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Opportunities for harnessing the increased contribution of glacier and snowmelt flows in the Ganges basin

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Abstract

The topography of the Ganges basin is highly variable, with the steep mountainous region of the Himalaya upstream and the large fertile plains in eastern India and Bangladesh downstream. The contribution from the glaciers to streamflows is supposed to be significant but there is uncertainty surrounding the impact of climate change on glaciers. An application of the Water Evaluation and Planning model was set up which contained an experimental glaciers module. The model also examined the possible impacts of an increase in temperature. The contribution from glaciated areas is significant (60–75%) in the Upper Ganges but reduces downstream, falling to about 19% at Farakka. Climate change-induced rise in temperature logically increases the quantity of snow and ice that melts in glaciated areas. However, this impact decreases from upstream (+8% to +26% at Tehri dam) to downstream (+1% to +4% at Farakka). Such increases in streamflows may create flood events more frequently, or of higher magnitude, in the upper reaches. Potential strategies to exploit this additional water may include the construction of new dams/reservoir storage and the development of groundwater in the basin through managed aquifer recharge. The riparian states of India, Nepal and Bangladesh could harness this opportunity to alleviate physical water scarcity and improve productivity.

Keywords: Ganges basin; Managed aquifer recharge; Snow and glacier melt; Water Evaluation and Planning (WEAP) model

1. Introduction

The Ganges basin in South Asia is a large basin with good supplies of both surface and groundwater but it faces wide economic and physical water scarcity. The Ganges basin is the world's most populous basin with more than 500 million people inhabiting it in 2001 (average population density of 520 persons per km^2) with an expected rise to 720 million by 2025 (Pun, 2004). Large populations place considerable pressure on the availability of freshwater resources. Land and water productivity for

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most crops and fisheries is low and the population dependent on agriculture (>85%) is very poor (Sharma *et al.*, 2010). The Ganges basin is about 1.09 M km^2, distributed between India (79%), Nepal (13%), Bangladesh (4%), and the rest in Tibet (China). The topography of the Ganges basin is highly variable, with a steep mountainous region of the Himalaya upstream and large plains in eastern India and Bangladesh downstream. The primary source of water resources of the Ganges river is the Gangotri glacier near Gomukh (Uttarakhand, India) at an elevation of about 4,010 m above mean sea level. As the Ganges river flows 2,525 km from its headwater to the Bay of Bengal, its flow increases from large tributaries originating in Nepal and Tibet, including the Mahakali, Gandak, Koshi and Karnali and decreases as a result of large canal diversions (Hosterman *et al.*, 2012). Surface water resources of the Ganges (i.e. its long-term mean annual flow volume as it enters the Bay of Bengal) have been assessed at 525 BCM (billion[1] cubic meters). The alluvial deposits from the river system have formed the vast fertile Gangetic plains (Jain *et al.*, 2007). In the Ganges basin, the main source of water is the (south-west) monsoon rainfall, and also the snow and ice melt in the Himalaya during the summer season. More than 70% of the annual rainfall is received from the south-west monsoon (June–August). Spatial variation can be noticed, annual precipitation increasing as we move eastward, varying from 350 mm in the west to about 1,500 to 2,200 mm in the delta region (Mirza, 1997). The mountainous catchments of Chisapani, Devghat, Kampughat and Everest are marked with high precipitation, which exceeds potential evaporation (Kirby *et al.*, 2009). During the dry months of December to February, water supply declines significantly with reduced outflow to the delta region in Bangladesh (Islam & Gnauch, 2007). During these dry months, snow and ice melt from the region's mountains are critical. The transboundary water sharing between India and Bangladesh is regulated by the Ganges Water Treaty (1996). This treaty has the limited purpose of sharing the waters during the dry season only, from January to May each year (Chowdhury, 2010).

The Ganges basin receives a net annual input of 1,170 BCM and, after all the uses in the basin have been satisfied, net runoff from the basin is about 429 BCM (37% of the input). The Ganges basin is one of the most heavily cultivated areas in the world and vitally important to food security in South Asia. Agriculture production varies throughout the basin and different regions rely on distinct combinations of rainfed systems, and surface and groundwater irrigation, to support crop growth (Hosterman *et al.*, 2012). Rainfed agriculture in the basin covers almost 52% of the basin area, with a mean annual use of 372 BCM (32% of water used). Irrigated agriculture covers 25% of the basin, with 17% of the total area irrigated from surface water resources and 8% from groundwater (210 BCM, 18% of total water use). Most of the irrigated water used is for crops irrigated with surface water (70%), with the remaining 30% from groundwater irrigated crops (Kirby *et al.*, 2006a, b; Eastham *et al.*, 2010). In the upper mountainous catchments, agricultural production is low and mixed with livestock systems. Agricultural production is intensive and highly developed in the western portion of the basin and relies heavily on large-scale surface water diversion canals from the Ganges, and on groundwater irrigation to produce rice, wheat, sugarcane and other crops. Land and water productivity in the rice–wheat systems is relatively high in this region (Cai & Sharma, 2010). Farmers in the eastern portion of the basin (eastern Uttar Pradesh, Bihar and West Bengal states in India, the Nepal Terai and parts of Bangladesh) primarily produce rice, wheat, maize, vegetables and fish. Yet, despite the abundance of surface water and the prolific groundwater aquifers, productivity has remained low due to the limited

