; however, scientific studies have shown that such mitigation is not necessarily more effective than natural recovery (for example, Wagenbrenner et al. 2006; Geier-Hayes 1997; and Beyers 2004).

5.2 Upper Indus Basin, Pakistan

The sources, forms, incidence and impacts of debris flows in the Himalayan terrain of the Upper Indus basin are different and more diverse than those described in southern California. Fire, for example, is relatively unimportant compared to glacial activity, permafrost, snow avalanches, natural dam-break floods, and intense, local convective storms.

Debris flows, typically numbering in the hundreds or thousands annually, are probably the most widespread and frequent cause of death and property damage by any earth surface process in the region; a direct consequence of how prevailing forms of settlement, land use and other activities relate to regional landforms (Said 1994). On the other hand, debris flows are rarely the primary natural hazard that is reported nationally, let alone internationally. Like most landslides, most debris flows are associated with earthquakes, severe storms, and natural dam-break floods. In these cases, instead of one or a small number of localized debris flows, there may be dozens or hundreds that affect many communities and magnify the losses from other natural hazards.

For the region as a whole, debris flows are a year-round threat, due to the mountainous terrain and regional climatology. Local relief typically exceeds 4,000 m, and in some cases over 7,000 m. Most communities, arable land, roads and other infrastructure are located in the arid and semi-arid intermontane valley floors and lower slopes. The above hillsides are located in environments whose humidity increases with elevation. More than 80% of regional precipitation is snowfall and debris flows are often triggered after heavy snowfalls or where moisture is concentrated by snow avalanches in gullies, by glacial activity, by natural damming, or by intense summer rainstorms.
The higher elevation sources and downslope pathways of water are typically tapped for irrigation and other uses. Downslope sediment transfer, especially from debris flows, constructs the countless debris fans that are favored sites of communities and arable land. So the recurrent, destructive nature of debris flows is critically interwoven with many positive aspects of the region. As a result, it may be unreasonable to forego the use of areas prone to debris flows. However, risks may increase as the combination of environmental and socio-cultural change aggravates or changes socio-cultural priorities.

There are two main sets of risks: those to village communities and the few small towns in the region, and those that affect infrastructure, mainly roads and especially the all-weather Karakoram Highway linking Pakistan and China. In both cases, debris-flow impacts are typically confined to relatively small, local areas, although climatic extremes or earthquakes can result in many of these events—and countless rockfalls as well—that are scattered widely through the mountains at a given time. During the torrential rains in September 1992, hundreds of individual debris flows were triggered, some causing damage to villages and irrigation channels, and severing the road network in dozens of places (Hewitt 1993). As is typical, the event is recorded as a severe rainstorm rather than one of mass movements. In general, while there are multiple events in most years, annual casualties rarely reach double figures and destruction and disaster relief appear to be in the thousands rather than millions of dollars.

Responses to debris flows are also distinct between events that affect small and local communities, and those that affect major infrastructure, mainly the Karakoram Highway. The former have received very little attention by the state or geoscientists. In most cases, traditional community arrangements govern responses, sometimes identified as ‘coping strategies’ (Hansen 1997). A detailed account of the stories and practices of villagers and herdsmen of Chitral, Northern Pakistan facing flash floods and debris flows is found in Dekens (2007). NGOs have become increasingly involved in mitigative measures at the village level. For the most part, local reports and media tend to show villagers complaining bitterly about the lack of government assistance before, during or after destructive events.

The highways, on the other hand, receive constant attention and immediate response from maintenance crews and military forces permanently based in the region, and there have also been a number of research reports by geoscientists (for example, Jones et al. 1983; Brunsden and Jones 1984; Haigh 2001). They have had exceptional assistance from Chinese engineers and road crews. Hence, because debris flows are a major problem, essentially inescapable in the spring and during major rainstorms, there is a permanent system in place to work on them for the highway system, but no official plan for local communities.

5.3 Guatemala, Central America

Debris flows are becoming more frequent and catastrophic in Guatemala. Events caused by rainfall from Hurricane Stan in 2005 destroyed houses and local infrastructure and killed approximately 1,000 persons in the Central Highlands. A shallow landslide-initiated debris flow of approximately 360,000 m$^3$ completely buried Panabaj, a small village close to the Toliman volcano in the Western Highlands of Guatemala (Geotimes 2005; Sheridan et al. 2007). Eighty-two bodies were recovered from a muddy deposit almost 3 m thick. More than 600 people were declared officially missing. Ironically, Panabaj means “debris flows” in the native language. Both of these events primarily affected poor and poorly educated indigenous groups. Small destructive debris flows are also an emerging natural hazard in the poorer areas of Guatemala City.
In Guatemala, poverty and extreme poverty are forcing people to live on steep, inappropriate land for development. Ravines, steep hillsides, fluvial terraces, and floodplains are hazardous and risky alternatives for low-income families. The problem is increased by the lack of governmental policies to create safe and affordable housing. In addition, environmental degradation, over-exploitation of natural resources (such as rainforests, water, and soil), and inappropriate land-use planning all result in increased water runoff during the rainy season. Even worse, hazards and risks are exacerbated by a lack of laws and regulations regarding land-use planning, use of poor construction techniques and materials, and inadequate education. High population density in the larger cities also contributes to the negative effects of natural hazards.

