Synthesis Report

Climate Vulnerability, Hazards and Risk:

An Integrated Pilot Study in Kullu District, Himachal Pradesh

IHCAP Indian Himalayas Climate Adaptation Programme

About Indian Himalayas Climate Adaptation Programme (IHCAP) IHCAP is a project under the Global Programme Climate Change (GPCC) of the Swiss Agency for Development and Cooperation (SDC), and is being implemented in partnership with the Department of Science and Technology, Government of India. The goal of the project is to strengthen the resilience of vulnerable communities, and to enhance the capacities of research institutions, communities and decision makers.

Objectives

- Strengthening capacities for adaptation planning and implementation in Himachal Pradesh through research,training and capacity building
- Scientific capacity building in the field of Glaciology and related areas
- Facilitating dialogues between Himalayan states and key stakeholders for mainstreaming climate change concerns into development planning

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Synthesis Report

Climate Vulnerability, Hazards and Risk: An Integrated Pilot Study in Kullu District, Himachal Pradesh

Executive summary

The Indian Himalayan Region (IHR) is among the most complex and diverse mountain ecosystems in the world, and is home to an estimated 72 million people. Nearly one billion people depend upon hydrological resources and ecosystem services that originate from this unique environment. All mountain environments are extremely sensitive to the changes in the global climate system, with widespread glacier retreat being one of the clearest signals of warming temperatures over the past century. The glacial retreat when coupled with increased infrastructural expansion, urban growth, and other environmental pressures can lead to severe climate-related threats to lives and livelihoods. Recognizing the pervasive and complex challenge that the communities face in the IHR, the Swiss Agency for Development and Cooperation (SDC) together with the Department of Science and Technology, Government of India, initiated the Indian Himalayas Climate Adaptation Programme (IHCAP). Under IHCAP, a pilot study has been completed in Kullu district, Himachal Pradesh, to provide an integrated assessment of climate vulnerability, hazards and risk. The study represents a knowledge gathering process and is implemented within a framework that can be outscaled to other districts and states, to provide the scientific basis for prioritizing, planning and implementing adaptation measures across the IHR. The framework that guides the integrated climate vulnerability, hazards and risk assessment in Kullu draws on the latest concepts used by the Intergovernmental Panel on Climate Change where climate-related risk is considered as the consequence of a physical event (hazard) intercepting with an exposed and vulnerable system (e.g. community or ecosystem).

Several studies addressed the fundamental atmospheric and cryosphere baseline data requirements to provide the basis from which historical and future changes can be established. Due to lack of reliable long-term observations for high-mountain environments, modern approaches were implemented that drew upon remotely sensed data, gridded climatological datasets and modelling. Over the reference period (1981 – 2010) there has been a widespread increase in mean annual air temperatures over Kullu, with greatest warming observed during the spring months (~ 0.35 °C per decade). Glacier inventories that have been compiled since the mid-1960s, show a substantial retreat of glaciers over the past 50 years with associated formation of numerous glacial lakes over recent decades. An estimated 26 km^3 glacial ice volume remains in Kullu that represents a significant hydrological resource within the Beas catchment area. The extent of the permafrost (or frozen ground) across Kullu is less certain since permafrost being a sub-surface phenomenon cannot be directly mapped. However, the new studies implemented under IHCAP demonstrate that up to 420 km^2 of the high elevation land area in Kullu could be underlain by permafrost. Hence, thawing of this ground in response to warming could have significant implications for the stability of steep slopes or moraine dammed lakes, hydrological systems and sediment load in rivers.

Studies assessing climate vulnerability, hazards and risk in Kullu emphasized the threat to floral biodiversity and the economically important agriculture-horticulture sector, and catchment-scale flood, landslide, and avalanche hazard and risk studies. A household survey revealed that communities in Kullu already perceive significant climate-related impacts on their lifestyles and livelihoods. The variability in rainfall and snow cover, increased temperatures, and glacial retreat are considered to be impacting most notably on horticulture and agricultural productivity, and water resources. At the same

time, communities are shifting away from traditional agricultural practices towards the cultivation of cash crops, and increased employment opportunities are emerging in the tourism sector. A comprehensive vulnerability assessment for the agriculture-horticulture sector indicates that Anni and Banjar are the most vulnerable blocks within Kullu district.

The steep topographic environment and monsoon climate combine to produce pervasive flood and landslide problems across Kullu, with both the Parvati Valley and upper Beas catchment identified as the highest hazard zones. Significantly, communities have indicated that although climate-related hazards such as floods and landslides are common, they are not aware of appropriate response strategies. At least 66 major flashflood disasters have occurred in Kullu over the past 50 years, mostly triggered by cloud-burst events during the peak monsoon months. Studies using dendrochronology have provided new understanding of the past flood characteristics in ungauged streams. These studies demonstrated that potential flood magnitudes are largely underestimated if based only on limited instrumental data. This new knowledge directly feeds into the design and implementation of flood-risk reduction strategies. Glacial lake outburst floods (GLOFs) are comparatively rare events, but the 2013 Kedarnath disaster in the neighbouring state of Uttarakhand demonstrated the possible devastating and far-reaching consequences. A complete GLOF risk assessment has been conducted at the tehsil-scale for the Kullu district. It shows that the greatest GLOF threats originate from the heavily-glaciated Parvati Valley, with large events potentially reaching the heavily-populated downstream areas of the Kullu Valley. As glacial lakes continue to expand and new lakes form over subsequent decades, GLOF hazard will increase significantly across Kullu and will result in increased exposure of habitations, roads, hydropower infrastructure, and agricultural-horticultural land. GLOF hazard, thus, necessitates long-term planning and adaptation solutions.

Based on the results and experiences from the Kullu pilot study, a series of key overarching policy-relevant messages for climate change adaptation and disaster risk reduction in the Indian Himalayan context are outlined. In particular, the need for ongoing international collaboration and knowledge exchange at all levels is highlighted, together with the requirement for strengthened communication between researchers, decision makers, and practitioners to ensure that real-world adaptation solutions are developed. Ultimately, concrete planning and implementation of adaptation measures must proceed in close cooperation with local stakeholders (community, government and private sector) and be supported by best available scenarios of future climate.

Outscaling of the assessment framework and methodological approaches, developed under IHCAP, to other Indian Himalayan states and districts will now allow crucial new knowledge and experiences to be transferred beyond Kullu. It will ensure strengthened capacities and will provide a robust scientific basis for climate adaptation planning across the IHR.

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Cover image: Rohtang Pass, linking Kullu with the district of Lahual and Spiti.
(Photo taken by Praveen Bhardwaj)

Contents

Appendix I (electronic only)
Extended project report summaries (available from www.ihcap.in)

1. Introduction

The Indian Himalayan Region (IHR) is facing important challenges in view of coping with adverse effects of climate change. Like many other mountainous regions worldwide, the IHR is also sensitive to changes in global climate, from both physical and societal perspectives. Physically, the retreat of mountain glaciers, the decrease of snow cover extent and the rise of snowline elevations are among the most visible indicators of changes in the global climate system, and are associated with potentially severe and far reaching downstream impacts. As ice melts and glaciers retreat, vastly different landscapes emerge, where glacial lakes form behind steep and unstable accumulations of debris, surrounding steep bedrock slopes become unstable, and previously frozen ground begins to thaw. Besides the direct threat of related natural hazards (glacial lake outburst floods, rockfalls etc.), increased eroded sediment transported downstream is a problem for infrastructure (e.g. hydropower dams) and ecosystems.

Flood and landslide disasters are common across the IHR, owing to the unfavourable interaction of climate, lithology, topography, and seismicity. Potential changes in timing and quantity of rainfall are therefore a significant concern, with a general increase in extremely heavy precipitation projected for the twenty first century in South Asia. On the other hand, seasonal precipitation in combination with snow- and glacier-melt water is crucial to sustain agricultural sectors and ecosystem services, and even small changes in rainfall patterns can have significant impacts on dependent livelihoods.

The key objective of the IHCAP pilot study was to develop and apply a comprehensive conceptual framework to assess these and other climate-related threats in the Kullu district. By framing the pilot study under the Intergovernmental Panel on Climate Change (IPCC) concept of climate risk, it is ensured that there is a clear and internationally accepted understanding of the key concepts of vulnerability, hazards and risk. In addition, emphasis has been given to the development of methodological approaches that may be transferred to the larger IHR. By bringing together Indian and Swiss-based scientists with a diverse range of backgrounds and expertise, this integrated study provides a true interdisciplinary perspective of climate vulnerability, hazards and risk in the Kullu district.

The purpose of this synthesis report is to bring together the various components of the pilot study, highlight key findings, discuss the main learnings and implications for climate change adaptation (CCA) and disaster-risk reduction (DRR) in Kullu district, and provide perspectives to transfer the methodological approaches to the broader IHR.

A brief introduction about Kullu – the study region - and a detailed description of the integrated assessment framework are provided in sections 2 and 3 respectively. The key results that emerge from the various joint Indo-Swiss study components are presented in two sections. Studies that address fundamental baseline data requirements are reported in Section 4, while the findings from the specific climate vulnerability, hazards and risk studies are reported in Section 5.

For full methodological details and results from the various joint studies completed in Kullu district under IHCAP, readers should refer to the extended executive summary documents listed in Appendix I which is available electronically.

2. Kullu district, Himachal Pradesh

The IHR stretches across 12 states in the western and eastern Himalayas and is home to an estimated 72 million people. However, the region provides hydrological resources and ecosystem services not only for local communities, but also for an estimated 900 million people living downstream upon the fertile grounds of the transnational Indo-Gangetic Plain.

Under IHCAP, Kullu district (population 437,900) within the north-west Indian state of Himachal Pradesh was selected as a focus region to develop and implement an integrated framework for climate vulnerability, hazards, and risk assessment (Figure 1). Kullu district (5500 km^2) is centred along the north-south axis of the Kullu Valley formed by the Beas river. The main valley extends approximately 90 km from Larji in the south to Rohtang Pass in the north and is a significant national transportation corridor. Major urban settlements include Manali, Kullu and Bhuntar. Overall, the district has seen a significant recent growth in urban population, with a 35 per cent increase recorded between 2001 and 2011. A unique feature of the Kullu Valley is the broad U-shaped profile, relative to many other more deeply entrenched river valleys of the Himalaya. The wide, gently sloping valley floor supports well-developed soils that in turn provide a rich agricultural resource to maintain a significant component of the local economy. The three major crops that are widely cultivated on this soil are wheat, apples and maize.

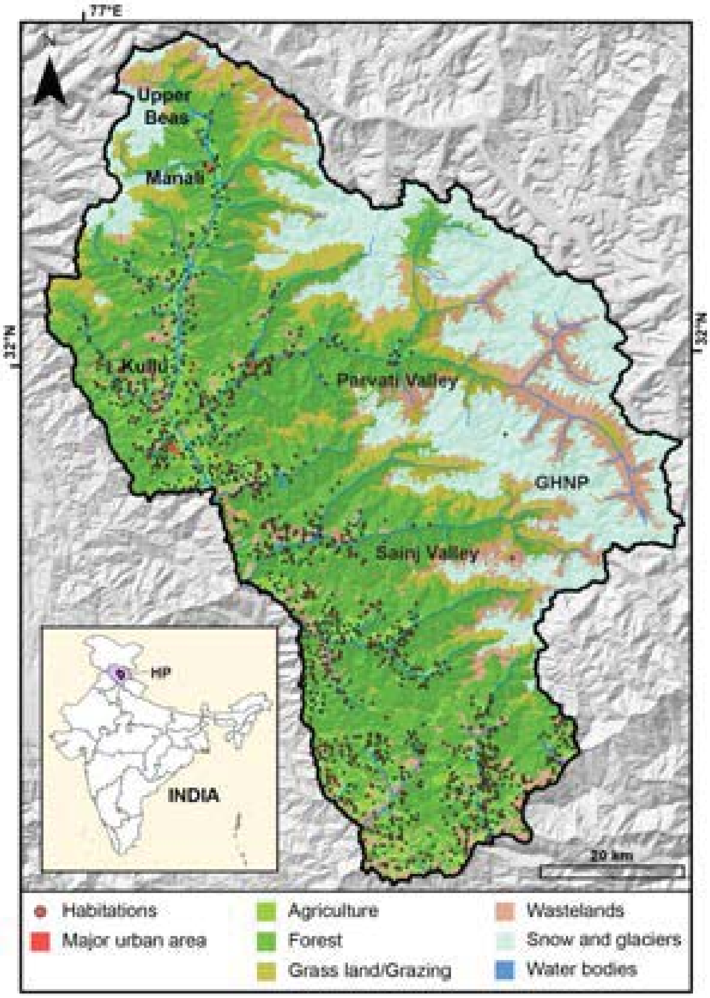

Figure 1: Overview of Kullu district showing major land use and land cover classes (from national LULC mapping using IRS LISS-II data), and habitations. Identified climate-change "hot-spots" (after IHCAP 2013) of the Parvati Valley, Upper Beas catchment, and Great Himalayan National Park (GHNP) are indicated.

The inset map indicates the location of Kullu district in northern India, within the Himalayan state of Himachal Pradesh (HP – shaded pink).

In total, the climate-sensitive agricultural sector provides direct employment to about 70 per cent of the total population (Census of India 2011). Above the valley floor, slopes steepen significantly, and evidence of landslides and other mass wasting processes scar the landscape. Approximately 35 per cent of the district is under forest cover, giving way to alpine tundra at higher elevations. The largest mountain peaks extend above 6500 m above sea level (a.s.l), with numerous glaciers and snowfields feeding the Beas catchment.

The overall climate regime of the Kullu district is considered to be sub-tropical monsoon characterized by cool, snowy winters at higher elevations; a warm, dry spring and autumn; and a warm, wet monsoonal summer. An increase in mean annual air temperature of 1.6 °C has been measured across the north-western Himalayan region during the past century, which is far in excess of mean global warming (Bhutiyani et al. 2007[1]).

In preparation for the pilot study, a scoping report (IHCAP 2013[2]) identified three particular climate-change 'hot-spots' in Kullu district based on potential adverse impacts to hydropower, forestry and agricultural sectors, and potential threats to sensitive ecosystem services which sustain local indigenous communities (Figure 1). Therefore, while most of the individual study components provide results at state to district scales, several of the studies reported herein give additional emphasis to one or more of these hot-spot areas.

3. Integrated assessment framework

The framework described herein is based on the concepts introduced in the IPCC (2012[3]) Special Report on *Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation*, and the Fifth Assessment Report of the IPCC (2014[4]). These reports represented important milestones that marked the confluence of the fields of climate adaptation and risk management. Both reports underscored the importance of taking a risk perspective in order to assess the different dimensions of threats linked to climate change. On one hand, climate change clearly contributes to increased climate extremes and significantly exacerbates adverse impacts, while on the other hand non-climatic factors shape the vulnerability of exposed societies.

Within the broader climate change adaptation context (Figure 2), the framework developed for the Kullu district is intended to guide the knowledge generation process, consisting of a scientific assessment of the past, present and future changes in physical and human systems. The scientific assessment thereby provides the sound basis for adaptation options and decisions, supported by the ongoing dialogue between the scientists and decision makers. The scientific assessment in the Kullu district has been preceded by a comprehensive scoping stage that involved wide engagement of stakeholders and research communities. Within the initial scoping stage for climate change adaptation studies, particular emphasis should be given to the importance of common and homogenous baseline data (climate, socio-economic and environmental) which allows various contributing studies and assessed components to be brought together in a coherent and policy-relevant synthesis.

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[1] Bhutiyani, M. R., V. S. Kale, and N. J. Pawar, 2007: Long-term trends in Maximum, Minimum and Mean Annual Air Temperatures across the Northwestern Himalaya during the Twentieth Century. *Climatic Change*, 85, 159-177.

[2] IHCAP, 2013: Climate Change in the Kullu Valley - A Scoping Study. Indian Himalayan Climate Adaptation Programme.

[3] IPCC, 2012: Managing the Risks of Extreme Events and Disasters to Advance Climate Change Adaptation. A Special Report of Working Groups I and II of the Intergovernmental Panel on Climate Change. C. B. Field, et al., (Eds), Cambridge University Press, UK and New York.

[4] IPCC, 2014: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. C. B. Field, et al., (Eds), Cambridge University Press, UK and New York.

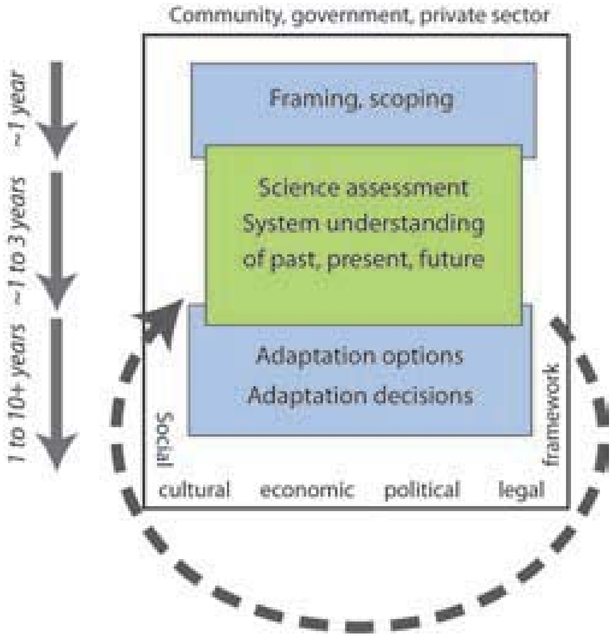

Figure 2: The scientific assessment viewed within the broader climate change adaptation process (Huggel et al. 2015[5]).

The framework for integrated climate vulnerability, hazards and risk assessment in the Indian Himalayas integrates the traditionally diverging perspectives from the disaster risk management community, and the climate adaptation community. The framework recognizes that *climate-related risk results from a physical event (hazard) intercepting with an exposed and vulnerable system (e.g. community or ecosystem)* (Figure 3).

‘Vulnerability’ is defined as the predisposition of a person or group to be adversely affected. Vulnerability is thus determined primarily by the social, cultural, political and institutional characteristics that influence a system’s capacity to anticipate, respond to, and recover from the adverse effects of climate change. The key distinction from earlier vulnerability assessment frameworks (e.g. IPCC AR4) is that the exposure component is now considered independent from vulnerability, i.e. a community may be exposed to a climate-related hazard, but not vulnerable (for example, if there are sufficient resources to protect a community living on a floodplain).

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[5] Huggel, C., et al., 2015: A Framework for the Science Contribution in Climate Adaptation: Experiences from Science-policy Processes in the Andes. *Environmental Science and Policy*, 47, 80-94.

