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Adaptation to changing water resources in the Ganges basin, northern India

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ABSTRACT

An ensemble of regional climate model (RCM) runs from the EU HighNoon project are used to project future air temperatures and precipitation on a 25 km grid for the Ganges basin in northern India, with a view to assessing impact of climate change on water resources and determining what multi-sector adaptation measures and policies might be adopted at different spatial scales.

The RCM results suggest an increase in mean annual temperature, averaged over the Ganges basin, in the range 1–4 °C over the period from 2000 to 2050, using the SRES A1B forcing scenario. Projections of precipitation indicate that natural variability dominates the climate change signal and there is considerable uncertainty concerning change in regional annual mean precipitation by 2050. The RCMs do suggest an increase in annual mean precipitation in this region to 2050, but lack significant trend. Glaciers in headwater tributary basins of the Ganges appear to be continuing to decline but it is not clear whether meltwater runoff continues to increase. The predicted changes in precipitation and temperature will probably not lead to significant increase in water availability to 2050, but the timing of runoff from snowmelt will likely occur earlier in spring and summer. Water availability is subject to decadal variability, with much uncertainty in the contribution from climate change.

Although global social-economic scenarios show trends to urbanization, locally these trends are less evident and in some districts rural population is increasing. Falling ground-water levels in the Ganges plain may prevent expansion of irrigated areas for food supply.

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Changes in socio-economic development in combination with projected changes in timing of runoff outside the monsoon period will make difficult choices for water managers.

Because of the uncertainty in future water availability trends, decreasing vulnerability by augmenting resilience is the preferred way to adapt to climate change. Adaptive policies are required to increase society's capacity to adapt to both anticipated and unanticipated conditions. Integrated solutions are needed, consistent at various spatial scales, to assure robust and sustainable future use of resources. For water resources this is at the river basin scale. At present adaptation measures in India are planned at national and state level, not taking into account the physical boundaries of water systems. To increase resilience adaptation plans should be made locally specific. However, as it is expected that the partitioning of water over the different sectors and regions will be the biggest constraint, a consistent water use plan at catchment and river basin scale may be the best solution. A policy enabling such river basin planning is essential.

1. Introduction

How future climate change will affect flows in rivers draining from Himalayan headwater tributaries is of serious concern for sustainability of downstream water resources throughout the densely populated Gangetic plain. Runoff from mountain basins is particularly likely to be susceptible to climatic warming as much of such flow is derived from melting of seasonal snow pack and glacier ice. Along the length of the Himalayan arc, however, runoff is influenced not only by snow- and ice-melt but also to varying extents by monsoonal precipitation, the timing, duration and amounts of which are likely to be modified by climatic change.

Under contemporary climatic conditions, relative contributions of monsoon precipitation and seasonal snow- and ice-melt to runoff from headwater basins vary with location along the arc and with elevation and topographic setting. Runoff from these headwater basins then contributes to the agglomerating downstream discharge of the major tributaries of the Ganges, swelled also by monsoonal rainfall over the lowlands in summer, so that the importance of snow-/ice-melt to total runoff declines with distance down basin. Nonetheless, snow- and ice-melt make significant contributions to total flow in both spring and fall so that changes in the ice-melt component of runoff as glacier area decreases with declining glacier mass will affect future water availability.

Snow and glacier melt contributions to major Himalayan rivers in India influenced by the monsoon are significant, with on average from 35% of annual flow, estimated for the Beas at Pandoh dam (Kumar et al., 2007), to 60% for the Satluj at Bhakra dam (Singh and Jain, 2002). According to Barnett et al. (2005), though, as much as 70% of the summer discharge of the Ganges is contributed by melting glaciers.

There are few analytical studies of the impacts of increasing melt and declining glacier area on runoff for the monsoon-dominated Himalaya. A first-order estimate suggests that the importance of seasonally delayed glacier meltwater runoff to water availability in large river basins, including the Ganges, is minor in monsoon climates (Kaser et al., 2010). Storage and release of water in the seasonal snow cover is however likely to be of more importance. Modelling approaches probably best partition snow and ice-components of runoff in large basins draining from the Himalayas (e.g. Immerzeel et al., 2010). For a 1–3 °C increases in air temperature, annual runoff declined by 4–7%, but the timing of snowmelt moved forward from summer to spring (Singh and Bengtsson, 2004) in the Satluj basin, north-west of the Ganges basin.

There is much discussion of the magnitude of recent climate change in the Himalaya (e.g. Bhutiyani et al., 2008; Krishnamurthy et al., 2009), but extreme events appear more frequently to affect the Ganges basin and create flooding (Bookhagen, 2010; Thayyen and Gergan, 2010; Goswami et al., 2006; Singh et al., 2008). Indications of change in the frequency of droughts are ambiguous (Burke and Brown, 2008). Uncertainty in trends on the basis of historic data in the Indus basin suggested that recent climate change had not affected available water resources (Archer et al., 2010).

Changes in water demand as well as changes in water availability may lead to possible conflicts between types of water usage. It is essential therefore in studies of water management to take into account future socio-economic changes driving water demand. Estimates of future water demand in India are driven both by projected population growth and by strong economic growth with the associated changes in desired quality of life. Gupta and Deshpande (2004) projected increasing water demand from 630 $km^3\ yr^{-1}$ in 1998 to 1450 $km^3\ yr^{-1}$ in 2050. Although irrigation is by far the largest consumer of water in India, its proportion of total water use is projected to decline, as a result of increasing water demand for other sectors (Gupta and Deshpande, 2004). Increased food-demand will have to be produced from the same land resource, or less, due to increased competition for land and other resources by non-agricultural sectors and degradation of agricultural lands due to water logging and salinization (Aggarwal et al., 2004). Intensification of current agricultural production will be required.

