Water Resources of the Ganga Basin under a Changing Climate: interaction between Glaciers and Monsoon in the Himalaya

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Abstract Climate change is expected to have a profound impact on the availability of water in the Ganga basin. Combined changes in glacier melt and monsoon precipitation will affect the total amount of water available. Increasing greenhouse gases are likely to lead to intensification of the water cycle, causing an increase in extreme events, especially droughts. However, magnitudes of these changes are highly uncertain. Being largely an agrarian society, India is vulnerable to adverse impacts of current and long-term changes in climate. In order to improve adaptive capacity in the Ganga River basin it is necessary (a) to improve representation of feedback mechanisms of glacier melting within regional and global climate model predictions of future water resouce availability, (b) to understand the impacts and associated vulnerability at the local level and related to district, state and national levels, and (c) to develop new methods enabling prioritization of adaptation measures.

Key words glacial melt, monsoon, climate change, water resources, Ganga

INTRODUCTION

The hydrological system of Northern India is based on two main phenomena: monsoon precipitation and melt of the snow and ice cover in the Himalaya. Climate change is expected to modify these phenomena and have a profound impact on snow cover, glaciers and related hydrology, water resources, and the agricultural economy on the Indian peninsula (Singh and Kumar, 1997). The perennial rivers in the north, Ganga, Indus and Brahmaputra, are particularly susceptible to climate change influences on snow and ice as they originate from the Himalayas. Climate change is projected to have both short and long term impacts on the hydrological system. In the short term discharge of rivers in the north will increase due to the increased melting of snow and glaciers. Over the long term, snow and glaciers will become much reduced in extent and their contribution to river flow will decrease. (Eriksson, 2006).

Presence of the snow cover and the timing of snow fall on the mountains and the Tibetan plateau also influence the monsoon. Cold, wet winters lead to less severe monsoon. Excessive snowfall in winter/spring delays the build up of the monsoonal temperature gradient as solar energy is used to melt the snow or is reflected by the snow. The heat-induced low over northwest India will be less strong resulting in a weak monsoon and decreased precipitation. The latest IPCC WG1 report stated: "There is a tendency for monsoonal circulations to result in increased precipitation due to enhanced moisture convergence, despite a tendency towards weakening of the monsoonal flows themselves. However, many aspects of tropical climatic responses remain uncertain" (Christensen et al., 2007). In the same report, it was concluded that the observed maximum rainfall during the monsoon season is poorly simulated by many models, the most likely cause being the coarse resolution of the models preventing a good representation of the steep topography of the area.

These expected changes in glacier melt and monsoon precipitation may not only affect the total amount of available water, but may also cause changes in seasonality, creating new and, sometimes, unexpected vulnerabilities. Intensification of the water cycle is likely to result in an increase in extreme events such as floods and droughts. Drought especially impacts the agricultural sector, which relies on the success or failure of irrigation schemes.

Besides climate change, socio-economic development will also have an influence on the use of water resources, the agricultural economy and adaptive capacity. Socio-economic development determines the level of adaptive capacity. It is a challenge to find appropriate adaptation strategies with stakeholders for each of the sectors agriculture, energy, health and water supply.

This paper presents a short overview of future changes in the main drivers of the water resources of the Ganga, the expected impacts, and possible strategies to come to sustainable adaptation options under a changing climate. As such the paper reflects the outcome of a scientific seminar and a panel discussion between policymakers and scientists, organised by the European Union FP7 High Noon project in New Delhi on 13th and 14th May 2009.

CLIMATE CHANGE AND GLACIER AND SNOW MELT

There is substantial evidence of rapid depletion of snow and glaciers, the fresh water reserve in the Himalayas. Among the many glaciers that have been studied, is Glacier AX010, Shorong in the eastern Nepal Himalaya (see Fig 1).

