Knowledge Priorities on Climate Change and Water in the Upper Indus Basin: A Horizon Scanning Exercise to Identify the Top 100 Research Questions in Social and Natural Sciences

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Abstract

River systems originating from the Upper Indus Basin (UIB) are dominated by runoff from snow and glacier melt and summer monsoonal rainfall. These water resources are highly stressed as huge populations of people living in this region depend on them, including for agriculture, domestic use, and energy production. Projections suggest that the UIB region will be affected by considerable (yet poorly quantified) changes to the seasonality and composition of runoff in the future, which are likely to have considerable impacts on these supplies. Given how directly and indirectly communities and ecosystems are dependent on these resources and the growing pressure on them due to ever-increasing demands, the impacts of climate change pose considerable adaptation challenges. The strong linkages between hydroclimate, cryosphere, water resources, and human activities within the UIB suggest that a multi- and inter-disciplinary research approach integrating the social and natural/environmental sciences is critical for successful adaptation to ongoing and future hydrological and climate change. Here we use a horizon scanning technique to identify the Top 100 questions related to the most pressing knowledge gaps and research priorities in social and natural sciences on climate change and water in the UIB. These questions are on the margins of current thinking and investigation and are clustered into 14 themes, covering three overarching topics of 'governance, policy, and sustainable solutions', 'socioeconomic processes and livelihoods', and 'integrated Earth System processes'. Raising awareness of these cutting-edge knowledge gaps and opportunities will hopefully encourage researchers, funding bodies, practitioners, and policy makers to address them.

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Key Points:

- The Top 100 research questions on climate change and water in the Upper Indus Basin in the social and natural sciences are identified.
- Many questions are cross-disciplinary given the strong linkages between climate, water, and human activities in the Upper Indus Basin.
- Questions are identified using horizon scanning, which is a technique used to identify knowledge gaps relevant to emerging challenges.

Abstract

River systems originating from the Upper Indus Basin (UIB) are dominated by runoff from snow and glacier melt and summer monsoonal rainfall. These water resources are highly stressed as huge populations of people living in this region depend on them, including for agriculture, domestic use, and energy production. Projections suggest that the UIB region will be affected by considerable (yet poorly quantified) changes to the seasonality and composition of runoff in the future, which are likely to have considerable impacts on these supplies. Given how directly and indirectly communities and ecosystems are dependent on these resources and the growing pressure on them due to ever-increasing demands, the impacts of climate change pose considerable adaptation challenges. The strong linkages between hydroclimate, cryosphere, water resources, and human activities within the UIB suggest that a multi- and inter-disciplinary research approach integrating the social and natural/environmental sciences is critical for successful adaptation to ongoing and future hydrological and climate change. Here we use a horizon scanning technique to identify the Top 100 questions related to the most pressing knowledge gaps and research priorities in social and natural sciences on climate change and water in the UIB. These questions are on the margins of current thinking and investigation and are clustered into 14 themes, covering three overarching topics of 'governance, policy, and sustainable solutions', 'socioeconomic processes and livelihoods', and 'integrated Earth System processes'. Raising awareness of these cutting-edge knowledge gaps and opportunities will hopefully encourage researchers, funding bodies, practitioners, and policy makers to address them.

1 Introduction

The Upper Indus Basin (UIB) is located in the mountainous Hindu-Kush Karakoram Himalaya (HKH) region and is drained by a transnational river system that includes both western (the Upper Indus, the Kabul, the Jhelum, and the Chenab) and eastern (the Ravi, the Beas, and the Satluj) rivers (see Figure 1). UIB water resources are highly seasonal as they are heavily reliant on runoff from snow and glacial melt during spring and summer, as well as summer monsoonal rainfall (Bookhagen and Burbank 2010; Lutz et al., 2014, 2016; Shrestha et al., 2015).

These rivers are of exceptional economic, social, cultural, and political importance to hundreds of millions of people across four riparian countries – Afghanistan, Pakistan, India, and China (Eriksson et al., 2009; Mukherji et al., 2019; Wester et al., 2019). The water resources of the UIB are used for agriculture, power generation, domestic use, industry, tourism, fishing, and religious practices, as well as supporting a rich diversity of terrestrial and aquatic ecosystems (Xu et al., 2019). They supply the world's largest contiguous irrigation system (Qureshi, 2011), and its numerous hydropower projects are crucial for reliable electricity supplies to downstream populations (Nie et al., 2021).

UIB populations live in both urban and rural areas and are challenged by endemic poverty and increasing vulnerability to social-ecological change (Gioli et al., 2019; Vinca et al., 2021). This vulnerability is driven, in large part, by a historic lack of effective water demand management. Policies and water management practice in the region have, so far, consistently emphasized increasing the supply of water to the various users, irrespective of the financial, social, or environmental costs. This has resulted in the UIB being particular vulnerable to water stress, which is likely to worsen in the future (Immerzeel et al., 2020; Smolenaars et al., 2021), with knock-on effects on the ecosystems and communities that depend on them. At the same time, global climate change is likely to result in considerable (yet poorly quantified) changes to the seasonality and composition of runoff in the future, which are likely to have considerable impacts on the regional hydrologic regime and water supplies (Immerzeel et al., 2013; Lutz et al., 2014, 2016; Krishnan et al., 2019; Sabin et al., 2020; Dahri et al., 2021a). Future alterations to hydrology – driven both by climate change and changing water management regimes - will in turn impact ecosystem conditions, water-induced hazards, hydropower generation, water resources management, agriculture, income generation, livelihoods, and migration, along with the overall socioeconomic development and politico-regulatory decisions of the riparian states (Wester et al., 2019).

These complex challenges call for radically revised policy responses informed by inter- and cross-disciplinary knowledge involving the social and natural/environmental sciences. Knowledge gaps pertaining to climate change and water in the UIB have been identified previously. For example, significant knowledge gaps for the HKH region related to climate change, sustainability, and people were identified by Wester et al. (2019), while Widmann et al. (2018) and Sabin et al. (2020) respectively identified knowledge gaps related to hydroclimatic services and climate change in the Indian Himalayas. However, given the strong linkages between climate, water resources, and human activities within the UIB, a comprehensive study identifying priority research questions related to the entire linked socioenvironmental system is necessary to achieve more effective and equitable resource management (Pederson, 2016; Vinca et al., 2021).

This study makes a beginning towards identifying what knowledge gaps need to be filled to enable this, which it achieves by bringing together experts in these key disciplines to identify the Top 100 questions related to climate change and water in the UIB. Our list of questions focuses deliberately on those on the margins of current thinking and investigation and takes particular cognizance of the fact that these research efforts must include joint involvement of the social and natural sciences and explore the relationship between these areas (Heberlein, 1998; Eriksson et al., 2009; Billi et al., 2019). The Top 100 questions are identified using a horizon scanning approach, which is a foresight technique used to detect emerging threats, opportunities, and risks, and to systematically identify pressing knowledge gaps. Our approach has previously been used to identify emerging issues or key knowledge gaps involving environmental change (Petty et al., 2010; Kennicutt et al., 2015; Sutherland et al., 2019). It is particularly relevant under conditions of complexity, uncertainty, and rapid change – and so, is ideal for use in relation to knowledge gaps related to climate change and water in the UIB.

The Top 100 questions are presented in sections 3, 4 and 5. Section 3 is focused on 'Governance, policy, and sustainable solutions' and contains questions (numbers 1 to 31) related to the themes of governance and innovation, geopolitics, water resources management, and adaptation. Section 4 is focused on 'Socioeconomic processes and livelihoods' and contains questions (32 to 58) related to the themes of socioeconomic processes and livelihoods, vulnerability and poverty, gender and social inclusion, agriculture, and natural hazards. Section 5 is focused on 'Integrated Earth System processes' and contains questions (59 to 100) related to the themes on hydroclimatology, cryosphere, hydrology, ecosystems, and data. Each set of questions is prefaced by text stressing the importance of the respective theme. Note that the ordering of sections, as well as the questions within each section, does not represent a value judgment on the importance or relevance of categories, themes, or questions. In addition, Section 2 describes the methods and Section 6 is a Discussion.

