SCIENTIFIC BRIEFING

HYDROLOGICAL PROCESSES
Hydrol. Process. **30**, 4214–4223 (2016)
Published online 21 June 2016 in Wiley Online Library (wileyonlinelibrary.com). DOI: 10.1002/hyp.10919

A clear and present danger: Ladakh's increasing vulnerability to flash floods and debris flows

Alan D. Ziegler,[1]*
Sebastian I. Cantarero,[2]
Robert J. Wasson,[3]
Pradeep Srivastava,[4]
Sonam Spalzin,[5]
Winston T. L. Chow[1,3] and
Jamie Gillen[1]

[1] *Geography Department, National University of Singapore, Singapore, 117568*
[2] *Tropical Marine Science Institute, National University of Singapore, Singapore*
[3] *Institute of Water Policy, Lee Kuan Yew School of Public Policy, National University of Singapore, Singapore*
[4] *Wadia Institute for Himalayan Geology, Dehra Dun, India*
[5] *Archeological Survey of India, Srinagar, India*

*Correspondence to: Alan D. Ziegler, Geography Department, National University of Singapore, Singapore 117568.
E-mail: geoadz@nus.edu.sg

Received 21 October 2015
Accepted 11 May 2016

Abstract

This preliminary investigation of the recent spate of deadly flash floods and debris flows in Ladakh (India) over the last decade identifies uncontrolled development in hazardous locations as an important factor contributing to loss of life and property damage in this high mountain desert. The sediments exposed in the channel banks and on the alluvial fans of several mountain streams in the area indicate a long history of flash floods and debris flows resulting from intense storms, which appear to have increased in frequency within the last decade. The signposts of these recurrent hazards are being ignored as a growing economy, which is boosted by a well-established tourism industry, is now driving development onto lands that are susceptible to floods and debris flow hazards. In this science briefing we argue that the increasing vulnerability in Ladakh should be addressed with sound disaster governance strategies that are proactive, rather than reactionary. Copyright © 2016 John Wiley & Sons, Ltd.

Key Words floods; vulnerability; debris flows; tourism; climate change

Introduction

The nature of a flood disaster is shaped primarily by a combination of the increasing exposure and impacts arising from the geophysical hazard itself (i.e. a flood), and from changing socio-economic vulnerabilities (e.g. Wisner *et al.*, 2004). Worldwide, flood vulnerability has been increasing, in part, because of encroachment into flood prone areas (e.g. Chang *et al.*, 2009; Tripathi *et al.*, 2014; Dutta *et al.*, 2015). Much attention has been given to increased vulnerability on the flood plains of large continental rivers because of the associated catastrophic economic consequences (Jongman *et al.*, 2014). In this science briefing, we explore the issue of increasing vulnerability and disasters on flood plains of rivers draining headwater catchments, where deadly floods and debris flows can be triggered rapidly by short-lived, extreme rainfall events. We focus on Ladakh, India, where we visited for research in August 2015 following a recent flash flood, which was preceded by an even deadlier event in 2010. Ladakh is representative of places where vulnerability is intensifying because of a rapidly growing economy, which includes a strong tourism industry, associated population growth, strains on infrastructure, and limited governmental response.

The region of Ladakh is nestled amongst the Zanskar and Ladakh Mountain ranges within the Trans-Himalayan Region, between the Great Himalayas to the south and the Karakoram to the north (Eakins, 2010). Ladakh settlements have proven resilient to the harsh high altitude desert-climate occurring at elevations ranging from 3300 to 6120 m asl. Temperature extremes range from −28 °C to 33 °C; mean annual precipitation is 115 mm (Thayyen *et al.*, 2013). Its capital Leh, built along a tributary of the Indus River, is historically an important crossroad for trade between India and

Copyright © 2016 John Wiley & Sons, Ltd.

Central Asia (Hassnian, 1975) and has been a religious centre of Buddhism for more than a millennium (Bedi, 1981). Now renowned as a tourist hub, it is a popular base for trekking, ecotourism, meditation, and religious activities in the mountains and valleys within the Jammu and Kashmir State of India (Michaud, 1991; Geneletti and Dawa, 2009). Four decades after the region opened to foreigners in 1974, tourism in Ladakh has become one of the most rapidly growing industries in the country (Pelliciardi, 2013). More than 1.5 million people now visit Jammu and Kashmir annually (Dutta, 2014). Historically, environmental hazards, including floods, seem to have been tamed by centuries of adaptation. However, recent rapid urbanization, largely in response to a growing tourism industry, has changed this situation (Dolkar, 2015a).

Recent Ladakh Floods

In 2010, intense rain fell in the vicinity of Leh during the period 4–6 August (Juyal, 2010; Rasmussen and Houze, 2012). Some initial reports claim the rainfall intensity reached $100\,mm\,h^{-1}$ (Lahiri and Pokharel, 2010). The official record lists rainfall depths of only 12.8 mm on 5 August, and 21.4 mm on 6 August (Thayyen *et al*., 2013), suggesting that the lone station may not have recorded the full intensity of the storm. Nevertheless, Leh and surrounding areas experienced deadly flash floods and debris flows that caused at least 234 deaths. But based on Army hospital records, another 800 were reported missing (Gupta *et al*., 2012). Also lost were crops, roads, bridges, schools, and countless livestock. A total of 71 villages were badly affected, with >1450 houses completely or partially destroyed (Disket Dolma, 2014). Most of these houses were located in dangerous areas on flood plains and along stream banks.