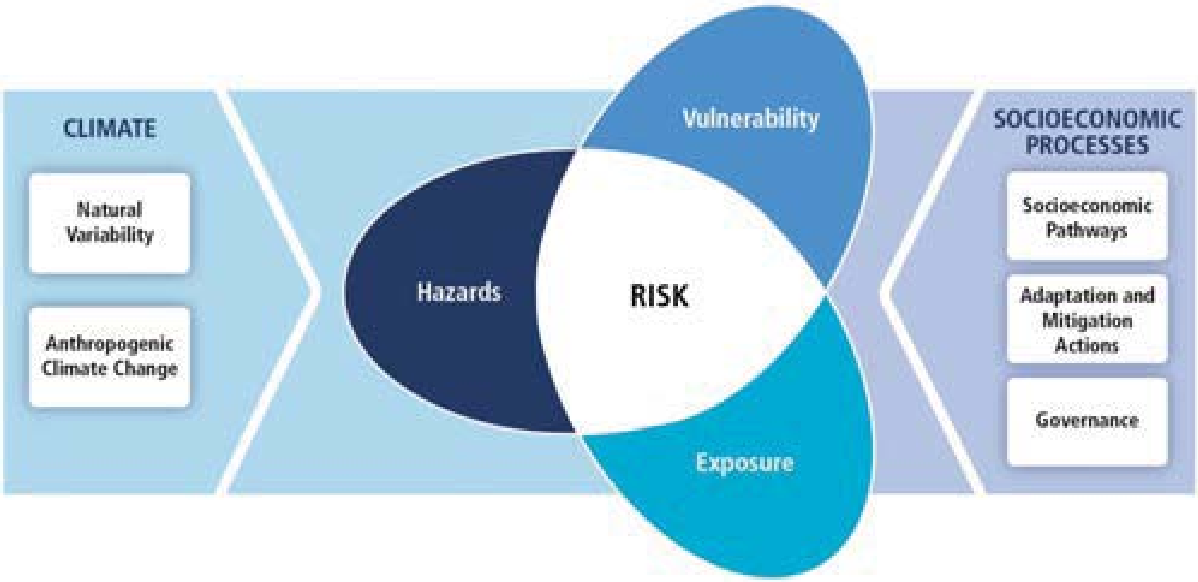


Figure 3: Schematic overview of the integrated IPCC concept of climate-related risk. Changes in both the climate system (left) and socio-economic processes including adaptation and mitigation (right) are drivers of hazards, exposure and vulnerability (IPCC 2014[4]).

To quantify vulnerability, the various components can be represented by proxy variables which can be normalized, weighted and indexed. However, there is no common set of vulnerability indicators that is generally valid, and appropriate indicators may considerably vary among different local and social settings. When the results of a vulnerability assessment are to be used as a comparative measure or for prioritization of resources across states, districts or villages, homogeneity of the data collection methods and analytical procedures must be given highest priority.

'Exposure' marks the presence of people, livelihoods, environmental services and resources, infrastructure, inventory of elements or economic, social or cultural assets in places that could be adversely affected. Exposure can be 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.

'Hazard' refers to the potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause severe adverse effects. Hazards are often associated with unusual or extreme hydrometeorological events, but non-extreme physical events also can lead to disasters where physical or societal conditions foster such a result. A broad climate vulnerability, hazard and risk assessment must consider both slow onset hazards (e.g. species extinction, biodiversity loss and groundwater shortages) and fast onset hazards (e.g. flooding, heat waves and landslides).

'Risk', therefore, results from the interaction of vulnerability, exposure and hazard. Risk is the potential for consequences where something of value is at stake (where value is a diverse and subjective concept) and where the outcome is uncertain.

The assessment and communication of this uncertainty to the decision makers is an important outcome from the scientific studies. Risk assessment and risk maps are key components of science-based climate change adaptation that provide the basis for risk reduction measures such as land use planning, early warning systems, preparedness and awareness-building activities.

The selection and acquisition of common baseline data (climate, socio-economic and environmental) is the single most important element for an integrated climate vulnerability, hazard and risk assessment. This allows various contributing studies and assessed components to be brought together and synthesized to provide a robust scientific basis for climate adaptation and policy recommendations. There are two key requirements regarding the common baseline data: 1) an agreed time window, and 2) agreed common datasets.

Studies conducted under the IHCAP Kullu pilot project were generally designed to address one or more of the main framework components of hazards, vulnerability, exposure and ultimately risk. An emphasis in the initial phase of the project has been given to climate-driven changes in risk.

4. Establishing baseline conditions

Studies completed under IHCAP aim to establish baseline climatic conditions for the beginning of the twenty first century in the Kullu district. Focus is given to two primary components of the climate system: the atmosphere and the cryosphere. Wherever possible, we assess the current climatic conditions as the period between 1981 and 2010. This provides a standard 30-year reference period against which historical and future changes in natural or physical systems can be assessed. In order to extend our baseline understanding, tree-rings have been examined to reconstruct local hydrometeorological conditions back beyond the instrumental record.

4.1. Atmospheric baseline

High-mountain environments are particularly sensitive to climate variability – be it natural or anthropogenically driven. However, understanding and quantifying such changes are often limited due to the scarcity of reliable long-term observations in remote high-mountain regions. This furthermore reduces the ability to develop and calibrate reliable future projections of climate, and thereby represents a fundamental challenge for related climate impact and adaptation studies. Baseline atmospheric studies undertaken for Kullu have attempted to overcome these limitations by deriving and analyzing spatial and temporal continuous temperature datasets based on observational gridded data and re-analyses. Additionally, satellite-based precipitation estimates are compared to ground-based gridded products.

The local climate assessment based on gridded observational data and re-analyses for the Kullu district over the time window 1981 – 2010 clearly demonstrates that mean annual air temperatures have generally increased across all elevation levels. This warming is seen in all datasets.

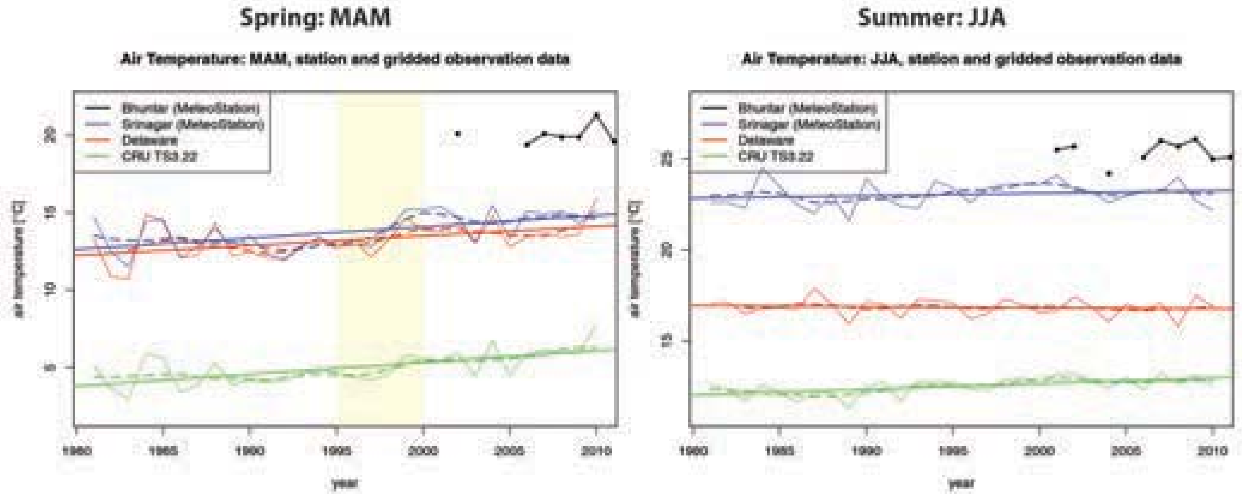
There has been significant seasonal variation in the observed warming trend: (i) a positive linear trend for spring temperatures of about 1 °C over 30 years (~0.35 °C per decade), (ii) a stagnant (or even decreasing) trend for summer temperatures, and (iii) no relevant linear trends for autumn and winter temperatures (Figure 4).

The enhanced spring warming appears to become stronger at higher elevations. Increasing temperatures in spring may lead to an upwards shift of the snowline with related impacts on precipitation, snowmelt, glacier mass balance and hazards from the high mountain environment. The stagnant temperatures in summer imply that the snow line likely did not further rise in summer.

In Kullu district and Himachal Pradesh in general, the amount of precipitation from December to March is significantly higher than that in the eastern parts of the Himalayas. This is predominantly due to the western disturbances that bring humidity at this time of the year. During the monsoon period, from May to September, this pattern is reversed. During this time, the amount of precipitation is less than that in the eastern Himalayas.

The precipitation analyses revealed that satellite-based precipitation estimation TRMM-3B42 generally overestimated monsoon precipitation and under-estimated winter precipitation relative to the India Meteorological Department (IMD) gridded data, with large monthly variability. Compared to the IMD product, local intensive rainfall events are often underestimated with this satellite product, whereas the amount and extent of persistent large-scale catastrophic precipitation events are mostly well captured.

According to the Global Precipitation Climatology Centre (GPCC) dataset, for the time period between 1981 and 2010, 43 per cent of the total annual precipitation over Kullu occurred during the monsoon months (July–August), 15 per cent during September–November, 19 per cent during December–February, and 24 per cent during March–May.



Spring: MAM

Summer: JJA

Figure 4: Temperature trends established over Kullu from gridded observation data for spring (March, April, May), and summer (June, July, August). The station data from Bhuntar (Kullu district) and Srinagar (neighbouring state of Jammu & Kashmir) are also included. The yellow shading highlights a large shift in mean spring temperature between 1995 and 2000.

4.2. Hydrometeorological reconstruction

Dendrochronology (analyses of tree-rings) provides an approach to reconstruct an extended hydro-meteorological baseline for regions where instrumental observations are limited in both temporal and spatial scales. Such reconstructions improve our understanding of long-term variability in regional climate and hydrological systems. It thereby provides a historical context from which we can quantify changes in climate extremes and related impacts. Particularly within ungauged river catchments, tree-rings can provide crucial information on decadal to multi-decadal scale variability in stream flow relevant for drought- and flood-impact studies. In this study, tree-ring width data from the Himalayan cedar have been used to *reconstruct seasonal stream flow discharge for the Sainj Valley.*

The seasonal flow discharge reconstruction based on the residual tree-ring chronology of 55 *Cedrus deodara* (Himalayan cedar) covers the time span from 1795 to 2014 CE. It thus provides evidence of long-term hydrological variability in the Sainj Valley (Figure 5). Tree-rings and peak discharge linkages showed significant correlations for the common period August–December. Based on this relationship, data suggest that during the reconstructed period, high flow years (+ 1 standard deviation) occurred 164 times, whereas low flow years (- 1 standard deviation) were detected only 22 times.

More specially, data reveals distinct periods of high stream flow during 1801–1876 and again during 1939–1960. These results broadly coincide with the flood years identified in time series of all Indian summer monsoon rainfall (IITM) and have been interpreted as resulting from changes in the intensity of monsoon. Therefore, despite uncertainties about future changes in South-Asian monsoon strength in most climate models, results here indicate that under a hypothetical strengthening of monsoon intensity in this region, an increase in peak flow and flood frequency is likely. Consequently, adaptive measures should be considered which are related to both hydrological resources (including hydropower) and risk reduction.

Out of a large number of rivers in the Indian subcontinent, so far only few have long discharge records available for analyses. The new reconstruction of August–December discharge for the Sainj river that extends back to 1795 CE, therefore, provides a crucial local basis to assess past and future changes in water flow, and a basis for studies concerned with the detection and attribution of hydroclimate change within the Sainj catchment (i.e. distinguishing anthropogenic and natural causes of the past changes).

Regarding the low stream flow events, several major Indian droughts reported in earlier studies (e.g. in 1905, 1915, 1918, 1951, 1966, 1972 and 1974) correlate with the reconstructed data. Furthermore, the reported monsoon failure and great droughts during the late eighteenth century are also reflected in the reconstructed data.

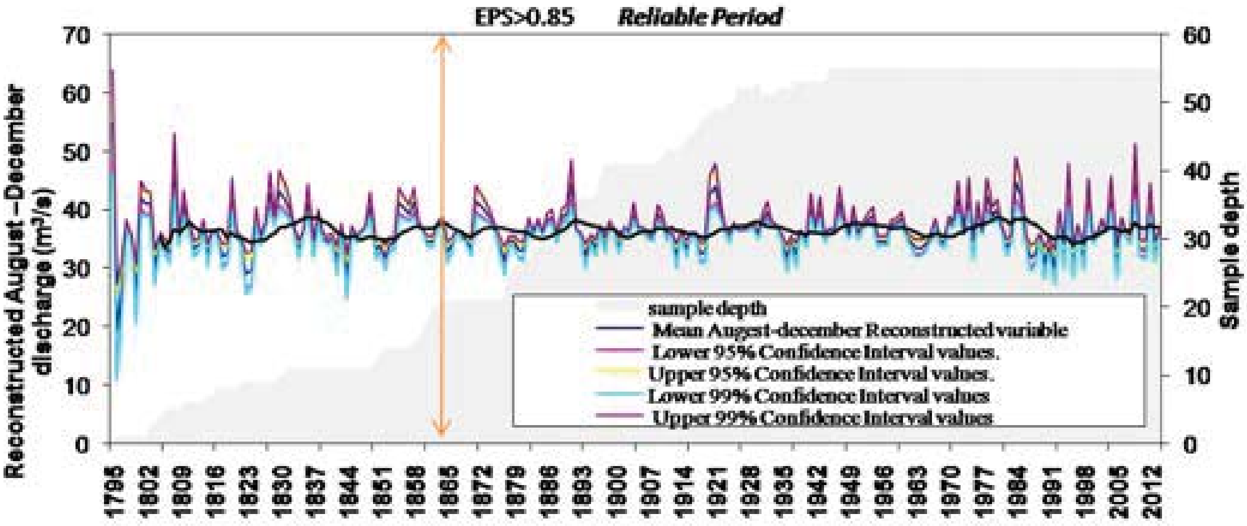


Figure 5: Reconstructed August–December discharge (m^3/s). The dark blue line represents the reconstructed discharge and yellow, purple, pink and sky blue lines represent confidence intervals (95 per cent and 99 per cent confidence levels). Note that prior to around 1800 CE the reliability of the reconstructed data should be considered very low due to a low sample size.

4.3. Cryospheric baseline

The retreat of mountain glaciers and associated formation of new lakes is one of the clearest symbols of change in our climate system. Together with changes in seasonal snow cover and thawing of permafrost, related hydrological and geomorphic impacts can be significant and far-reaching. Establishing baseline cryospheric data for the Kullu district draws primarily on satellite-based remote sensing techniques for mapping glaciers, glacial lakes, and snow-covered areas for various time intervals. In addition, first maps of estimated permafrost distribution in the Kullu district have been produced based on locally validated modelling approaches.

4.3.1. Glaciers

In this study, various glacier inventories for Kullu have been compiled using either manual digitizing or semi-automated classification techniques. Historical data sources include Survey of India toposheets for 1962 and 1965, while more recent inventories are based on Landsat and LISS-III satellite images (Figure 6).

There is some uncertainty in the accuracy of historical glacier boundaries mapped from the Survey of India toposheets. However, if we consider only the manually digitized glaciers common to both the 1962/1965 inventory, and the 2002 Landsat inventory, we calculate that the total area of these glaciers has decreased from 598 km^2 in 1962/1965 to 544 km^2 in 2002. Many of these glaciers have fragmented over time as they retreat, such that the total number of glaciers mapped in 2002 has actually increased, i.e. what was previously mapped as one large glacier in 1962/1965, may now be mapped as several smaller ice bodies in 2002.

For the year 2002, the results of the manually produced glacier inventory for the Kullu district were compared to the semi-automated inventory, both derived from satellite imagery. In total, 697 glaciers were mapped with the semi-automated approach in 2002 which covered a total area of 590 km². The manually mapped inventory contained 265 glaciers that covered a total area of 553 km². Hence, the two methods are in good agreement in terms of mapped glacier-covered area (difference of only 37 km^2). The large difference in the number of mapped glaciers results from the semi-automated procedures which tend to capture small ice or snowfields, and which are designed to divide large ice bodies into specific glacier entities (Figure 6).

Close examination of the manually and semi-automated produced glacier boundaries show greatest differences in the interpretation of debris-covered parts of the glacier, and overall good agreement for clean, debris-free parts of the glacier (Figure 6). Such differences are well known in literature and deriving improved techniques to map debris-covered glacier tongues remains an ongoing challenge for the global glaciology community.

Based on the semi-automated inventory of 2002, a total ice volume of 26 km^3 is estimated for the 697 glaciers within the Kullu district. Hence, the glaciers can be considered a significant hydrological resource within the Beas catchment area.

While comparing the common glaciers manually digitized within both the 2002 Landsat inventory and the 2006 IRS LISS-III inventory, we found that a total of 236 glaciers were mapped in 2002 (total area of 529 km^2), whereas the same glaciers when mapped in 2006 have fragmented to become 242 individual glacier entities (total area of 489 km^2).

An overall change assessment for the glaciers inside the borders of the Kullu district based on semi-automated inventories from 2002 and 2013 reveals an area loss of about 9 km² (~ 1.5 per cent), an increase in mean elevation of about 30 m, and an upward shift of glacier to a minimum elevation of about 160 m.

A direct comparison between modelled and measured ice thicknesses at 5 GPR profiles from Chhota Shigri glacier confirm an approximate uncertainty range of ± 30 per cent for the ice thickness estimation model. These results are consistent with other studies and demonstrate the usefulness of this model to provide baseline information on ice volumes, which is crucial to understand the future evolution of glaciers, and related hydrological impacts of glacial change. The model results generally capture well the geometries of the measured glacier cross-sections.

A first debris thickness map was calculated for the entire debris-covered area of Bara Shigri glacier based on satellite images. The debris thickness values computed here remain below 30 cm in most cells and the model thus seems to underestimate debris thickness, but the relative pattern seems to represent the reality well. Debris cover on glaciers will influence their response to climate change, and can be important in the formation of lakes and other glacial hazards.