Integrated watershed development has emerged as an effective approach for augmenting water supply through conservation of rainwater in rain-fed farming systems. Watershed development has been given high priority in India, as evidenced by the fact that the country implements one of the largest watershed development programmes in the world. In more general terms, policy makers are challenged to design and implement adaptive policies which are robust enough to be useful in a rapidly changing and uncertain future. Useful tools for adaptive policy (re)design and implementation include: enabling self-organisation, decentralising decision making, promoting variation in policy responses, multi stakeholder deliberation, integrated and forward looking analysis, formal policy review, and continuous learning for improvements (Swanson and Bhadwal, 2009).

This paper aims to address the following questions: How are changes affecting water resources in the Ganges basin?, what policies are in place to address these changes? and what policies are needed to facilitate future challenges?

In this paper we give a short overview of current knowledge of present and future changes in water availability and demand as is being collected within the HighNoon project ‘‘Adaptation to changing water resources availability in northern India with Himalayan glacier retreat and changing monsoon pattern’’ (www.eu-highnoon.org). The HighNoon project assesses climate impact and multi sector adaptation measures at different spatial scales. The assessment of changes in water availability focuses on the Ganges basin as a whole (Fig. 1). Changes in water demand and policies are specifically addressed for northern India.

Section 2 describes expected changes affecting water availability in the Ganges. Impacts in the headwaters of the Ganges are discussed in Section 3, and changes in water demand driven by socio-economic changes, especially important for the lowlands, are discussed in Section 4. Section 5 describes the policies that are presently in place and assesses the challenges that have to be faced. Policy opportunities to enable efficient design and implementation of adaptation measures are then discussed in Section 6.

2. Changes in future climate in the Ganges basin

Global and regional projections of climate are the primary information source for assessing climate change impacts. However, global climate model (GCM) simulations often have too coarse a resolution to provide sufficiently detailed information to inform adaptation. This study uses regional climate model (RCM) runs from the HighNoon project to downscale from global model projections to the regional scale (25 km). Use of physically based models means that simulations are more representative of detailed processes and surface properties than statistical methods. In particular, higher resolution RCMs better resolve topography (Fig. 2) and improve simulated orographic precipitation. Ensemble runs of the 50 km resolution PRECIS RCM showed significant improvements in representation of regional processes over South Asia, including the monsoon, by comparison with the corresponding GCM (Rupa Kumar et al., 2006). RCMs have also been shown to be useful in providing historical regional climate information in data-poor regions like the Himalaya (e.g. Akhtar et al., 2010), allowing better understanding of current vulnerabilities.

To assess future uncertainty in climate for the Ganges we use an ensemble of 4 RCM simulations. The GCMs HadCM3 and ECHAM5 are both used to drive the two RCMs, HadRM3 and REMO (Jacob, 2001, 2009) to give the four simulations used in the HighNoon project. The two GCMs, chosen to be representative of the IPCC AR4 multi-model ensemble, were forced using the SRES A1B scenario. The SRES A1B scenario, the future projection used here, contains no mitigation and represents only one of several possible futures considered in the 4th Assessment Report of the IPCC (Christensen et al.,

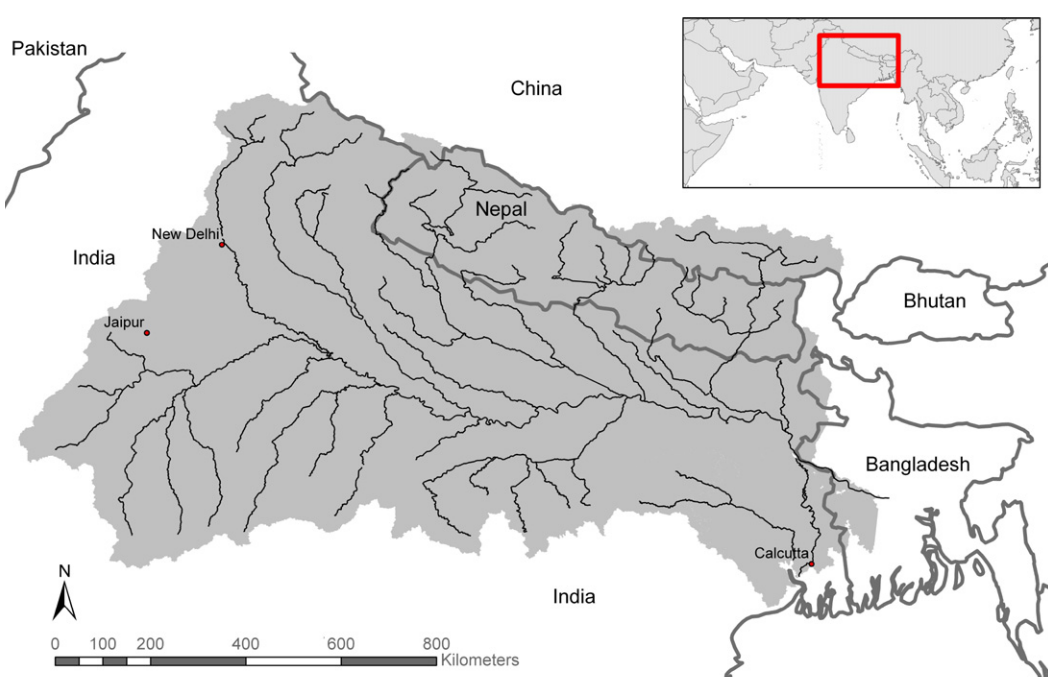

Fig. 1 – The Ganges basin case study area.

