Reg Environ Change (2014) 14:683–698
DOI 10.1007/s10113-013-0526-3

ORIGINAL ARTICLE

Resilience and adaptation to extremes in a changing Himalayan environment

Vaibhav Kaul · Thomas F. Thornton

Received: 22 February 2013 / Accepted: 25 August 2013 / Published online: 8 September 2013

Abstract Human communities inhabiting remote and geomorphically fragile high-altitude regions are particularly vulnerable to climate change-related glacial hazards and hydrometeorological extremes. This study presents a strategy for enhancing adaptation and resilience of communities living immediately downstream of two potentially hazardous glacial lakes in the Upper Chenab Basin of the Western Himalaya in India. It uses an interdisciplinary investigative framework, involving ground surveys, participatory mapping, comparison of local perceptions of environmental change and hazards with scientific data, identification of assets and livelihood resources at risk, assessment of existing community-level adaptive capacity and resilience and a brief review of governance issues. In addition to recommending specific actions for securing lives and livelihoods in the study area, the study demonstrates the crucial role of regional ground-level, community-centric assessments in evolving an integrated approach to disaster risk reduction and climate change adaptation for high-altitude environments, particularly in the developing world.

Keywords Climate change adaptation · Adaptive capacity · Resilience · Disaster risk reduction · Mountain environments

Introduction

Context and aim

In large parts of the Himalaya, proglacial meltwater lakes, dammed between glacier termini and unconsolidated terminal moraine deposits, are expanding due to glacial recession associated with climate change. This is heightening the risk of catastrophic glacial lake outburst floods (GLOFs) for downstream populations (ICIMOD 2003, 2004, 2005; Rosenzweig et al. 2007). The high-altitude Chenab Basin in the Indian Himalayan state of Himachal Pradesh has 31 moraine-dammed glacial lakes (Randhawa et al. 2005). The largest two lakes (Samudratapu or Samundari glacier terminus, 32°29′59.42″N, 77°32′40.51″E; altitude: 4,157 m; area: 1.05 km^2 and Gyephang or Ghepan Ghat glacier terminus, 32°31′45.20″N, 77°12′40.12″E; altitude: 4,073 m; area: 0.55 km^2) are enormous compared with the other 29 lakes (<0.1 km^2). They are also among the five lakes identified in the basin as potentially hazardous (Bhagat et al. 2004; ICIMOD 2003, 2004, 2005).

In Himachal Pradesh, precipitation intensity and frequency of high-intensity precipitation events during the summer monsoon (June–September) are projected to increase in response to climate change (Revadekar et al. 2011). Summer monsoon cloudbursts are already common in the region (Das et al. 2006; India Meteorological Department 2010). Apart from directly causing slope failures and flash floods (see, for example, Guzzetti et al. 2008; Caine 1980; Au 1993; Delrieu et al. 2005; Sah and Mazari

---

Electronic supplementary material The online version of this article (doi:10.1007/s10113-013-0526-3) contains supplementary material, which is available to authorized users.

V. Kaul · T. F. Thornton
Environmental Change Institute, School of Geography and the Environment, University of Oxford, South Parks Road, Oxford OX1 3QY, UK

V. Kaul (✉)
104/8, East End Apartments, Mayur Vihar Phase I Extension, Delhi 110096, India
e-mail: vkaulgeo@gmail.com

1998), extreme precipitation events may trigger GLOFs (Costa and Schustler 1988), either directly or by inducing mass movements into glacial lakes. Since GLOFs and extreme precipitation are sudden phenomena with similar (and potentially linked) hydro-geomorphic impacts, their implications for human communities are comparable. The study, therefore, aims at assessing the possibilities for enhancing the adaptation and resilience of communities living immediately downstream of the two proglacial lakes to glacial hazards and hydrometeorological extremes and their potential geomorphic impacts.

Objectives

The specific objectives of the study are as follows:

1. To compare local perceptions with available local scientific data on environmental change and glacial and hydrometeorological hazards.
2. To identify, using a participatory approach, the community assets and livelihood resources most at risk and the financial and social costs associated with their potential loss.
3. To assess the preparedness and adaptive capacity already in place at the community and district administration levels.
4. To identify the most suitable structural and non-structural measures for reducing disaster risk and supporting adaptation in the context of livelihoods.
5. To understand how community resilience can be sustained in the long run.

Approach

A crucial task in deescalating vulnerability to natural hazards, particularly hydrometeorological extremes, is to accelerate integrative interaction among the largely insulated research, policy and practitioner communities associated with disaster risk reduction (DRR) and climate change adaptation (CCA) (Thomalla et al. 2006; see Hyogo Framework for Action (HFA) 2005–2015 in UNISDR 2007). Venton et al. (2008) argue that the DRR community should actively build frameworks that account for the creation of new risks and amplification of existing risks by climate change. The CCA community, on the other hand, should give adequate attention to the social, economic and political dimensions of risk management, taking advantage of established DRR tools and community-based know-how. Accepting this view, the present study advocates a combined approach to DRR and CCA for remote settlements in rapidly changing high-altitude environments.

The study appreciates the role of adaptive strategies such as mobility, exchange, revitalisation, diversification and innovation (Thornton and Manasfi 2010) in increasing resilience and decreasing vulnerability at the community and regional levels. It also acknowledges the policy bias in favour of ‘planned’, externally engineered top-down approaches to adaptation, which may undermine the potential for enhancing naturally evolving, home-grown ‘autonomous’ adaptation strategies. To remedy this, the study focuses on ground-level participatory methods for appraising adaptive capacity.

Study area

The Upper Chenab Basin lies in the high-altitude tribal territory of Lahaul in the remote rural Lahaul and Spiti district (13,833 km^2) of Himachal Pradesh. It is bounded by the Great Himalaya on the north and the Pir Panjal range on the south, with ridges rising to 5,500–6,500 m, valley floors descending from over 4,500 to 2,800 m and permanent snow cover (Sharma 1986) above 4,260 m. Access is seasonal by road from the lower Kullu valley on the south through the pass of Rohtang La (32°22′15.26″N, 77°14′46.68″E; 3,980 m), the high and arid Spiti valley on the east through Kunzum La (32°23′42.74″N, 77°38′08.22″E; 4,551 m), and the Indian state of Jammu and Kashmir on the northwest by following the Chenab river gorge upstream.

The two source streams of the Chenab, Chandra (‘Moon’s Daughter’) and Bhaga (‘Sun’s Son’), rise near Phara-La-Rtse (‘Crossroads-Pass-Peak’), better known as Baralacha La (32°45′36.70″N, 77°25′24.15″E; 4,830 m), a pass connecting Lahaul and Spiti to Ladakh in Jammu and Kashmir. The streams diverge initially to unite at Tandi (32°33′02.36″N, 76°58′33.94″E; 2,862 m), enclosing an extensive spade-shaped glaciated massif. The Chandrabhaga or Chenab eventually drains into the Indus.

The study area includes the two uppermost Gram Panchayats (rural administrative units), Khoksar and Sissu, in the 115-km-long valley of the Chandra (see Table 1; maps in Online Resource A). The potentially hazardous lakes of Samudratapu and Ghepan Ghat drain into the river at locations upstream of hamlets in Khoksar and Sissu, respectively.

Methods

This is a social science study with earth science inputs. It employs an interdisciplinary, field-based and primarily, but not exclusively, qualitative research framework. The framework was devised in response to recent work on similar themes (see Online Resource B), including the Regional GLOF Risk Reduction Project in the Himalayas, 2008–2009 (UNDP-BCPR and ECHO 2008). The methods used are discussed below.

Table 1 Profile of Khoksar and Sissu Gram Panchayats

	Khoksar	Sissu
General information		
Gram Panchayat headquarters	Dimpuk (Damphung)	Khwagling-Shashan
Coordinates	32°25′00.94″N, 77°14′02.94″E	32°28′45.19″N, 77°07′37.43″E
Altitude (m)	3,118	3,065
Number of hamlets[a]	12 (+3 seasonal)	15
State (capital)	Himachal Pradesh (Shimla)	
District (headquarters under deputy commissioner)	Lahaul and Spiti (Keylong)	
Sub-district (sub-division, Tehsil and block)	Lahaul	
Sub-district headquarters (under sub-divisional officer, Tehsildar and block development officer)	Keylong	
Nearest urban settlement (distance in km)	Manali (68)	Manali (83)
Population[a] (2011)	592	777
Number of households (2011)[a]	125	120
Mean household size (persons)[a]	4.74	6.48
Mean land holding size per household[b] (ha)	0.89	1.43
Per capita agricultural income[b] (nominal; INR/USD p.a.)	28,970/525	33,929/615
Mean livestock ownership per household[b]		
Cows	1.04	1.82
Bulls	0.19	0.71
Sheep	1.15	9.04
Proportion of dwellings with cemented walls[b] (%)	63	60
Proportion of dwellings with electricity[b] (%)	100	100
Proportion of scheduled Tribes in population[a] (%)	100	98.7
Ethnicity[b]	Lahauli ethnicity based on mixed Tibetan, Munda[c] (eastern Indian aboriginal Austro-asiatic) and Indo-Aryan (northern Indian) ancestry and linguistic heritage, and religious beliefs, traditions derived from Tibetan Buddhism and Kullu-Chamba Hinduism	
Religion[b]	Buddhism (Drukpa Kagyu order), with marked influence of Hindu beliefs	
Language[b]	Bhoti	Ranglo dialect of Tinan
	(Tibeto-Kanauri or Bodish-Himalayish languages of Tibeto-Burman branch of Sino-Tibetan family[d])	
Principal occupation[b]	Agriculture; livestock rearing important in Sissu	
Major crops[b]	Potato (for seeds), pea: cash crops	