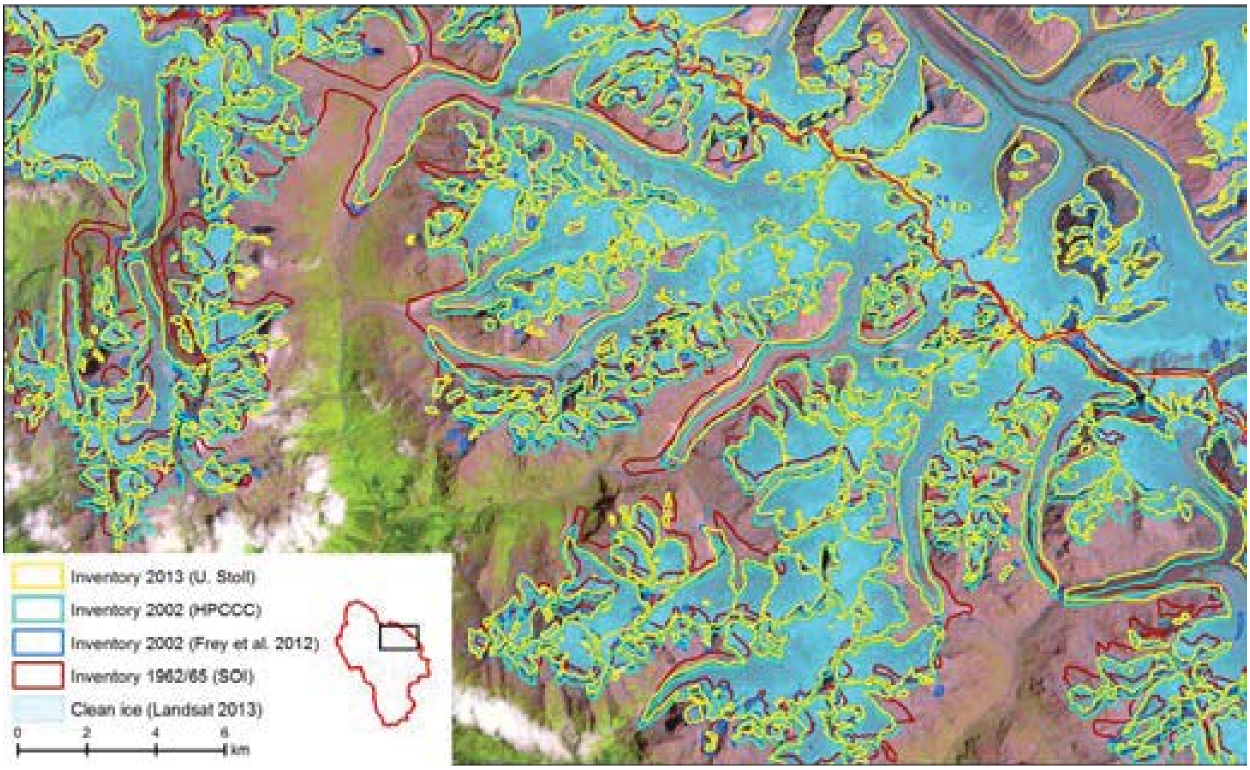


Figure 6: Comparison of glacier inventories for a sub-scene in the east of Kullu district for different years, and using different mapping techniques. The glacier inventory for the years 1962/65 has been manually digitized from the Survey of India toposheets. For 2002, inventories have been manually digitized (HPCCC) and semi-automatically derived (Frey et al. 2012) from satellite imagery. The 2013 inventory (U. Stoll) was again derived with semi-automated classification of satellite images. The background scene is a false-colour composite Landsat ETM+ image from October 2013.

4.3.2. Glacial lakes

This study employed two different methodologies to map changes in glacial lakes over time from satellite imagery (manual digitizing and semi-automated classification). In addition, modelling techniques provide early anticipation of where future lakes are likely to develop as glaciers continue to retreat over the twenty first century.

Based on the manual lake mapping carried out in the Kullu district using satellite imagery (Figure 7), a considerable increase in the number of lakes has been found. In the Beas basin, there has been an increase from six (1989) to 33 (2011) lakes, in the Parvati Valley catchment area there has been an increase from 12 (1989) to 77 (2014) lakes, and in the Great Himalayan National Park and in the catchment area of Sainj Valley there has been an increase from 12 (2002) to 39 (2013) lakes. While an increase in lake formation is expected with the retreat of glaciers, it is also possible that some lakes were not accurately captured in earlier inventories due to cloud or snow cover for example.

Lake mapping has been expanded beyond the Kullu district to include other significant basins of Himachal Pradesh using satellite data for the year 2013. In the Chenab basin a total of 116 lakes have been mapped of which three lakes have an area > 10 ha, eight lakes are between 5 – 10 ha and 105 lakes are < 5 ha. Likewise in the Satluj basin which includes the Tibetan region, a total of 391 lakes were mapped, out of which 40 lakes have an area > 10 ha, 75 lakes are between 5 – 10 ha and 275 lakes are < 5 ha. Similarly, in the Ravi basin a total 22 lakes were mapped, of which two lakes are > 10 ha, one lake has an area between 5 – 10 ha and 19 lakes are < 5 ha.

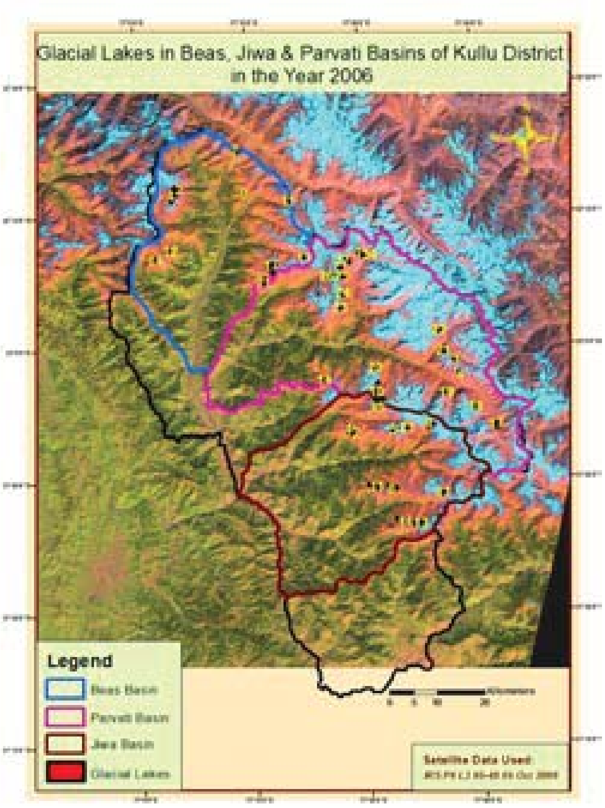


Figure 7: Example of a manually digitized glacier lake inventory compiled for the main basins of the Kullu district using satellite imagery from 2006.

Lake detection using semi-automated methods do not typically capture smaller lakes, particularly supraglacial lakes, and hence overall lake inventory numbers are lower with this method. Over the watershed areas of Himachal Pradesh, 120 glacial lakes have been identified using semi-automated mapping based on Landsat imagery for the year 2013. Five new lakes have clearly emerged over the past decade and 15 lakes have increased in surface area in the order of 10 to 200 per cent.

The application of two lake-mapping methodologies in this study demonstrates the various limitations associated with glacial lake inventories. Manual lake mapping has the distinct advantage to capture all lakes visible in a satellite image regardless of their size, and local experts can target specific critical situations. Semi-automated methods are best suited to monitor larger glacial lakes (> ca.

$0.01\ km^2$) and can be rapidly applied for multiple time-steps over entire Indian Himalayan states.

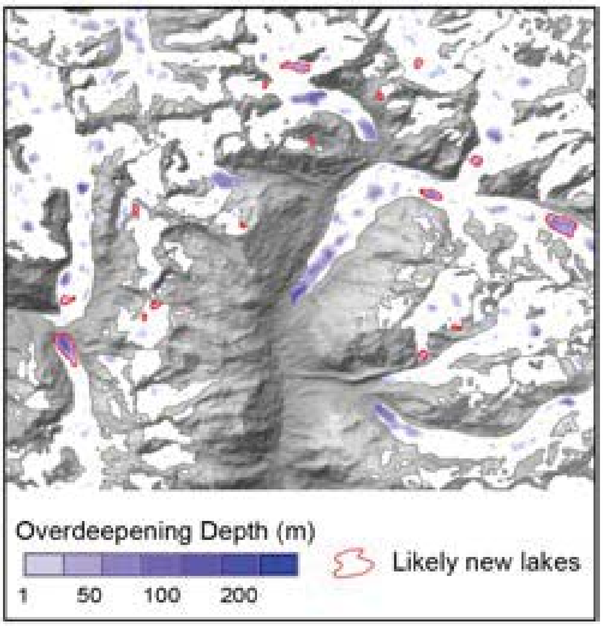


Figure 8: Modelled overdeepenings in the bed topography for a glaciated area above the Parvati Valley, Kullu district. Final identified overdeepenings where new lakes are considered most likely to develop as glaciers continue to retreat over the next century are indicated.

Direct measurements of lake volumes are difficult and lack for most remote mountainous regions. Based on empirical estimates, the vast majority of glacial lakes in Himachal Pradesh currently have relatively small volume less than 1 million m^3, with only a few notable lakes exceeding 10 million m^3. The rapidly expanding Gopeng Garth (22–37 million m^3) and the neighbouring Chandra Taal (41–65 million m^3) located in the Chenab basin, both in Lahaul and Spiti, are the two largest lakes in Himachal Pradesh. Chandra Taal, however, is not considered dangerous or a threat to downstream areas.

Across Himachal Pradesh, more than 4000 potential overdeepenings with areas > $0.01\ km^2$ have been modelled in the glacier bed topography. As glaciers retreat, these overdeepenings can fill with water to form lakes (Figure 8).

Not all overdeepenings will develop into glacial lakes. Therefore, a selection was refined based on locations below the current glacier Equilibrium Line Altitude, potential volume greater than 500,000 m^3, and where topography narrows and steepens below the overdeepening (Figure 8). Following this criteria, 279 potential new lakes have been identified across Himachal Pradesh (63 within the Beas catchment, Kullu district) and used for subsequent GLOF hazard and risk analyses.

4.3.3. Snow

Moderate Resolution Imaging Spectroradiometer (MODIS) satellite data has been used to derive a continuous time series of daily gap-free snow cover maps for the period 4 July 2002 to present. Thus, for the first time, the evaluation of the snow cover extent of Kullu is accessible on a continuous daily basis for the last 13 years. Additionally, for each snow cover map a corresponding map with quality information has been produced.

The new gap-free snow cover maps can be used as a basis to investigate the degenerating permafrost and related problems, disaster risk reduction solutions or the feasibility of small hydropower plants. Furthermore, the snow cover maps can help optimize irrigation and water supply and, therefore, are an important basis to guarantee food security.

A user-friendly data portal has been developed where daily gap free snow cover maps for the Kullu district and the corresponding quality information maps can be visualized and downloaded. The data portal is accessible to authorized persons and can provide the basis for further studies.

For each satellite image pixel, complete time series of daily pixel values – with the information whether a pixel is snow covered or not – can be extracted from the database. This makes it possible to analyze the snow cover evolution and variability for any given location. The data portal is updated regularly in order to provide the latest available data to the users.

As a first result based on this new time series, we can see that even in today's warmer world, precipitation events can still bring snow down to less than 1500 m a.s.l during Kullu's winter season (Figure 9).

In addition to snow cover extent, snow depth and snow water equivalent (SWE) are two further Essential Climate Variables. Whereas snow cover extent can be monitored remotely, snow depth and SWE are difficult to measure with satellite-based methods and require in situ measurements. However, in the Kullu district, like in the entire Greater Himalayan region, station data are scarce and hardly accessible to the international research community.

The scarcity of insitu measurements of snow cover and related variables severely hampers accurate estimation of the snow cover and possible impacts related to runoff.

Based on AWIFS satellite data analysis using semi-automated snow cover mapping, a decreasing trend of area under snow cover during 2004 – 05 to 2009 – 10 has been observed in the Beas, the Parvati and the Jiwa basins (comprises the Great Himalayan National Park and the Sainj catchment). Since 2010, all the basins reflect an increasing trend. When averaged over the entire 10-year period (2004 – 2014) and across all months, the average snow-covered area in the Parvati basin is greater than in the Beas and Jiwa basins (Figure 10).

In a separate study, the snowfall elevation limit during precipitation events was assessed using satellite-based precipitation radar data, as well as records from a meteorological station and radiosondes. The methodology was developed and tested for the Kashmir Valley because of the radiosonde availability there. In principle, this approach can be replicated for the Kullu district. The snowfall limit over Kashmir Valley shows strong seasonal and monthly variability and can rise up to almost 6000 m a.s.l in summer. This knowledge on snowfall elevation limits will support hydroclimatic modelling related to impacts and hazards.

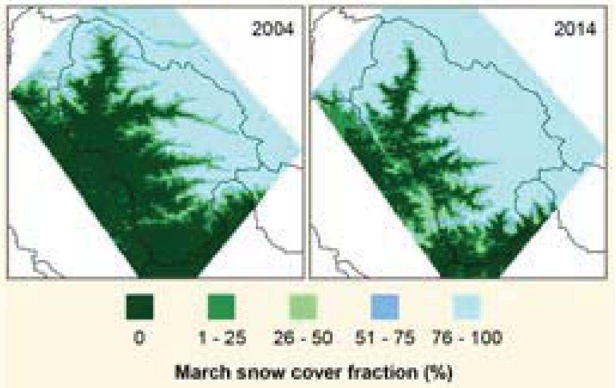


Figure 9: Monthly mean snow cover fraction in March derived from daily cloud free MODIS images. Examples from two contrasting years are shown with much more snow-free land area (dark green) evident in 2004 as compared to 2014.

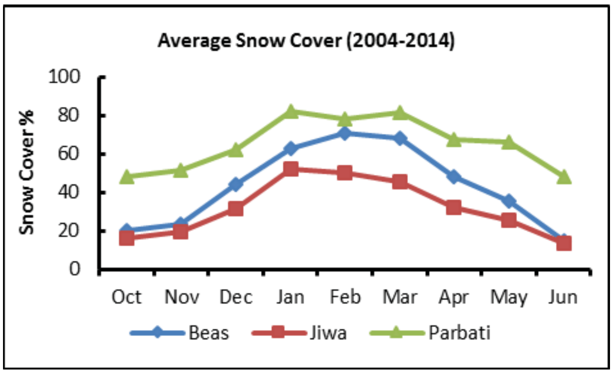


Figure 10: Monthly average snow cover derived from semi-automated mapping using AWIFS satellite data for the three main basins of the Kullu district, 2004 – 2014.

4.3.4. Permafrost

Permafrost refers to any ground material that remains at or below 0 °C for at least two consecutive years. In response to global climate change and the close coupling between atmospheric and ground temperatures, permafrost is warming and thawing in many regions. The thawing of permafrost can have widespread impacts related to destabilization of steep slopes, changes in sub-surface hydrology and increased sediment load in rivers.

First maps of estimated permafrost distribution in the Kullu district have been produced combining physically-based modelling, simple topographic and climatic principles and mapping of permafrost indicators (namely rock glaciers).

Results from numerical modelling suggest that permafrost may extend down to 4200 m a.s.l in isolated instances, comparing favourably with the observed lower elevation limit from the ca. 60 mapped rock glaciers in the Kullu district (interquartile range of 4280 – 4560 m a.s.l), and approximate lower limits to permafrost distribution established in relation to the local 0 °C mean annual air temperature (MAAT) isotherm (Figure 11).

Between about 4200 m and 5000 m a.s.l permafrost underlies a surface area comparable in size to that overlaid by glacial ice. Hence, permafrost is identified as a significant component of the local cryosphere. Permafrost is most prevalent between 4750 m and 5000 m a.s.l.

The variation in modelled ground surface temperature (MAGST) between shaded (north-facing) and sunny (south-facing) slopes is considerably less than has been modelled and observed in alpine regions of Europe and New Zealand owing to the difference in latitude. This needs to be considered when transferring simple empirical relationships from one region to another.

In total, about 9 per cent (420 km^2) of the modelled land area in the Kullu district (excluding glacier-covered areas) is classified as permafrost.

More than 50 per cent of the modelled permafrost land area in Kullu is characterized by slopes less than 35°, a threshold which is commonly used to distinguish debris-covered slopes from bedrock. This suggests that the potential hazards from thawing of permafrost in the Kullu district will relate foremost to debris instabilities as debris reservoirs are prone to be triggered by heavy monsoon rainfall or melt water.

Permafrost appears to be of potential direct relevance for many glacial lakes in the region. Around half of the 51 glacial lakes mapped for Kullu and its neighbouring districts are formed within terrain where MAGST is below 0 °C (Figure 11). In these cases thawing of ground ice in the lake dam and outlet area could lead to gradual or catastrophic failure of the dam structure particularly where conditions are already marginal (i.e. MAGST approaching 0 °C).

Most of the glacial lakes are situated within the potential path of mass movements that can originate from the surrounding steep rockwalls where permafrost conditions prevail. Thawing of these rock slopes could increase the likelihood of rockfall and, therefore, overtopping waves from impacts into lakes (see also GLOF hazard and risk study).

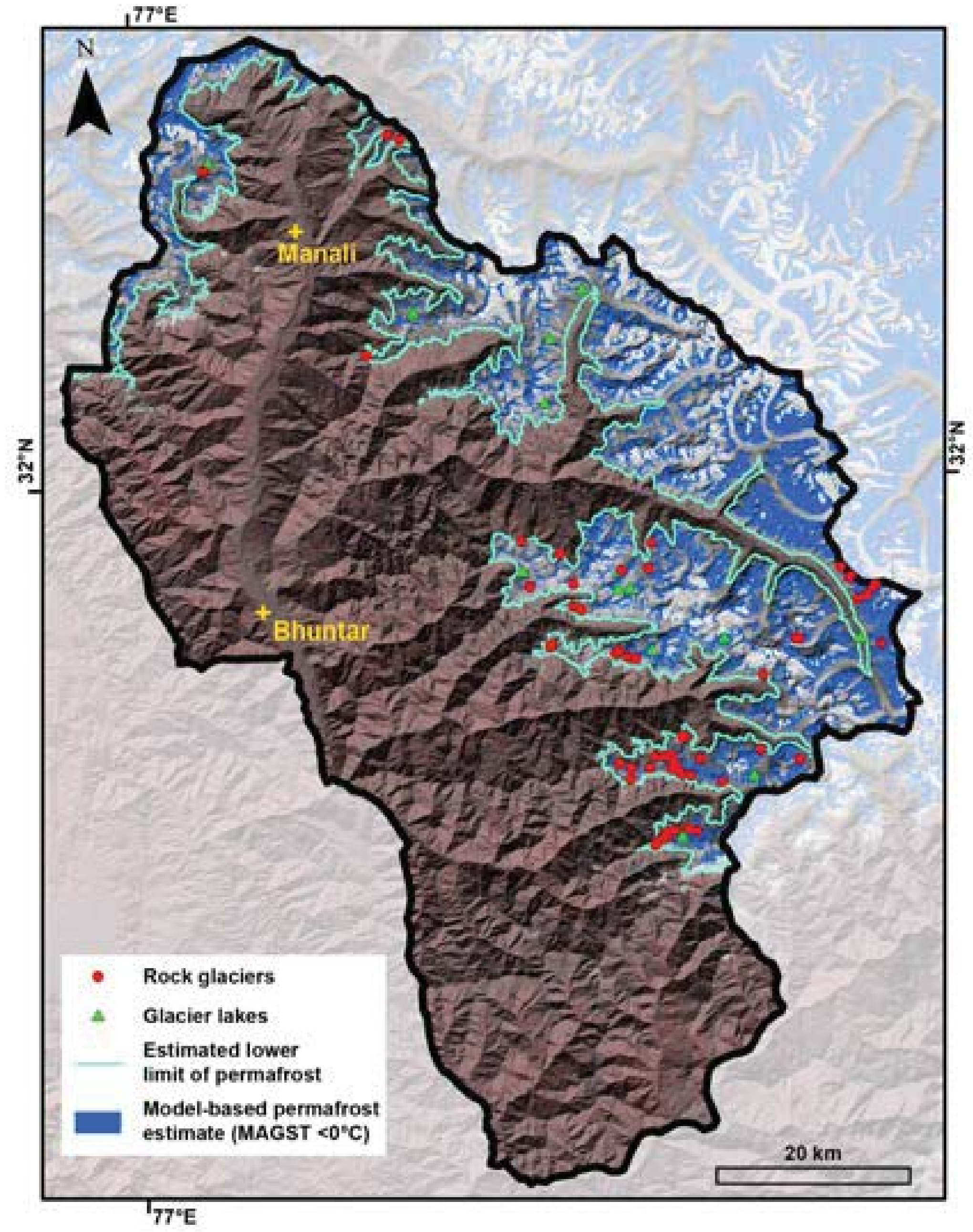


Figure 11: Mapped rock glaciers across the Kullu district are compared to a model-based estimated permafrost distribution. An empirically-derived estimated lower limit of permafrost in the Kullu district is also indicated where permafrost might be expected in extremely favourable topographic situations only.