As a result, a complex mix of socio-cultural factors increase the vulnerability of the poor in mountainous areas and in densely populated urban areas. Therefore, single-approach mitigation is typically ineffective, and integrated, multi-task approaches are preferred.

In general, decision makers and government officers are prioritizing risk-related topics as strategic and necessary components of their development plans and policies. Although this attitude change may not necessarily be due to self-awareness or education as much as a response to the last catastrophe, it is an important evolution to provide protection to a vulnerable population. A considerable effort is being made by the municipal governments to promote not only structural mitigation as in the past but also disaster preparedness at the community level. International cooperation has promoted scientific research to understand landslide-related hazards and improve accuracy and effectiveness of the existing early warning systems. As a result of these efforts, more communities are empowered to take actions to reduce their own risk levels.

6 Examples of severe debris-flow events

A review of a six case studies covering differing geographic regions, populations and initiating mechanisms serves as an overview to the types of severe debris-flow events. The examples are not comprehensive, but represent a range of typical situations. Although disaster-focused literature typically emphasizes extreme events, the following examples are intended to represent different socio-cultural and geographic settings, where fatalities could have been avoided.

6.1 San Bernardino, California, USA

In October and November of 2003, the Grand Prix and Old Fire wildfires burned more than 57,000 ha in the mountains above the communities of San Bernardino, Rancho Cucamonga, and other small suburbs. In December, less than 2 months after the wildfires, a rainstorm generated 68 debris flows in the burned areas, including two that killed 16 people.

Of the 16 fatalities, two were killed at a campground located within the floodplain of Cable Canyon. The campground had been evacuated during the wildfires, and even though there was ample warning of water flood and debris-flow hazards and risks from natural hazard management officials (Florey 2004), 52 people were stranded and 30 trailer homes were washed away during the December storm. According to a survivor, “Nobody could have ever imagined this, not even the rescue people”. However, the survivor also stated that “[The fire crews] knew that the mountain was going to wash down. You could see it. There’s no vegetation up there at all” (Bustillo 2003).
The other 14 people were killed in a debris flow at another camp located on the floodplain of Waterman Canyon (Fig. 2). Most of these fatalities were immigrants from Guatemala and Mexico, who perhaps did not recognize the debris-flow hazards and risks common to the area (McCarthy 2004). Similar to Cable Canyon, there was a substantial effort to warn residents of the water flood and debris-flow hazards and risks following the wildfire (Florey 2004).

The rain storm that caused these events was not large, estimated to be below the 2-year recurrence interval (Cannon et al. 2008). Although the total rainfall was 180 mm in some areas, the average storm intensity ranged from 2 to 10 mm/h (Cannon et al. 2008). According to a local amateur weather observer who lives just above the Waterman Canyon, “It wasn’t the hardest rain I’ve ever seen, but I’ve never seen that little creek run like that” (Bustillo 2003), which shows that runoff was substantially higher than expected because of the burned hillsides.

In addition to the local recognition of the debris-flow hazards and risks, which was reinforced by door-to-door warnings by officials, there were other significant efforts to reduce the potential for debris flows and to reduce the risk to residents. After the wildfires, mulch was spread by helicopter on the hillsides to reduce the erosion potential of the bare soils. While the effectiveness was uncertain (deWolfe and Santi 2009; Santi et al. 2007), it would have been clear to the residents that this noisy operation was intended to help mitigate a substantial new hazard and risk brought about by the wildfires. The level of comfort or complacency imparted to the residents by mulching is unknown.

In the weeks following the wildfires, and before the December rainstorm, the U.S. Geological Survey prepared emergency assessment maps showing anticipated debris-flow probability and peak discharge for each canyon and for various size rainstorm events (Cannon et al. 2003). Both canyons where fatalities occurred were assigned annual debris-flow probabilities of 1–33%, a substantial hazard, but not nearly the highest in the area.

In this example, substantial warning systems and local awareness protected the thousands of people who lived in or near the canyons that experienced debris flows. However, in two unfortunate situations, the warnings were ignored or not taken seriously and fatalities resulted.

![Fig. 2](image_url) Aftermath of a debris flow, St. Sofia camp in southern California. Fourteen people were killed when the debris flow removed the upper floor of the structure in the foreground. Photograph by P. Santi.
6.2 Harihara River, Japan

In 1997, a 160,000-m$^3$ landslide mobilized into a debris flow near midnight and struck a community along the Harihara River, killing 21 sleeping residents (Nakagawa et al. 2000). Rainfall of 365 mm during the previous 24 h triggered the landslide. Residents should have been aware of the potential for rainfall-induced debris flows, since a Sabo dam (a dam to control debris-flow-like events) was under construction on the local drainage at the time of the debris flow. This dam intercepted approximately half of the debris volume, but at the time it may have been partially filled with water and actually contributed fluid to the flow (Nakagawa et al. 2000).

