Editorial

Changing monsoon patterns, snow and glacial melt, its impacts and adaptation options in northern India: Synthesis

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ABSTRACT

This paper gives a synthesis of this special issue on the sensitivity to climate change of the main bio-physical processes in the Hindukush–Karakoram–Himalayas. It also describes the impacts on the water resources with a special focus on the Ganges. Consequences of changes in water resources and possible adaptation measures for different sectors are discussed.

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1. Introduction

Rivers draining from Himalayan headwater basins, in which precipitation is enhanced orographically, deliver large quantities of runoff to the major tributaries of the Ganga river and hence make substantial contributions to the water resources of northern India. Flows in such Himalayan rivers are derived from both contemporary precipitation and melting of accumulated snow and ice from glaciers. Runoff from partially glacierised mountain basins is important as a water resource not just in quantity. Glaciers effectively moderate intra-annual variations in river flow, in cooler wetter years by runoff arising from precipitation over the ice-free areas offsetting reduced glacier melt, and in warmer drier summers through enhanced melt making up for reduced precipitation (e.g. Collins, 2007; Collins et al., in this issue; Rohrer et al., in this issue). Glacier melt water runoff is a particularly useful resource where it provides water in places and at times when other sources are scarce, for example in downstream arid areas or during hot and dry seasons.

Depressions in the westerlies deliver significant amounts of winter precipitation to the Himalayan region of north India (Dimri et al., in this issue). Under the influence of the Asian monsoon, however, most of the annual precipitation occurs in summer (Collins et al., in this issue). Monsoon precipitation generally declines from east to west, and from south to north, south facing windward slopes receiving greater amounts of precipitation than shadowed leeward west–east valleys (e.g. Bookhagen and Burbank, 2006, 2010). At higher elevations monsoonal precipitation falls as snow, so that overall ice ablation on glaciers in the Indian Himalaya is reduced in July and August in comparison with June and September.

In the Ganges, Indus and Brahmaputra basins, which are in particular susceptible to climate change (Singh and Bengtsson, 2004), millions of people rely on freshwater supply originating from melt-water of snow and glaciers and monsoon precipitation. Demands of industry, energy, agriculture and domestic use already make the economy show signs of water stress. Together with increasing freshwater demand from industry, agriculture and domestic use, a decrease in base flow will likely cause water stress. Climate change will be another factor adding to the stress.

Based on historic data, the Fifth Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC) stated that the "warming of the climate system is unequivocal, and since the 1950s, many of the observed changes are unprecedented over decades to millennia. The atmosphere and ocean have warmed, the amounts of snow and ice have diminished, sea level has risen, and the concentrations of greenhouse gases have increased" (IPCC, 2013). However, the report also made clear that a number of trends remain poorly explained or uncertain, not least with respect to precipitation events in regions such as the one targeted by this special issue, i.e. the Hindukush–Karakoram–Himalayas and floodplains of the Ganges. By way of example, the AR5 stated that outside the mid-latitude land areas of

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the Northern hemisphere, only low confidence exists for area-averaged long-term positive or negative trends in precipitation, and that the confidence in changes in heavy precipitation events was considered at the most medium outside North America and Europe.

The retreat of glaciers (Bolch et al., 2012) and a possible change in monsoon precipitation and pattern (Kumar et al., in this issue; Mathison et al., in this issue) will have a great impact on the temporal and spatial availability of water resources in Northern India. Besides climatic changes, socio-economic developments will also influence the use of water resources in the area as well as agricultural economy and adaptive capacity. The level of adaptive capacity will be determined by the socio-economic development, which renders the development of appropriate adaptation strategies based on impact outputs of hydrologic and socio-economic models a challenge, even more so in view of the large spectrum of stakeholders involved in the process and representing the agricultural, energy, health and water supply sectors.

To meet this challenge we synthesise here the main outcomes of this special issue dedicated to "Changing water resources availability in Northern India with respect to Himalayan glacier retreat and changing monsoon patterns: consequences and adaptation", where a broad set of papers seeks to understand, model and quantify some of the key driving processes of the Himalayan water resources, the impact on glacier retreat and possible changes of the Indian summer monsoon on the spatial and temporal distribution of water resources in northern India. In addition, we synthesise the recommendations for response strategies that might eventually strengthen the cause for adaptation to hydrological extreme events.

