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Translating the concept of climate risk into an assessment framework to inform adaptation planning: Insights from a pilot study of flood risk in Himachal Pradesh, Northern India

Allen S.K.[a,b,*], Ballesteros-Canovas J.[a,c], Randhawa S.S.[d], Singha A.K.[e], Huggel C.[b], Stoffel M.[a,c]

[a] Institute for Environmental Sciences, University of Geneva, Switzerland
[b] Department of Geography, University of Zurich, Switzerland
[c] Department of Earth Sciences, University of Geneva, Switzerland
[d] Himachal Pradesh State Centre on Climate Change, State Council for Science, Technology and Environment, Shimla, India
[e] CTRAN Consulting, Bhubaneswar, Odisha, India

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ABSTRACT

Climate risk assessments provide the basis for identifying those areas and people that have been, or potentially will be, most affected by the adverse impacts of climate change. They allow hot-spots to be identified, and serve as input for the prioritization and design of adaptation actions. Over recent years, at the level of international climate science and policy, there has been a shift in the conceptualization of vulnerability toward emergence of 'climate risk' as a central concept. Despite this shift, few studies have operationalized these latest concepts to deliver assessment results at local, national, or regional scales, and clarity is lacking. Drawing from a pilot study conducted in the Indian Himalayas we demonstrate how core components of hazard, vulnerability, and exposure have been integrated to assess flood risk at two different scales, and critically discuss how these results have fed into adaptation planning. Firstly, within a state-wide assessment of glacial lake outburst flood risk, proxy indicators of exposure and vulnerability were combined with worst-case scenario modelling of the outburst hazard. At this scale, first-order assessment results are coarse, but have guided the design of monitoring strategies and other low-regret adaptation actions. Secondly, an assessment of seasonal monsoon and cloudburst-related flood risk was undertaken for individual mapped elements exposed along the main river valleys of Kullu district, drawing on innovative techniques using dendrogeomorphology to reconstruct potential flood magnitudes. Results at this scale have allowed specific adaptation strategies to be targeted towards hot-spots of risk. A comprehensive risk assessment must integrate across disciplines of physical and social science, to provide the necessary robust foundation for adaptation planning.

1. Introduction

Robust scientific assessment of the present and future impacts of climate change is a cornerstone of both national and international climate policy, providing the basis for adaptation planning and resource mobilisation (Huggel et al., 2015). At the international level funding instruments are called to target those potentially most affected by climate change, as highlighted recently, for instance, under Article 7 of the Paris Agreement of the Conference of Parties of the United Nations Framework Convention on Climate Change (UNFCCC). However, diversities across the different concepts and approaches used in climate impact studies have limited the ability of science to clearly inform policy. As a consequence, the allocation of adaptation funding (e.g., Green Climate Fund) remains controversial and challenging (Muccione et al., 2016). Similarly, at the national level, authorities are tasked with disentangling the multitude of socio-physical driving processes to identify regions most affected by climate change, and thereby target adaptation planning and strategies accordingly. With the recent emergence of climate risk as a key concept in the science-policy dialogue, led by the Intergovernmental Panel on Climate Change (IPCC 2014), these socio-physical processes are at least theoretically more clearly distinguished. Yet, this concept has rarely been applied in an assessment context (Muccione et al., 2016). As a consequence, there is a lack of clarity over how the concept of climate risk – increasingly favoured by policy and decision makers – should guide the scientific assessment of climate change impacts, at national, state, or district scales, and thereby provide the fundamental basis for adaptation planning.

The Indian Himalayan Region (IHR) faces particular challenges in

* Corresponding author at: Institute for Environmental Sciences, University of Geneva, Switzerland.
E-mail address: simon.allen@unige.ch (S.K. Allen).

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view of coping with the adverse effects of climate change, exacerbating other physical (e.g., topographic, geological) and anthropogenic (e.g., land-use practices, socio-economic) stressors (Hofer, 1993; Pande, 2006; Sati et al., 2011; Sati and Gahalaut, 2013). The IHR stretches across 12 states and is home to an estimated 72 million people, providing hydrological resources and ecosystems services to more than 900 million people living downstream upon the fertile grounds of the transnational Indo-Gangetic Plain. Recognising this challenge, the Indian government established in 2008 its National Action Plan on Climate Change (NAPCC), identifying eight core missions in the context of adaptation and mitigation planning (see Awasthi et al., 2016 for a comprehensive overview). This included the National Mission for Sustaining the Himalayan Ecosystem (NMSHE), calling specifically for scientific assessment of the vulnerability of the Himalayan ecosystem to variability in weather and climate, considering physical, biological and socio-cultural dimensions. With an emphasis on evidence-based policy measures, the NMSHE supports the Himalayan state governments in the planning and implementation of climate impact assessments, which serve as a basis for their State Action Plans for Climate Change (SAPCC). To this end, a need was identified for a homogenous assessment framework to be developed, drawing on the latest international concepts and allowing results to be compared across states and sectors.

Within this context, research collaboration between Indian and Swiss scientists was initiated under the Indian Himalayan Climate Adaptation Program (IHCAP). The overall goal of the joint research activities was to implement a pilot study of climate vulnerability, hazard, and risk, focussing upon Kullu district, Himachal Pradesh, within an integrative assessment framework that could be upscaled to other districts and states of the IHR or elsewhere. The research covered diverse climate-related threats ranging from landslides, avalanches and floods, to impacts on biodiversity and the agriculture-horticulture sector (IHCAP, 2016). Drawing on experiences gained through this pilot study, here we focus on how the IPCC concept of climate risk was operationalised to guide our assessment in Kullu, highlight key considerations, challenges and approaches used, and then critically reflect on how the results from these studies have informed local adaptation planning. Hence, we provide a rare end-to-end case study and analysis of science-based climate adaptation in action. We specifically focus on flood risk, as floods represent a key climate-related threat not only within the IHR, but also across many other mountainous regions of the world (e.g., Jongman et al., 2012; Peduzzi et al., 2009; Singh and Kumar, 2013). Our assessment in Kullu considers floods related primarily to seasonal monsoon rainfall and cloudburst events (for simplicity referred herein as monsoon floods) and Glacial Lake Outburst Floods (GLOFs).