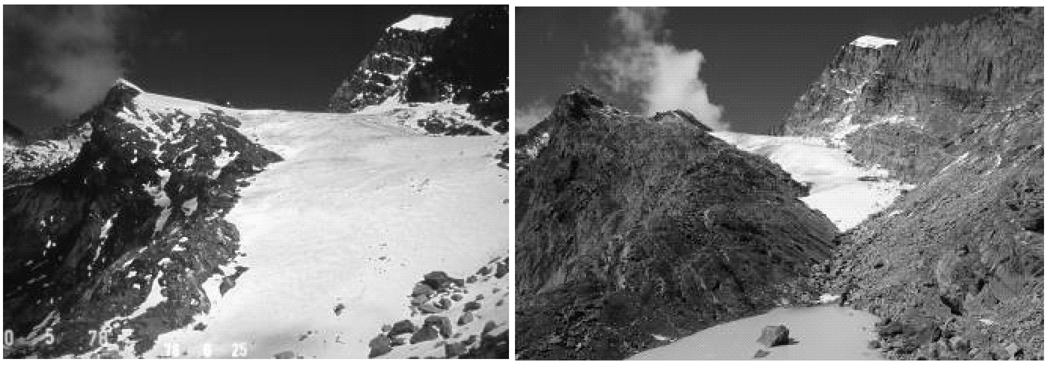

Fig. 1 Changes over 30 years of Glacier AX010, Shorong, eastern Nepal Himalaya, between 1978 (left) and 2008 (right).

Depletion of this glacier shows more rapid shrinkage than the worldwide trend (Fujita et al., 1997). Most of the glaciers in the Nepal Himalayas show such decline, and in the context of warmer climate scenarios, there will be significant changes in inflow to the lowland Ganga. It has also been observed that temperature rises are more greater at high elevations than in lowland areas.

At present, how these glaciers changes will influence inflow to the Ganga is associated with large uncertainty. This uncertainty is not only caused by inherent uncertainty of climate scenarios and predictions, but also because of a lack of reliable data on changes in glacier volumes and melting rates. A large part of the estimated glacier decline is based on changes in area. There are however many unknowns in the relationship between Himalayan glacier volume and area.

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. Although the contribution to the runoff from glacierised mountain basins to the annual total discharge of the Ganga is less than 10%, it is important as a moderator in time. Glaciers effectively moderate intra-annual variations in river flow. In cooler wetter years runoff arising from precipitation over ice-free areas offsets reduced snow and glacier melt, and in warmer drier summers enhanced melt makes up for reduced precipitation (e.g. Collins 2007). 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 dry seasons.

Monsoon precipitation generally declines from east to west, and from south to north, south facing windward slopes receiving greater amounts of precipitation than rain-shadowed leeward west-east valleys. 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 by comparison with June and September.

Runoff from highly-glacierised (> 40%) Himalayan basins shows two maxima. A build up of snowmelt from April is followed by icemelt from late May into June/July. Depending on the timing of summer snowfall, slightly reduced flow follows, building to a secondary peak in late August-September (e.g. Collins & Hasnain, 1995). Downstream, as basin size increases, decreasing percentage glacierisation and increasing influence of monsoon precipitation, flow is enhanced in July and August as quickflow from rainfall is superimposed on the glacial signal (~ 10% glacierisation e.g. Singh & Bengttson (2004)). Snow and glacier runoff provides most of the flow downstream into the Ganga in the spring and autumn 'shoulders' before the onset and during the retreat of the monsoon (Barnett and others 2005).

During the period of sustained climatic warming, runoff from glaciers might be expected first to increase as a result of enhanced melting of snow and ice. Melt water discharge will not however continue to increase indefinitely as, during progressively warmer summers, declining glacier extent will reduce the surface area of ice over which energy exchange can occur. As glaciers recede, a component of flow in excess of that related to contemporary precipitation, a deglaciation discharge dividend, is added to basin runoff from depletion of the amount of water stored as ice. That dividend will decline, and ultimately cease, as some glaciers disappear altogether. Basin runoff will then solely reflect whatever the future level of precipitation. The simple prediction of the complete disappearance of the Himalayan glaciers needs, however, to be treated with some caution. Glaciers will respond to both increasing temperature and changing precipitation patterns. In addition, Himalayan glaciers cover a wide altitudinal range so that even with substantial rises in temperature, thick glaciers at higher elevations are likely to survive into the 22nd century.

Future decline of glacier runoff will affect both inhabitants of mountain villages as small glaciers disappear and the four - five hundred million inhabitants of the entire Ganga basin as spring and autumn flows in particular decline, at differing timescales. Reviews from the region suggest that the timescales are short, and that glaciers may be reduced to 20% of the present ice area by the 2040s (Cruz et al., 2007) or the 2050s (Xu et al., 2007). Monsoon precipitation in the Indian and Nepal Himalaya, however, appears to stave off the rate of glacier recession in the central and eastern Himalaya by comparison with the drier Karakoram in the west (Rees & Collins 2006).