Tropical Rainfall Measuring Mission Project (TRMM) satellite estimates indicate that rain fell over four days and stretched across the Ley Valley, affecting several communities on subsequent days (Figure 1): Nhey, Nimmu and Basgo (3 August 2010); Pathar Sahib (4–5 August); and Phyang Tokpo, Tyagshi, Leh, Choglamsar, Shey, Stakmo, Ego, Latho (Gya), and Rumtsey (5–6 August). Satellite-estimated rainfall for 2–6 August ranged from 40 to 90 mm in the most impacted areas surrounding Leh (Figure 1).

Mud deposits 2–3 m thick draped Choglamsar Village, located along a tributary draining the Sabu Catchment near its confluence with the Indus River (Arya, 2011). Many people died when floodwater and a debris flow swept through lowland areas adjacent to the Sabu Stream where houses had been constructed beside ephemerally active channels, in paleochannels, or on the floodplain (Arya, 2011; Morup, 2010; Gupta *et al*., 2012). Ground floors were filled with mud and boulders—many abandoned dwellings are still partially buried after five years.

The devastation may have been caused by multiple waves of floodwater and debris, arriving asynchronously from distant tributaries, or following the bursting of temporary landslide dams that formed during the storm (cf. Arya, 2011). The estimated peak flood discharge in the Sabu Stream was $905–1070\,m^3s^{-1}$ for a catchment area of only $56–65\,km^2$ (Hobley *et al*., 2012; Thayyen *et al*., 2013). Discharges of this magnitude, although estimates, are particularly large for a catchment of this size (Thayyen *et al*., 2013). A recent hydrological evaluation by Thayyen *et al*. (2013) determined that the floodwaters were generated by spatially variable rainfall that often occurred in very small areas (0.8 to $1.6\,km^2$) with exceptionally high short-term rainfall intensities exceeding 200–300 mm within 9–12 min.

Elsewhere, damage occurred in a new section of Leh when floodwaters and hyperconcentrated flows (see below for more detail) crashed into at least two densely populated areas near the market and bus terminal (Juyal, 2010). One debris flow travelled about 3 km, destroying parts of settlements, a major bus stand, and a mobile telecommunications hub; and it severely damaged the Sonam Norboo Memorial Hospital and the local radio station (Daultrey and Gergan, 2011)—all critical components of emergency response. Throughout the greater area, debris flows uprooted telephone towers, temporarily wiping out all communication networks, and covering highways with several metres of mud and boulders (Daultrey and Gergan, 2011). Officials estimated that 80% of Ladakh's infrastructure was damaged or destroyed (IFRC, 2011).

Just prior to our visit in August of 2015, the Indus Valley experienced another destructive storm. Accounts of rainfall intensity again vary. The lone weather station at Leh measured 10.5 mm in a 24-h period; another source reported a total of 24.6 mm in 48 h (Skymet, 2015). However, our satellite-based estimate suggests some areas received more than 90 mm during the three-day period (Figure 1), resulting in flash floods and small debris flows that damaged several villages, including Wari-la, Sakti, Chushut, and Basgo (Yusuf, 2015). Floodwaters in the Skampari Stream slammed into a neighbourhood situated above the old market in Leh. The stream drains a steep catchment of about $3\,km^2$ above Leh and has now been converted into a small lane that winds past small hotels and residences to the market in the city centre (Figure 2).

Once again, the Sabu Stream flooded Choglamsar Village, but the 2015 damage was much less than in 2010. Information collected by the Ladakh Buddhist Association in Leh indicated that only two people died and one other was missing in Leh and the vicinity. A total of 235 residential and 139 non-residential buildings were

Copyright © 2016 John Wiley & Sons, Ltd.