2. Kullu District, Himachal Pradesh

Kullu district (population 437,900; land area 5500 km^2) within the north-west Indian state of Himachal Pradesh was selected as the focus region for the pilot study. The district is centred along the north-south orientated valley of Beas river, and provides a significant national transportation corridor. Major urban settlements and tourism hot-spots located along the broad, highly fertile floodplains of the U-shaped valley include Manali, Kullu and Bhuntar. The main tributary rivers of the Parvati, Sainj, and Tirthan are characterized by narrow side valleys, where villages are located on steep slopes or on the limited, yet often flood-prone, flatter reaches. Approximately 35 per cent of the district is under forest cover, giving way to alpine tundra and glacial landscapes at higher elevations, where the largest mountain peaks extend up to 6500 m a.s.l. The climate regime of the Kullu district is considered to be sub-tropical monsoon characterized by cool, snowy winters at higher elevations; as well as warm, dry spring and autumn; and a warmer, wetter monsoonal summer. An increase in mean annual air temperature of 1.6 °C has been measured across the northwestern Himalayan region during the past century, which is far in excess of mean global warming (Bhutiyani et al., 2007). Demographically the district has seen significant growth recently in urban population, with a 35 per cent increase recorded between 2001 and 2011 (Census India). Floods are the major threat to the district, triggered primarily by seasonal monsoon rain and cloud-burst events, often associated with significant bank erosion and landslide activity (Ballesteros-Cánovas et al., 2017). The formation and bursting of landslide dammed lakes has also been responsible for flood events in the region (Ruiz-Villanueva et al., 2016). The potential for GLOFs is thought to be increasing significantly as glaciers melt and lakes expand (Allen et al., 2016), while hydropower plants and other infrastructure being built at higher altitudes closer to the glacier lakes is increasing the associated risk (Schwanghart et al., 2016).

3. Components of climate risk

The recent emergence of climate risk as a key integrative concept arising out of the IPCC's fifth assessment cycle (IPCC, 2014) provided a logical framing for pilot studies in Kullu. Integrating the traditionally diverging perspectives from the disaster risk management and climate adaptation communities, climate risk is conceptualised by IPCC as a physical event (hazard) intercepting with an exposed and vulnerable system (e.g., community or ecosystem) (Fig. 1). In the subsequent sections we introduce core terminology and methodological approaches used to assess these three components of flood risk in Kullu district, and across the surrounding state.

3.1. Hazard

As defined by IPCC 2014, hazard refers to *"the potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources"*. Within the framework of the risk assessment, identifying and quantifying the hazard determines what it is that communities or systems are exposed and vulnerable to. Hazards in this context include both slow onset processes (e.g., increase in mean temperature or decrease in rainfall leading to impacts such as species changes or extinction, vegetation change or ground water shortages) and sudden onset events (e.g., flooding, heatwaves, landslides). Hazards are often associated with unusual or extreme hydro-meteorological events, but non-extreme events also can lead to disasters where other physical or societal factors precondition such an outcome (Seneviratne et al., 2012).

For the hazard assessment, information is required on both the intensity of the event (or magnitude), and the probability of occurrence (or frequency). Where there is reliable historical data and observations these quantities may be relatively simple to establish based on a catalogue of past events. However, in the context of flood hazard assessment in Kullu two fundamental problems arose which are indicative of the challenges researchers face working in many of the worlds mountain regions:

i Stream-gauge records are sparse and incomplete, and are often damaged during the most extreme (and important) events.

ii GLOFs are a rapidly evolving flood threat in many glaciated mountain catchments, and historical records are therefore often completely lacking or of limited value.

3.1.1. Dendrochronology to reconstruct hazard baseline

In an effort to overcome the lack of historical data, analyses of tree rings (dendrochronology) have been widely used to reconstruct the timing and magnitude of hydrogeomorphic hazards, including floods, debris flows, landslides, and snow avalanches (see Stoffel et al., 2010 for a comprehensive review). The approach is based on the concept that trees affected by hydrogeomorphic processes will conserve information

