

# Implications of climate change for water resources development in the Ganges basin

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## Abstract

This paper presents the first basin-wide assessment of the potential impact of climate change on the hydrology and production of the Ganges system, undertaken as part of the World Bank's Ganges Strategic Basin Assessment. A series of modeling efforts – downscaling of climate projections, water balance calculations, hydrological simulation and economic optimization – inform the assessment. We find that projections of precipitation across the basin, obtained from 16 Intergovernmental Panel on Climate Change-recognized General Circulation Models are highly variable, and lead to considerable differences in predictions of mean flows in the main stem of the Ganges and its tributaries. Despite uncertainties in predicted future flows, they are not, however, outside the range of natural variability in this basin, except perhaps at the tributary or sub-catchment levels. We also find that the hydropower potential associated with a set of 23 large dams in Nepal remains high across climate models, largely because annual flow in the tributary rivers greatly exceeds the storage capacities of these projects even in dry scenarios. The additional storage and smoothing of flows provided by these infrastructures translates into enhanced water availability in the dry season, but the relative value of this water for the purposes of irrigation in the Gangetic plain, and for low flow augmentation to Bangladesh under climate change, is unclear.

*Keywords:* Climate change; Economic optimization; Ganges basin; Hydrological simulation; Water resources development

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## 1. Introduction

The Ganges basin, covering an area of 1.2 million m<sup>2</sup>, is the most populous in the world, home to more than 650 million people living in China, Nepal, India and Bangladesh. Poverty is widespread, and population density in the Gangetic plain and delta is extremely high. People living in the basin

doi: 10.2166/wp.2013.107

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have long coped with the extreme temporal and spatial climatic variability of the South Asian monsoon, and the floods and droughts that accompany it. Nonetheless, they remain highly exposed to these irregularities today (World Bank, 2013). This vulnerability is closely related to the low levels of development in the basin, and to the highly variable and dynamic nature of the Ganges and its large Himalayan tributaries.

With their powerful monsoonal flows, the rivers in the Ganges basin, both in the Gangetic plain upstream and in the delta downstream, have long been unstable. Geomorphological research and early maps of the region show that the downstream outlet of the Ganges River has steadily been shifting eastward towards the Brahmaputra over the last several thousand years (Allison, 1998). The implications of this river migration have been great, first leading to efforts to save the port of Calcutta, and today resulting in a steady drying of areas in the Gorai distributary. Even after the merging of the Ganges with the Brahmaputra, the powerful flow of the Ganges continues to push water eastwards. Meanwhile, upstream in the Indian State of Bihar and in the Terai in Nepal, the Kosi River recently temporarily reverted to flowing through an old river channel abandoned several centuries ago, following an embankment breach. This sudden movement led to the displacement of millions of people (Dixit, 2009; Singh et al., 2009).

Beyond the challenges associated with living in this dynamic system, the prospect of climate change presents new challenges. The Ganges basin countries today routinely figure on lists of the most climate vulnerable nations in the world. Increases in temperature, changes in precipitation and glacier melt, intensified monsoons, water-induced disasters, sea level rise – all the impacts of climate change – are expected to upset the delicate hydrological balance existing in this basin today, giving rise to new water management challenges. Though the most dire predictions are only speculative, some have claimed that the dynamics of climate change could exacerbate existing environmental pressures in the basin, creating social destabilization and possibly conflict (Wirsing & Jaspardo, 2007). Such effects would be consistent with hypotheses related to the difficulties associated with rapid hydrological and institutional change in river basins globally (Wolf et al., 2003). The countries of the Ganges basin have limited capacity to deal with today's weather and hydrological variability, much less the intensification expected with climate change.

Climate change predictions in the basin are, however, also plagued by enormous uncertainties. These uncertainties are compounded by a profound lack of data and the inability so far to construct a credible methodology for modeling predictions of how monsoon patterns and resulting hydrology might change. Reflecting these deficiencies in understanding, the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) highlighted South Asia and the greater Himalaya as one of several key regions having greatly divergent predictions of future changes in precipitation (IPCC, 2007). A new generation of global circulation models is being developed and efforts are underway to downscale existing models on a regional basis in South Asia, but it is unlikely that this will increase model convergence. For the time being, tremendous uncertainty will thus remain in predictions of South Asian, and Ganges-specific, climate futures.

To address this gap, this paper, undertaken as part of the Ganges Strategic Basin Assessment of the World Bank, presents the first basin-wide analysis of the potential impact of climate change on the hydrology of the Ganges, and the first to assess how this translates into changes in the economics of water use in this system. A series of modeling efforts – downscaling of climate projections, water balance calculations, water systems simulation, economic optimization and hydrodynamic simulation – inform the effort. Data limitations severely limit the degree of confidence that should be placed in our results, but they do

represent a necessary first step to understand the potential for change in this basin over the first half of the 21st century. The next section provides background on the climate and hydrological features, and on water use patterns of this basin, and provides a summary of previous work on climate change in the basin. Section 3 describes the methodology used to obtain climate change predictions. Section 4 presents modeling results, and Section 5 discusses these results and their implications.

## 2. Background: historical climate variability and previous work on climate change in the Ganges basin

### 2.1. Historical climatic, physical, and hydrological characteristics

The South Asian monsoon system largely defines the climate and hydrology of the Ganges system. The arms of the monsoon sweep up both coasts of the Indian sub-continent until they are blocked by the towering Hindu Kush–Himalaya mountain range, and deliver to the region about 80% of annual rainfall in June–August. In correspondence with this rainfall pattern, river flows in the Ganges basin rise from very low levels in May to a sharp peak in July to October. During an average hydrological year, some 500 billion<sup>1</sup> cubic meters (BCM) flow into the Ganges River; 80% of the 248 BCM average historical river flows measured at Farakka (the border of India and Bangladesh), following withdrawals in the upstream countries, come during just 4 high flow months (Figure 1). Base flow in the river, net of upstream abstractions in India and Nepal, are very modest: flows at Farakka from January to May comprise just 6% of total annual flow.

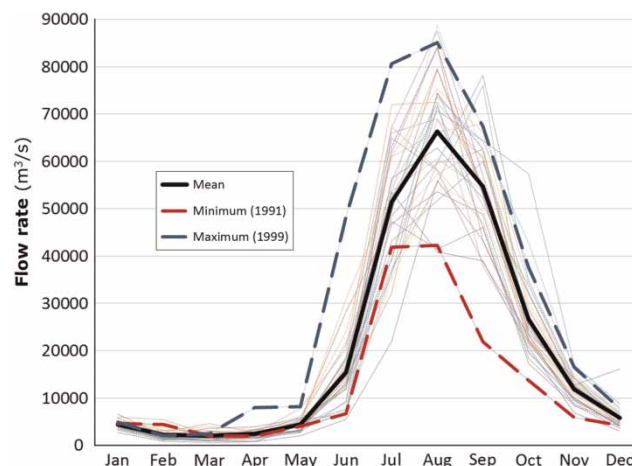


Fig. 1. Historical flows at Farakka (India–Bangladesh border), for 1969–2001. Flows in individual years are shown by thin lines; historical low (1991) and high years (1999) are shown by dotted lines; average flows are shown by a solid black line. *Source:* World Bank (2013), using data from the Climate Research Unit (CRU), University of East Anglia. (Full color versions of all the figures in this paper appear online.)

<sup>1</sup> In this paper, 1 billion =  $1 \times 10^9$ .

Average annual temperatures are high throughout the basin except in the Himalaya (Figure 2), and reach their maximum in the pre-monsoon months (April–June). Precipitation is highest in the eastern Himalayan belt and in the delta areas of the basin (>2,000 mm annually), and lowest in the Thar desert of Rajasthan in the west (<250 mm annually). In addition to the roughly 500 BCM that flow into the Ganges basin as runoff, 800 BCM of ‘green water’ is absorbed into groundwater aquifers or returned to the atmosphere through evapotranspiration (ET) (World Bank, 2013).

Climate and hydrological variability in this system is extremely high. The time series of flows at Farakka gives some indication of the inter-annual variability in the basin’s climate. During the historical low year for flows (1991), just 153 BCM flowed through Farakka (38% lower than average), while the historical high of 369 BCM in 1999 had 49% higher flow than average. Monthly variation across years can be even higher (see Figure 1). Irregular cycles of inundation and drying have both beneficial and destructive aspects, and the basin’s inhabitants have been experiencing these effects for centuries. High flows typically lead to increased crop production during the winter (rabi) planting season (Yu et al., 2010). Short periods of inundation also help to mitigate land subsidence and coastal erosion by moving large amounts of silt downstream (ESA, 2011), though this silt is not particularly fertile (Subramanian et al., 1996). Indeed, the Ganges remains one of the top three most sediment laden river systems in the world, and together with the Brahmaputra carries over a billion tons of silt to the Ganges–Brahmaputra–Meghna (GBM) delta every year (Milliman & Ren, 1995; Kuehl et al., 2005).