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[1] In this paper, 1 billion = 1×10^9.

development of water and other infrastructure, small farm size and high population density, and frequent flooding and poor drainage (Dixit, 2009; Sharma *et al.*, 2010). As such, large populations have remained poor and vulnerable. Unfortunately, the high seasonal concentration and variability of precipitation are predicted to increase the intensity and frequency of extreme events, with the potential for increased flooding during periods of high precipitation (Bates *et al.*, 2008). These predictions have not yet taken into account the impact of snow and glacier melt on the streamflows.

The water quality position of the Ganges is dismal, particularly in the plains, due to point source pollution caused by the discharge of sewage and industrial wastewater from major cities like Delhi, Agra, Kanpur, Varanasi, Patna and Kolkatta, and from arsenic contamination in the downstream regions in West Bengal and Bangladesh (Chakraborti *et al.*, 2004).

2. Contribution of snow and glaciers

The primary source of water in the Ganges basin is the summer monsoons and snow and ice melt from the Himalayan mountains. Himalayan basins have considerable snow- and glacier-covered areas (~40,000 km^2; Raina & Srivastava, 2008). Significant proportions of annual precipitation fall as snow in the high Himalayan mountains and, over long periods of time, the snowfall has built up into glaciers which are semi-permanent reservoirs of water preserved as ice. Snowpacks accumulate during the winter periods to be released as melt waters during spring and summer, giving a distinct seasonal rhythm to annual flow regimes in streams. The Ganges river, located in the monsoon climate, receives much of its snow during the summer; this snow is then melted almost immediately to contribute to streamflow. The release of water stored as glacier ice is particularly significant in years of low precipitation and during the late summer period when seasonal snowpacks have largely melted. Thus, glaciers provide a buffering effect on streamflow, acting as regulators and providing insurance against times of low flow (Singh *et al.*, 2011). During the dry months (December to February), snow and ice melt from the mountains is critical. However, while in the short-term glacier melt will provide extra water to the rivers, in the longer term (when those ice masses melt out) the extra water will no longer be available and the all-important buffering effect will disappear.

Snow and ice comprise 2.4, 0.5 and 0.04% of the Ganges source (2,004 km^2), Ghaghara (570 km^2) and Upper Yamuna (11 km^2) catchments, respectively. The Ganges basin has a total of 1,020 large glaciers (WWF, 2005). The International Centre for Integrated Mountain Development (ICIMOD) estimated a total of 7,963 glaciers covering an area of 9,012 km^2 and with a total ice reserve of 793.53 km^3 for the Ganges river system (Bajracharya & Shreshtha, 2011). Various studies examining the Himalaya have quantified the changes using detailed climate–snowmelt models to estimate the contribution of glaciers to the Ganges river; one such study arrived at a value of 9% on an annual basis (Jianchu *et al.*, 2007). However, there is a wide variation among the different studies. More importantly, these contributions are quite large in the upstream catchments and become less important downstream. With the debate over melting glaciers in the Himalayan region becoming more pronounced (Ren *et al.*, 2006; Kulkarni *et al.*, 2007; Prasad & Singh, 2007; Solomon *et al.*, 2007; Jain, 2008; Kehrwald *et al.*, 2008; Gautam *et al.*, 2009; Lau *et al.*, 2010) and with the paucity of data for very precise process-based studies, there is an urgent need to study this aspect in a basin-wide mode. Such an analysis would help to identify the impacts of future climate change on water resources and opportunities for harnessing the potential benefits.

The present study is an attempt to provide a preliminary analysis of the following research questions:

(i) What are the potential contributions of glacier and snow melt to the flows of the Ganges basin in the context of climate change?
(ii) What are the potential impacts of the additional water, from glacier and snowmelt, on trans-boundary water sharing?
(iii) What are the available opportunities for harnessing the potential impacts?