(a) Demographic, socio-economic data exclude seasonal agricultural labourers and construction workers, primarily from northwestern Nepal and the eastern Indian state of Bihar, and transhumance-practising Gaddi pastoralists

(b) Per capita annual agricultural income based on the following assumptions: 0.0844 ha (1 Bigha) land produces, on average, 2,240 kg (28 sacks × 80 kg) potatoes sold at INR 7/kg, or 675 kg (15 sacks × 45 kg) peas sold at INR 25/kg; cropped areas of potatoes and peas are equal; 80 % of land holding of average household is under potato/pea cultivation; 1 USD = 55.19 INR

[a] Census data from office of Block Development Officer, Keylong

[b] Primary survey data

[c] Punjab Government (1918)

[d] See Benedict (1972) and van Driem (2001)

Since up-to-date literature on the study area is scarce, documentation through a rapid ground survey of the area and the upstream basin was undertaken to understand the environmental and spatial context of glacial and hydro-meteorological hazards. This was accomplished using a handheld GPS device, a camera and the expertise of local residents and nomadic pastoralists. Quick maps were generated by superimposing features on Google Earth satellite imagery. Travel modes included motor vehicles, horseback and walking.

Available post-1980 precipitation and temperature datasets (mean monthly minimum and maximum temperatures, monthly precipitation and number of rainy/snowy days) from the only India Meteorological Departmentoperated weather station in the region (46 and 33 km away from the two communities) were analysed to generate a climate profile of the region, and assess changes in temperature, precipitation, precipitation intensity and precipitation variability. Early twentieth century datasets for the same station from a government gazetteer (Punjab Government 1918) were studied. Available local and regional scientific assessments of glacial change, glacial hazards (mainly GLOFs) and hydrometeorological extremes were compared with community perceptions.

Semi-structured interviews were conducted with 60 adults (4.4 % of population; 30 per community) to obtain their perceptions of environmental change; glacial, hydrometeorological and related hazards; disaster preparedness; infrastructure critical to vulnerability and community-level adaptive capacity. Spatial cluster sampling was used to represent various geographical areas within each community. Samples within each cluster were based on availability of community members, considering their engagement with farm operations. Nevertheless, an effort was made to include all income groups (assessed through land holdings). Only 37 % of the respondents were women as they were preoccupied with household and outdoor work, while men assumed only outdoor responsibilities.

Participatory exercises were organised with each community, including risk perception mapping sessions and a focus group discussion with 10 persons (including five women, two members of village administrative body). Mapping involved delineation of perceived high-risk zones for major hazards by asking participants to observe and describe the landscape from vantage points and walking with the GPS device along the identified high-risk zone boundaries, wherever physically possible. Recorded boundaries were superimposed on Google Earth satellite imagery to generate rough local-scale maps. The focus group discussions were aimed at understanding past community experiences with disasters, identifying potential impacts and community-borne costs of hypothetical disaster events in perceived high-risk zones, and identifying the most suitable structural and non-structural (institutional, behavioural, technological and information-related) measures for reducing disaster risk, supporting adaptation and sustaining resilience in the context of livelihoods.

A high-level state government meeting on disaster management was attended in the state capital and discussions were held with six local administrators at the district headquarters to assess disaster preparedness, management capacity and planning and identify appropriate long-term measures for enhancing adaptation and resilience. National-level legislation and newly developed state- and district-level plans were also reviewed in the context of the international policy framework for disaster risk reduction.

A comprehensive SWOT (strengths-weaknesses-opportunities-threats) analysis was undertaken in relation to preparedness and adaptive capacity of the community. The study is community centric (directed at communities), rather than community based (rooted entirely in communities), since adaptive capacity exists both within and beyond resident communities.

Based on a synthesis of the knowledge acquired using the above methods, recommendations were made for enhancing community adaptation and resilience to climate change-related glacial hazards and extreme hydrometeorological events in the study area.

Theoretical background

Environmental change, high-altitude glacial hazards and hydrometeorological extremes

High-altitude geomorphic systems have been disrupted on a large scale by thermal perturbations and deglaciation resulting from the rise in global temperatures during the last 100–150 years (Huggel 2009; Evans and Clague 1993). This has led to amplification of slope failure- and flooding-related disaster risks for human activity in the vicinity of glacierised areas, and in some cases, at distant downstream locations (Evans and Clague 1994). Moreover, the recent acceleration in infrastructural development, particularly tourism- and hydroelectricity related, at traditionally unoccupied unsafe locations has heightened the exposure of mountain communities to glacier-related geomorphic hazards (Haeberli et al. 1989; Richardson and Reynolds 2000; Clague and Evans 2000).

GLOFs, in particular, have emerged as a major hazard due to the ongoing recession of glaciers with resultant expansion of moraine-dammed meltwater lakes (Rosenzweig et al. 2007; ICIMOD 2003, 2004, 2005; Bajracharya et al. 2007; Reynolds 1999). Among slope failures that initiate moraine dam failure by lake displacement, ice avalanches are the most significant because the post-Little Ice Age upslope retreat of many glaciers has occurred over precipitous rock surfaces, leading to deeply crevassed glacier snouts, often with sizeable séracs (unstable ice columns), almost dangling above proglacial lakes (Clague and Evans 2000).

Richardson and Reynolds (2000) analyse records of 26 Himalayan GLOF events in the twentieth century to find that over half were triggered by displacement waves from collapses of ice avalanches into the lakes from hanging or calving glaciers. All events took place during June–October, when the combined influence of high temperatures and summer monsoon rainfall caused ablation rates, meltwater influxes and lake water levels to peak. This conforms to evidence from other mountain systems of a positive relationship between glacier outbursts (see Haeberli 1983) and episodes of anomalously high temperature or rainfall in summer or early autumn, during which the input of water, as glacial melt or rain, to the glacier bed via moulins and crevasses rises sharply (Walder and Drieger 1995; Warburton and Fenn 1994).Therefore, a future increase in extreme weather events could have direct implications for glacial hazards.

On a global scale, hydrometeorological, i.e. precipitation-related, extremes are expected to increase with climate warming, which enhances the moisture-holding capacity of the atmosphere (Trenberth et al. 2003; Groisman et al. 2005). Based on the Clausius-Clapeyron relation (concerned with phase transition; see Salzman 2004), moisture-holding capacity increases at a rate of about 7 % per degree of warming (Lenderink and van Meijgaard 2010). Results from some global climate models indicate that precipitation extremes also increase with warming at the same rate (Pall et al. 2007; Allen and Ingram 2002). However, based on four independent observational records in western Europe, hourly precipitation extremes show increase at a rate of about 14 % per degree (twice the rate derived from the Clausius-Clapeyron relation) for temperatures above 10 °C (Lenderink and van Meijgaard 2010, 2008).

Since large interregional variations occur in observed and projected changes in precipitation extremes, it is necessary to consider regional-scale assessments such as IPCC reviews for South Asia and the Tibetan Plateau, which represent the Himalayan region. Here, a general increase in heavy precipitation is projected, albeit with low confidence (Seneviratne et al. 2012). Considerable uncertainty is associated with the behaviour of the southwest monsoon and the El Niño Southern Oscillation (see, for example, Paeth et al. 2008), which govern summer rainfall in southern Asia (Krishna Kumar et al. 2006; Gadgil et al. 2004).

Adaptive capacity, resilience and vulnerability

The adaptive capacity of a community dynamically regulates its vulnerability to hazards by altering the levels of exposure and sensitivity or responsiveness (Yohe and Tol 2002; Engle 2011). Some authors perceive adaptive capacity as comprising coping capacity and resilience, which makes resilience a subset of adaptive capacity (Gallopin 2006). In this case, increasing resilience would result in adaptive capacity enhancement, and therefore (see Engle 2011), vulnerability reduction. Others identify coping capacity and adaptive capacity as constituents of resilience, which implies that adaptive capacity is a subset of resilience (Turner et al. 2003). In this case, boosting adaptive capacity would increase resilience. Although the notion that resilience is the reciprocal or exact converse of vulnerability (Folke et al. 2002) remains controversial, it is generally recognised that high resilience leads to low vulnerability (Gallopin 2006). Thus, whether efforts are intended to augment adaptive capacity or strengthen resilience, the outcome will be a decline in vulnerability, which is identified as a 'core common element' (IPCC 2012) of climate change adaptation and disaster risk reduction.

The present study adopts a combined approach to enhancing community adaptive capacity and resilience. It builds on the basic analytical design and indicators of community resilience used in the disaster resilience of place (DROP) model (Cutter et al. 2008) to generate a simple framework that incorporates adaptive capacity into the resilience-vulnerability relationship (see execution in community SWOT analysis: "Discussion: community SWOT analysis" section). This framework is intended to address Engle's (2011) concern that although resilience-vulnerability linkages have been widely explored (see, for example, Turner et al. 2003; Turner 2010; Miller et al. 2010; Polsky et al. 2007; Vogel et al. 2007; Nelson et al. 2007), insufficient attention has been given to assessment of adaptive capacity in the context of resilience and vulnerability (see Fig. 1).