The downside of climate variability is, however, manifest in extreme floods and droughts, and in the substantial uncertainty that accompanies the timing of the onset of the monsoon. Floods take a significant toll on lives and livelihoods, damage infrastructure, homes and other assets, and generally limit investment and disrupt economic activities (Jain & Sinha, 2003a; Dasgupta et al., 2011). For example, the Government of Bangladesh estimates that flood-affected areas in that country during 1954–2004 ranged from 0 in just 6 years to over 100,000 km<sup>2</sup> in 1998 (with a median just over 30,000 km<sup>2</sup>). In the Indian state of Bihar, people have been affected by flood in all years since 1979 (with over 20 million people affected in 1987, 2004, and 2007) and with flood-related deaths occurring in all but 1 year (World Bank, 2013). Finally, in Nepal, floods account for 90% of the economic cost of natural

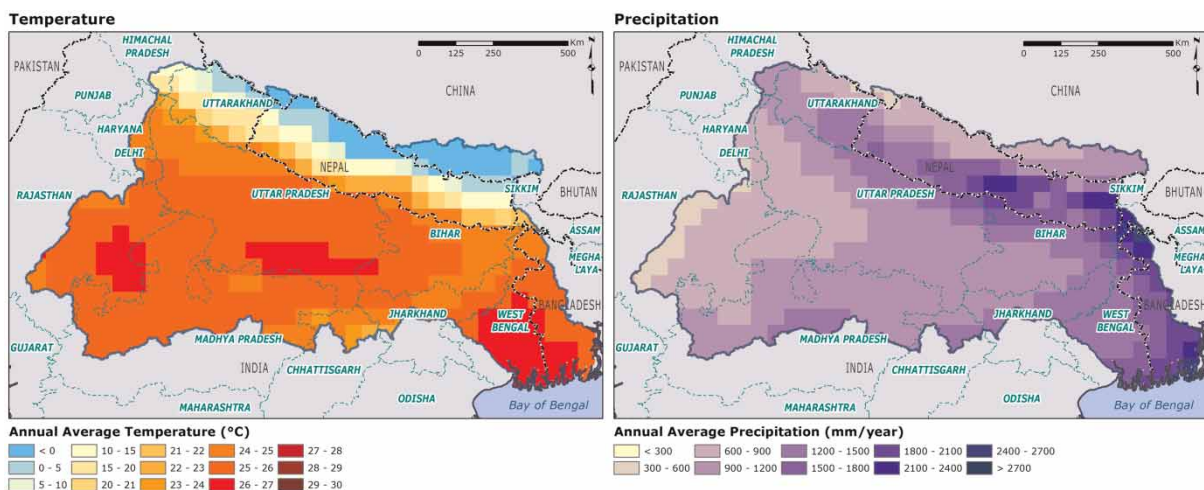


Fig. 2. Historical average temperature and precipitation in the Ganges. Source: CRU TS 3.0 1901–2006.

disasters (Nepal Ministry of Home Affairs, 2010). Even larger areas of the basin are affected by drought, particularly among vulnerable populations with limited or poor access to irrigation schemes (Moench & Dixit, 2007; World Bank, 2013).

Unlike some other river systems nearby (e.g. the Indus) and throughout the world, glaciers contribute a relatively small share (just 2%) of the total river flow in the basin, and much of the melt occurs during the early monsoon when rainfall is already quite heavy (Alford & Armstrong, 2010). Still, glaciers provide much of the water storage that ensures the perennial flow of the Himalayan tributaries of the Ganges. In the Budhi Gandaki basin in Nepal, for example, glacier contribution to the total measured stream flow is about 30%. The average for all Nepal's rivers is only about 4% (Alford & Armstrong, 2010). Snowmelt likely contributes more significant flow to the basin, though precise estimates of snowmelt are lacking.

## 2.2. *Water use*

It is necessary to have a sense of the scale of the irrigation withdrawals that depend on the Ganges to begin to understand the effect that climate change could have on the system's economic productivity. Irrigated agriculture is critical for coping with the unpredictable monsoon rainfall in the Gangetic plain. The basin is home to some of the largest surface water irrigation schemes in the world (e.g., the Upper Ganga system, the areas supplied by the Sarda Sahayak and Surya canals, and the Gandak and Kosi schemes), and 90% of consumptive water use in the basin is agricultural (World Bank, 2013). However, surface water only supplies a fraction of the water used in these areas; groundwater pumping from the vast aquifers underlying the Gangetic plain provides the rest. In fact, land irrigated with at least some groundwater, which can be obtained on demand, tends to be most productive and most capable of supporting double cropping (Shah, 2008).

The surface and groundwater irrigation systems in the Ganges plain are highly inter-connected. Percolation through surface irrigation canals recharges aquifers, and groundwater is often used to supplement surface water, especially in western Uttar Pradesh. Assessments of the full impacts of climate change must therefore account for changes in the long-term supply of both surface water in the basin and storage in the groundwater aquifers under the Gangetic plain. Though this paper focuses on the surface water contributions to the system (via direct canal irrigation and indirect recharge through these schemes), discussions of long-term water availability cannot ignore the potential for much lower water availability from both sources, if there is drying in the future, or the danger of increased water-logging, if the future becomes significantly wetter.

In contrast to the vast groundwater stores in the basin, there is limited active surface water storage capacity in the system (World Bank, 2013). This is due to several features of the basin and its existing dams. First, most of these reservoirs are modest in size; only five are more than 100 m tall. Second, many of the more than one thousand Ganges dams are in relatively flat portions of the basin and have very low volume to area ratios (total storage capacity in the system is only about 55 BCM, and active storage is a mere 36 BCM, less than 10% of annual flow). Third, some of the largest tributaries originating in Nepal (e.g., the Ghagara, the Gandak and the Kosi) have almost no storage, due to lack of water resources development in Nepal, as well as concerns over seismic risks (Bandyopadhyay, 1995). Thus, there is limited existing capacity to regulate upstream flows to generate storage-backed hydropower, to reduce flooding and/or to augment low flows for irrigation or ecosystem needs in the delta.

Given the limited ability to control floods with upstream storage, water resources managers have traditionally relied on embankments in an effort to reduce flood risks in the downstream system (Bandyopadhyay, 2009; Dixit, 2009). Over time, these embankments have been raised to deal with silt deposition in river channels and increased population exposure to peak flows (World Bank, 2013). With the increased variability and more intense rainfall events and silt flows predicted under climate change, problems related to maintenance of embankments in such rivers could become more severe.

### 2.3. Previous Ganges basin climate change studies

There have been several analyses of climate trends and future projections in the Ganges basin. Not surprisingly, the most consistent predictions across such studies pertain to increased temperatures. Over the past 100 years, weather station data suggest that the broader region has warmed by about 0.5 °C, and 6 of the 10 warmest years of the past century in the nearby Brahmaputra basin occurred after 1994 (Ahmed & Alam, 1999; Immerzeel, 2008). Westphal (2011) similarly detects recent increases in temperature in Nepal and several states in India. These and other analyses generally predict additional increases of 1–1.5 °C by 2050 and 2.5–3 °C by 2100, with the largest changes during the winter and at higher elevation (Agrawala et al., 2003).

This predicted rise in temperature has important consequences for regional hydrology. Higher temperatures imply increased ET from crops irrigated using surface water, as well as from reservoirs (Jeuland, 2010a). They are also expected to increase summer glacier melt in the Himalaya. Moving from the east to the west across the Himalaya, monsoon rainfall decreases greatly. Summer rain and snowfall at high elevation in the eastern catchments of the Ganges therefore contributes much more to total basin runoff than glacier melt does, outside the more heavily glaciated sub-basins in the western Ganges (Rees & Collins, 2006). This precipitation gradient implies that changes in glacier melt will have more limited impacts in the Ganges than in the Indus basin on the western side of the Himalaya, though effects on the seasonality of snowmelt are harder to predict (Immerzeel et al., 2010; Alford et al., 2011; Pal et al., 2011).