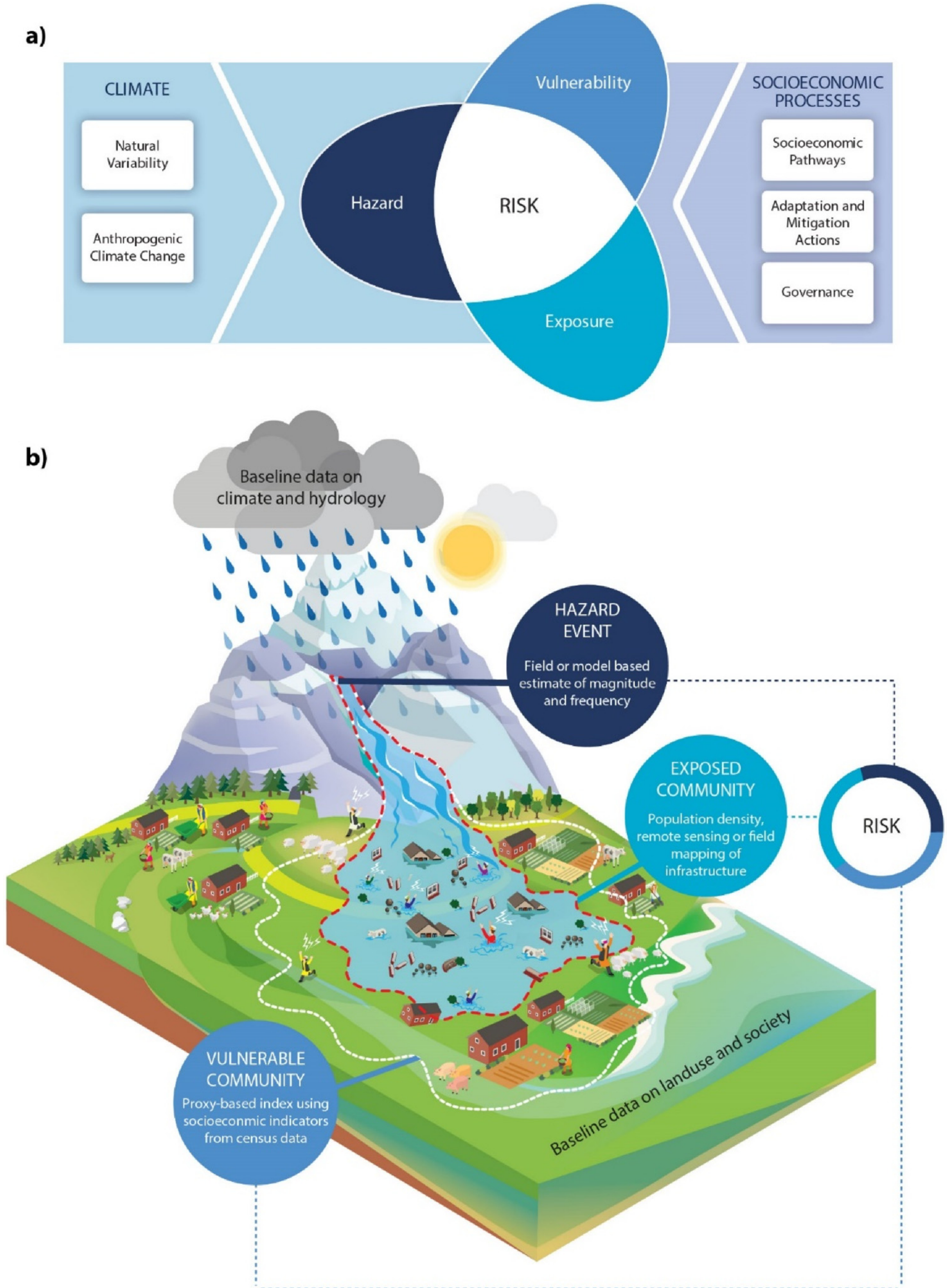

Fig. 1. Schematic overview showing how (a) the integrative concept of climate risk as presented by the IPCC (2014) was (b) operationalised for the assessment of flood risk in Himachal Pradesh, Northern India. (Figures modified from IPCC, 2014 and IHCAP, 2017; used with permission).

on the event within their growth-ring records. While the applicability of dendrochronology for reconstructing regional-scale flood activity and deciphering climate linkages has been demonstrated across several mountain regions of the world (e.g., Ballesteros-Cánovas et al., 2015a, 2016; Rodriguez-Morata et al., 2016; Šilhán, 2015), the Kullu pilot study provided an opportunity to advance the use of dendrochronology for science-based climate change adaptation at the state level in India.

The highly fragmented and temporally short systematic flow gauge series from Kullu were complemented with peak discharge estimations of recent (i.e. 20th and 21st centuries) extreme floods based on evidence from scarred trees growing on the river banks. These scars were dated following the procedures described in Ballesteros-Canovas et al., (2015b), and the scar height used to apply a one-dimensional hydraulic equation and estimate peak discharges of each of the events. The reconstructed extreme floods were then incorporated into the systematic flow-series to provide a regional monsoon flood frequency for Kullu (see Ballesteros-Cánovas et al., 2017), providing a basis for flood hazard estimation at 1 km intervals along the entire river network. For Kullu, hazard was quantified as the ratio of the calculated 100-year flood discharge (Q_{100}) relative to the bankfull discharge level (Q_b), multiplied by the mean channel slope (S):

$$\text{Hazard} = Q_{100}/Q_b.\ S$$

where values for both Q_{100} and Q_b (equivalent to a return period of 3 years) are derived from Ballesteros-Cánovas et al., (2017). A hydrologically corrected version of the Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM) at 30 m resolution was used for all topographic analyses (see supplementary material for further details).

3.1.2. Rapidly evolving hazards

Some types of hazard have limited historical precedence or can occur only once, such that there can be no local empirical basis upon which to derive the hazard assessment. This is often the case for GLOFs, as lakes have appeared and/or expanded rapidly during recent decades bringing often unforeseen and rapidly evolving threats. Furthermore, once a lake has catastrophically drained, the eroded channel through the dam typically minimises the likelihood of any subsequent events (Clague and O'Connor, 2014). In Kullu, or more broadly across the State of Himachal Pradesh, no known GLOFs have been documented to date, although numerous glacial lakes are expanding rapidly (HPCCC, 2014). This represented a methodological challenge, but also a communication challenge, as the lack of any historical precedence can lead to widely diverging perceptions amongst local stakeholders, who may vastly over- or understate a poorly understood threat (see also Section 6). In the absence of historical data, a large-scale first-order approach to GLOF hazard assessment was implemented for the entire state of Himachal Pradesh utilising so-called "worst-case" scenario modelling, whereby the potential likelihood of an outburst (hazard frequency) and potential downstream affected area (hazard magnitude) were quantified for each watershed, with results aggregated to the tehsil (sub-district) administrative unit. The underlying methodology and results of the GLOF hazard assessment are comprehensively described in Allen et al. (2016), and hence, only briefly summarised here (full details are also provided in the supplementary material). Glacial lakes were firstly mapped from satellite imagery, then topographic criteria (steepness of surrounding slopes and angle of reach to the lake) were used to quantify the likelihood of ice or rock falling from the surrounding steep slopes into each lake, which could cause a catastrophic displacement wave. Secondly, the maximum downstream length of the floodplain from each lake was simulated using the modified single flow (MSF) simple flow path model.

3.2. Vulnerability

Vulnerability is defined as "*the propensity or predisposition to be adversely affected. Vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt*" (IPCC 2014). Whereas earlier concepts of climate vulnerability embedded the magnitude of climate change or related physical event to which a society may be exposed within the definition, here vulnerability is seen as a social construct, linked to socio-economic, cultural and institutional factors (Birkmann et al., 2015). For example, a community living on a floodplain might be considered exposed to significant flood hazard, yet not vulnerable, if sufficient warning, protection, community support and response systems are in place. In forest ecological systems, Upgupta et al. (2015) referred to this as inherent vulnerability, largely determined by physiological characteristics of a species. To characterise vulnerability across larger scales (entire states or countries) vulnerability indexes are typically created from a series of quantifiable proxy indicators that represent the main components of vulnerability. While there are ongoing scientific debates on how best to quantify vulnerability, and which indicators should be included (Birkmann, 2014), indexes typically draw on Census data, which provides regular, transparent, homogeneous sampling of socio-economic conditions at the national scale (e.g., Chen et al., 2013; Cutter et al., 2003; Cutter and Finch, 2008).