Ironically, residents took refuge during the rainstorm, but returned to their homes once the rain stopped. The debris flow initiated approximately 3 h later (Nakagawa et al. 2000). Such a relatively long time lag is not typical, and may have increased the number of fatalities. Numerical modeling carried out after the event showed that the houses were inundated within 1–3 min after the landslide occurred, indicating that the warning or evacuation time after the initial failure was extremely short (Nakagawa et al. 2000).

6.3 Campania Region, Italy

In 1998, a rainfall event of 120 mm caused approximately 300 debris flows in the Campania region in Italy, resulting in 161 fatalities (Guadagno and Revellino 2005). The region has a long record of rainfall-induced debris flows, with the earliest recorded event in 1632 and the latest previous event in 1997 (Calcaterra et al. 2000). Maps of the region show dozens of towns constructed on debris-flow fans in river valleys, and maps of the 1998 flow events show many towns were struck by multiple debris flows. For example, the town of Quindici was impacted by five separate debris flows emanating from at least five separate valleys rising above the town (Calcaterra et al. 2000).

After the event, rainfall alert thresholds of 40 and 60 mm (1/3 and 1/2 of the triggering event, respectively) were established for the region (Calcaterra et al. 2000).

6.4 Larcha, Nepal

In 1996, a debris flow of approximately 104,000 m$^3$ overwhelmed sleeping residents in Larcha, Nepal, killing 54. Survivors reported ground shaking half an hour before the event and again immediately before the event, coinciding with upstream slope failures that mobilized into debris flows. While previous studies suggested a threshold of 100 mm of rainfall to initiate debris flows in the region, the 1996 monsoonal storm amounted to only 80 mm, although levels may have been higher at higher elevations where the landslides occurred (Adhikari and Koshimizu 2005). Only recently has a rainfall duration-intensity threshold been established for debris flows in Nepal (Dahal and Hasegawa 2008), and the 1996 intensity of 80 mm in 3 h is approximately in the range of this threshold. Debris flows are reported every year on the same river, so residents were aware of the hazards and risks, and rainfall intensities and duration should have caused alarm.

6.5 Vargas, Venezuela

In 1999, 3 days of rainfall totaling approximately 1,200 mm caused debris flows on 24 streams in Vargas, Venezuela, affecting several communities and killing over 19,000 people (Garcia-Martinez and Lopez 2005; USGS 2001). It has been called the worst natural
disaster in Venezuela and possibly in all of Latin America (Garcia-Martinez and Lopez 2005). Because of the close proximity of the steep mountains to the coast, communities were crowded onto debris fans, many of which extended into the Caribbean Sea as lobate deltas. According to USGS (2001), late-stage evacuation would have been impossible, as there was essentially no nearby high ground. Furthermore, many residents were killed in their homes, as they had “little advanced warning” (USGS 2001).

In this example, prior awareness of the hazards could have been developed by the historical records of one or two debris-flow events every 100 years (USGS 2001), by geologic indications of debris-flow deposits, and by intense rainfall.

6.6 Casita Volcano, Nicaragua

In 1998, a debris-flow disaster on the flanks of Nicaragua’s Casita volcano has been called the “archetypal example of communities located in the wrong place” (Scott 2000). Following 5 days of rain from Hurricane Mitch, totaling almost 1,000 mm, a small flank failure on the volcano mobilized into a debris flow, growing nine-fold in transit, and burying two towns and 2,513 residents in its path, all within 3 min. The towns were fairly new communities, less than 20 years old, but were unknowingly located on top of old debris-flow deposits. The local terrain provided no higher ground, so only advance evacuation would have been effective.

Scott (2000) notes that the situation that led to this disaster is common, as nearly every deadly event in the Western hemisphere over the last several decades was preceded by historic or prehistoric events along the same pathway. According to Scott (2000), hazard assessment would have identified prehistoric flows underlying the towns.

6.7 Overview

Several elements are common to these examples, which in aggregate represent a broad range of the conditions leading to debris-flow fatalities throughout the world:

• the lack of awareness of the hazards and risks is less of an issue than the lack of appreciation of the level of hazard and risk by those with resources to plan for them;
• total rainfall or rainfall duration-intensity thresholds may be useful in some situations, but orographic effects can make such thresholds ineffective, and debris flows can occur hours after rainfall. In burned or logged areas, thresholds are much lower, and residents may not be aware of the increased hazard and/or risk;
• construction on old debris-flow deposits and fans is common, and potential disasters are exacerbated by high population density, focus on other hazards, a lack of other suitable building sites, and a lack of higher ground;
• rumbling sounds and shaking ground typically provide no more than 1–3 min of warning time; and
• residents seem less likely to evacuate or respond to warning signs at night (also noted by California Geological Survey, 2003).

7 Debris-flow mitigative methods

A substantial body of literature is available describing various debris-flow mitigative methods. Much less information is available that discusses when and where the mitigative
methods are effective or how to design and implement the methods. This section discusses what factors should be considered in selecting a particular mitigative method and not actual design. Reference to valid and easy-to-implement published designs are also included. Table 1 summarizes application issues for many of the methods.

7.1 General considerations

Mitigation of debris flows can be divided broadly into two categories: passive and active (VanDine 1996). Passive methods involve no direct engineering because no attempt is made to reduce the occurrence or the effects, or otherwise control the debris flow. Examples of passive mitigative methods include avoidance of the area, land-use regulation, notification and education of the public, and warning systems.