Sea level rise associated with increased temperatures will also have important implications for flooding and storm-surge in the Ganges delta, which has a very low elevation gradient (Karim & Mimura, 2008). Accounting for storm surge, low-end projections of sea level rise (0.3 m) would increase the coastal area at high risk of flooding by roughly 15%, and increase flood depths in the severely affected zones by 30–40%. A 1 m rise in sea level would inundate 2,062 km<sup>2</sup> (1.5% of the area of Bangladesh), affect over 1.5 million people, and would exacerbate salinity intrusion (World Bank, 2013). Still, it is unclear whether the delta will suffer a net loss in land area, since sediment deposited in the delta by the silt-laden rivers of the region have recently led to net accretion.<sup>2</sup> Indeed, the balance of sea level rise and accretion will depend on the extent to which silt transport changes with upstream perturbations.

Finally, many speculate that higher temperatures will lead to an intensification of the water cycle, increasing the frequency of extreme drought and flood events (Trenberth et al., 2003). Westphal (2011) found increased frequency of drought over much of India, and flood in West Bengal and Bangladesh, consistent with increasing future variability predicted by climate models. There is, however, little consistency in General Circulation Model (GCM) predictions of future mean changes in

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<sup>2</sup> See, for example, analysis from a World Bank study in DHI GRAS (2010).

precipitation in South Asia (Bandyopadhyay, 1995). Finer scale analyses with regional climate models similarly yield varying predictions: analysis with RegCM3 found overall suppression and delay in onset of summer precipitation (Ashfaq et al., 2009), while precipitation projections using PRECIS indicate a spatially variable but generally increased annual rainfall over much of India (GOI, 2010). Importantly, studies of historical precipitation also fail to detect a significant trend in rainfall (Mirza et al., 1998). Some existing studies using GCM projections indicate the possibility of decreased monsoon season runoff in the Brahmaputra and Ganges (Moors et al., 2009; Gupta et al., 2010), while others suggest that peak flows will increase and that extreme low flows will become less frequent (Mirza et al., 2003; Gain et al., 2011).

The inconsistencies across such studies partly stem from their reliance on different models or analytical techniques. As we will show in this paper, there is a wide variation of rainfall projections obtained from the suite of GCMs being used to produce climate change projections. For example, Moors et al. (2009) use a single regional climate model in their analysis; Mirza et al. (2003) instead rely on four GCMs which all show increased precipitation over the region; others use a wider array of models (Gain et al., 2011). Some studies treat different GCMs as independent scenarios (Mirza et al., 2003). Others instead create discharge-weighted ensembles that depend on individual models' ability to reproduce historical river discharge (Gain et al., 2011). Correspondingly, there is little consistency in predictions of how runoff will change, and therefore in how economic processes in the system could be affected (with implications for adaptation and infrastructure development). By studying the divergent GCM results across different scenarios of infrastructure development and looking for consistent trends and outcomes, this study aims to begin to address that gap.

### 3. Methodology: modeling and use of climate change projections

#### 3.1. Hydrological and economic modeling

In order to explore the implications of climate change in the Ganges, this research developed and applied a series of basin-wide models for assessments of various development scenarios for the Ganges basin, including:

- (a) a water systems model to explore how changes in climate and runoff would affect basin water availability;
- (b) an economic optimization model to test the sensitivity of optimal water allocations to modified hydrological conditions;
- (c) several other tools for further assessments related to saline intrusion and hydrodynamics in the GBM delta, flood impacts, and implications of changes in glacier melt in the Himalaya.

Basin-wide models are needed to fully capture the complexities and inter-relationships between potential hydrological changes and proposed development options, and to better inform basin management decisions. The models were calibrated using available hydrological data (World Bank, 2013). Additional data, particularly with regard to rainfall in the upper areas of the Ganges basin, and on flows and water use in India, would significantly improve the predictions obtained. Despite significant data limitations, however, the models are able to simulate flows at the India–Bangladesh border with sufficient accuracy for the purposes of basin-wide assessments (World Bank, 2013).

*3.1.1. Water systems model.* To better understand systems linkages and to explore the implications of the combined effects of development and climate scenarios in the basin, the Soil Water Assessment Tool (SWAT) simulation model (Arnold *et al.*, 1998) was used. SWAT is a semi-distributed model which efficiently simulates hydrology at different scales. Sub-basins are divided into hydrological response units based on unique soil, land use, and average slope range. The model then calculates six components of the water balance: (i) precipitation; (ii) ET; (iii) surface runoff; (iv) lateral flow; (v) water yield; and (vi) groundwater flow. The SWAT model was calibrated and tested using independent simulated and observed flow sequences at hydrological gauge stations for which data are available (on two major tributaries in Nepal and at the Hardinge Bridge gauge downstream in Bangladesh).<sup>3</sup> The Ganges SWAT model contains 414 sub-basins.

*3.1.2. Economic optimization model.* The Ganges Economic Optimization Model (GEOM), described in Wu *et al.* (2012), is an annual model used to explore the economic implications of various scenarios of climate change, relative to historical hydrological conditions. It is composed of 77 sub-basins. The model maximizes benefits from hydropower production, irrigation and downstream low flow augmentation, as well as reduced damages due to flood overflows. The user specifies parameters for the unit values of hydropower and water supply; these do not vary with population and economic growth. Constraints are imposed to assure that treaty obligations which apply at Farakka (Crow *et al.*, 1995) are respected, and that municipal water demands are met. The model uses a monthly time step and is solved using nonlinear optimization techniques in the General Algebraic Modeling System. We used the optimization model to solve for the releases from dams and water use in irrigation that maximize economic production under the different hydrological conditions that correspond to GCM projections of future climate change.

*3.1.3. Additional modeling tools.* Several independent research efforts provided additional inputs to the process of modeling climate change impacts. A MIKE-BASIN model, with the same basic schematic as the GEOM, was developed by the Institute for Water Modeling in Dhaka and integrated with existing hydrodynamic and salinity models of the delta in Bangladesh to explore potential impacts of changes in hydrology and sea level rise on salinity (Nishat & Rahman, 2009).<sup>4</sup> Analyses were also provided by models of flood extent, which complement results obtained from the water systems models (RMSI, 2010). We did not model glacier melt, because of its modest flow contribution in this basin (Alford & Armstrong, 2010).

## 3.2. Climate projections

Temperature and precipitation projections for 2050 from 16 GCM models (with the A2 emissions scenario of the IPCC AR4) were used to drive the SWAT and GEOM models, using a monthly time

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<sup>3</sup> Further details and diagnostics on the Ganges model calibration and testing are available from the authors upon request.

<sup>4</sup> MIKE-BASIN is a multi-purpose, geographic information system (GIS)-based river basin simulation package designed for the analysis of water sharing problems and environmental issues at international, national, and project scale. More information available at: <http://www.dhisoftware.com/Products/WaterResources/MIKEBASIN.aspx>.



step (IPCC, 2007).<sup>5</sup> The year 2050 was selected because it represents a sufficiently long time horizon to explore variation across model projections, while remaining relevant for the assessment of the value of infrastructure development scenarios. Projections were downscaled, using statistical methods, to the catchment units defined in the SWAT model (Maurer & Hidalgo, 2008); the runoff obtained for each sub-catchment was then aggregated as needed for use in the GEOM.

The A2 emissions trajectory was selected because it represents a high-range trend from among the plausible storylines of future development selected by the IPCC, which best corresponds to current emissions trends. The A2 storyline corresponds to a heterogeneous world with moderate and regionally oriented development, and with no particular focus on clean energy technology (Nakicenovic *et al.*, 2000). In fact, actual emissions trends have been slightly higher than the A2 trajectory (Betts *et al.*, 2011; Raupach & Fraser, 2011). For the purpose of comparison and understanding of the longer-term climate change picture, this paper also briefly discusses temperature and precipitation changes in the basin for 2100, and for the balanced, lower emission A1B scenario.

Each of the GCM projections were routed through the hydrological model to yield a distinct set of river flows, which were transferred to the GEOM to obtain optimal reservoir storage levels, hydropower production, and irrigation withdrawals at different nodes in the system. These outputs were in turn used to construct system performance indicators, specifically:

- primary impacts: average basin-wide temperature and precipitation (and seasonality);
- secondary impacts: snowmelt, runoff, ET, streamflow, and saline intrusion;
- tertiary physical and economic impacts: system hydropower, irrigation water use or downstream low flow augmentation, flood flows exceeding normal channel capacities<sup>6</sup> and economic values for different infrastructure development scenarios. Note, however, that most flood-prone rivers are now embanked to mitigate flood events (Sinha, 1998; Jain & Sinha, 2003a, b; Roy & Sinha, 2007).