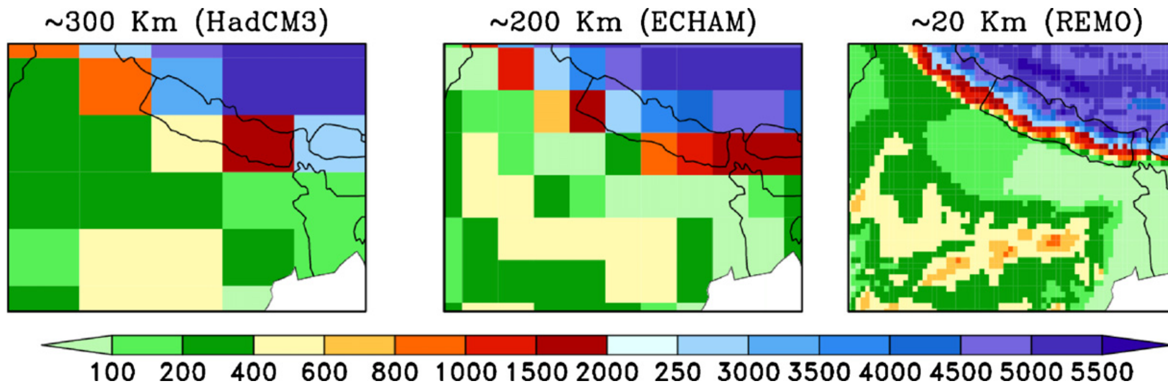

Fig. 2 – The effect of increasing resolution on the resolution of topography over the Ganges. Elevation ranges from <100 m to >5500 m above sea level.

2007). The regional model HadRM3 is based on the global HadCM3 model described by Pope et al. (2000). Some uncertainty is associated with the choice of future greenhouse gas emission scenario SRES A1B. However, it is unlikely, given inertia in socio-economic systems, that global mitigation will affect projected changes in the global climate in the coming decades.

The IPCC AR4 report shows that since the pre-industrial period the globe has warmed on average by ~0.7 °C, and, should atmospheric greenhouse gases be stabilized at year 2000 levels, future warming would be ~0.6 °C. Regional change can be strongly influenced by local processes and feedbacks such as land-use change and aerosol emissions, and hence deviate from the global mean change.

Fig. 3 shows the results from both the IPCC AR4 multi-model GCM ensemble and the ensemble of 4 RCMs used in this study. Averaged across the Ganges region, the climate simulations show a consistent warming, albeit with a large spread (Fig. 3a). The high-resolution RCM simulations are cooler by approximately 1.5 °C with respect to those of their forcing GCMs. This may be related to a stronger hydrological cycle leading to evaporative cooling. The projected warming between 2000 and 2050 given by the AR4 and RCM ensemble is in the range 1–4 °C.

The projected response of precipitation to a global rise in greenhouse gas emissions is more uncertain with few of the AR4 models able accurately to simulate the monsoon (Annamalai et al., 2007). The uncertainty in change in precipitation (Fig. 3b) is large with no consistent trend amongst simulations from the various models (Christensen et al., 2007). Down-scaling GCMs using RCMs improves the simulated precipitation patterns over the Indo-Gangetic plain, as a consequence of better orographic representation. The RCMs suggest an increase in annual mean precipitation in this region. However, the RCMs do not reduce the overall uncertainty in future projections of precipitation by comparison to the IPCC AR4 ensemble. The transport of water vapour, and consequent precipitation into the Ganges basin is determined by the large scale atmospheric circulation. The wide range of circulation patterns in the IPCC AR4 models contributes to the uncertainty in the predicted regional precipitation.

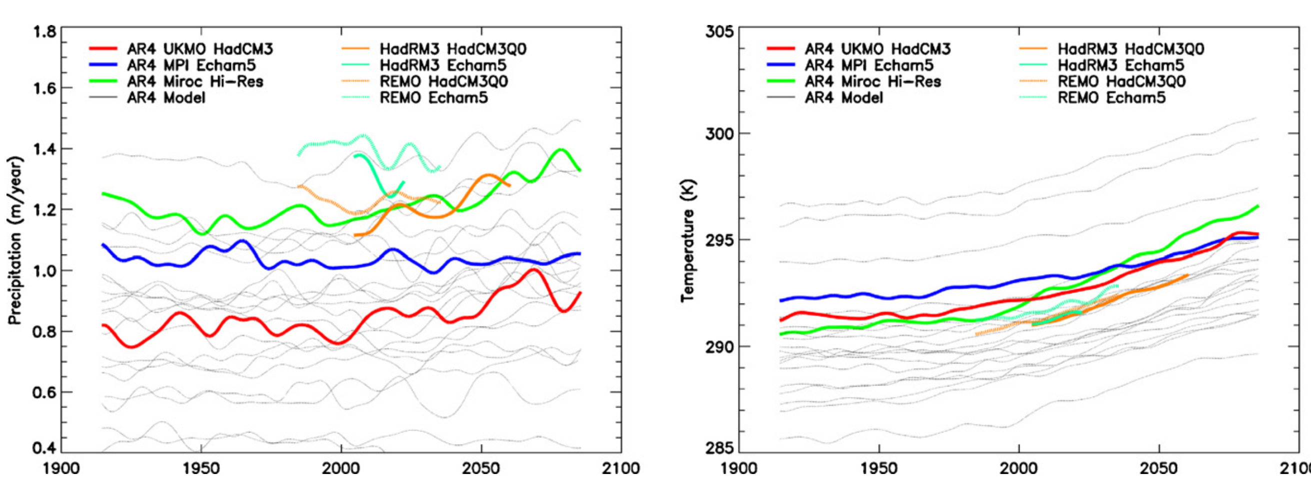

Fig. 3 – Annual precipitation (left) and temperature (right) time-series for the global AR4 multi-model ensemble (grey lines). Highlighting Echam 5 (blue), HadCM3 (red) and Miroc HiRes (green). Also shown are the high-resolution RCM simulations. The curves are filtered by a 30-year Gaussian weighted algorithm area-averaged over the land-only region shown in Fig. 2.