Results

Climate profile

The climate of the permanently inhabited altitudinal belt (2,800–3,400 m) in the Upper Chenab Basin is represented

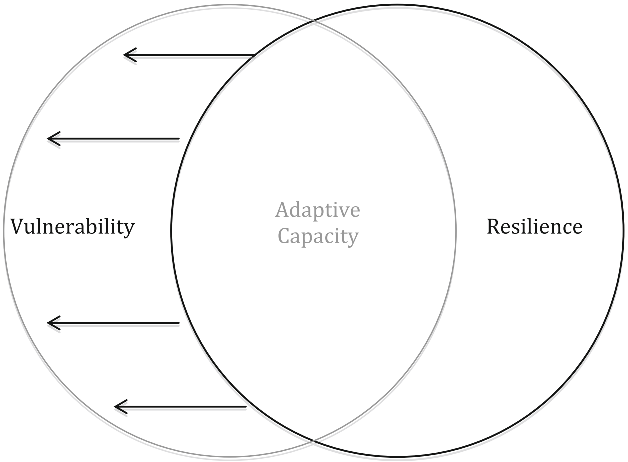


Fig. 1 A resilience-adaptive capacity-vulnerability framework. Cutter et al. (2008) depict resilience and vulnerability frameworks as overlapping, Engle (2011) labels the intersecting space as adaptive capacity, and this study adds the *arrows* to the *diagram* to indicate that increasing resilience or adaptive capacity (which are dynamic) would reduce vulnerability

by Keylong (32°34′15.30″N, 77°02′04.39″E; 3,104 m), the district headquarters and the only station of the India Meteorological Department in the region.

Keylong has a mean annual temperature of 7.6 °C, with sub-zero mean temperatures during December-February. The mean annual rainfall is 669.9 mm, of which only 24 % is received as monsoon rain during June–September, whereas 56 % is received as extratropical snow during December-March and the remaining 20 % as predominantly extratropical rain or snow in the intervening periods. The late winter months of March and February are the wettest, while the post-monsoon autumn months of October and November are the driest, but extremely variable (coefficients of variation of precipitation >120 %). The area is highly prone to avalanches in late winter (Government of Himachal Pradesh 2012). Flash floods, mudflows and landslides occur in late summer along the otherwise small Nallahs (steep rivulets, sometimes torrents), damaging property and disrupting road connectivity.

The Upper Chenab Basin falls in the orographic interior beyond the Middle Himalayan barrier; yet it is not in the Trans-Himalayan rainshadow. Consequently, it forms a peculiar transitional climatic zone with only a mild, but fluctuating, influence of the summer monsoon (coefficient of variation of seasonal precipitation >100 %). The climate of Keylong fits into the *Dfb* (humid continental climate with cold snowy winters and warm summers, and neither dry winters nor dry summers) category of the Köppen-Geiger classification. However, it is arguably a variant of the *Dsb* type (humid continental climate with cold snowy winters and warm *dry* summers), because although the driest summer month is not drier than the driest winter month, the precipitation in the driest summer month is less than 40 mm and also less than one-third of the precipitation in the wettest winter month (see Online Resource C).

Environmental change: local perceptions and scientific observations

Temperature change (see Online Resource D)

Community members in both Gram Panchayats report a general rise in summer temperatures between 1980 and the present. While all respondents in Khoksar perceive summers to have become warmer, 27% of the respondents in Sissu perceive cooling, and 30 % notice no clear trend but higher intra-seasonal variability. Both communities report generally falling winter temperatures, although the consensus is weaker in Sissu (40 %) than in Khoksar (70 %). In Sissu, 27 % of the respondents perceive no clear trend but higher intra-seasonal variability in winter temperatures, and 23 % report higher temperatures. All respondents who report colder winters associate the fall in temperature with increased dryness, particularly in early winter.

Assessment of available monthly temperature data from Keylong for the periods 1896–1916 and 2007–2012 reveals that over the twentieth century, spring and summer temperatures rose by 2.2–3.3 °C, while early winter temperatures fell by 0.2–2.0 °C. The mean annual temperature increased by 1.3 °C, from 6.3 to 7.6 °C. Though community perceptions of temperature change during 1980–2012 are fairly congruent with these observations, no temperature record is available for 1980–2006.

Precipitation change (see Online Resource E)

A decline in winter snowfall since 1980 is reported by 90 % of the respondents in Sissu and all in Khoksar. Summer rainfall is perceived by the majority of respondents to have increased in Khoksar (particularly in late summer) and decreased in Sissu. Considering the short distance between the two areas, the reported spatial contrast is noteworthy. Khoksar is situated directly below Rohtang La, a significant depression in the Pir Panjal orographic barrier. Therefore, the putative local variation could potentially be associated with a strengthening of southerly monsoon air currents that enter the Chandra valley through Rohtang La, contemporaneous with a weakening of westerly currents that follow the Chenab-Chandra gorge upstream.

In Sissu, the drying is seen as most pronounced in the critical post-sowing month of July. Yields of peas, and to a lesser extent, potatoes, are reported by all respondents in Sissu and Khoksar to be falling consistently over the last two decades. Over two-thirds of respondents consider lower rainfall during and immediately after the sowing period in June as at least partially responsible for this change.

All respondents in both communities report a significant increase during the last decade in the incidence of unseasonal snowfall and hailstorms at harvest time in late summer, increased variability in the amount and timing of early summer rainfall and upsurge in the frequency of very short spells (between 10 and 75 min) of highly localised extreme-intensity rainfall in summer.

Precipitation data from Keylong confirm that mean precipitation (principally snowfall) from October to March has decreased by 43 % between 1980–1995 and 2002–2012. The drying was particularly strong during October-December (−64 %) and March (−58 %). Extratropical precipitation in April–May (partly snow) also decreased by 44 %. As pointed out by farmers in Sissu, July (−32 %) witnessed the greatest rainfall reduction among the monsoon months. Only September became wetter (+6 %), consistent with the reported proliferation of unseasonal snowfall and hailstorm events. Mean annual precipitation declined by 36 %, from 798 to 507 mm in the same period. Trends in monthly precipitation since 1980, with linear and polynomial regression functions, are shown in Online Resource E.

Extreme variability is an inherent characteristic of the precipitation regime of the area (see "Climate profile" section). Interannual variability in precipitation increased substantially in November and May, and decreased substantially in February, August and September between 1980–1995 and 2002–2012. The exceptionally sharp rise in the ratio of standard deviation to mean for November, from 106 to 203 %, is associated with a 67 % fall in the mean resulting from a higher incidence of years with no precipitation in November. Community perceptions indicate an increase in variability only for early summer, possibly because precipitation in May is of greater relevance to agriculture than that in November.

Precipitation intensity, measured as the mean amount of precipitation received per rainy/snowy day (day with a minimum of 2.4 mm precipitation), nearly halved from 15.6 to 8 mm day^{-1} between 1980–1995 and 2002–2012. Hourly data are not available for verification of the community members' contradictory observation of an increase in the incidence of very short spells of high-intensity rainfall in summer, despite a reduction in the total amount.

Significantly, between 1891–1916 and 1980–1995, there was a 36 % increase in mean annual precipitation, from 586 to 798 mm, which was more than offset by the drying between 1980–1995 and 2002–2012. Winter (October–March) precipitation rose more dramatically (+55 %) than summer (April-September) precipitation (+17 %) from 1891–1916 to 1980–1995, just as it declined more rapidly than summer precipitation thereafter. November, December and March, which witnessed the sharpest increases in precipitation (+203, +148 and +74 %, respectively) between 1891–1916 and 1980–1995, also experienced the steepest declines thereafter. Similarly, July, the summer month with the highest rainfall increase (+67 %) between 1891–1916 and 1980–1995, became the summer month with the highest rainfall decline between 1980–1995 and 2002–2012. This reversal warrants further investigation to determine whether there have been several decadal or multi-decadal wetting–drying cycles.

Glacial change

All respondents in both communities perceive an ongoing reduction in glacial mass in the region. For instance, a 96-year-old respondent in the hamlet of Toche in Sissu, which overlooks the Sheeti Glacier, identifies the 1930s snout position of the glacier at a point (32°26′58.44″N, 77°07′27.62″E; 3,282 m) over 3 kilometres downstream of the current snout position (32°25′21.44″N, 77°06′33.74″E; 3,385 m). Glaciological studies confirm that glaciers in the Chandra Basin are receding. Mean retreat rates of some large glaciers are as follows: Samudratapu: 19.5 my^{-1} (during 1962–2000; Kulkarni et al. 2006); Bara Shigri: 29.8 my^{-1} (1906–1995; Sangewar 1995, reported in Swaroop and Shukla, GSI 1999); Chhota Shigri: 6.8 my^{-1} (during 1962–1995; *ibid.*); Hamtah: 14.4 my^{-1} (1961–2005; GSI, cited in Government of India 2011); Ghepan Ghat: 14.8 my^{-1} (1981–2008; Sangewar 2011).