In Kullu, we focussed our assessment on available indicators from Census India that best capture societal capacities to anticipate, respond to, and recover from a flood disaster (Table 1). For example, the ability to read and having access to communication systems (e.g, mobile phone, radio, and internet) enhances a household's ability to heed warnings, prepare accordingly, and follow through with an emergency response plan. Information on population demographics is also important, with research highlighting differences in the capacity to respond to a disaster based on age, gender, religion, health, and other social factors (Cardona et al., 2012). Recovery from a disaster may be

Table 1
Indicators used in the flood vulnerability assessment for Himachal Pradesh, India. The main components of vulnerability represented by each indicator are listed, and the dependency of the relationship with vulnerability is given (after Allen et al., 2016).

Indicator	Components represented	Dependency[1]
Female population	Sensitivity, capacity to prepare, respond and recover	+
Population < 6 years of age	Sensitivity, capacity to prepare, respond and recover	+
Population > 60 years of age	Sensitivity, capacity to prepare, respond and recover	+
Literacy rate	Capacity to prepare, respond and recover	–
Unemployment	Capacity to prepare, respond and recover	+
Employment in farming	Sensitivity, capacity to recover	+
Disabled population	Sensitivity, capacity to prepare, respond and recover	+
Home renters	Capacity to recover	+
Derelict houses	Sensitivity, capacity to respond and recover	+
Water availability	Capacity to prepare and respond	–
Medical facilities	Capacity to prepare and respond	–
Education facilities	Capacity to prepare, respond and recover	–
Banking services	Capacity to prepare and recover	–
Access to radio	Capacity to prepare and respond	–
Access to TV	Capacity to prepare and respond	–
Access to internet	Capacity to prepare and respond	–
Access to mobile	Capacity to prepare and respond	–
Access to vehicle	Capacity to prepare, respond, and recover	–

(1) A positive (+) dependency means that an increase in the measured variable indicates an increase in vulnerability. A negative (-) dependency means that an increase in the measured variable indicates a decrease in vulnerability.

hindered by a lack of income, particularly for the unemployed or agricultural workers whose livelihoods are most susceptible to climate related threats such as floods, while home owners are generally considered to be in a stronger position post-disaster than those who rent, for whom financial support mechanisms may be lacking. State-wide results at the tehsil level were first presented by Allen et al. (2016), and have been complemented here with a new village level assessment that better supports local risk assessment and adaptation planning for Kullu (Sections 4 and 5).

Indicator values were standardized to a common range (e.g., 1–10) with the final vulnerability index calculated as the unweighted average across all standardised values. More advanced approaches may apply weighting schemes to emphasise what are known to be more important drivers of vulnerability, but generally such weighting is difficult to justify in the absence of detailed local studies at the ground-level. Weighting can furthermore be defined during a scoping process with stakeholders, and be informed by an evaluation of driving factors of vulnerability trajectories observed in the past.

3.3. Exposure

As defined by IPCC 2014, exposure refers to *"the presence of people, livelihoods, species or ecosystems, environmental functions, services, and resources, infrastructure, or economic, social, or cultural assets in places and settings that could be adversely affected"*. Exposure is therefore typically assessed based on an inventory of elements located within an area in which hazards or adverse effects of climate change may be expected to occur. At large scales (state to district level), human exposure is difficult to directly quantify, and studies must rely on proxy indicators such as population density or housing density to provide an approximate indicator of the level of human exposure. Such an approach was implemented for the GLOF study conducted across Himachal Pradesh

(Allen et al. 2016), and these results serve as the basis for the integrated assessment of GLOF risk presented here (Section 4). It was assumed that higher population densities at the level of a tehsil indicated an increased number of people living or working in flood-prone areas. This is considered a reasonable assumption for Himachal Pradesh, and perhaps for the Himalayan region in general, given the cultural, hydrological, ecological, and economic importance of the rivers and their surrounding floodplains where major habitations and infrastructure are frequently located. However, this approach may poorly capture exposure of highly transient populations, such as pilgrims, tourists, or migrant labourers, and thereby lead to an underestimation of risk within some remote mountain valleys. For example, many of the estimated 6000 fatalities during the 2013 Northern India flood disaster included pilgrims stranded along the sacred Chota Char Dham Hindu pilgrimage circuit in the Garhwal Himalaya (Allen et al., 2015; Uniyal, 2013).

For local-scale assessment of flood risk it becomes desirable and feasible to map more precisely the residential dwellings, tourist infrastructure and other assets that sit in harm's way. High-resolution satellite or aerial imagery provides an important source for mapping such elements, and repeat mapping can be used to explore changing trends in exposure over time. For the district of Kullu, freely available imagery from Google Earth has been used to map buildings (both residential and industrial) exposed to monsoon flooding. All clearly distinguishable elements located within a circular buffer of 200 m from the centre of the river were mapped. 200 m was considered a conservative distance based on field evidence and understanding of past flood events in the region. Exposure was then quantified as the elevation difference (in metres) between the mapped element and the river bed, assuming logically that elements located higher above the river bed are less exposed to floods than elements located at lower elevations relative to the river bed. The method is sensitive to inaccuracies in the imagery and topographic data, and some elements (< 1%) were excluded from the analyses where errors were evident due to small data voids in the DEM. However, the concept has significant potential for upscaling to other areas utilising crowd-sourcing initiatives for large-scale mapping and exploiting the increasing availability of improved high-resolution topographic data. For example, a more comprehensive approach could also examine where key community lifelines (bridges, roads, electricity lines) are exposed.

4. Integrated risk assessment

Here we demonstrate with two illustrative examples how the risk components outlined in Sections 3.1–3.3 were integrated at both the state (Himachal Pradesh) and district (Kullu) scale, to address relevant adaptation questions and challenges. Firstly, we built on the work of Allen et al. (2016) at the state scale, where the challenge was to characterise the GLOF threat across the tehsils of Himachal Pradesh, raise awareness with local stakeholders, and provide a first basis for adaptation planning. Following the standardization of the hazard, exposure, and vulnerability layers to a common index (i.e., with scores ranging from 1 to 10), the values were multiplied to establish an overall risk index.

$$\text{Risk} = \text{Hazard} \cdot \text{Vulnerability} \cdot \text{Exposure}$$

The final risk classification (5 quantile ranges) provides a relative indication of the threat level across the state, identifying tehsils where the GLOF risk is most pronounced (Fig. 2a). For tehsils such as Pangi and Dodra Kwar, the high risk levels are a manifestation of high levels of hazard and vulnerability, while exposure is relatively low (Fig. 2b). Conversely, for the large mountainous tehsil of Lahaul, where hazard levels are also comparatively high, very low levels of both exposure and vulnerability lead to low overall levels of risk. Similar, yet more subtle variations are highlighted within the district of Kullu, where significantly higher vulnerability levels for the tehsil of Banjar, lead to relatively high overall levels of GLOF risk.