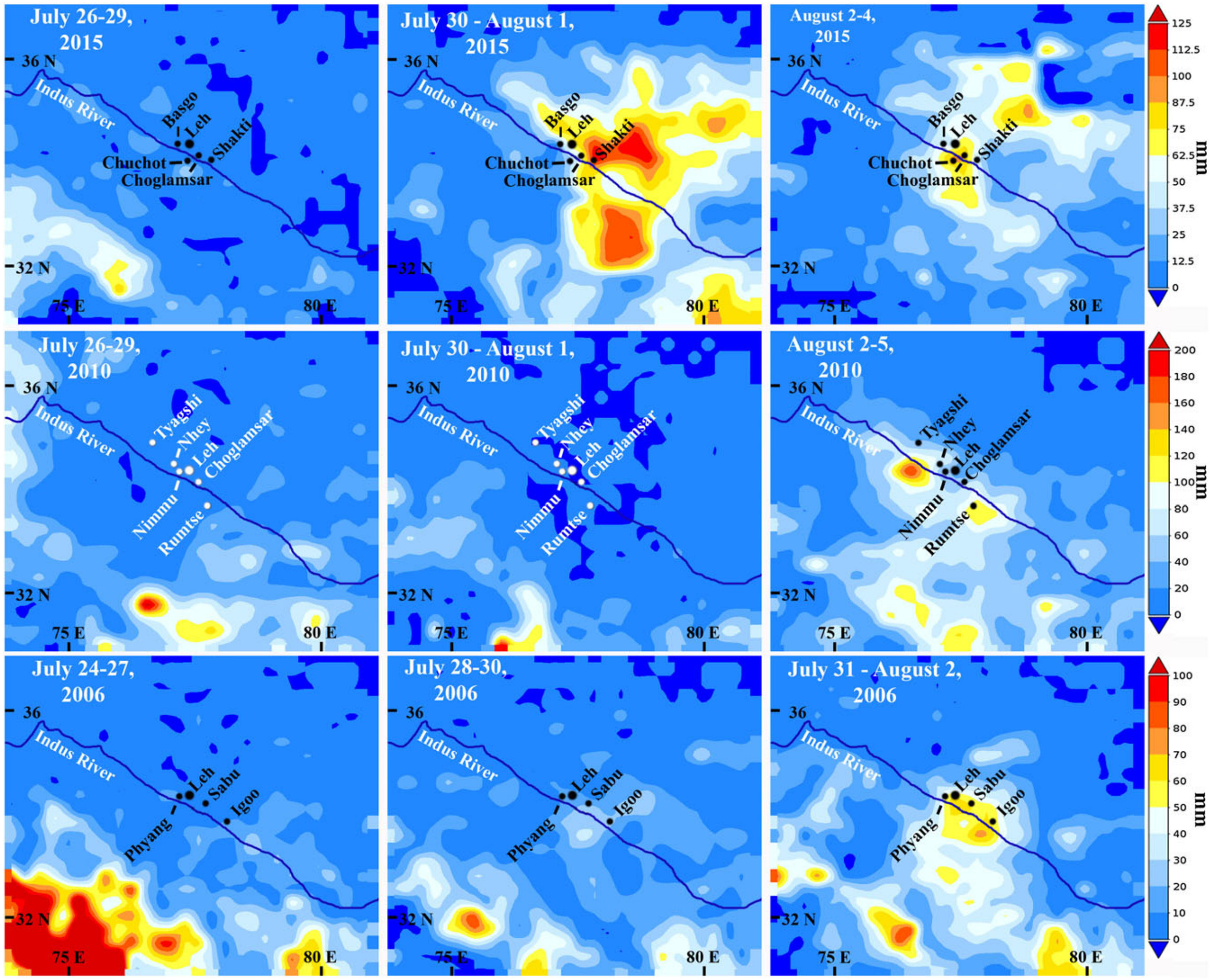

Figure 1. The right column shows total rainfall associated with flash flood and debris flow events in the Leh area of Ladakh in 2015 (top row), 2010 (middle), and 2006 (bottom). The middle column shows the rainfall occurring 1–3 days in advance of the storms. The left column shows the rainfall 4–6 days in advance. Preceding rainfall is a proxy for wetting prior to the storms, which may be an important process amplifying runoff generation (Kumar *et al.*, 2014). All estimates are based on the Tropical Rainfall Measurement Mission Project (TRMM) 3B42 V7 products (http://trmm.gsfc.nasa.gov/)

destroyed, 202 head of livestock were lost, 5 km of road connectivity was disrupted, 47 foot and motor bridges were washed away, and tens of thousands of standing crops and trees were damaged. In addition, water shortages as a result of damaged water channels, and loss of local power generation and distribution networks, compounded the dire circumstances for local residents (Dolkar, 2015b).

A History of Floods

Recollection of floods in the region over the past few decades is variable, with some residents recalling a 2006 flood that affected both Sabu and Leh, which share a common mountain peak. Before then, farmers in Leh Valley were caught unprepared in 1999 by flooding that killed livestock and destroyed crops and houses. A major flood resulting from a glacial lake outburst caused massive destruction to Nyemo village in 1971 (Morup, 2010). Dewan (2004) wrote that the Ladakh Valley had never seen floods before the 1970s, and that in 1977 just one inch of rainfall caused a flood. Early in the 20th century, however (ca. 1907), Leh Bazaar is believed to have been filled with floodwaters and mud (Morup, 2010). Few accounts of regional floods throughout the 19th century exist, and are predominantly attributed to glacial lake outbursts (Sheikh, 2015).

The sparse accounts of extreme events in Ladakh in the 19th and 20th centuries demonstrate that floods, hyperconcentrated flows, and debris flows are natural yet uncommon phenomena. During our 2015 trip we found paleoevidence of multiple, large, historical debris flows in the stratigraphy of several streams in Ladakh Valley. Nang Village, which lies about 25 km east of Leh,

Copyright © 2016 John Wiley & Sons, Ltd.