### 3.3. Development scenarios and legal constraints

The Ganges basin today offers significant opportunities for new development of water storage and uses (World Bank, 2013). The steep topography of the Himalaya offers a number of attractive storage and hydropower sites, mostly in Nepal. The Gangetic plain could support enhanced irrigation if extensive untapped groundwater resources in the eastern plains were utilized in a different way. The analysis presented in this paper thus explores a set of four infrastructure development scenarios: (a) present level of infrastructure development; (b) three mega dams (Chisapani, Pancheshwar, and Kosi High Dam); (c) 20 large dams or run-of-the-river hydropower projects in Nepal that are smaller than the three mega dams; and (d) all 23 projects.<sup>7</sup> Unit values of hydropower were assumed to be US\$0.1/kWhr, based

<sup>5</sup> The GCMs included are: BCM2.0 (BCCR), CGCM3.1 (CCMA), CM3 (CNRM), MK3.0 (CSIRO), CM2 (GFDL), CM2.1 (GFDL), GISS-ER, CM3 (INM), CM4 (IPSL), MIROC3.2, ECHO-G (MJIB), ECHAM5 (MPI), CGCM2 (MRI), CCSM3 (NCAR), PM1 (NCAR), and HADCM3 (UKMO).

<sup>6</sup> Namely the Upper Ganga, the Yamuna, the Ghagara, the Gomti, the Rapti, the Gandak, the Kosi and the Ganges mainstem. These thresholds have been set using data from several studies of channel capacities but do not account for the protection provided by river embankments. As a result, they should not be considered flood overflows.

<sup>7</sup> These are the same development scenarios explored in the accompanying paper on economic optimization modeling, which also appears in this journal (Wu *et al.*, 2012).

on assessments of the lowest cost of alternative energy production in India, while the value of water for downstream uses was varied to explore the sensitivity of water allocations and tradeoffs to those assumed values. We focused on three correlated values for downstream water uses, rather than allowing for tradeoffs between low flow augmentation and irrigation uses: high (\$0.1/m<sup>3</sup> in both uses), moderate (\$0.05/m<sup>3</sup> in both uses), and low (\$0.01/m<sup>3</sup> in agriculture, and \$0 for low flows in Bangladesh).<sup>8</sup> Existing studies of the marginal productivity of water in irrigation are at the low end of this range and the economic value of low flow augmentation is unknown (Wu *et al.*, 2012), so the moderate and high values represent cases with enhanced water productivity.

All Ganges water sharing agreements are bilateral, between India and Nepal, or India and Bangladesh (World Bank, 2013). The treaties between India and Nepal, for each of the three major tributaries originating in Nepal, deal primarily with management of floods and the development of upstream infrastructure projects in Nepal. These agreements do not specify legal water allocations and therefore are not assumed to constrain water use patterns in the development scenarios that are explored. The Ganges Water Sharing Agreement between India and Bangladesh, on the other hand, includes specific water allocation rules that govern minimum dry season flows at Farakka, towards Kolkata and to Bangladesh (Crow *et al.*, 1995). This agreement does not specify how much water can be withdrawn by India upstream of Farakka, nor does it address high flow (flood) issues. Therefore, only existing minimum allocations at Farakka have been imposed as constraints in the development scenarios included here.

## 4. Results

This section reports on the analysis comparing basin performance under historical and climate change conditions explored in this paper. The average temperature and precipitation change results for the A2 emissions trajectory are first described and are then compared with the A1B projections. The results of analysis of the secondary impacts (A2 scenario) are then presented, as described above. Finally, the range of changes in the indicators of basin production of hydropower, the use of surface water in irrigation or for low flow augmentation, as well as the potential economic implications of these changes, are discussed.

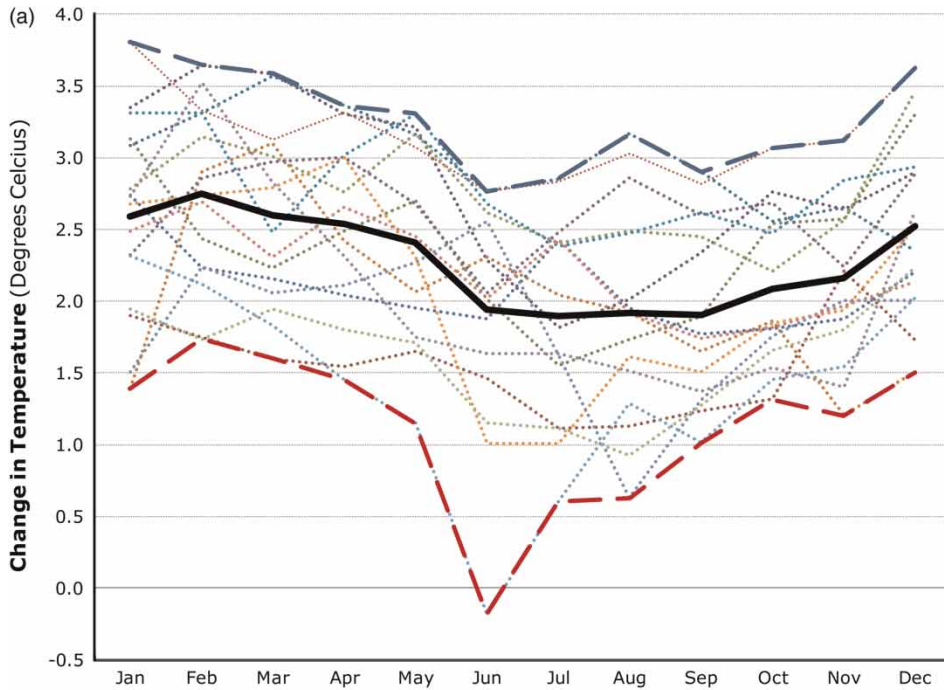
### 4.1. Temperature and precipitation projections

All of the climate models considered in this research predict rising average temperatures, by roughly 1.4–3.2 °C (A2) by 2050 and 2.8–3.9 °C (A1B) to 3.5–4.8 °C (A2) by 2100. These ranges show the variation across climate models but the temperature changes also vary across space and by season (Figure 3). In general, temperature increases appear highest during winter months (December to April) and in upstream areas – the Himalaya and northwest Gangetic plain – of the basin. The GCMs with the greatest increases in temperature are CM2 and CGCM3 (2–3 °C warmer), while PCM1 and BCM2.0 predict the lowest increases (just over 1 °C warmer).

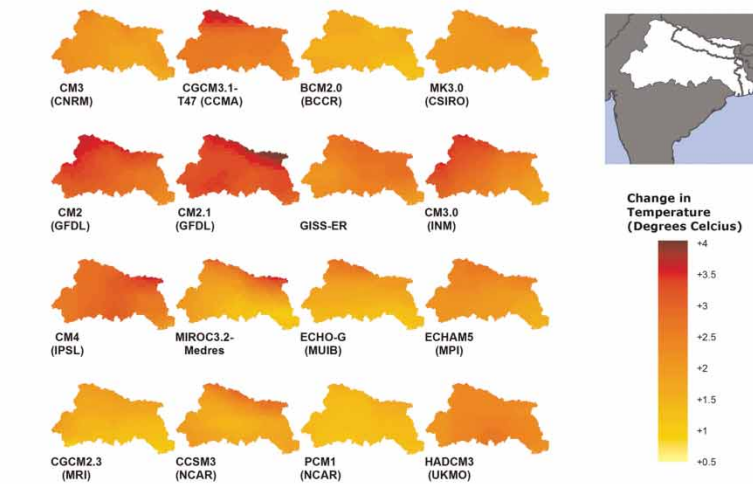
The direction of overall precipitation change, on the other hand, is much less clear. Figure 4 presents basin precipitation predictions obtained from the different GCMs (A2). The projections vary greatly,

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<sup>8</sup> Allowing for such tradeoffs by specifying a relative productivity difference between the two downstream uses does not generally alter the economic benefits generated by hydropower versus downstream uses.



(b) Ganges - Differences between GCMs, in terms of Change in Annual Temperature by the 2050s



This map shows the temperature change projected by the considered climate model, under the A2 scenario for 2040 - 2069 as compared to 1961 - 1990. Map displays gridded data (cell size=0.5dd).

Disclaimer: The boundaries, colors, denominations, and other information shown in any map do not imply any judgment on the part of the World Bank concerning the legal status of any territory or the endorsement or acceptance of such boundaries.

Sources: WCRPs CMIP3 (Meehl et al. 2007), downscaled by Maurer et al. (2008).