2. What do regional climate projections tell us?

The Indian subcontinent has often been described as a hotspot for land atmosphere interactions (Harding et al., in this issue). At the same time, northern India also has the highest concentration of irrigated land and the highest population density in the world. Water availability in the region depends substantially on the Asian monsoon, presence of groundwater and to some degree on snow and ice melt from the Himalayas (Bolch et al., 2012; Moors et al., 2011; Collins et al., in this issue; Rohrer et al., in this issue). Interaction between the land surface and atmosphere occur at various scales, but in particular in irrigated land, for which Harding et al. (in this issue) describe a recycling of up to 60% of the evaporation in the summer months to rainfall during the Indian Summer Monsoon (ISM) and thereby to river flows in the wider South Asia region in general and to the Ganges in particular.

The ISM influences daily lives and economies in many countries in the South Asian region. Regional climate models (RCMs) have been demonstrated to be able to capture the spatial distribution of rainfall (1981–2000) using re-analysis ERA-40 as lateral boundary forcing data, especially over the central and west coast of India (Lucas-Picher et al., 2011). Most model runs of the past have, however, been overly warm in northern India and underestimated sea level pressure, with related major overestimation of precipitation for the west coast of the Indian subcontinent by up to 100% and underestimations (in the order of 50%) for the Himalayan foothills (Dobler and Ahrens, 2010).

The EU-FP7 HighNoon ensemble is the most complete data for the region providing useful information on a wide range of variables for the regional climate of the Brahmaputra–Ganges region. Kumar et al. (in this issue) forced three Regional Climate Models (RCM) with ECMWF reanalysis data for the period 1989–2008 at a horizontal resolution of ~25 km. They then compared results against independent observations. Climate model runs up to 2099 were driven by lateral boundary conditions from two global climate models (GCMs: ECHAM5-MPIOM and HadCM3) using the SRES A1B scenario, except for one RCM, which used data from only one GCM. The ensemble shows a clear signal of gradual and widespread warming throughout the 21st century of 1.5 °C in 2050, and 3.9 °C at the end of the century with respect to the reference period of 1970–1999 (Kumar et al., in this issue). Using four

RCM simulations for the Indian subcontinent and the Himalayas at high resolution (25 km) from 1960 to 2100, Mathison et al. (in this issue) provide another ensemble of simulations for the region, and illustrate an increase in temperature between the baseline (1970–2000) and the 2050s (2040–2070) of between 2 and 4 °C. The authors also observe an increase in the number of days with maximum temperatures above 28 °C and 35 °C. These temperatures are critical thresholds for among others human physiology. From the analysis of a larger ensemble of global climate models (GCMs) using the A1B scenario, a widespread warming (~3.2 °C) seems very likely by the end of the 21st century (Kumar et al., in this issue).

The pattern of projected precipitation changes shows considerable spatial variability (Kumar et al., in this issue). Increased precipitation totals are expected over the Indian Peninsula and coastal areas, and no change or even a decrease further inland. However, precipitation and runoff assessments remain uncertain with considerable variability, even in the relatively small ensemble used (Mathison et al., in this issue), and therefore suggest that important feedbacks and processes of the ISM are still only poorly – or even not at all – taken into account in state-of-the-art RCMs (Lucas-Picher et al., 2011). Based on the analysis of a larger ensemble of GCMs using the A1B scenario, an overall increase (~8.5%) in mean monsoon precipitation is very likely by the end of the 21st century, but the influence of the driving GCM on the projected precipitation change simulated with each RCM still seems to be as strong as the variability among the RCMs driven with one (Kumar et al., in this issue).

The paper of Dimri et al. (in this issue) focussed on changes in the Indian winter monsoon over the western Himalayas, where almost one-third of annual precipitation falls during cyclonic winter storms embedded in the westerlies, also locally known as "western disturbances". Using two RCMs forced with large-scale fields from ERA-Interim data, Dimri et al. (in this issue) illustrate the important role of local topography in moisture fluxes, transport and vertical flows, with the result that uncertainties related to future precipitation changes and liquid–solid precipitation ratios are still very large with subsequent consequences for hydrological and glaciological modelling studies. Rohrer et al. (in this issue) confirm these limitations and stress the importance of in-situ data on (temporarily) stored freshwater resources. According to the authors, the role of runoff from snow cover has received comparatively little attention in the past, despite the fact that its contribution can be equally or even more important than that of ice melt in many catchments of the Himalayas. The assessment of changes in the amount of future snowmelt runoff and its timing is not straightforward. A larger partial pressure of H_2O, CO_2, CH_4, and other greenhouse gases may significantly increase net long-wave input for snowmelt in a future atmosphere. Changes in short-wave energy balance – such as the pollution of snow cover through black carbon – or the sensible or latent heat contribution to snowmelt are likely to alter future snowmelt and runoff characteristics as well. The authors remind that for the assessment of snow cover extent and depletion, and also for the monitoring of other properties of the snow cover, remote sensing is likely to become more important in the future. However, for the calibration and validation of data obtained by remote sensing, and even more so in light of possible changes in snow-cover energy balance, Rohrer et al. (in this issue) strongly call for more in-situ measurements of snow parameters across the wider Himalayas.