2 Methods

Our horizon scanning method is drawn from Sutherland et al. (2019), following adaptations made by Foulds et al. (2020) and Bharucha et al. (2021). The Horizon Scanning exercise was largely facilitated by a multidisciplinary Working Group (WG) of 38 experts and coordinated by a smaller Steering Group (SG) of 12. The SG selected WG members from their scholarly networks, facilitated expert deliberation and led on the editing and categorization of the questions received.

Following Foulds et al. (2020), the composition of both the SG and WG were carefully considered to ensure diversity in gender, geographic location, disciplinary affiliation, and seniority. The resulting group of experts includes representation from the four riparian countries India (11 participants), Pakistan (9), Afghanistan (2), and China (2). The remaining 26 experts are located in a further nine countries based globally, but with recognized expertise and background in the topics we considered. Of the 50 participants involved in this study, 19 (38%) identify as female and 31 (62%) as male, 9 (18%) are so-called 'frontrunners' who are pushing forward the boundaries of their field and 41 (82%) are 'gatekeepers' who have established track records within their field, while 29 (58%) are affiliated with various social science disciplines and 21 (42%) in the disciplines of science, technology, engineering, and mathematics (see Figure 2).

The list of 100 questions was arrived at through a four-stage process:

Firstly, all members of the WG and SG were asked to canvas their professional networks by circulating an email containing a link to a short online survey, asking respondents to nominate the top 3-5 research questions related to the impact of climate variability and change on water resources in the UIB. Respondents were asked to consider the following criteria for 'good' research questions: i) answerable through a realistic research design by an individual researcher or a team/programme, ii) capable of a 'factual' answer, iii) novel and not already been answered, and iv) not answerable by a simple yes or no. Following Foulds et al. (2020), the respondents were additionally asked to provide some brief text justifying the importance/relevance of each suggested research question.

This resulted in a total of 688 questions received, which were subsequently edited down by the SG to 249 questions after duplicate or overlapping questions were merged and unsuitable or non-convincing questions (i.e., those not corresponding to the criteria above) were removed. As we sought to identify cutting edge research questions, we de-prioritized questions pertaining to longstanding and well-established research topics or approaches. The edited list of 249 questions were then categorized by the SG into the following 14 themes: governance and innovation, geopolitics, water resources management, adaptation, socioeconomic processes and livelihoods, vulnerability and poverty, gender and social inclusion, agriculture, natural hazards, hydroclimatology, cryosphere, hydrology, ecosystems, and data. These themes were selected on the basis of the questions received (i.e., we did not make any *a priori* judgement on which themes would be relevant).

Following Foulds et al. (2020), the WG and SG members then used their expert judgement to sort the 249 responses in terms of importance. This was done using voting software online where each question was awarded a score of between 1 (i.e., definitely exclude from the final list of questions) and 5 (i.e., definitely include in the final list of questions). Each of the WG and SG members voted on all of the 249 questions, even though clearly some of the questions were outside their area of expertise. The justification text for each of the 249 responses was included in order to help with the voting. Questions were automatically rejected if they had a median score of less than 3.

Next, the WG members were subsequently invited to form small expert groups for each theme. Each sub-group was facilitated by one member of the SG, with a preference that their expertise matched that of the theme. These sub-groups were tasked with reviewing the questions for their respective themes and recommending which should be selected and which should be rejected, as well as whether any additional questions should be added, based on their expert judgement and experience. This stage was done using videoconferencing with follow up input via email. This resulted in reducing the 249 questions down to 149 questions.

Finally, the SG reviewed the list of 149 questions to decide which should be deleted to reach 100. The main consideration at this stage was to ensure that the composition of the final 100 questions should address a balance between the different themes, i.e., address a breadth of important topics that will be important for research, policy, and practice in climate and water resources in the UIB. At this stage, an additional two themes were added on governance and innovation, and vulnerability and poverty, which took the total number of themes to 14. The WG then subsequently reviewed the list of 100 final questions, which included further opportunities for rewording them, and signed them off.

3 Governance, policy, and sustainable solutions

The hydrology of the UIB is deeply impacted by and in turn impacts human society. From developmental visions incorporating dams, hydroelectricity, roads, urbanization, livelihoods, and agriculture, to hazards driven by climate change, as well as conflict over and through water. The UIB is in fact co-constituted by the interactions of social and physical factors of concern for us. In this section we attempt to capture the socio-political mosaic overlaying the UIB through the themes of governance and innovation, geopolitics, water resources management, and adaption.

3.1 Governance and innovation

The UIB has significant traditions of innovative hydroclimatic governance (e.g., Kreutzmann, 2000). In addition, supporting resilience, in particular through local-scale governance and innovation, is an organizing objective/principle for much of the development/NGO (non-governmental organization) activity, with a focus on agricultural adaptation and diversification of livelihoods (Nüsser et al., 2019a). Identifying the potential of information sharing, digital connectivity, and diffusion of innovations for risk reduction and response to hydroclimatic change in the UIB is of particular importance. The capacities of local governments, community-based institutions, and grassroots organizations to respond to this threat requires attention from policy makers and development practitioners, with the potential for creating or seizing opportunities in water, climate, and resilience planning (Jiwa, 2021).

Decision-making and governance in the UIB suffer from a lack of transboundary initiatives and cooperation, such as the Upper Indus Basin Network (Shrestha et al., 2021), as a result of geopolitical constraints (see section 3.2). Decision-making and governance are also deeply biased towards dominant scientific/market-driven frameworks, often resulting in the marginalization or erasure of local innovation and epistemologies. The prevalence of technological fixes also ignores how climate change transformations in the UIB remain embedded within historic relationships of power (Nightingale et al., 2020). While local knowledge and external development interventions need to be integrated towards sustainable pathways beyond one-fit all technofixes in the UIB, context-specific water governance structures are crucial for the implementation of innovative, effective, and socially accepted climate adaptation measures. The questions listed below focus on these issues.

1. How can we adapt and scale up socioeconomic development innovations and lessons of grassroot organizations across the riparian countries of the UIB?

2. What innovative water governance structures can promote climate adaptation and resilience in the UIB?

3. How can the capacity of local governments and communities be enhanced to address climate-sensitive vulnerabilities in the UIB?

4. What local governance structures and institutions are involved in (local) water management in the UIB and how are they evolving?

5. What changes are necessary to make the current water policy instruments more effective in mitigating climate change in the UIB?

6. How can infrastructure development contribute to local and regional scales of poverty alleviation and vulnerability reduction in the UIB?

3.2 Geopolitics

The UIB straddles some of the most highly militarized geopolitical fault lines in the world. With the militarized Kashmir region, along with the India-China border, the importance of paying attention to international conflict and varying geopolitical visions between the state and non-state actors cannot be over emphasized (Baghel and Nüsser, 2015). The recent Taliban victory in Afghanistan, however, ensures that in the absence of international financing for any major water infrastructure in the Kabul River basin, and Taliban's close relationship with Pakistan, water conflict is unlikely to be on the agenda across the Pakistan-Afghanistan border. Water distribution and hazards are also increasingly being viewed in a geopolitical register, especially between India and Pakistan and more recently between China and India (Mustafa, 2007). The key questions listed below were guided by the principle that while it is important to tap into neo-realist geopolitics premised upon physical geography, it is also contingent to recognize the national scale, sub-national scale and non-state actors and discursive constructs on national security, climate change, resilience and human security that inform the actions of state and non-state actors across spatial scales (Mustafa, 2021).

With climate change present and already impacting lives, livelihoods, and ecologies in the UIB it is imperative to seek out ways of negotiating international and sub-national water conflict, in addition to undertaking diagnostics of what developmental visions and geopolitical discourses drive those conflicts. Accordingly, the key questions listed below are attentive to recent developments such as China's 'One Belt, One Road' initiative, China-Pakistan Economic Corridor (CPEC), legacy frameworks like the Indus Waters Treaty (IWT) signed in 1960, and pathways to exploring more cooperative frameworks for negotiating climate change (Qamar et al., 2019).