Fig. 3. Range of projected average temperature change in the Ganges basin for the A2 emissions scenario: (a) by month, in 2050 (each GCM outcome indicated by the dotted lines; median in solid black); and (b) across space, for 2040–2069 relative to 1961–1990. *Note:* The maxima and minima in (a) do not correspond to any single GCM, and these results do not account for temperature changes in the highest parts of the Himalaya. *Sources:* WCRP CMIP3 (Meehl *et al.*, 2005), downscaled by Maurer & Hidalgo (2008).

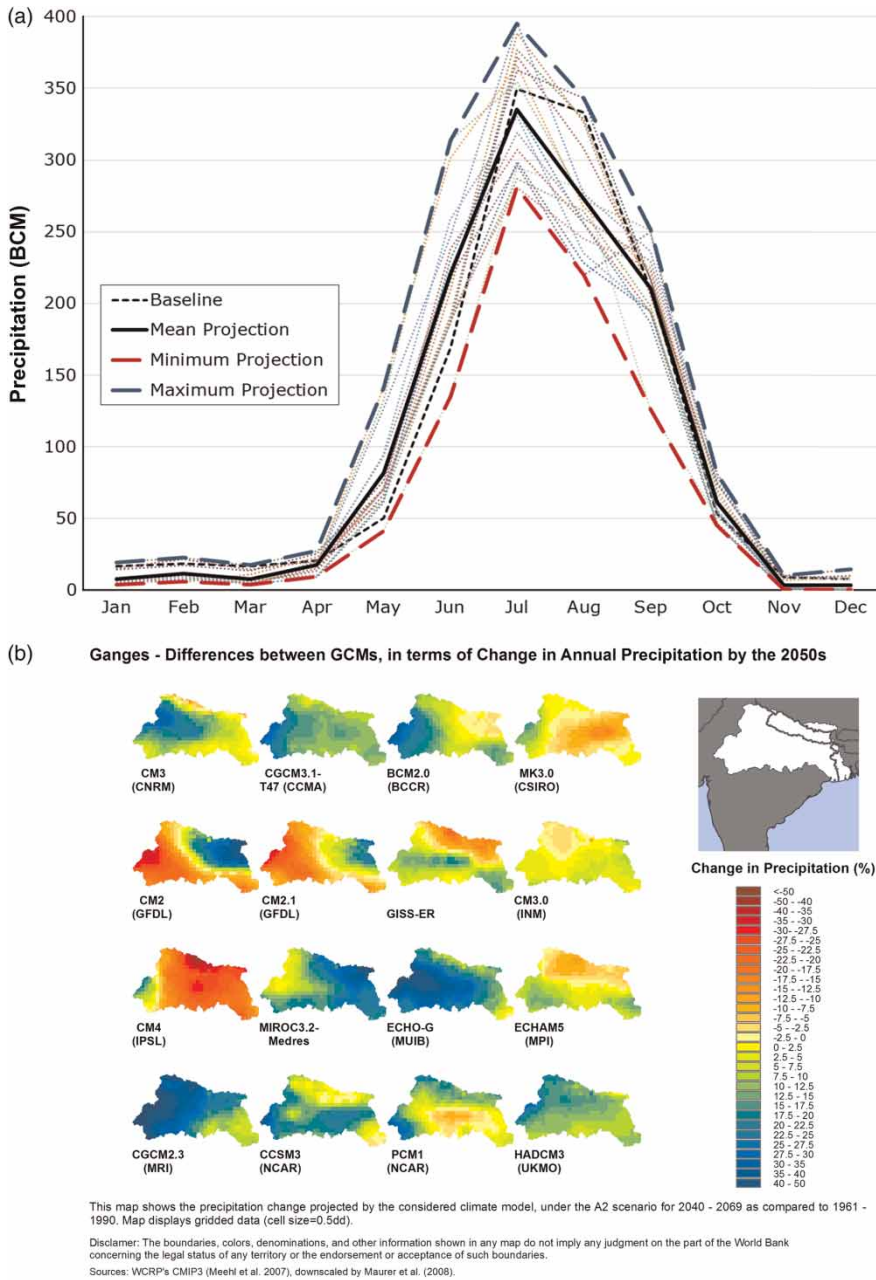


Fig. 4. Range of projected average precipitation in the Ganges basin for the A2 emissions scenario: (a) by month, in 2050 (each GCM outcome indicated by the dotted lines); and (b) across space, for 2040–2069 relative to 1961–1990. *Note:* The maxima and minima in (a) do not correspond to a single GCM. *Sources:* WCRP CMIP3 (Meehl et al., 2005), downscaled by Maurer & Hidalgo (2008).

both seasonally (Figure 4(a)) and spatially (Figure 4(b)), underscoring how difficult it is to draw conclusions about precipitation change in the basin. The individual models allow for a range of changes in rainfall over the region that spans from  $-22\%$  to  $+14\%$  (Median change =  $-2\%$ ). In addition, there is little agreement across models as to which sub-regions of the basin will be most affected (Figure 4(b)). Some models indicate very high rainfall increases in the Himalaya (e.g., the CGCM2 (MRI) model) whereas others indicate just the opposite (e.g., the CM4 (IPSL) model). Results are similarly divergent for the A1B trajectory (not shown).

#### 4.2. Secondary impacts on the water cycle

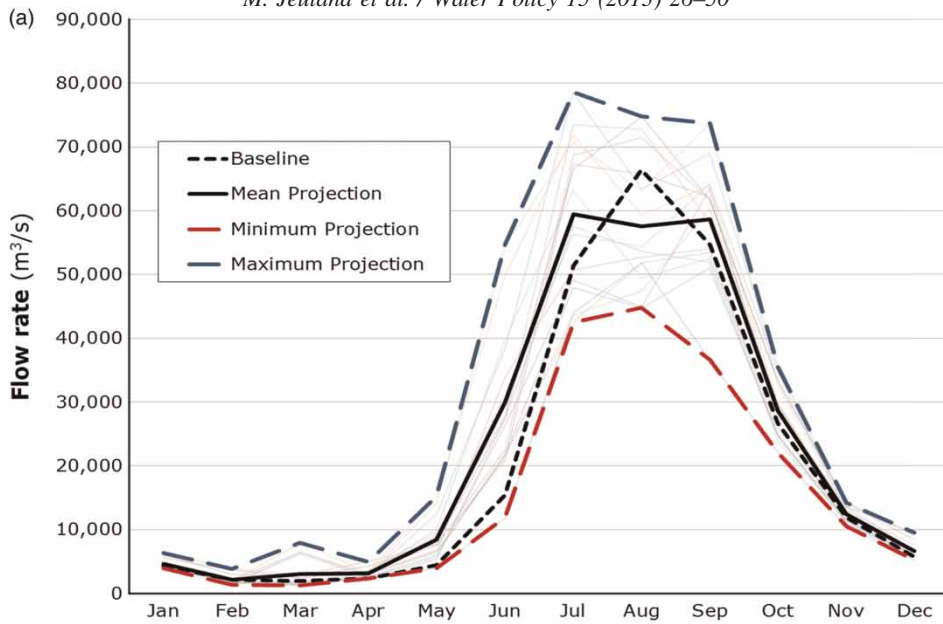
Higher temperatures and precipitation change will impact various parts of the hydrologic cycle. The zero degree isotherm (above which precipitation remains frozen) is expected to shift from an average elevation of 5,400 to 6,100 m by 2100. This shift should gradually reduce the stock of Himalayan glaciers, though their contribution to flow is modest, and significant glacial presence at high elevations is projected to remain at the end of this century (Alford & Armstrong, 2010). In contrast, the snow system will respond more quickly to temperature change. This increase will result in less precipitation accumulating as snow and cause acceleration in the melting of snow. Still, changes in snowmelt are complicated by the potential for a shift in the spatial distribution, timing, and intensity of precipitation. Snow in the Himalaya acts as a natural ‘reservoir’ system that stores monsoon precipitation and provides low flows throughout the basin (due to time lags in melting). Perturbation of this process will affect seasonal runoff and could therefore reduce low flows. Our SWAT modeling suggests that annual snowmelt will decrease from a current average of 19 BCM to 5.3–13 BCM in 2050 (10–24% reduction of the dry season flow from December to May), based on these combined changes in temperature and precipitation.

Mirroring the variation in projections of precipitation across GCMs, simulations of future runoff into basin tributaries are widely divergent. Figure 5(a) shows the overall temporal variation in runoff across GCMs aggregated to the flow gauge at Farraka; Figure 5(b) shows the variation in water yield (combining runoff, snowmelt, and groundwater recharge) across space. As shown, some GCMs project greatly increased water yield in the Himalaya, while others suggest just the opposite (Figure 5(b)). Results for other sub-regions are similarly divergent.

