Nat Hazards
DOI 10.1007/s11069-016-2400-3

ORIGINAL PAPER

Review of challenges of and practices for sustainable management of mountain flood hazards

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Received: 28 December 2015 / Accepted: 19 May 2016

Abstract Mountain areas are the source of important cultural, ecological, and life-sustaining resources, but are also subject to devastating losses from floods. To work toward reducing these losses, this paper aims to (a) synthesize understanding on the elements that make flood risk management challenging in high mountain areas and (b) identify practices that can be applied in reducing the exposure and vulnerability of mountain communities. Through a review of the literature and case studies, we identified the flood-related challenges associated with complex topography and hydrogeology, insufficient data and infrastructure, weakly defined governance structures, and sensitivity to climatic and landscape changes. We examined five practices needed for reducing flood risk in these vulnerable areas, involving (1) the acquisition and effective dissemination of information about floods, (2) basin-scale hazard assessment and disaster response planning, (3) clearly defining governance responsibilities and distributing them across multiple jurisdictional layers, (4) implementing effective and diverse mitigation measures, and (5) training and engaging local residents and officials in flood risk reduction. Considerations and needs for implementing these practices in mountain areas are discussed, highlighting the commitment of resources needed for distributed governance, effective planning, land use and building regulations, and engagement of the public.

Keywords Flood risk reduction · Governance structures · Early warning systems · Land use regulations · Hazard assessment

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Published online: 28 June 2016

1 Introduction

Floods are among the most frequent and most destructive natural disasters globally (Noji and Lee 2005) and are the most frequent of all natural disasters in Asia, affecting 2.2 billion people between 1975 and 2000 (Asian Disaster Reduction Center 2002). The impacts of floods include the widely reported effects, such as direct mortality, loss of agricultural productivity, damaged infrastructure, and disruptions to business and education, as well as less-reported social impacts on communities (Lindell and Prater 2003) and human health (Ahern et al. 2005; Du et al. 2010).

Floods are particularly devastating in high mountain areas, including the North American Front Range (Gochis et al. 2015), South American Andes (NASA 2015), European Alps (de Jong 2015), and the Himalaya (Webster et al. 2011). The losses associated with flood hazards are high due to both the elevated exposure and vulnerability in mountain areas. The high exposure of communities to floods can result from a hazardous location in relationship to the river system, or from high population density. In Bangladesh alone, it is estimated that 6.3 million people are exposed to frequent flooding from mountain areas (Brammer 1990). In India and Pakistan, catastrophic flooding struck the upper Indus (Jhelum River) basin in 2014, killing over 400 people. Scientists debated whether the primary driver of vulnerability in the upper Indus basin was urbanization and conversion of floodplains (Meraj et al. 2015) or the earthquakes, faulting, and other geologic hazards that occur there naturally (Shah 2015). Geologic hazards, including landslides, debris flows, and Glacial Lake Outburst Floods (GLOFs), are a particularly devastating flood threat (Bajracharya et al. 2007) in mountain areas.

While the effectiveness of flood risk management in floodplains has advanced over the last century, mountain areas remain highly vulnerable and lack resilience due to unique challenges in effective management of mountain floods. The result is elevated flood risk, associated with (1) a lack of basic data that limits knowledge of the complex hydrology in mountain areas (Shrestha et al. 2000), (2) water resources management and governance that focus on short-term development goals, but often fail to achieve long-term sustainability (Gupta 2013), (3) a broad suite of socioeconomic, environmental, and geopolitical factors (Ives and Messerli 1989); and (4) sensitivity to land use and climate changes that can increase the prevalence of destructive landslides, GLOFs (Bajracharya et al. 2007), cloudburst events (Devi 2015) and other local precipitation events, and geophysical flows. These issues span a range of spatial and temporal scales that make managing flood risk in mountain areas particularly complex (Gardner 2015).

The objective of this review is thus (1) to characterize the elements that make flood risk management challenging in high mountain areas and (2) to review case studies of flood management practices to identify practices that can be applied in reducing the exposure and vulnerability of mountain communities.

2 Challenges to flood management in mountains

Floods generated in mountainous areas can be very different from those that accumulate in low-elevation valley floodplains in a number of key ways. These differences, summarized below, lead to challenges in the forecasting of, response to, and recovery from floods.

2.1 Limited data, accessibility, and infrastructure

Establishing instrumentation and response systems in high mountain areas is difficult due to issues with accessibility, remoteness, and limited communication networks and other infrastructure. For example, key challenges for data collection include the logistics of travel to and access of gauging sites, failing infrastructure during heavy storms, sharing of data across transboundary river basins, and the cost of deployment and maintenance for gauges. Furthermore, cellular coverage and radio telemetry are often not available in river basins with steep valley walls, providing extremely limited options for transmitting hydrographic data for long-term monitoring and early warning systems. To overcome the challenges of in situ measurements, remote sensing platforms may be used, such as those applied in the studies on intense precipitation (e.g., Anders et al. 2006; Barros et al. 2000; Bookhagen 2010; Romatschke and Houze 2011; Shrestha et al. 2012a, b). However, these also have significant limitations in mountain areas, including inadequate spatial and temporal resolutions for the complex topography, on top of standard limitations of the data (e.g., resource-intensive processing of remotely sensed data, limited data records, impacts of cloud cover or other biases in the data).

Because data collection is difficult and data are often scarce, the hydrology in high mountain areas is often not thoroughly understood and is considered to be a “black box” (Bandyopadhyay 2009). The lack of basic climate and hydrologic data, particularly in regions such as the Himalayan region (Panthi et al. 2015), significantly impedes forecasting, projection, and evaluation of climate events that generate catastrophic flooding (ICIMOD 2009), as well as the establishment of the flood warning and other management systems that are known to save lives (Curtis 2013).

Furthermore, the complex and variable terrain, limited accessibility, scarcity of hydrometeorological data, and inadequate statistical and process-based models make it particularly difficult to forecast localized, extreme events that are highly destructive. Mountain areas are often subject to localized flood events, associated with landslides, landslides with lake outbursts, GLOFs, and cloudbursts, that range from difficult to impossible to forecast. For example, landslides represent an important flood hazard mechanism in mountain areas that are impacted by an area’s elevation, slope, soil depth, vegetation, antecedent soil moisture, and heavy precipitation (Iverson 2000; Baum and Godt 2010). The physical processes of landslides are generally well understood and somewhat reliably modeled using process-based models, but are difficult to monitor and forecast in mountain areas. One-dimensional, process-based, and statistical models (Wilkinson et al. 2002), often based on precipitation thresholds, can be used to predict when hillslope conditions might result in triggering a landslide. However, these models lack the ability to predict the spatial footprint of the landslide, which establishes the degree of hazard resulting from the landslide. Predicting landslide size requires three-dimensional models that are generally computationally prohibitive (Bellugi et al. 2015), particularly for mountain areas with limited resources. Thus, existing tools allow for identification of high-hazard areas, but limit the ability of managers to reliably provide early warnings to residents (Baum and Godt 2010). Forecasting GLOFs for early warnings is similarly problematic. As a result, rather than real-time forecasting, planning for GLOFs has focused on hazard characterization, including identification of the depths and extent of floods downstream using dam breach models (ICIMOD 2011), which may be coupled with vulnerability assessments to support planning and mitigation of flood impacts.

The lack of hydrometeorological data and historical flood records in mountains hinders forecasting of even precipitation-based flooding. Regardless of whether process-based, statistical, or neural network models are applied, flood forecasting is generally data intensive (Hapuarachchi et al. 2011). Global flood models (Alfieri et al. 2013) based on remotely sensed data are a valuable resource, but their model resolution is still too coarse to provide guidance for local-level design and decision-making (Ward et al. 2015). Given that the limitations of global flood models are due to limited quality and availability of data on topography, boundary conditions, and community exposure and vulnerability, the application of global flood models is particularly problematic in mountain areas. Furthermore, assessing flood risk and establishing flood frequencies for the design of flood infrastructure are difficult because they depend on land use, channel capacity, precipitation patterns, and existing flood protection infrastructure (Hirsch et al. 2004), which are rapidly changing in mountainous areas (Gardner 2015).

2.2 Complex hydrology and limitations to knowledge on flood processes

Mountains are characterized by areas of complex terrain, high relief, and large precipitation variability. The complex and steep topography leads to their uniquely sharp transitions in atmospheric (i.e., temperature, precipitation, pressure, radiation, humidity), soil, vegetation, and hydrologic conditions over short distances (Beniston 2003; Whiteman 2000; Becker and Bugmann 1997). These sharp gradients across the landscape regulate the intensity, frequency, and type of precipitation, soil moisture, groundwater interactions, and vegetation, which in turn contribute to high variability in flood levels over short distances (Beniston 2003). Futhermore, many of these gradients are impacted by atmospheric processes at local and global spatial scales that occur over short and long timescales (Diaz et al. 2003). When combined with the limited hydrometeorological data in mountain areas, these complexities lead to limited knowledge on flood generation processes, particularly those associated with localized, extreme events, such as cloudbursts and other convective storms, landslides, and glacial lake outbursts.

Cloudburst flood events in the Himalaya are one of the least understood weather systems (Das et al. 2006). The result is that cloudbursts are impossible to forecast with current technology and are often blamed for flood losses, even when it is not clear that the heavy precipitation that generated flooding was a cloudburst event. For example, widespread flooding in Uttarakhand, India, that occurred in June 2013 was reported as a cloudburst event by some (Varghese and Jose Paul 2013), while others claimed it did not fit the criteria and characteristics of a cloudburst (Gulati 2013). The terms cloudbursts and thunderstorms have been used interchangeably for decades (Woolley et al. 1946), but cloudbursts are difficult to study because they are very localized events that are rarely instrumented with rain gauges, often occur on remote mountain slopes, and are only documented if lives are lost (Thayyen et al. 2013).