Figure 2. Leh 2015. The top photo shows the location of a former channel of the ephemeral Skampari Stream that ends abruptly in a residential neighbourhood at a small road leading to the Leh Market. The 1-m high water marks from the 2015 flood can be seen on the building on the right. The debris pile on the left was deposited during the 2010 flash flood and debris flow that entered the city. The bottom photo shows the (now) dry Skampari Stream where it enters the neighbourhood; the ephemeral stream flows from the bottom left corner of the photo (arrow)

is built almost entirely on the rubble field of historical debris flows that were probably triggered by landslides. The ruins of Shey Monastery sit on the gravels of a former channel of the Indus River, where it once intersected hillslope colluvium generated by prior mass movements and sheet flows caused by surface runoff. Recurrent floods forced the inhabitants to rebuild at higher elevation. The destructive and recurrent nature of these rare environmental hazards, which can be seen in the sedimentary record exposed in stream banks and below old settlements, is cause for alarm. The evidence suggests that these events can be expected to continue, as they are part of the geomorphic fabric of the area.

Anatomy of a Cloudburst

The colloquial term 'cloudburst' is commonly applied in India to extreme, high-intensity rainfall events throughout the subcontinent characterized by precipitation rates >100 mm/h. They can occur when monsoon clouds associated with low-pressure travel northward across the Ganges Plain into the Himalaya (Das *et al.*, 2006; Gupta

Copyright © 2016 John Wiley & Sons, Ltd.

et al., 2012). Intense events in general are often associated with thunderstorms occurring over desert and mountainous regions, and over interior regions of continental landmasses during the monsoon (Kashmir Observer, 2015). A simple definition of a cloudburst is a sudden high-intensity rainstorm falling for a short period of time in a small geographical area (<20–30 km^2), producing short-term rainfall rates on the order of ≥100 mm h^{-1} (Das *et al*., 2006).

Cloudbursts have been associated with several recent floods in the region, including the 2010 and 2015 floods in floods, and the 2013 Uttarakhand Flood (Juyal, 2010; Ziegler *et al*., 2014). Little information is known about flash floods prior to 2010, but in 2006, an estimated 50–70 mm of rainfall fell in the vicinity of Leh over a three day period (31 July – 2 August) with only minor rainfall falling near Leh during the preceding week (Figure 1). According to Thayyen (2015), there were at least three separate cloudbursts affecting nearby areas in July–August of 2006. Other recently reported cloudbursts in the area around Leh occurred in 2003, June 2005, July 2005, and August 2008 (Daultrey and Gergan, 2011; Thayyen, 2015). Thus, potentially as many as eight high-intensity storms occurring in the last 13 years were capable of generating localized flash floods and debris flows in the Ladakh region.

For the genesis of the 2010 floods in Ladakh, Rassmussen and Houze Jr (2012) describe a large (meso-scale) rain-producing cloud system that formed over the high Himalaya and Tibetan Plateau. The system received additional moisture from monsoon air masses moving northward from the Arabian Sea and Bay of Bengal. Diurnal heating of the Tibetan Plateau triggered isolated convective cells forming in the afternoon over the high terrain. The easterly 500-mb jet, which was diurnally enhanced, pushed the cells west-southwestward to the edge of the Tibetan Plateau, where they tapped the moist airflows associated with circulation around a midlevel vortex and rose up over the Himalayan wall. This moist air energized the meso-scale convective system(s) passing over the plateau, deepened convection, and enriched the precipitation-producing capability, generating discreet, spatially discontinuous, intense rain in the valley for a period of 3–4 days.

Kumar *et al*. (2014) later explained that the 2010 event was unusual for two reasons: (1) convection over the Tibetan Plateau rarely forms mesoscale systems, as smaller convective-scale locally intense showers are more typical; and (2) squall-line systems with trailing stratiform regions are rare in this region—probably because of the absence of a midlevel jet that organizes convection into squall lines. Based on their coupled land surface–atmospheric modelling simulations, they also found that significantly increased soil moisture via precipitation from the organised mesoscale convective systems likely amplified the flood impacts (Kumar *et al*., 2014).

While detailed analysis is required to assess the hydrometeorological conditions, research that is beyond the scope of this short scientific briefing, it appears that the genesis of the 2015 floods differs from those of 2010. Based on time-lapse analysis of water vapor data from the Kalpana-1 satellite (available from the Indian Meteorological Department; http://www.imd.gov.in/), a mesoscale convective cell developed over the Tibetan Plateau during the early afternoon of 2 August with the storm front arriving over Leh at about 1400 h IST. The moist air mass over the plateau prior to cell development originated from westerly upper-air advection of water vapor from previous storms along the Indo-Pakistan border on 25 July, with notable storms of smaller duration and intensity occurring on 26 and 28 July (Figure 1). The rainfall on 26 and 28 July would have increased antecedent soil moisture conditions in the catchment prior to the cloudburst on 2 August (Figure 1), and could be a factor in amplifying surface runoff.

The Nature of the Ladakh 'Floods'

The 'floods' in and near Leh in 2010 had three forms (cf. Hobley *et al*., 2012): muddy water flow, hyperconcentrated flow, and debris flow (https://youtu.be/4ezX-DJ9Z5w; https://youtu.be/RHANGY1Js-w). Muddy water flow was characterized by marked turbulence without large boulders suspended in the flow. Hyperconcentrated flows were characterized by lower turbulence with boulders that appear at the surface then sink and reappear further downstream (see videos listed above). Hyperconcentrated flows typically contain about 40% sediment by volume; debris flows contain about 65% sediment (USGS, 2005). As the sediment concentration increases so does the ability of a flood to carry very large boulders in suspension—as was the case in 2010.