3. Methodology and data

The assessment of water resources and the impact of climate change on changes in their availability have been studied in the past by employing a number of models such as the Soil Water Assessment Tool (SWAT) (Mulligan *et al.*, 2011), NASA fvGCM (Lau *et al.*, 2010), GOCART (Yu *et al.*, 2010) and by employing general mass balance equations. However, most of these models are highly data intensive and cannot be employed under the data scarce conditions of the Himalaya. We applied the Water Evaluation and Planning (WEAP; http://www.weap21.org/) model, which contains an experimental glacier module that accounts for snow and glacier processes in the Ganges basin, i.e. seasonal mass variations and contributions to streamflow. The WEAP system is an initiative of the Stockholm Environment Institute. It emerged from the water resources management modelling tradition, where the focus is on simulating the management of built hydraulic infrastructure and the implementation of regulatory regimes in a multi-objective setting, based on assumed hydrologic input information. WEAP employs a unique approach where a database maintains water demand and supply information to drive a mass balance model on a link-node architecture. As climate change becomes an increasingly important challenge facing water managers, WEAP has expanded to include integrated hydrologic simulation functionality. The simulation calculates water demand, supply, runoff, infiltration, crop requirements, flows and storage. With this enhanced version, dynamically integrated rainfall/runoff routines translate information on climate and catchment conditions into hydrologic fluxes that drive the existing water system simulation routines (Yates *et al.*, 2005). It has been applied to various regions in the world, such as North and South America (e.g., Null *et al.*, 2010; Sandoval-Solis *et al.*, 2011), West Africa (e.g., de Condappa *et al.*, 2009) and the Middle East (e.g., Al-Omari *et al.*, 2009). It has also been coupled with MODFLOW to enable a dynamic planning of surface and groundwater (Droubi *et al.*, 2008). Recent work in the Andes and the Himalayan regions has allowed for the integration of a glacier routine into these rainfall/runoff calculations by employing the degree-day method.

The WEAP model helped to: (i) simulate the surface water resources in the Ganges basin with special focus on the contribution from snow and glacier melting, as well as the anthropogenic utilization of the resources; and (ii) enable an effortless development of prospective scenarios to climate change (increase in temperature). The first step was to gather the input data, such as the digital elevation model (DEM), land use, climate time series, observed streamflows, glacier coverage and water diversions/uses in the Ganges basin. The basic units of modelling were the sub-basins, sub-divided by elevation bands. The Ganges basin was discretised with respect to elevation so as to account for the variation with altitude of the glacier coverage and climate. In the second step, WEAP was calibrated and partly validated on observed streamflows. The task of setting WEAP-Ganges meant validating the hydrological objects so as to reproduce the observed streamflows at the outlet of the given sub-basin. As time series of observed streamflows and glaciers area were not available, the WEAP application developed in the study could not precisely model the processes and, instead, provided general trends. In a third step, we applied WEAP to analyse the current context of the surface water resources in the Ganges basin, in particular the contribution from the melting of glaciers. We also examined possible impacts of an increase in temperature of +1, +2, or +3 °C over 20 years.

The data for the streamflows were obtained from the Global Runoff Data Centre (GRDC, 2008), Global River Discharge (RivDIS; Vorosmarty *et al.*, 1998) and the Research Data Archive maintained by the Computational and Information Systems Laboratory at the National Centre for Atmospheric Research, USA; dataset ds552.1 was chosen. Additionally, the datasets available from the International Water Management Institute for the Upper Koshi (Nepal part) and Upper Ganges were used. The DEM was the version from the Shuttle Radar Topography Mission, pre-processed by Jarvis *et al.* (2008). The information required for the glaciers module of WEAP is the time variation of the glaciers' area. The Global Land Ice Measurement from Space (GLIMS) and geographic information system (GIS) files from the Indo-Gangetic Basin Tool Kit (IGanges basin Tool Kit; www.iwmi.org) provide the glacier coverage at a given date. These sources were finally chosen, though there are certain differences between both datasets (Figure 1). The WEAP glaciers module also requires the degree-day coefficient for ice and the snow coefficient governing the melting rate from snow packs and glaciers. The values