The simulations show significant natural variability in precipitation, in part associated with the Southern Oscillation (Kinter et al., 2002), and uncertain trends. The lack of a significant trend in future annual mean precipitation is consistent with recent observations in the central north eastern region of India (Pal and Al-Tabbaa, 2011). For shorter periods such as seasons or months, positive as well as negative trends have been reported based on actual observations (e.g. Subash et al., 2011; Pal and Al-Tabbaa, 2011). In addition a shift to higher intensity precipitation events has been observed (Krishnamurthy et al., 2009; Pattanaik and Rajeevan, 2010), suggesting enhanced risks associated with extreme rainfall. Further analyses of the RCM results will have to be made before firm conclusions can be drawn on the direction of these trends in the future.

3. Direct impacts in Himalayan headwaters

There is limited information concerning glacier mass balance in the Himalaya, and retreat rates are variable (Raina, 2009) so that it is difficult to assess the impact of climate change on glaciers. Between 2000 and 2008, more than 65% of monsoon-influenced glaciers that were observed by remote-sensing were retreating (Scherler et al., 2011). However, heavily debris-covered glaciers with stagnant low-gradient terminus regions typically have stable fronts. How glacier area changes as icemelt lowers the surface is an important variable necessary for predicting future meltwater yield as climate warms. In the short-term, as melt is enhanced, runoff first increases, but, as the area of ice starts to decline, in the long-term, the volume of water produced will decline, ultimately to a level related solely to the amount of future precipitation as the effect of the deglaciation discharge dividend is removed (Collins, 2008).

Assessing the 3-D geometry of glaciers remains an outstanding task for modelling future runoff in Himalayan tributaries of the Ganges. Rees and Collins (2006) used hypothetical glacier geometries in an attempt to model the impact of climate change on Himalayan glaciers. Summer monsoonal snowfall appears so to offset icemelt that reduction of meltwater runoff might be delayed in tributaries of the Ganges in contrast to the regime in the Indus basin, where glaciers in the Karakoram are less exposed to summer snowfall raising the albedo of glacier surfaces.

Modelling studies of the Western Himalaya for scenarios of temperature increases within the range of 1–4 °C suggest up to a 20% decrease in melt from snow-dominated catchments but an initial increase of melt up to ~30% from strongly glacierized catchments (Singh and Bengtsson, 2005). The latter increase will however be progressively offset by shrinking glacier area. Larger basins and the lowland areas integrate the effects of basins with snowmelt contributions with those of high-elevation catchments with icemelt arising to the proportion of basin covered with ice. It is likely that ongoing climate change will significantly affect seasonal patterns of stream discharge, especially with reductions in the summer (Singh and Bengtsson, 2004).

While changes in the inter-annual and intra-annual runoff variability have continuous impacts on water resource management, extreme hydrological events such as floods occur only periodically but can suddenly destroy many years of development effort and investment. Glacier lake outburst floods are on the upper scale of extremes (Dortch et al., 2011), and therefore may also be termed the extremes of extremes. The Himalayas are known as being periodically affected by extreme floods from glacier lake outbursts (GLOFs). Due to rapid changes in glacial and periglacial environments existing glacier lakes are growing and new lakes forming while others may disappear because of slow or sudden drainage. For a basin in Nepal, Bajracharya and Mool (2009) found an increase of glacier lake area in the Dudh Koshi catchment of up to a factor of 6 and more for the period 1962–2000, while the development of glacier lake area seems to be more variable in the 21st century so far (Bolch et al., 2008). In western Indian Himalaya, glacier lakes have grown at a relatively constant rate of about 5 ha/yr between 1990 and 2009 (Gardelle et al., 2011). Little is known about extreme floods from GLOF events in the Indian Himalaya. Ives et al. (2010) recently reported a total of 156 and 127 glacier lakes in Himachal Pradesh and Uttaranchal, respectively. The number of potentially dangerous glacier lakes is under debate but may be in the order of 10% of the total.

In terms of hazards it is important to consider that GLOFs have been observed to produce discharges 7–59 times higher than those of seasonal floods (Cenderelli and Wohl, 2001), and that damage may reach more than 100 km downstream. Maximum flood discharge can be on the order of thousands to tens of thousands of cubic meters per second for lake volumes of tens to over hundred million cubic meters (Cenderelli and Wohl, 2001; Xin et al., 2008). Recent fieldwork within the HighNoon project has concentrated on selected glacier lakes in Himachal Pradesh and confirmed that much stronger efforts combining remote sensing, ground surveys and advanced modelling methods are needed to facilitate risk assessment and necessary adaptation measures.

Based on daily rainfall data, amongst others Goswami et al. (2006) have shown that, while the amount of monsoon rainfall remained stable over the past century, a significant raising trend can be observed in the frequency and magnitude of monsoon rainfall extremes over the Indian subcontinent. There are suggestions (Kishtawal et al., 2010) that the changes in rainfall extremes may be related to land use change, in particular urbanization. Extreme rainfall recorded during the summer monsoon of 2010 not only caused floods in the main rivers, but also caused substantial flash floods, debris flows and landslides in Himalayan tributaries. In this sense, the 2010 events seem to confirm recent findings that very large ($>10^6$ m^3) landslides and periods of stronger fluvial dynamics in river valleys in the Himalaya of northern India would tend to occur much more frequently during periods of intensified monsoon rains (Dortch et al., 2009; Juyal et al., 2010). The strong link between landslide occurrence and monsoon activity over the Indian sub-continent, including the Himalaya, has also recently been shown by Petley (2010).