Our observations verify that all three forms of flow were also present during the 2015 events. The deposits are certainly indicators of debris flows and floods, although the latter consist of sand and gravel with little mud, suggesting that the fines were transported down valley either during the main event or subsequently. We also found some deposits with the characteristics of hyperconcentrated flows. In contrast, the events in 2010 were much more intense and damaging (Hobley *et al*., 2012). For example, we did not find that very large boulders were transported by debris flows in streams at Choglamsar or Sabu in 2015, as was the case in 2010 (Figure 3).

Ladakh is an ideal location for intense rainfall events to turn into deadly flash floods and debris flows. First, the

Copyright © 2016 John Wiley & Sons, Ltd.

Figure 3. (Top) Partially buried homes and piles of debris still remain in 2015 adjacent to the stream in Choglamsar where a debris flow devastated a residential area in 2010. Most local residents rebuilt in place—and as a result, many were victims of flooding again in 2015. (Bottom) A home rebuilt along the Sabu Stream on a former debris flow

paucity of vegetation on hillslopes to intercept rainfall and the thin hillslope soils with limited water storage capacity contribute to flash flood generation. Second, ample sediment is present to contribute to the initiation of debris flows. Leh and surrounding villages are located in one of the widest segments of the Indus River valley, which is bound by intensely deformed sedimentary rocks of the Zanskar Range in the south and a batholith of foliated granite in the north. The Indus River is flanked by wide and steeply dipping alluvial and colluvial fans that originate from the Zanskar Range, funnel-shaped fans originating from the batholith, and fluvial terraces (Santi *et al*., 2010). The valley walls at places are mantled by sand ramps. All these geomorphic elements create extensive barren surfaces with semi-consolidated sediments beneath that potentially become sources of clastic material transported by floodwaters. Finally, the creation of small debris dams in streams can generate waves of floodwater and mass sediment flows once they break (cf. Juyal, 2010; Arya, 2011).

Examination of the Nang Stream to the east of Choglamsar and Leh revealed a history of exceptionally large debris flows (Figure 4). In one section, we found distinct debris flow layers, some with boulders in excess of 1 m (largest axis). While we do not yet know the age of the flows, we know that large debris flows have been recurrent in the past in several locations along the valley. Collectively, these events are potential indicators of either a past climate regime that was different from today or extreme events of this climate regime that have not reoccurred recently. If they are the latter, the people in the area are likely more vulnerable to flash flood and debris

Copyright © 2016 John Wiley & Sons, Ltd.

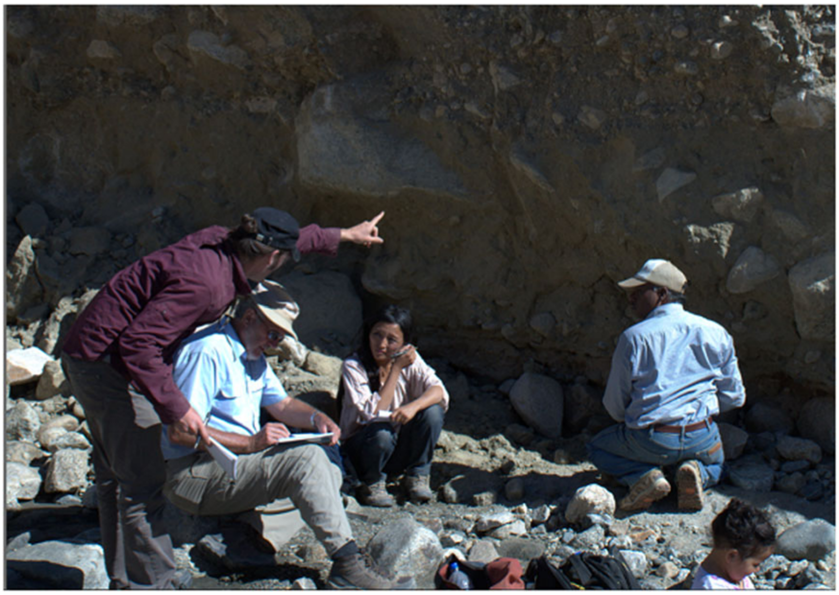

Figure 4. Several of the authors collecting samples for optically stimulated luminescence dating of debris flows (used to calculate reoccurrence intervals) in the Nang Stream, which drains from headwater glaciers to the Indus River

flow hazards than the tragedies of the last decade have exposed.

Increasing Vulnerability

Vulnerability refers to the characteristics of a person or group and their situation that influence their capacity to anticipate, cope with, resist, and recover from the impact of an environmental hazard (Wisner *et al.*, 2004). The hazards in this case are infrequent, extreme rainfall events and associated flash floods and debris flows that are naturally occurring phenomena in the headwaters of the Indus River in Ladakh. It is not possible to know with certainty if a changing climate has increased the frequency of these events recently, contributing to increased flooding. A recent trend analysis of 16 years of TRMM products reports increases in heavy rainfall over the region (Bharti, 2015). However, the association of extreme events and elevation is not conclusive, producing some uncertainty in the analysis. Also, the shortness of the time series limits our ability to infer much about climate change. Earlier, Bhutiyani *et al.* (2010) failed to find significant changes in monsoonal rainfall for Leh during the period 1901–1989 (based on monthly data).