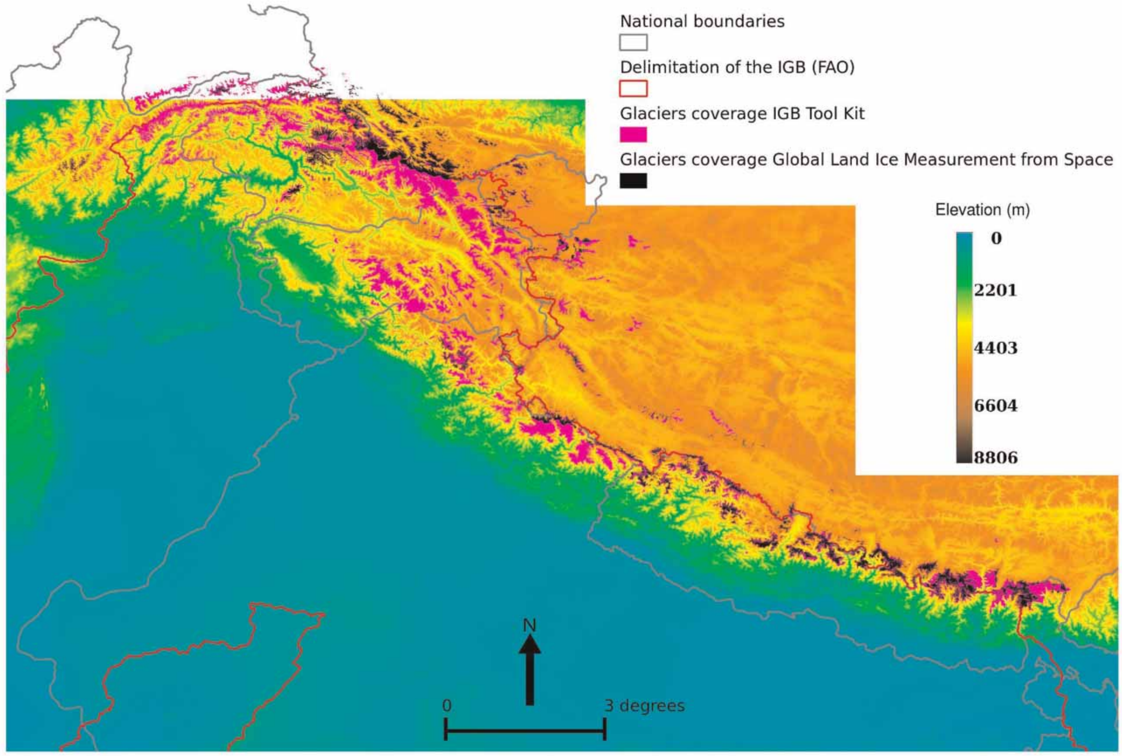


Fig. 1. Available glacier coverage in the Ganges basin region in the Himalayan mountains. The delimitation of the Ganges basin boundary is as per the IDIS IG Basin toolkit at the International Water Management Institute (IWMI).

found in the literature are compiled in Table 1. Finally, the recurrent value for the rain–snow temperature threshold read in three references (Hasnain, 1999; Thayyen *et al*., 2005; Singh *et al*., 2008) for the region is 2 °C.

Following the approach of Condom *et al*. (2007), the Ganges basin was further discretised with respect to elevation so as to account for the variation with altitude of glacier coverage and of the climate. In their study of the Gangotri glacier, Singh *et al*. (2008) used 400 m elevation bands. Given that the Ganges basin is such a huge area, we opted for a coarser cut. Analysis of the GLIMS database showed that glaciers are not present below 3,000 m, their occurrence increasing with elevation, reaching a maximum between 5,000 to 6,000 m before decreasing. Hence we chose 0 to 3,000 m for the first elevation band and defined an elevation band every 1,000 m, upwards. Obviously such a choice does not subdivide further sub-basins that are in the plains, below 3,000 m, and which have no glaciers.

These spatial units, defined by subdividing the sub-basins with elevation bands as explained above, were the spatial modelling entities of WEAP-Ganges. We proceeded by river system (e.g., Ganges, Yamuna, Koshi), from upstream to downstream, with a monthly calculation time step. In each modelling entity were placed:

(i) hydrological objects that simulate (a) land-use-related rainfall/runoff and snow melting processes in non-glaciated areas and (b) glaciers and snow melting in glaciated areas; and
(ii) water infrastructures and demand objects that account for water uses.

Setting WEAP-Ganges meant calibrating and possibly validating the hydrological objects so as to reproduce the observed streamflows at the outlet of a given sub-basin. In concrete terms, calibration was achieved by matching the parameters of the hydrological objects that pertain to the following:

(i) The glaciers, i.e., the degree-month coefficient, calculated by multiplying the degree-day coefficient by 30, and the rain–snow temperature threshold. As initial values, we referred to values mentioned in Table 1.
(ii) Land use-related rainfall/runoff processes, i.e., land parameters, such as the soil layers' retention capacities, their conductivity and a runoff coefficient. The initial values were those plausible for the given land use.

Whenever large time series of observed data were available, i.e., more than 10 recent years, part of this time series was kept aside for validation. We also evaluated the quality of the WEAP-Ganges and found that it was satisfactory (as it was possible to simulate average monthly and annual flow trends) for the Nepalese sub-basins, where observed time series were available and where most of the glaciers are present. As such, it was possible to consider monthly average trends for glacier-related analyses.

Table 1. Some values for the degree-day coefficient.

Source	Degree-day coefficient
Singh *et al.* (1995)	Ice: 5.4 mm/°C/6 h
Singh *et al.* (1999)	Ice: 8 mm/°C/day; Snow: 6.3 mm/°C/day
Singh *et al.* (2008)	Ice: 2.5 to 9 mm/°C/day

In several other sub-basins the quality was variable and as such was good for providing average trends. Other limitations of the current version of WEAP-Ganges include the following:

(i) WEAP-Ganges does not cover the entire Ganges basin but just the part up to the Farakka barrage in India. Below that point the impact of glaciers on streamflows was rather small.
(ii) No time series for glacier coverage was available; hence the calibration of the WEAP glacier module aimed at reproducing streamflows, while an additional calibration target could be the variation of the glaciers' area.
(iii) The description of glacier behaviour is based on a simple conceptual model, which may not capture all glacier processes.

As such, the authors would like to emphasize that the results of the study are preliminary, given the model's inherent assumptions, the uncertainties of climate change and any future developments in the basin. However, they can provide average annual trends for the basin.