While the exact mechanisms for the formation of cloudburst events are not completely understood, they appear to be associated with interactions between the atmosphere and the landscape, and particularly between convection and orography. Convection within the cumulonimbus clouds associated with cloudbursts can rise to 15 km, with instability, deep convection, and strong up and down drafts from orographic forcing (Thayyen et al. 2013). Convective energy may be provided at night from evapotranspiration of vegetation, convergence on windward valley slopes, and evaporative cooling of rainfall as seen in some areas of the Himalaya (Barros et al. 2004). Alternate atmospheric mechanisms have also been proposed, such as the collision of two clouds systems (Srivastava and Bhardwaj

2013), illustrating the wide uncertainty regarding the processes that generate cloudburst floods. Given the degree of their damage to infrastructure and human capital, understanding the processes that generate cloudbursts and developing models for forecasting them are critical.

Cloudbursts represent only one example of the diversity of flood processes in mountain areas that need further investigation. Floods associated with geophysical flows, such as landslide dam outburst floods (e.g., Mason 1929), river avulsions (e.g., Sinha 2009), glacial lake outburst floods (Richardson and Reynolds 2000), and surging glacial dam burst floods (Hewitt 1982), are also highly destructive and lack adequate data and models to understand and manage them in mountain areas.

2.3 Governance structure and response resources

Risk governance in mountain areas is highly complex and is evolving. Risk management has been shifting from the historical paradigm of local, community efforts to a more current model of regional, national, and international efforts as the increasing flow of people (e.g., via road construction, development, natural resource extraction) and information (e.g., via television, cell networks, internet, and roads) reduce the historical isolation of mountain areas (Gardner 2015). The result is more national and international attention and resources committed following large natural hazards, which often focus governance on external institutions. The cumulative effects of many small events can be catastrophic to local communities, but not necessarily draw national or international attention. The transitioning of responsibility for flood risk management and response can lead to weak or unclear governance structures and a lack of/or limited hazard planning and response, including a failure to establish funding and protocols for monitoring and post-flood analyses.

2.4 Sensitivity to climate and landscape changes

Mountain areas are particularly sensitive to climate and landscape changes due to the rapid response of glaciers, snow, permafrost, water, vegetation, and soils to global changes (Diaz et al. 2003; Beniston 2003; de Jong 2015). As a result, high-elevation areas are among those responding most rapidly to climate change (Shrestha et al. 1999; Shrestha et al. 2012a, b; Qiu 2013). In fact, some of the earliest evidence of the impacts of atmospheric warming came from high mountain areas, where changing glaciers provided insight into changing cryospheric processes (Haeberli and Beniston 1998). Studies have highlighted how other hydrologic processes are rapidly changing in high mountain areas, including shifting seasonal snowpack (e.g., Cayan 1996), which drives the runoff draining mountain landscapes (e.g., Bookhagen and Burbank 2010). For areas in mountains near the melting point, small changes in temperature may result in large changes in snowpack (Mote 2006; López-Moreno et al. 2009; Stewart 2009). For example, it has been projected that the snow–rain transition will rise by 150 m for every 1 °C rise in temperature (Beniston 2003).

These changes can cascade into a range of effects on flood generation processes. Decreasing size and extent of glaciers will initially enhance runoff, until the ice has shrunk to a point that it no longer contributes to runoff, temporarily increasing flood depths and potentially triggering landslides, GLOFs, and other geophysical flows. Impacts of a changing climate may already be evident. For example, the June 2013 floods in northern India, which killed 5700 people and caused USD$2 billion in damages, resulted from unusually intense monsoonal rains, which may be a direct result of the warming climate in the Himalayan region (Qiu 2013). Similarly, unusually intense precipitation triggered massive devastation in Pakistan's Indus River basin in 2010, affecting over 20 million people and causing USD$40 billion in damages (Webster et al. 2011). The sensitivity of mountain areas to climate change (Beniston 2003; de Jong 2015) translates to increasing vulnerability of mountain communities as changing snowpack, glacial extent, and precipitation patterns increase frequency and severity of many mountain flood processes.

3 Case studies

We review five case studies of practices for flood management in lower-valley areas to identify principles for reducing flood losses and investigate how they might be applied in mountain areas.

3.1 Integrating flood risk management across multiple governance levels

Across the globe, there are multiple approaches to distributing responsibilities for and governance of flood risk management, each with positive and negative aspects. This case study outlines the governance approaches employed in the Netherlands and the USA, and identifies their evolution, strengths, and weaknesses. Critical factors in the assessment of governance structures include the attention given to the concepts of solidarity, subsidiarity, resource availability, and integrated management. Common to all of these approaches is the critical role played by those directly threatened by floods and their consequences.

3.1.1 Distributed governance in the Netherlands

The Dutch trace their efforts with flood management to the 13th century and earlier. Because of their position within the delta of the Rhine River, it was recognized early that settlements could not exist without some protection from the frequent high-water events that naturally occurred. Local groups were formed to support not only flood risk management, but also irrigation and drainage efforts. These groups relied on cooperation and collaboration, rather than laws and regulations, to accomplish water resources goals. These local groups eventually were transformed into what are now identified as water boards and grew in number so that by 1850, there were over 2500 in the country. Following the disastrous 1953 Netherlands North Sea flood, the Dutch government began a major reduction in the number of water boards to consolidate responsibilities for managing flood risk (Toonen et al. 2006). Furthermore, as modern communications developed, the need for organizational efficiency expanded, and an increased level of technical expertise became obvious, the number of water boards was gradually reduced through various reforms to 24 by 2014. A similar response occurred in the USA after the 2005 Hurricane Katrina disaster, when the State of Louisiana similarly reduced the number of its levee boards (similar to water boards in the Netherlands) to consolidate responsibilities for flood management.

At the heart of the water boards is the concept of local involvement and direction of activities, which may also deal with water quality and navigation issues in some cases. Today, water boards in the Netherlands are independent entities acting through governing assemblies that operate under the authority of the National Constitution and a Water Board Act, with the supervision of provincial (regional) governments. The national government frames the countrywide approach to flood risk management and carries out development of projects beyond the capacity of the water boards. Water boards have the power to establish budgets for their operations, levy taxes to support these operations, and develop water management plans. They also have responsibility for the supervision and maintenance of the structures that make up the flood defenses in their areas of authority and for reporting the results of periodic inspections to the national government.

The governing assemblies of the water boards generally are composed of representatives of those who live and work in the area (i.e., landowners, households, building owners, and industry) and are elected every four years. The assemblies establish their tax rates based on who benefits from the water board works, the need for cost recovery, and adherence to the principles of solidarity and polluter pays.

Because of the criticality for adequate flood protection, the national government continues to play a major role in oversight, planning, and coastal development to ensure that the proper steps are taken to address potential flooding, both from major riverine floods and from the devastating effects of coastal storms. However, through the water board system, those living in harm's way have direct involvement in managing their flood risk and generally understand the relationship of their efforts to those of others, the costs of carrying the needed work, and their personal role in providing for local flood defenses. Furthermore, because the majority of land in the Netherlands is flood prone, land use decisions are closely tied to decisions on infrastructure that reduces the risk of flooding. The government recognizes the high probability of losses associated with short-term perspectives that permit development where protection does not exist. In part, because a major flood could literally destroy the economic and social viability of the country, individuals who are likely to be affected by flooding are brought into the flood discussion at a fundamental level via the payment of taxes, the democratization of governance through election of water boards, and a national culture that understands catastrophic consequences of failure in the flood risk reduction systems.

3.1.2 Shifting governance in the USA

The management of flood risk in the USA is diffuse due to lack of regulations, rather than a deliberate flood management policy that distributes governance. Under the US Constitution, all powers not specifically delegated in the Constitution to the federal government belong to the states. Water law and land planning are not addressed in the Constitution and thus fall to the responsibilities of the states, with some notable examples discussed below. In the case of land use, most states have delegated these responsibilities to the local governments.

At the federal (national) level, two laws drive most national efforts with respect to flood risk reduction. The first was the Flood Control Act of 1936, in which Congress indicated that, "… destructive floods upon the rivers of the United States, upsetting orderly processes and causing loss of life and property, including the erosion of lands and impairing and obstructing navigation, highways, railroads, and other channels of commerce between the States, constitute a menace to national welfare … [and] flood control… is a proper activity of the Federal Government in cooperation with States, their political subdivisions and localities" (33 U.S.C. 701a, 1936). As a result, both the federal government and local institutions have constructed levees, dams, and other flood control structures across the nation to reduce the risk to those living in floodplain areas. While initially the focus of flood reduction efforts was on major cities, it was extended over time to smaller communities and non-urban areas. Projects developed by the federal government, on completion, were often turned over to the local governments to maintain and operate at their expense. To supplement federal efforts in areas not likely to be supported by a federal program, locally organized drainage districts and flood control organizations were established to fund, build, and maintain necessary structures. These local organizations typically represented the owners of the major land holdings of the regions, as opposed to the public at large. The approval of the establishment of these organizations largely rested with state and local governments, which approved the rules under which they operated. The infrastructure was developed under the supervision of state and federal agencies, whereas the operation and maintenance of flood management infrastructure were left to the local organizations. However, since each state established its own laws, the governance structures differed markedly across the nation (Holmes 1972; Holmes 1979; Galloway 2011a, 2011b).

The second law was passed in 1968 and, with supporting subsequent acts, established a national flood insurance program (NFIP). The NFIP identified areas within the 100-year (1 % annual chance) floodplain as high-risk areas and supported a flood insurance program for communities that adopted land use regulations and prohibited future construction below the 100-year flood elevation. Since 1968, more than 22,000 communities have joined the NFIP, and those in the communities have purchased over 5 million flood insurance policies. In most cases, participating communities have regulated development in 100-year floodplain. However, flood losses in the USA continue to rise for a variety of reasons. There has been only limited control over development in areas outside of the 100-year floodplain, which are still subject to floods. In addition, many of the initial designations of the 100-year floodplain are out of date because they do not reflect changes in hydrology and the advancement of flood assessment tools. Furthermore, increased runoff from upstream development has expanded the extent and frequency of flooding so that individuals and businesses that were previously outside the 100-year flood zone now find themselves at greater risk, and development behind levee-protected areas has had unintended consequences, resulting in a reduction in the probability of flooding, but increases in damages when floods do occur (CA-DWR 2012).