With these limitations in mind, Ridley et al. (in this issue) analyzed the anomalous gain of mass for the Karakoram glaciers of the Western Himalaya, also known under the name of "Karakoram Anomaly" (e.g. Bolch et al., 2012). The authors state that changes in the winter synoptic patterns can influence the amount and seasonality of Himalayan snowfall and consequently influence the mass balance of regional glaciers. Ridley et al. (in this issue) have therefore used a clustering method to analyse sea level pressure patterns which most influence Karakoram snowfall and determined if the frequency of these synoptic patterns is likely to change in future scenarios, using a RCM to assess changes in severity and frequency of snowfall events. Several weather patterns

influence winter precipitation over the western Himalayas, among those the westerly disturbances described by Dimri et al. (in this issue). According to the RCM results, these westerlies could likely increase in frequency of occurrence up to 2100. Thus, Ridley et al. (in this issue) conclude that the Karakoram glaciers could likely continue to grow, or decline at a slower rate, compared with those glaciers across the rest of the Himalayas.

3. What are the impacts?

3.1. Water availability

Himalayan headwaters supply large quantities of runoff derived from snowmelt and monsoon rainfall to the Ganges river. The contribution of snow and glacial melt has been a longstanding point of discussion.

Collins et al. (in this issue) have used climate records for locations across the southern slope of the Himalaya between 77°E and 91°E together with discharge measurements from gauging stations on rivers draining partially-glacierised tributary basins to the Ganges, with a view to assessing impacts of climatic fluctuations on year-to-year variations of runoff during the recent sustained period of glacier decline. The authors demonstrate that summer monsoon precipitation dominates runoff across the central Himalaya. Flow in tributaries of the Ganges in Nepal fluctuated from year to year but the general background level of flow was usually maintained from the 1960s to 2000s. Flow in the Sutlej, however, declined by 32% between the 1970s and 1990s, reflecting substantially reduced summer precipitation. Over the north-west Ganges–upper Sutlej area, monsoon precipitation declined by 30–40% from the 1960s to 2000s. Mean May–September air temperatures along the southern slope of the central Himalayas dipped from the 1960s, after a long period of slow warming or sustained temperatures, before rising rapidly from the mid-1970s so that in the 2000s summer air temperatures reached those achieved in earlier warmer periods. Runoff measurements from highly glacierised headwater basins are generally scarce in the region, and a clear need exists for more measurements in the proximity of glaciers.

Siderius et al. (in this issue) used four macro-scale hydrological models, appropriate for coupling with regional climate models, to provide a baseline estimate of snowmelt contribution to flow at seasonal and annual timescales. The models constrain estimates of snowmelt contributions to between 1 and 5% of overall basin runoff for the period 1971–2000. Snowmelt was found however to be significant in spring months, a period in which other sources of runoff are scarce (see Fig. 7, Siderius et al., in this issue). Exact snowmelt contribution to discharge in the Ganges however remains unclear under both present and future climatic conditions (see e.g. Immerzeel et al., 2013).

Climate change may affect water quality in different ways. Water quality induced by diffuse sources is mainly coming from agriculture and is impacted by both increased soil water stress or by increased surface runoff. For nutrient emissions, increased soil moisture stress implies that the rate of denitrification processes will decrease. This would further imply a reduction in natural removal of excess nitrogen from agricultural lands thereby leading to higher nitrate concentrations and loads getting transported to groundwater water systems in the absence of appropriate water and nutrient management strategies. An increase in surface runoffs during the monsoon months with an increase in rainfall intensities will lead to an increase in nutrient loss due to wash-off especially for phosphates and heavy metals that have chemical tendency to be bound to soil particles and get transported by surface pathways. Narula and Gosain (in this issue) showed for the Upper Yumani catchment area using different climate change scenarios that similar to stream flow, nitrogen loads under future climate change scenarios (2071–2100) also increase by 40–50% over the baseline (1961–90) in the monsoon months but decrease by 15–30% in winter months compared to those in baseline periods. The annual nitrogen load is found to increase on average by 15%.