For the second example of monsoon flood risk, the starting point of the assessment was very different. In this case there was already long-standing awareness amongst local stakeholders of the threat that monsoon rainfall and cloudburst events bring, with regular disasters occurring across Himachal Pradesh, including within Kullu district (DoES&T, 2012; Gardner, 2010). However, adaptation actions are generally lacking. Therefore, the challenge within this context was to integrate the improved quantification of monsoon flood hazard (Section 3.1.1) with the other risk components of exposure and vulnerability at a scale that provided meaningful information for development and ultimately implementation of on-ground adaptation and risk reduction strategies. To this end, vulnerability and hazard values were aggregated to each of the 1700 exposed elements (buildings) mapped along the main river valleys of Kullu district. For the hazard component, the value was assigned as calculated for the adjacent reach of the river. For vulnerability, the census-based approach was implemented at the village level (Section 3.2), with each mapped element then being assigned a vulnerability score corresponding to the nearest village (where village locations were given as a central point). While polygons defining the village boundaries more precisely would have been preferred, such data were not available for this study. All components were again standardised to common index ranging from 1 to 10, and multiplied to give the final risk value for each element, classified according to 5 quantile ranges.

The resulting assessment clearly elucidates the pattern of monsoon flood risk across Kullu district, and identifies several hot-spots within all sub-basins where adaptation and risk reduction strategies could be focussed (Fig. 3). While more elements are exposed along the heavily populated floodplains of the main Beas river valley, it is clear that proportionally more dwellings located within the remote valleys of Parvati, Sainj and Tirthan face moderate, high to very high levels of risk. Hence, any monsoon flood events could result in catastrophic impacts to these communities. In the more populated Beas valley, significant infrastructure located within lower risk zones may escape unharmed, meaning that complete loss of community functionality may be avoided, and response capacities may therefore be generally better.

5. From scientific assessment to adaptation action

Following an iterative process of stakeholder consultation, results from the pilot studies in Kullu have provided the basis for the design of adaptation strategies outlined in a series of Detailed Project Reports (DPR's), submitted by the Government of Himachal Pradesh to national and international adaptation financing schemes (Fig. 4). As a first step, key assessment findings and an associated basket of potential adaptation options covering a range of climate impacts and sectors were presented to local stakeholders during a series of result sharing and exchange workshops. In relation to both monsoon floods and GLOFs, this basket included a suite of disaster risk reduction strategies, including Early Warning Systems (EWS), land-use zoning, structural engineering defences, community awareness and preparedness, and emergency response strategies (IHCAP, 2016). From this initial basket, a grouping of nine adaptation measures was then further developed into concept notes. Several consultation workshops and community meetings followed, before arriving at a final selection of three adaptation ideas to be developed into full DPR's. A key component of the workshops was a prioritisation exercise, where participants were tasked with ranking the nine adaptation ideas in accordance with several criteria, including climate relevance, urgency, sustainability, and feasibility.

Following this consultative process in Kullu, the Parvati Valley was selected for design of an integrative lake monitoring and monsoon flood EWS strategy (Fig. 3 and 5). While a scientific argument could be made that monsoon flood and GLOF risk is greater in other areas of the district (Section 4), this decision reflected more broadly the needs and