Following increased national interest in flood loss reduction after the disastrous 1927 and 1993 floods in the Mississippi River basin (Barry 1997; IFMRC 1994) and the highly visible consequences of Hurricane Katrina in 2005 (NCLS 2009), examinations of the national flood management efforts indicated that local governments were often ineffective at limiting development in areas of high flood risk. Studies have also determined that maintenance of many of the flood infrastructure has been severely neglected (ASCE 2013) as local governments in the organizing bodies for these protective structures did not have the resources to upgrade the structures to meet engineering standards (McGinnis 2014). It was also identified that the requirement for those living in the floodplain to buy insurance was being ignored in some cases due to a lack of enforcement of the regulations (NRC 2013).

Despite frequent calls for it, the USA does not have a national flood risk management policy, and few states have directly addressed comprehensive floodplain management. Strict land use planning does not seem to be in the immediate economic interest of local governments. Local governments look to higher-level authorities for supervision of flood risk reduction structures and program development, in part due to lack of capacity and resources and in part because of the existence of the two major national programs (1936 Flood Control Act and NFIP). However, the state of California has recently initiated a transformational program that integrates local land managers into flood risk reduction efforts in an approach that should be transferrable to other areas.

3.1.3 Evolving Jurisdictional integration in California's Central Valley flood management system

The Central Valley water supply and flood management system includes ten multi-purpose reservoirs on major tributaries and more than 1400 miles of levees to redistribute water and protect the floodplain and water infrastructure from flooding. Responsibility for and operation of the system are shared by local utilities, water districts, the USACE, the US Bureau of Reclamation (USBR), and the California Department of Water Resources (DWR). Despite the extensive implementation of flood reduction actions across the Central Valley, it is still highly susceptible to flooding. Four recent major floods (1983, 1986, 1995, and 1997) have caused well over USD$3 billion in damage (DWR 2012). Economic development in the floodplain behind levees and downstream of dams has actually increased the damages from higher-elevation floods in some areas, resulting in an increase in overall flood risk due to flood infrastructure for the largest flood events (DWR 2012). At the same time, the importance of Central Valley rivers and floodplains in providing municipal, industrial, and agricultural water supply, fisheries and wildlife habitat, and recreation has increased as a result of population growth and environmental degradation in the State of California.

In November 2006, California voters passed the Disaster Preparedness and Flood Prevention Bond Act (Proposition 1E) and the Safe Drinking Water, Water Quality and Supply, Flood Control, River and Coastal Protection Bond Act (Proposition 84), authorizing the sale of nearly USD$5 billion in state bonds for flood management improvements throughout California, with over USD$4 billion of this amount specifically earmarked for repairs and improvements to state and federal flood projects within the Central Valley. The California Legislature enacted six interrelated bills in 2007 (Senate Bills 5 & 17 and Assembly Bills 5, 70, 162, and 156) to improve flood management, strengthen the linkage between local land use planning decisions and flood management practices, and guide the use of Propositions 1E and 84 funds. Together, these bills added or amended over 25 sections in the California Government Code, Health and Safety Code, Public Resources Code, and Water Code.

The 2007 California flood legislation package outlined a comprehensive approach to improving flood management at the state and local levels, including the requirement of the local governments, as land use authorities, to consider potential flood risks in the Sacramento-San Joaquin Valley. This requirement is reflected in the Central Valley Flood Protection Plan (CVFPP), which outlines how USD$14–17 billion would be invested in flood management over the next 20 years (DWR 2012; CVFPB 2012). The investment plan articulates three landscape-scale policy directives, which are expected to be applied in future state funding eligibility criteria. One directs that the state will not invest in growth-inducing flood management improvements and will oppose such improvements even if local agencies are fully responsible financially. Implementing this, and the other directives, requires a new model for establishing coordination and accountability across jurisdictions.

This model is reflected in Senate Bill (SB) 5 of 2007 (Code §65302.9, §65860.1), which requires cities and counties within the Sacramento-San Joaquin Valley to amend their general plans, zoning, and ordinances to be consistent with the regulations laid out in the 2007 legislative package. Since the 2012 CVFPP adoption on July 2, 2013, cities and counties had up to 24 months to amend their local general plans and an additional 12 months thereafter to update local zoning ordinances. To facilitate the implementation, DWR collaborated with cities and counties, planning professionals, and interested parties to develop the Urban Level of Flood Protection Criteria (DWR 2012) to provide guidance and additional details for complying with the legislative requirements. The Urban Level of Flood Protection Criteria are not regulations, and the legislation provides no enforcement authority. The seemingly apparent gap is deliberate since any citizen could enforce the law through litigation if they demonstrate that the city or county did not apply the Urban Level of Flood Protection Criteria or make a finding with insufficient evidence. This alleviates the State of California from potential interference with local land use authorities or enforcement costs, and holds the cities and counties accountable for their own decisions on land use development. However, this approach does provide economic incentives for complying with directives that lead to flood risk reduction via access to state funds for project development and operations.

3.1.4 Summary

Each of the case studies examined faces unique problems. The USA has 320 million people, land area of 9.1 million km^2, and a gross domestic product (GDP) of USD$17.4 trillion, while the Netherlands with a population of 16 million only has 33,000 km^2 in land area and a GDP of USD$880 billion. California has a population of 39 million people, a land area of 423,970 km^2, and a GDP of USD$2.3 trillion. The differences in resources, coupled with the varying flood threats they face, drive the ability of these nations and state to carry out their flood risk management efforts.

Netherlands has clearly placed its focus on bringing management of flood risk to the local level and empowered those at the local level with the ability to deal with flood-related challenges. Where local institutions cannot deal with major flood challenge and infrastructure (e.g., the large Delta projects), the federal government accepts responsibility. The federal government also helps link local efforts of the water boards and oversees their execution. Solidarity, subsidiarity, and self-sustaining fiscal resource development play major roles in creating this balance among different levels of government.

In the USA, the federal government's 1936 move into assuming responsibilities for flood control placed state and local officials into a secondary role in development of long-term approaches to flood risk reduction. The 1968 flood insurance program furthered this federal focus by linking homeowners and individual communities directly with the federal government, in effect bypassing the states. Given these two federal programs, few states and localities have moved into strong floodplain regulation and long-term land use planning. Lack of effective national, state, and local oversight has led to the deterioration of many structural works that fell to the responsibility of local governments to maintain, but now lack the resources to repair or improve. A federally centered approach seemingly offers resources that might not otherwise be available at the local level, but as federal resources to reinvest in flood infrastructure declined (McGinnis 2014), local institutions must assume responsibilities that they have often neglected and for which they are often not prepared. Furthermore, there have been few fiscal incentives or penalties placed on local governance for their inability or lack of willingness to carry out land use regulations and flood risk management activities. Unfortunately, it is often easier to dedicate more attention and resources toward disaster recovery than to pre-disaster activities that can dramatically reduce losses in the future.

California has implemented a more proactive program for distributing responsibility of flood risk reduction, recognizing that land use regulation is a critical component of sustainable, bottom-up approach to reduce flood-related losses. With land use authority often residing at local government level, the key element of this practice is to connect local land use decisions and the potential consequence of the land development for flood risk management. Land use regulation was successfully scaled to a large area where land use authority is held by multiple cities and counties. Though this program, California has also attempted to clarify the roles and responsibilities of the State and Federal governments, and to align land use planning with other flood management actions by different levels of government and agencies as an integrated system.

3.2 Coordinated and joint operating centers for flood alert and response

Management of flood disasters requires a well-coordinated effort, a theme that is common in the management of all natural hazards. In this section, we describe a process through which hurricane emergencies are managed in a large water resources agency in South Florida and discuss elements that are relevant to the management of floods in high mountain areas.

Florida is more likely to be hit by hurricanes than any other state in the USA (Malmstadt et al. 2009). The state has an insured coastal property exceeding $2 trillion, and has been hit by eight of the ten most expensive hurricanes ever to make landfall in US history. Landfalling hurricanes in Florida cause extensive property damage through extreme winds and floods, and they challenge the extensive water control system that consists of numerous canals, levees, and water control structures. Because safeguarding the life and property of the citizens is a direct responsibility of each government agency in Florida, emergency management programs have been developed and implemented for all phases (i.e., before, during, and after) of natural hazards. Here, we describe the emergency management program that has been established by the South Florida Water Management District (SFWMD), an agency of the state for integrated management of water resources in the south Florida region. This program is based on the principles of the Incident Command System (ICS), an essential element of the National Incident Management System (NIMS) developed and used by the FEMA (2008). The ICS is a valuable tool for directing operations within a centralized, emergency management center and coordinating with other similar centers in the region.

3.2.1 Overview of incident command system

The ICS enables effective and efficient incident management by integrating a combination of facilities, equipment, personnel procedure, and communications operating within a common organizational structure (FEMA 2008). It was developed in the 1970s following a series of catastrophic fires in California, where a postmortem analysis discovered that the response to the disasters were not caused by lack of resources or failure of tactics, but rather were a result of inadequate management of the disaster. The ICS integrates many levels of government including federal, state, and local institutions and agencies, and establishes five major management functions as the foundation of the ICS: (1) incident command; (2) operations; (3) planning; (4) logistics; and (5) finance and administration (Table 1). The ICS is designed to expand or contract based on the incident complexity. Large and complex incidents may require more supervisory layers to the organization structure than smaller incidents. Establishment of ICS in any agency requires customization based on the needs, resources, and nature of the hazard.