7. Who are the potential (state and non-state) actors responsible for water resources planning and implementing cross-country climate adaptation measures in the UIB?

8. What are the impacts of investments via the 'One Belt, One Road' initiative on the vulnerability of the UIB to climate change?

9. How do international tensions and conflicts affect the feasibility of climate change adaptation strategies in the UIB?

10. How are climate-related security risks (economic, ecological, social) in the riparian countries of the UIB understood and addressed by governments/key stakeholders in the region?

11. What will be the economic, ecological, and social costs of regional non-cooperation and the benefits of cooperation among the UIB countries in the face of climate change?

12. How will climate change affect the water use allocations under the IWT?

13. What is the potential for the UIB riparian states to consider a cooperative framework addressing the impact of climate change on the basin?

3.3 Water resources management

The physical, social, and political geography of the UIB is marked by uneven distribution of water resources. These are stored naturally in streams, rivers, lakes, wetlands, and aquifers, as well as artificially using dams. However, weak management of increasing water demand coming from socioeconomic changes at both national and transnational level exacerbates water resources vulnerability, e.g., resulting in overexploitation of groundwater (Zhu et al., 2021). The focus is often on increasing supplies irrespective of the financial, social, or environmental costs, rather than sustainable water resources management. Sustainable water resources management requires a willingness to do what is needed and knowledge of the multiple institutional, political, and social complexities of the UIB, as well as the relevant natural/environmental sciences and technological issues. Just how well we are able to plan and manage our water quantity, quality, and accessibility is a major determinant for the healthy functioning and resilience of ecosystems, the strength of economies, and the vitality of societies in the UIB (Loucks and Beek, 2017).

Identification and evaluation of alternative water management strategies in the UIB is crucial to sustainably manage its water resources. These alternative measures need to consider the requirements of the multiple water users in the basin and should explore ways to enhance water storage (to ensure water resources are available during the dry season and/or droughts, which may alter due to climate change), improve the efficiency in current water use and allocation, increase wastewater recycling and reuse, and support the sustainable development of water infrastructure such as hydropower installations (Qureshi, 2011; Pritchard, 2019). Both traditional and modern knowledge needs to be explored to identify pathways that integrate water quantity and quality management to create new livelihood opportunities, enhance water security, and support healthy ecosystems (and associated ecosystem services). The UIB is already considered one of the most water stressed water towers in the world (Pritchard, 2019; Immerzeel et al., 2020). The gap between the supply and demand of water for various uses may worsen with socioeconomic and climate change (Smolenaars et al., 2021). With this perspective, some key questions focused on identification of water management practices for the UIB, for now and in the future, are highlighted here.

14. What are the main water management narratives across the UIB, how have these vested interests been used to accrue benefits, and what has been the impact on current water management challenges, including building climate change resilience?

15. What are the available indigenous water management strategies in UIB and how could they be used to improve water management and adaptation to climate change?

16. How effectively has the concept of water stewardship been used in the UIB for agricultural, industrial, and domestic water use and can this concept be used for enhancing adaptation and climate resilience?

17. What are the existing and projected gaps between water supply and demand in the UIB across the various human and environmental water users at both state and sub-basin level?

18. What are the surface-groundwater flow relationships in regions where water infrastructure has been established or planned in the UIB, and what is the potential of this to improve water security?

19. What is the effect of increasing use of wastewater and brackish groundwater for irrigation on the hydrological regime of the UIB, and how do resultant changes alter local and basin scale water availability?

20. What possibility is there for decentralized water supply, irrigation, and sanitation systems in rural and urban areas to advance the transition to a more resource-efficient and circular economy in the UIB?

21. What role can nature-based solutions play in water management and ecosystem conservation in the UIB?

22. How can the various water storage opportunities in the UIB be utilized to achieve sustainable development goals related to water-energy-food security and climate and disaster resilience?

23. How can water management provide opportunities for livelihoods in the UIB, such as eco-tourism and upscaling production of high value indigenous crops?

24. How will hydropower and water infrastructure expansion in the UIB affect the water and land resources available to local communities and ecosystems and alter downstream water availability?

25. How can the water-energy-food-environment linkages across the riparian states in the UIB provide opportunities for transboundary cooperation at both national and provincial level?

3.4 Adaptation

The impacts of climate change in UIB on hydrological systems are having grave implications for water availability, agricultural yields, hydroelectric power generation and ecosystem services (Zhang et al., 2007; Garee et al., 2017; Smolenaars et al., 2021). In addition, the adverse effects of extreme weather events (see section 4.4) on the life, assets, and livelihood of communities in the region are also coming to fore (Mishra et al., 2019; Shrestha et al., 2021).

Instances of adaptation responses – both autonomous and planned – abound in the UIB. Locally adopted autonomous adaption measures find their origin in community networks, indigenous knowledge, collective action, and innovation facilitated by local people and grassroots institutions. In comparison, government-initiated planned adaptation responses at national and sub-national levels are implemented through specific policies, programmes, and projects (Mishra et al., 2019). In the Hunza-Nagar, Soan and Chaj Doab basins located in the Pakistan region of the UIB, crop diversification (towards nuts, vegetables, sugarcane, medicinal plants, etc.), change in timing of sowing, inter-cropping, and reliance on modern irrigation techniques (such as drip, sprinkler, and furrow irrigation) have increased. Farmers have also started cultivating high yielding varieties and drought resilient crop types, with greater reliance on herbicides, fertilizers, and modern agricultural practices. Switch to alternative occupations, such as handicraft manufacturing and tourism, are also being relied upon as adaptation mechanisms (Abbasi et al., 2017).

Similar adaptation responses in agriculture and transitioning to alternative occupations (such as tourism and services) can also be observed in India's Ladakh region of the UIB. With agriculture dependent on irrigation in this region (Nüsser et al., 2012; Barrett and Bosak, 2018), seasonal water deficiency has led to villagers to evolve four types of artificial ice reservoirs: basins, cascades, diversions, and ice stupas. The ice reservoirs permit water storage during the autumn and winter seasons, which freezes and is held until spring, when it melts and flows down to the agricultural fields (Clouse et al., 2017; Nüsser et al., 2019b). Dry conditions in the Chinese region of the UIB have induced farmers to select crop varieties that can adapt to water stress and yield better prices. In addition, farmers are keen to invest in improved irrigation and water-saving technologies to cope better in the face of increasing water scarcity due to climate change (Wang et al., 2010).

Even through there is an urgent need to adapt to climate change, the prevailing level of knowledge and understanding of adaptation needs and interventions in the UIB remain limited, especially for the mountain communities. This is compounded by socioeconomic challenges (see section 3.2) of a large and burgeoning population and urgent need for transboundary cooperation due to shared river basins of the countries in the region (Wada et al., 2019; Shrestha et al., 2021; Vinca et al., 2021). Considering these, the following research questions gain prominence.

26. What measures are being taken in terms of climate-adaptive infrastructure and capacity building for the UIB communities so they can protect the environment and ecosystem as well as livelihoods of the mountain areas?

27. How can the water-energy-food-climate nexus framework help identify future adaptation pathways, especially for better water resources governance, energy security, sustainable food production and ecosystems management (including protection of aquatic species) in the UIB and downstream areas?

28. How do individual riparian states in the UIB address hydroclimatic adaptation and governance and have any common principles, approaches or metrics emerged that could support shared regional adaptation mechanisms?

29. How are Indigenous and local knowledge in the UIB incorporated in adaptation policies and plans, and how best can we ensure an inclusive, intersectional development approach through community participation?

30. How are policymakers implicitly or explicitly adapting their agendas (especially in the provisioning of sector-specific infrastructure) for climate change adaptation in the UIB and to what extent are the resulting policies actually being implemented?