As shown in the previous section, climate models indicate a wide range of future precipitation changes over northern India. Notwithstanding, an increase in monsoon rainfall intensity must be considered, as suggested also by other recent studies (Rajendran and Kitoh, 2008; Sabade et al., 2011). Therefore, adaptation strategies should also focus on risk reduction measures in relation to devastating mass-movement events such as landslides, debris flow, or torrential floods that can severely impact mountain and fore-land communities.

4. Socio-economic changes and impacts on water and food demand, especially in the lowlands

A pressure on the available water resources only exists if the demand for water at a specific location and at a specific time cannot be met. India is a rapidly changing country where the demand for food and water will change as a result of fast population increase, industrialization and agricultural intensification. Therefore, it is not only important to estimate changes in water availability, but also in water demand caused by these socio-economic changes. Their combined effect will therefore determine the stress on available water resources that would exist across regions in any point of time, and hence which people and areas are vulnerable.

On a global scale climate and socio-economic scenarios are developed and updated in a consistent way, using integrated assessment models like IMAGE (e.g. Bakkes et al., 2008; Bouwman et al., 2006). Estimates of associated water demand for households, industry and livestock are calculated with the WaterGAP model (Alcamo et al., 2003) (Fig. 4). As the water demand scenarios presented here are developed for global scale applications, they do not incorporate heterogeneities within the country. District scale scenarios for population development, water demand and land use are being developed within the HighNoon project and will be used to improve the spatial representation of heterogeneity in water demand.

Water demand for irrigation is influenced by different factors like the total extent of irrigated area, the cropping pattern, the efficiency of the irrigation system and the climate dependent evaporative demand. Unfortunately, future scenarios of land use change for India or the Ganges basin (including cropping patterns and irrigated areas) do not yet exist. However, with an increase in the population the demand for food is likely to increase in future. Thus there has to be an increase in the food production for the country to meet the growing demands. This increasing food production will have to be based on a mix of approaches, through an intensification of current agriculture or imports when there are huge deficits.

One of the options to meet a growing food demand is increasing crop production by expanding irrigated area. The effect of expanding irrigated area on water demand, sources to extract this water as well as effects on crop yields has been evaluated by using an integrated vegetation and hydrology model, LPJmL (Biemans et al., 2011; Fader et al., 2010; Rost et al., 2008). In this land use change example, all current rain fed crop areas are changed to irrigated. According to calculations with LPJmL, the water demand for irrigation would increase from 383 to 953 $km^3 yr^{-1}$ i.e. 2.5 fold higher (Fig. 5). However, the available surface water and water from reservoirs cannot supply all of this demand (Fig. 5). Most of the additional supply should come from "other sources", e.g. groundwater or interbasin transfers. The total crop production could grow with 90%, if all crops would be fully irrigated, well above the estimated greater demand for food grain requirement in the region of almost 50% by 2020 (Paroda and Kumar, 2000).

Decline of the groundwater table has been observed in many parts in the Ganges basin. The average rate of decline is about 0.15 $m\,yr^{-1}$ in the western Ganges plains and in some places as high as 0.35–0.4 $m\,yr^{-1}$ over the period 1994–2005 (Samadder et al., 2011). Based on the GRACE satellite data, Rodell et al. (2009) estimated a depletion rate of the groundwater aquiver at $0.04 \pm 0.01\,m\,yr^{-1}$ equivalent height of water over the period 2002–2008. They attributed this depletion mainly to irrigation and other anthropogenic use. Groundwater usage as a percentage of recharge decreases down the Ganges basin from more than 100% in the states in the western part to 30% near the outlet. This trend in lowering groundwater tables in combination with the increasing future need of especially irrigation water requires adaptation of the current water management and supporting policies.

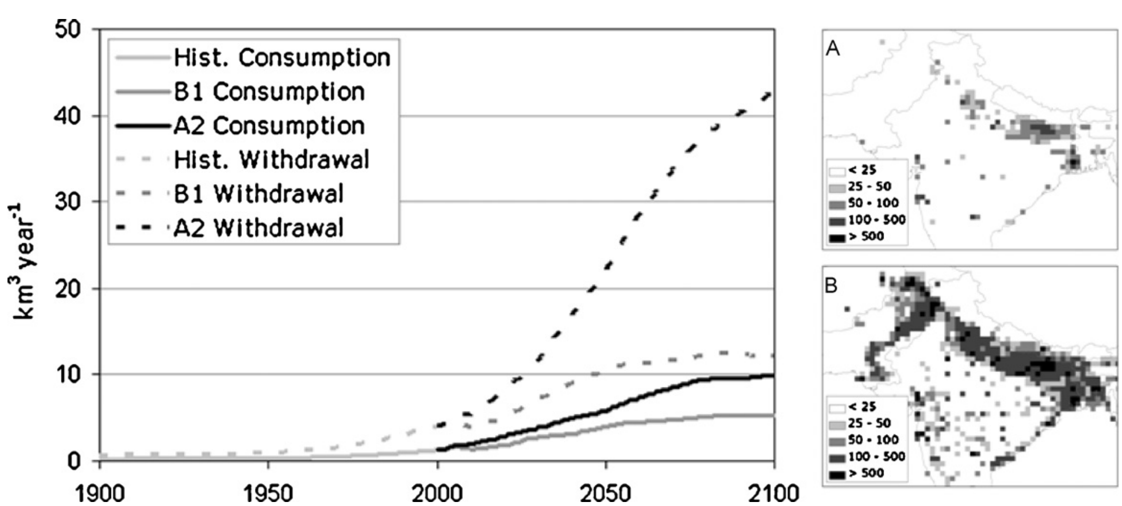

Fig. 4 – (left) Annual withdrawal and consumption of water for industry, households and livestock in the Ganges–Brahmaputra basin as calculated by the WaterGAP model for the EU WATCH project (in $km^3 yr^{-1}$). (right) Spatial distribution of this water consumption in 1971–2000 (A) and 2036–2065 for the A2 scenario (B) in million cubic meters per year.