Table 1 Five essential management functions of ICS

Incident command	Sets the incident objectives, strategies, and priorities and has overall responsibility for the incident. The Incident commander has overall responsibility for managing the incident by establishing objectives, planning strategies, and implementing tactics
Operations	Conducts operations to reach the incident objectives. Establishes the tactics and directs all operational resources
Planning	Supports the incident action planning process by tracking resources, collecting/analyzing information, and maintaining documentation
Logistics	Provides resources and needed services to support the achievement of the incident objectives
Finance and administration	Monitors costs related to the incident. Provides accounting, procurement, time recording, and cost analyses

All these functions are standard organizational units in the ICS structure established in SFWMD (Fig. 1)

3.2.2 Establishment of the organizational structure for implementing ICS at SFWMD

The first step in establishing ICS was to identify an Emergency Management Advisory Committee (EMAC) consisting of individuals representing positions in the emergency management organizational structure. This team identified the personnel, equipment, and other local, state, federal, and private agency resources that were needed to support emergency operations. Based on the initial brainstorming of the team, several key impacts of hurricanes were identified, including: (1) infrastructure damage (critical facilities, roads, etc.); (2) debris in canals; (3) loss or failure of the communication system; (4) shortage of fuel; (5) impact to business and to flood management staff; and (6) power failures. The next step was to create a permanent position of an emergency manager for facilitating the development and implementation of the emergency management program. This person has the responsibility for the development of the Comprehensive Emergency Management Plan (CEMP) and supporting documents using an "all-hazard" approach. An all-hazard approach takes advantage of the common capabilities necessary to respond to any type of disaster or emergency, but allows for incorporating unique response needs for particular types of hazards, such as natural hazards, hazardous material incident, radiological incident, or an act of terrorism. This emergency manager also facilitates coordination among various individuals and departments within the organization, and identifies training needs and practice exercises. Managers of individual divisions in the agency are responsible for development of standard operating procedures (SOPs) and the assignment of personnel. In SFWMD, the primary divisions include engineering, construction, operations, planning, regulation, and field stations. The SOPs define the roles of personnel in various organizational units depending on their experience and skills. After the declaration of an emergency, the employees assume assigned duties and their reporting switches to the emergency management structure.

A key step in the emergency management program was the creation of an Emergency Operations Center (EOC). The physical setting of EOC is a permanent location where meetings, training, and exercises are held. During an incident, it becomes the location where EOC staff conduct centralized incident coordination. The building has been constructed to protect response staff, critical infrastructure such as the computing systems, and vital records such as hydrologic data, financial records, and infrastructure design documents. The facility can withstand wind speeds of up to 200 miles per hour. Critical data are

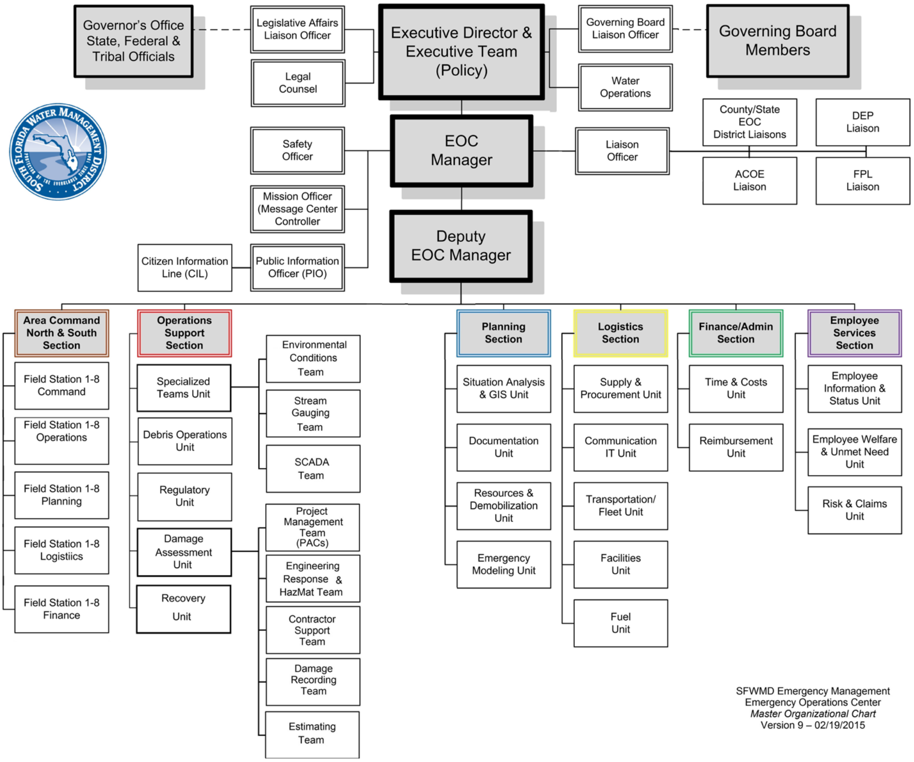

Fig. 1 Organizational structure of SFWMD EOC. The functions of ICS (Table 1) have been implemented as sections in the EOC structure. The functional units within each section have unique functions identified. Acronyms define the Army Corps of Engineers (ACOE), the Florida Department of Environmental Protection (DEP), and Florida Power and Light (FPL). All other acronyms are defined in the text

also duplicated in a remote location to ensure continuity of operations. The EOC is a locational focal point for emergency or disaster management, and it permits a faster response and recovery than a decentralized system would provide. When activated, the EOC is a complete management system consisting of executive staff, affected organizational units, employee teams, and key external partners who have been trained on respective emergency roles and responsibilities (Fig. 1).

3.2.3 Activation and functioning of EOC

In consultation with the Executive Management Team of the agency, the emergency manager initiates the declaration of the emergency (also known as an "incident") when necessary. The activation of EOC for dealing with the emergency typically occurs in levels. The sequence moves from Level 3 (normal day-to-day operation) through Level 2 (partial activation) to Level 1 (full activation). During Level 1 activation, all normal SFWMD operations not supporting the particular emergency are suspended. The EOC provides for the following functions: (1) determining incident priorities through situation assessment. A situation assessment is a snapshot of the present conditions that is used to plan for the future, involving the gathering, analysis, synthesis, communication, and discussion of data for making planning decisions about goals, objectives, and developing response strategies; (2) providing strategic coordination and drafting action plans; (3) acquiring critical resources and deploying them to impacted areas. For SFWMD, these resources range from heavy equipment (i.e., cranes, excavating and earthmoving equipment, dump trucks, backhoes, front end loaders, and pumps) to fill dirt, rip rap, fuel, communications equipment, and appropriately trained or qualified personnel for the task assignment; and (4) inter- and intra-agency coordination, including agencies outside of the district that include the local power company, County Emergency Operations Center, State departments of Environmental Protection and Emergency Management, and federal agencies such as USACE and FEMA.

The EOC collects information from a variety of sources, such as other county EOCs and impact assessments conducted by district response teams. This information is used by the SFWMD's Public Information Officers to develop statements and update external media during the emergency for dissemination to the public, including through social media. Additionally, liaison officers facilitate interagency collaboration and information sharing (Fig. 1). Finally, specialized teams are deployed to share information on impacts to SFWMD facilities, structures, and operations.

During an emergency, the Planning Section of EOC is responsible for the development of two primary documents. The first document is an incident action plan, which is created to define the incident objectives and reflects the tactics necessary to manage the incident during a specified operational period. An operational period is the period of time scheduled for executing a given set of tactical response actions as specified in the incident action plan. Operational periods can vary depending upon the stage of the response. The length of the operational period is established at the beginning of the operational planning cycle and subsequently reviewed and adjusted throughout the life cycle of the incident. The period is typically 12–24 h at the beginning of an incident requiring extensive response efforts. As the SFWMD's response transitions from immediate response to short- and long-term recovery, operational periods may be several days or a week. For example, if a culvert is washed out, the priority during the first few operational periods may be to stabilize the culvert to prevent further damage. Once it is stabilized, the objectives may transition to more permanent repair. Operational periods transition to one week or longer when operations are focused primarily on recovery programs.

The second document is the Situation Report, which communicates the incident status to audiences outside of the EOC and is an outcome of daily briefings, situation assessment, and interactions with external entities. At a minimum, this document is produced once a day during the response phase, but may be produced more frequently depending upon the nature of the incident. It is the primary means for communicating the status to SFWMD governing board members, executives, local, state, and federal agencies.

During the activation of the EOC, extensive coordination among local, state, and federal agencies occurs to ensure there is no duplication of effort, and an efficient response is provided to manage the hurricane emergency. In addition to liaisons who directly coordinate with other management agencies, Web-based software systems (e.g., WebEOC, Intermedix 2015) are now available for incident tracking, used extensively by SFWMD to provide secure, real-time information sharing to assist emergency response personnel and regional field stations in mission assignments. These systems provide the ability to request and track resources, facilitate briefings, and provide complete documentation of all actions that were taken in response to an emergency incident.

3.2.4 Summary

The development and implementation of the emergency management program at SFWMD was challenging because the daily problems or situations that generate the public interest will always have a higher priority. However, the emergency management system, based on ICS, has been very beneficial in managing hurricane response. The EOC organizational structure supports disaster response planning effectively through proper coordination of internal staff and external stakeholders, development of standard operating procedures, and training. The system consists of clearly defined responsibilities, governance, a central command, and communication. The acquisition and communication of reliable information to the public and agencies external to and internally within EOC involves several tools, such as interviews with both print and television media, liaisons located within EOCs of several agencies, citizens' information hotlines, employee communication through the Web, social media, and software tools such as WebEOC.