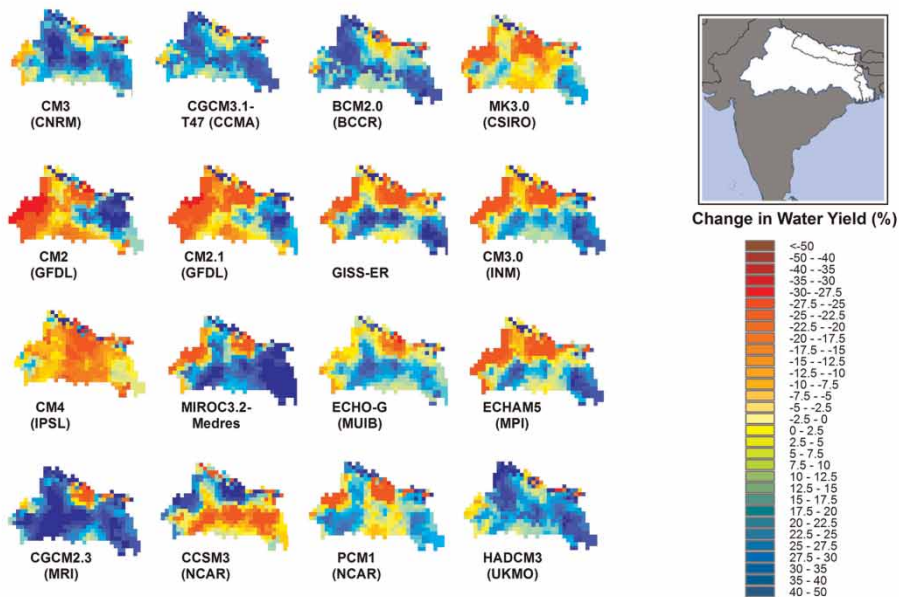
All else being constant, higher temperatures also imply increased evaporation rates in the system, and greater theoretical crop water requirements in both irrigated and natural systems. Where increased crop water demands can be met using available water supplies (precipitation or irrigation), higher ET from irrigated and rainfed crops will result in lower river flows. However, if precipitation and water availability decrease, the amount of actual ET in the basin could be reduced. The change in total basin ET obtained using the SWAT from the various GCMs thus actually ranges from an increase of 3.2% to a decrease of 6.4%, where decreases occur in drier models with reduced precipitation and water availability.<sup>9</sup> Increased temperatures will also raise non-productive evaporative losses from rivers, irrigation canals, and reservoirs, and may increase demands (e.g. increased cooling requirements for power plants, greater domestic water use) – two effects which we do not model.

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<sup>9</sup> This range is, however, likely to be biased downwards, since land use has been assumed to be unchanged in time and space. In reality, irrigators would alter the timing of their activities, and natural land cover would evolve, to adapt to changing rainfall patterns.



(b) Ganges - Differences between GCMs, in terms of Change in Annual Water Yield by the 2050s



This map shows the water yield change projected by the considered climate model, under the A2 scenario for 2040 - 2069 as compared to 1961 - 1990. Map displays gridded data (cell size=0.5dd).

Disclaimer: The boundaries, colors, denominations, and other information shown in any map do not imply any judgment on the part of the World Bank concerning the legal status of any territory or the endorsement or acceptance of such boundaries.

Sources: World Bank (Escarra, 2011).

Fig. 5. Range of projected (a) average flow at Farakka in the Ganges basin for the A2 emissions scenario by month, for 2050 (with each GCM outcome indicated by the dotted lines) and (b) change in runoff across space, for 2040–2069 relative to 1969–2001. Note: The maxima and minima in (a) do not correspond to a single GCM. Sources: WCRP CMIP3 (Meehl et al., 2005), downscaled by Maurer & Hidalgo (2008).

Collective changes in snowmelt, runoff and ET have important consequences for flows in the tributaries and main stem of the Ganges. In the flood-prone Kosi sub-basin, due to higher precipitation and runoff, average simulated flows in India are higher for all but the CM4 (IPSL) model (decrease of 14%). The average increase in flow across all models is 26%, with a maximum of 69% (MIROC3.2). The effect such large increases would have on flood risks in this flood-prone catchment is unclear, given the existence of embankments. The Kosi embankments have frequently been breached but have never technically been overtopped, even in years with flows 23% above the 1969–2001 mean (World Bank, 2013).

Results for other tributaries are summarized in Table 1. The GCM projections that imply the lowest or highest flows vary by tributary. For example, the lowest flows in the western and southern tributaries of the basin (the Upper Ganga, the Yamuna, and the Son rivers) come from the GFDL0 model, while different models generate the lowest average flows in each of the major Himalayan Nepalese tributaries (ECHAM for the Ghagara, GISS for the Gandak, and IPSL for the Kosi). Similarly, the models leading to maximum runoff vary across tributaries. The ranges of model projections also generally fall within the range of natural variability for the tributaries, except perhaps for the Kosi, which appears likely to carry significantly more flow in the future (13 of 16 GCMs generate flow averages that are more than 10% above the historical mean), and the Gandak, which may carry somewhat less (13 of 16 GCMs generate decreased flow in this tributary).

Table 1. Average historical and projected flows (in BCM/yr) at Farakka and in major tributaries of the Ganges across different climate GCMs (year 2050).

Indicator	Ganges at Farakka	Yamuna (including Chambal)	Upper Ganga	Son	Ghagara (Karnali)	Gandak	Kosi
Historical flows <sup>a,b</sup>	1969–2001	Simulated: 1998–2007	Simulated: 1998–2007	Simulated: 1998–2007	Simulated: 1998–2007	Simulated: 1998–2007	Simulated: 1998–2007
Average	493	101	60	42	109	69	74
Minimum	306 (1979)	54 (2002)	47 (1999)	19 (2004)	96 (2006)	51 (2006)	51 (2006)
Median	492 (1997)	104 (2003)	51 (2004)	49 (2000)	108 (1999)	72 (2005)	77 (1999)
Maximum	735 (1971)	141 (2005)	77 (2007)	73 (1999)	142 (2003)	97 (2001)	97 (2001)
Projected future flows in 2050 <sup>a,c</sup>							
Ensemble mean	542	116	61	41	115	59	89
Minimum	448 (IPSL)	75 (GFDL0)	51 (GFDL0)	31 (GFDL0)	91 (ECHAM)	41 (GISS)	61 (IPSL)
Median	541 (NCAR CSM)	123 (MRI)	61 (NCAR CSM)	41 (ECHAM)	112 (NCAR PSM)	56 (MRI)	89 (CNRM)
Maximum	651 (MIROC)	138 (BCM)	75 (MRI)	50 (MIROC)	142 (UKMO)	79 (UKMO)	120 (MIROC)

<sup>a</sup>Flows reported here are virgin flows where the tributaries meet the Ganges mainstem, prior to withdrawals for irrigated agriculture or other purposes.

<sup>b</sup>Minimum, median, and maximum years are identified in parentheses; these are simulated for the tributaries since historical gauge data are not available.

<sup>c</sup>Minimum, median, and maximum GCMs from the simulations are identified in parentheses.

The resulting hydrograph for flows at Farakka (near the downstream end of the basin) suggests the possibility of significantly higher or lower average flow in the Ganges (Figure 5(a)). Three of 16 models project decreased flows at Farakka and six project flow increases of more than 20%, and the overall range of the change in mean flows is from a decrease of 21% (CM4 (IPSL)) to an increase of 37% (CGCM2 (MRI)). Comparing these changes to the natural hydrological variability in the system (Figure 1), we note that mean annual flow for 1969–2001 was about 20,800 m<sup>3</sup>/s (standard deviation of 3,400 m<sup>3</sup>/s, or 16.5% of the mean, and range of 12,900 (38% below the mean) to 30,900 m<sup>3</sup>/s (49% above the mean)). The projected changes in mean flows therefore represent average changes that are not outside the natural variability in the system. But it must be emphasized that these are changes in mean flows and that variability around the range of projected mean changes could potentially create major new challenges for populations in the basin.

Finally, the supplementary modeling tools suggest that the projected changes in Ganges flows into Bangladesh would not significantly alter the progression of the saline front during the low flow season (World Bank, 2013). This is largely driven by two factors/assumptions in our model. First, we maintained the minimum flows guaranteed to Bangladesh by the Farakka Agreement, so that further decreases in dry season flows are modest. With the driest GCM, these average flows decrease only 9%, to 2,480 m<sup>3</sup>/s. Second, the flows during the dry season in wet scenarios, though appearing to represent substantial increases (increasing by 66% to about 4,510 m<sup>3</sup>/s), are insufficient to substantially alter the lean season hydrology of the GBM delta.