MONSOON-SNOW INTERACTION AFFECTING WATER RESOURCES

Snow is regarded as an important indicator of climate change because of its influence on the energy and moisture budgets on the Earth's surface. Changes in snow depth and extent directly influence absorption of incoming radiative energy, the prevailing surface temperature, and wind circulation patterns. Fresh snow, particularly in the summer months, reduces surface albedo and hence radiatively-driven icemelt. When snow cover is increased over an area, more energy is required to melt the snow so that less is left to warm the Earth's surface and lower atmosphere. Snow/ice feedback has a large impact on the sensitivity of a climate model. If a marginally snow-covered area warms, snow tends to melt, lowering the albedo, and hence leading to more icemelt (i.e ice-albedo feedback). These feedbacks are represented in most climate models. However, the complexity of altitudinal and topographic relationships between snow/ice cover, temperature and melt are lost in the very large scale parameterisations required in global and regional climate models.

The link between the Himalayan/Tibetan/Eurasian snowcover and Indian Summer Monsoon Rainfall (ISMR) has been long recognized (e.g. Blanford (1884), Dey et al. (1983)). Himalayan and Tibetan snowcover has a direct or indirect influence on Indian summer monsoon. For example the Indian Meteorological Department (IMD) has been using Eurasian snow in December for Indian summer monsoon forecasting. Variation in snow depth over the Himalaya will not only affect monsoon rainfall but also surface runoff especially over the Indo-Gangetic plain of northern India. The linear correlation coefficient between December-to-March snow extent in the Himalayas and June-to-September monsoon rainfall was found to be approximately 0.6 (Dey et al. 1983). Kriplani et al (2003) presented the monthly climatology and variability of the Indian National Satellite (INSAT) derived snow cover estimates over the western Himalayan region. They suggested that the changes in observed snow cover extent and snow depth due to global warming may be a possible cause for weakening of the winter snow-ISMR relationship. Dash et al. (2006) examined the effect of contrasting years of observed snow depth over Eurasia on summer monsoon rainfall by using a spectral General Circulation Model (GCM). They found that enhanced Eurasian snow depth in spring is followed by deficient Summer Monsoon Rainfall and vice versa. Model simulations also show weak/strong lower level monsoon westerlies and upper level easterlies in response to high/low April snow over Eurasia. Using the RegCM3 model, a sensitivity experiment based on snow depth anomaly over Tibet was conducted and associated changes in circulation pattern and rainfall over India examined (Dash et al. 2007).

Most observational and modelling studies have been focused on separate variations of either snow or surface temperature over the Himalaya/Tibet/Eurasia. Earlier studies show that snowcover is declining everywhere as a result of global warming (IPCC, 2001) resulting to decrease in snow depth and snow cover in the northern hemisphere. But there is lack of observations and modelling studies of the impact of global warming on the variation of snowcover over the Himalaya/Tibet/Eurasia. As climate warms, variations of the Himalayan/Tibetan/ Eurasian snow and ground surface temperature and links with IMSR are not clear, although some progress has been made in analyzing snow depth and surface temperature over the western Himalaya under a doubling CO_2 scenario (Parth Sarthi et al, 2009).

CHANGES IN DISCHARGE OF THE GANGA

Unlike the Indus and Brahmaputra, the Ganga and its tributaries do not flow through long mountainous tracts. The total mountain area drained by the Ganga and its tributaries is about 150,000 km^2. Of this, three tributaries flowing down from Nepal account for more than 100,000 km^2. The average annual flow of the rivers from the Nepal Himalayas is 121 x 10^9 m^3 (Subba, 2001).

Figure 2 shows the location of the Ganga river basin with sub-basin configuration covering an area of 871 800 km^2 as investigated using the SWAT hydrological model (Gosain et. al., 2006). This model was used to simulate a total of 40 years using the HadRM2 daily meteorological data; for 20 years control (present) and the remaining

20 years (future) under a Greenhouse Gas (GHG) climate scenario. Monthly average precipitation, actual evapotranspiration and water yield as simulated by the model over the total Ganga basin for control and GHG scenarios are depicted in Figure 3.