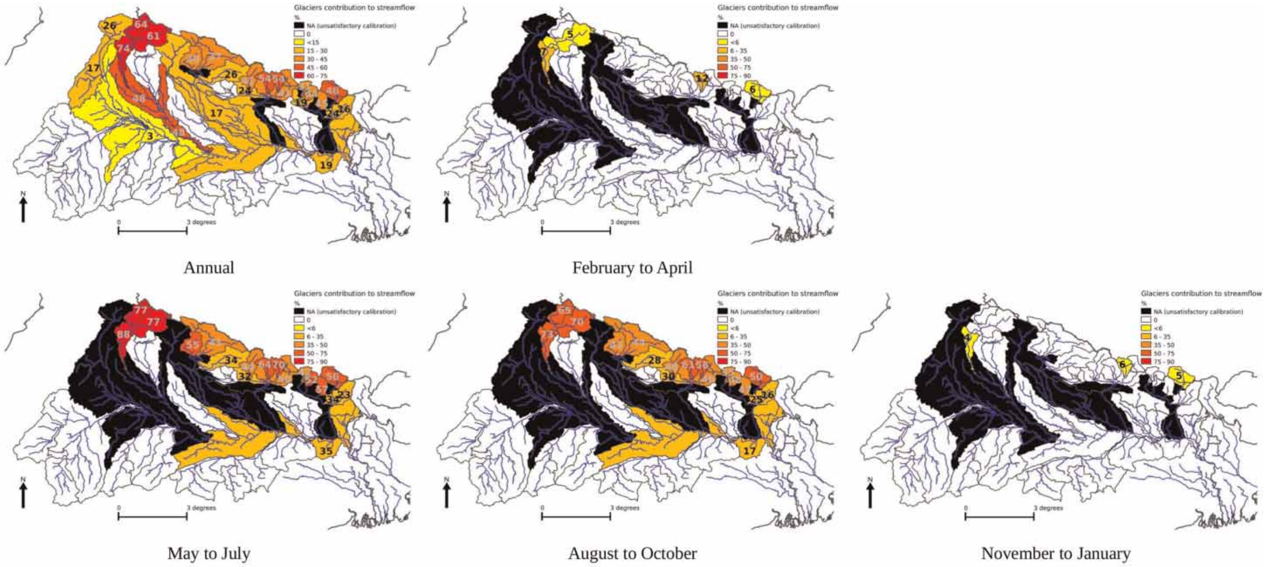
4. Results and discussion

4.1. Contribution from the melting of snow and ice in the glaciated areas

Snow and glacier melt is an important water source for the Ganges basin and hence of water for irrigation. It should be mentioned that the Climatic Research Unit (University of East Anglia, UK) rainfall data used in this study appear to underestimate the precipitation in mountainous regions, and hence the contribution from glaciers presented here may be overestimated. Figure 2 shows that part of the annual streamflow in the Ganges basin that comes from the melting of snow and ice in glaciated areas. This contribution is important (60–75%) in the Upper Ganges and in the Nepalese sub-divisions of the Ghagra, Gandak and Koshi rivers (40–55%). The contribution, however, reduces significantly further downstream, falling to about 19% at Farakka as flows from glaciated areas are diluted by streamflows generated by rainfall/runoff processes.

The average seasonal contribution is much contrasted. As shown in Figure 2, the flows from glaciated areas occur predominantly in the months of June to September, being almost nil in other months. The particularly high values of this contribution at Narora (74%) can be explained by viewing the monthly values (Figure 3). The canal diversion is made all the year around, in particular during the lean flow season when flows from glaciated areas are nil. As such, the relative contribution is greater at Narora after withdrawal from the canals. Another interesting result is that glaciers are apparently buffers against the inter-annual variability of rainfall. As evident from data shown in Table 2, annual streamflow contributions from glaciers have a smaller inter-annual coefficient of variation than annual flows generated by rainfall/runoff, and thus mediate the inter-annual variability of total annual streamflow.

This buffer characteristics is visible in sub-basins where the model setting is 'very good to good' during years with low rainfall (Table 3). In these cases, the proportion of streamflow which is generated from the melting of snow and ice in glaciated areas is greater in dry years than during wet years, and hence the contribution from glaciated areas is important during years of weak monsoon.