Active methods require some form of engineering. Examples of active mitigative methods include reducing the probability of the debris flow occurring in the source zone, or reducing or modifying the size, velocity, and flow path or effects of the debris flow in the transportation zone and/or deposition zone.

The implementation of appropriate passive or active mitigation, or a combination of the two methods, first requires the appropriate recognition, evaluation and assessment of the debris-flow hazards and risks. Debris flows, debris floods, water floods, and landslides are very different types of natural hazards and therefore require quite different types of mitigation. To make this task more challenging, recognition and identification has to be carried out before the hazardous event occurs. Therefore, the conditions suitable for the natural hazard occurrence, transport, and deposition have to be correctly recognized and identified.

Once recognized and identified, the debris flow hazards and risks have to be appropriately evaluated. Evaluation includes estimating the probability/frequency of future occurrences, determining the likely character of the material involved, estimating the likely volumes of material involved, and determining the likely flow path. Evaluation should also address socio-cultural elements, such as the health and well-being of the residents, material property such as buildings and infrastructure, and the environment. It must also take account of existing and anticipated development (Jones 1992).

Risk assessment is a comparison of the results of the evaluation of the hazard and the elements at risk with established or implied levels of acceptable or tolerable risk. What is acceptable or tolerable varies greatly with the socio-cultural conditions in the geographic region and the country in question.

Final evaluation factors include whether the study area is an area of existing development or a proposed new development, the status of land ownership, and what resources are available. Resources include:

- financial, both direct and indirect;
- professional engineers and/or geoscientists with some knowledge of debris flows;
- government authorities, various levels of government, with some knowledge of debris flows;
- numbers and skills of the potential labor force;
- construction equipment; and
- building materials.

Appropriate resources are required both for the recognition, evaluation and assessment of the debris-flow hazards and risks, and for the selection, design, construction, operation, and maintenance of an appropriate mitigative method.
<table>
<thead>
<tr>
<th>General category</th>
<th>Specific category</th>
<th>Expense</th>
<th>Design complexity</th>
<th>Construction complexity</th>
<th>Maintenance requirements</th>
<th>Vulnerability to vandalism or scavenging</th>
<th>Typical effectiveness</th>
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<tr>
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<td>Popularized sayings</td>
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<td>+</td>
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<td>++</td>
<td>0</td>
<td>--</td>
<td>0</td>
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<tr>
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<td>Concrete traffic barriers</td>
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<td>++</td>
<td>+</td>
<td>0</td>
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<td>0</td>
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<td>0</td>
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<td></td>
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<td>0</td>
<td>--</td>
<td>+</td>
<td>+</td>
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<td>--</td>
<td>--</td>
<td>--</td>
<td>0</td>
<td>++</td>
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<tr>
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<td>Cable fences</td>
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</tr>
<tr>
<td></td>
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<td>Hillside treatment</td>
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<td>+</td>
<td>+</td>
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<td>Log erosion barriers</td>
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</tr>
</tbody>
</table>

"--" very undesirable, "-" undesirable, "0" neutral, "+" desirable, "++" very desirable, "blank" not applicable. Expense rating for Interception and Hillside Treatment categories is from Santi et al. (2006)
Depending upon the character of the hazards and risks, the socio-cultural conditions and the availability of resources, arguments can be made to try to keep the selection, design, construction, operation, and maintenance of mitigative methods relatively simple and consistent throughout a particular geographic region. In certain situations and under certain circumstances, such relative simplicity and consistency can potentially result in many more successes. In other situations and circumstances, however, the application of relatively complex and/or watershed-specific mitigative methods may be more appropriate.

7.2 Education

Some of the best tools to reduce debris-flow hazard and risk are awareness of the hazard, correct perception of the likelihood of the hazard occurring, and knowledge of appropriate responses when the hazard is imminent.

Residents should be able to recognize the noise and ground shaking that are precursors to debris flows. Survivors of debris-flow events usually report “roaring” noises, sounds like “prolonged thunder claps” (Scott 2000) or trees or boulders knocking together (USGS 2005). Likewise, debris flows are often preceded by increases or decreases in water flow, change from clear to muddy water, or small volumes of mud or debris (USGS 2005).

Hazard and risk awareness and appropriate responses can be conveyed by popularizing sayings or messages. General awareness has improved in southern California because the saying, “After the fire, comes the flood” makes the link between dry season fires and wet season debris flows common knowledge for residents. Scott (2000) suggests that local versions of the message “in case of earthquake or loud rumbling noise, seek high ground” can direct residents uphill to possible relative safety. This behavior is sometimes in direct contrast with people’s instinct: for example, in Peru in 1962, some of the 4,000 who were killed by a debris flow were aware of the imminent danger, but ran downhill to seek refuge in a cathedral that was subsequently destroyed (Scott 2000). Other suitable messages might include some adaptation of “heavy rainfall brings more than water,” “better to evacuate than be late,” “it has happened before, it will happen again,” or “the end of the rain or the end of the day do not mean the end of the hazard or risk.”