Regardless of the role of climate change, we believe that flash floods have turned into disasters, in part, because of the reckless urbanization that has been taking place within and along the channels and floodplains of fluvial systems draining mountain catchments in the valley. Ladakh has been inhabited for centuries, with villages established historically in safe locations with respect to floods. One can see evidence of time-tested resilience, for example, in the relocation of the monastery at Shey at least twice in the past in response to flooding. Further, traditional stonewalls were once built for defence against invaders, and to some degree, invading flood waters. The rapid pace of development may now compromise this resilience.

Increasingly, in the vicinity of Leh, many buildings are constructed on fans, which themselves were built mainly by debris flows. The fans were once used solely for agriculture, but houses have replaced many fields as urban areas have expanded far from the city centre. Some of the new houses springing up in Leh since the 2010 flood are located in or near channels (Figure 5). The owners, new immigrants from nearby Kargil, constructed the houses unaware of the recent violent history of the stream. A reminder came in 2015, but its relatively small magnitude may not have been a strong enough deterrent to stop building in such hazardous areas.

Contemporary urbanization has ignored the environmental signposts—for example those recorded in the sedimentary archives of many streams—that demarcate dangerous locations that have been struck by floods and debris flows in the past. Building codes that should prevent unsafe construction and site location have been ignored or have not been enforced. In response to recurrent flooding in recent years, many of the local people we spoke to recognize the dangers, but claimed they had no alternatives to (re)building and living in such locations. Rebuilding on the site of a prior disaster is not a new situation. Examples can be found in the mountainous Upper Indus Basin in Pakistan following frequent debris

Copyright © 2016 John Wiley & Sons, Ltd.

Figure 5. A new house built in the dry channel of the Skampari Stream, which flooded both in 2010 and 2015. The house (right) and the toilet (left) are built on opposing 'banks' of the ephemeral stream. New housing has sprung up in response to a wave of recent immigrants. Over the last 50 years, the numbers of houses in the area have also increased with the change from polyandrous to nuclear families. Tourism is also driving urbanization

flows (Santi *et al*., 2010), in Thailand and India following recent large floods (Ziegler *et al*., 2012 a,b, 2014), as well as on coasts following tsunami inundation (Ziegler *et al*., 2009). Rebuilding or relocating is also a very complex and sensitive issue because it often results in unintended negative social consequences (Barenstein, 2015).

Unique in Ladakh (as in Kedarnath in the Upper Ganges) is the potential threat to thousands of tourists visiting the area at naturally risky times (Ziegler *et al*., 2014). In 2010, one hundred foreign nationals or non-local tourists lost their lives (Gupta *et al*., 2012). Tourism is an important driver of economic development, unchecked urbanization, and rural-to-urban migration in the region (Fewkes, 2008). As of now the industry has not developed contingency plans for visitors or for the sustainability of businesses should a catastrophic event take place.

In the 2010 event, the immediate response of the Indian Army for search, rescue, and relief greatly mitigated the loss of life (Gupta *et al*., 2012). Disaster governance, however, should begin before events happen to minimize impacts by anticipating their occurrence. The need for knowledge-based policy to achieve Disaster Risk Reduction rather than response alone is consistent with the objectives of the Sendai Framework (UNISDR, 2015), the latest effort of the international community to reduce the damage from environmental disasters.

A Clear and Present Danger

The current situation in Ladakh is alarming. The diminutive protective retention walls that are being built along streams, for example the Sabu Stream in Choglamsar, to hold back the flood waters of the next cloudburst will likely only increase vulnerability by giving residents a false sense of security (cf. Newell and Wasson, 2002). The floodwaters of 2010, which were an estimated 2–5 m deep in the upper part of the catchment (Thayyen *et al*., 2013), were much higher than the walls now being constructed. Arguably, some parts of this community and others should be relocated—but key underlying questions are to where do they move and what might be the unexpected negative impacts? Regardless, all construction should be developed and performed to code, and planning pertaining to hazard safety should be enforced as new homes and hotels are built. Our 2015 visit revealed many new structures being located in extremely dangerous locations (Figure 5), demonstrating the need for greater oversight of urban developments that incorporate assessments of both the hazard characteristics and the compounding human vulnerability components.

The recurrence of flash floods and debris flows over the last decade should be motivation to prepare for the next event. In addition to the obvious need for risk assessment and hazard mapping based on calculated recurrence intervals and paleoflood reconstructions, a fine-tuned study of vulnerability, from the perspective of both residents and visitors, is needed. For example, in Nepal, Nyaupane *et al*. (2014) showed how historical environmental change cannot be divorced from the transformations caused by tourism. This attitude is critical for understanding how people living in and visiting Ladakh can adapt to the forces of nature and contribute to development over time. It is also critical for effective disaster governance (Tierney, 2012).

Copyright © 2016 John Wiley & Sons, Ltd.