Glacial and precipitation-related hazards: risk perceptions, scientific observations and potential impacts

Perceptions of risks, impacts and costs

The highest levels of current risk are perceived by both communities to be associated with winter avalanches, and no major change in risk is expected by 2050 (see Fig. 2). In Sissu, unseasonal snowfall, followed by flash floods in Nallahs, earth or debris slides, GLOFs and mudflows or debris flows are in the medium–high range of perceived current risks. Risks associated with unseasonal snowfall, GLOFs and flash floods in Nallahs are expected to rise to high-very high by 2050. Cloudburst risk is also expected to rise from just below medium to just below high, and drought risk (associated with climate drying) from low-medium to medium–high (see Fig. 2a). In Khoksar, unseasonal snowfall, followed by earth or debris slides, GLOFs, cloudbursts, rockfalls, debris flows and non-GLOF floods in the Chandra River are in the medium–high range of perceived current risks. Risks of GLOFs, unseasonal snowfall and cloudbursts are expected to rise to high-very high by 2050 (see Fig. 2b). Major current risks, as perceived by the two communities, are represented geographically (as risk perception maps) in Online Resource F. In the event of a high-magnitude avalanche or flooding-related disaster, households in the perceived high-risk zones are estimated (based on hypothetical scenarios) to potentially suffer direct financial losses ranging from 43 to 82 % of their mean annual agricultural income, excluding loss of lives and severe disruption of connectivity with the outside world (see detailed assessment in Online Resource G).

Scientific observations and modelled impacts

So far, no significant scientific risk assessment and mapping exercises have been carried out for the Upper Chenab Basin. However, apparently on the basis of past disasters, the Government of Himachal Pradesh (2012) places the Lahaul and Spiti district in the 'very high

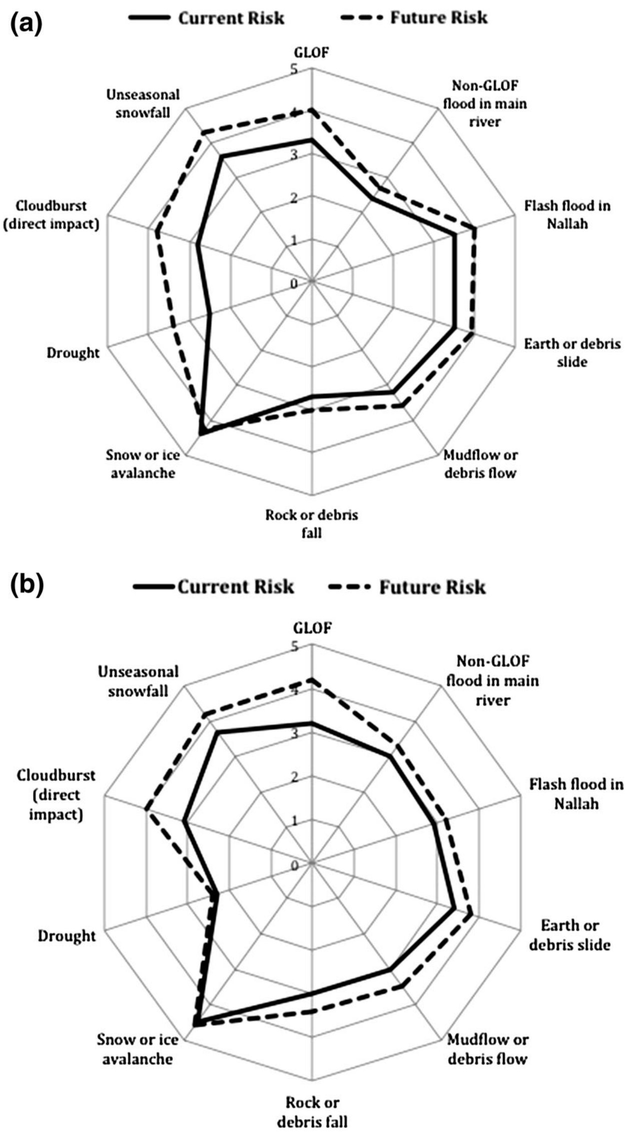


Fig. 2 Risk radar: perception of current and future (2050) risks associated with glacial and precipitation-related hazards in **a** Sissu and **b** Khoksar. Rating scale: 0 = no risk, 1 = very low, 2 = low, 3 = medium, 4 = high, 5 = very high. Mean ratings based on sample size of 30

hazard threat' category for avalanches and cloudbursts, and the 'medium hazard threat' category for landslides, floods and drought.

Some recent studies are available on one of the two potentially GLOF-prone proglacial lakes above the study area. Randhawa et al. (2005) observe a 105 % increase in the area of the Ghepan Ghat lake above Sissu, from 0.270 km^2 in 1976 to 0.554 km^2 in 2001. Worni et al. (2012) use Basement, a Swiss numerical simulation software tool, to develop models of two outburst scenarios for this lake. The probable damage in Sissu estimated by Worni et al. (see Online Resource H) matches fairly well with community perceptions of risk (see Online Resources F and G). A similar modelling study is not yet available for the larger Samudratapu Lake upstream of the Khoksar Gram Panchayat. However, a visual inspection of the lake, its terminal moraine and outlet, and its wide gently sloping glacial trough gives the impression that a damaging GLOF may occur only in conjunction with an extreme precipitation event.

Revadekar et al. (2011) use the PRECIS regional climate modelling system to project changes in precipitation extremes over India between the 1961–1990 baseline period and 2071–2100 under the SRES A2 and B2 emissions scenarios. For Himachal Pradesh, they predict an average increase of over 30 mm in maximum one-day precipitation (A2 and B2), with sharp escalations of 40–80 mm day^{-1} in parts of the state during the summer monsoon (A2). They also predict increases in the number of days with precipitation exceeding 10 mm and 20 mm, and a 240–250-mm rise in the amount of precipitation received as heavy precipitation exceeding the 95th percentile (A2 and B2). These findings are congruent with multi-model projections for the Nepal Himalaya, including increases in maximum one-day and five-day precipitation in the summer monsoon, and in the proportion of monsoon precipitation falling as heavy rain by the 2060s under the A2 emissions scenario (Nepal Climate Vulnerability Study Team 2009). However, these projections contrast with the falling trend observed in mean (not maximum) daily precipitation intensity at Keylong.

The interior valleys north of the northwestern Himalayan orographic barrier receive significantly less precipitation as monsoonal rain in summer than as snow in winter; yet fluvial erosional processes and suspended sediment fluxes are driven largely by sporadic high-intensity rainfall events in the monsoon season (Wulf et al. 2010). Any increase in monsoonal rainfall extremes in the region may therefore accelerate erosion of inhabited hillslopes, and sedimentation of future hydroelectric projects.

Existing preparedness and adaptive capacity

Preparedness

Overall preparedness for natural disasters is rated by both communities as poor-average (Sissu: 1.8, Khoksar: 1.6 on scale of 1–5) and government capacity to manage natural disasters in the village as poor (1.4, 1.1), while the cooperative ability of the community is perceived as very good–excellent (4.8, 4.4). Preparedness for response and recovery is evaluated against specific indicators (Table 2), assuming that response preparedness is a manifestation of coping capacity, while recovery preparedness is a manifestation of resilience.

Table 2 Some indicators of disaster preparedness in Sissu and Khoksar

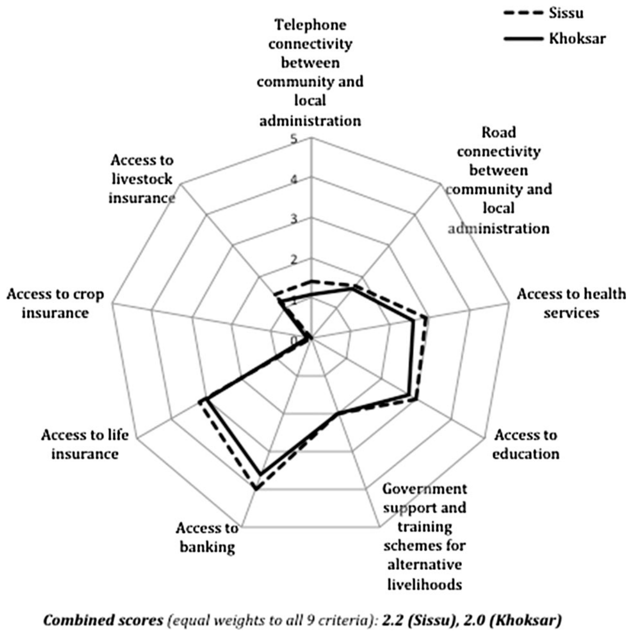
Community-level preparedness indicator	Proportion of respondents reporting adequate preparedness (%)	
	Sissu	Khoksar
Response preparedness		
Awareness of any emergency action plan to be followed in case of natural disaster	0	0
Access to household first aid kit	13	17
Access to rescue equipment	0	0
Access to household-level food storage	100	100
Access to unfailing means of communication with outside world during disaster event	0	0
Personal experience in managing disaster situations	57	37
Acquaintance with any community member trained in disaster response	17	0
Availability of support from other community members during and immediately after disaster event	100	93
Existence of local organisational mechanism for collective disaster response	100	100
Recovery preparedness		
Savings in bank account	79	87
Investments in gold or silver	93	83
At least one household member employed outside agriculture	70	63
Life insurance (covers deaths due to natural disasters)	70	42
Crop insurance	0	0
Livestock insurance	7	0
Skills useful for livelihood diversification	47	40
Education higher than primary school	53	72

Critical infrastructure

The perception of infrastructure critical to vulnerability/adaptive capacity is average (see Fig. 3), though slightly more favourable in Sissu, which has a primary health centre, senior secondary school, bank and helipad, and is nearer the district headquarters.