Posted warnings or reminders are also simple ways to keep the awareness level high, especially when several years have passed since the last debris flow. Placards or signs can be located along typical flow paths for debris flows, at canyon mouths, in low-lying areas, and at higher ground locations that are expected to be safer. In some cultures, widely distributed scientific fact sheets can have positive effects (for example, USGS 2005).

Finally, alert and evacuation levels should be made clear to local residents. Conventional wisdom, tradition, and stubbornness can lead to bad decisions, and natural hazard managers should look for socio-culturally sensitive ways to help people recognize the thresholds that indicate increasing hazard and risk potential, and to encourage people to respond appropriately.

7.3 Avoidance/warning

Ideally, high hazard and risk areas should be permanently excluded from development or set aside for temporary uses that do not include residences or workplaces. This type of solution requires three components. First, debris-flow professionals or natural hazard managers must recognize the debris-flow hazards and risks and identify areas where hazards and risks are highest. Second, local government must be willing to set aside the land from future development or provide proper incentives for relocation of existing
development. Third, hazard and risk awareness must be maintained at a high enough level that the pressure to develop the land in the future can be resisted.

Recognizing where debris flows might occur is one of the most obvious, yet overlooked, mitigative elements. Geomorphic indicators of debris-flow terrain, debris-flow deposits, and activity levels of alluvial and colluvial fans are summarized in Jackson (1987), Wilford et al. (2004), Giraud (2005), and Jakob (2005) Part of this recognition includes delineation of expected inundation zones, whether by mapping of old debris-flow paths or modeling and prediction of new paths. Forecasting is difficult, but a variety of methods have been developed ranging from straightforward calculation of runout distance to more complex computer modeling of depositional areas. One of the simplest methods to estimate runout distance is based solely on the topographic profile of the debris-flow channel and the point at which deposition is expected to begin (typically the “fan head”), as described in Prochaska et al. (2008a). Inundation area can be predicted with reasonable accuracy using the computer model LAHARZ for volcanic lahars (Iverson et al. 1998), for non-volcanic debris flows (Berti and Simoni 2007; Griswold 2004), and for burned areas (Bernard 2007). Other methods of mapping runout and inundation are summarized in Hungr (1995), Fannin and Wise (2001), and Rickenmann (2005). The use of probabilistic and risk-based techniques, such as those summarized and compared in Fuchs et al. (2008), provides tools to make informed hazard and risk-management decisions and is useful in communicating hazard and risk levels.

Identifying when debris flows might occur is a companion requirement to recognizing where they might occur. Recurrence intervals can be established based on historical records of an area (for example, Zimmerman et al. 1997) or on careful stratigraphic mapping and age dating of debris-flow deposits (for example, Strunk 1992). Local rainfall thresholds can also be established, and an extensive, world-wide database summarizing methods, threshold values and equations is maintained by Balducci (2010). Details of a warning system in southern California, based primarily on rainfall thresholds, are provided in USGS (2005) and NOAA-USGS (2005). Volcanic eruptions and wildfires cause drastic changes in terrain conditions, so rainfall thresholds and debris-flow likelihood will change following such events. Examples of post-wildfire debris-flow likelihood calculations are included in a number of emergency assessments conducted by the U.S. Geological Survey (for example, Cannon et al. 2003).

Numerous debris-flow mitigative elements, such as culvert or bridge sizing, retention basin design, channel depth requirements, and most inundation area prediction models depend on estimates of expected debris-flow volume. Debris-flow volume can be estimated using geomorphologic approaches (for example, Hungr et al. 1984; Jakob 2005), which must also include estimates of sediment bulking rates for debris flows in burned areas or on hillsides with abundant loose colluvial material (Hungr et al. 1984; VanDine 1985; Williams and Lowe 1990; Giraud 2005; Jakob 2005). Site-specific volume estimation equations have been developed for some regions using empirical data and multiple regression statistical techniques, including the Italian Alps (Bianco and Franzi 2000; Marchi and D’Agostino 2004) and southern California (U.S. Army Corps of Engineers 2000; Cannon et al. 2007; Gartner et al. 2008). In the past, estimates of debris-flow volume have been made based on multipliers applied to specific water flood flow volumes, such as the 100-year water flood. Such estimates are not recommended because, as noted in Giraud (2005), “empirical bulking does not consider shallow landslide-generated debris flows, channel bedrock reaches with no stored sediment, and the typically longer return period of debris flows.”

Alarm systems and associated warning devices have been used successfully to warn local residents of impending debris flows. Itakura et al. (2005) summarizes and provides
examples of use of these systems worldwide. Badoux et al. (2009) documents the successful use of a system in Switzerland that relies on geophones and flow-depth sensors. Their entire alarm system, which also included hazard and risk awareness education, catchment observation, and weather-related thresholds, issued 20 alarms in the first year of use, with only one false alarm.

7.4 Channelization

In some circumstances, it may be expedient to channelize, deflect, or otherwise direct moving debris flows away from areas of concern. Although this does require funding and expertise, the design and construction is relatively straightforward and the channelization can often be located alongside existing stream or debris-flow channels, so it may be possible to complete such work without disturbing adjacent communities.