3.2. Risk of flooding

Glacial lake hazards and glacial lake distributions occur in all glaciated regions of the world, but very limited attention has been paid to this phenomenon in the Indian Himalayas in the past. Worni et al. (in this issue) present a first area-wide glacial lake inventory of 251 glacial lakes with surfaces >0.01 km². Lake distribution patterns and lake characteristics were found to differ significantly between the five states spanning the Indian Himalayas. Lake outburst probability, potential outburst magnitudes and associated damage have been evaluated for three lakes in the states of Jammu and Kashmir, Himachal Pradesh and Sikkim. At the study site in Sikkim, a dam breach could trigger drainage of ca. 16×10^6 m³ water and generate maximum lake discharge of nearly 7000 m³ s^{-1}. The identification of critical glacial lakes in the Indian Himalayas and the detailed risk assessments at three specific sites allow prioritising further investigations and help in the definition of risk reduction actions.

3.3. Agriculture

The pressure on water resources on the Indian subcontinent is already high, and potential effects of climate change may even further confound the question whether sufficient water will be available in the coming years. Even more water will be required to sustain the food production needed facing a population expected to grow from 1.2 billion in 2011 (Census of India, 2011) towards 1.6 billion around 2050 for the medium fertility variant (United Nations, 2013) in India.

Taking into account projected land use change and climate change for 2050, the most surface-water-scarce regions are located in the south-western part of the Ganges basin and the western parts of the Godavari and Krishna basins (see Biemans et al., in this issue for details). In these water stressed regions, a large fraction of irrigation water demand needs to be extracted from groundwater. However, these are exactly the same regions (Punjab, Haryana, Rajasthan and Gujarat) where groundwater is already reported to be overexploited (GOI, 2006). For the Ganges basin, these findings are confirmed in a spatially more detailed study and using a different modelling approach by Mishra et al. (in this issue). Based on RCM projections (Mathison et al., in this issue), they found for the period 2011–2040, the largest reduction in potential rice and wheat yield will occur in the upper IGB, i.e. potential rice and wheat yield respectively by 43.2% and 20.9% by REMO, and 24.8% and 17.2% by HadRM3. The differences between especially the rice potential yield indicate the strength of a model ensemble approach. That not only a model ensemble for the climate drivers could be a strong tool, but also for the impact models, is demonstrated in e.g. the study by Asseng et al. (2013). The disadvantage of an ensemble approach is that it may hide the existing extremes. In similarity to data assimilation, the use of an ensemble is a strength only if the differences in theoretical concepts and parameterisations of the models can be justified. For example in the case of the Ganges basin study, different response function of yield and maximum temperature for different crop varieties is a strength, while having different response functions in different models for the same crop variety may be considered a weakness. Especially improving temperature and CO_2 relationships for the high end tail of the distributions in crop yield models will improve assessments of the impact of climate change.

3.4. Health

Human health is one of the sectors affected by climate change (Haines et al., 2006; McMichael, 2013). How seriously human health will be impacted by climate change is not well established and is part of on-going research. Moors et al. (in this issue) discuss the impact of climate change on diarrhoea as a representative of a waterborne infectious disease affecting human health in the Ganges basin of northern

India. Using a conceptual framework based on climate exposure–response relationships for four climate variables: temperature, increased/extreme precipitation, decreased precipitation/droughts and relative humidity, they show that the combined impact of all four parameters on diarrhoea in northern India is expected, for the projected changes between current and future (2040s), to range from no change to an increase of 21% in incidences, with 13.1% increase on average for the whole of northern India. Although the average impact corresponds well with global averages (e.g., Kolstad and Johansson, 2011) the spatial differences projected by Moors et al. (in this issue) seem to require more detailed assessments.