3.3 Early warning systems: saving lives in Colorado

3.3.1 Overview of early warning systems

Advance warning of floods can substantially reduce the loss of life and damage of property (Sorenson 2000) by providing time for people to evacuate and to move valuables to higher elevations. Early warning systems have been developed over time to include a suite of field observations (i.e., river depth, precipitation), satellite-based observations (i.e., precipitation, wind speed), software (i.e., weather prediction, hydrologic models), data storage and management, hazard assessments, and transmission and alert systems (Fig. 2). Technical

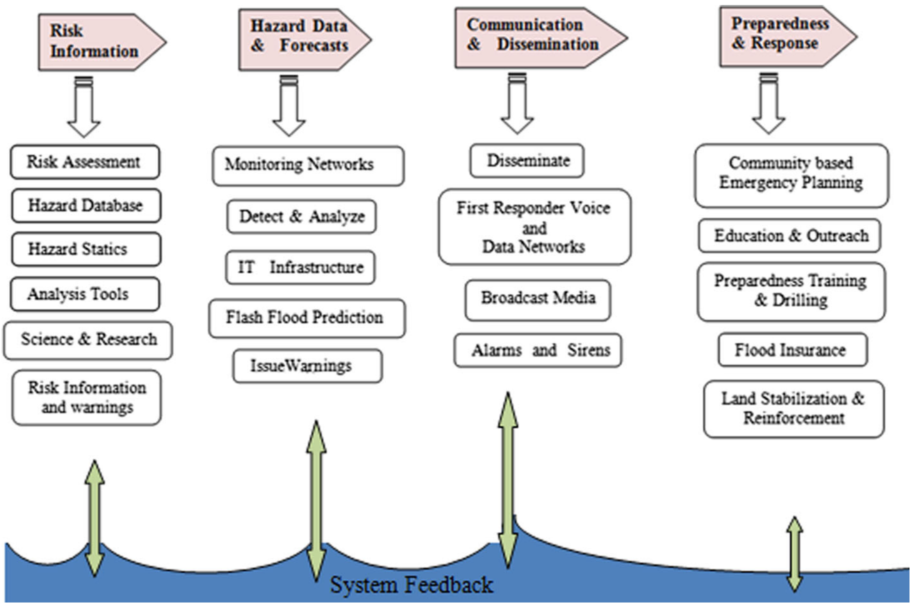

Fig. 2 Components of an early warning system Modified from University Corporation for Atmospheric Research 2010

challenges typically focus on providing adequate accuracy and lead time for the advance warnings (University Corporation for Atmospheric Research 2010) to generate appropriate and timely precautionary action. However, the perception of risk and response of people to the warnings is one of the most important, and often underemphasized, elements of early warning systems, significantly impacting the ability to reduce losses (Twigg 2003). Thus, in addition to the technical elements of a forecasting system, effective early warning systems must also have a strong focus on the characteristics and social vulnerabilities of the people exposed to the floods (Basher 2006) to help them prepare for and appropriately respond to early warnings.

3.3.2 Success and challenges of an EWS in Colorado

The Colorado Front Range is the portion of the Rocky Mountains that is drained by the headwater channels of the South Platte River basin. Primary flood generation mechanisms in this semiarid, dry gulch include intense local thunderstorms that lead to flash floods, intense widespread rainfall, and snowmelt (Collins et al. 1991). The area has a long history of flash floods from local thunderstorms, the most destructive of floods, which generally occur from May through September (University Corporation for Atmospheric Research 2010). In the summer, subtropical Pacific moisture can generate both widespread rainfall events and intense local thunderstorms, primarily in the southwestern mountainous areas of the state. During these events, runoff from the mountains quickly causes the water levels of small creeks and dry streambeds to rise to unsafe levels, regularly reaching heights of 10–20 feet. The most destructive of the flash floods was the 1976 Big Thompsons Canyon floods (NOAA 1976), which resulted in the loss of 146 lives. However, the event was a catalyst for change, resulting in collaboration between county, local emergency management agency officials, and weather forecast offices to develop early warnings and other mitigation measures for flash floods (NOAA 2014).

Subsequently, another major flash flood event occurred in this same area during September 2013. A low-pressure system centered on the western side of Colorado Front Range pulled a plume of warm, tropical, moisture-rich air from the Gulf of Mexico into Colorado from the southeast (Scott 2013). Torrential rainfall occurred from September 9 through 16, resulting in severe flash flood conditions that stretched for about 150 miles, from Colorado Springs north to Fort Collins. Over 17 inches of precipitation fell during this 7-day period (Fig. 3), exceeding historical records and resulting in a 1-in-1000 year rainfall event that fell on already saturated soils. The flood resulted in over USD$2 billion in damages and nine deaths, destroying almost 485 miles of roads and 50 bridges in the impacted counties. Over 18,000 homes and businesses were damaged or destroyed by the ensuing flood (Fig. 4) (Smith et al. 2014). Mountain landslides and streambank failures were common, with floodwaters carrying large boulders and debris, carving new channels and creating new floodplains.

Although the infrastructural losses were inevitable, the proactive planning, coordination, and early warning systems are attributed to reducing life losses in 2013 by over 93 % in comparison to 1976 flood (Curtis 2013). The Urban Drainage and Flood Control District, NWS, and local emergency management offices worked closely together to deliver critical warning messages to response agencies and the public prior to and during the flooding (NOAA 2014).

The city of Boulder, one of the hardest hit communities, and their management partners prepared for flood hazards by, (1) deploying automated early flood detection network of rain and stream gauges; (2) developing flood warning plans within individual basins that

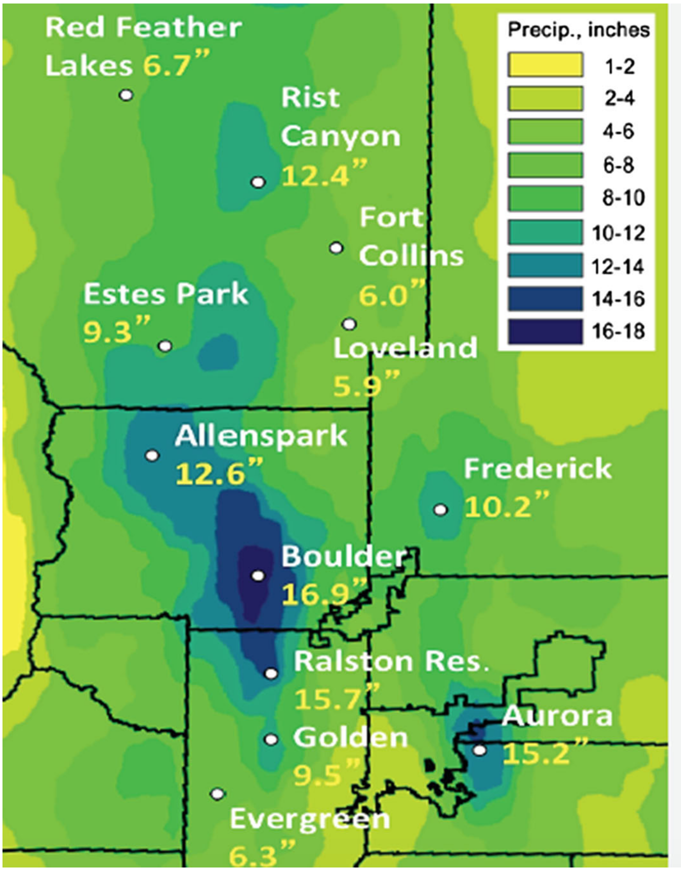

Fig. 3 Total precipitation map from September 9–15, 2013, flood event *Source*: Lukas 2013

Fig. 4 Examples of severe flood damages in Colorado counties (*Source*: Andy Cross, Getty Images)

were based on the different zones of flood risk, and creating polygons specific to flood prone areas with crafted messages that were unique to that polygon area (Pittman 2014); (3) revising standard operational procedures to better address flood threats; (4) conducting annual flood training exercises (e.g., message dissemination, evacuation, emergency response procedures); (5) introducing technological enhancement (e.g., data collection and transmission system, higher lead time forecast models); (6) improving the public warning system; and (7) increasing coordination, cooperation, and communication.

In addition, a number of forecasting and warning tools were critical during the 2013 event. The NWS Weather Prediction Center began issuing 48–72-h forecasts as early as 5 days in advance of the occurrence of event. WPC refined these forecasts as the event approached and highlighted areas of slight and moderate risk for excessive rainfall capable of producing flash flooding. Another useful tool was the Short-Range Ensemble Forecast System, which produced more consistent rainfall magnitudes than the Weather Prediction Center, though the location and timing of the heaviest rain was not consistent. In addition, Colorado's Automated Local Evaluation Real-Time (ALERT) system, comprised of 220 rain and stream gage networks, was developed more than three decades ago in response to 1976 Big Thompson flood event, The ALERT system generated over 240 rainfall alarms during the week-long storm period of September 2013, disseminating notifications to a large number of forecasters, emergency managers, public works officials, and others via e-mail and text messages. In addition, stream gages recorded record peaks at 39 locations, resulting in over 800 total alarms (Stewart 2013). Beyond the ALERT networks, the Urban Drainage and Flood Control District operates a flood prediction and notification service for local governments during the flood season, deployed by a private meteorological service, which produced 162 forecast products and initiated 266 voice contacts with local governments between September 9 and 15, 2013. Furthermore, over 440 NWS communications were relayed by the Denver-regional Emergency Managers Weather Information Network during that same week. Combined, these communications contributed to the situational awareness that local residents and decision makers relied upon to anticipate and react to the flood conditions (Stewart 2013). Collectively, 78 Flash Flood Warnings were issued with an average probability of detection of 94 % and an average lead time of 69 min. Alerting methods included sirens, texts, calls, e-mails to residents through Government Everbridge Mass Notification System, activated Emergency Alert System and Wireless Emergency Alerts, and messages distributed via social media.

The major lessons learned from September 2013 flooding centered around the awareness that static flood hazards often do not accurately convey flood risks in steep gradient watersheds in the western USA (Varrella and Turner 2014). As the start of the September 2013 event approached, deterministic model guidance displayed considerable variability for timing, location, and magnitude of heavy rainfall. While deterministic models may improve for steep catchments in the USA, decision-making and alert systems should be structured to incorporate and manage uncertainties in forecasts. In addition, the flood warning gauges were susceptible to severe damage, resulting in some key installations becoming inactive in the first one to two days of the flood event. Thus, the most robust warning systems will include gauging stations at locations and configuration where flood hazards are least likely to impact data collection and transmission, and will integrate redundancy for stations with critical data.

3.3.3 Summary

The local flood warning system that evolved over the past 37 years, following the 1976 Big Thompson Canyon flash flood, helped save lives during the September 2013 floods in Colorado. Through the coordination and communication between the NWS and other local flood agency programs and resources, expanded data collection and analysis infrastructure, and extensive pre-event planning, and efforts to increase public awareness, people were more successful in protecting themselves during the flash flooding of 2013, relative to 1976. However, despite the significance of flash flood events and the demonstrated benefits of early warning systems, few countries have implemented flash flood warning systems. This is due in part to the technical complexity of forecasting and resources required to predict flash flood events with enough confidence (accuracy) and lead time (advance warning) to take precautionary action. Furthermore, improving the effectiveness of early warning systems does not, in itself, lead to reduced risk for disaster prone communities. The early warning system is only effective if it can successfully trigger correct and early actions to reduce losses.