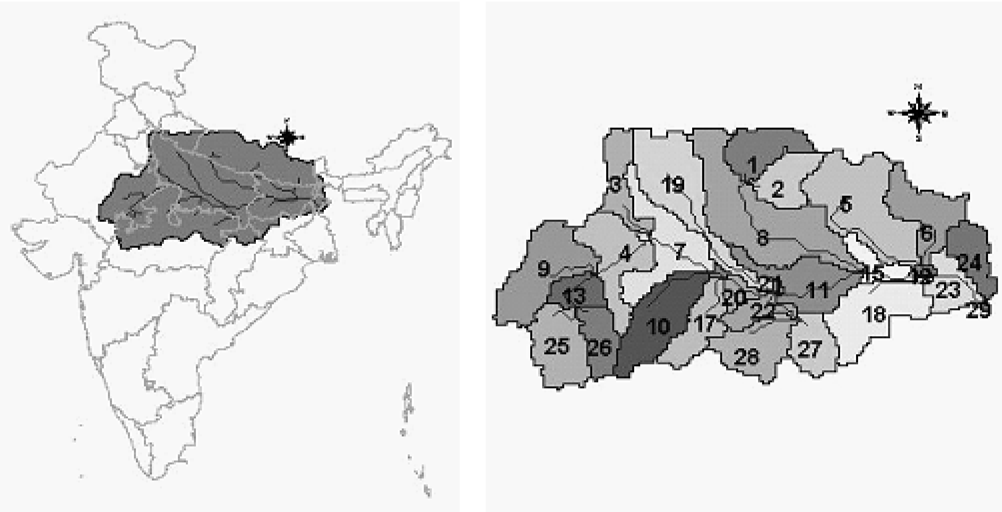

Fig. 2 Location of the Ganga river basin in the Indian subcontinent (left) together with 28 sub-basins (right)

Increased precipitation was predicted in all months except June, for which a slight decrease was indicated. The magnitude of increase in precipitation over the Ganga basin was distributed fairly uniformly over the months March – May and July and August, whereas corresponding increases in flow were concentrated in April and May, increases of around 140%. In these computations, land-use change and glacier melt could not be incorporated because of non-availability of data. However, the model takes snowmelt into account.

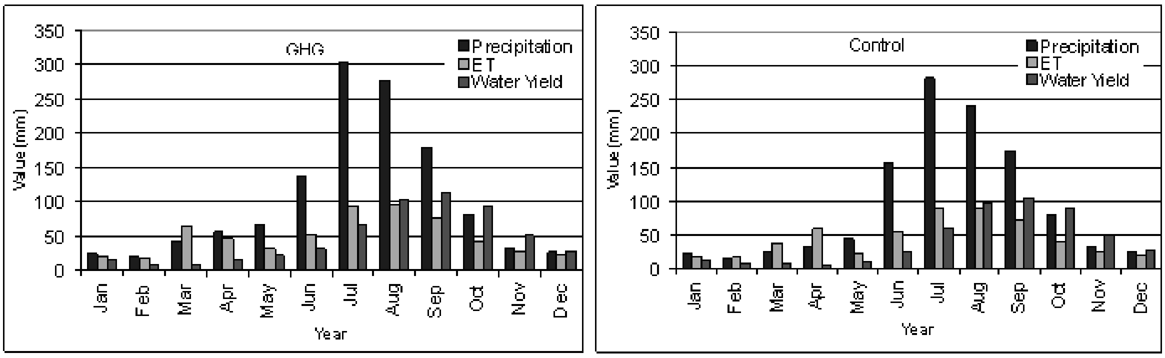

Fig. 3 Mean monthly water balance components (precipitation, evapotranspiration (ET) and water yield) for the control period (left) and GHG scenario period (right) for the Ganga basin.

Drought Analysis

Numbers of drought weeks in the sub-basins of the Ganga Basin were computed using the Palmer Drought Index (Gosain et. al., 2006). Figure 4 presents the total number of drought weeks experienced in each of the sub-basins of Ganga basin during the 20-year control and GHG periods. The majority of sub-basins were predicted to be under higher stress level under the GHG scenario. The impact of climate change on the dependability of the water yield of the river system has been analyzed by comparing the flow duration curve for the control with that of the GHG period. Under climate change, the frequency of high flows occurring less than 25% of the time decreased whereas that of 50% remained unchanged. The biggest changes were found in the 75% and 90% dependable levels, where the frequency of low flows, i.e. $< 100\ m^3s^{-1}$ was increased considerably for the GHG scenario by comparison with the corresponding control flow magnitudes.