Annual

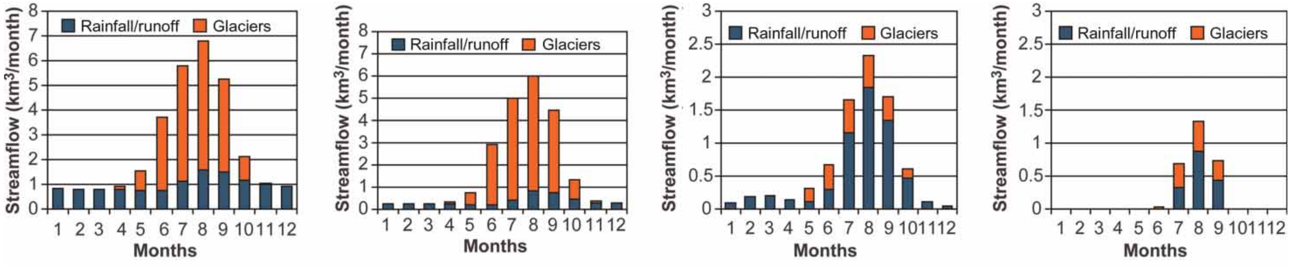
February to April

May to July

August to October

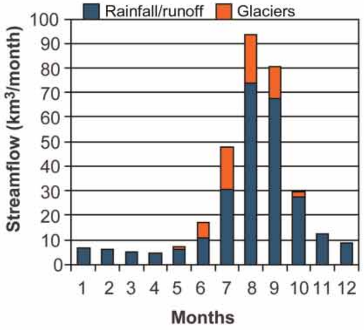
November to January

Fig. 2. Average percentage of the annual and seasonal streamflow that comes from the melting of snow and ice in glaciated areas, in the Ganges basin upstream of Farakka (simulated for the period 1982–2002). (Full colour versions of all the figures in this paper appear online.)



Before canals After canals Before canals After canals

Haridwar (sub-basin No. 2) Jewala (sub-basin No. 8)



Farakka (sub-basin No. 53)

Fig. 3. Average monthly contribution from the melting of snow and ice in glaciated areas at some locations in the Ganges basin (simulated for the period 1982–2002).

Table 2. Partitioning of average annual streamflow generated from rainfall/runoff and glacier processes at Haridwar and Farakka (simulated for period 1982 to 2002).

	Haridwar sub-basin (upstream)			Farakka sub-basin (downstream)		
Parameter	Total	Rainfall/runoff	Glaciers	Total	Rainfall/runoff	Glaciers
Average flow, km^3/yr	30.4	12.0	18.4	335.2	275.0	60.2
Coeff. of variation, %	11	20	11	21	24	8

The estimates are 'Preliminary' due to the coarse detail achieved in the modelling.

Table 3. Average contribution from melting of snow and ice in glaciated areas simulated for some sub-basins where the WEAP-Ganges' setting was 'very good' to 'good'.

		Average proportion of annual streamflows from glaciated areas		
No.	Sub-basin	For 1982–2002	For 3 wet years	For 3 dry years
44	Busti	44%	40%	46%
46	Rabuwa Bazar	45%	40%	50%
51	Chatara Kothu	24%	22%	26%

The estimates are 'Preliminary' due to the coarse detail achieved in the modelling.

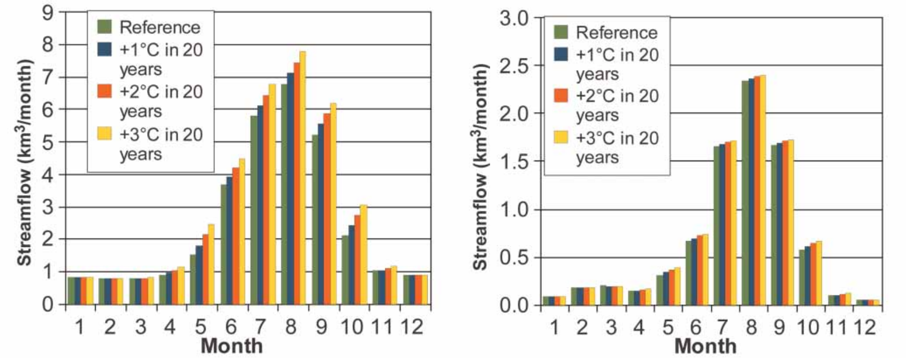
4.2. Impact of temperature rise on the melting of glaciers

Intergovernmental Panel on Climate Change (IPCC) and other reports agree on the potential rise in atmospheric temperatures due to a variety of anthropogenic and other factors (Solomon *et al.*, 2007). However, the magnitude of the rise in temperature is quite variable. The IPCC (Christensen *et al.*, 2007) indicates that, in the Tibetan range, the temperature rise at the end of the century could be +3.8 °C. Studies by ICIMOD (2009) and other agencies provide information of the same magnitude. Therefore, we considered the following three scenarios:

(i) An increase of 1 °C after 20 years, i.e., a rate of +0.05 °C/year (optimistic).
(ii) An increase of 2 °C after 20 years, i.e., a rate of +0.10 °C/year (business-as-usual).
(iii) An increase of 3 °C after 20 years, i.e., a rate of +0.15 °C/year (extreme scenario).