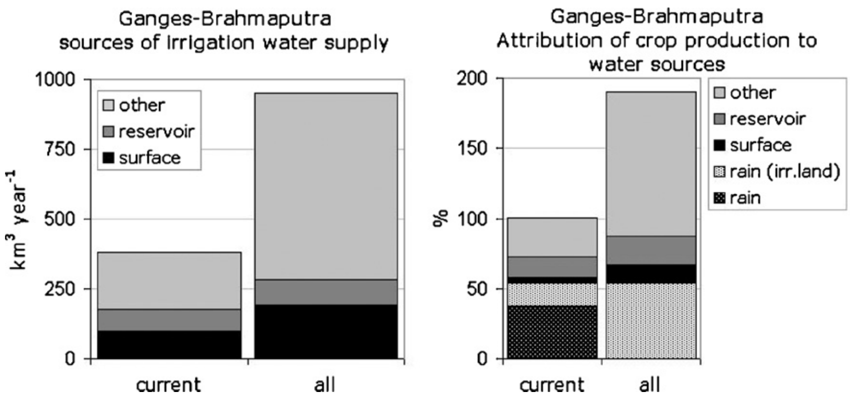

Fig. 5 – (left) Sources of irrigation water for current irrigated areas, and if all current crop land would be irrigated. (right) Attribution of crop production to the different sources of water on current cropland (rain fed and irrigated) and if all current cropland would be irrigated.

5. Current policy frameworks in relation to climate change

5.1. *Policies affecting water availability and water distribution*

India's National Action Plan on Climate Change (NAPCC) was released in 2008 and sets eight national priority missions for adaptation and mitigation. This includes the National Solar Mission, National Mission on Enhanced Energy Efficiency, National Mission on Sustainable Habitats, National Water Mission, and National Mission on Sustaining the Himalayan Ecosystem, National Mission for a 'Green' India, National Mission for Sustainable Agriculture and the National Mission on Strategic Knowledge for Climate change. The NAPCC is an inclusive and sustainable strategy launched by the Government of India that is sensitive to climate change concerns and indicates a directional shift in India's development pathway. Of the eight missions that have been announced, three missions are known to have a direct relevance from an adaptation point of view and all of these either focus on the subject of Water, Sustainable Agriculture or on the concept of Himalayan Ecosystems. Following the NAPCC, a directive was issued from the national level to all states of India in early 2010 to prepare the State Action Plans on Climate Change. These are in line with the NAPCC and formulated with the objectives to:

- Identify regions where investment inputs are required
- Allocate resources to address climate concerns
- Identify institutional structures
- Mainstream the policy development framework

With the aim to utilize water more effectively and avoid wastage of water, the National Water Mission indicates the need to enhance water use by 20% (MWM, 2009). This shall also address the reduced availability of water and the increased demand. However, apart from the policies, legislative actions need to be taken, to be able to meet the deficits. These legislative actions would be essential tools not only from the point of view of avoiding water wastage, but also from the point of view of polluting the existing sources that are accessible for use for various purposes.

With a large share of India's population dependent on agriculture and the perspective that there would be an increase in the food demand with the yet so ever increasing population, the agriculture sector in India remains to be of vital importance. Some of the government's ongoing programmes for sustainable agriculture may well help to improve the resilience of the agricultural sector to extreme weather events, including future trends and variability. Examples of measures being part of the sustainable agriculture programme, and having the capability increasing adaptive capacity are:

- Drought-proofing measures through water storage and rainwater harvesting
- Promotion of integrated pest management
- Promotion of zero-tillage practices
- Development of drought-resistant varieties
- On-farm water management and promotion of water conserving technologies like drip and sprinkler irrigation
- National Agriculture Insurance Scheme

The National Water Policy (NWP) formulated by the Ministry of Water Resources, Government of India (GoI) is the guiding document for planning of water resources in the country. The NWP^{2002} incorporates the vast experience in water management across the country and aims at laying a roadmap for water resource planning. The policy does recognize the need for a change in the management of water resources in lieu of the severe threat to the resource due to multiple pressures. Further the policy also mentions the menace of floods and droughts across the country with one-sixth of the country being drought prone and over 40 million hectares being flood prone and the need for a coordinated effort at the national level for management of such extreme events. It lays emphasis on use of hydrological boundaries like watershed/river basin for planning of water resources rather than administrative boundaries while planning for development of water resources.

It also calls for non-conventional methods of resource utilisation such as inter basin transfers, groundwater recharge and use of brackish/sea water. It also advocates the use of watershed management approach through extensive soil and water conservation measures with the objective of conserving water within the catchment itself.

However there are certain limitations within the policy frame, though the National Water Policy does discuss the multiple pressures being faced by the resource it does not include the impact of climate change on availability of water resources and extreme events. This is particularly challenging given the uncertainties in future climate. The NWP[2002] emphasises the importance of flood and drought control measures. It does not, however, address issues related to vulnerability of various subgroups to such extreme events and the adaptive strategies that communities need to establish.