Governance issues

In pursuance of the Hyogo Framework, India enacted The Disaster Management Act, 2005. The Act is oriented predominantly towards disaster response, relief and reconstruction. However, a fairly all-inclusive National Policy on Disaster Management (NDMA 2009) has been formulated. While the National Plan for disaster management envisaged in the Act is yet to be prepared, Himachal Pradesh recently released its first draft State Disaster Management Plan (Government of Himachal Pradesh 2012), detailing the types of disasters affecting the state, response mechanism, responsibilities of various actors and strategies for mainstreaming DRR into development planning. The District Disaster Management Plan for Lahaul and Spiti



Combined scores *(equal weights to all 9 criteria):* ***2.2 (Sissu), 2.0 (Khoksar)***

Fig. 3 Perceptions of critical infrastructure associated with vulnerability in Sissu and Khoksar. Rating scale: 0 = severely limited, 1 = poor, 2 = average, 3 = good, 4 = very good, 5 = excellent. Mean ratings based on sample size of 30

(Lahaul and Spiti District Administration 2011) is a rudimentary response plan that mainly lists the roles of various agencies in a disaster situation. Considering that the priorities of the Hyogo Framework include promotion of "diversified income options for populations in high-risk areas to reduce their vulnerability to hazards", both the District and State Plans, and the future National Plan, need to more deeply and holistically address the issue of community resilience in the context of livelihoods. As a precursor to this, systematic community-level hazard and vulnerability assessment and mapping exercises must be completed.

Discussion: community SWOT analysis

The chart below presents a summary of key *strengths*, *weaknesses*, *opportunities* and *threats* facing the communities in relation to resilience and adaptation (Table 3).

Recommendations for action

The ongoing post-Hyogo exercise (UNISDR 2012) is moving the focus of DRR from institution building and database creation to community-level initiatives. With only 3 years remaining in the Hyogo Framework implementation period, India and Himachal Pradesh need to urgently review institutional gaps, expedite technical database preparation and ground-level mapping and integrate DRR with CCA initiatives. The extremely low density of weather stations in the high-altitude Himalaya and conspicuous gaps in the limited meteorological data available are matters of particular concern. The data on local perceptions of microclimates show that, in at least some cases, there are significant differences in environmental impacts and associated vulnerabilities from climate change at local scales, which are not captured by the regional weather data.

Based on a synthesis of the social and natural science findings, the following practicable high-priority action strategy is recommended to governmental and non-governmental agencies for enhancing community adaptation and resilience to climate change-related glacial hazards and extreme hydrometeorological events in the study area (Fig. 4).

Connect and communicate

Establishing an unfailing all-weather system of instant communication between the two communities and the administration is critical to DRR. The use of INMARSAT (International Maritime Satellite Organisation) satellite phone services is permitted in India, subject to the issue of a 'No Objection Certificate' by the Department of Telecommunications, Ministry of Communications and Information Technology, Government of India (DOT 2002). Assuming a unit cost of USD 600 (Sat Phone Store 2012), all 30 hamlets in the study area could get telephone connectivity for USD 18,000. The system could be used for disaster response and disseminating severe weather warnings. Moreover, upstream/uphill populations could provide real-time predisaster warnings to exposed downstream/downhill populations. Disaster management plans must incorporate standard operating procedures (SOPs) for immediate community response to various disaster scenarios.

Equip and empower

It is vital to minimise the disaster response-related dependence of communities on the local administration, which often cannot immediately access disaster-affected areas because of severe damage to roads and failure of helicopter services in inclement weather. Each hamlet must be provided with basic safety, search and rescue equipment. Where a dispensary is considered economically unviable, the government should ensure regular supplies of medications, with instructions for self-administration. The far-reaching postal service network could be used for this purpose.

A disaster response demonstration was organised by the government at a Sissu school in June 2012. Such training sessions should be held regularly and include mock drills. The design should account for regional environmental peculiarities. Members of hamlet-level youth collectives (*Yuva Mandal*) could be enrolled in specialised training courses, organised in collaboration with the ABV Institute of Mountaineering and Allied Sports, Manali, the Indo-Tibetan Border Police (ITBP) and local organisations like the Layul Mount Training Club, Keylong.

Prevent and protect

Exigent intervention is required to limit exposure of new infrastructure to slope failure- and flooding-related hazards. The local administration, in collaboration with communities, should devise an implementable (possibly extra-legal) mechanism to regulate siting of buildings, especially in view of the expected expansion of tourism from the Kullu valley to the Chandra valley following the operationalisation of the Rohtang Tunnel in 2015. Seasonal tented dwellings of immigrant labourers must be relocated urgently from high-risk riverside locations to safe campsites on terraces. Emerging risks associated with GLOFs and hydrometeorological extremes should be incorporated into feasibility assessments of hydroelectric and other expensive construction projects.

Table 3 Community SWOT analysis

Dimensions of adaptive capacity	Strengths (increasing resilience)	Weaknesses (increasing vulnerability)	Opportunities (reducing vulnerability)	Threats (reducing resilience)
Environmental	Extensive flat terraces available for settlement, cultivation at relatively safe locations well above main river channel and away from Nallahs (S)	Remote geomorphically unstable high-altitude environment (S) Region snowbound from late October to May; short growing season (S, CI) Extreme variability in seasonal precipitation (E)	Possible lengthening of growing season, caused by climate warming, reduced snowfall (E)	Lack of data, high uncertainty about future climate (E) High rates of deglaciation, heightening risks associated with glacial and related geomorphic hazards (E) Possibility of more extreme and unseasonal precipitation events in drier climate (E)
Economic	At least one household member employed outside agriculture in majority of households (CI) Organised economic activity and effective market access through Lahaul Potato Society (LPS), a commercial farmers' collective (CI)	Incomes largely agricultural, therefore low[b] (CI). Falling cash crop (especially pea) yields (CI, A) Low diversity in income sources, low crop diversity within agriculture (CI) Gradual inheritance-related fragmentation of agricultural land[a], especially due to collapse of polyandrous family structure (CI)	Untapped potential for livelihood diversification through promotion of tourism (adventure, village-based, ecotourism, especially post-2015[c]), traditional handicrafts, food processing practices and flute music (CI, CO)	Possibility of reduced economic viability of agriculture due to more extreme and unseasonal precipitation events in drier future climate (CI, E)
Infrastructural and institutional	Settlements generally situated away from main river and Nallahs Cemented walls in majority of households (CI) Access to basic healthcare, education (CI, S) Effective penetration of banking, life insurance services (CI, S) Access to inward communication through television, subject to electricity supply (CI) Traditional household-level storage of 80–100-day food supplies, extra bedding for emergency use and sharing, particularly in winter (CI, CO)	Intermittent telephone and road connectivity between community and local administration (CI, CO, A, S) No effective means of conveyance faster than walking during 40-day peak-snow period in winter (CI) Emergency helicopter evacuation services available from Sissu, but helicopters cannot be flown in turbulent weather (most past disaster events have involved stormy weather) (CI, A) No early warning system (CI, A) No community access to rescue equipment, limited access to training (CI) No enforcement of building codes (CI, A, M) No crop insurance scheme available for highland potato, peas; unattractive Livestock Insurance Scheme (cattle only) with complicated procedures (CI, A) Non-availability of medical specialists; dependence on services in the often inaccessible Kullu valley (A) Disaster management planning is still in early stage (R, M)	Year-round road connectivity post-2015[c]; regular snow clearance in winter, better maintenance in summer (CI, A) Potential to provide each hamlet with safety/rescue equipment, one snowmobile for emergency use, and at least one satellite phone (at present there is only one satellite phone in the valley: A) Potential to provide each hamlet with regular phone/SMS updates on weather from Regional Meteorological Centre in state capital Potential for covering the area and crops under three government risk transfer schemes: Weather Based Crop Insurance, Rainfall Insurance and National Agricultural Insurance Scheme (CI, A)	Connectivity loss in extreme weather, flooding and slope failure events due to: (1) Disruption of electricity supply to cellular towers (and failure of diesel generator-based backup) often causing mobile phone connectivity loss for >15 days in winter (CI, CO, A) (2) Damage to landline telephone optical fibre cables, 80 % of which are over-ground. Roads along which cables run are being widened, so under-grounding of cables cannot be undertaken for several years (A) (3) Damage to roads and bridges at numerous Nallah crossings (CO, A, S) Possible unregulated construction growth in traditionally unoccupied high-risk zones, owing to post-2015 tourism boom[c] (CI) Uncertainty about future climate (E) precludes effective long-term agricultural planning