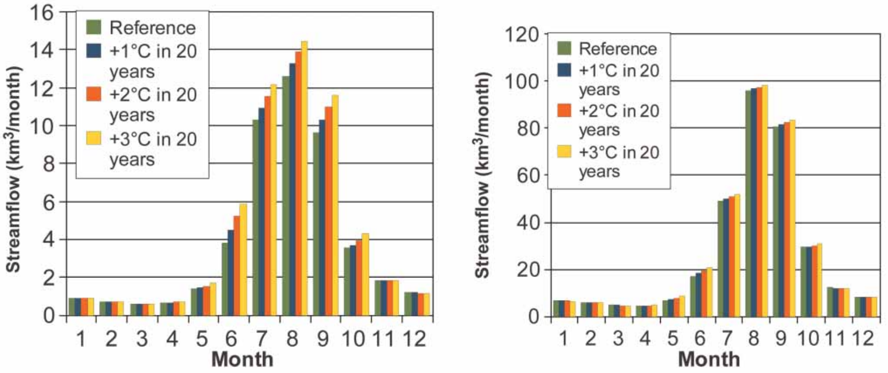
As calibration of the glacier parameters was based solely on observed streamflow data, we only analysed simulated streamflows and not, for instance, variations in glacier area. In each scenario, the temperature was raised gradually every year. Rise in temperature increases the quantity of snow and ice melt in the glaciated areas and thus augments the streamflows. However, the impact decreases from upstream to downstream, as: (i) enhanced contribution from rainfall dilutes flows from glaciated areas; and (ii) increased temperature also leads to greater evapotranspiration in the plains, and thus smaller streamflows. The amount of extra flow is rather insignificant at the Farakka barrage but it is significant upstream, as for instance in the Upper Ganges at Haridwar and Narora, or in the mountainous sub-basins (e.g., Tehri dam).

The simulated impact on average monthly flows in selected locations of the Ganges basin is shown in Figure 4. As the contribution from glaciated areas mainly occurs during the high flow season, the increase in streamflow occurs predominantly during the high flow season of June–September. Although



Haridwar (sub-basin No. 2), before canal diversion

Tajewala (sub-basin No. 8), before canal diversion



Devghat (sub-basin No. 37)

Farakka (sub-basin No. 53)

Fig. 4. Simulated impact of a gradual increase in temperature over 20 years on average monthly streamflows in a number of locations in the Ganges basin. (N.B. each sub-basin graph has a different vertical scale.)

Table 4. Simulated average change in annual streamflow at selected locations in the Ganges basin when temperature increases gradually over 20 years (as compared to the reference scenario).

Scenarios	Change in annual streamflow, km^3/year					
	Tehri dam (Sub-basin No. 1)	Haridwar (Sub-basin No. 2)	Narora (Sub-basin No. 3)	Tajewala (Sub-basin No. 8)	Delhi (Sub-basin No. 9)	Farakka (Sub-basin No. 53)
+1 °C over 20 years	+0.6 (+8%)*	+1.9 (+6%)	+1.8 (+8%)	+0.2 (+2%)	Negligible	+4.2 (+1%)
+2 °C over 20 years	+1.2 (+17%)	+3.9 (+13%)	+3.6 (+15%)	+0.3 (+4%)	Negligible	+8.8 (+3%)
+3 °C over 20 years	+1.9 (+26%)	+6.0 (+20%)	+5.4 (+23%)	+0.4 (+5%)	Negligible	+13.4 (+4%)

*The estimates are 'Preliminary' due to the coarse detail achieved in the modelling.

there is little modification during the lean flow season, melting of snow and ice starts earlier (in April) and ends later (in November). Such a phenomenon is likely to create more flood events and of higher magnitude, whether in the Upper Ganges or in the mountainous sub-basins of Devghat and Tehri dam

(Table 4). Such a perceived change is of great consequence for the water infrastructure and the lives and assets of the populations in these regions.

On a long-term basis, the combination of glacial retreat, decreasing ice mass, early snowmelt and increased winter streamflow suggest that climate change is already affecting the Himalayan cryosphere (Kulkarni *et al.*, 2007). Reduced surface runoff will reduce groundwater recharge and affect groundwater dynamics in the region, which will be critical in the western region, where most irrigation is from groundwater. SWAT analysis showed an overall reduction in runoff under all greenhouse gas emission scenarios (Gosain & Rao, 2007).

5. Impacts and potential opportunities

The extra water from the glaciated areas in the short to medium term presents a set of potential opportunities and some threats. The extra water can be potentially used for intensification of surface water use and augmentation of groundwater aquifers.

5.1. Surface water resources

The extra water from glaciated areas does not flow when water is most required, i.e., during the lean flow winter season. Nevertheless, making best use of this extra water presents a potential opportunity. For instance, the Upper Ganges canal currently diverts about 6 km^3/year at Haridwar, where the extra water due to the increase in temperature is about of the same order of magnitude (Table 4). Using this extra water would require the ability to withdraw and use/store the water during the high flows at suitable locations, such as Tehri dam, Haridwar, Narora, etc., which may be somewhat difficult with the existing storage capacities and the magnitude of high flows. Nevertheless, the following opportunities could be considered earnestly:

(i) The extra water could be captured by additional reservoirs/dams, in particular in small reservoirs. This water may be used locally or in the context of transboundary agreements between the riparian countries (Bhaduri & Barbier, 2008a). Water storage, in its various forms, provides a mechanism for dealing with variability (and extra flows) which, if planned and managed correctly, increases water security, agricultural productivity and adaptive capacity (McCartney & Smakhtin, 2010). It should also help to sufficiently moderate the frequency and intensity of the expected floods in the upstream reaches. As such, these additional storages can make an important contribution to safeguarding livelihoods and reducing poverty. Amarasinghe & Sharma (2011) showed that a large part of the rural population in the Ganges basin is chronically poor and almost 10% of the rural poor have monthly per capita expenditure below 20% of the poverty line. How well the poor can cope with natural hazards and external shocks, and improve their livelihoods, depends upon considerable improvement of the water infrastructure in the basin. India, Nepal and the bilateral donors need to undertake well-planned feasibility studies and make financial commitments for a variety of storage projects in the region.