4. Adaptation options and pathways to arrive at the desired options

To determine spatially explicit regional water scarcity hotspots taking into account seasonal differences, Biemans et al. (in this issue) analysed two different adaptation strategies to improve crop production: an overall improvement in irrigation efficiency, and an increase of reservoir storage capacity. They concluded that increasing the irrigation efficiency will be beneficial in all basins, but most in the Indus and Ganges, as it decreases the pressure on groundwater resources and decreases the fraction of food production that would be at risk because of water shortage. A combination of both options seems to be the best strategy in all basins. The gains in the Ganges basin would be largest under improved irrigation efficiency. Further, Biemans et al. (in this issue) suggested that in certain areas, e.g. in the southern part of the Ganges basin, the presented options would not be suitable to reduce water scarcity. Sadoff et al. (2013) showed that increasing reservoir capacity for hydropower generation in the headwaters of the (tributaries of the) Ganges could double low flows in the dry months, but that the economic value is unclear and that similar water storage volumes could be created by improved groundwater management.

Agricultural management also plays an important role in the amount of contaminating substances from diffuse sources reaching surface and groundwater bodies. To reduce water contamination by these diffuse sources, future water and nutrient management strategies will have to focus on optimising fertiliser application implying increase in efficiency of nitrogen and irrigation water use. Reduction in excessive use and application of chemical fertilisers such as urea, as well as improvement in supply-chain systems that ensure availability of organic fertilisers would also be required (Narula and Gosain, in this issue).

Changes in the extreme events will have direct implications on life and property. Adapting to the adverse effects of climate change becomes critical to avoid huge material and immaterial damages. How to involve stakeholders in developing adaptation strategies is discussed in the paper by Bhadwal et al. (in this issue). They discuss the use of a multi-level and participatory approach to develop adaptation options to deal with climate related risks in a manner that contributes to stakeholder engagement, understanding of the risks, identification of the adaptation responses as well as its prioritisation for risk reduction. Bhadwal et al. (in this issue) show that stakeholders at different administrative levels have different adaptation priorities. At the state level priorities are largely informed by the shape of policies and plans for implementation, at district level the interest is driven by the implementation of state policy and programmes, while at the community level the focus is merely on acceptability and feasibility of the adaptation options. This becomes also clear from the health sector, where well-known preventive actions like washing hands with soap, household water treatment and safe storage, and safe sanitation facilities, have the potential to counterbalance the expected increase of more than 10% incidences of diarrhoea (Moors et al., in this issue). But given the limited progress in reducing incidences over the past decade concerted actions and effective implementation and integration of existing policies are needed.

To improve the engagement of stakeholders and thereby the quality and effectiveness of adaptation strategies, a methodology is required that enhances both backward- and forward integration and sharing of information. Particular effort needs to be put in the involvement of stakeholders in the development of future scenarios and in the linkage between the qualitative "stories" of stakeholders and quantitative model results (Bhadwal et al., in this issue).

5. Open research questions

The EU-FP7 project HighNoon (www.eu-highnoon.org) has contributed substantially to an improved understanding of climate change processes over northern India and has produced the most comprehensive and most detailed set of Regional Climate Model data for the region (Kumar et al., in this issue; Mathison et al., in this issue) and for related studies on impacts to the Ganges basin (Moors et al., 2011) so far. At the same time, new gaps have been identified and a need for new research observed in several fields. In the following, we list a selection of topics where further research is needed.

Further development is clearly needed in Regional Climate Models to include the quantity and spatial distribution of monsoon precipitation more realistically — even for the control period. More research on Regional Climate Models is of utmost importance to reduce the large spread, high uncertainty and opposing trends between different models. Monsoon precipitation is a substantial source of water for large populations living in the foothills and at higher elevations of the Himalayas and their agriculture, and any change in their occurrence and intensity will have major impacts on glacier mass balance (Bolch et al., 2012; Frey et al., 2012; Ridley et al., in this issue), but also on runoff (Immerzeel et al., 2013; Collins et al., in this issue; Siderius et al., in this issue). Snow, as one of the key sources of runoff outside of the monsoon season, needs to be monitored more thoroughly and with a larger network of in-situ measurements (Rohrer et al., in this issue). Similarly, estimates of glacier ice stored in the Indian Himalayas and changes thereof (in terms of length and volume, but also in view of mass balance analyses) are still diverging, and more research should focus on a more detailed and more accurate assessment of glacier volumes in the region (Frey et al., 2012) and its changes over time (Bolch et al., 2012). Benchmark glaciers should be identified and monitored over longer periods.