#### 4.3. Infrastructure development scenarios

Optimization model results across climate models and infrastructure scenarios are summarized in Table 2. In general, median outcomes for hydropower and irrigation water use are somewhat reduced from the historical case across infrastructure scenarios. This is partly due to the decreased flow predicted for several major tributaries in the western Ganges. In the case of irrigation, it is also due to increased ET and a change in the seasonality of flows, which translates into lower runoff into the system in the Gangetic plain during higher irrigation months.<sup>10</sup>

These results vary considerably across space, as can be seen from the range across GCMs of changes in hydropower production from potential new Himalayan dams (Figure 6). Projects in the Gandak system – Kaligandaki I and II, Marsyangdi, Andhi Khola, Buhri Gandaki, all except Trisuli – tend to generate less hydropower under most GCMs (consistent with the streamflow results), whereas projects in much of the Kosi sub-basin, with its increased flow, tend to generate more hydropower under most GCMs. The Kosi High Dam in particular is projected to generate more power, which explains why median hydropower production for the infrastructure scenario with 3 mega dams (including Kosi) is somewhat higher than the historical case, unlike that for the other infrastructure combinations.

The optimal allocation of low flows (for irrigation and low flow augmentation in Bangladesh) is less clear (Table 2). For the valuation conditions assessed here, median outcomes show somewhat decreased surface water use in irrigation, ranging from 3 to 10 BCM across infrastructure cases. High value conditions for low flows increase water use in irrigated systems by 3–15 BCM, with more dam storage

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<sup>10</sup> This outcome is, however, at least partly an artifact of the assumption that the temporal pattern of surface water irrigation withdrawals would not be modified under climate change.



Table 2. Indicators of basin productivity for historical and across climate GCMs (year 2050), with varying assumptions about downstream values.

	Average historical flows				Flows generated using GCM model projections in SWAT and hydrological routing models for 2050							
	Existing	3 Mega Dams	Small Dams	All Dams	Existing		3 Mega Dams		Small Dams		All Dams	
					Med <sup>a</sup>	Range	Med <sup>a</sup>	Range	Med <sup>a</sup>	Range	Med <sup>a</sup>	Range
<i>Hydropower (TW-hr/yr)</i>												
Low d/s value	26.9	74.9	56.3	105.0	22.5	(21.5–24.3)	77.7	(68.8–83.7)	48.5	(42.4–52.6)	104.8	(91.2–113.0)
Medium d/s value	25.5	72.0	52.4	100.3	20.7	(19.7–22.8)	73.9	(65.2–80.6)	45.1	(39.9–49.1)	100.4	(87.4–108.1)
High d/s value	24.4	70.7	50.9	99.2	20.5	(19.2–22.6)	73.4	(64.6–79.2)	44.2	(38.6–48.7)	99.1	(86.7–106.6)
<i>Irrigation water (BCM/yr)</i>												
Low d/s value	80.3	87.5	97.8	107.2	77.5	(71.2–84.7)	84.9	(78.4–94.6)	97.5	(90.3–106.0)	102.7	(94.9–109.5)
Medium d/s value	83.9	99.6	110.0	124.3	80.5	(74.4–87.2)	94.0	(87.9–104.6)	104.0	(99.8–109.7)	114.5	(109.0–117.4)
High d/s value	84.7	100.4	112.2	124.9	80.9	(75.5–87.8)	95.9	(89.5–105.2)	106.6	(101.3–109.9)	116.7	(111.0–117.8)
<i>Low flow in Bangladesh (BCM/yr)<sup>b</sup></i>												
Low d/s value	4.1	4.1	4.1	4.1	11.4	(4.3–27.2)	11.6	(5.7–28.5)	11.6	(5.7–28.5)	11.6	(5.7–28.5)
Medium d/s value	5.1	10.6	10.6	4.9	19.0	(9.9–36.4)	22.2	(10.3–38.0)	22.2	(10.3–38.0)	22.2	(10.3–38.0)
High d/s value	4.1	4.1	4.1	4.1	18.8	(9.8–36.2)	20.9	(10.5–40.2)	20.9	(10.5–40.2)	20.9	(10.5–40.2)
<i>Flood flows in system (BCM/yr)<sup>c</sup></i>												
Low d/s value	37.1	34.1	25.9	20.6	30.1	(0–105.0)	25.9	(0–100.0)	20.6	(0–93.8)	16.7	(0–89.6)
Medium d/s value	35.4	30.6	21.2	17.2	26.9	(0–100.1)	21.4	(0–94.1)	18.5	(0–88.2)	15.1	(0–84.6)
High d/s value	34.4	29.4	21.5	17.7	26.8	(0–99.7)	21.3	(0–93.8)	18.4	(0–87.3)	15.0	(0–83.8)

Notes: The downstream value scenarios reported in this table are: (a) Low value (values of irrigation water and low flows in Bangladesh are \$0.01 and \$0 per m<sup>3</sup>, respectively); (b) Medium value (both values are \$0.05 per m<sup>3</sup>); and (c) High value (both values are \$0.1 per m<sup>3</sup>).

<sup>a</sup>‘Med’ is the median annual outcome across GCMs and does not correspond to any specific GCM; the range spans the lowest to highest values across the 16 modeled GCMs. Historical indicators correspond to an average year.

<sup>b</sup>‘Low flow in Bangladesh’ is as measured/simulated at Farakka.

<sup>c</sup>‘Flood flows’ are flows above channel capacity thresholds in key tributaries and in the Ganges mainstem.

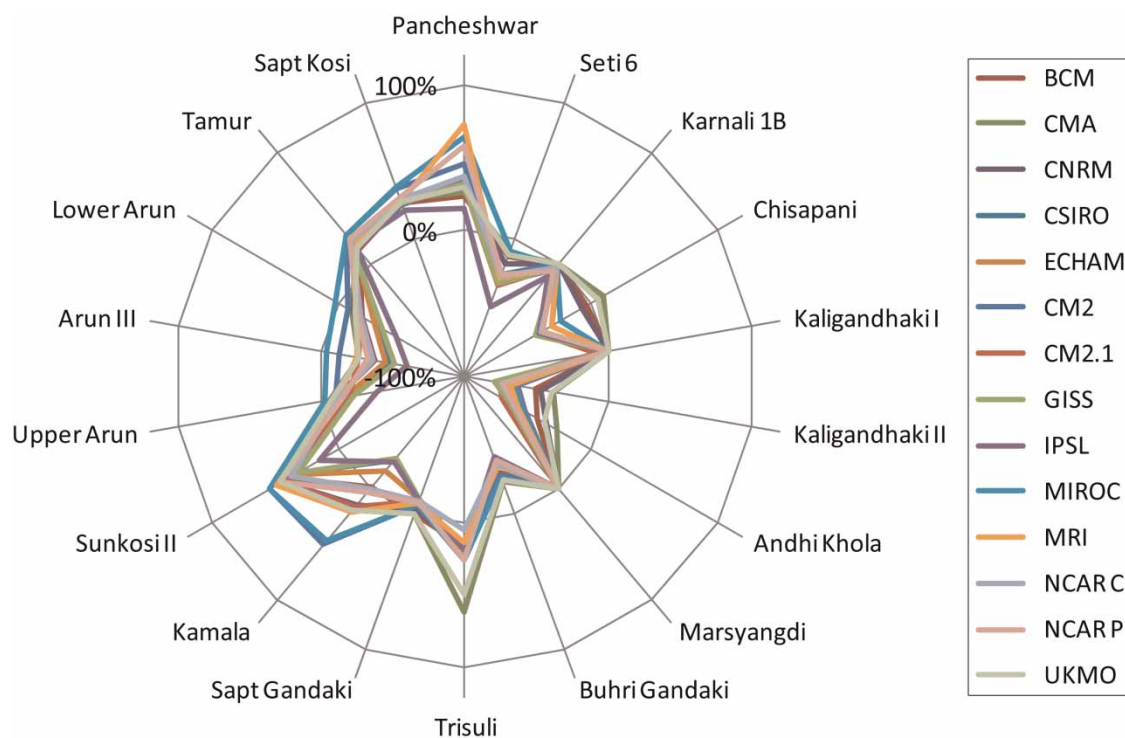


Fig. 6. Range of changes in hydropower production from potential new dams in Nepal across GCMs, relative to mean historical flow conditions, for the A2 emissions scenario for 2050.

coinciding with a higher increase. The ranges across climate models suggest the possibility of either lower or higher water use in irrigation under climate change, particularly in low infrastructure development scenarios. As infrastructure development increases, however, water use in irrigation using wetter climate model projections remains below the historical case, in part because the peak in monsoon precipitation appears to come later.<sup>11</sup> Indeed, this shifting seasonality of water availability also affects modeled impacts on irrigation water use, since crop water requirements have been assumed to follow the historical patterns. In reality, it is likely that irrigators in the Gangetic plain would alter cropping patterns and shift to groundwater to adapt to such changes, and surface water use patterns would be much more responsive to changing seasonality. As such, the reduced water availability in many model runs may be somewhat overestimated.<sup>12</sup>

Meanwhile, low season flows in Bangladesh appear to increase somewhat in the median scenario (and even with the driest GCM projections). This is roughly consistent with the flows simulated at Farakka

<sup>11</sup> This result may be inaccurate, since GCMs do not generally simulate the process of monsoon precipitation in South Asia very well (IPCC, 2007). More research and improved climate modeling is essential.