Table 3 continued

Dimensions of adaptive capacity	Strengths (increasing resilience)	Weaknesses (increasing vulnerability)	Opportunities (reducing vulnerability)	Threats (reducing resilience)
Social	Extremely high social cohesion, cooperative ability within hamlets (often occupied by branches of a single formerly polyandrous extended family); very high cohesion among hamlet communities (CI) Empowered, smoothly functioning village administrative bodies with adequate representation, robust political influence of women (CI, CO) Seasonal migration of 30–60 % members of each household to the lower Kullu valley, as an environmental risk avoidance and income augmentation strategy in winter (CI)	High incidence of alcoholism, with most men intoxicated at night (CI, CO) *Equity issue:* Exclusion of low-income immigrant farm labourers and construction workers from core social structures (possibly associated with extreme ethnic homogeneity of local population) (CI, CO)	Potential to augment capacities of existing women's collectives (*Mahila Mandal*) for post-disaster financial cooperation and youth collectives (*Yuva Mandal*) for disaster response in each hamlet (CI, CO)	Growing proportion of aged persons in population, due to migration of better educated youth to more economically developed lower-altitude regions such as Kullu valley[c] (CI) Possible post-2015 social challenges (e.g. increased crime leading to social mistrust and reduced cohesion) associated with access to Kullu valley[c] (CI) Potential post-2015 reduction in seasonal migration to Kullu valley, owing to the new possibility of daily commutes between Chandra and Kullu valleys[c] (CI)

Letter symbols in parentheses indicate data source. S, area survey; E, environmental data analysis (see "Climate profile", "Environmental change: local perceptions and scientific observations" sections); CI, community interviews; CO, community observations; G, group exercises; A, interviews/discussions with administrators; M, inputs from government meeting; R, review of government planning (see "Governance issues" section)

[a] Per capita incomes (annual, nominal, @ 1 USD = 55.19 INR): *Sissu/Khoksar* (agricultural only): USD 615/USD 525 (2012, primary data; see Table 1), *Himachal Pradesh:* USD 1,060 (Government of Himachal Pradesh 2011), India (2011): USD 1,676 (IMF 2012)

[b] Mean land holding sizes: *Sissu/Khoksar*: 1.43/0.89 ha (2012, primary data; see Table 1), *India:* 1.06 ha (2002–2003), a 37 % fall from 1981 to 1982 (Press Information Bureau, 2006)

[c] By 2015, the 8.8-km Rohtang Tunnel is expected to provide year-round connectivity between Kullu and Chandra valleys by bypassing Rohtang La, which remains impassable in winter (Press Information Bureau 2010)

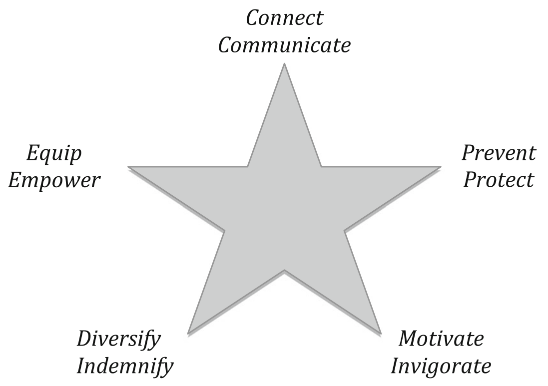


Fig. 4 The action star: a five-pronged action strategy for reducing disaster risk, enhancing adaptation and sustaining resilience

Plantations on non-rocky slopes and wire-crate retaining walls are in use at some locations for structural protection against avalanches, other slope failures and flash floods. Some existing structures (e.g. wire-crate walls across Pagal Nallah in Sissu) remain ineffective due to incorrect positioning in the absence of community consultations. Community members argue that they are more familiar with the tracks and dimensions of potential slope failures and floods than any external civil engineer. There is an urgent need to extend defences to all perceived high-risk zones. Specialised structures, such as snow nets and snow bridges for avalanches, could be installed. The government should consider deploying emerging infrasonic technologies (see Kogelnig et al. 2011) to monitor mass movements such as debris flows along Nallahs.

Diversify and indemnify

For long-term resilience, the communities need livelihood alternatives to the cultivation of highland potatoes and peas, whose yields are reported to be falling, at least partly in response to drier sowing seasons. Interestingly, these crops were extensively popularised by the government during 1960–1980, probably as an adaptive response to climate wetting (see "Environmental change: local perceptions and scientific observations" section).

Key non-agricultural income-generation possibilities include development of village-based and adventure-based ecotourism, and cultural micro-enterprises based on traditional handicrafts, flute music and food preservation practices. After the opening of the Rohtang Tunnel in 2015, the region could benefit significantly from improved connectivity (and associated mobility and exchange opportunities: see Thornton and Manasfi 2010) with the Kullu valley, a tourism hub. Therefore, over the next three years, governmental and non-governmental agencies should extend financial, technical and logistical support to communities for developing innovative projects. Hamlet-level women's collectives (*Mahila Mandal*) and the local cooperative bank could be mobilised to augment financial capacity.

Within agriculture, the local sea-buckthorn plant (*Hippophae rhamnoides*), which is particularly well adapted to cold arid climates in the neighbouring Ladakh and Spiti valleys, may be a valuable alternative cash crop, particularly if the climate becomes significantly drier in future. The shrub provides fodder, fuel and slope stabilisation and its nutritious berries can be processed into beverages, jams and medicinal and cosmetic preparations (Dharmananda 2004; Beveridge et al. 1999; Li and Schroeder 1996). The district administration and the CSK Himachal Pradesh Agricultural University have initiated expansion of sea-buckthorn cultivation, processing and marketing under the National Agricultural Innovation Project. The government is funding a small-scale processing unit in Lahaul (Selvam 2012). However, local interest in the crop is limited because it has the same harvest time as potatoes, which are currently more profitable. Since profitability is directly related to the scale of production, a vigorous campaign is required to fast-track adoption of sea buckthorn. The government should galvanise the relatively dormant Lahaul Seabuckthorn Society (an opportunity for revitalisation: see Thornton and Manasfi 2010).

The chief crops of the region, highland potatoes and peas, must immediately be covered by available government insurance schemes: Weather Based Crop Insurance, Rainfall Insurance and National Agricultural Insurance Scheme. The relatively unpopular Livestock Insurance Scheme should also be promoted, incorporating farmers' suggestions for improvement. Farmers must be educated about the role of risk transfer instruments in enhancing resilience to natural hazards.

Motivate and invigorate

District-level government has an important role to play in motivating, coordinating and invigorating responses to environmental risk. Community members acknowledge being demoralised by environmental hardships. Regular empathetic engagement with communities and their concerns on the part of officials can help revitalise their sense of security and confidence. The disaster planning process at any level must not overlook the psychological dimension of community resilience (see Reyes and Jacobs 2006; Miller 2012).

Conclusion

Many communities in extreme environments like the high Himalaya face urgent environmental risk and vulnerability challenges in the face of climate change. The investigative framework developed for this study offers an integrative grounded assessment of environmental risks and community resilience and adaptive capacities at a meaningful level for coordinated action and response.

Significant congruence was observed between available scientific data and community perceptions of environmental change and glacial and hydrometeorological hazards. Overall, the inherently variable climate of the study area appears to be shifting towards a warmer and drier state, with an increase in the incidence of unseasonal and extreme precipitation events, which could exaggerate the geomorphic fragility of the area. Local observations of glacial retreat were confirmed by scientific reports. The highest levels of current disaster risk were perceived by communities to be associated with avalanches, and no major change in risk factors was expected by 2050. Risks associated with unseasonal snowfall, GLOFs and cloudbursts were expected by communities to rise to the high-very high range by 2050. Risks of flash floods in Nallahs, and slope failures (flows, slides and falls) were also expected to increase. There is a significant lack of local-level scientific hazard assessments, except for modelled outburst scenarios for one of the potentially hazardous glacial lakes.

The community assets and livelihood resources most at risk and the costs associated with their potential loss were identified through participatory exercises, involving group discussions and micro-level risk perception mapping. In the event of a high-magnitude disaster, households in the perceived high-risk zones were estimated to potentially suffer direct financial losses ranging from 43 to 82 % of their mean annual agricultural income.

Based on community perceptions, the overall preparedness for natural disasters was assessed as poor-average and the state of critical infrastructure associated with vulnerability and adaptive capacity was found to be average (see "Existing preparedness and adaptive capacity" section). Key infrastructural limitations include tenacious obstacles to connectivity between the communities and the local administration, and poor access to agricultural insurance services. The review of macro- and micro-level governance issues revealed an urgent need for addressing institutional gaps, strengthening technical databases and broadening the existing disaster planning framework to include long-term community resilience. The community SWOT analysis facilitated appraisal of the environmental, economic, infrastructural, institutional and social dimensions of the existing adaptive capacity.

A high-priority action strategy is recommended to governmental and non-governmental agencies for reducing disaster risk through structural and non-structural measures, supporting adaptation in the context of livelihoods and sustaining community resilience and key autonomous adaptation pathways. The strategy focuses on minimising the weaknesses and threats, and maximising the strengths and opportunities identified in the SWOT analysis.

The study demonstrates the vital role of ground-level community-centric assessments in evolving an integrated approach to disaster risk reduction and climate change adaptation for high-altitude environments, particularly in the developing world. The low-cost and broad investigative framework could be suitably adapted in developing countries, where disaster management and climate change adaptation planning are gradually coming into focus. With the evolution of institutions, databases and research networks, the frameworks of such studies should become progressively more refined. Yet, the inherent community-centric, solution-oriented character of the present approach must remain at the core of future climate adaptation research if it is to enhance the adaptive capacity of historically resilient communities in remote and extreme environments.