In relation to these changes in monsoon precipitation, snow and ice melt, more efforts should be dedicated to runoff studies, provided that long series of hydrological data will become accessible. Studies of runoff series will also be essential with respect to extremes and changes in cloud bursts and floods (Hobley et al., 2012). Along these lines of thoughts, one could study the floods of June 2013 in Uttarkhand and Himachal Pradesh. Extreme floods triggered from outbursting glacier lakes are another issue, especially in Sikkim, where a large series of moraine-dammed lakes are possibly unstable (Worni et al., in this issue).

Large-scale hydrological models as used in global or continental scale studies are suitable to identify hotspot areas and support the first step in the policy process, however the final design and implementation of adaptation options requires supporting studies at finer scales (Biemans et al., in this issue). Both, for large scale as well as for fine scale hydrological impact models, enhancing the capacity of the climate projections to explain changes in seasonal variations is essential, in order to formulate better strategies and measures to altered seasonal hydrological conditions.

Insights into changes over time linked to possible futures and related climatic risks stimulate awareness raising and learning. However, forward looking facilitation methods still need more empirical research to discuss multiple uncertain futures with stakeholders and enable them to decide on which robust adaptation option to choose (Bhadwal et al., in this issue).

6. Conclusions

In the preface of this special issue (Moors and Stoffel, in this issue), a number of questions have been posed. The EU-FP7 project HighNoon

has provided answers to most of these, but also gave rise to a series of new questions. The main conclusion from the project and this special issue are that:

- Up to 60% of summer rainfall stemming from the Indian Summer Monsoon are in fact recycled from irrigation water.
- The higher spatial resolution (25 × 25 km) of the Regional Climate Models (RCMs) used in the HighNoon project points to the predominant role of local topography, even more so in areas with extreme topography as is the case for the Himalayan region.
- The ensemble of RCM, using the IPCC Special Report on Emission Scenarios (SRES) A1B scenario, exhibits a clear signal of gradual and widespread warming throughout the 21st century. The warming is in the order of 1.5 °C for the coming decades and 4 °C by the end of this century with respect to the reference period 1970–1999.
- Annual total precipitation changes across northern India are still uncertain. Against a backdrop of considerable decadal variability, the slight increase in precipitation sums by 2050, as indicated by Regional Climate Models (RCM), is unlikely to be significant.
- Uncertainties related to future precipitation changes and the liquid–solid precipitation ratios are still very large, with subsequent consequences for hydrological and glaciological modelling studies.
- Improving on the wet bias over high-elevation sites requires the availability of more high-altitude observations, in combination with further research on how physics and dynamics are represented within the model fields. In addition research is needed to study the benefits and possibilities of further refining the spatial resolution of the RCMs for mountainous areas.
- Flow in tributaries of the Ganges in Nepal fluctuated from year to year but the general background level of flow was usually maintained from the 1960s to 2000s.
- Snowmelt in the Himalayas was found to be a significant water source especially for the head waters of the Ganges in spring months, a period in which other sources of runoff are scarce.
- Taking into account projected land use change and climate change for 2050, the most surface-water-scarce regions are located in the southwestern part of the Ganges basin where groundwater is already reported to be overexploited.
- The combined impact of four meteorological parameters on incidences of diarrhoea in northern India is expected to range from no change to an increase of 21% in incidences for the projected changes between current and future (2040s).
- Agricultural management practices can play a crucial role in adaptation strategies in northern India, not only because of possibilities to increase water efficiency, but also because of possibilities to reduce the risks of increased contamination of water resources by emissions of nutrients and pesticides.
- Well-known preventive actions have the potential to counterbalance the expected increase of more than 10% incidences of diarrhoea.
- To improve the engagement of stakeholders and thereby the quality and effectiveness of adaptation strategies, a methodology is required that enhances both backward- and forward integration and sharing of information.
- Even more than in other regions (Beniston et al., 2012; Salzmann et al., in press), an increase in the availability of good data is pivotal to further understanding of the main processes driving the biophysical as well as the socio-economic systems governing water resources and their use in Northern India.

Despite the large uncertainties persisting in measured (historical) precipitation records and the possibly large variability in precipitation projections in RCMs, the adaptation options that have been elaborated by the HighNoon project should be considered for implementation, not least because of the simultaneous changes in population growth, which are calling for instant action. The insights gained in the project can also be used for further climate proofing of the policy efforts already taking place, such as the improvement of irrigation efficiency included in the Government of India's current Five Year Plan (GOI, 2007).

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