Rock glaciers are sporadically found across the Kullu district. However, they are most prevalent in the south where mean winter precipitation is reduced (Figure 11).

Rock glaciers generally appear to creep out from the zones where permafrost is expected. However, frontal lobes in some instances extend down below 4000 m a.s.l, which suggest that some mapped features are likely inactive and no longer indicative of permafrost. About 90 per cent of the rock glaciers are located above a lower elevation of 4130 m a.s.l.

The Kullu pilot study has provided some first and preliminary understanding of the possible extent and relevance of permafrost in this area of the Indian Himalayas, while generating fruitful new scientific partnerships and discussions on novel concepts and methodologies. A sound basis has now been established upon which further measurement and monitoring projects can be initiated. As a crucial next step, field studies are recommended to further validate the modelling approaches to provide the necessary scientific basis for outscaling the methodological approach to other regions.

Permafrost is clearly of broad importance, and potential exists to integrate the approaches and experiences of the Kullu pilot study within larger Himalayan regional programs. As permafrost is an Essential Climate Variable according to World Meteorological Organization (WMO), it is somewhat astonishing that till date no related monitoring activities are ongoing in the region. With this initial baseline work completed now within the IHCAP framework in Kullu, the Indian and Swiss scientists are well positioned to take a lead in initiating the ongoing permafrost monitoring activities.

5. Vulnerability, hazards and risk

Guided by the integrated assessment framework, studies completed under the IHCAP pilot project for Kullu addressed the key components of climate vulnerability, hazards and ultimately the risk. Methodological approaches range from community surveys to gain insights into ground-level perceptions of climate change, through to physical modelling of climate-related hazards. Particular emphasis is given to understand the vulnerability and climate-related threat to floral biodiversity and natural ecosystems, and to the economically important agriculture-horticulture sector. Climate change may influence a wide range of hydrometeorological hazards. In the steep and dynamic landscape of the Kullu district we focus our studies on the threat from flood and mass movement hazards, owing to the close coupling of these processes, with changes in atmospheric and cryospheric conditions.

5.1. Community perceptions

The IHR occupies a special place in the mountain ecosystems of the world, being among the most complex and diversified among all global mountain systems. Despite an abundance of natural resources, most people in the region still live on the subsistence level, while the exploitation of natural resources leads to an increase in environmental degradation and aggravates the impact of climate-related hazards. This ground-level study aimed to understand community perceptions of climate vulnerability, hazards and risk in the Kullu district, while also gaining insight into existing adaptation responses. In a first study of this type conducted in the IHR, structured questionnaires were completed by 791 community participants from within the hot-spot areas of the Parvati Valley (31 villages and 370 households sampled) and upper Beas catchment (13 villages and 421 households sampled). In total, 30 per cent of all households in each village were sampled (Figure 12).

In both study sites, the maximum female population is in the age group of 16 – 30 years, while the maximum male population is in the 16 – 30 years age group in the Parvati Valley and 31 – 60 years age group in the upper Beas catchment. The present demographics indicate a sustainable and stable population density that is likely to lead to a balanced and controlled population in the future.

In both the study sites, horticulture is the main occupation rather than agriculture, possibly to maintain higher livelihood levels and high income generation. Some inhabitants of both the sites were employed within businesses such as motels and hotels, transportation, river rafting, as adventure and trekking guides and in snow sports. This reflects the good income generation that comes from tourism in the Parvati Valley and upper Beas. Very few people are employed in government services possibly because horticulture and other businesses provide an alternative and better source of income.

Figure 12: A researcher completes the structured questionnaire with community participants in the Parvati Valley (Photo: G. B. Pant Institute).

During 1980 – 1990 inhabitants of the valleys were mainly dependent on wood and kerosene, and sometimes on electricity for energy requirements. Until 2010 when a very small proportion of the population started to use LPG as an alternative energy option, electricity, wood and kerosene were used by a majority of the people as a source of energy. Between 2010 and 2014 a majority of the households used electricity, LPG, wood and kerosene. In spite of the increased availability of these alternative energy sources, people still continue to use fuel wood for various purposes.

Emigration and immigration of the inhabitants in both study sites has mostly happened due to employment purposes. Intra-valley migration of the inhabitants occurred due to accruing comfortable livelihoods, better road and transport, business opportunities, avoidance of extreme environmental conditions in the higher elevations, and improved communication and infrastructural facilities. These migration patterns clearly suggest that the inhabitants have started to follow adaptive measures in response to climate change.

The number of livestock owned by the inhabitants in both study sites has decreased due to changing lifestyles and shift from agricultural sector into horticulture and business. Similarly, most land areas are used by the inhabitants to cultivate horticultural crops and other cash crops rather than traditional agricultural crops or vegetables possibly due to the higher income earned from these crops.

Most villagers agreed that horticultural activities have been largely affected by irregular rainfall, rise in temperature, outbreaks of pests and diseases, less snowfall, forest degradation and decrease in cattle population. Similarly, the respondents agreed that their agricultural crop productivity has been largely influenced by these same factors.

Factors like irregular rainfall, snowfall, rising temperature, pest attack and diseases are considered the major causes for low vegetable yield in the valleys.

Spice productivity has been largely influenced by irregular rainfall, rise in temperature and outbreaks of pests and diseases. Other factors such as less snowfall, forest degradation and decrease in cattle population also play roles in low productivity.

Due to increase in temperature, insects and pests are gradually moving to higher altitude. Therefore, communities have increased their use of chemical fertilizer, insecticides and pesticides which causes soil degradation and low fertility.

The housing pattern in both study sites is shifting from mud and wooden houses to cement houses and cement-wood mix houses. This could be due to modernization as well as decline in the timber species.

Households were dependent on glaciers, rivers, lakes, ponds and other water bodies for water until 2000. After 2000 and mostly during 2010 – 2014, they have started to use handpumps for water. This may indicate that some of the above perennial water resources have either dried or have become seasonal. However, it could also indicate improved availability of handpumps that require less distance to be travelled to access water. Overall, the water table is decreasing due to the changes in environmental conditions.

Inhabitants of both study sites were also dependent on spring/talai until 2000, but since, and mostly during 2002 – 2010, they became dependent on stream/kuhal. Since 2010 they have become increasingly dependent on tap water.

Households were dependent on rain-fed irrigation until 2001. But, after 2001, and mostly during 2005 – 2014, they have started to use channels/pipelines for irrigation.

The study revealed that mainly large hydropower projects were constructed until 2010 in the Kullu Valley. However, since 2010 construction of large hydropower projects has declined sharply and rather the construction of small hydropower projects has been promoted. This could be due to decrease in volume of water in perennial streams as a related consequence of environmental changes, including climate.

Natural hazards like floods, cloud bursts, landslides, rockfalls, debris flows and earthquakes are very common in both the Parvati Valley and upper Beas. However, the inhabitants do not have or are not aware of appropriate response strategies.

An overall community perception is that gradual warming of the climate has happened over the last two decades (70 per cent of all respondents). Respondents agreed that the onsets of summer and monsoon have advanced during the last 10 years. The winter season has become shorter and warmer according to some respondents. The patterns of rainfall have also become totally unpredictable.

Both natural calamities and anthropogenic calamities have led to rapid loss of biodiversity and resources have not been used sustainably. Due to overexploitation, flora, fauna and habitats are in severe danger. Unusual climatic conditions have changed the phenology of many temperature sensitive species such *Rhododendron* spp., and most of the rosaceous species such as *Prunus persica*, *Prunus domestica*, *Prunus armeniaca, Prunus cerasoides, Pyrus pashia, Pyrus communis* and *Malus pumila.* Thus, proper management and conservation is urgently required.

The pressure of increased tourist inflow is more significant in the upper Beas catchment than in the Parvati Valley. The number of tourists has sharply increased during 1980 – 2014 in the Kullu Valley, particularly in regard to ecotourism. Cultural, adventure, rural, wildlife and sport tourism are increasing gradually in both the study sites. This tourism has brought positive impacts like income generation and cultural exchange for the inhabitants. However, there are negative impacts like air, water and noise pollution, forest degradation, unhygienic environment, and outbreaks of diseases. These findings clearly indicate a conflict between the increased income tourism can bring, and thereby enhanced capacity for climate change adaptation measures, and the strain on the fragile natural environment.

Overall, based on the perceived impacts on agriculture, horticulture, water resources, housing, employment and incomes, the inhabitants feel that climate change is changing lifestyles and livelihoods. Furthermore, the study findings indicate that the inhabitants of the Parvati Valley and upper Beas catchment have started to follow adaptive measures in response to climate change.

5.2. Biodiversity and natural ecosystems

The IHR with its unique topography, climatic conditions, diverse habitats and large altitudinal variations constitutes one of the most important global biodiversity hot-spots. However, biodiversity in the IHR is threatened by anthropogenic activities coupled with changing environmental conditions. In particular, climate change is an important confounding factor which shapes the future of mountain ecosystems, and the wide-ranging economic and cultural services these ecosystems provide to local people. In view of future climate change, the need to understand the magnitude and direction of potential-related impacts on the composition, structure and functioning of biodiversity in the region is urgently required. This study of biodiversity and natural ecosystem vulnerability has been conducted in the Parvati Valley (1544 – 3407 m a.s.l) and the upper Beas catchment (2100 – 4280 m a.s.l) and integrates a comprehensive survey of floral diversity with community interviews and scientific assessment.

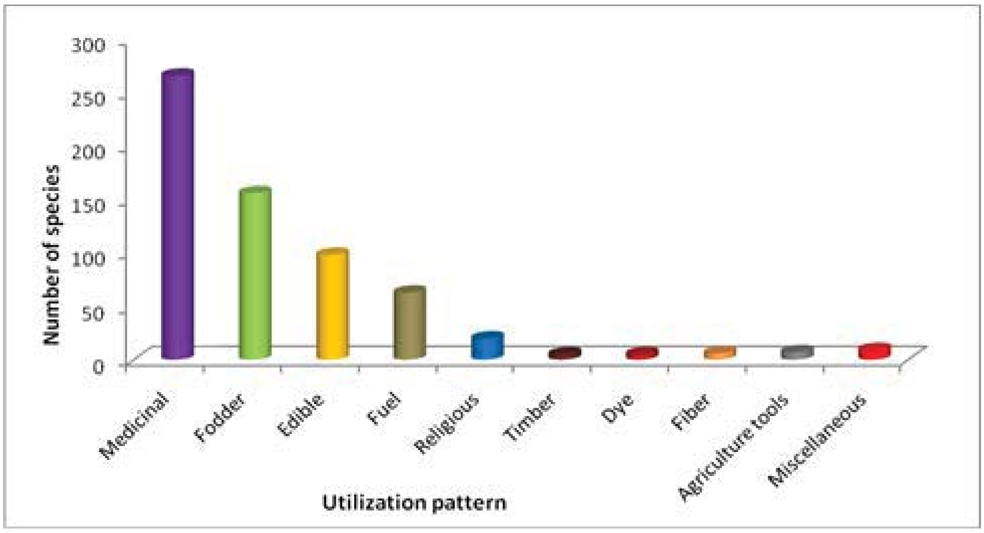
About 734 species of vascular plants from the Parvati Valley and about 637 species from the upper Beas catchment have been recorded. This includes trees, shrubs, herbs and ferns. Species have been analyzed for altitudinal distribution. In general, the species diversity decreased with increase in altitude.

From the Parvati valley, 363 species were native, 11 endemic and 119 near endemic. From the upper Beas catchment, 348 were native, 11 endemic and 187 near endemic. The high percentage of natives, near endemics and endemics in the study sites indicates the high conservation value of the region.

In the Parvati Valley, 475 species and in the upper Beas catchment 415 species were classified as economically important. They are used as medicine, wild edible, fodder, fuel, building construction, timber, making agricultural tools, fibre, religious and various other purposes (Figure 13).

In the Parvati Valley 115 representative sites were surveyed and sampled for the qualitative and quantitative analysis of vegetation. In this site 56 plant communities have been delineated. In the upper Beas catchment 51 representative sites were surveyed where 41 plant communities have been delineated. For each site/habitat, physical characteristics such as habitat type, latitudes and longitudes, aspect, slope and dominant species have been given. Habitat/site-wise occurrence of the communities as well as altitudinal distribution has been analyzed. Factors analyzed included species richness, species diversity and concentration of dominance. The forest tree communities showed different trends based on the saplings and indicated the changing dynamics of the vegetation. This clearly indicates that the dynamics of the forest communities is changing due to changing environmental conditions, including climate.

The vulnerability assessment of floristic diversity in the Parvati Valley identified five species as critically endangered, 11 endangered, 90 vulnerable and 188 near threatened. In the upper Beas catchment, nine species were identified as critically endangered, 14 as endangered and 47 as vulnerable. Continued anthropogenic pressures and changing environmental conditions may lead to species extinction in the near future.



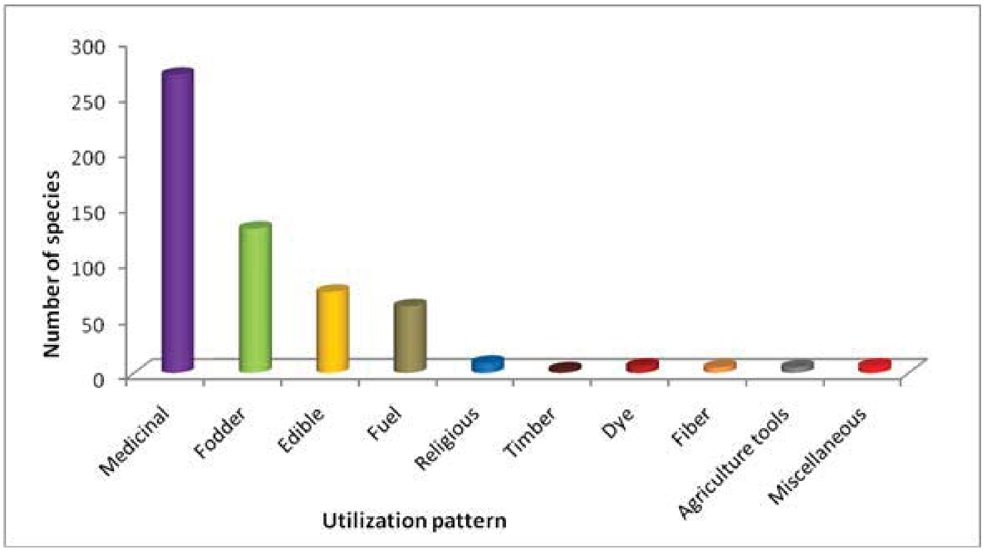


Figure 13: Utilization of economically important floral species in the Parvati Valley (top) and the upper Beas catchment (bottom)

The forest communities near to habitations were more vulnerable than the communities distant from the habitations. This is due to the dependence of the communities on forests for their sustenance in various ways. The sub-alpine communities were more vulnerable due to heavy snowfall, avalanches and climate change effects.

The altitudinal shift of species such as *Betula utilis*, *Abies pindrow*, *Populus ciliata*, *Aesculus indica* and *Pinus wallichiana* and the changing pattern of the composition and structure of the forest communities have been observed. This could be a consequence of climate change over the past century. Particularly sub-alpine and alpine vegetation are sensitive to climate change as evidenced by the altitudinal shift of the species and habitat alteration. Regular monitoring of the plots that represents these zones would provide further understanding of the impact of climate change.

Based on published literature, it is known that rapid climate changes, pressure of overpopulation, interferences in native ecosystems and introduction of non-native species cause increased pressure on the survival of native species. Anthropogenic activities such as extraction of resources by human beings, tourism and livestock grazing cause intrusion of non-native species in the forest zone. It is well known that such disturbances lead to the invasion of non-native species.

The present study provides important first information on biodiversity and natural ecosystem vulnerability in the Kullu district. Based on the findings in this study, we can assume that the changing pattern of the forest communities may be due to anthropogenic activities and climate change.

For improved understanding of the dynamics of the forest communities in relation to climate change, the present sampling plots that represent the different communities need to be further monitored. Ongoing monitoring will provide a comprehensive database on the impact of climate change on biodiversity and ecosystems upon which robust management plans could be developed.

5.3. Agriculture-horticulture

The agriculture-horticulture sector is central to the economic capacity of the Kullu district, and is the major provider of employment opportunities in the district (see Section 5.1). Climate variability, in the form of erratic precipitation patterns and long-term increase in temperature are already thought to have affected agricultural production systems and ultimately the livelihoods and food security of the people in the mountains. Productivity levels have been adversely affected and numerous problems like the incidence of diseases and pests have become more severe. It is within this context that a block-level vulnerability assessment of the agriculture-horticulture sector has been completed for the Kullu district. The primary data for this study comes from interviews conducted with farmers located within selected villages (total of 200 – 250 households), supported with secondary data from meteorological stations and block administrative authorities.

The vulnerability index (VI) assessment for different blocks was based on various indicators categorized into exposure, sensitivity and adaptive capacity. The vulnerability components were differentiated for agriculture, horticulture, and livestock sectors, and a separate VI based on demographic factors was established. For each component, methodologies were followed to assign different weights to each indicator. The composite VI was assessed by averaging the VI across all sectors.

The VI values for agriculture developed for different blocks of the Kullu district ranged between 0.400 and 0.909. The lowest vulnerability was established in Naggar followed by Nirmand and Kullu, whereas the highest vulnerability was recorded in Banjar and Anni.

The VI for horticulture developed for different blocks of the Kullu district ranged from 0.214 to 0.934. The lowest vulnerability was established in Naggar followed by Nirmand and Kullu, and the highest vulnerability was established for Anni and Banjar.

Similarly, for the livestock sector, VI ranged from 0.017 to 0.879. The lowest vulnerability was established for Naggar followed by Kullu and Nirmand. The most vulnerable block was Anni followed by Banjar.