Acknowledgments We are indebted to the following persons for their invaluable academic insights: Prof John Boardman, University of Oxford; Mr Raphael Worni, University of Berne; Dr R.K. Sood, Indian glaciologist; Dr Thomas E. Downing, Global Climate Adaptation Partnership; Dr Örjan Bodin, Stockholm Resilience Centre; Dr Fai Fung, University of Oxford and Mr Rajeev Issar, BCPR-UNDP. We also acknowledge with gratitude the logistical and informational support provided by the Government of Himachal Pradesh; the Regional Meteorological Centre, Shimla and the India Habitat Centre Library, New Delhi. The study could not have been completed without financial assistance from the Felix Scholarship, Environmental Change Institute and St. Anne's College at the University of Oxford.

References

Allen MR, Ingram WJ (2002) Constraints on the future changes in climate and the hydrological cycle. Nature 419:224–232

Au SWC (1993) Rainfall and slope failure in Hong Kong. Eng Geol 36:141–147

Bhagat RM, Kalia V, Sood C, Mool PK, Bajracharya, SR (2004) Himachal Pradesh Himalaya, India: inventory of glaciers and glacial lakes and the identification of potential glacial lake outburst floods (GLOFs) affected by global warming in the mountains of the Himalayan region. Report of the Asia-Pacific Network for Global Change Research Project. ICIMOD, CSKH-PAU, APN, START and UNEP, 254 pp

Bajracharya SR, Mool PK, Shrestha BR (2007) Impact of climate change on Himalayan glaciers and glacial lakes: case studies on GLOF and associated hazards in Nepal and Bhutan. ICIMOD, Kathmandu, Nepal

Benedict PK (1972) Sino-Tibetan: a conspectus (series: Princeton-Cambridge Studies in Chinese Linguistics, vol. 2.). Cambridge University Press, Cambridge

Beveridge T, Li TSC, Oomah BD, Smith A (1999) Sea buckthorn products: manufacture and composition. J Agric Food Chem 47:3480–3488

Caine N (1980) The rainfall intensity—duration control of shallow landslides and debris flows. Geografiska Annaler A 62:23–27

Clague JJ, Evans SG (2000) A review of catastrophic drainage of moraine-dammed lakes in British Columbia. Quat Sci Rev 19:1763–1783

Costa JE, Schustler RL (1988) The formation and failure of natural dams. Geol Soc Am Bull 100:1054–1068

Cutter SL, Barnes L, Berry M, Burton C, Evans E, Tate E, Webb J (2008) A place-based model for understanding community resilience to natural disasters. Glob Environ Change 18:598–606

Das S, Ashrit R, Moncrieff MW (2006) Simulation of a Himalayan cloudburst event. J Earth Syst Sci 115:299–313

Delrieu G, Ducrocq V, Gaume E, Nicol J, Payrastre O, Yates E, Kirstetter P-E, Andrieu H, Ayral P-A, Bouvier C, Creutin J-D, Livet M, Anquetin S, Lang M, Neppel L, Obled C, Parent-du-Châtelet J, Saulnier G-M, Walpersdorf A, Wobrock W (2005) The catastrophic flash-flood event of 8–9 September 2002 in the Gard Region, France: a first case study for the Cévennes–Vivarais Mediterranean Hydrometeorological Observatory. J Hydrometeorol 6:34–52

Dharmananda S (2004) Sea buckthorn. Institute for Traditional Medicine, Portland, Oregon, USA. http://www.itmonline.org/arts/seabuckthorn.htm. Accessed 25 Aug 2012

DOT (2002) INMARSAT. Government of India. http://www.dot.gov.in/inmarsat/inmarsatindex.htm. Accessed 20 Aug 2012

Engle NL (2011) Adaptive capacity and its assessment. Glob Environ Change 21:647–656

Evans SG, Clague JJ (1993) Glacier-related hazards and climate change. In: Bras R (ed) The world at risk: natural hazards and climate change. AIP conference proceedings, vol. 277. American Institute of Physics, New York, pp 48–60

Evans SG, Clague JJ (1994) Recent climate change and catastrophic geomorphic processes in mountain environments. Geomorphology 10:107–128

Folke C, Carpenter S, Elmqvist T, Gunderson L, Holling CS, Walker B, Bengtsson J, Berkes F, Colding J, Danell K, Falkenmark M, Gordon L, Kaspersson R, Kautsky N, Kinzig A, Levin SA, Mäler K-G, Moberg F, Ohlsson L, Olsson P, Ostrom E, Reid W, Rockström J, Savenije H, Svedin U (2002) Resilience and sustainable development: building adaptive capacity in a world of transformations. Background paper. Swedish Environmental Advisory Council, Ministry of the Environment, Stockholm, 74 pp

Gadgil S, Vinayachandran PN, Francis PA, Gadgil S (2004) Extremes of the Indian summer monsoon rainfall, ENSO and equatorial Indian Ocean oscillation. Geophys Res Lett 31:L12213

Gallopin GC (2006) Linkages between vulnerability, resilience, and adaptive capacity. Glob Environ Change 16:293–303

Government of Himachal Pradesh (2011) State profile. Department of Information and Public Relations. http://himachalpr.gov.in/hpglance.asp. Accessed 20 Aug 2012

Government of Himachal Pradesh (2012) State disaster management plan (draft). Disaster Management Cell, Department of Revenue, Government of Himachal Pradesh, Shimla, 191 pp

Government of India (2011) Base document on geoscience for sustainable development. Committee XII, Central Geological

Programming Board, Geological Survey of India. Ministry of Mines, Government of India, 112 pp

Groisman P, Knight R, Easterling D, Karl T, Hegerl G, Razuvaev V (2005) Trends in intense precipitation in the climate record. J Clim 18:1326–1350

Guzzetti F, Peruccacci S, Rossi M, Stark CP (2008) The rainfall intensity-duration control of shallow landslides and debris flows: an update. Landslides 5:3–17

Haeberli W (1983) Frequency and characteristics of glacier floods in the Swiss Alps. Ann Glaciol 4:85–90

Haeberli W, Alean JC, Müller P, Funk M (1989) Assessing risks from glacier hazards in high mountain regions: some experiences in the Swiss Alps. Ann Glaciol 13:96–102

Huggel C (2009) Recent extreme slope failures in glacial environments: effects of thermal perturbation. Quat Sci Rev 28:1119–1130

ICIMOD (2003, 2004, 2005) Reports of the Asia-Pacific Network for Global Change Research 2004-03-CMY Project: 'inventory of glaciers and glacial lakes and the identification of potential glacial lake outburst floods (GLOFs) affected by global warming in the mountains of India, Pakistan and China/Tibet Autonomous Region'. DVD from International Centre for Integrated Mountain Development (ICIMOD), Kathmandu, Nepal, produced in 2007. Online product information: http://www.rrcap.unep.org/issues/glof/glof/index.htm. Accessed 22 July 2012

IMF (2012) Report for selected countries and subjects. World economic outlook database (online version). http://www.imf.org/external/pubs/ft/weo/2012/01/weodata/weorept.aspx?pr.x=51&pr.y=6&sy=2009&ey=2012&scsm=1&ssd=1&sort=country&ds=.&br=1&c=534&s=NGDPD%2CNGDPDPC%2CPPPGDP%2CPPPPC%2CLP&grp=0&a=. Accessed 20 Aug 2012

India Meteorological Department (2010) Cloudburst over Leh (Jammu and Kashmir). Observations. www.imd.gov.in/doc/cloud-burst-over-leh.pdf. Accessed 15 Feb 2012

IPCC (2012) Summary for policymakers. In: Field CB, Barros V, Stocker TF, Qin D, Dokken DJ, Ebi KL, Mastrandrea MD, Mach KJ, Plattner G-K, Allen SK, Tignor M, Midgley PM (eds) managing the risks of extreme events and disasters to advance climate change adaptation (SREX). A special report of working groups I and II of the intergovernmental panel on climate change (IPCC). Cambridge University Press, Cambridge, pp 1–19

Kogelnig A, Hübl J, Suriñach E, Vilajosana I, McArdell BW (2011) Infrasound produced by debris flow: propagation and frequency content evolution. Nat Hazards. doi:10.1007/s11069-011-9741-8

Krishna Kumar K, Rajagopalan B, Hoerling M, Bates G, Cane M (2006) Unraveling the mystery of Indian monsoon failure during El Niño. Science 314:115–119

Kulkarni AV, Dhar S, Rathore BP, Govindha Raj KB, Kalia R (2006) Recession of Samudra Tapu glacier, Chandra river basin, Himachal Pradesh. J Indian Soc Remote Sens 34:39–46

Lahaul and Spiti District Administration (2011) Disaster management plan: Lahaul and Spiti District. District Administration, Keylong, 10 pp. http://hplahaulspiti.nic.in/Disaster%20management%20plan.PDF. Accessed 20 Aug 2012

Lenderink G, van Meijgaard E (2008) Increase in hourly precipitation extremes beyond expectations from temperature changes. Nat Geosci 1:511–514

Lenderink G, van Meijgaard E (2010) Linking increases in hourly precipitation extremes to atmospheric temperature and moisture changes. Environ Res Lett 5:025208

Li TSC, Schroeder WR (1996) Sea buckthorn (*Hippophae rhamnoides*): a multipurpose plant. Hortic Technol 6:370–378