The simplest form of debris-flow channelization is stacked sandbag walls, parallel to the direction of flow. Sandbag walls only provide a small addition to the freeboard, so they are only effective for relatively small flows or flows that have spread out and are therefore relatively thin. Sandbag walls are typically used to prevent debris intrusion into limited areas, such as driveways or walking paths, and are considered temporary methods of debris-flow control. They lose effectiveness if water is against them for extended periods of time. Examples of the use of sandbag walls and stacking methods in the United States are provided in publications by San Bernardino County (2004) and Los Angeles County (2009), both in California.

Temporary concrete traffic barriers (referred to locally by different terms such as Jersey barriers or K-rails) are an alternative to sandbag walls and may be more expedient than sandbag walls for longer reaches or if larger impact forces are expected (Fig. 3). They are typically 0.8 m high or less and may be pinned to the ground with steel stakes, thereby increasing resistance against sliding or overturning. No standard designs have been published, but VanDine (1996), Lo (2000) and Prochaska et al. (2008b) suggest calculations for impact forces and debris run-up heights.

Fig. 3 Temporary concrete traffic barriers were used to extend the natural debris-flow channel along Greenwood Avenue, Devore, southern California. Inset shows sandbag walls that were placed across driveways as necessary. The debris-flow material near the geodesic dome was deposited before the barriers and sandbag walls were installed. Photograph by P. Santi
Earthen and concrete deflection and terminal berms and walls may be constructed much higher than sandbag walls or concrete traffic barriers, and they can withstand much greater debris impact forces and water saturation. However, these structures require appropriate design, require more space and material, and are usually considered permanent structures.

Channels may be, in part, excavated to pass increased peak discharges. Conceptual layouts, general construction methods and some example specifications are given in VanDine (1996) and Martin et al. (1984). Scale modeling of deflection berms and their effectiveness is demonstrated in Nasmith and Mercer (1979). Calculations for many of the input parameters required for design are summarized in Lo (2000). Complete design procedures are given in Prochaska et al. (2008b).

7.5 Interception

Debris-flow material may also be intercepted at some point along its path, with the goal of preventing this volume from continuing downstream. Large debris basins are usually constructed within the deposition zone, near the mouths of debris-flow producing gullies or canyons. Smaller structures, such as check dams, fences, racks, and baffles can be constructed within the transportation zone or the deposition.

Debris basins are considered one of the most effective and reliable debris-flow mitigative methods (Santi et al. 2006). They are used extensively, where room permits, in the western United States. Because they require a relatively large area, they are impractical for many locations. They are generally constructed as earthen berm enclosures, sized to be able to contain expected flow volumes and to handle impact forces and run-up. They should contain appropriate spillways and outlet works (Fig. 4). Complete design procedures are given in Prochaska et al. (2008b), Nasseri et al. (2006), and Easton et al. (1979) and example specifications are given in VanDine (1996). Methods of predicting flow velocity (used to estimate impact forces) and run-up are provided in Prochaska et al. (2008c), Lo (2000).

Fig. 4 Conceptual layout of a debris basin and outlet works (from VanDine, 1996)
and Hungr et al. (1984). Estimation of design debris-flow volumes is very important, so that basins are sized properly and risk from overflow is minimized. Removal of accumulated debris flow and fluvial sediment is essential to maintain adequate storage volume.

Check dams, placed in series along the lengths of debris producing and transportation channels, are designed to be filled and remain filled, with the excess debris continuing downstream, but at a lower velocity and magnitude. They reduce the volume of incoming flows and they reduce the ability of flows to incise into the channels and generate more debris. Conceptual layouts, spacing calculation, and other design concerns are provided in VanDine (1996), Jaeggi and Pellandini (1997) and Santi et al. (2006). While check dams require less space and are easier to construct than debris basins because of their smaller size, access to upper reaches of channels may limit where they can be built. Improperly constructed and/or anchored check dams may fail during a debris flow and therefore can increase the peak flows and magnitudes of the debris flows, increasing the hazards and risks. Case histories of such failures are documented in Hubbert and Associates (2005) and White et al. (1998).

Debris-flow fences can be stretched across the mouths of narrow canyons, typically less than 30 m in width. They can be constructed of anchored steel cables, ring nets and high strength chain links fine enough in mesh size to retain large rocks and woody debris, but coarse enough to allow finer debris and muddy water to pass. Design is typically completed by the manufacturers and installers, but reports of successful applications are given in Duffy and DeNatale (1996), Thommen and Duffy (1997), and Rorem (2005). Geotextile silt fences located across the flow channel are not robust enough to intercept anything but small volume and slow-moving debris flows and are not recommended (Fig. 5).

Debris flows may also be slowed down and encouraged to deposit by a collection of baffles located within the flow path. Baffles can mature trees, or a pattern of earthen mounds or timbers constructed in flow areas. Construction is simple and inexpensive but, like debris basins, space must be available for both the pattern of baffles and the deposited debris. Example layouts are provided in VanDine (1996) (Fig. 6).