The National Water Policy needs to incorporate various measures that will have to be undertaken to increase the adaptive capacities of various subgroups especially farmers. It has been felt by the Ministry of Water Resources that special attention should be addressed to vulnerable areas and groups to be able to adapt to increased frequency of climate related extreme events like droughts and floods. Instruments like crop diversification, efficient irrigation systems, conjunctive use of surface and groundwater, reuse of wastewater etc. needs to be encouraged. Appropriate incentive mechanisms need to be devised for this purpose. These requirements have been realized and as part of the National Water Mission (NWM, 2009), it is contemplated to revise the present Nation Water Policy and a comprehensive process to this effect has already been initiated by the Ministry. The need for revamping the river conservation programme was widely recognised in view of the shortcomings in the approach followed in GAP. It was felt necessary that a new holistic approach based on river basin as the unit of planning and institutional redesign may be adopted. Accordingly, the Government of India has given Ganges the status of a National River and has constituted the National Ganges River Basin Authority in 2009 (Government of India, 2009). The NGRBA is a planning, financing, monitoring and coordinating body of the centre and the states with Prime Minister as the Chairman. The objective of the NGRBA is to ensure effective abatement of pollution and conservation of the river Ganges by adopting a river basin approach for comprehensive planning and management. Such cooperation for an effective abatement of pollution and conservation of the river Ganges is in line with what is prescribed in EU Water Framework Directive on transboundary cooperation on water protection and management (European Community, 2002).

5.2. *Challenges for IWRM*

It is important that adaptation options are founded on sound scientific knowledge. For example, intents such as 'harvest every drop where it falls' might be dangerous from an ecological and environmental angle. Such action has the capability of bringing about biophysical changes to the extent that the total character of the existing hydrological regime is changed and there might not be adequate surface flow available any more to the downstream areas to carry out the environmental functions. It must be understood that every area has a prevalent water balance and any intervention caused is bound to change its local water balance, the extent of which is dictated by many factors including the local biophysical characteristics and weather conditions. It is unfortunate that the emphasis in watershed development programmes is still firmly based on the belief that water is essentially an infinite resource and can be managed through the continual development of groundwater abstraction together with the implementation of water harvesting techniques.

The difficulties in disseminating knowledge, experience, scientifically validated information and methodologies are aggravated by the lack of any common framework between states and their departments. Integrated watershed management does not merely imply the amalgamation of different activities to be undertaken within a hydrological unit. It also requires the collation of relevant information at various scales so as to evaluate the cause and effect of all the proposed actions (Gosain and Rao, 2004). The river basin is considered as the highest level of the drainage system, the catchment as the intermediate level and the watershed as the lowest level. The evaluation of man-induced impacts upon natural resources with respect to the water balance approach becomes only possible when taking these natural units into consideration. Hence, the watershed is the smallest unit at which an integrated management of the water resources is feasible. Such an integrated management of water resources could enable the transfer from surface water storage to managed aquifer storage. Managed aquifer storage is considered as one of the adaptation options to improve water availability in general and address region specific changes in precipitation distribution and increased evaporation rates (Shah, 2009). Prevention of overexploitation may be stimulated by regulating the power supply for farmers.

As the impacts resulting from actions taken at the watershed level will be experienced at a higher level within the drainage basin, the assessment of these impacts will require the availability of a framework which enables the mapping of such units and their entities and the interconnections from River Basin at the highest level of drainage system to catchment at the intermediate level and the watershed at the lowest level. Such a framework will need regular maintenance and updating to reflect fully the most accurate ground-truthed data or the infrastructure requirements for planning and management of the natural resources. This framework, once available, could be used by all the line departments and updated by the relevant departments which have designated areas of jurisdiction over the data entry. Such a framework shall also be used to enumerate the freshwater ecosystem services each system is providing as well as integrating the demands of other sectors such as industrial and domestic. An initial attempt has been made in creating a common framework (see e.g. http://gisserver.civil.iitd.ac.in/natcom).

6. Policy opportunities to enhance adaptation to climate change

Recently, the debate on policies supporting climate change adaptation in India is enriched by the outcomes of a large study on adaptive policy mechanisms (Swanson and Bhadwal, 2009). Today's policy makers have to perform under highly complex, dynamic and uncertain conditions. Even though several main trends regarding socio-economic development and climate change in the Ganges basin seem rather clear (an expected rise in temperature over the coming decades of some 1–2 °C in 2050s, a large increase in population) there is still much uncertainty (on changes in precipitation, water demand as a result of socio-economic change) (e.g. Archer et al., 2010). Moreover, large scale trends are difficult to translate to regional and local scale impacts as is the translation from averages and the changes in these averages to changes in variability and extremes (Terwisscha van Scheltinga and Van Geene, 2011; IPCC, 2007; Adger et al., 2007). To effectively support adaptation to climate change under these dynamic and uncertain conditions and proceeding at several levels and sectors simultaneously, there is a role for public policy (Adger et al., 2007). Such policy includes reducing vulnerability of people and infrastructure, providing information on risks for private and public investments and decision-making, and protecting public goods (Adger et al., 2007).

Based on a large study on public policies in the context of global climate change in Canada and India, Swanson and Bhadwal (2009) put forward the need for adaptive policies which are robust enough to be useful in a rapidly changing and uncertain future. They contend that mainstream policies assume a predictable and manageable future using static policies. However as policies are often faced with unexpected challenges outside the range of conditions for which they are designed, a more adaptive approach that understands and appreciates the complexity of socio-economic and ecological systems is required. Tools for developing and implementing adaptive policies include integrated and forward looking analysis, multi stakeholder deliberations, automatic policy adjustment, decentralization of decision making, promoting variation, enabling self organization, formal policy review and continuous learning (Swanson and Bhadwal, 2009; Pahl-Wostl et al., 2008; Bankes, 2002; Holling, 2001).

Policies geared at increasing the adaptive capacity of people are crucial as a society's ability to effectively undertake adaptation strategies is largely a function of its ability to respond successfully to climate variability and change (Adger et al., 2007). Where adaptive capacity is limited, the potential benefits of specific adaptations may be quite limited. For example, an extreme weather warning system is of limited value if the people at risk have no televisions or radios, or no means of evacuation.