Miller JL (2012) Psychosocial capacity building in response to disasters. Columbia University Press, New York

Miller F, Osbahr H, Boyd E, Thomalla F, Bharwani S, Ziervogel G, Walker B, Birkmann J, van der Leeuw S, Rockström J, Hinkel J, Downing T, Folke C, Nelson D (2010) Resilience and vulnerability: complementary or conflicting concepts? Ecol Soc 15:11

NDMA (2009) National policy on disaster management. Ministry of Home Affairs, Government of India, 42 pp. http://nidm.gov.in/PDF/policies/ndm_policy2009.pdf. Accessed 20 Aug 2012

Nelson DR, Adger WN, Brown K (2007) Adaptation to environmental change: contributions of a resilience framework. Annu Rev Environ Resour 32:395–419

Nepal Climate Vulnerability Study Team (2009) Vulnerability through the eyes of the vulnerable: climate change induced uncertainties and Nepal's development predicaments. Institute for Social and Environmental Transition, Nepal (ISET-N), Kathmandu and Institute for Social and Environmental Transition (ISET), Boulder, Colorado, 95 pp

Paeth H, Scholten A, Friedrichs P, Hense A (2008) Uncertainties in climate change prediction: El Niño-Southern Oscillation and monsoons. Glob Planet Change 60:265–288

Pall P, Allen M, Stone D (2007) Testing the Clausius–Clapeyron constraint on changes in extreme precipitation under CO_2 warming. Clim Dyn 28:351–363

Polsky C, Neff R, Yarnal B (2007) Building comparable global change vulnerability assessments: the vulnerability scoping diagram. Glob Environ Change 17:472–485

Press Information Bureau (2006) Some aspects of operational land holdings in India, 2002-03. National Sample Survey Organisation, Government of India. Press release, 31 August. http://www.mospi.gov.in/nss_press_note_492.htm. Accessed 20 Aug 2012

Press Information Bureau (2010) Rohtang tunnel—cutting through the mighty Himalayas. Ministry of Defence, Government of India. Press release, 17 June 2010. http://pib.nic.in/newsite/erelease.aspx?relid=62648. Accessed 5 Aug 2012

Punjab Government (1918) Punjab district gazetteers vol. XXX A: Kangra district, part III—Lahul, 1917. Superintendent, Government Printing, Lahore, pp 181–251 [Compiled and republished in 2003 by Himachal Academy of Arts, Culture and Languages, Shimla, India]

Randhawa SS, Sood RK, Rathore BP, Kulkarni AV (2005) Moraine-dammed lakes study in the Chenab and Satluj river basins using IRS data. J Indian Soc Remote Sens 33:285–290

Revadekar JV, Patwardhan SK, Rupa Kumar K (2011) Characteristic features of precipitation extremes over India in the warming scenarios. Adv Meteorol 2011:1–10

Reyes G, Jacobs GA (eds) (2006) Handbook of international disaster psychology: fundamentals and overview. Praeger Publishers, Westport

Reynolds JM (1999) Glacial hazard assessment at Tsho Rolpa, Rolwaling, Central Nepal. Q J Eng Geol 32:209–214

Richardson SD, Reynolds JM (2000) An overview of glacial hazards in the Himalayas. Quat Int 65:31–47

Rosenzweig C, Casassa G, Karoly DJ, Imeson A, Liu C, Menzel A, Rawlins S, Root TL, Seguin B, Tryjanowski P, IPCC (2007) Assessment of observed changes and responses in natural and managed systems. In: Parry ML, Canziani OF, Palutikof JP, van der Linden PJ, Hanson CE (eds) Climate change 2007: impacts, adaptation and vulnerability. Contribution of working group II to the fourth assessment report of the intergovernmental panel on climate change. Cambridge University Press, Cambridge, pp 79–131

Sah MP, Mazari RK (1998) Anthropogenically accelerated mass movement, Kulu Valley, Himachal Pradesh, India. Geomorphology 26:123–138

Salzman WR (2004) Clapeyron and Clausius–Clapeyron equations. In: Salzman WR (2001) Chemical thermodynamics. University of Arizona. [online textbook] http://www.chem.arizona.edu/~salzmanr/480a/480ants/clapeyro/clapeyro.html. Accessed 25 Aug 2012

Sangewar CV (2011) Remote sensing applications to study Indian glaciers. Geocarto Int 2011:1–10

Sat Phone Store (2012) Inmarsat Isat Phone Pro—standard package. http://www.satphonestore.com/featured/handheld-sat-phones/isatphone-pro.html. Accessed 20 Aug 2012

Selvam R (2012) An innovation under DPP. Lahaul and Spiti District Administration. http://hplahaulspiti.nic.in/InnovationDDP.htm. Accessed 25 Aug 2012

Seneviratne SI, Nicholls N, Easterling D, Goodess CM, Kanae S, Kossin J, Luo Y, Marengo J, McInnes K, Rahimi M, Reichstein M, Sorteberg A, Vera C, Zhang X, IPCC (2012) Changes in climate extremes and their impacts on the natural physical environment. In: Field CB, Barros V, Stocker TF, Qin D, Dokken DJ, Ebi KL, Mastrandrea MD, Mach KJ, Plattner G-K, Allen SK, Tignor M, Midgley PM (eds) Managing the risks of extreme events and disasters to advance climate change adaptation (SREX). A special report of working groups I and II of the intergovernmental panel on climate change (IPCC). Cambridge University Press, Cambridge, pp 109–230

Sharma MC (1986) Regional geomorphology of Lahul (Central Himalayas). Masters dissertation. Jawaharlal Nehru University, Delhi, 125 pp

Swaroop S, Shukla SP, GSI (1999) Report on glacier front fluctuation studies in parts of Himachal Pradesh and Uttar Pradesh. Final compiled report: FS 1994-95 to 1996-97. GSI Glaciology Division Northern Region.Geological Survey of India, Lucknow, 23 pp

The Disaster Management Act (2005) http://mha.nic.in/pdfs/DM_Act2005.pdf. Accessed 20 Aug 2012

Thomalla F, Downing T, Spanger-Siegfried E, Han G, Rockström J (2006) Reducing hazard vulnerability: towards a common approach between disaster risk reduction and climate adaptation. Disasters 30:39–48

Thornton TF, Manasfi N (2010) Adaptation—genuine and spurious: demystifying adaptation processes in relation to climate change. Environ Soc Adv Res 1:132–155

Trenberth KE, Dai A, Rasmussen R, Parsons D (2003) The changing character of precipitation. Bull Am Meteorol Soc 84:1205–1217

Turner BL II (2010) Vulnerability and resilience: coalescing or paralleling approaches for sustainability science? Glob Environ Change 20:570–576

Turner BL II, Kasperson RE, Matson PA, McCarthy JJ, Corell RW, Christensen L, Eckley N, Kasperson JX, Luers A, Martello ML, Polsky C, Pulsipher A, Schiller A (2003) A framework for vulnerability analysis in sustainability science. PNAS 100:8074–8079

UNDP-BCPR, ECHO (2008) Preparatory Assessment Study Report, Sutlej Basin, Himachal Pradesh, India. Capacity Building for Disaster Risk Reduction Regional Glacial Lake Outburst Floods (GLOF) Risk Reduction in the Himalayas, 50 pp. http://www.managingclimaterisk.org/index.php?menu_id=9&pagetype_menu=2&content_id=MEN-9> Accessed 26 Aug 2012

UNISDR (2007) Hyogo framework for action 2005–2015: building the resilience of nations and communities to disasters. World conference on disaster reduction, 18–22 January 2005, Kobe, Hyogo, Japan, 22 pp. http://www.unisdr.org/we/inform/publications/1037. Accessed 20 Aug 2012

UNISDR (2012) Towards a post-2015 framework for disaster risk reduction. 10 pp. http://www.unisdr.org/we/inform/publications/25129. Accessed 20 Aug 2012

van Driem G (2001) Languages of the Himalayas: an ethnolinguistic handbook of the Greater Himalayan Region. 2 vol. Brill, Leiden

Venton P, La Trobe S (2008) Linking climate change adaptation and disaster risk reduction. Tearfund, London

Vogel C, Moser S, Kasperson RE, Dabelko GD (2007) Linking vulnerability, adaptation, and resilience science to practice: pathways, players, and partnerships. Glob Environ Change 17:349–364

Walder JS, Drieger CL (1995) Frequent outburst floods from South Tahoma Glacier, Mount Rainier, USA: relation to debris flows, meteorological origin and implications for subglacial hydrology. J Glaciol 41:1–10

Warburton J, Fenn CR (1994) Unusual flood events from an Alpine glacier: observations and deductions on generating mechanisms. J Glaciol 40:176–186

Worni R, Huggel C, Stoffel M (2012) Glacier lakes in the Indian Himalayas—From an area-wide glacial lake inventory to on-site and modeling-based risk assessment of critical glacial lakes. Sci Total Environ. doi:10.1016/j.scitotenv.2012.11.043

Wulf H, Bookhagen B, Scherler D (2010) Seasonal precipitation gradients and their impact on fluvial sediment flux in the Northwest Himalaya. Geomorphology 118:13–21

Yohe G, Tol RSJ (2002) Indicators for social and economic coping capacity—moving toward a working definition of adaptive capacity. Glob Environ Change 12:25–40