The composite VI established across all sectors indicated Naggar block to be the least vulnerable followed by Kullu and Nirmand. Overall, Anni was the most vulnerable block followed by Banjar. The relative low vulnerability of Naggar and Kullu is considered to result from greater institutional support and disease/insect control measures. Furthermore, the low vulnerability in Naggar is attributed to fertile soils for crops, establishment of new orchards and shift towards off-season vegetable production.

The farmers' perceptions of locally idealized traditional weather cycles and climate change are analyzed and compared for different blocks of the Kullu district. Climate change is described by farmers as being a temporal displacement of weather cycles that reflects changes in crop enterprises and livelihood options. The main experiences of the farmers regarding climate change impacts across the blocks included increase in summer temperature, prolonged summer, delayed onset and uneven distribution of south-west monsoon, delayed onset of winter, short winter period, temperature above normal during winter, decrease in snowfall during winter, delayed snowfall and shorter winter, low temperature spells at high altitudes during winter and unpredictable rainfall. Increase in trends of foggy and cloudy days were also perceived by farmers across all blocks.

The threat from high intensity rainfall and related floods was perceived to be low in Banjar, Anni and Nirmand. Kullu and Banjar were considered to be more threatened by floods. Kullu, Anni and Nirmand were considered most prone to mudslides.

More than 97 per cent of farmers in Nirmand block followed by Banjar (96 per cent) and Kullu (94 per cent) reported insufficient rains during south-west monsoon. This was also substantiated by surplus water balance analysis for Banjar region.

Diseases in agricultural/horticultural crops are reaching higher altitudes where they were not earlier reported. The disease/insect spread is perceived to be greater in Kullu, Banjar and Naggar but management of the problem is considered better in Kullu and Naggar.

Overall, the farmers' perceptions clearly indicated Kullu and Banjar as most vulnerable amongst all blocks of Kullu. In the case of Kullu block, this finding is inconsistent with the VI analyses.

As a climate adaptation measure, there has been a shift of the fruit belt to higher altitudes, most notably in Naggar followed by Kullu and Banjar. Other adaptation measures perceived by the farmers indicated a shift from agricultural crops (vegetables such as, tomato, cauliflower and cabbage) to horticultural crops (fruits such as pomegranate, plum and peach), especially at lower altitudes in Kullu and Banjar. Due to favourable environmental conditions for these fruit crops (high temperature during summer) and labour-intensive nature of vegetables, the farmers are shifting to these horticultural crops (Figure 14). Some farmers have changed from old varieties of apple to new varieties like Red Chief, which shows better results in lower altitudes of Kullu.

Figure 14: Example of climate adaptation measures implemented in Kullu. Tomato crops are planted here between apple crops.

Agrometeorological advisories can be valuable measures in the field of risk reduction in agriculture. Agro-meteorological advisory services provide weather and climatic information together with farm management options in order to cope more efficiently with climate variability and the increasing incidence of extreme meteorological events such as droughts, floods, frosts and others. Generally, weather-based advisories can make the agricultural production system more resilient because agrometeorological advisories can substantially contribute to increased agricultural productivity and farmer livelihood and, thus, contribute to food security and poverty reduction. An important advantage of agrometeorological advisories is the fact that they are so called 'no-regret adaptation measures' which yield benefits for all stakeholders under all future climate scenarios.

5.4. Floods

The IHR is subjected to intense and frequent hydro-meteorological hazards that result from the large lift of humid monsoon air mass along the steep and seismically active Himalayan relief. These characteristics together with the fact that human activities are mostly concentrated in the valley bottoms lead to significant flood risk, with frequent disasters having caused debilitating societal and economic impacts. Due to the steep watershed characteristics, flash floods are a particular concern. Flood studies conducted under IHCAP focus on two different themes. Firstly, at the district to state-level, underlying river basin potential for flooding has been assessed based on historical archives of flood events, geomorphic interpretation and GIS-based susceptibility modelling. Secondly, dendro-chronology techniques have been combined with statistical analyses to reconstruct and understand the past flood characteristics for specific local sites within the Kullu district.

5.4.1. Basin-scale flood potential

The study has implemented a multi-scale and multi-disciplinary approach to assess flood hazard, underlying river basin disposition, flood-prone areas and fluvial dynamics across the main river basins in Himachal Pradesh, and particularly Kullu district. The compilation of a flood database derived from scientific publications, technical reports, press and Internet sources allowed the historical analysis of floods, including seasonality, frequency and main triggers. In addition, the most affected areas have been identified. More than 5000 fatalities have been reported in Himachal Pradesh from flood disasters that occurred between 1950 and 2014. Some of the most devastating events occurred in 1959, 1971, 1978, 1985, 1988, 1989, 1990, 1995, 2000, 2005 and 2013. Most of these events occurred during the monsoon season, mainly in August, and resulted from long duration rainfall (monsoon) and high intensity, short duration rain (cloudbursts).

Across Himachal Pradesh, cloudbursts are revealed to be the most frequent trigger of flood events. Based on recorded flood events, Kullu has been the most affected district in Himachal Pradesh (Figure 15), and also the district where cloudbursts have triggered the most floods.

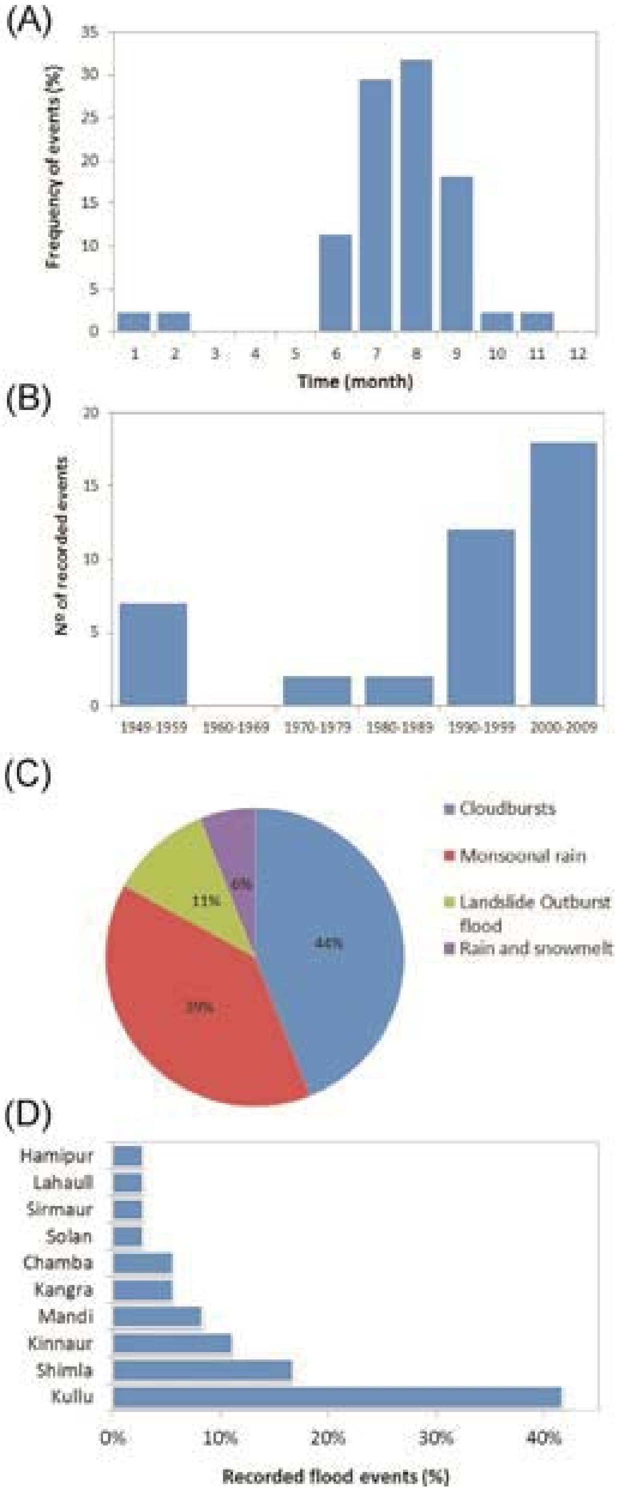


Figure 15: Overview of flood activity in Himachal Pradesh since 1950. (A) Seasonality; (B) Number of events per decade; (C) Triggers mechanisms; (D) Affected districts

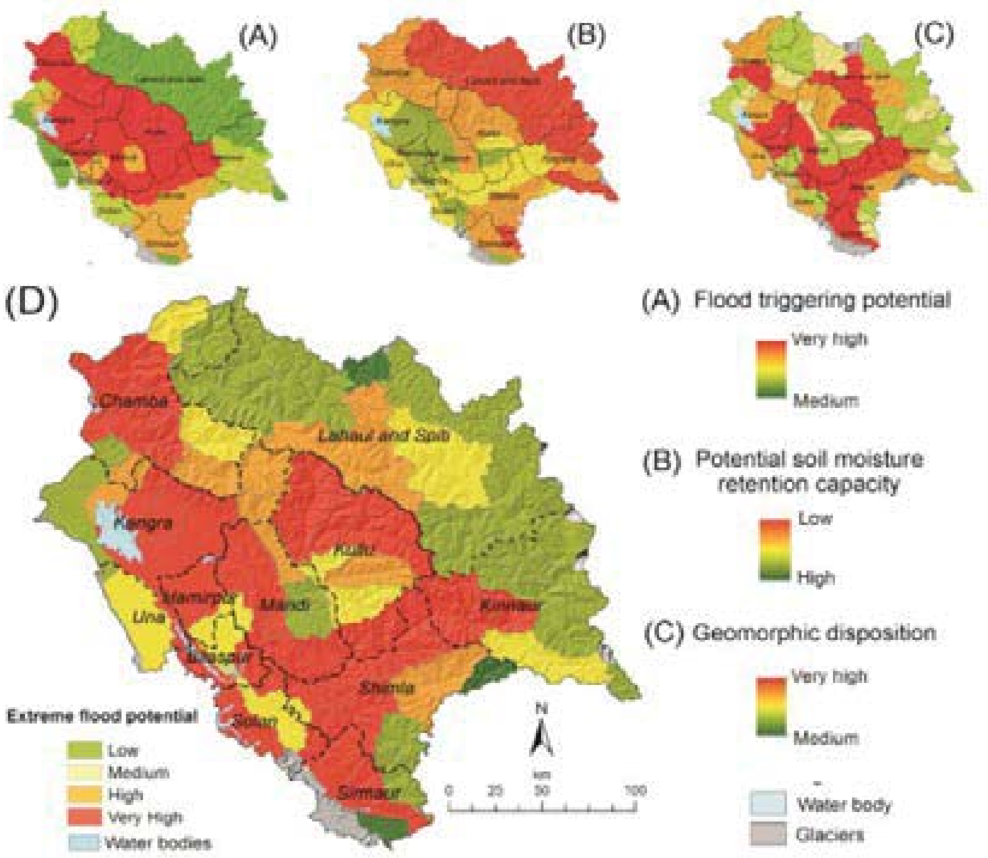


Figure 16: GIS-based semi-automated assessment of (A) basin flood triggering potential, (B) potential soil moisture retention capacity, (C) geomorphic disposition and, (D) the final potential for extreme floods in Himachal Pradesh.

The basin disposition to extreme floods has been identified state-wide based on 20 morphometric indexes, the potential hydrological response and climatic conditions (potential triggers). The different indicators were defined for 48 sub-basins of Himachal Pradesh. From the analyzed sub-basins, 17 were classified as high or very high flood potential, nine as medium and 22 as low flood potential (Figure 16). For the Kullu district, the Parvati Valley and the upper Beas catchment area were identified as having very high flood potential, with high flood potential assessed for the Sainj Basin.

Regarding the potential source of flood triggering, most of the area (47 per cent) is classified as monsoon fed, 28 per cent as cloudburst monsoon, and 24 per cent as glacial-snow and snow-cloudburst fed. Those areas classified as monsoon are potentially affected by long rainfall events from spring to autumn, triggering large-scale floods in the monsoon season. Those classified as snow-cloudburst are potentially affected by snowmelt in spring and heavy convective storms in summer which trigger flash floods.

Another important trigger of extreme floods in Himachal Pradesh are landslides damming a main river valley, forming a lake which can then catastrophically burst to develop an extreme downstream flood. Landslide dams introduce additional geomorphic hazards that may threaten locations at significant distances up- or downstream of the dammed lake. Due to the large scales involved, detection, monitoring, and mitigation of related threats can require district, state, and even transnational cooperation.

Based on land cover mapping, the immediate flood plain area of the Beas catchment constitutes about 47 per cent agriculture/plantation land, 10 per cent dense or open vegetation cover and about three per cent urban land cover which is likely to be affected in case of a flood. Likewise within the flood plains of the Parvati catchment, the affected area under agriculture or plantations is about 21 per cent followed by about 24 per cent vegetation, and 15 per cent grazing land. In Sainj and the Great Himalayan National Park catchments, 18 per cent of affected area is under agriculture, 36 per cent under vegetation, and 9 per cent under grazing land.

Fluvial dynamics have been analyzed in order to assess changes in the fluvial systems. The analysis is based on the assessment of the temporal changes in the spatial distribution of riparian vegetation and channel positions. Trends have been identified and the most significant detected changes have been related to important flood events. The identification of highly dynamic reaches is extremely important for river management.

The analyzed rivers are rarely in a steady state. This indicates that the valley bottoms are still under active construction. For example, very low vegetation cover in 1972 resulted from the significant flood in 1971. This flood affected the four rivers with the strongest impacts on the Tirthan, the Parvati and the Beas. Similar flood impacts on vegetation are seen in subsequent years.

This study represents the first step for sound river corridor planning which should include channel dynamics that occurs during flood events, as these can both substantially modify the flooding pattern and cause direct damage to buildings and infrastructures. The flood hazard zonation together with the analyses of fluvial dynamics will be useful for preparing /updating the disaster management plans in the Kullu district. These plans are building resilience and reducing risks by way of having appropriate preparedness measures, by adopting effective warning systems, increasing community awareness, and sustainable land use planning.

5.4.2. Reconstructing past events

Kullu district has been frequently affected by flash flood events during the last decades. At least 66 flood incidents have taken place since 1965 that established an average frequency of 1.3 events per year.

Past flood events in the Kullu district are recorded as both widespread regional events, and also as catchment-specific events. 56 per cent of the recorded flood years (a year when at least one flood occurred) are attributable to more than two catchments, of which 15 per cent are attributable to more than four catchments. Conversely, therefore, 44 per cent of the flood years are exclusively attributable to only one specific catchment. Hence, both large-scale atmospheric conditions and specific local weather conditions (e.g. cloudburst events) have operated as flood triggers in the Kullu district.

The reconstructed data on flash flood occurrences in the Kullu district suggests that in the last five decades there were five distinct phases of flood activity: i) high flood activity between 1967 – 1981, 1988 – 1995 and 2003 – 2014; and ii) low flood activity between 1981 – 1987, and 1996 – 2001 (Figure 17A). These phases probably reflect the impact of variability in large-scale atmospheric features.

Based on the available flow discharge measurements at the Kullu district and paleoflood reconstructions, the largest specific peak discharges have been identified in the upper Beas river (up to Manali) and the Sainj river at Talara Dam. The Allain and Dhungan Nallah, the Tirthan at Larji, and the Parvati at Bhuntar were categorized to have an intense specific flow discharge (percentile > 75 per cent). The Beas reaches up to Bhuntar and Thalout have been categorized as moderate specific peak discharges (above 25 per cent percentile), whereas lower specific flow discharges were observed in Sainj at Larji and Beas Pandoh, presumably due to the influence of the intense flow regulation (i.e. hydraulic infrastructures) in this area. These results suggest contrasting flood hazard across the Kullu district. However, the current analysis remains limited by data availability.

The unique integration of the peak discharge reconstructions from tree-rings for ungauged extreme flood events, with the flood frequency analyses based on measured flow discharge, results in improved understanding of flood magnitudes and related uncertainties. This study provides evidence that instrumental data underestimates the flood hazard systematically across the Kullu district.

The reconstruction of eight intense flood events with magnitudes between 178 m^3/s and 1114 m^3/s in the Sainj Valley resulted in a ~ 10 per cent increase in the 100-year flood discharge value calculated at Talara Dam, as well as a reduction by ~ 90 per cent in the related flood uncertainties. The observed changes after the inclusion of two extreme flood reconstruction events at the Tirthan Valley was 176 per cent with a reduction in the uncertainties by almost 32 per cent. Finally, at Beas-Manali flow gauge station, the changes in the 100-year flood discharge value after incorporating the flood disaster at Palchan in 2012, was 240 per cent, with a reduction in the uncertainty range of almost 63 per cent.

The combination of peak discharge information together with field-based geomorphic analyses has highlighted the potential causes of three paradigmatic flood disaster incidents in the Kullu district Specific examples in the upper Beas catchment and the Tirthan Valley demonstrate that infrastructure (e.g. schools, hotels) have been constructed on active flood plain areas, even though there is abundant geomorphological evidence that recent flood events have occurred.

These observations suggest that the lack of baseline scientific knowledge on the past flood disasters could play an important role in limiting the implementation of flood DRR strategies at three levels, i.e. civil engineering, local authorities and inhabitants. These analyses show that more efficient and reliable DRR implementation at different levels is critically required, although at present hampered by a lack of data to characterize the flood processes. Building community resilience against future extreme events will be enhanced with improved flood understanding and rigorous implementation of this new knowledge within DRR strategies.