Also needed is a better understanding of the physical mechanisms that produce the high-intensity events that generate deadly flash floods and debris flows, such as those in 2010 and 2015. While satellite images showing rainfall distribution, water vapor, and cloud formation have been useful for post-event assessments, their incorporation into advanced warning systems has not been realized. Some warning may be gleaned from the tendency of these systems to linger for a few days before the cloudburst occurs. Therefore, from a governance standpoint, it might be sufficient in the meantime to simply recognize that Ladakh is susceptible to rapidly occurring flood-generating storms during the summer monsoon season, particularly after initial rainfall (even of small depths) has wetted the thin soils of headwater catchments. This susceptibility is certainly clear now. The stratigraphy of alluvial and debris flow deposits of several rivers and streams we observed in the area suggest it has been present for a very long while.

Acknowlegements

This study was partially funded by the following: (a) HSS seed money grant (R-109-000-174-646) from the University of Singapore; (b) Lee Kuan Yew School of Public Policy of the National University of Singapore; and (c) Wadia Institute of Himalayan Geology, Dehra Dun, India. The project also benefited from the financial support of a Singapore Ministry of Education Academic Research Fund Tier 2 grant entitled 'Governing Compound Disasters in Urbanising Asia' (MOE2014-T2-1-017). We thank Dorje Dawa Shamsu and C.P. Dorje for their invaluable assistance.

References

Arya R. 2011. Leh Flood 2010: an extreme geological event. *Disaster and Development* **5**: 103–129.

Barenstein DJE. 2015. Continuity and change in housing and settlement patterns in post-earthquake Gujarat, India. *International Journal of Disaster Resilience in the Built Environment* **6**: 140–155.

Bedi R. 1981. *Ladakh: the trans-Himalayan Kingdom*. Roli Books International: New Delhi.

Bharti V. 2015. Investigation of extreme rainfall events over the northwest Himalaya Region using satellite data. MSc thesis, Faculty of Geo-information Science and Earth Observation, University of Twente, Enschede, The Netherlands, March 2015.

Bhutiyani MR, Kale VS, Pawar NJ. 2010. Climate change and the precipitation variations in the northwestern Himalaya: 1866–2006. *International Journal of Climatology* **30**: 535–548.

Chang H, Franczyk J, Kim C. 2009. What is responsible for increasing flood risks? The case of Gangwon Province, Korea. *Natural Hazards* **48**: 339–354.

Daultrey S, Gergan R. 2011. Living with Change: adaptation and innovation in Ladakh. Climate Adaptation. Accessed 7 September 2015 from http://www.ourplanet.com/climate-adaptation/Daultrey_Gergan.pdf

Das S, Ashrit R, Moncrieff MW. 2006. Simulation of a Himalayan cloudburst event. *Journal of Earth System Science* **115**: 299–313.

Dewan P. 2004. *Jammu, Kashmir and Ladakh: Ladakh*. Manas Publications: New Delhi, India.

Disket Dolma. 2014. Ladakh Stak-seng. Vol 1 – Summer 2014. Downloaded 7 October 2015 from http://www.ydaladakh.org/images/Magazine/Ladakh%20Stak-Seng%20Summer%202014.pdf

Dolkar T. 2015a. Water management: challenges and impact. Stawa Vol 2. Issue 8, August 2015.

Dolkar T. 2015b. Aftermath of the floods. Stawa Vol 2. Issue 9, September 2015.

Dutta S. 2014. Ladahk tourism boom sets off alarm bells in green zone. The Times of India, 12 July 2014. Accessed 6 September 2015 from: http://timesofindia.indiatimes.com/india/Ladakh-tourism-boom-sets-off-alarm-bells-in-green-zone/articleshow/38273908.cms

Dutta V, Kumar R, Sharma U. 2015. Assessment of human-induced impacts on hydrological regime of Gomti river basin, India. *Management of Environmental Quality* **26**: 631–649.

Eakins N. 2010. *Exploring Ladakh Markha Valley*. Hanish & Co. Publishers: Delhi, 10 p.

Fewkes J. 2008. *Trade and contemporary society along the Silk Road: an ethno-history of Ladakh*. Routledge: London.

Geneletti D, Dawa D. 2009. Environmental impact assessment of mountain tourism in developing regions: a study in Ladakh, Indian Himalaya. *Environmental Impact Assessment Review* **29**: 229–242.

Gupta P, Khanna A, Majumdar S. 2012. Disaster management in flash floods in Leh (Ladakh): a case study. *Indian Journal of Community Medicine* **37**: 185–190.

Hassnian FM. 1975. *Ladakh: the moonland*. Indus Publishing Co: New Delhi, 28 p.

Hobley DEJ, Sinclair HD, Mudd SM. 2012. Reconstruction of a major storm event from its geomorphic signature: the Ladakh floods, 6 August 2010. *Geology* DOI:10.1130/G32935.1

IFRC. 2011. International Federation of Red Cross and Red Crescent Societies. Case Study: Leh, India Floods 2011 DREF Operation. Downloaded 7 September 2015 from http://ifrc.org/Global/Publications/disasters/dref/cs-India.pdf

Jongman B, Hochrainer-Stigler S, Feyen L, Aerts JCJH, Mechler R, Botzen WJW, Bouwer LM, Pflug G, Rojas R, Ward PJ. 2014. Increasing stress on disaster-risk finance due to large floods. *Nature Climate Change* **4**: 264–268.