31. What is the local people's perception of climate change in the UIB, including its impact and their ability to adapt?

4 Socioeconomic processes and livelihoods

The UIB has undergone major socioeconomic transformations in recent decades with respect to land use change, cropping systems, digital and physical connectivity and access to markets, urbanization, demographic shifts, and human mobility along with glacio-hydrological changes. Multiple transitions are affecting socio-hydrological interactions that are context specific and require plural and place-based perspectives (Nüsser et al., 2012; Chakraborty et al., 2021). Recognition of the relationships between socioeconomic development and climate change point to a need for a better understanding of the ways in which water resources are the target of national sustainable development plans.

Ongoing shifts are underway from mountain livelihoods based on agro-pastoral subsistence to multi-local livelihood diversification strategies that integrate on-farm and off-farm activities (Kreutzmann, 2006; Yi et al., 2007; Mukherji et al., 2019)**.** The shift to high-value horticultural crops and livestock products has also been facilitated by other factors, such as improved road networks providing market access for previously isolated communities, growth of remittance inflows, expansion of cooperatives, increased presence of NGOs, and targeted government activities (Dame and Nüsser, 2011; Jiwa, 2021).

32. How will socioeconomic well-being and resource demands in rural and urban areas of the UIB be affected by hydroclimatic changes?

33. How will hydroclimatic changes impact the dynamic of social power and irrigation water control in the UIB, particularly considering the equity and efficiency issues among the irrigation water user's communities?

34. How can increased human connectivity (both digital and physical) enhance the resilience to climate change of remote UIB communities?

35. How important are migration (both internal and external) and remittances for adapting to climate change and building climate-resilient futures for the UIB communities?

36. How can climate-smart tourism (or other nature-based livelihood options) that shares the benefits with the local communities in UIB become a more sustainable socioeconomic and cultural strategy?

37. How are the spatial patterns and settlement processes of communities vulnerable to climate risks changing in the UIB (e.g., in socioeconomic functions, income distribution, spatial distribution, morphology, connectivity, and resource dependence)?

38. How will livelihood opportunities evolve in the UIB due to changes in infrastructure development (roads, water supply, hydropower, irrigation canals) and distribution of natural resources?

39. What are the potentials and opportunities for and challenges to green and inclusive farm and non-farm enterprises and sustainable development in the UIB?

4.1 Vulnerability and poverty

The complexity of environmental and socioeconomic aspects of mountain development shapes development pathways (Nüsser et al., 2012). Within the UIB, historic concerns of economic marginalization, poverty, inequality, and human mobilities influence current and future plans for sustainable development. The Sendai Framework for Disaster Risk Reduction (SFDRR) synergizes risk reduction efforts with sustainable development goals (SDGs) and the post-2015 climate change agreement under the United Nations Framework Convention on Climate Change (UNFCCC). Strong parallels can be found between the SDGs and SFDRR with respect to creating resilient infrastructure (Ray et al., 2021). To meet these integrated challenges, we need to understand historical evolution and spatial patterns and bases of poverty and inequality in the UIB, vulnerability to climate change, and vulnerability trends (Fraser et al., 2011). The assessment of resilience provides insights into complex interdependencies and drivers of it (Schlüter and Herrfahrdt-Pähle, 2011), which needs to be attentive to how various aspects of identity (wealth, religion, caste, class, ethnicity, and gender) intersect to produce conditions of both resilience and vulnerability and result in vastly different experiences of hydroclimatic change.

40. How can the socioeconomic priorities of poverty alleviation and vulnerability mitigation be addressed in an uncertain hydroclimatic future in the UIB?

41. What are the most pressing climate-sensitive health-related vulnerabilities for mountain communities in the UIB?

42. How do climate and water related disasters impact communities in the UIB (e.g., wellbeing, loss of livelihoods, economic and social stability, agricultural land, and resettlement etc.) and what are the implications of these impacts for short- and long-term adaptation?

4.2 Gender and social inclusion

UIB communities have socio-cultural constructs that define disparate leadership roles and management responsibilities divided along gender lines (Abbasi et al., 2019). Over time, the ingrained societal inequalities among traditionally marginalized social groups such as women, Indigenous people, and ethnic and sexual minorities have severely undermined their livelihood and landholding prospects, access to knowledge, and participation in decision-making (Arora-Jonsson, 2011). The drivers of such inequalities vary locally within the UIB but are collectively caused by a lack of access to adequate education and knowledge resources, lack of independence, lack of authoritative power or decision-making position, and lack of mobility (for either education or livelihood) among the marginalized social groups (Gioli et al., 2014).

Below are the key socio-cultural and politico-economic questions associated with social inequalities, inclusive roles, and decision-making power among these social groups in the UIB. Social inclusion through the involvement of women and ethnic minorities is crucial for adequate maintenance, allocation, and use of shared water resources. To prioritize inclusion, we need to ensure arrangements through appropriate training programs to generate a sense of responsibility and ownership among this vulnerable group. Additionally, legal access to land and water for women-headed households and other minorities will ensure a more inclusive approach to water resources and management. It is imperative to allow and safeguard modifications in the existing regulatory and governance response towards gender sensitivity in the UIB to address the climate-related water scarcity and to formulate inclusive, transparent, assured, and effective policy implementations.

43. What specific policies are required to ensure involvement of socially marginalized groups in the decision-making processes to address the climate crisis and growing water challenges in the UIB?

44. What are the major drawbacks of the regulatory and governance responses towards social inclusion in the context of climate-related water scarcity in the UIB?

45. How does the level and quality of participation of socially marginalized groups in the UIB vary in the development and implementation of the climate change agenda?

46. How do water scarcity and related policy interventions affect people from different gender, class, and backgrounds and what are the specific exclusions and barriers faced by women, girls, and people from other backgrounds in overcoming these impacts and participating in policy formulation and implementation?

47. How are socially inclusive knowledge systems contributing to building adaptive capacity and resilience in the face of water and climate stress in the UIB, and what roles are they anticipated to play in the future?

4.3 Agriculture

In the UIB, farmers are mainly smallholders with an average landholding size of 0.63 hectares (Hussain et al. 2016). Agriculture and livestock rearing by UIB farmers contributes around 30-40% to annual food requirements of the local people (Hussain et al., 2021). Over time, the contribution of these two sub-sectors in local food requirement is gradually declining, and dependency on external food items is increasing (Kreutzmann 2000; Rasul et al., 2016). These two sub-sectors also partially or significantly contribute to the income and livelihoods of more than 80% households in the UIB. However, they are primary income source for only 10% households (Hussain et al., 2016). Among several challenges to agriculture and food systems in the UIB are climate change, loss of agrobiodiversity, deterioration of traditional irrigation systems, declining dietary diversity, a gradual shift from organic farming to additional input of industrial fertilizer, and declining interest of economically active population in farming. These changes are not only resulting in the declining contribution of agriculture and livestock in local food requirements and income but also impacting the sustainability of food systems (Hussain and Qamar, 2020).

There is a need to better understand the impacts of climate change on agriculture and livestock rearing (including pastoralism and agro-pastoralism) as well as the impacts of socioeconomic changes such declining youth participation in farming, outmigration, labour shortages. Changes in local food habits are also impacting farmers decisions on diversity and types of crops and livestock (Dame and Nüsser, 2011; Rasul et al., 2019; Hussain et al., 2021). It is also important to further explore the impacts of a shift from organic to inorganic farming and declining agro-biodiversity (diverse to monoculture) on water use in food systems of the UIB, provided the traditional irrigation systems fed by glaciers and snow-melt water (locally called as *kuhl* or *gole*) and springs are gradually degrading due to various climatic and non-climatic factors. In this regard, it is also important to explore how the traditional irrigation systems can be revived and better managed for improving land and water productivity in the UIB (Nüsser et al, 2019a).

48. What will be the impact of climate change and associated socioeconomic changes on agricultural productivity (including livestock, agropastoralism, aquaculture, and horticulture), highland pastures and overall food security in the UIB?

49. How are the diverse changes in agriculture practices across the UIB impacting the spatial variation in agricultural water availability and use?