3.4 Utilizing remotely sensed data in hazard assessments

3.4.1 FEMA's HAZUS-MH Methodology for estimating flood losses

Remotely sensed data can provide a critical resource to managing floods in areas where field data are scarce. However, remotely sensed data alone are not enough, and algorithms to translate those data into assessments of flood risk and losses can require expertise that may not exist in rural and mountain areas. This capacity issue is addressed to some extent in HAZUS-MH, a GIS-based methodology established by FEMA to rapidly estimate potential physical, economic, and social losses from floods, as well as earthquakes and hurricanes. The output can contribute to the preparation for, mitigation of, response to, and recovery from natural hazards, and has been shown to successfully contribute to a variety of flood management projects, such as the evaluation of vulnerable populations to levee breaches (Burton and Cutter 2008) and of alternatives for activation of floodways (Luke et al. 2015).

Very broadly, the HAZUS algorithm first characterizes the flood hazard based on flood elevations to define the flood boundary and depths (Scawthorn et al. 2006a), then calculates potential damages (e.g., buildings, vehicles) and losses (e.g., life, agriculture) (Scawthorn et al. 2006b). Direct loss calculations are made based on a library of depth–damage curves (e.g., Figure 5), which are provided with the model or can be entered manually by the user. The model also contains algorithms to estimate indirect economic losses, shelter needs, and the benefits of early warnings, levees, and other flood management practices.

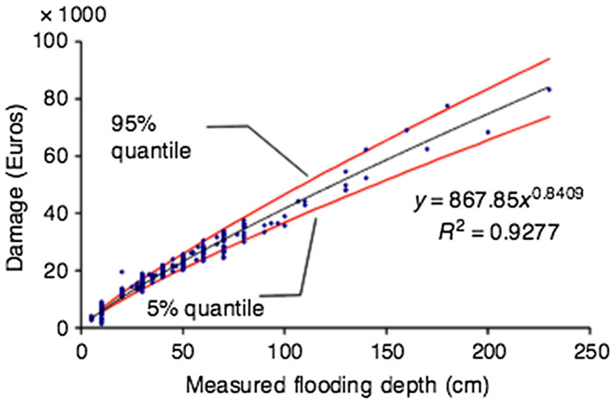

Fig. 5 Example damage curve for building contents, with uncertainty *Source*: Freni et al. 2010

The level of analysis can be coarse to site-specific, with varying levels of accuracy (Ding et al. 2008), depending on the users' data, resources, and needs. For application in the USA, users load remotely sensed and/or default data into the HAZUS-MH model, including topographic data that lead to a digital elevation model, ground elevations of buildings, flood elevations, floodplain boundary information, FEMA's Q3 and/or Digital Flood Insurance Rate Map flood layer data, Flood Insurance Rate Map data, hydrology, agriculture products, vehicles (approx. # per occupancy classification), essential facilities, transportation and utility facilities, census demographics, and census tracts and blocks. In addition, the user can define individual facilities, defined by the parcel shape, number of stories, foundation type, first-floor height, content cost, square footage, and building value, among others. Resulting loss estimates include (1) area-weighted damage estimates based on the depth of flooding within a given census block, (2) cost of repair/replacement, shelter needs, temporary housing, vehicles, crop and livestock losses, (3) induced losses from debris resulting in direct damage to buildings, based on floor areas for census blocks; (4) indirect losses for sectoral economic impacts; (5) annualized losses; (6) direct economic losses as afunction of business inventory, restoration time, and income loss data; and (7) damage for individual facilities.

Though valuable, the HAZUS approach is not without limitations, including those inherent to flood modeling generally and those specific to HAZUS (Merz et al. 2010). Strengths of the approach include the ease of use for the GUI and GIS interface, the ability to address both riverine and coastal floods, the available tools for preprocessing data for input, and the thorough documentation of the tools. Weaknesses include the fact that the algorithms run on proprietary software (ArcMap), issues with model instability, and the simplistic representation of levees. In addition, the spatial scale of analysis occurs at the census block level (unless buildings are entered as user-defined facilities), which is valid only if the composition of buildings is evenly distributed throughout the block. However, some of these limitations can be overcome, and thus the reliability of loss estimates with HAZUS-MH improved, by replacing default databases with local data, particularly for the input DEM, if they are available (Tate et al. 2015).

3.4.2 Example remote sensing-based hazard assessment: ice jam floods in Eagle, AK

HAZUS has been applied in a number of locations and across a range of scales, including a national-scale study of averaged annual loss (FEMA 2010). This example focuses on an application in Eagle, Alaska, where HAZUS was applied to identify areas where risk to ice jam floods is low for rebuilding following a flood. Eagle, Alaska, is a small (2010 population 86) rural town located along the south bank of the Yukon River. Despite its small size, the town has important historical significance, with buildings from the Gold Rush era listed as a National Historic Landmark and the town serving as an important stop along the Yukon Quest sled dog race.

The Yukon River is the fifth largest river in North America, with a catchment of about 300,000 km^2 upstream of Eagle (Brabets et al. 2000). The river drains glaciated mountains in northwest British Columbia and southern Yukon Territory, flowing north toward the Bering Sea. The typical annual hydrograph exhibits two peaks (Livingston et al. 2009). The first peak, which occurs in early May, is associated with ice jams, which generate the highest flood risk of the two flood processes. Ice jams are stationary accumulations of ice fragments that restrict and/or block flow (Ashton 1978). During ice breakup periods in the spring, ice jams can result in flooding by elevating river elevations upstream of the jam. Alternately, ice jams can fail instantaneously, sending a rapid and destructive wave (aka jave; Jasek and Beltaos 2008) of floodwater and ice fragments downstream (Smith 1980). Ice jams develop at geometric transitions in the channel (Smith 1980), such as in a reach between Dawson and Eagle, AK, where the channel transitions to a narrow, single-thread channel with steep valley slopes and a contracted floodplain (Livingston et al. 2009). The second peak in unrelated to ice, occurring later in the summer (e.g., June) as snow and glaciers melt upstream in the catchment.

Ice jam floods represent important flood hazards due to their destructive nature, the difficulty in providing early warnings due to the complex suite of factors that contribute to ice jam failures (Smith 1980) and the logistical and instrumentation challenges associated with gauging them (Livingston et al. 2009; Jasek et al. 2001). The reach of the Yukon near Eagle, AK, is particularly hard hit by ice jam floods. Analysis of a 108-year record at Dawson, approximately 100 miles upstream of Eagle, illustrates the geomorphic and hazard significance of these events. Ice jam events occur frequently in this reach, on the order of five times in 111 years (Jasek et al. 2001). Furthermore, ice jam floods appear to be the only hydrologic events that generate out-of-bank flows in this reach (McCreath et al. 1988). A dyke was constructed in 1959 to protect Dawson from ice jam floods, though the height had to be raised several times (McCreath et al. 1988), due to the challenges associated with design of flood protection for ice jam events that are often not reliably predicted with the standard frequency-based flood analysis.

The 2008–2009 water year in Alaska was characterized by record-high snowfall, followed by high April temperatures. This sequence led to flooding throughout the Yukon region from runoff of melting snow and ice. An ice jam formed approximately 10 miles (FEMA 2009a) downstream of Eagle on May 04, resulting in floodwaters rising over a steel retaining wall. As water and ice accumulated in the reservoir behind the ice jam, businesses, homes, and trees were damaged and/or pushed off their foundations by the water and "house-sized" ice (FEMA 2009a). The damages were severe (Fig. 6), with up to USD$6.9 million provided by FEMA and the US Small Businesses Administration to assist in the recovery efforts (FEMA 2009b) that included funding to repair and replace housing, property losses, and business losses.

HAZUS-MH simulations were rapidly conducted during the response phase of the flood to focus and facilitate recovery efforts by identifying areas most severely impacted (FEMA 2010). Furthermore, HAZUS-MH was used after the event to identify areas outside of the likely ice boundary for rebuilding after the flood (Fig. 7). By integrating HAZUS-MH simulations with aerial photography and perishable data collected during the event, managers were able to identify the boundaries of the flood and ice to establish recommended building setbacks and minimum first-floor elevations (FEMA 2010). The result was that some residents moved to higher-elevation areas in a new part of the town, whereas other homes were elevated at their original location (FEMA 2009b).

The HAZUS-MH toolkit can be an important resource for hazard assessment in mountain floods in a variety of ways. In areas where local information and expertise is scarce, and/or decision and response times are short, HAZUS-MH can be an invaluable tool for developing information on flood hazards that lead to more informed decisions prior to and following floods. It also provides a venue for collaboration and communication across management jurisdictions, researchers and managers, and managers and the public (Jackman and Beruvides 2014).

Fig. 6 Ice jam damage in Eagle, AK *Source*: FEMA 2010

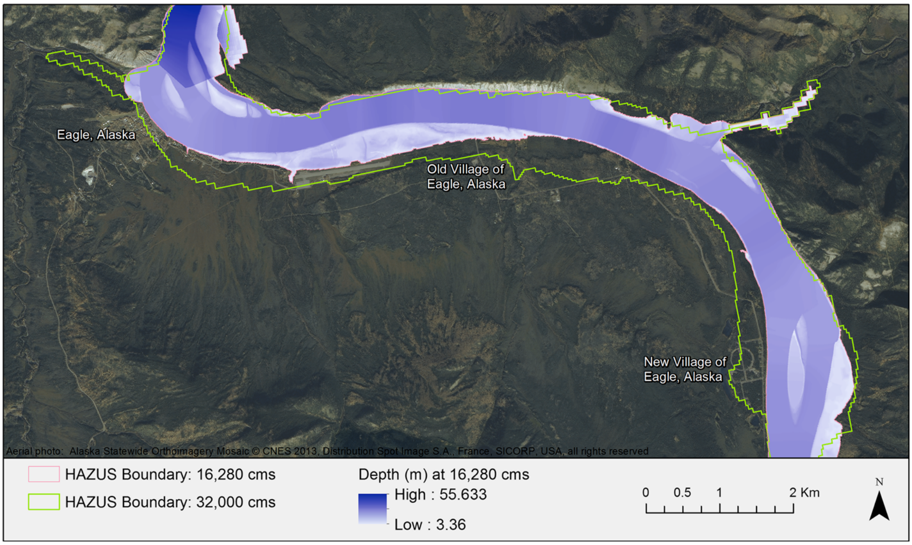

Fig. 7 Depth grid and ice boundary for 2009 Eagle ice jam, generated using HAZUS *Data source*: Kelly Stone, FEMA

3.5 FEMA's community rating system

3.5.1 Background on the community rating system

FEMA's Community Rating System (CRS) is an innovative program that incentivizes flood risk reduction activities through reduced flood insurance rates. The CRS has three primary goals (FEMA 2015a, b): (1) reduce flood insurance costs by reducing the damage caused by floods; (2) utilize the framework established by the NFIP to improve floodplain management beyond the required baseline already in place through the NFIP; and (3) utilize every aspect of flood loss prevention through floodplain management, including public education, early warning systems, and other non-structural and ecological approaches to flood mitigation. Through the CRS program, communities implement projects that demonstrate improvement in flood management and effort toward reducing flood impact. Communities are assigned to classes based on the number and type of projects implemented, with each class having a corresponding flood insurance premium reduction (Table 2). Communities start as a Class 10, representing 0 % discount on flood insurance premiums. Each project is associated with a number of credit points that are organized by four elements of the program (Table 3), such that the number and level of projects completed determines the percent reduction in flood premium costs, with a maximum attainable 45 % reduction from normal flood insurance rates for a Class 1 community. CRS has established a list of 18 qualifying projects, which are categorized under public information, mapping and regulations, flood damage reduction, and flood preparedness (Table 2, FEMA 2015a, b).