There are numerous other types of debris-flow control structures, most of which require greater expense and detailed design, such as debris racks, grizzlies or straining structures, and sabo and slit dams. Examples of these structures are provided in Okubo et al. (1997) and VanDine (1996).
7.6 Hillside treatment

Source-area control of debris flows may be a useful mitigative method in areas where hillsides have been recently disturbed and natural vegetation has been removed, such as after a wildfire, logging, or clearing for construction or mining. Summary reviews of the performance of various slope treatment methods are provided in deWolfe and Santi (2009), deWolfe et al. (2008), Santi et al. (2006), (2007). In general, these reviews concluded that:

- Most reseeding efforts did not improve resistance to erosion on hillsides;
- Natural revegetation was just as efficient as artificial seeding;
- Mulch was more effective than artificial seeding. It was most effective when spread evenly, because clumped mulch suffocated new growth. Mulch was less effective if exposed to high winds (Fig. 7), but hand-crimping mulch into the ground prevented it from blowing away, in addition to breaking up hydrophobic layers of the soil (deWolfe et al. 2008);
- The effectiveness of log erosion barriers (LEBs) was mixed. LEBs are felled and limbed trees, aligned along contour, and held in place with stumps or wooden stakes. They were often bypassed or undercut by flowing water, and Wagenbrenner et al. (2006) found them to be effective only during low to moderate intensity rainfall events.

8 Example socio-culturally sensitive mitigative approaches

The following paragraphs present several examples of integrating socio-culturally aware approaches into mitigative programs. The examples seek to answer the question, “what mitigation is the local population receptive to, given its specific geographic layout, cultural
perceptions and history of habitation?" These examples demonstrate a range of approaches, incorporating several different elements and are by no means comprehensive.

8.1 Greenwood Avenue Neighborhood, Devore, California, USA

The Greenwood Avenue neighborhood has been occupied for approximately 30 years. This middle income neighborhood flanks a residential road that is located on a debris fan, at the mouth of a steep mountain canyon (Fig. 3). The San Andreas fault follows the mountain front just uphill of the end of Greenwood Avenue. The chronology of recent debris-flow events is as follows:

1. The hillsides above the neighborhood were burned in the Old Fire wildfire of October and November, 2003.
2. A December 2003 rainstorm of slightly over 10 cm (estimated as a 2–5 year return period event) caused a debris flow that affected several houses and properties.
3. A rainstorm of similar size in October 2004 generated a similar debris flow with similar effects.
4. A January 2005 rainstorm, in excess of 15 cm (estimated as a 50–100 year return period event) generated elevated levels of muddy water but no debris flow.

As a result of these events, the residents have a very high awareness of debris-flow hazards and risks, and there is a political will to address them. However, because only a small portion of the regional population is affected by debris flows, only limited funding is available. Table 2 summarizes the suggested mitigative approaches. Note that some of these elements were actually implemented and some were not.

8.2 Kande, Pakistan

The community of Kande in the Upper Indus Basin in Pakistan was partially buried in a monsoon-rainfall initiated debris flow in 1997 (Fig. 8). The only access is by a rough, unpaved road. Its location near the confluence of two mountain rivers in the high Himalaya
has rendered it susceptible to earthquakes, rockfall and seasonal flooding events in addition to frequent debris flows. As a consequence, the populace has a high awareness of natural hazards, and there is a strong association between hazard events and monsoon-season rainfall.

The community is largely agricultural and the alluvial and debris-flow deposits on which they are located are the only arable, flat-lying habitable land areas in the vicinity. People in Kande are poor, have few resources to apply toward debris-flow mitigation, and are accustomed to receiving little governmental support, which seems to be available only for highway repair following hazard events. Occasional NGO and foreign aid is available following the largest and most widely reported events. Table 3 suggests possible mitigation options for this cultural, geographic, and economic setting.

### Table 2 Example mitigative approach for Greenwood Avenue neighborhood, Devore, Southern California

<table>
<thead>
<tr>
<th>Category</th>
<th>Mitigation element</th>
<th>Discussion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Education</td>
<td>Distribute fact sheets</td>
<td>Fact sheets are available for the region, but were not specifically distributed to the local population in 2003–2004</td>
</tr>
<tr>
<td></td>
<td>Recommend alert/evacuation rainfall levels</td>
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<tr>
<td>Avoidance/warning</td>
<td>Develop a set of hazard maps showing expected inundation areas, probabilities of occurrence, and estimated debris volumes for various design storm events</td>
<td>Because hazard and risk awareness were already high, hazard maps were to help residents understand levels of hazard and risk</td>
</tr>
<tr>
<td></td>
<td>Set up a reverse emergency telephone system to be implemented when rainfall intensity-duration thresholds are exceeded</td>
<td>Use recently published rainfall intensity-duration thresholds for alert system</td>
</tr>
<tr>
<td></td>
<td>Exclusion zones are not considered practical as area is already developed</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Alarm systems, using geophones or flow depth sensors, are probably too expensive because of the small number of residents at risk</td>
<td></td>
</tr>
<tr>
<td>Channelization</td>
<td>Deepen the natural debris-flow channel, at least to the point where it exits onto the street</td>
<td>These forms of channelization were implemented during the winter of 2003–2004</td>
</tr>
<tr>
<td></td>
<td>Use temporary concrete traffic barriers and sandbags during the first 1–3 years after wildfire</td>
<td>Temporary concrete traffic barriers should be used only where they could handle the expected peak discharge. Sandbag walls proved to have mixed effectiveness. Both elements were considered unsightly and accepted by residents only for a limited time</td>
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<tr>
<td>Interception</td>
<td>Create a small retention basin near the mouth of the canyon, containing earth-mound baffles to enhance debris deposition</td>
<td>There is no space for a large debris basin. A small basin built to contain only part of the expected flow may actually be problematic, as people will think it is meant to contain all of the flow and will have a false sense of security. Post signs declaring it a “debris attenuator” a “flow reducer” or a “speed reducer”</td>
</tr>
<tr>
<td></td>
<td>Check dams are not practical because of access and expense considerations</td>
<td></td>
</tr>
<tr>
<td>Slope treatment</td>
<td>Spread mulch on the hillsides directly after the fire, but crimp it in place to keep it from moving in the wind and clumping</td>
<td>Mulch was spread in 2003–2004, but had limited effectiveness because of clumps and bare patches created by wind</td>
</tr>
</tbody>
</table>
8.3 Santiago Atitlan, Guatemala