(ii) The increased flows in May and June (with the early melting of snow and glaciers) could be most beneficial in terms of water use, as they happen just after the dry season. This presents a good possibility for capturing the magnitude of this extra flow. The additional water would be useful for the irrigation of rice nurseries and for short-duration pulse and vegetable crops, and could more importantly satisfy high demands from the domestic and industrial sectors during the hot summer season.

5.2. Groundwater resources

Over the last 50 years, groundwater has become an important source of water for irrigation (Mukherji, 2012). The need to produce more food in the near to medium term, given the constraints on available water resources, compounded by the challenges and uncertainties associated with climate change, strongly points towards increased and more efficient use of groundwater as one of the key solutions. The western and southern regions of the Ganges basin are witnessing an unprecedented growth in groundwater use (Jain *et al*., 2009). By virtue of its nature, groundwater presents an excellent opportunity to augment recharge during the high availability period and for a planned use during low/no availability periods of surface supplies. Managed Aquifer Recharge (MAR) (Gale *et al*., 2006) is the practice of purposefully recharging aquifers via surface spreading, or through wells and dykes, for subsequent utilization. The benefits of MAR in the Upper Ganges basin (Lakauti distributary) have already been successfully demonstrated and documented (Sakthivadivel, 2007). Large regional programs in the basin and adjacent areas could be successfully implemented using the extra water made available through the melting of snow and glaciers upstream.

5.3. Impacts for transboundary states and countries

The Ganges basin in India is shared by a number of Indian states (Uttarakhand, Uttar Pradesh, Madhya Pradesh, Rajasthan, Delhi, Haryana, Bihar and West Bengal) and by Nepal and Bangladesh. Most of the Indian states in the basin face either economic water scarcity (Uttar Pradesh, Bihar and West Bengal) or severe physical water scarcity for drinking and irrigation (Delhi, Rajasthan, Madhya Pradesh). The existing water sharing mechanisms between the riparian states of India and between India–Nepal–Bangladesh are weak and a cause of transboundary conflicts (Bhaduri & Barbier, 2008b; Bhaduri *et al*., 2009). The additional water supplies provide an opportunity for the upper riparian states to beneficially share these waters with the downstream, physically water scarce, regions for mutual benefits. The positive externalities generated by water transfers from Nepal may influence the water share of both India and Bangladesh. Higher water supplies in the upper catchments in Nepal provide an additional reason to think seriously about the development of its much neglected hydropower potential (Gyawali & Dixit, 2011) and to exhibit political altruism towards resolving transboundary water conflicts with India and Bangladesh. The Ganges water sharing mechanisms between India and Bangladesh have seen several changes and even the existing treaty appears to fall short of the expectations of Bangladesh (Chowdhury, 2010). With the projected change in temperature of 1–3° C, the additional water flows at Farakka may provide a good opportunity for the riparian countries to devise the best means for gainful utilization of the additional supplies.

6. Conclusions

The Ganges basin is a vast landmass that has been densely populated and intensively cultivated over 2,000 years. Today, it is one of the most populous basins in the world. Mastering and manipulating snow-fed perennial streams and rivers to water fertile soils has remained the secret of the Ganges basin's endemically high population-carrying capacity. Unfortunately, intense anthropogenic activities and the impacts of climate change are now threatening past fortune. The hydrology of the Ganges basin is partly dependent on glaciers and there are uncertainties about the impact of climate change on them.

This study developed an application of the WEAP model which contained an experimental glacier module simulating snow and ice melting in glaciated areas. The analysis (within the limitations of the model and the data) showed that:

(i) the contribution of glacier and snow melt decreases from upstream mountainous sub-basins to downstream flat sub-basins, with a magnitude variation of 75 to 3%;
(ii) glaciated areas contribute to streamflows predominantly during the wet period from June to September, i.e., when flows are actually already high; and
(iii) glaciers are apparently a buffer against inter-annual variability of rainfall.

The paper has also examined the impact of temperature rises of 1–3°C over a period of 20 years on streamflows across the river course. These impacts would be significant upstream while minor downstream. There are potential opportunities to exploit this additional available water through the construction of a number of storage reservoirs that could be used locally, or within the transboundary agreements between India, Nepal and Bangladesh. There is also a good opportunity to capture this extra water just at the end of the dry season, when flows from glaciated areas become noticeable and the demands from agriculture and domestic sectors are at a peak. Using the extra flows for the augmentation of groundwater resources through regional MAR programs is an attractive option for intensive and sustainable use of groundwater resources in the agriculturally important regions of the Ganges basin. The riparian states within India and India–Nepal–Bangladesh have a potential opportunity to alleviate the physical water scarcity in stressed regions and to better address regional transboundary water conflicts.

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