50. How can irrigation, including irrigation from glacial melt springs, be managed (with reference to Indigenous knowledge and local knowledge) to enhance land and water productivity for crops in the UIB in response to climate change?

51. What climate-resilient agriculture practices in the UIB are suitable for small farmers and can these be used to support a sustainable transition from traditional practices?

4.4 Natural Hazards

Natural hazards have catastrophic impacts across the UIB, including loss of human life and livestock, and damage to settlements and farmlands, infrastructure, and ecosystems. Their impact is significantly exacerbated by socioeconomic factors such as poverty and lack of adaptive capacity/preparedness (Vaidya et al., 2019) and historic inequalities in access to resources and engagement with decision making. These hazards are partly of hydrometeorological nature, including: i) floods and/or flash-floods due to localised extreme rainfall rapidly filling steep narrow valleys and rivulets (Thayyen et al., 2013; Dimri et al., 2017), ii) landslides on steep terrain triggered by heavy rainfall weakening the anchorage of soil and rock (Hunt and Dimri, 2021), and iii) snow avalanches on steep terrain triggered by warmer temperatures or heavy snowfall. Glacial lake outburst flood events (involving the abrupt release of huge amounts of water stored in glacial lakes), rockfalls triggered by permafrost thaw, and glacier debuttressing pose additional catastrophic hazards for the UIB (Kääb et al., 2005; Abbas Gilany et al., 2020; Mal et al., 2021). Additionally, many glaciers in the Karakoram region are susceptible to periodic surging (Quincey et al, 2011, 2015), often creating localised hazards (e.g., Bhambri et al, 2020).

The frequency and magnitude of hydrometeorological hazards in the UIB are likely to increase in the future as climatic change results in extreme rainfall increases, warmer temperatures, and precipitation falling more often as rain rather than snow at high elevations (Pandey et al., 2015). Glacial lake outburst events and associated hazards are also likely to increase as additional glacial lakes form due to climate change induced glacial retreat (Veh et al., 2020; Furian et al., 2021; Zheng et al., 2021). The vulnerability to natural hazards is also impacted by societal changes, such as population and resettlement changes possibly resulting in increased numbers living in vulnerable regions, but these hazard increases can often be mitigated through planning and management adaptations (Schmidt et al., 2020). The questions here focus on improving our regional understanding of the vulnerability of the UIB to natural hazards, which is necessary to help quantify the risks, as well as deal better with the impacts and build resilience.

52. Which economic sectors, industries, and large infrastructures in the UIB are most impacted by hydrometeorological and cryosphere-related hazards?

53. How does vulnerability to hydrometeorological and cryosphere-related hazards vary across the UIB and how might this change due to climate and socioeconomic changes?

54. What are the frequency and magnitude of hydrometeorological hazards in the UIB, and how will this be affected by climate change?

55. How might climate change affect the frequency and magnitude of glacial lake outburst flood events in the UIB under different climate change scenarios, and what are the impacts on community assets and livelihoods in vulnerable regions?

56. To what degree will glacier surging in the UIB be affected by climate change in the coming decades, and does this increase or decrease surge-related hazards to communities?

57. How (and where) might climate change affect slope stability, frequency and intensity of landslides, debris flows, and rockfalls in the UIB?

58. Where can effective early warning systems (EWS) be developed with community knowledge and scientific basis to efficiently save lives and infrastructure in the UIB?

5 Integrated Earth System processes

The physical processes of the UIB form a complex Earth System that involves several diverse but interacting components, including the hydroclimate, cryosphere, hydrology, and ecosystem. Spatio-temporal variations in air temperature, precipitation, snowmelt, glacial-melt, and runoff induced by climate change in the UIB region determines future alterations in hydrology, which in turn influence the terrestrial and aquatic ecosystem components.

5.1 Hydroclimatology

The precipitation regime in the UIB is dominated by large-scale circulation patterns associated with both winter westerly disturbances and the summer monsoon (Bookhagen and Burbank, 2010, Dimri et al., 2015; Forsythe et al., 2017; Krishnan et al., 2019). The westerly disturbances are primarily responsible for the renewal of the snowpack each winter, and the UIB is unique in the HKH in that the major contribution to runoff comes from snow and glacier meltwater (Lutz et al., 2014; Shrestha et al., 2015). The region is also characterized by pronounced local-scale variations of snow and rain due to strong orographic forcing (Bookhagen and Burbank, 2010; Baudouin et al., 2020). For example, precipitation is thought to be five to ten times higher above 5000 m asl. than in the valleys (Duan et al., 2015; Immerzeel et al., 2015). The warming signal is also elevationally dependent, with stronger warming at higher elevations (Pepin et al., 2015). Knowledge of how present-day climate change is affecting frozen water reserves (attributed to elevation dependent warming temperatures) and precipitation has increased in recent years, however the complexities of different synoptic influences and considerable small-scale variation in climate variables mean there are still gaps in the understanding of present-day climate variability, trends, and extremes (Fowler and Archer, 2006; Bannister et al., 2019; Sabin et al., 2020). This is partly because a profound lack of in-situ hydrometeorological data, particularly at high elevation, considerably hinders attempts to assess spatial variability and trends at the local scale (Archer and Fowler, 2004; Fowler and Archer, 2006; Krishnan et al., 2019).

Climate projections in mountainous terrain, including the UIB, have various uncertainties (Lutz et al., 2016). Despite large uncertainties, projections suggest that accelerated melting of snow and glacial reserves in the UIB will result in increased river discharge in the coming decades, with this contribution not peaking until at least 2050 (Lutz et al., 2014, 2016; Nie et al., 2021), contrasting with local trends in runoff (Sharif et al. 2013). However, considerable uncertainty regarding future water resources remains due to the possible impacts of climate change on monsoon and westerly disturbance patterns and consequently precipitation trends (Immerzeel et al., 2013, Krishnan et al., 2019; Hunt et al., 2019; Sabin et al., 2020). The impact of climate change on precipitation extremes and droughts is particularly uncertain (Wijngaard et al., 2017; Hunt et al., 2019; Krishnan et al., 2019). Reducing uncertainty in future projections is constrained by several factors, including limitations in the climate models (Sanjay et al., 2017), the large sensitivity to greenhouse gas emission scenarios (Immerzeel et al., 2013), the poor representation of land-surface to atmosphere interactions (Pritchard et al., 2019), as well as limited understanding of the influence of anthropogenic aerosols (Sanap and Pandithurai, 2015) and global teleconnections such as El Nino – Southern Oscillation (ENSO) (Archer and Fowler, 2004). The questions on hydroclimatology included here reflect some of the most pressing questions related to these aspects.

59. What are the key characteristics of local and regional-scale weather and climate in the UIB (e.g., precipitation, its phase, and its spatial variation) and how well is this captured by the current observational network and climate models?

60. What is the potential to narrow uncertainties in projected changes of precipitation and temperature in the UIB over the twenty-first century?

61. What are the impacts of anthropogenic aerosols (such as black carbon) on the regional and large-scale circulation patterns that affect the climate of the UIB, such as winter westerly disturbances and the summer monsoon?

62. What are the relationships between tropical (and extra-tropical) drivers such as ENSO and precipitation/temperature over the UIB and how are these likely to change in the future?

63. How will future climate change affect the spatial and temporal dynamics of the monsoon and the monsoonal incursions into the mountain regions of the UIB, and how will these changes affect the large-scale and local-scale hydroclimate?

64. How will climate change affect UIB wintertime precipitation from western disturbances, in terms of both normal and exceptional conditions?

65. How will climate change affect the frequency and intensity of extremes in the UIB, such as heat waves, cold waves, and heavy precipitation events?

66. What are the possible mechanisms of the propagation from meteorological drought to hydrological drought in the UIB?

5.2 Cryosphere

Changing climate and a continued lack of demand management across the UIB have raised crucial concerns for the discordant future of cryosphere reserves, downstream communities' access to meltwater, downstream river flow, and sediment flux in the UIB (Kraaijenbrink et al., 2017, 2021; Ashraf and Ahmad, 2021). The present and predicted glacier retreat suggests major fluctuations in the overall hydrological regime, and subsequent water availability (Hasson, 2016; Huss and Hock, 2018).