One clear result from research on adaptive capacity is that some dimensions of adaptive capacity are generic, while others are specific to particular climate change impacts. Generic indicators include factors such as education, income and health. Indicators specific to a particular impact, such as drought or floods, may relate to institutions, information and the ability to develop new technology (Burton et al., 2006). The assessment of institutions on their ability to enhance the adaptive capacity of society received little attention until recently. A comparison of national adaptation strategies of different European countries showed that multi-level institutional problems may be a greater challenge then finding the appropriate technical solutions for climate change (Biesbroek et al., 2010). Recent research on institutions promoting adaptation to climate change revealed that dimensions such as leadership, the ability to adjust, the learning capacity, fair governance and embracing variety heavily influence a society's capacity to adapt to new or anticipated risks of any type (Gupta et al., 2010).

In the Fourth IPPC assessment report much attention is given to the insight that the capacity to adapt to climate change is unequal across and within societies and is uneven within nations. New policies should be assessed in terms of their potential impacts on adaptive capacity, particularly for groups and systems that already exhibit high vulnerability and/or exposure to climate hazards. The impacts of policies on systems and communities in sensitive ecosystems, such as coastal and riverine zones, should be given special attention (Adger et al., 2007).

In the climate change context, the term 'mainstreaming' is increasingly used to refer to needs for climate change adaptation policies to be integrated or to be consistent with other related government policies and programmes such as water management, land-use planning and particularly sustainable development (e.g. Van Aalst and Helmer, 2004). As the adaptation challenge cuts across a wide range of policy areas, ministries and other stakeholders need to operate at the intersection of policy areas. Application of this principle appears difficult in practice due to compartmentalisation of government departments, barriers in the cooperation between government and development-cooperation agencies and trade-offs between climate and development objectives.

As adaptation to climate change is a relatively new policy issue, the policy instruments for dealing with climate change are still in the process of developing. New forms of public governance based on the principle of (knowledge) co-creation and joint fact finding show promising results. Such approaches will also contribute to (partly) overcome the barrier of uncertainty in future trends as is now often faced in decision-making. One means of more closely integrating adaptation into policy decision-making would be the systematic application of climate risk assessment to projects. Proposed investments could be assessed for their own vulnerability to climate variability and climate change and for any broader effect on climate vulnerability within the host country. As with the environmental impact assessments now performed routinely by multilateral lenders, this would in the first instance provide critical information to decision-makers and would help them to assess whether proposed investments face significant climate risk. The World Bank Screening Tool ADAPT (Assessment & Design for Adaptation to Climate Change) is an example of a software based tool for assessing development projects for potential sensitivities to climate change. The use of the tool provides policy makers and project managers with a summary of the climate trends from global climate model projections at a project site. It identifies components of the project that might be subject to climate risk; explains the nature of the risk; and provides guidance to further assistance (see http://beta.worldbank.org/climatechange/content/additional-tools-adaptation (World Bank, 2011)).

The HighNoon project purposefully applies some of the principles of adaptive policies and aims to increase the adaptive capacity of stakeholders involved in the development of multi sector adaptation strategies. Forward looking analysis tools such as the so called Shell scenario method (Cornelius et al., 2005) will be used to encourage stakeholders to think in terms of multiple possible futures and to identify adaptation options that are relevant and robust for a range of future scenarios. Multi stakeholder deliberations will be organised to assist stakeholders in self-assessing past and current coping strategies as a basis for identifying adaptation strategies to better deal with climate change. Negotiations will be facilitated to set priorities amongst adaptation strategies. Such a participatory approach to adaption to climate change will contribute to increase the awareness of climate change which is an important precondition for increasing the adaptive capacity of a society.

7. Summary and conclusions

The RCM results for northern India project an increase in mean annual temperature of 1–4 °C between 2010 and 2050. There is no clear indication of a climatically induced change in annual mean precipitation by 2050, due to strong natural variability. We find that changes in the future water availability are mainly determined by decadal variability, with great uncertainty in the contribution from climate change.

The seasonal water availability depends not only on precipitation but also on snow and glacier melt. Through the detailed modelling of the melt from Himalayan glaciers, feeding into hydrological models of the Ganges, an improved assessment of future changes in the seasonality of water is needed.

The total water demand mainly depends on the agricultural use. Crop production could see a 90% growth by 2020, if all crops were fully irrigated, 50% above the projected food requirement for the region. However, the available surface water and water from reservoirs will not supply such a demand. Most of the additional water would have to come from ''other sources'', e.g. groundwater or inter-basin transfers. District scale scenarios for population development, water demand and land use are being developed within the HighNoon project and will be used to improve the spatial representation of heterogeneity in water demand.

Since water availability is expected to vary on decadal timescales, the State National Action Plans on Climate Change will be an important policy with the aim to utilize water more effectively and avoid wastage. However, legislative actions also need to be taken, not only to be able to meet the deficits and to handle periods of surplus, but also to assure good water quality.

Existing programmes such as for sustainable agriculture and the National Water Policy or the Jyotigram scheme (Shah et al., 2008) are potentially instruments that may help to increase the adaptive capacity of these sectors. The HighNoon project will address the requirements of vulnerable areas and groups, to enable them to adapt to variability of water availability, and deal with the risks associated with glacial lake outbursts in the headwaters of the river basin. Appropriate incentive mechanisms will be devised for this purpose.

Climate change introduces huge unknowns for policymaking. Increasing the capacity of society to better cope with an uncertain future is imperative. Public policies can help build this capacity. However, a key challenge for this to occur is to design adaptive policies with the ability to adapt to both anticipated and unanticipated conditions. The HighNoon project purposefully applies some of the principles of adaptive policies by applying forward looking approaches to encourage stakeholders to think in terms of multiple possible futures, and to identify adaptation options that are relevant and robust for a range of future scenarios.

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