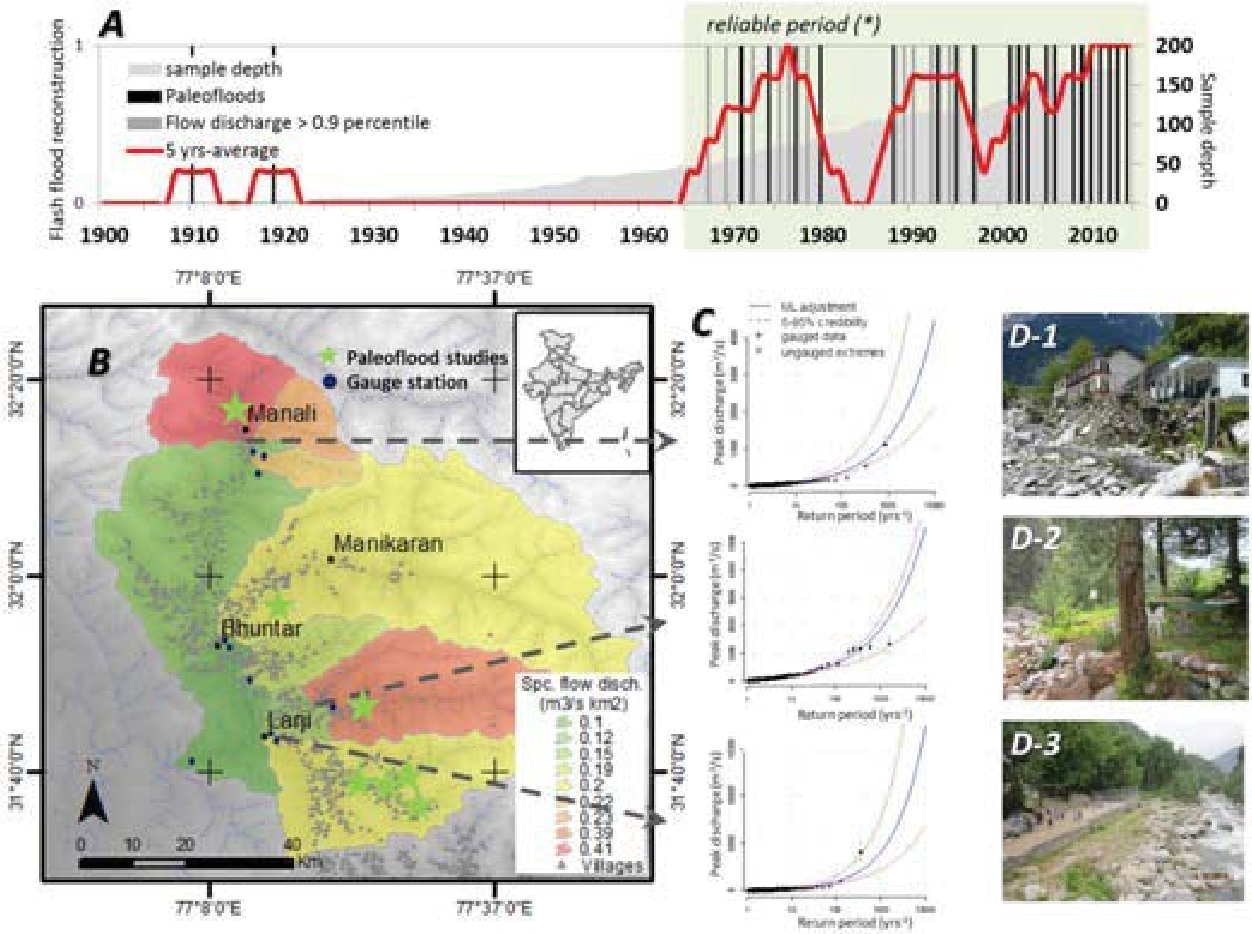


Figure 17: A) Regional flash flood reconstruction at the Kullu district. Due to the availability of living trees and flow discharge measurements the reliable period is considered between 1965 and 2014. B) Representation of the main catchments in the Kullu district and average specific peak discharge based on both flow measurement and paleoflood discharge reconstruction. C) Obtained flood quartiles at each studied catchment after paleoflood incorporation. D) Pictures of three hot-spot flood-risk river reaches.

5.5. Glacial lake outburst floods

The disappearance of mountain glaciers and expansion of large glacial lakes are amongst the most recognizable and dynamic impacts of climate warming in the alpine environment. In combination with altered stability of surrounding rock and ice walls, the potential threat from glacial lake outburst flooding is thus evolving over time. With residential, tourism, and particularly hydropower infrastructure expanding higher into alpine valleys, increasing conflicts with the natural environment are expected. This study has implemented a broad suite of modern approaches to assess current and future glacial lake outburst flood (GLOF) hazard, underlying socio-economic vulnerability, exposed communities and infrastructure, and ultimately GLOF risk at the tehsil-scale, across Himachal Pradesh, with an emphasis given to results pertaining to the Kullu district. This study thereby provides an end-to-end example of integration across all components of the IHCAP integrated assessment framework.

GLOF risk is currently the highest in Chamba, a north-western district in Himachal Pradesh. Despite there being many glacial lakes formed within the mountainous district of Lahaul and Spiti, there is only low GLOF risk owing to the low population density and low levels of societal vulnerability. Exposure and vulnerability patterns across the state broadly correlate, with generally lower vulnerability and lower population densities (exposure) evident towards the north-east. The distribution of vulnerability is broadly consistent with previous assessment reports, despite differences in concepts and methodological approaches used.

In the Kullu district, actual GLOF hazard is the highest in the Kullu tehsil where potential GLOFs originate in the heavily-glaciated Parvati Valley and can in a worst-case scenario reach the main Kullu Valley. However, the assessed GLOF risk (considering also the exposure and vulnerability of communities) is the highest for Banjar and Sainj tehsils.

As existing lakes continue to expand and new lakes develop over subsequent decades, GLOF hazard can be expected to increase significantly across all currently-threatened districts and tehsils, as the overall potential for GLOFs being triggered from mass movement of ice and rock avalanches increases, and as new or further-reaching GLOF paths affect larger land areas. For some communities entirely new threats may emerge as new lakes may form upstream in areas where currently no lakes are found (Figure 18a).

A most striking consequence of future deglaciation is the significant increase in GLOF hazard expected in the Parvati and the Kullu valleys (Kullu tehsil) relative to current conditions. This is a consequence of a modelled sevenfold increase in the potential for GLOFs to be triggered from mass movement of ice and rock avalanches, and threefold increase in the area affected by potential GLOF paths.

It has been demonstrated that the formation of new glacial lakes over subsequent decades will result in an increased threat to habitations, road infrastructure, and agricultural land areas across most of the Kullu district. However, particularly significant is the increased threat to roads and agricultural lands that have been modelled for the Manali tehsil in the upper Kullu Valley (Figure 18b-c). Even in sparsely populated and largely inhabitable mountainous areas, any potential significant increase in GLOF hazard should be considered in view of planned infrastructural developments, in particular related to the hydropower sector.

In north-eastern areas of Himachal Pradesh the threat of ‘transnational’ GLOFs is evident, where potential outbursts from glacial lakes located in the upper Satluj Basin in China can reach the downstream areas of Lahaul and Spiti, and Kinnaur districts of Himachal Pradesh (Figure 18a). This highlights the large scale involvement and transnational approaches required to manage GLOF risk.

Strengthening resilience and reducing the risk to the current GLOF threat through early warning systems, increasing community awareness and preparedness, and sustainable land use planning would be a significant first step towards adapting to the future GLOF threats in many instances.

In those valleys where potential GLOFs from new lakes will flow primarily along existing GLOF paths, any adaptation measures implemented now will offer duel benefits – it will reduce not only the current GLOF risk, but will also respond to the emerging threat anticipated for the coming decades. Such adaptation strategies can be considered ‘low-regret' measures, i.e. responses that offer immediate benefits to communities now while also offering benefits over a range of possible future scenarios. Even if the predicted new lakes in these instances do not eventuate, any risk-reduction measures implemented now would be worthwhile.

Where the formation of new lakes over the coming decades may create an entirely new hazard, i.e. potential GLOF paths will affect areas currently not exposed to any GLOF threat, local authorities are encouraged to consider long-time scales in their climate adaptation planning. New infrastructural developments must consider not only the current GLOF hazard, but also the new threats that could emerge during the intended lifetime of any development. This is particularly relevant for the hydropower sector where dams often encroach into glaciated high mountainous catchments.

The results from this study will allow early anticipation of future threats, thereby providing a scientific basis for planning and implementing adaptation strategies.

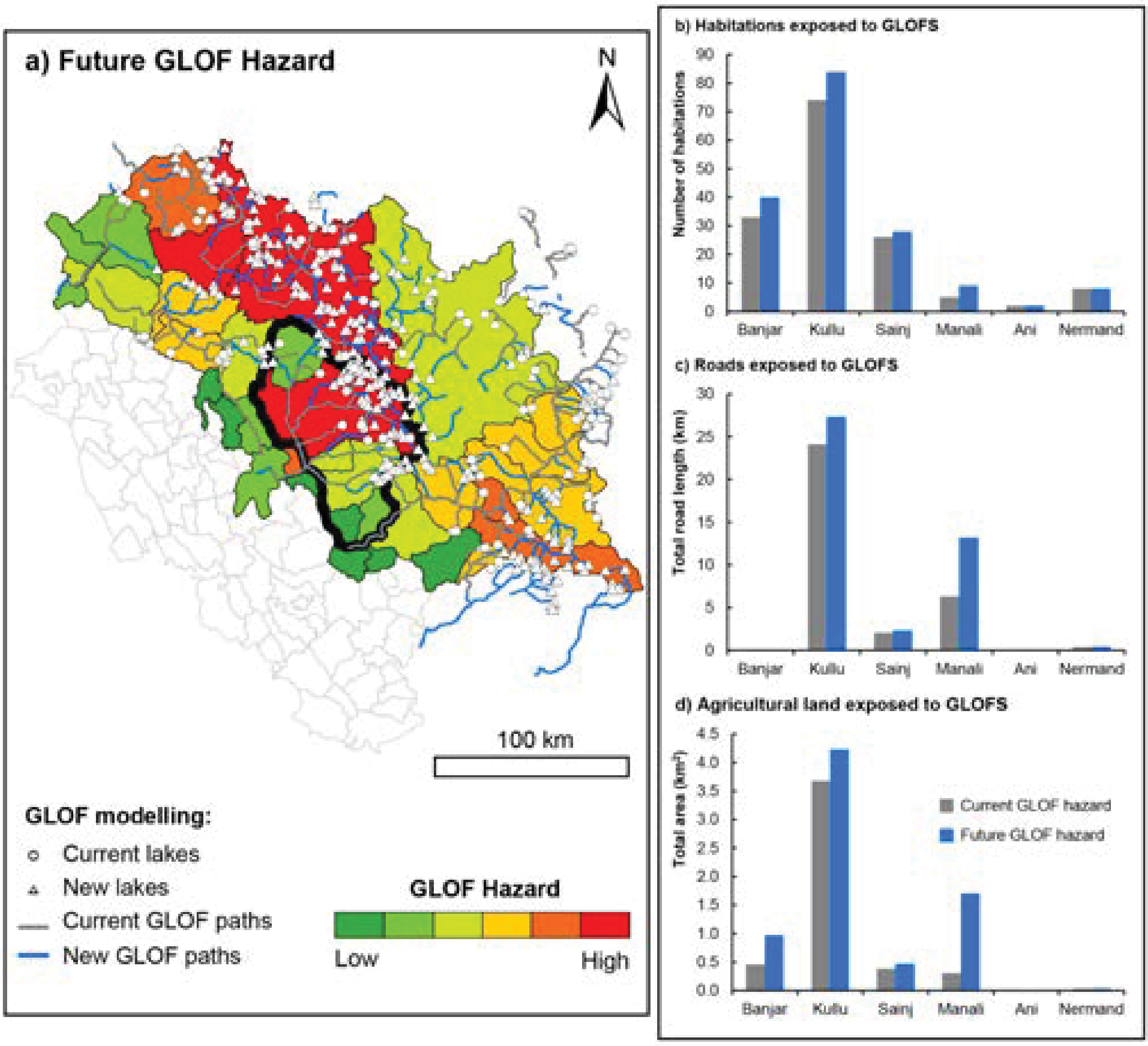


Figure 18: a) Future GLOF hazard across the tehsils of Himachal Pradesh considering the worst-case scenario modelling of potential GLOF paths from the current glacial lakes, and from new lakes that are projected to develop as glacier recession exposes overdeepenings in the bed topography. b – d) Human habitations, road infrastructure, and agricultural land areas exposed to GLOF hazard within the six tehsils of Kullu district under both current and future conditions. Human habitations and roads have been digitized directly from the Indian topographical maps, while the agricultural land areas are extracted from the land cover data of the Indian National Remote Sensing Centre.

5.6. Landslides

Landslides are a major threat to life, infrastructure, and transportation networks across the Himalayan states of northern India. Steep slopes fractured by tectonic forces, erosion and destabilization following glacial retreat, saturation during heavy rainfall or snowmelt, thawing of previously frozen ground and poor land use practices contribute towards frequent slope failure in the foothills and in the main Himalayan range. In addition *to direct impacts, landslides can block drainage systems and form lakes which may subsequently breach as catastrophic outburst floods. In this study, satellite-based mapping has provided a basis for an inventory of the past landslide activity across the Kullu district. From geological and geomorphic understanding, landslide hazard zones have been derived, identifying areas within Kullu that are most susceptible to landslide hazard.*

Kullu district has been divided into four landslide-hazard zones based on the physical susceptibility of each zone towards landslide and erosional processes (Figure 19). The common types of landslide in the Kullu district include rotational slips, debris slides, and debris flows from the valley sides, and rockfall and large rock avalanches from high mountain slopes. In addition to the natural processes that influence hillslope stability, poorly planned and unsustainable human activities like deforestation, construction of roads, terracing and changes in agricultural practices have further enhanced the landslide problem across the district.

Zone-I is a very high landslide-hazard zone. It comprises the Beas catchment, part of the Parvati Valley and part of the outer Sainj catchment. Very high landslide hazard results from high drainage density, moderately to highly fractured and dissected geological structures, steep slopes ranging from 18° – 53°, and dominance of agriculture on hillslope terraces. The vast majority of mapped landslides are observed from within this zone.

Zone-II is classified as a high landslide-hazard zone. It mainly comprises the north-eastern area of the Beas catchment, upstream of the Kullu town. This is predominantly a snow-bound region underlain by grassland and vegetation cover on lower slopes, with some scarce agriculture pockets along the terraces. Slope angles are generally in the range of 18° – 71°. However, the slopes are barren and vertical rock faces are found in the highest areas.

Zone-III is a moderate landslide-hazard zone. It mainly comprises the areas immediately adjacent to the Beas river upstream and downstream from Manali, and the high mountain catchment areas of the Parvati Valley and the Great Himalayan National Park. The middle and upper areas are more susceptible to erosional processes in comparison to the lower areas where drainage density is comparatively low. Upper hillslopes are very steep, while the lower slopes are in the range of 18° – 53°. The upper slopes have extensive glaciers and snow-covered areas with alpine wasteland, while the lower slopes have grassland and vegetation with a few agriculture pockets along the depressions/terraces.

Zone-IV is considered to be the low landslide-hazard zone. It is mainly confined to the flood plain areas along the banks of the Beas river. This zone is the most inhabited area of the district. It comprises the low gradient alluvium valley fill and the terraces here support agriculture and forests. Toe cutting and erosion caused by the river can destabilize the surrounding hillslopes and can thus activate landslides in this zone. Furthermore, the valley is surrounded by agricultural terraces which have led to oversaturation of the unconsolidated sediments along the river banks, thus, leading to hillslope failure. Therefore, although the overall landslide hazard is considered low, anthropogenic factors can have a significant influence on slope stability within this zone.

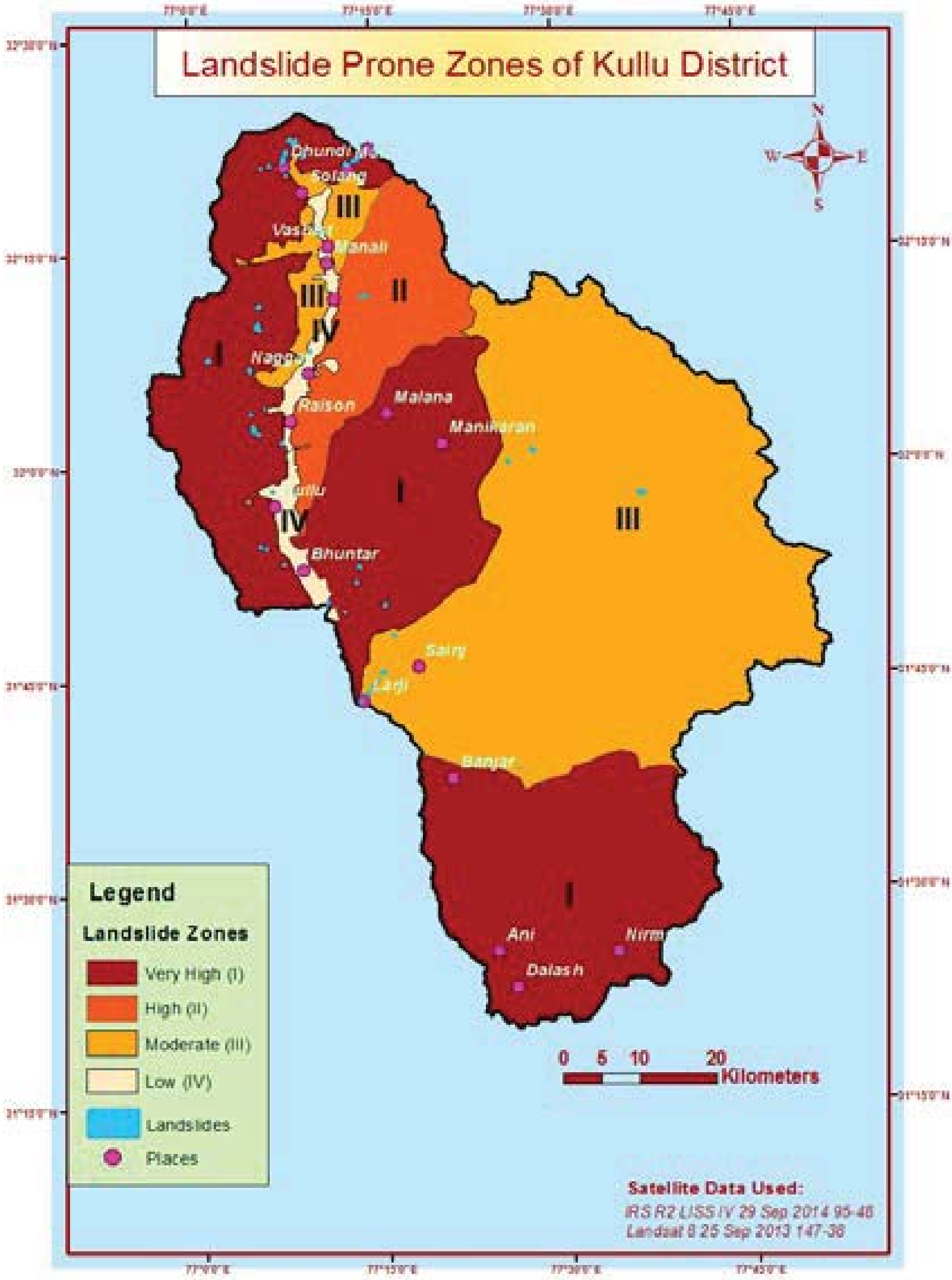


Figure 19: Assessed landslide hazard for the Kullu district based on lithological variations, drainage density, geomorphology and slope characteristics.

Landslide risk must consider not only the hazard, but also the vulnerability and exposure of the people and infrastructure. For example, in Zone-IV (low hazard) population density is high, there is considerable urban development, highly fertile land, a dense road network, and high concentration of tourism activities. Hence, any landslide that occurs in this zone will have devastating consequences. Significant infrastructure and other exposed elements are also located within Zone I (very high hazard), while zones II and III are comparatively remote and undeveloped.