The CRS impacts flood losses in two key ways. The first is the implementation of mitigation measures, with credits designed to emphasizing some actions (e.g., strengthening land use regulations) over others (e.g., flood elevation certificates). The more measures implemented in the community, the lower the class of the community and the higher the insurance rate reductions (Table 2). The other key impact of the CRS on flood losses is the promotion of public involvement. In order to be considered a CRS community,

Table 2 Percent reductions in NFIP flood premiums across CRS ratings *Source*: FEMA 2015a, b

Class	Discount (%)		Credit points required
	SFHA	Non-SFHA	
1	45	10	4500+
2	40	10	4000–4499
3	35	10	3500–3999
4	30	10	3000–3499
5	25	10	2500–2999
6	20	10	2000–2499
7	15	5	1500–1999
8	10	5	1000–1499
9	5	5	500–999
10	0	0	0–499

SFHA refers to Special Flood Hazard Areas where the NFIP's floodplain management regulations are enforced and flood insurance is required. Insurance discounts are lower for areas outside of the SFHA and increase as the class, reflecting number of projects implemented, increases to incentivize implementation

Table 3 Points credited for various mitigation actions taken under CRS

Mitigation action	Maximum points
Public information	
Elevation certificates	162
Map information service	140
Outreach projects	380
Hazard disclosure	81
Mapping and regulations	
Additional flood data	1346
Open space preservation	900
Higher regulatory standards	2740
Flood data maintenance	239
Stormwater management	670
Flood damage reduction	
Floodplain management planning	359
Acquisition and relocation	3200
Flood protection	2800
Drainage system maintenance	330
Flood preparedness	
Flood warning program	255
Levee safety	900
Dam safety	175

The CRS has 18 projects with a maximum attainable number of points under each projects (FEMA 2015a, b)

a community must demonstrate public involvement, such as educational opportunities or workshops to enhance knowledge and awareness on flooding. As seen in King County, where 15 % of their efforts focused on public outreach, public involvement can have a large impact on the effectiveness of flood mitigation approaches (Fig. 8).

3.5.2 CRS participation in King Co., Washington

Across the USA, over 1250 communities, representing over three million policyholders, participate in the CRS, and the benefits of the program appear to be large. For example, in the Clear Creek watershed near Houston, Texas, a 10-year study documented an 88 % reduction in flood insurance claims after the CRS program was implemented there (Blessing et al. 2014). In this case study, we report on the participation of communities within King County, Washington, which represents a model community due to its extensive efforts to reduce the impacts of flooding. Located in the western portion of Washington State, King County is a large political district that drains six catchments with a range of flood and socioeconomic conditions. Since 1990, the year King County began participating in the CRS, the County has experienced 12 federally recognized flood disasters (King County 2015a). Between 1990 and 2007, they implemented a variety of projects to reach a Class 2 status, resulting in a 40 % reduction in flood insurance premium that translates to 1400 policyholders receiving, on average, a $550 insurance reduction per year (King County 2015b).

The projects implemented within King County support the four elements of the CRS (Table 3). King County advanced public records and informed the public on flood management by utilizing a number of approaches. For example, maps regarding flood

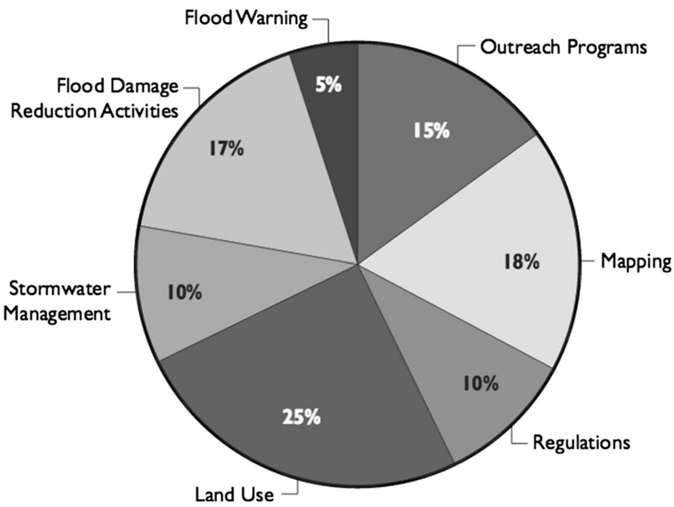

Fig. 8 Breakdown of CRS credits in King County *Source*: King County 2007

insurance rates and FEMA elevation certificates now have a regular maintenance schedule. King County also conducts substantial outreach on flood status and planning, protection assistance, and other topics through a variety of venues, including online, at libraries, through brochures, and walk-in inquiries. Furthermore, King County communicates regularly with residents regarding the limitations, purchase requirements, and motivations behind flood insurance policies (King County 2015b).

King County has tackled both mapping and land use regulations to reduce flood risk. Since joining the CRS, the county has mapped hundreds of miles of waterways to more effectively understand the impacts of floods (King County 2015b). Land use regulations require any development above the 100-year flood level to have three feet of protection to prevent damage. In addition to setting a limit on the distance of development from the floodplain, over 100,000 acres of floodplain in King County has been preserved in its natural state (King County 2015b). King County has also delineated channel migration zones, the areas into which the river is expected to migrate over time, in order to reduce development in areas subject to flood hazards over time.

Flood damage reduction was addressed in part through establishing the King County Flood Control District in 2007. Organized as a council, the members provide suggestions of projects to reduce flooding, which are to be carried out by the King County Department of Natural Resources and Parks. Projects include elevating houses to above the 100-year base flood elevation and improving flood mitigation facilities (King County 2015a, b).

Flood preparedness has been addressed in King County through extensive flood warning systems, including a flood warning system that provides flood forecasting to over 5000 people (King County 2015b), and through recognition by the National Weather Service as a StormReady community.

3.5.3 Summary

While the CRS represents an effective, incentive-based program for engaging communities in flood mitigation, participation within the USA is still limited, with only 1300 of the

22,000 participating and only 12 achieving the CRS classes of 1–4. The low participation is presumably associated with the cost of implementing the practices needed to reduce flood risk and achieve low CRS class designations, as well as the issues of centralized flood management in the USA, as discussed in Sect. 3.1.2. Despite the limited participation in the USA's CRS program, the model is still valuable, and can be modified to fit the available resources and social and geopolitical conditions of other areas. The key component to making the CRS unique from other flood mitigation approaches, ultimately, is the fact that it is community-driven and that the incentives are compelling to those communities. Particularly in mountain areas, such a program may be crafted to focus on public education, improving flood infrastructure, and/or increasing the data available related to flooding and access to that data. However, application of a similar program in mountain areas requires identifying the right incentives for the communities involved.

4 Discussion

It has been 17 years since the United Nations declared 2002 the International Year of the Mountains (Diaz et al. 2003). This declaration reflects the importance of mountains to the environment, economies, and social systems of the world. Mountains provide up to 100 % of water resources for people living the lowlands beneath them (Meybeck et al. 2001) and are considered to be "biodiversity hotspots" (Price et al. 2000). However, the lack of research on and comprehensive management of mountain flood hazards threatens the sustainability of these globally important socioecological systems (Diaz et al. 2003, ICIMOD 2009).

Based on the case study synthesis provided herein, review of peer-reviewed and gray literature on flood hazards, and discussions with global leaders in flood management (Tullos and Jain 2015), we identified five key practices that are needed to address the substantial and unique challenges of reducing flood risk in mountainous areas.

4.1 Acquire and effectively communicate reliable information

The first practice reflects the development and effective dissemination of information about flood hazards. Developing new information about flood hazards requires robust and long-term monitoring of floods and instrumenting of the elements of the landscape that trigger floods. Our case studies highlight how the communication and dissemination of information, via Incident Control Systems, early warning systems, and through the CRS, have contributed to reduced flood risk. However, the effectiveness of acquiring and communicating flood information is situationally dependent on the communication networks and other local constraints. Thus, monitoring programs will need to be customized to the local resources, needs, and nature of the flood hazard. The World Meteorological Organization (WMO) produced the Guide to Hydrological Processes (2008), which offers several suggestions for hydrologic gauging of mountains. For example, given the variability in runoff across elevations in a mountainous region, precipitation and streamflow gauging networks should be located such that they equally represent the distribution of flood events across the network. In addition, because mountain rivers are typically characterized by high velocities and turbulent flows, transport of boulders and other large debris, and high variability of flows depths, gauging locations should be located in areas of stable channel geometry and rectilinear flow to avoid damage during floods, which may require modification of the channel. Beyond the WMO's (2008) basic principles for traditional gauging of mountain areas, as well as the use of remotely sensed precipitation and other hydrometeorological data, new instrumentation is needed to provide reliable and timely gauging of mountain areas that are durable under flood events for advancing understanding and management of flood events.