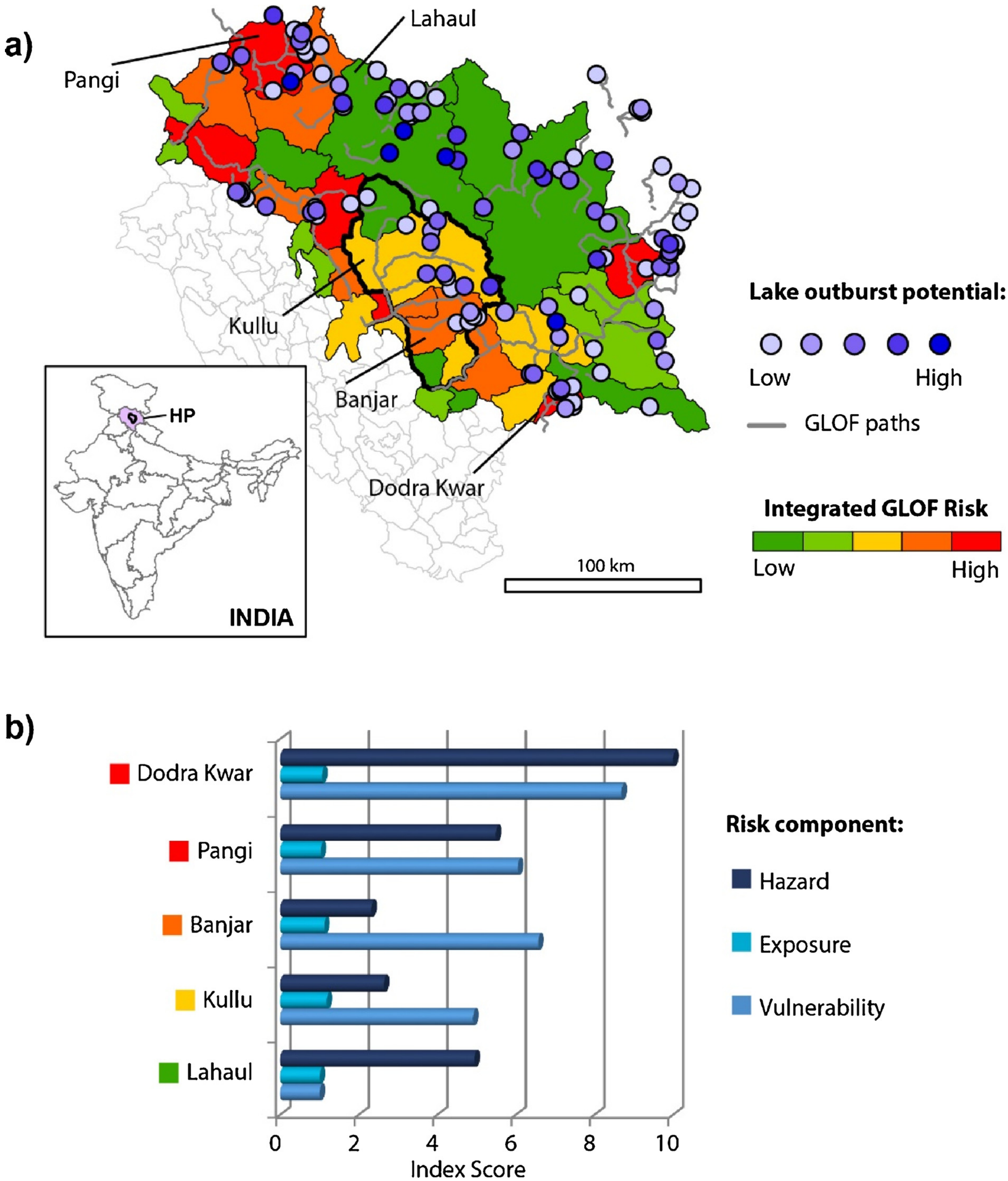

Fig. 2. a) Integrated GLOF risk assessment for the tehsils of Himachal Pradesh (HP). Tehsils positioned beyond the worst-case maximum reach of any GLOF paths are excluded from the assessment. b) For selected tehsils, the contribution of hazard, exposure, and vulnerability to the overall assessed risk level is indicated.

wishes of local stakeholders, political considerations, and the local institutional context and capacities. Crucial in this regard was ensuring that the planned EWS was well supported by the District Disaster Management Authority (DDMA). Hence, a series of meetings were undertaken with the Deputy Commissioner of the Kullu District Administration and officers of the DDMA, to both discuss key findings from the risk assessment, and to ensure the proposed adaptation options aligned with local legislation and priorities outlined under the Disaster Management Act of 2005. The final design of the DPR drew heavily on the underlying science, incorporating two main components: 1) Catchment-scale annual to seasonal monitoring of glacial lake development based on remote sensing and supported with field studies, and 2) an instrumental monsoon flood EWS to protect identified hot-spots of risk along the Parvati Valley (Fig. 5). This strategy recognised that monsoon floods are the very real and frequently observed threat to lives and property in Parvati Valley, while acknowledging the strong stakeholder interest in responding to the potential GLOF threat. Future risks may to some extent be anticipated (e.g., possible maximum expansion of glacial lakes and changing potential for impacts from rock or ice, or based on projected changes in hydrological extremes), but uncertainties generally remain large. Hence, the need for regular and long-term monitoring of changing environmental conditions is emphasised, with

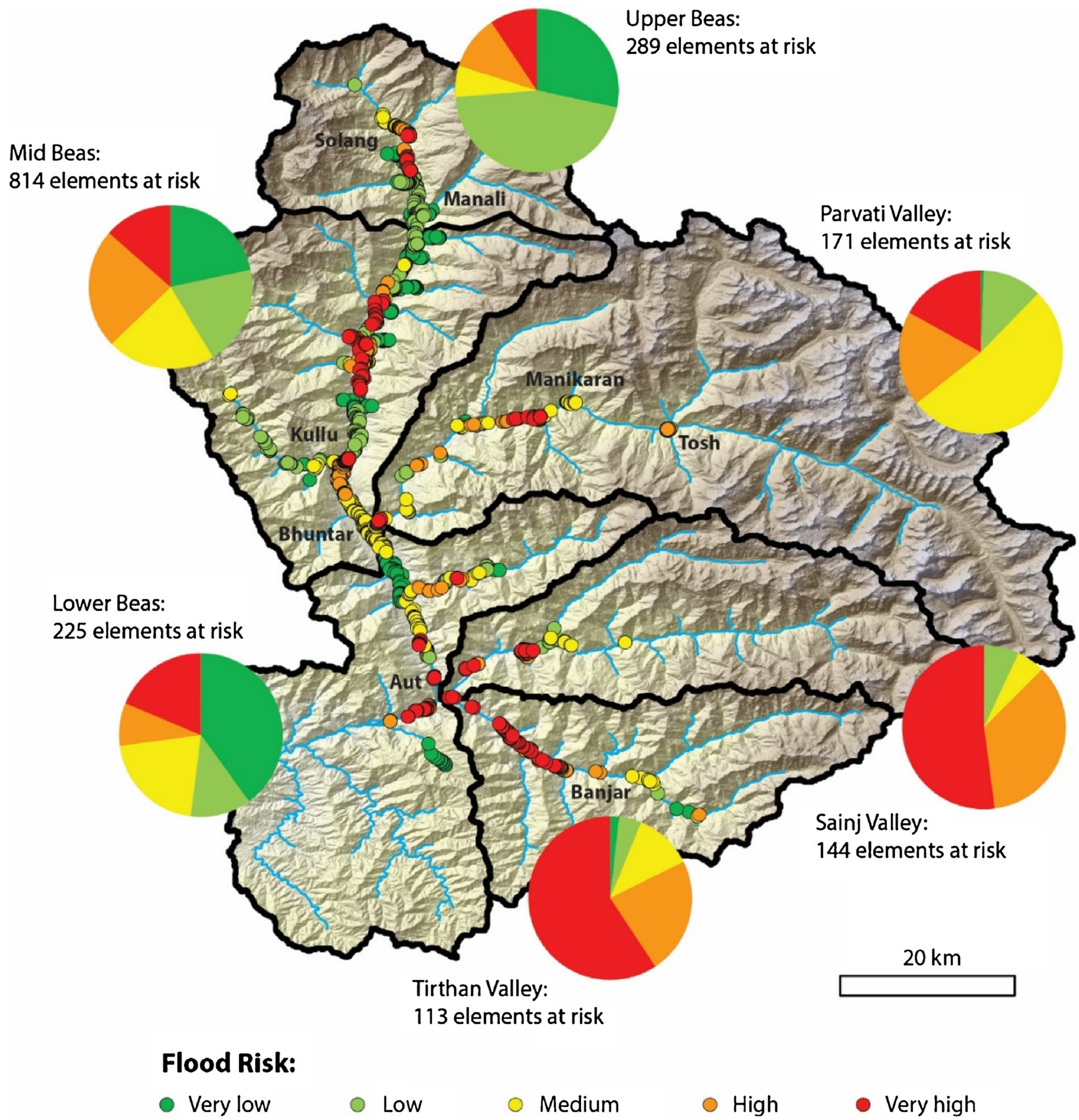

Fig. 3. Integrated monsoon flood risk assessment for the main watershed areas of Kullu district. Elements at risk are buildings mapped from high-resolution google earth imagery. Main villages along the river valleys are labelled.