Earthquake risk in Kullu

Within the IHCAP integrated study of climate risk for the Kullu district, it is important to recognize the potential interaction of geological, cryospheric and hydrometeorological hazards. This is particularly relevant for landslides, where earthquakes and monsoon rainfall can together destabilize and ultimately trigger slope failures. Large earthquake-triggered landslides can block major rivers and form lakes which subsequently fill and catastrophically drain following monsoon rain or spring snowmelt. Enhanced erosion that results from earthquakes can increase debris accumulation within steep catchment areas which may in turn become mobilized during flood events. On longer time-scales, the widespread retreat of glaciers and thawing of permafrost expose steep unstable moraines and destabilizes adjacent mountain slopes – preconditioning for large mass movements of rock and debris triggered by earthquakes. In addition to such process interactions, on the development side, building resilience and reducing societal vulnerability to non-climatic threats such as earthquakes should lead to simultaneous benefit for climate change adaptation.

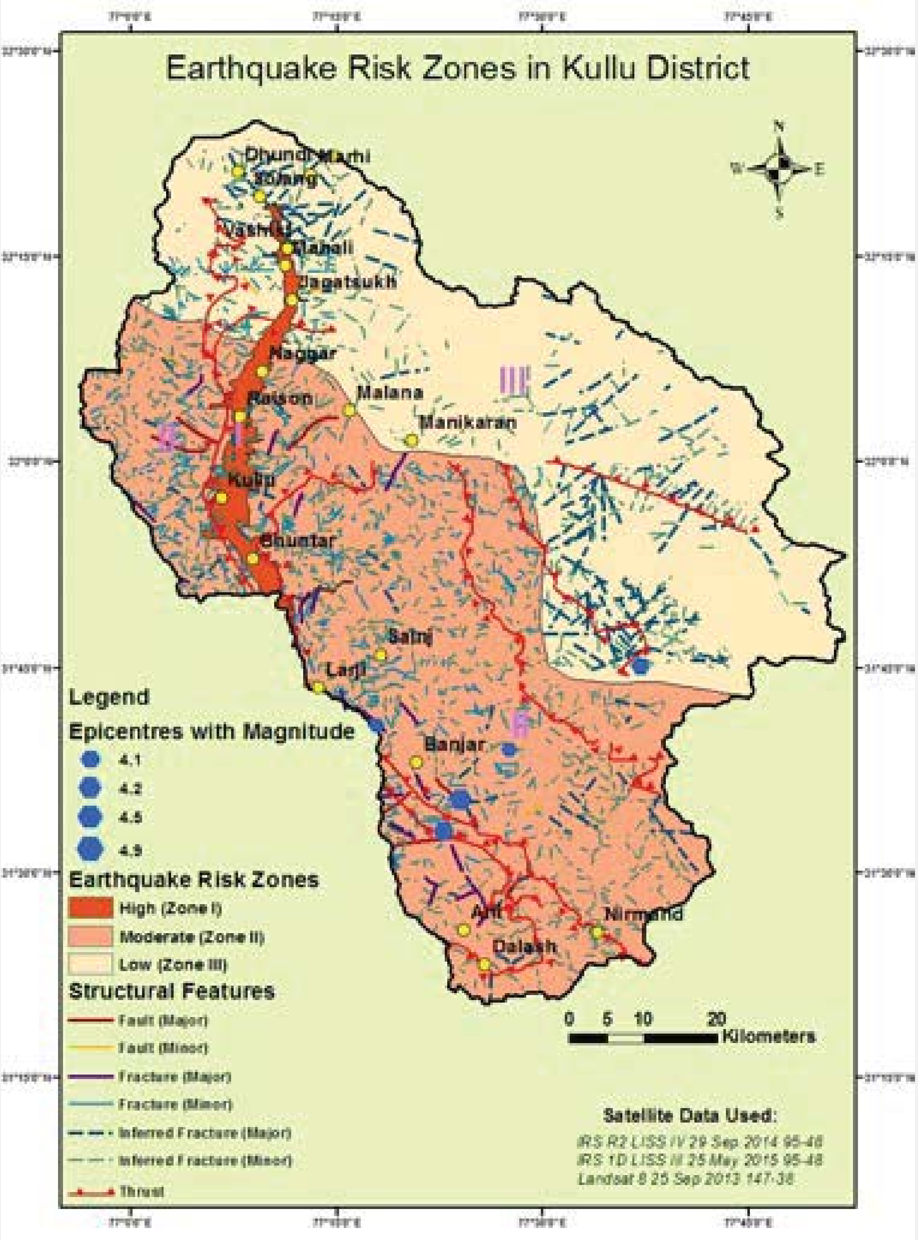


Figure 20: Assessed earthquake risk for Kullu district

Kullu district sits within an area of significant seismic potential with possible seismic events having intensities of magnitude VII to IX and above (Modified Mercalli Intensity Scale). Based on the bedrock fracture intensity, lineaments, faults, thrusts, morphotectonics and the lithology of the area, combined with population and infrastructure patterns, the Kullu district has been broadly divided into three zones of earthquake risk (Figure 20).

Zone-I (high risk) is mainly confined to areas immediately adjacent to the Beas river that is formed by alluvium deposits of sand, gravel, silt and clay. Within this zone, population and agricultural activities are most dense. Moreover, because of the presence of unconsolidated sediments along low-lying areas of the Beas river, earthquake vibrations and shock waves may be stronger here than in the adjacent areas that have hard rocks. Landslides may be triggered or reactivated from the surrounding slopes, and post-earthquake effects like liquefaction and settlement could cause severe damage.

Zone-II (moderate risk) mainly comprises the three major catchment areas, i.e. the Beas catchment, the Parvati Valley catchment and areas within the Great Himalayan National Park and the Sainj catchment. Despite previous earthquake activity, major tectonic lines, high relief and high fracture intensity, the moderate to scarce level of human habitation lowers the overall assessed earthquake risk within this zone.

Zone-III (low risk) mainly includes areas within the Beas catchment above Manali, upper Parvati Valley, some of the northern parts of the Great Himalayan National Park and Sainj catchments. This zone is heavily glaciated, and hence sparsely populated. Nonetheless, earthquake-triggered landslides and erosion from within this seismically active zone may have far reaching downstream consequences or secondary impacts.

Across Himachal Pradesh there are numerous examples from the past decades of landslides blocking major rivers, forming lakes, and catastrophically breaching as outburst floods. Particularly devastating events have occurred in the upper Satluj Basin, including the recent disasters in 2000 and 2005, when landslide-dammed lakes in Tibet have breached and caused fatalities, destroyed villages, and significantly damaged transport and hydropower infrastructure in downstream districts of Himachal Pradesh. Under IHCAP, these events from 2000 and 2005 have been carefully analyzed, and lessons extracted, highlighting that cooperation and information sharing across political boarders are essential requirements to ensure that potentially far-reaching, trans-national disasters are mitigated.

5.7. Snow avalanches

Snow avalanches are major threat to mountain infrastructure and transportation routes, isolating and disrupting communities and livelihoods. Understanding snow avalanche activity and potential climatic controls on this activity is therefore essential for implementing effective risk reduction strategies. Data on past events and their spatial distribution are not only useful to understand climate-event linkages, but also to support advanced modelling approaches to determine hazard zones and risk mapping. This study has combined several novel approaches to compile and analyze the longest snow-avalanche reconstruction in the IHR. The study was focussed on the vital transportation corridor between Solang and

Dhundi (upper Beas catchment) where the Rohtang Tunnel will link Kullu district with Lahaul and Spiti district to the north.

The transport infrastructure located in the upper part of the Beas catchment is affected by snow avalanches, which represents an important threat to the long-term service reliability of the future Rohtang Tunnel. More than 50 snow avalanche events have been reconstructed since 1855 based on evidence from 144 disturbed trees. This result gives an average frequency of ~ 0.3 events per year. However, over the shorter term (since 1980s) the frequency has increased to 0.63 events per year (Figure 21a).

At least three distinct phases of activity have been observed since the 1970s: higher frequency from 1970 – 1977 and 1989 – 2003; and lower frequency from 1977 – 1989 and 2003 – present (Figure 21a). The analyses suggest that snow avalanche activity at the study site in the upper Beas catchment may be characterized by some of the highest frequencies observed worldwide, based on published literature.

Based on the spatial pattern analyses of the avalanche-affected trees, three clusters of snow avalanche magnitude have been detected. Cluster 3 considered as large events have affected the entire studied slope (43 per cent), cluster 2 have affected an important part of the slope (33 per cent), and cluster 1 was characterized as channelized events (23 per cent). These results suggest that snow avalanches frequently affect the entire slope.

Statistical hazard modelling suggests that the current/past threat to the exposed transport corridor is noteworthy (Figure 21b). For a snow avalanche with a magnitude defined by a 10-year return period, the probability of the road being affected is 0.54 (54 per cent). Considering a return period of 25 years, the probability may increase up to 0.80. The affected road area increases considerably with return periods of 50 to 100 years with probabilities close to 0.90.

The results of the statistical modelling have been confirmed using numerical snow avalanche simulations (Figure 21c). For the extreme scenario considered, the entire road area within the avalanche path can be affected, but highest flow velocities are confined to the main flow paths. For the intermediate scenario considered, larger parts, in particular along ridges, are not affected by the flowing part of the simulated avalanches. Finally, for the frequent scenario considered, only the main gullies of the avalanche path are affected. However even the avalanches simulated in the small scenario overflow the road and reach the river in the valley bottom.

The simulated deposition heights of snow avalanches can reach up to 3 m with pressures higher than 30 kPa at the road even in the frequent scenario. In this example, the good match between field observations and modelling indicates that tree-rings can be used for model calibration, and consequently to improve hazard and risk assessment in large ungauged areas. These results indicate that even frequent avalanches significantly endanger the exposed road corridor.

The data on past snow avalanche activity has been linked with climate triggers by mean generalized lineal model (GLM). Results indicate that rather than precipitation, changes in temperature regimes played and will play an important role in snow avalanche triggering. We detected a seasonality shift in the most likely climate trigger from December-January temperatures (period 1900 – 2013) to January-March temperatures (period 1950 – 2013). This shift remained evident when considering only the major events (cluster 3), and may indicate the role of wet snow avalanches in late winter. This finding has important consequences for planning reliable defence structures, and needs further investigation with respect to projected future changes in temperature.

Overall, our results suggest that risk reduction measures along this transport corridor should be based on well-designed defence strategies at the road level, considering new understanding of past snow avalanche activity and characteristics, in order to avoid future disruption and loss of services.

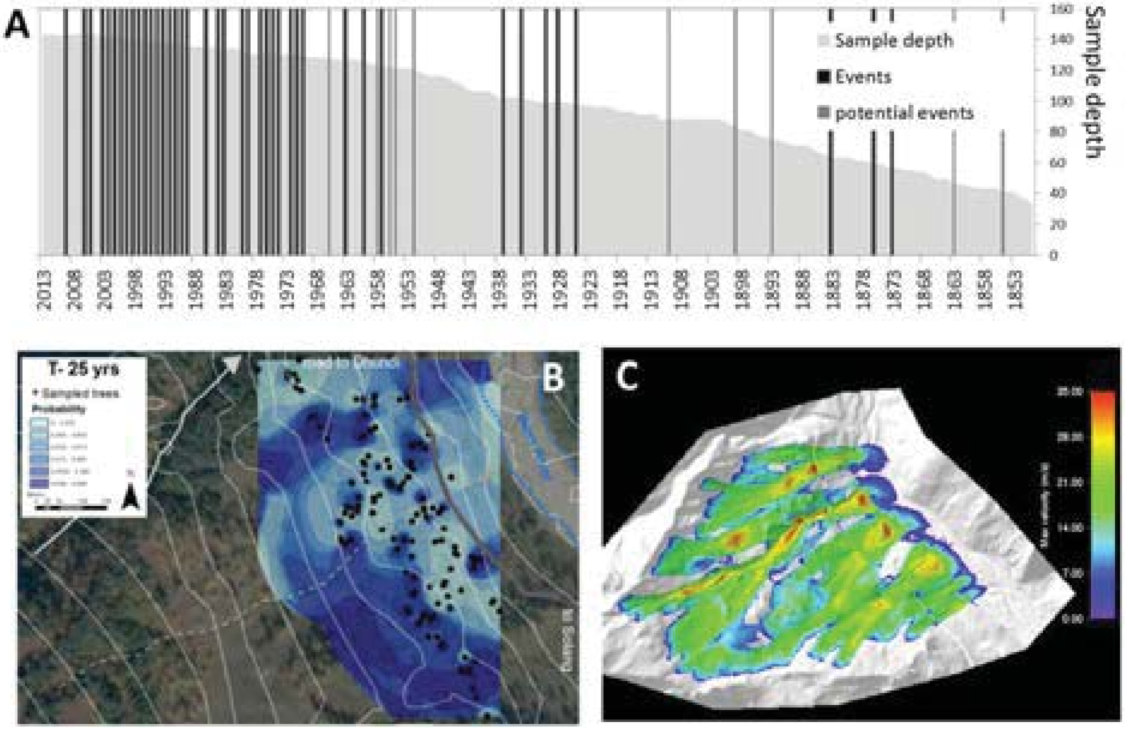


Figure 21: A) Snow avalanche occurrence based on tree-ring reconstruction. Sample depth refers to the number of affected trees analyzed. B) Probabilistic map for a snow avalanche event with a return period of 25 years. C) Simulated maximum velocities for an intermediate event scenario based on RAMMS simulations using highly accurate topographic data.

6. Policy perspectives and potential climate adaptation measures

Based on the study results presented in sections 4 and 5, key overarching policy perspectives for climate change adaptation (CCA) and disaster risk reduction (DRR) in the Indian Himalayan context are presented here. These perspectives are not intended as prescriptive guidelines, but rather as a series of policy relevant messages that emerge from across the various pilot studies and experiences gained in the Kullu district. A basket of potential climate change adaptation measures is then outlined to provide a basis from which decision-makers and local stakeholders can discuss and identify most appropriate measures for the Kullu district.

6.1. Policy perspectives

Integrating CCA and DRR is a necessity in the Himalayas. In the Himalayan region it is evident that disasters are more often than not associated with climate variability and extremes, albeit as direct triggers or as compounding factors. Therefore, an Integrated Vulnerability, Hazards and Risk Assessment Framework was developed to guide the Kullu studies. The use of this integrated framework provides for assessments which combine concepts and approaches from the complimentary fields of CCA and DRR, and contributes to efficient and effective developmental planning.

Systematic long-term monitoring networks and data provision are fundamental requirements for effective, knowledge-based CCA and DRR. Improved coordination of research activities and data sharing as well as establishment of long-term monitoring programmes are a pre-requisite to understand regional-scale climate change impacts, which in turn provide the scientific basis for sound adaptation planning. Based on specific case studies in the Kullu district, a lack of baseline data on past flood, landslide, and snow avalanche events was highlighted as a limiting factor for the implementation of DRR strategies. Baseline studies on key atmospheric and cryospheric components completed under IHCAP relied heavily on remotely sensed data and coarse resolution gridded global data products. While such data are freely available, and not restricted by administrative boundaries, it is not a surrogate for locally measured, ground-based data. When data is collected through individual, national or even international initiatives, it is essential that user-friendly mechanisms are developed (e.g. web data portals) where historical data can be archived (including supporting metadata), accessed and used within climate impact studies. Modelling approaches implemented under IHCAP have provided fundamental new knowledge on local cryosphere components to enable a first estimate of the glacier ice volume, and areal extent of permafrost distribution across the Kullu district. Only through local field measurements can these estimates be truly validated, uncertainties reduced, and impacts of a warming world assessed. Hence, field campaigns and monitoring programmes should not be seen as a fulfilment of scientific curiosity, but rather as a crucial step on the way towards effective CCA.

International collaboration, knowledge exchange and capacity building provide a robust scientific foundation for successful and sustainable CCA and DRR. Long-term monitoring and research activities can only be maintained with strong, local scientific support. Himachal Pradesh is strongly positioned in this regard with the State Centre on Climate Change (HPCCC) and several local research institutions leading established monitoring programmes on glaciers, snow cover, biodiversity, hazards, and other climate-related themes. Collaborative studies undertaken in the Kullu district, under IHCAP, have served to strengthen these existing programmes, with the exchange of knowledge between Indian and Swiss research institutions leading to new methodological approaches and novel perspectives. In parallel, IHCAP has recognized the need to train and encourage the next generation of local scientists through the Indo-Swiss Capacity Building Programme on Himalayan Glaciology. The success of IHCAP in areas of scientific exchange and capacity building illustrate what can be achieved when international development and cooperation programmes are supported by national and local authorities, together with university partners, all willing to invest in activities which provide the basis for long-term, sustainable adaptation planning.

Multi-hazard, catchment-scale approaches most effectively capture the full complexity of potential climate impacts. A key theme that emerges across the various studies implemented in the Kullu district is the interconnectivity of systems and processes, both human and physical. Hence, CCA and DRR strategies implemented in the heavily-populated valley townships (e.g. Bhuntar, Kullu and Manali), must consider processes that originate many kilometres upstream in the glaciated catchment areas. A broad, wide-ranging perspective is required with events such as extreme monsoon, glacial or landslide lake outburst floods that are capable of travelling exceptional distances, across district, state or even national boundaries. Where threats are recognized, cooperation and information sharing across political borders are essential to ensure that potentially far-reaching disasters are avoided. The connectivity between the upland hillslopes and rivers is crucial in the Himalayan environment as landslides, debris flows, erosion of glacial moraines and thawing ground are the main sources of sediment supply to the rivers. Therefore, monitoring and understanding the impacts of climate change even in the highest, most remote mountainous areas is of fundamental importance to manage downstream risks to hydropower infrastructure, and communities or infrastructure located on the dynamic flood plains.

A long-term perspective to CCA and DRR planning is required. Globally, risk reduction and adaptation strategies tend to focus on responding to current, known or perceived threats. In Himachal Pradesh, for example, the State Centre on Climate Change provides high quality, high resolution monitoring of glacial lakes as part of an effective overall strategy to mitigate the risk from related outburst floods. However, under IHCAP, approaches have been demonstrated that can provide early anticipation of entirely new threats that could emerge as glaciers continue to retreat over the twenty first century and new lakes are formed. Planning for new infrastructural development (e.g. within the hydropower or agricultural sectors and urban expansion) should thereby consider not only the current climate-related threats but also the new threats that could emerge during the intended lifetime of any development. By adopting a long-term perspective to CCA and DRR planning, surprises can be avoided, and investments in risk-reduction strategies may by optimized to ensure long-term sustainability of communities and infrastructure.

Low-regret adaptation measures offer immediate benefits to vulnerable communities and sectors. So-called low-regret (also termed no-regret) adaptation measures are those responses that bring immediate benefits to a community or sector, while also offering benefits over a range of possible future scenarios. In other words, these are smart adaptation solutions that a community or sector benefits from, irrespective of what the future uncertain climate might bring. Examples in relation to flood or landslide hazards in the Kullu district could include early warning systems, community education and preparedness, and disaster response planning. Given the scientific uncertainty regarding future changes in precipitation in the Kullu district, and how this will influence flood and landslide activity, implementing such measures will now greatly reduce the vulnerability of exposed communities under current conditions while building their capacity to prepare and respond to future threats. A well cited international example of low-regret adaptation is the creation of green-belts or reserve areas where vegetation is untouched and urban development restricted. Such green areas not only prevent development in the most exposed locations (e.g. along an active river flood plain), but also enhance biodiversity, create a visually attractive landscape, can stabilize areas of high erosion, and benefit the global climate through uptake of carbon dioxide .