4.2 Conduct basin-scale hazard assessment and flood response planning

Hazard assessment and disaster response planning are essential to reducing flood losses and can be applied in a number of ways. Broadly, hazard assessment involves establishing boundaries of high-hazard areas and the degree of hazard within those areas, identification of risk mitigation measures, and the application of risk assessment outputs as a way of prioritizing to prevent the greatest losses. While conducting hazard assessments in mountain areas is complicated by limited and understanding on flood processes, some tools exist that provide estimates of hazard boundaries and likelihoods, with a range of reliabilities. For example, HAZUS-MH can be an effective tool during the response and post-flood redevelopment in a high-mountain flood, though defaults within HAZUS-MH are not likely to be valid for many high mountain areas. Localizing inputs, such as structure inventories and high-resolution DEMs, are likely to be necessary for output from the tool to be reliable. In addition, early warning systems can be effective in reducing the loss of life even in areas subject to flash floods, which can be challenging to forecast. However, the collection of data and communication of warnings in high mountain areas, where access to gauging stations difficult and steep catchments can limit connection to the cellular network, remain a critical limitation and development need. Remotely sensed data and satellite communication networks offer promise, but are likely to result in lower accuracy and shorter lead times of flood warnings.

Other tools also exist and should be included in a comprehensive flood response plan. For example, the flood inundation and hazard from GLOFs has been mapped in Nepal (ICIMOD 2011). That effort involves analysis of aerial photos and satellite images to map glacial lakes, dam break modeling, and hazard assessments for people and infrastructure downstream, which is valuable for identifying vulnerable populations, but can be unreliable in estimating the probability and timing of occurrence. However, all of these tools require the collection and integration of field-based and/or remotely sensed data, highlighting the importance of adequate local capacity, in terms of personnel, instruments, and motivation. Furthermore, the data and analysis results alone do not complete a hazard response plan. Data and analyses must be applied in the identification of actions and responsibilities prior to a flood event.

4.3 Clearly defined and distributed governance responsibilities

Conflicts and questions around responsibility arise, as occurred during the destructive Jammu Kashmir floods of 2014 (Najar and Barry 2014), when response by officials is slow and inadequate. This finger pointing appears to occur most often when the scale of the disaster is beyond the capacity of local governments to respond. This trend suggests that raising the capacity of local governments and explicitly articulating the roles of different institutions during a natural hazard are especially critical in mountain areas. Effective governance in mountain areas requires that management of local needs and resources must be balanced with management and resources from national and international institutions (Gardner 2015). By clearly defining responsibilities, flood managers, responders, and the public know who is in charge of what actions and the chain of command for decision-making during and following a flood event. The ICS model implemented in the SFWMD provides an important framework for structuring responsibilities across jurisdictions.

A central theme in the sustainable management of flood risk appears to be the shift toward shared responsibility (Fig. 9) for mitigation and response, and especially including individual residents and local agencies. The concept of shared responsibility requires coordinated and complementary actions by state and local agencies and avoiding overreliance on federal support and subsidies. From the case studies we reviewed, we see the benefits of this shared responsibility is most evident in the Dutch system and California's new land use regulations, whereas the problems associated with centralized flood management at the federal level are evident in the federal US system. A key result of weak governance is reflected in a lack of or limited hazard planning and response, and/or the lack of resources to manage hazards as they arrive. Strong governance systems include funding, protocols, and clearly delineated responsibilities for the planning, response, and recovery phases of a hazard, including monitoring and post-flood analyses.

4.4 Implement effective and diverse mitigation measures

Dams and levees have been effective at reducing flood losses in many areas of the world. However, unintended consequences, including social (Tilt et al. 2009) and environmental (Ligon et al. 1995; Hillyard and Goldsmith 1989) impacts, increases in flood risk when coupled with unregulated floodplain development (CA-DWR 2012), and changing hydrology (Milly et al. 2008), all call into the question the long-term effectiveness and sustainability of centralized, structural flood management strategies for every location. These strategies are particularly problematic for high mountain areas, where the limited predictability of floods (e.g., from GLOFs, landslides, cloudbursts) generate substantial design and operational uncertainties and limit the degree and reliability of flood risk reduction provided by centralized, gray (i.e., dams) flood infrastructure. For example, construction of concrete dams throughout the Himalaya to protect downstream communities from landslide-triggered floods and GLOF is neither practical from a cost perspective nor is it effective from a risk reduction perspective. Instead, academics and water resources

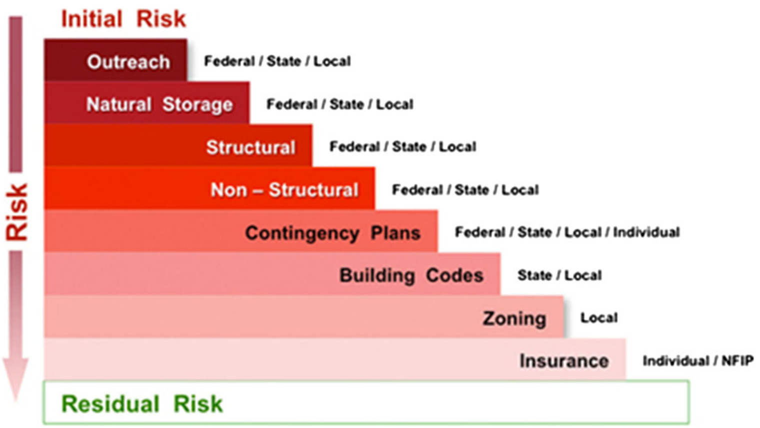

Fig. 9 Shared responsibility in flood risk management *Source*: USACE 2015, which is modified from original source: Riley 2008

managers (Bandyopadhyay and Ghosh 2009; Gleick 2003; Hall and Murphy 2012; Rijsberman 2006) have argued that there is an urgent need to shift focus from more traditional engineering philosophies on centralized flood management to a more comprehensive management approach that distributes flood management across many different strategies and stakeholders and increases flexibility of flood management systems under a changing landscape (DiFrancesco and Tullos 2015). These strategies, such as the land use regulations discussed in Sect. 3.1.3, as well as other practices such as floodplain reconnection and early warning systems can be highly effective in reducing flood losses. In addition, for mountain areas in particular, preserving and restoring vegetative cover, through sustainable agriculture and forestry practices, is a critical element to minimizing the generation and impact of floods in mountain areas (Beniston 2003). In addition to land use regulations, the implementation and enforcement of building standards and codes (i.e., flood proofing, retrofits for existing buildings) for buildings, roads, and bridges are an essential element of fostering resilience to floods (Burby et al. 2000) in mountainous areas. However, such strategies to flood management require collaborative research, the acquisition and sharing of reliable data, policy development (Juarez Lucas and Kibler 2015), and engagement of public officials and the public.

4.5 Train and engage local residents and officials

Establishing public involvement in flood risk management is essential in any flood management setting. Indeed, a primary barrier to switching toward more sustainable and effective flood management is the public's lack of awareness of and individual responsibility for reducing their vulnerability to floods (Riley 2014; Moran and Russell 2014). The historical "flood control" paradigm has led citizens to: a) believe that the government can prevent all catastrophic flooding; b) obtain very limited and only required knowledge (e.g., FEMA's Flood Risk Maps of inundation zones) about their own flood risk (Galloway 2014); and c) maintain little to no awareness of their individual responsibility for reducing flood vulnerability.

Instead, the public should be involved in flood mitigation planning and flood response. For example, the public may develop and serve on neighborhood planning and response teams. In addition, evacuation planning should include both early warning systems and early warning drills. Furthermore, public officials need to be part of those developing knowledge on flood risk and engaging in its reduction, contributing to hazard assessments and planning, dissemination of reliable information, and implementation of effective flood mitigation measures. Furthermore, each of these means of engaging the public requires that flood managers develop types of information that are useful to specific groups and work continuously to ensure that the communities are indeed engaged.

5 Conclusions

Mountain areas are an important source of cultural, ecological, and life-sustaining resources, but are also subject to devastating natural hazards. Flood hazards in mountain areas are generated by a number of landscape processes (e.g., landsliding, glacial lake failures, local convective and orographic precipitation events) that do not occur in the valley floodplains, where most flood hazard planning and infrastructure has historically been developed. Special attention is needed to effectively manage floods in mountain areas, taking into consideration the challenges posed by the complex topography and hydrogeology, the limited data and infrastructure, weakly defined governance structures, and sensitivity to landscape and climatic changes.

Five practices were identified as necessary for reducing flood risk in these vulnerable areas, involving (1) the acquisition and effective dissemination of information about floods, (2) basin-scale hazard assessment and flood response planning, (3) clearly defining governance responsibilities and distributing them across multiple jurisdictional layers, (4) implementing effective and diverse mitigation measures, and (5) training and engaging local people and officials in flood risk reduction. These practices represent elements of comprehensive flood management and may be considered a checklist for managers organizing flood disaster prevention and response plans. Specific examples were discussed on implementation of these practices in mountain areas that reflect the physical, infrastructure, technological, and social challenges that these communities face. Broadly, implementation of a comprehensive flood management program in mountain areas requires a logistical and scientific commitment to long-term monitoring and analysis, integrated model-based studies of environmental change and management impacts, and process-based studies of hydrology along altitudinal gradients and across mountain regions. Implementation also requires commitment to the resources needed for distributed governance, effective planning, development and enforcement of appropriate land use and building regulations, and successful and continued engagement of the public.

The more these practices are implemented in mountain areas, the easier it will be for other communities to adapt and adopt them. As such, it would be beneficial to implement pilot projects to demonstrate a flood safe community in the mountains as a model for other communities. Such a demonstration project should emphasize the implementation of projects within a culture of adaptive management and with sensitivity to equity issues that often occur with marginalized communities in rural areas. The impact of such a program is likely to spread beyond the pilot projects to other communities and beyond the mitigation flood disasters to other natural hazards.

Acknowledgments This manuscript derived from discussions at a workshop on Modeling and Managing Flood Risk in Mountainous Areas, funded by a grant from the Indo-US Science and Technology Forum. We also gratefully acknowledge comments from anonymous reviewers that helped improve the clarity of the manuscript.

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