Juyal N. 2010. Cloud burst-triggered debris flows around Leh. *Current Science* **99**: 1165–1167.

Kashmir Observer. 2015. Frequent Cloud Bursts Wreak Havoc, Spark Panic. Published 24 July 2015. Downloaded 7 September 2015 from http://www.kashmirobserver.net/

Kumar A, Houze RA, Rasmussan KL, Peters-Lidard C. 2014. Simulation of a flash flooding storm at the steep edge of the Himalayas. *Journal of Hydrometeorology* **15**: 212–228.

Lahiri T, Pokharel K. 2010. Leh's Cloudburst: How much did it rain? IndiaRealtime. Published 6 Aug 2010. Downloaded 7 September 2015 from http://blogs.wsj.com/indiarealtime/2010/08/06/lehs-flash-floods-how-much-did-it-rain/

Michaud J. 1991. A social anthropology of tourism in Ladakh, India. *Annals of Tourism Research* **18**: 605–621.

Morup T. 2010. History of Flood in Ladakh. South Asian Media Briefing on Climate Change, New Delhi – 2010. Media Briefing Workshop. Downloaded on 5 September from: http://www.cseindia.org/content/south-asian-media-briefing-climate-change-new-delhi-2010

Newell B, Wasson RT. 2002. Social System vs Solar system: Why policy makers need history. IHP-VI; Technical Documents in Hydrology (TDH), No. 62. UNESCO: Paris.

Copyright © 2016 John Wiley & Sons, Ltd.

Nyaupane GP, Lew A, Tatsugawa K. 2014. Perceptions of trekking tourism and social and environmental change in Nepal's Himalayas. *Tourism Geographies* **16**: 415–437.

Pelliciardi V. 2013. Turnover of the booming tourism industry in Leh District. *Ladakh Studies* **29**: 6–12.

Rasmussen KL, Houze Jr RA. 2012. A flash-flooding storm at the steep edge of high terrain: disaster in the Himalayas. *Bulletin of the American Meteorological Society* **93**: 1713–1724. DOI:10.1175/BAMS-D-11-00236.1

Santi PM, Hewitt K, VanDine DF, Barillas Cruz E. 2010. Debris-flow impact, vulnerability, and response. *Natural Hazards* **56**: 371–402.

Sheikh AG. 2015. Floods of Ladakh: A Glimpse Through Recent History. Stawa Vol 2. Issue 9, September 2015

Skymet. 2015. Flash floods wreak havoc in Leh. Accessed 7 September 2015 from http://www.skymetweather.com/content/weather-news-and-analysis/flash-floods-wreak-havoc-in-leh/

Thayyen RJ. 2015. Floods in the Himalayas. Indo-US bilateral workshop on Modeling and Managing Flood Risk in Mountain Areas. Available at http://rivers.bee.oregonstate.edu/sites/default/files/WorkshopPPTs/floods_in_the_himalayas.pdf. (Accessed on 16 Feb 2016)

Thayyen RJ, Dimri AP, Kumar P, Agnihotri G. 2013. Study of cloudburst and flash floods around Leh, India, during August 4–6, 2010. *Natural Hazards* **65**: 2175–2204.

Tierney KJ. 2012. Disaster governance: social, political, and economic dimensions. *Annual Review of Environment and Resources* **37**: 341–363.

Tripathi R, Sengupta SK, Patra A, Chang H, Jung IW. 2014. Climate change, urban development, and community perception of an extreme flood: a case study of Vernonia, Oregon, USA. *Applied Geography* **46**: 137–146.

UNISDR. 2015. Sendai Framework for Disaster Risk Reduction 2015–2030.

USGS. 2005. Distinguishing between Debris Flows and Floods from Field Evidence in Small Watersheds. USGS Fact Sheet 2004-3142. Downloaded 5 Oct 2015 from http://walrus.wr.usgs.gov/infobank/programs/html/factsheets/pdfs/2004_3142.pdf

Wisner B, Blaikie P, Cannon T, Davis I. 2004. *At risk. Natural hazards, people's vulnerability and disasters*. Routledge: London.

Yusuf SI. 2015. Flash floods hit Kupwara, Leh areas of Jammu Kashmir. Accessed 7 September 2015 from http://www.greaterkashmir.com/news/kashmir/flash-floods-hit-kupwara-leh-areas-of-jammu-kashmir/193302.html

Ziegler AD, Wong PP, Grundy-Warr C. 2009. Still vulnerable to killer tsunamis. *Science* **326**: 1188–1189.

Ziegler AD, Lim HS, Tantasarin C, Jachowski N, Wasson RJ. 2012a. Floods, false hope, and the future. *Hydrological Processes* **26**: 1748–1750.

Ziegler AD, Lim HS, Jachowski N, Wasson RJ. 2012b. Reduce urban flood vulnerability. *Nature* **481**: 145–146.

Ziegler AD, Wasson RJ, Bhardwaj A, Sundrial YP, Sati SP, Juyal N, Natival V, Srivastava P, Gillen MJ, Saklani U. 2014. Pilgrims, progress, and the political economy of disaster preparedness. *Hydrological Processes* **28**: 5985–5990.

Copyright © 2016 John Wiley & Sons, Ltd.