Strengthening science-policy-practice dialogue is useful in designing sustainable solutions. It is important that an interface is provided for interactions between researchers, decision makers and the practitioners to ensure that the right questions are being asked and that the solutions therefore which are being offered are implementable in the real world. The studies undertaken in the Kullu district benefited from regular consultations with decision and policy makers and the civil society. This was useful to frame the right research questions and guided the research work in ways which are useful in the development process and respond to the needs of society.

Local stakeholder engagement is crucial for the implementation and long-term sustainability of CCA and DRR measures. As emphasized in framing the Kullu studies (Section 2), early engagement of local stakeholders (community, government, private sector) is an essential component of the climate adaptation process. At the framing or scoping stage of the process, the diverse objectives, experiences and expectations among the actors involved in climate adaptation can be laid out. This, therefore, provides a first entry point to establish a joint science-policy-society process, and experiences around the world have shown that early engagement of local people and institutions enhances subsequent implementation of adaptation solutions. For the Kullu district, approximately 12 months was devoted to the scoping and framing of the subsequent scientific assessment. Once the scientific assessment is underway, local stakeholders may be direct subjects in the data collection (e.g. the community perception study in the Kullu district), or engaged in community-led measurement or monitoring programmes. Finally the process should be iterative, such that study outcomes are communicated back to the stakeholders through informative policy briefs and public presentations. In turn, negative or positive local experiences with adaptation solutions should be communicated back into the framing and scoping process, such that lessons may be learnt and embedded into future research and adaptation initiatives.

6.2. Basket of potential climate adaptation measures

CCA and DRR both share a common goal to modify wide-ranging physical, environmental and human factors that contribute to climate-related risk, and thereby enhance sustainable economic and social development. Based on the studies and experiences not only in the Kullu district, but also in other mountainous regions of the world (particularly the Alps and the Andes), a basket of potential adaptation measures can be proposed for the IHR. However, it must be emphasized that it was outside the scope of the initial phase of the IHCAP pilot study in the Kullu district to design and recommend concrete adaptation measures. In the second phase of IHCAP (i.e. during 2016), the basket of adaptation measures will serve as the basis for further discussion, and concepts will be developed for a number of selected measures which will eventually be implemented in the Kullu district. As outlined in Section 3, the assessment completed within the Kullu pilot study provides the necessary scientific grounding for this next phase of adaptation planning. Concrete planning, development and implementation of selected adaptation measures must be done in close cooperation with local stakeholders (community, government and private sector) and supported with best available scenarios of future climate.

The adaptation measures outlined in this section are intended to address one or more of the three components that contribute to climate-related risk (hazard, exposure and vulnerability) (Figure 3, Section 3). For example, monitoring of high mountain climate variables provides the fundamental baseline data to understand, model, and anticipate climate-related hazards. Other adaptation measures generally involve societal decisions, pathways, and actions that either reduce vulnerability and/or exposure, or directly mitigate the hazard potential. Adaptation measures related to agriculture primarily aim to reduce the vulnerability of farmers to adverse weather and climate events, through enhancing resilience and coping capacities. DRR strategies primarily aim to reduce both the exposure and vulnerability of communities and infrastructure to climate-related threats such as floods and landslides, while ecosystem-based adaptation recognizes that healthy, well-functioning ecosystems enhance natural resilience levels and thereby reduce the vulnerability of people to climate change.

Potential adaptation measures are outlined below and grouped under five themes. Adaptation measures that may be considered as low-regret options are indicated with (*). Such adaptation measures can bring immediate benefits to a community or sector, while also offering benefits over a range of possible future scenarios (Section 6.1).

1. Monitoring and availability of high-mountain Essential Climate Variables (ECVs[6])

Measuring and monitoring of critical atmospheric variables at high altitudes: Missing atmospheric data at high elevation hampers monitoring and future assessment of changes of the cryosphere, and important downstream impacts. In addition to monitoring and change detection in high altitudes, these variables are a fundamental component for any downstream early warning system. The crucial variables include:

- Air temperature
- Precipitation
- Wind
- Humidity
- Radiation

Measuring and monitoring of the cryosphere: Continuation of remote sensing-based monitoring (glacier surface changes and lakes) as initiated during the Kullu studies. For those variables that cannot be directly measured remotely (notably permafrost), establishment of ground-based monitoring is required to support and calibrate modelling studies initiated in phase 1. The key components include:

- Glacier changes (area, length and mass balance)
- Glacial lakes
- Snow cover parameters (snow water equivalent, snow-covered area and thickness)
- Permafrost (ground surface temperature, borehole measurements, geophysical surveys and terrain displacements)
- Stream flow measurements at critical and undisturbed locations in upper regions of the catchments (e.g. near glacier tongues)

Integrated monitoring networks: Important to detect and monitor chain reactions within dynamic changing high mountainous environments. For example, thawing of permafrost is linked to slope instability, impacts into lakes and outburst floods that may have far reaching consequences.

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[6] Essential Climate Variables as defined by the Global Climate Observing System (GCOS) under UNFCCC

Disasters may be triggered by a complex combination of extreme precipitation, temperature, snow cover and snow melt (as seen for the 2013 Kedarnath disaster).

[cf. sections 4.1 – 4.3 and 5.5]

2. Disaster Risk Reduction strategies (floods and mass movements)

Early warning systems: Utilizing the latest scientific understanding, monitoring technology, and local knowledge, to forecast and warn of imminent threats to lives and infrastructure. In addition to the technical requirements and the monitoring of related climate variables (see ECVs above) the human component is highly critical (institutional and individual responsibility, and evacuation plans). Hence, the implementation of early warning systems, and in fact, most DRR strategies, must be strongly linked with community-based training and education.

Landuse planning/zoning: Integrating science-based hazard and risk mapping into urban planning to reduce the exposure and vulnerability of people and critical infrastructure. This requires clarification of the local legal context and regulations, and understanding of community perceptions which influence landuse practices.

Sustainable ecosystem and land management*: Sustainable agroforestry practices and agricultural practices can reduce land degradation and erosion. Careful planning and construction of roads can reduce adverse effects on slope stability. As a low-regret adaptation measure, it is expected that sustainable ecosystems and land management have multiple benefits for a community beyond DRR, relating to recreation and tourism (see EBA).

Building secure and reliable infrastructure: Establishing building standards and maintenance programmes that mean exposed infrastructure is built to withstand potential climate-related threats. Regulations and building requirements are commonly linked to hazard zoning.

Community awareness and preparedness*: Local education and training to ensure that the communities and key organizations are aware of the threats, and to ensure strengthened coping capacities so that locals know what to do and how to respond during an event.

Emergency response strategies*: To ensure that local authorities and key organizations have well-developed response strategies to safeguard medical aid, key services and lifelines during the emergency phase.

Structural engineering defences: Defence structures and engineering solutions that reduce or prevent hazards from occurring in the first place. For example, artificial drainage of a glacial lake, or strengthening of a lake outlet channel.

[cf. sections 5.4 – 5.7]

3. Ecosystem-Based Adaptation

The Ecosystem-based Adaptation (EBA) uses biodiversity and ecosystem services as part of an overall adaptation strategy to help people and communities adapt to the negative effects of climate change. It is based on the principle that increased biodiversity levels and well-functioning ecosystems enhance natural resilience to the adverse effects of climate change, enhance and maintain vital ecosystem services and ultimately reduce societal vulnerability. Appropriately designed ecosystem management initiatives can also contribute to climate change mitigation by reducing emissions from ecosystem loss and degradation, and enhancing carbon sequestration. EBA measures include, but are not limited to:

Incorporation of EBA philosophy within landuse management: The implementation of specific measures focused on biodiversity conservation and maintenance of ecosystem functions.

Quantification and monitoring of biodiversity levels: Baseline data to understand earth system processes and feedbacks (e.g. carbon cycle).

Promotion of sustainable agroforestry practices: Communities are highly dependent on wood material for building and heating. Measures can reduce wood dependencies that in turn can lead to decreased rates of deforestation.

Promotion of resilient ecosystems: Planning based on afforestation using local species, and engagement of communities in restoration and management programmes.

Promotion of solid collection and waste management systems: Waste and sewage can have major adverse impacts on fluvial ecosystem. Regulated solid collection and waste management systems are useful to ensure future provision of ecosystem services, specifically related to the water cycle.

Cataloguing and protection of medical (and other valuable) botanical species: Promotion of research in this field and the implementation of nature-based industries.

[cf. sections 5.1 and 5.2]

4. Agriculture and horticulture

Meteorological based measures:

- Agro meteorological advisories: Tool for coping with adverse weather conditions in agronomy.
- Climate-smart insurance: Weather-parameter-based insurance instruments which reduce financial losses due to extreme weather.

Hydrological management:

- Rain water harvesting: Micro-reservoirs to save water to improve water security.
- Water budgeting and efficient irrigation methods: Allows agriculture during drought conditions.*
- Artificial spring recharge: Permeable ponds to allow recharge of local groundwater reserves.
- Traditional irrigation strategies: Using local traditional knowledge to ensure fair water allocation.
- Mulching: Reduces evaporation losses and pests and diseases.*

Food security:

- Agri-Aquaculture: Combining small holder agronomy with fish farming and rainwater harvesting to improve food security.
- Family gardens: Allows diverse crops and small animal husbandry to improve food security.*

Resilient farming and landuse practices:

- Minimum ploughing strategies: Reduces negative side effects of intensive soil cultivation on land erosion.
- Organic and biodiverse agriculture: More resilient to extreme weather and climate than traditional monocultures.
- Mixed cropping and crop rotation: Ensures soil fertility without necessity of a fallow phase (erosion).
- Selection of climate change-resilient varieties, species and genotypes: Improves resilience against humidity, drought, pests and diseases.

[cf. section 5.3]

5. Fundamental cross-cutting adaptation measures

There are some overarching core components that should accompany all adaptation measures to ensure the success and long-term sustainability of their implementation. They are:

<u>Scientific capacity building</u>: Strengthening local institutions and universities through education and capacity building by means of exchange programmes, joint research projects and international networking. For example, the collaborative studies undertaken in the Kullu district, under IHCAP, have facilitated the exchange of knowledge between Indian and Swiss research institutions leading to new methodological approaches and perspectives.*

<u>Community engagement, training and education</u>: Ground level capacity building and engagement of locals is a key pre-condition to ensure successful implementation of adaptation measures. Already at the framing or scoping stage of the adaptation process the diverse objectives, experiences, and expectations among the local stakeholders involved can be laid out.*

Finally, when planning, developing and implementing adaptation measures for the Kullu district and the IHR, underlying uncertainties regarding the future climate must be acknowledged, but should not provide an excuse for inaction. Clear guidance and recommendations in this regard is provided by the IPCC in their special report on managing the risks of extreme events and disasters:

> *"In the presence of deeply uncertain long-term changes in climate and vulnerability, disaster risk management and adaptation to climate change may be advanced by dealing adequately with the present, anticipating a wide range of potential climate changes, and promoting effective 'no-regrets' approaches to both current vulnerabilities and to predicted changes in disaster risk. A robust plan or strategy that both encompasses and looks beyond the current situation with respect to hazards and vulnerability will perform well over a wide range of plausible climate changes."*
> *(IPCC 2012, p. 49)*

7. Outscaling the assessment framework

When developing the integrated framework for vulnerability, hazards and risk assessment for the Kullu district, a key guiding principle was that the overall concept and research methodologies would be transferable to other districts or states across the IHR. Here we summarize the perspectives, requirements and the main considerations that will enable outscaling of the assessment framework and underlying methodologies from the local context in the Kullu district, to other geographical areas. Full technical requirements are outlined in the underlying study reports (Appendix I).

Data requirements

Studies completed under phase 1 of IHCAP in the Kullu district have primarily used baseline datasets (climate, cryosphere and socio-economic) that are available at the national-level, or in some cases, global-level. In addition, most of the baseline datasets are freely available. This means that outscaling to other regions can now proceed using the same underlying datasets and covering the same baseline reference period. This homogeneity of baseline datasets, including the defined reference time period (1981 – 2010) is crucial if results from one district or state are to be compared to another, and thereby provide the scientific basis for prioritization of adaptation resources.

For baseline climatological studies (e.g. trends in temperature, precipitation and snow cover), approaches have generally been based on gridded observations and model-based re-analyses. A key limiting factor in the Kullu district, and for subsequent outscaling, remains the availability of measured ground-based station data required to assess data quality and to evaluate analyses. This also holds true for the cryosphere, where remotely sensed or modelled baseline data on glacier extent, glacier volume, glacial lake volumes, and permafrost extent should all be validated with in situ measurements. Outscaling of methodologies to other regions must therefore be complimented and supported with a comprehensive focus on improved local data measurement and monitoring (including free accessibility to these data) to increase confidence in final assessment results.

The emphasis within Phase 1 of the IHCAP studies was to understand the current or recent changes in climate-related risk. As improved twenty first century regional climate projections are becoming available (e.g. through the CORDEX project), outscaling studies should be expanded to include and assess this data on future changes in climate. Additional data on future scenarios of economic and social development, and demographic changes should also be integrated wherever possible.

Methodological approaches

Standardized methodological approaches are needed to identify the threat of climate change and anticipate emerging challenges across the IHR. A wide range of methodological approaches have been implemented in the Kullu studies, including remote sensing and GIS-based analyses, advanced numerical modelling, field-based geomorphic mapping, dendrochronology reconstructions, and community participant surveys. Fundamentally all approaches are robust, having been applied extensively within CCA and DRR studies in various high mountainous regions of the world, with results published in peer-reviewed scientific literature. We are, therefore, confident in the transferability of these approaches to other districts in the Indian Himalayan states, albeit with appropriate caution and fine-tuning for local conditions. Using the example of GLOF hazard and risk assessment, simply transferring the approach taken in the Kullu district directly to another Indian Himalayan state would not be optimal, and rather different weightings could be considered for factors in different climatic regions. More emphasis might be given to rockfall triggering and thawing of ice-cored lake moraine dams in the dry, permafrost-dominated Himalayan states, and increased emphasis given to rainfall triggering in the wetter, monsoon-affected states. For all potential climate change impacts, such fine-tuning of the methodological approaches will be required to account for local geological, societal and climatological conditions.

Methodological approaches may also be expanded to account for new technological developments or changes in data availability. For example, precipitation analyses for Kullu were based on TRMM-3B42 satellite data – a data product which is no longer being updated and will be replaced by a new GPM project. In principle, the new GPM data products will be analogous to TRMM, with corresponding strengths and weaknesses, although data will be available at a significantly improved spatial resolution. This may allow for improved analyses of localized extreme rainfall events, such as cloud-bursts, and thereby increase the scope of subsequent studies.

All methodological approaches should be expanded to consider future projected changes in climate, economic and social development, and demographic patterns, thus recognizing the need to consider not only the current risk, but emerging threats over the twenty first century. A key challenge will be the treatment of scientific uncertainty inherent within future projections, and the requirement for clear communication of this uncertainty to policy-makers and stakeholders.

Anticipated outcomes

Based on outscaling of the assessment framework and methodological approaches, the following primary results can be envisaged.

- Baseline analyses on recent and future changes in climate variables of temperature and precipitation based on common gridded datasets and model projections for the entire IHR.
- Extended historical climate baseline, including stream discharge in ungauged catchments, from dendrochronology reconstructions in different climate regimes across the IHR.
- Glacier and snow-cover mapping for multiple time-steps during the satellite era to allow change analyses in catchment areas across the IHR.
- Mapping of potential permafrost based on methods used for the Kullu district and eventually complemented with in situ measurements and enhanced modelling approaches.
- Updated glacial lake mapping, integrated with modelling of future glacial lakes to provide a complete GLOF hazard and risk assessment for the IHR.
- Integrated flood and landslide risk assessment based on homogeneous methodologies employed across the IHR.
- Snow avalanche hazard and risk assessment for important transport corridors within mountainous areas of the IHR.
- Ground-level engagement of locals within community perception surveys across the IHR to gain important insights into their perceived climate-related vulnerabilities.
- Comprehensive knowledge on floral biodiversity, and related threats from climate change, for sensitive forest and ecosystems across the IHR.
- Homogeneous assessment of climate-related risk to the agriculture and horticulture sector which is a crucial component of most district economies within the IHR.

Implications and benefits for adaptation policy

Outscaling of the assessment framework and methodological approach developed for the Kullu district will most importantly provide a robust, objective, consistent and comprehensive climate vulnerability, hazards and risk assessment implemented across all Indian Himalayan states. As illustrated for various climate-related threats, impacts can be felt across district, state and even national administration boundaries. Hence, a consistent approach to identify the threat and to anticipate the emerging challenges is crucial in the Himalayan context. This will provide the necessary scientific basis which will empower state authorities to identify climate adaptation priorities and implement sound disaster risk reduction strategies. Here, it needs to be stressed that the resulting societal impact of an unusual or extreme climate event depends largely on the specific socio-economic and cultural context of the region (state, district) which importantly can modify the priorities for adaptation actions in that location. Moreover, it is critical that adaptation measures are jointly developed with the local population and are embedded in their local context. Only then, will adaptation measures prove successful and sustainable.

A cornerstone of the IHCAP studies in the Kullu district has been the successful engagement and integration of expertise from national and local authorities, Indian and Swiss university partners, and local communities. Outscaling of the assessment framework and methodological approaches to other districts and states will now ensure that this crucial new knowledge and experience gained is transferred beyond the Kullu district and Himachal Pradesh, to be enhanced through collaboration with additional partners in the new regions, strengthening scientific capacities across the IHR.

8. Concluding remarks

Under IHCAP, an integrated assessment of climate vulnerability, hazards and risk has been completed within a pilot project in the Kullu district, Himachal Pradesh. The wide-ranging studies brought together expertise from across multiple disciplines drawing from the physical and social sciences, while the fruitful exchange of knowledge between Indian and Swiss project partners has strengthened capacities leading to new monitoring initiatives, methodologies and perspectives.

Within the broader process of climate change adaptation, this pilot project in the Kullu district has provided the scientific basis upon which local risk-reduction strategies and adaptation measures can be prioritized and planned. As outlined in this report, next steps towards concrete planning, development and implementation of selected adaptation measures must proceed in close cooperation with local stakeholders to ensure that these measures are optimized and embedded within their appropriate local context.

The success of the pilot phase in the Kullu district should now facilitate outscaling of the assessment framework and methodological approaches developed under IHCAP to other Indian Himalayan districts and states. The collaborative joint-research programme under IHCAP may even serve as a template to guide successful science-based climate change adaptation not only in the Himalayas, but also in other high mountainous regions of the world.

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