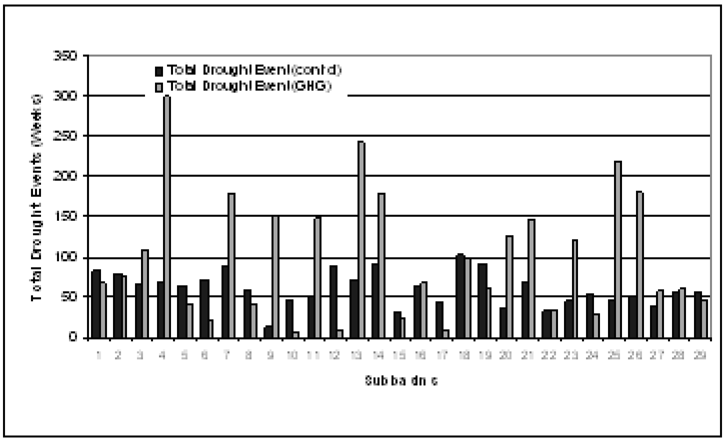

Fig. 4 Total drought weeks in sub-basins of Ganga Basin

IMPACTS

As indicated, climate change will have a profound impact on the availability of water in the Ganga basin, especially during low flow periods. However, pressure on these available water resources only exists if demand for water at a specific location and at a specific time cannot be met. India is rapidly changing and demand for water will change as a result of ongoing and projected socio-economic changes. Therefore it is not only important to consider future changes in water availability, but also in water demand. Supply and demand combined will determine the stress on available water resources. With expected developments in demography, industrialization, and agricultural intensification, estimation of future socio-economic boundary conditions is a critical factor in water resource assessments. It is important to evaluate socio-economic changes and associated water use projections in order to be able to obtain a complete picture of the most vulnerable areas and to identify the best locations for (combinations of) adaptation measures.

On a global scale climate and socio-economic scenarios are developed and updated in an consistent way, using integrated assessment models such as IMAGE (Bouwman et al., 2006). Corresponding scenarios for water use in the agricultural sector can be addressed with coupled vegetation-hydrology models that have been validated for global river basins (e.g. Biemans et al., 2009). The EU WATCH project (http://www.eu-watch.org) aims to provide a more consistent set of models outputs and scenarios for the assessment of water availability and use globally, and for the Ganga basin).

However, at the regional level, development of such consistent scenarios is still in an experimental phase. Global model results contain insufficient detail to relate directly to needs and wishes of stakeholders involved in water resources management at the basin scale, where adaptation to climate change will take place. On the other hand, scenarios developed at regional levels often lack the consistency and context of larger scale trends. To overcome this, there is a need to bring together local scenarios in a larger context, and develop a method that can offer more geographical and management detail through a nested approach. The socio-economic scenarios developed for India at the district level as part of the UK DEFRA phase I study on Impacts of Climate Change (http://www.defra.gov.uk/environment/climatechange/internat/devcountry/india.htm#impacts) can be linked to global scenarios and expanded to include demographics, water, agriculture, energy and health. Such linkages will produce improved scenarios at relatively small scales.

Such an approach provides the possibility to switch level of detail between scales, preserving the consistency of global scenarios but at the same time linking with local/regional needs. This information can be used within stakeholder processes as boundary conditions for adaptation measures. As a next step, the response of stakeholders on sets of adaptation measures can be used to investigate feedback effects on potential socio-economic developments and to evaluate the sustainability of the adaptation measures within the socio-economic scenario.

ADAPTATION STRATEGIES

Being largely an agrarian society, India is vulnerable to adverse impacts of contemporary and long-term changes in climate. India’s agriculture mainly depends on the strength of the monsoon as water availability is the most critical component for the agriculture sector. Floods as well as droughts afflict agriculture in the Ganga basin. Flood impact is exacerbated by high vulnerability of the population as the region has high level of poverty, poor access to education and health care.

Vulnerability can be reduced through adaptation in biophysical and/or social/human systems (Adger et al., 2007). The challenge remains to use up to date knowledge on system dynamics and to define adaptation strategies, which are location specific, accepted by stakeholder at all relevant levels and which integrate effectively the various sectors such as energy, agriculture and health.