It is thus imperative to discern the present, near-future, and long-term future relevance of cryosphere changes in the pattern and distribution of hydrometeorological conditions, snow cover, depth, and snow water equivalent at the watershed level, to accurately predict snow and glacier-melt runoff, and accordingly plan and support water management and adaptation strategies (Romshoo et al., 2015). Predicting climate change and associated glacier melt requires a comprehensive understanding of hydrological and climate models (Immerzeel et al., 2010; Lutz et al., 2014). Recent observational studies have shown that the rate of glacier retreat is accelerating, particularly the recession of glacier snouts and mass (Hugonnet et al., 2021). However, in the central Karakoram, comprising the highest reaches of the UIB, the balanced or even positive mass budgets of many glaciers contradicts this, indicating a divergent response to climate change for the past several decades (Romshoo et al., 2015; Bolch et al., 2017; Berthier and Brun, 2019; Farinotti et al., 2020). Therefore, improved quality and access to physical data (glaciological, hydrological, meteorological) can help strengthen our ability to model the cryosphere. The questions here focus on research that is necessary to improve/enhance our understanding of the UIB cryosphere.

67. How has UIB glacier behaviour (e.g., in terms of mass balance, velocity, and surging) changed in recent decades and how will it change in the coming decades, and how do these changes impact downstream river flows and sediment fluxes?

68. What are the spatial and temporal variations in snow cover, depth, and snow water equivalent in the UIB?

69. How sensitive are glacier mass balance rates and mass balance changes across the UIB to greenhouse gas emission scenarios?

70. What is the impact of air pollution (e.g., black carbon) on glacier and snow melt in the UIB, and to what degree will distinct emission scenarios affect the deposition of melt-enhancing particles on the basin's glaciers?

71. Which processes are the most important and least constrained in available glacio-hydrological models of the UIB, and what additional measurements are needed to reduce uncertainties?

72. How will climate change impact the formation, expansion, drainage, and hazard susceptibility of the glacial lakes in the UIB and the downstream water resources they support and how will these processes affect current trajectories of hydropower and infrastructure development?

73. How will the Karakoram Anomaly impact future projections of glaciers, snow cover, and water resources in the UIB?

74. What is the distribution of permafrost in the UIB and what will be the (hydrologic, geomorphic, geochemical, ecosystem) impacts of climatic warming on permafrost melting?

5.3 Hydrology

Across the UIB, our understanding of the key hydrological fluxes and storages is limited (Qazi et al., 2020). As a result, exploring the interactions between different parts of the hydrological cycle is central to many of the questions identified in this section. Climatically driven changes in the cryosphere, for example, have a direct impact on the magnitude and timing of runoff, impacting both water resources and risks associated with extreme events (Lutz et al, 2016; Nie et al., 2021). However, a lack of observational hydrometeorological information, particularly at high altitudes, and the need for further research into the complex feedback mechanisms between different processes mean that our ability to model and project how the UIB's hydrology may change in the near and far future is constrained (Momblanch et al., 2019a; Widmann et al., 2018).

Human interactions with the hydrological cycle vary significantly across the UIB. Naturally, these interactions are also subject to change over time. Urban migration, for example, can drive agricultural land degradation in rural mountainous areas, changing the way springs, field runoff and local water storages are managed, which ultimately impacts water availability. Many dams and barrages are proposed in national plans to support hydropower production and irrigation; materialization of these infrastructures will alter the timing and quality of river flows. When coupled with uncertainties around water availability as a result of the changing climate, such alterations in land and water use practices present complex questions around the response of hydrological systems to anthropogenic stressors.

Hydrological changes in the UIB have significant implications for both the mountain ecosystems and livelihoods within the upper basin as well as downstream areas, impacting both the quantity, timing, and quality of water available for anthropogenic and environmental needs. Questions on water management are included in another section (3.3) while the questions here focus on the advances necessary in our understanding of hydrological processes and their modelling.

75. How is the seasonality, partitioning and variability of stream flow and stream temperature in the UIB responding to climate change?

76. What are the tipping points for hydrological changes in the UIB?

77. What can paleo-climatic and hydrological proxies tell us about the frequency and intensity of past hydroclimatic events in the UIB?

78. How are hydroclimatic extremes (floods and droughts) expected to change over the UIB in the future?

79. How will spatio-temporal patterns of groundwater availability in the UIB be impacted by changes in precipitation and the cryosphere, and will this mitigate or exacerbate water scarcity?

80. How much of the observed spatio-temporal changes in springs in the UIB are driven by climatic and non-climatic changes and how are these impacting the importance of springs as water resource in different parts of the UIB?

81. How do changes in upstream hydrology and catchment connectivity in the UIB affect the spatial/temporal patterns of downstream water availability, both in the present and future?

82. How can we better understand and model the complex interactions between climatic and non-climatic drivers (e.g., land cover, population change) that alter the hydrological response of the UIB?

83. How do hydroclimatic, biological, geochemical, and socioeconomic processes interacted to impact water quality in the UIB and how could this change in the future?

84. How can socio-hydrological studies be used to improve the understanding of interactions between hydrological changes and their implications in the UIB?

85. What advances are necessary in integrated data, process-based, and/or system-based modelling approaches to improve quantification of key hydrological processes in the UIB and to minimize uncertainty under current and future climate, land use and socioeconomic scenarios?

5.4 Ecosystems

Owing to the large variability in topographic, meteorological, and geological conditions, the UIB holds very diverse and unique ecosystems that support well-being in its multiple dimensions, both locally and in hydrologically connected downstream regions (Xu et al., 2019; Momblanch et al., 2020). Freshwater ecosystems in the UIB evolve from glacial lakes and alpine rivers at high elevations to lowland rivers and wetlands at mountain foothills. These factors are known to generate drastic variations in biodiversity, metabolic performance, nutrient uptake and, thereby, the services ecosystems provide (Peralta-Maraver et al., 2021). Those ecosystems sustain iconic and endangered species of flora and fauna which play a key role for biodiversity in the region such as the snow leopard (Khan and Baig, 2020) and the Indus River Dolphin (Braulik et al., 2015).

Variations in temperature, flow regimes, and sediment loads caused by climate change are known to alter freshwater ecosystems energetics, which cascade into metabolic changes and food web dynamics (Kraemer et al., 2017; Bernhardt et al., 2018), modifying biodiversity and ecosystem functions. However, little is known about remote UIB ecosystems in terms of their structure, current status, and sensitivity to climatic factors which hinders our ability to understand their future evolution and, thus, develop protection and conservation interventions. These key research gaps are summarised in the questions below.

86. What is the current state of terrestrial and freshwater ecosystems in the UIB?

87. What are the impacts of current and future developments and interventions in the headwaters of UIB on ecosystems?

88. What are the impacts of re-vegetation on water availability and ecosystems in the UIB?

89. What are the impacts of transient glacial meltwater inputs on the glacier lake ecosystems in the UIB?

90. What should be the key priorities and strategies for conservation of iconic species, habitats, and ecosystems in the UIB?

91. What are the key drivers of change (physical and social factors) that impact ecosystems, habitats, and biodiversity in the UIB?

92. How does biodiversity and natural resource conservation contribute to building climate resilience in UIB?

93. What is the ecological status and condition of forests in the UIB (e.g., species diversity, regenerative capacity) and how is it being impacted by climate change?