The city of Santiago Atitlan is located on a small zone of relatively flat-lying ground between Volcan Toliman and Lake Atitlan (Figs. 9, 10). Its population is over 33,000, the
majority of whom are indigenous Mayans. The town is within 2 km of the community of Panabaj, which was buried by a debris flow in 2005.

The economy is agrarian, with some trading (crafts) and tourism, and the populace is dominantly poor, with a small portion of middle-income residents. The poorest residents have established housing on sloping ground above the city, especially in canyons with running water. Access to Santiago Atitlan is by paved highway and by ferry across the lake.

Guatemala’s recent history of civil war, uprisings, army attacks, and police corruption has reduced the level of trust in institutional approaches to hazard mitigation. However, work at the community level and some internationally based scientific research has shown
some recent success. Given this background, Table 4 proposes a set of mitigative approaches sensitive to the populace and setting.

### Table 4 Example mitigative approach for Santiago Atitlan, Guatemala

<table>
<thead>
<tr>
<th>Category</th>
<th>Mitigation element</th>
<th>Discussion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Education</td>
<td>Post information listing precursor warnings of debris flow (heavy rain, ground shaking, roaring noises, changes in stream color) Establish alert and evacuation criteria, clearly mark evacuation paths and safe locations</td>
<td>While these options are similar to those suggested in Table 3, the population in this case is much larger and there is more safe ground available nearby for evacuation</td>
</tr>
<tr>
<td>Avoidance/ warning</td>
<td>Establish “safe” zones above the expected and historic inundation areas based on topographic, geomorphic, and hydrologic conditions Establish warning alarms known by all the populace Develop rainfall threshold values above which debris flow warnings are activated Work with respected community leaders to develop alternate housing locations for the poor so that they are not living in valley bottoms</td>
<td>Requires mapping by trained geologists Bells or sirens should be sounded in a simple, predetermined pattern This may be the most sensitive and yet the most critical mitigation element</td>
</tr>
<tr>
<td>Channelization</td>
<td>To the degree possible, straighten and channelize flow paths through the town, building berms where necessary to better confine the flow</td>
<td>Straight, steep paths are needed to keep debris from slowing, depositing, and overflowing the banks. This work can rely on unskilled labor with only a small amount of technical direction</td>
</tr>
<tr>
<td>Interception</td>
<td>If land is available, establish one or more debris basins</td>
<td>Cultivation may be allowed inside the basin, but not habitation</td>
</tr>
<tr>
<td>Slope treatment</td>
<td>Encourage terracing and crop practices that reduce runoff and prevent contiguous patches of bare ground</td>
<td>Any efforts to reduce water and sediment runoff during heavy rainstorms will reduce debris flow likelihood and volume</td>
</tr>
</tbody>
</table>

### 9 Conclusions

Hazards and risks from debris flows are closely related to socio-cultural factors. The most vulnerable populations tend to be economically restricted to live in relatively inexpensive and more dangerous locations, have space restrictions, often caused by expansion and development, forcing them to live in topographically cramped areas, and have limited influence and power needed to bring about mitigative efforts. The collective judgment of many of those working toward natural hazards reduction, especially in developing countries, is that socio-cultural issues are at least as important as technical choices in their influence on the effectiveness of hazard and risk-reduction efforts (ICIMOD 2009).

With these points in mind, mitigative elements for debris flows should be selected with local socio-cultural characteristics in mind. For developing countries, these can include:

- Simple designs using local materials, local construction techniques and skills, and recognizing limited financial means;
- Minimal maintenance requirements, exposure to vandalism and scavenging, and misappropriation of resources; and
• Capitalizing on local techniques of dealing with other hazards, such as flooding, earthquakes, and landslides.

Because of the difficulty in predicting and controlling debris flows, it is useful if mitigative systems can employ multiple elements to enhance the chance of success. These can include education of the local populace, avoidance and warning to the degree possible, and some combination of channelization and interception of debris. For watersheds disturbed by fire, logging, mining, or construction, hillside treatment can be added to the mitigative system to reduce water flow and sediment transport. Examples provided in this paper show that these systems can be tailored to fit widely varying socio-cultural settings, with different geological characteristics and different debris flow–triggering events.

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