hazard and risk assessments to be updated accordingly to keep pace with rapidly evolving threats and changing stakeholder requirements. In addition to the technical components, the monitoring and EWS strategy is to be underpinned by a suite of 'low-regret' adaptation strategies, which aim to strengthen local institutional and community capacities, and ensure the long-term operability, maintenance, acceptance, and success of the project implementation. On an institutional level, this would include continued Indo-Swiss knowledge exchange and scientific capacity building, while at the community level, the DDMA would lead training programmes and workshops to empower local people to prepare and respond to any flood alert.

6. Discussion

In the Himalayan region, disasters are more often than not associated with climate variability and extremes, albeit as direct triggers or as compounding factors (e.g., Fujita et al., 2016; Mishra, 2015; Singh et al., 2014). Therefore, the use of an integrated risk assessment framework which combines concepts and approaches from the complimentary fields of climate change adaptation and disaster risk reduction is required to provide the necessary scientific basis for sustainable adaptation planning. Under the IHCAP, pilot studies focussing upon Kullu district, Himachal Pradesh, have operationalised the IPCC concept of climate risk for the assessment of flood risk at two different scales.

The state-wide assessment of risk from GLOFs provided results aggregated to the administrative level of a tehsil, relying on proxy indicators of exposure and vulnerability, and first-order worst-case scenario modelling of the outburst hazard. Studies at this scale typically provide an insufficient basis for the design of specific local adaptation strategies (e.g. early warning systems). However, such studies should be seen as a vital prerequisite step to support the mobilisation of additional financing that would then enable further monitoring, field investigation, and refinement of the problem. This was the approach taken in

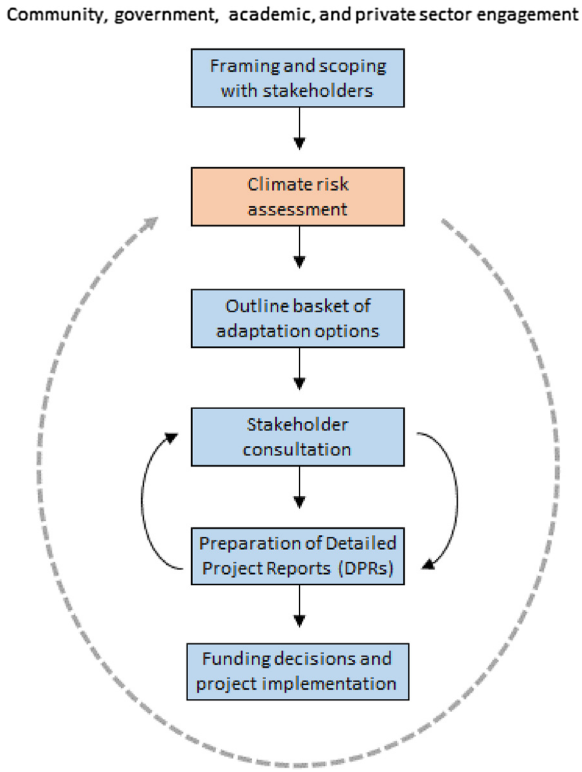

Fig. 4. Key steps in the process of transferring assessment findings into adaptation action (after Huggel et al. 2015), as undertaken for Kullu district, Himachal Pradesh. The process should be iterative and dynamic (grey dashed), with ongoing scientific assessment in response to changing environmental and societal conditions, and in support of project implementation.

Kullu, where the results of the GLOF hazard assessment were presented during stakeholder consultations to build understanding of this rapidly evolving and often poorly understood threat, leading to inclusion of a glacier lake monitoring component within the proposed flood adaptation project. Limitations and shortcomings of the large-scale hazard assessment were clearly acknowledged, recognising in particular that only one (albeit potentially most important) triggering mechanism (mass movements of ice and rock) was considered. Nonetheless, irrespective of the underlying triggering mechanisms, one of the fundamental key messages coming from the assessment concerned the potentially far-reaching impacts that GLOFs can produce, with some areas of enhanced risk located far downstream from where the potentially dangerous lakes originate (Fig. 2a). Particularly for threats which travel across administrative or even national borders, such large-scale risk mapping is crucial for identifying where vulnerable communities may be exposed to unexpected or previously unforeseen threats. Early identification and awareness of these potential far-reaching threats are critical, providing the necessary basis to initiate further collaborative research and monitoring activities that must in some cases span across politically sensitive regions.

For the assessment of monsoon flood risk within Kullu district, the reconstruction of historical flood frequency and magnitude relationships using tree rings enabled risk mapping to be undertaken for individual elements located along the main river valleys. This information then served as direct input to the design of the instrumental flood EWS for Parvati Valley, that will protect exposed and vulnerable communities within identified risk hotspots. A key limitation at this scale remained the characterisation of vulnerability, with all elements along a given stretch of river assigned the same vulnerability score, according to the census-derived socio-economic indicators from the nearest village. To overcome these challenges, further studies in support of the adaptation project will ideally incorporate participatory, community-based approaches for vulnerability assessment, which can delve much