5.5 Data

Improved quality and access to data in the UIB is vital to provide evidence-based support for adaptation to climate change (Salzmann et al., 2014; Singh and Thadani, 2015) as well as effective resource management more generally. The extremely complex topography that characterizes the UIB results in pronounced local-scale gradients in precipitation, and thus runoff from rain and snowmelt (Fowler and Archer, 2006; Immerzeel et al., 2015; Shrestha et al., 2015). Variability in mass balance is also apparent in the many glaciers that are located in the UIB (Kääb et al., 2015; Bolch et al., 2017; Azam et al., 2018), which affects the contribution of glacier melt runoff to flows. Furthermore, land use change and changing climate are affecting the numerous and highly diverse ecosystems that are located in the UIB (Xu et al., 2019). However, our ability to assess the present-day baseline state of these components is hampered by a profound lack of ground observations of the physical (glaciological, hydrological, meteorological) and ecological (biodiversity, land use, forest cover, and ecosystem services) components of the integrated UIB Earth system. For example, only a handful of glaciers and rivers in the UIB are regularly revisited and directly measured (Afran et al., 2019) and long-term analyses are only possible in a few cases (Nüsser and Schmidt, 2021). Furthermore, our knowledge of the volume of water stored in glacier ice is poorly understood, as are estimates of snowfall (Pritchard, 2021). There is also a need for better data on socio-demographic variables and human factors such as water demands, food demand, agricultural practices, cropping patterns, and infrastructure (Gioli et al., 2019; Rasul et al., 2019).

Attempts to understand trends, physical processes, evaluate extremes, and assess the accuracy of climate, hydrological, and water resource system models (Jain et al., 2010; Momblanch et al., 2019b) are also hindered by sparse and short observations. Additionally, exchanging data between the four UIB member countries is complicated (Salzmann et al., 2014; Qamar et al., 2019). Efforts to overcome the paucity of direct observations in the UIB include using gridded observational datasets (from sources such as gauge and satellite measurements) and reanalysis, which have various levels of accuracy and also can give contradictory results (Palazzi et al., 2013; Li et al., 2018; Dahri et al., 2021b). The questions below reflect attempts to improve data collection and monitoring across the UIB.

94. What is the quality of the physical, ecological, socio-demographic, and anthropogenic data available for the UIB, and can they be integrated to define the baseline present-day conditions for the region against which future changes can be measured against?

95. How accurate are available gridded datasets in the UIB, and how suitable are they for understanding hydrology, glaciology, climate, and meteorology at a range of spatial and temporal scales?

96. How can we transfer quantitative understanding from datasets, tools, and techniques from relatively well-instrumented/understood HKH catchments, and use this to fill information gaps in other parts of the UIB?

97. How can new sources of observational data, such as low-cost sensor networks or new measurement devices, be best harnessed to inform understanding and modelling of the UIB at different spatial (especially at high altitudes) and temporal scales?

98. How can crowdsourcing, via grassroot citizen science or Internet of Things, be leveraged to find novel ways to gather climatic, hydrological, ecological, and geophysical data in the UIB?

99. How can we ensure that climate data collected and produced in the UIB is useful for decision support, and which climate indicators are most useful for each sector and how are these best communicated?

100. How/where should new meteorological, cryospheric and hydrological stations be ideally placed to monitor the spatiotemporal heterogeneity in the UIB, as well as to provide a stronger basis for the validation of remote sensing data products?

6 Discussion and Conclusions

The horizon scanning exercise used to generate our 100 questions has been previously used extensively in multi- and cross-disciplinary settings to identify knowledge gaps relevant to emerging global challenges. We used a modified version of this process to identify knowledge gaps relevant to climate change and water resources in the UIB, a region characterised by significant social-ecological dynamism and recognised vulnerability to environmental change. Our resulting list of 100 questions is organised into 14 themes, selected by us from an initial list of 249 questions received after canvassing a wide multi-disciplinary field of relevant experts. Within this discussion, we reflect on a few salient features of our methodology, the final list of questions, their implications for on-going research and the research funding and policy environment.

First, given the strong linkages between climate, water resources, and human activities in the UIB, many of the questions identified in this study are cross-disciplinary. For example, although questions 32 and 33 are related to socioeconomic processes and livelihoods, they both require a robust understanding of hydroclimatic change. While question 76, which is focused on the tipping points for hydrological changes in the UIB, will require a robust understanding of how this affected by climate change as well as changing water management regimes and changes in demands from different sectors. This has implications for the ways in which questions are addressed, implying the need for multi-disciplinary consortia supported by novel partnerships between (traditionally discipline-centric) funding bodies.

Second, it is important to note that the spread of questions we present here cannot be considered fully comprehensive (covering all the most pressing knowledge gaps that could be considered important by all scholars in the field). As with other scans (Bharucha et al., 2020), ours is contingent on the process, the particular group of scholars involved, the networks they canvassed, and the deliberations we undertook to edit and select the final list of questions.

Third, it is also important to note that not all questions posed or included in the final list may necessarily be considered completely 'novel', in the sense of opening up new fields of enquiry. While 'novelty' was indeed a key criterion which we asked participants to consider when posing questions, our final list of questions was oriented towards selecting those considered to be *most important* - rather than focussing solely on novelty. For example, efforts to narrow uncertainties in projected changes of precipitation and temperature in the UIB over the twenty-first century (question 60) have existed since the development of climate models, with frameworks such as the Coupled Model Intercomparison Project (CMIP) setup in 1995 to foster this (Meehl et al., 1997). This reflects the considered view of our research consortium on the continued relevance of as yet under-researched problems.

Two features of our methodology that researchers may wish to consider when designing future scanning exercises are the following. Firstly, like several recent scanning exercises (Bharucha et al., 2020; Foulds et al., 2020), ours has been run entirely online. The online nature of the exercise has facilitated inclusivity and wider participation from many countries (at no cost), as well as introducing some challenges. Online facilitation has also allowed participants to convene several times, as well benefit from joint working tools, allowing participants to deliberate over shared documents and jointly edit questions over a longer timeframe than would be possible in a single, time-limited in-person meeting. On the other hand, ensuring in-depth deliberation on online platforms has been challenging. Given the multi- and cross-disciplinary nature of our topic, we would have benefited from the opportunity to facilitate in-person events with sufficient time for participants to bridge disciplinary divides through extended, in-person conversation. Secondly, we asked all contributors to provide a 'justification' for each question they wished to propose. These justifications, first used in scanning exercises in Foulds et al. (2020) were an important stand-in for cross-disciplinary conversation. They allowed our SG to understand the importance and thinking behind each question which was proposed, particularly those from other disciplines. Justifications were also important for editing questions, allowing us to reword for clarity while retaining the original meaning of questions.

One of the main priorities of this study was to emphasise the importance of identifying knowledge gaps in both the natural and social sciences, as research efforts to identify the impacts of climate change on the latter have for a long time often been neglected in favour of the former (Heberlein, 2008; Pederson, 2016; Billi et al., 2019). The consequences of neglecting social sciences are that our understanding of the dynamics and impacts of climate change are often limited. A clear indicator of the importance of the social sciences in this study is that both the most questions and most participants (29 of the 50 experts) are associated with various social science disciplines. Moreover, the comprehensive assessment of the HKH region by Wester et al. (2019) already includes input from a diverse range of experts, practitioners, researchers, and policymakers – so the importance of multi- and cross-disciplinary research integrating the social and natural/environmental sciences in this region (and by extension the UIB) has already been recognised. Moreover, the International Centre for Integrated Mountain Development (ICIMOD) and platforms like the Upper Indus Basin Network and the Indus Forum also promote bringing together different disciplines to better understand exisiting and future challenges due to climate change.

Due to the transboundary nature of the UIB the list of 100 questions is relevant to all four riparian countries. Therefore, despite being often challenging, harnessing cross-country (and regional) cooperation would be immensely beneficial to addressing these knowledge gaps (Molden et al., 2017; Vinca et al., 2021). The aforementioned ICIMOD, the Upper Indus Basin Network, and the Indus Forum encourage better transboundary and regional collaboration to address these challenges. This study has promoted this cooperation by bringing together 24 experts from the four riparian countries (and 26 experts located globally), despite China and Afghanistan (two participants each) being comparatively under-represented compared to Pakistan (nine) and India (eleven). Moreover, many of the research challenges are common throughout the HKH, suggesting that promoting better transboundary and regional collaboration across all HKH countries is necessary (Molden et al., 2017; Wester et al., 2019).