From coping to adaptation

Adaptation strategies are more than a collection of measures and above all need to be tailor-made to local circumstances in order to address site-specific vulnerabilities. In the EU project HighNoon (see www.eu-highnoon.org) possible adaptation measures for the Ganga basin are currently under investigation. The project includes three case study sites to represent upstream, midstream and downstream parts of the Ganga basin, allowing horizontal comparison between vulnerabilities and possible adaptation strategies.

The aim is to get from individual measures to coherent strategies and feasible action plans. In the three case studies of High Noon, stakeholders at different levels, from farmer to state government, are involved. Integration between sectors is most prominent in the upstream case study, around the Tehri dam, where hydropower, agriculture and water supply for Delhi compete for available water.

Local communities try to cope with climate variability based on past exposure and experience in managing climate extremes. Some of the coping strategies employed by communities are to migrate to nearby urban centres for labour (mainly unskilled), selling of personal assets during stress periods, and taking formal or informal credits (Kelkar and Bhadwal 2007). Other often-mentioned local coping strategies, to deal with known and observed climate risks are the use of short duration or traditional crop varieties (Attri and Rathore 2003). However, these local coping practices may not be sufficient to reduce the risk of increased climate variability and climate change appreciably. And most of the above mentioned coping strategies are reactive instead of proactive.

More proactive approaches are needed as being an important feature of adaptive capacity, together with the capacity for individuals to learn and adapt their behaviour (Pahl-Wostl, 2007). Some examples are:

- Promoting agricultural practices more adaptive to climate variability, for example cultivation of short cycle crops, promotion of drought resistant crop varieties and use of appropriate rice cultivars;
- Involving local organizations such as Panchayati Raj Institutions (PRIs) and Self Help Groups (SHGs) to build capacities to deal with climate variability and take informed decisions to address the same.

In designing adaptation strategies it is important to recognize and promote people's knowledge and skills on coping strategies; pay attention to local agro-climatic and socio-political realities; and promote people's institutions and self-help approaches. Hence preparing for climate change is not something that individuals can do alone. It is a shared responsibility that requires action at different levels and in different sectors, with partnerships across the community so that households, community groups, businesses and governments can make necessary changes effectively and efficiently.

Current gaps in adaptation strategy development

Although in recent years the Government of India has been spending about 2% of GDP to address climate change adaptation, there is still a need further to strengthen this effort. In India there has been a focus on involvement of stakeholders in implementing various projects, for example in watershed management and participatory irrigation management (TERI 2009). There is limited access for stakeholders to up to date information. Predicting and analyzing climate change is still mainly the domain of scientists, whose insight has not always reached the local levels. Hence, there are needs to strengthen structures for participation and widen the knowledge base of stakeholders so that their effective participation can be ensured.

CONCLUSIONS: POLICY VIEW AND RESEARCH STRATEGIES

In order to combat impacts of climate change, the Prime Minister of India’s Council on Climate Change released a National Action Plan on Climate Change (NAPCC) in 2008. At the core of the NAPCC is water, with Missions for Water, for Sustaining the Himalayan Ecosystem, and for Sustainable Agriculture as well as for strategic knowledge of climate change. To ensure success of the NAPCC, inter-disciplibany research is needed that cuts across the various missions with increased international collaboration.

Many open research questions need to be addressed:

Complex interaction between snow/glacial melt and monsoon requires better representation in models. High resolution observed and model simulated data are needed to provide basic information on variability of rainfall, snow and temperatures over Himalaya topography. Area/mass relationships are not well-known for Himalayan glaciers, giving uncertainty as to how glacier runoff will respond to climate cchange. In the data-sparse headwaters of the Ganga, remote sensing and ground based data collection will help improve understanding.

High resolution regional climate models are needed, coupled with hydrological models, to translate climate change scenarios into impacts on seasonal and overall water resources availability. These must be combined with modelling human demand for water resources.

The relative contribution to total discharge of snow and glacier ice melt decreases downstream along the Ganga, as monsoon precipitation increases. Impacts of climate change will therefore vary down the basin. Finding the right adaptation options at the right times for various places will indeed be challenging: what kinds of policy measures to regulate demand and allocation of water are necessary successfully to adapt to climate change?

Projects such as HighNoon and WATCH that aim at a transdisciplinary approach – combining tacit knowledge with scientific discovery - may well prove to be best suited for seeking sustainable strategies for adaptations in water utilisation as climate changes. The way forward must be to provide water resources policy makers not only more insight concerning expected changes in future climate and water availability but also with suitable adaptation strategies actually to be used to combat adverse impacts of climate change.

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