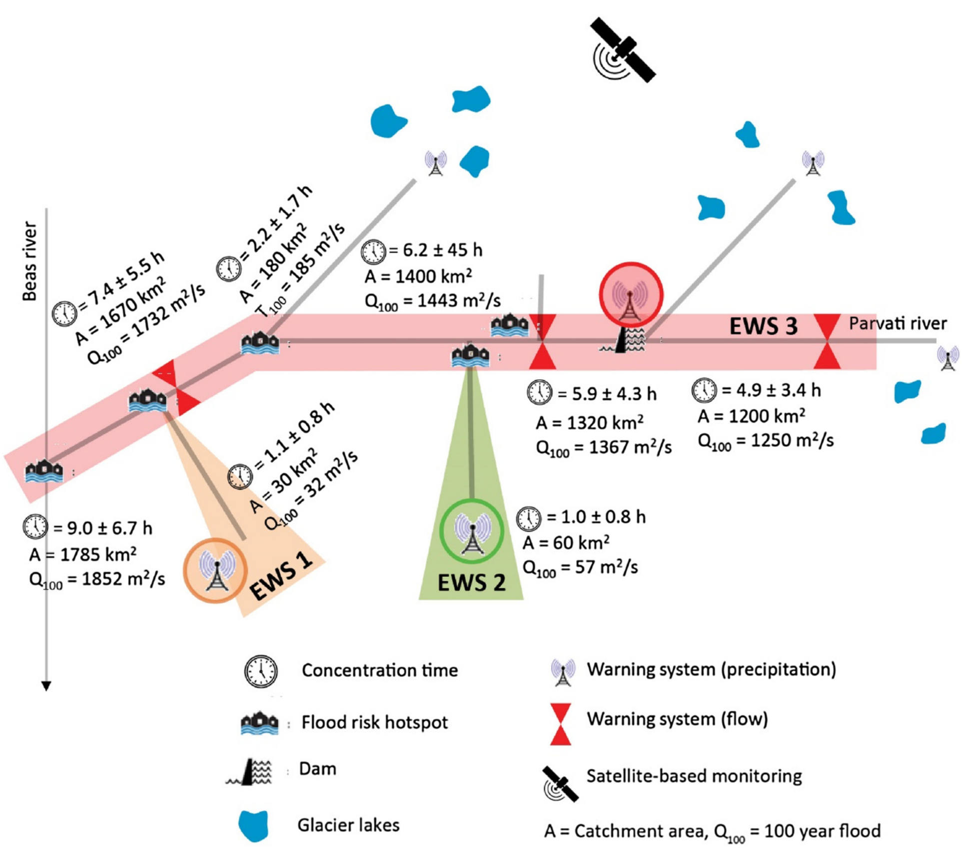

Fig. 5. Schematic overview of the integrated monsoon flood EWS and GLOF monitoring strategy for the Parvati Valley, Kullu District.

deeper into how local inhabitants perceive their own capacities to anticipate, respond to, and recover from a disaster (Jurt et al., 2015; O'Brien et al., 2004; Van Aalst et al., 2008). As well as providing secondary data with which to validate the proxy-based assessment, such community studies may highlight sub-village level patterns in the distribution of vulnerability, and have the advantage of engaging citizens directly in the knowledge generation process, building a foundation for successful and sustainable community-based adaptation strategies.

A key advantage of the broad concept of climate risk is its potential applicability to a wide range of climate related threats, paving the way for integrative and forward-looking adaptation strategies that address the underlying components of hazard, exposure and vulnerability. However, this also brings challenges, reconciling very real, observed, and reoccurring threats (e.g., flooding from cloudbursts and seasonal monsoon rainfall in Kullu), with rapidly evolving problems, such as GLOFs, for which past understanding is more limited. Our approach in Kullu, where stakeholders expressed a particularly strong interest in GLOF response strategies, was to combine a monsoon flood EWS and lake monitoring program with a broader suite of "low-regret" adaptation actions addressing the exposure and vulnerability components of risk. These low-regret actions (e.g., community education and preparedness, and development of disaster response plans) have the potential to reduce the vulnerability of exposed communities to the existing and well-quantified threat of monsoon flooding along Parvati Valley, while also building capacities to prepare and respond to the evolving and less certain GLOF risk.

Importantly, the scientific contribution to the adaptation process does not end with the delivery of the climate risk assessment to stakeholders. Rather, as highlighted by Huggel et al. (2015), the adaptation journey should be guided by ongoing iteration between scientists and decision-makers, where critical discussions on key assessment findings, associated limitations or uncertainties, and the further data requirements needed in support of any implemented adaptation strategies feed back into ongoing scientific assessment. This is particularly crucial for Kullu, where the scope of the scientific assessment under IHCAP was limited to only 12-months duration, which is clearly at the lower end of the 1–3 year period typically required for this phase of the science contribution to climate change adaptation (after Huggel et al. 2015). Hence, weaknesses and short-comings in the current assessment are to be expected (as pertaining for example to the characterisation of vulnerability), and these limitations have been clearly communicated to the stakeholders. In reality, project life-cycles are often such that insufficient time is allocated for this iterative phase of adaptation planning, as politicians or donor agencies want to see easy-wins and earn quick political capital, all of which enhances the risk of maladaptation. While the integrative concept of climate risk undoubtedly provides a stronger scientific basis for adaptation decision-making, the inherent multidisciplinary nature of the assessment and the need to integrate baseline data and methodological approaches across physical and social systems should be reflected in realistic project planning, selection of project consortia, and resource allocation.

7. Conclusions

Core concepts of hazard, exposure and vulnerability have been quantified and integrated at two spatial scales to assess flood risk and inform climate adaptation planning in Kullu, Himachal Pradesh. In a state-wide first-order assessment of GLOF risk, proxy indicators were combined with worst-case scenario modelling to identify where GLOF threats are most pronounced. Meanwhile, for the main river valleys of Kullu district, an assessment of monsoon flood risk was undertaken for individual mapped elements, drawing on reconstructed flood magnitudes from tree-rings. The subsequent design of adaptation actions was guided by an iterative process of exchange and discussion with stakeholders, recognising that while science should closely inform the decision-making process, only those actions that are strongly desired and supported by local stakeholders will prove sustainable in the long-term. A DPR outlining a proposed integrated monsoon flood and GLOF monitoring and EWS for Kullu has subsequently been finalised and submitted to national adaptation financing schemes. However, further scientific assessment will now be needed to guide and support the implementation of climate adaptation actions in Kullu. This pilot study has demonstrated that the integrated concept of climate risk can be usefully translated into an assessment framework, with results feeding into on-ground action, and potential therefore now exists to upscale approaches to other districts and states of the Indian Himalayan region.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi: https://doi.org/10.1016/j.envsci.2018.05.013.

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