The questions listed in this paper require immediate attention from researchers, which will have implications for funding bodies and organisations looking to support these activities over the coming years. For example, Pederson (2016) point out that while stakeholders acknowledge the need to include social sciences research into cross-disciplinary research to address key societal challenges such as climate change, efforts to improve the funding of such opportunities are still required. Additionally, the transboundary nature of the questions suggests that ideally research funding would also support cross-boundary and international collaboration. Overcoming both these obstacles is essential to reduce the gaps in knowledge relevant to climate change and water resources in the UIB.

Conflict of interests

The authors declare no conflict of interest relevant to this study.

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Data availability statement

This study did not use any data.

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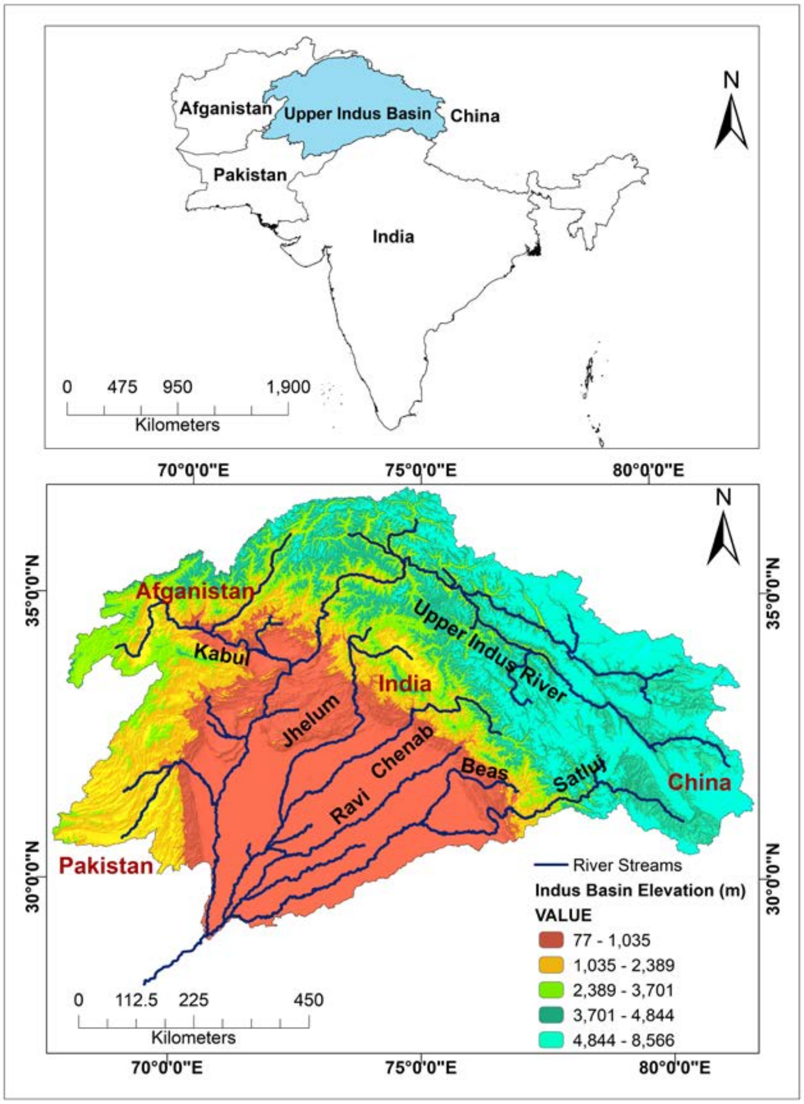

Figure 1. **(Top) Map showing the geographical limits of the Upper Indus Basin (shaded blue) used in the scan, which is shared by Pakistan, Indian, Afghanistan, and China. (Bottom) Zoom-in of the Upper Indus Basin region (shaded blue), defined as the region from the high-mountains of the Hindu-Kush Karakoram Himalaya (HKH) to the confluence or merger of the Upper Indus, the Kabul, the Jhelum, the Chenab, the Ravi, the Beas, and the Satluj rivers.**

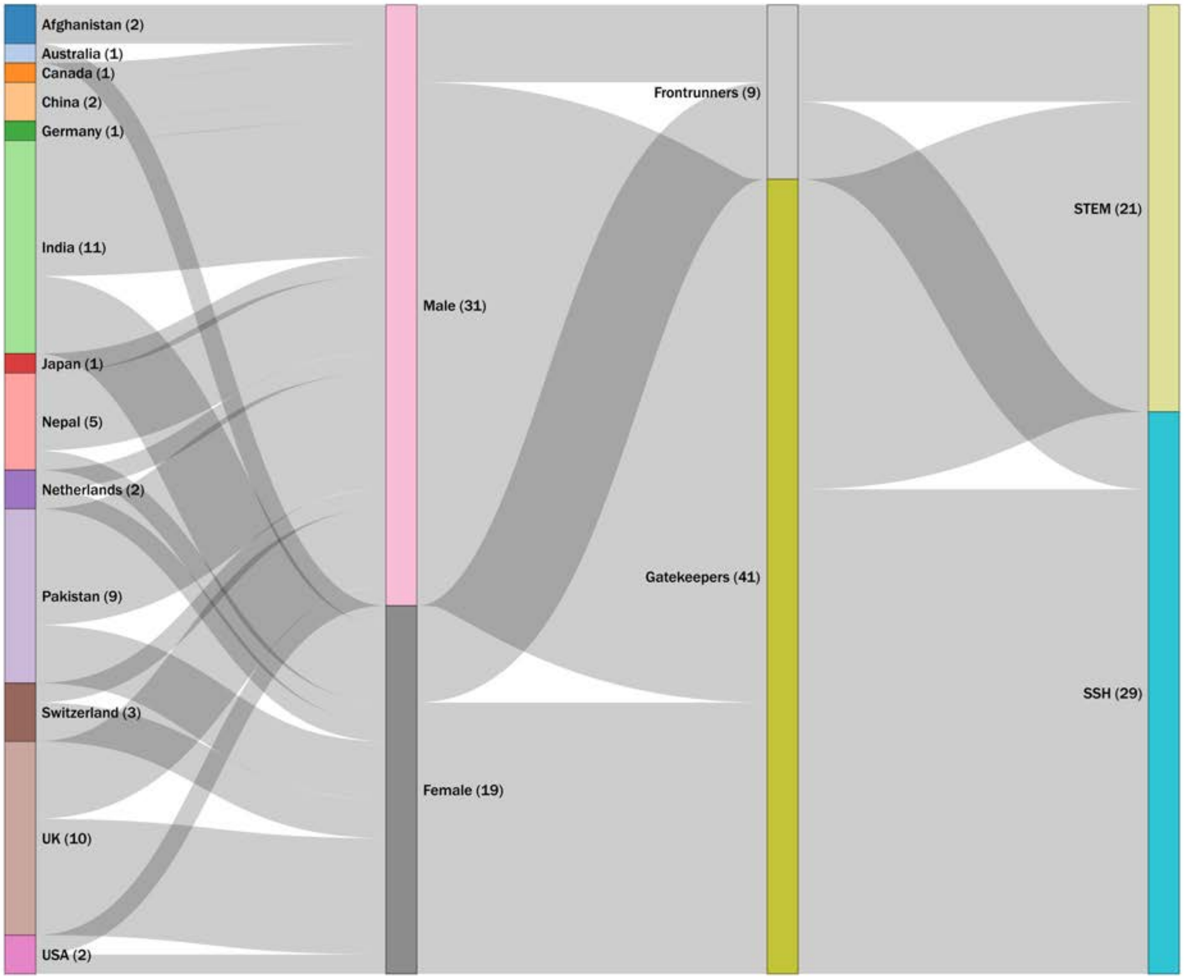

Figure 2. **Sankey diagram illustrating the diversity of the 50 participants involved in this study in terms of their location, gender, discipline, and whether they are frontrunners (i.e., new entrants) or gatekeepers (i.e., already established). Here SSH refers to 'social sciences and humanities', and STEM refers to 'science, technology, engineering, and mathematics'.**