<sup>12</sup> This is mitigated to some extent by the fact that the optimization model allows use of groundwater during periods of surface water shortage to meet crop water requirements. The model, however, does not allow for permanent depletion of groundwater over time (in other words, aquifer storage must be the same at the beginning and end of the year), so 'mining' of groundwater is not permitted in climate scenarios with reduced water availability.

by the SWAT model; for the mean GCM outcome, these increase somewhat, particularly during the month of May (Figure 5(a)). However, as discussed in Wu *et al.* (2012), optimal water allocations to irrigation or low flow augmentation in Bangladesh are highly sensitive to assumptions about the relative values of these two activities. Increasing the relative value of water in irrigation versus low flow augmentation in Bangladesh changes the optimal allocation to greater water consumption upstream, while decreasing the relative value of water in irrigation increases optimal dry season flow in Bangladesh (results not shown). These relative values are currently unknown and depend on the marginal values of water in agriculture and in ecosystem services produced by the delta.

The delta will also be impacted by sea level rise and by changes in the two other major rivers flowing into it, the Brahmaputra and Meghna. Thus, the impact of sea level rise needs to be considered in a larger systems context. Sea level rise is expected to increase inundation and storm surge effects in coastal areas, increasing seawater intrusion, but the net effects of these changes are complicated by the fact that the hydrology and sediment loads of the rivers of the system (particularly from antecedent basins such as the Kosi) will also influence land erosion and accretion in the delta. Indeed, the western movement of the river system is currently protecting the western coast of Bangladesh, and land accretion has in recent years exceeded that lost to erosion (Figure 7). Salinity levels already show large spatial and temporal variability, and these fluctuations could increase and become more threatening with more extreme weather events.

Unlike the irrigation–low flow tradeoff in India and Bangladesh, there is little tradeoff between hydropower and downstream water use, because the economics of hydropower push towards storage of flood season flows and gradual release of the stored flood throughout the year, which improves downstream water availability in the dry season. Moving from low to high value cases for downstream uses, the optimal production of hydropower decreases by only 5–10%, in both historical and climate change analyses

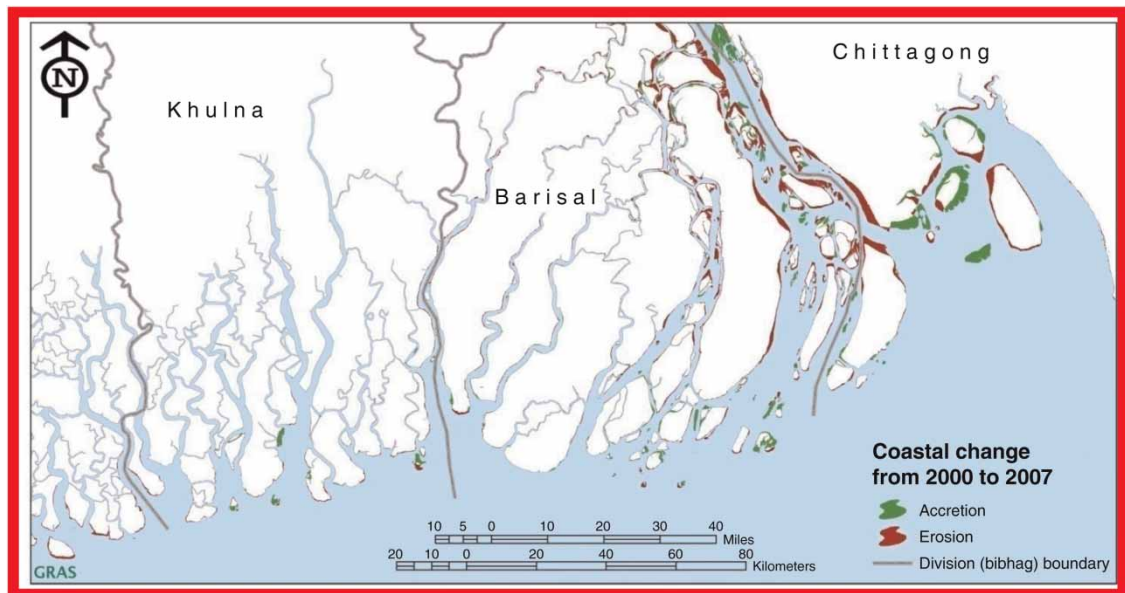


Fig. 7. Relative accretion and erosion of land in the Ganges–Brahmaputra–Meghna delta in Bangladesh. *Source:* European Space Agency collaboration with the World Bank (ESA, 2011).

and across infrastructure scenarios (Table 2). With existing infrastructure, the allocation to downstream uses (the sum of irrigation and low flows into Bangladesh) in the high value case, relative to the low value case, similarly increases by 5–10% (5–11 BCM/yr). It rises by somewhat more with increased infrastructure development (16–37 BCM/yr, depending on the infrastructures and climate scenarios), because additional storage capacity is helpful for augmenting low season flows. Full development could thus allow 25–40 BCM/yr of additional downstream use.

Analysis of high flow events further shows that infrastructure development enables some reductions of flow peaks above channel capacity thresholds in key tributaries and in the Ganges (Table 2). Yet the range of these high flows across GCMs is much larger than the effect of infrastructure, at least on the monthly scale modeled here. In the driest GCMs, flows never exceed channel capacity thresholds, regardless of which infrastructures are built. With the wettest GCM, full infrastructure development, however, only reduces above-threshold flows by about 15 BCM (or 15% of the base amount without additional infrastructure), mostly in the tributaries rather than the mainstem. The median reduction is about 12 BCM (roughly 40% of the base amount).

Infrastructure development generates large economic benefits, particularly from energy production (Figure 8; a moderate downstream valuation case with  $\$0.05/\text{m}^3$ ). With development of all dams, these benefits range from US\$6–9 billion/yr, depending on the climate scenario (the increases are US\$4–6 and US\$2–3 billion/yr for the mega dams and smaller dams, respectively). Drier models (e.g., IPSL) thus produce about 50% less economic benefit from hydropower than more favorable wet models (e.g., BCM). Irrigation benefits increase by about US\$1.7 billion/yr for full development, and by US\$0.8 and US\$1.3 billion/yr with the mega dams and smaller dams, respectively. The smaller dams enable more irrigation than the mega dams because they regulate flows in the Gandak tributary, which feeds several large irrigation canals in Uttar Pradesh. At the same time, these projects do not do as well under climate change relative to historical flow conditions because of the decreased flows in the Gandak. Finally, the three development options increase flows to Bangladesh by only a very small amount. Only if low flows in Bangladesh are economically more beneficial than use in irrigation water does the optimal allocation of such flows increase (results not shown).

The full set of infrastructures is estimated to cost about US\$35 billion (World Bank, 2013), whereas the total annual benefits generated by a system with all modeled storage infrastructures could range from US\$8 to 10 billion/yr, with moderate downstream water use values (or an incremental value of US\$6–8 billion above the benefits from existing infrastructure). If it is assumed that additional downstream water has very low unit values, as suggested in the literature, a conservative estimate of the incremental benefits would be US\$4–6 billion/yr. Assuming that projects take 10 years to construct and fill, it seems that this set of investments could generate economic net benefits for discount rates below 6.1% (conservative estimate) or 7.9% (moderate productivity estimate), discount rates well above the social discount rates favored by many economists (Jeuland, 2010b). Of course, some projects will be more or less economic than others, and more detailed project appraisals are needed to assess their full environmental and resettlement implications, as well as opportunity costs (in terms of capital).

## 5. Discussion

This study found that climate change could bring new challenges to the Ganges basin but that the mean predicted changes are not outside of the experience of natural variability in the basin. Natural variability,

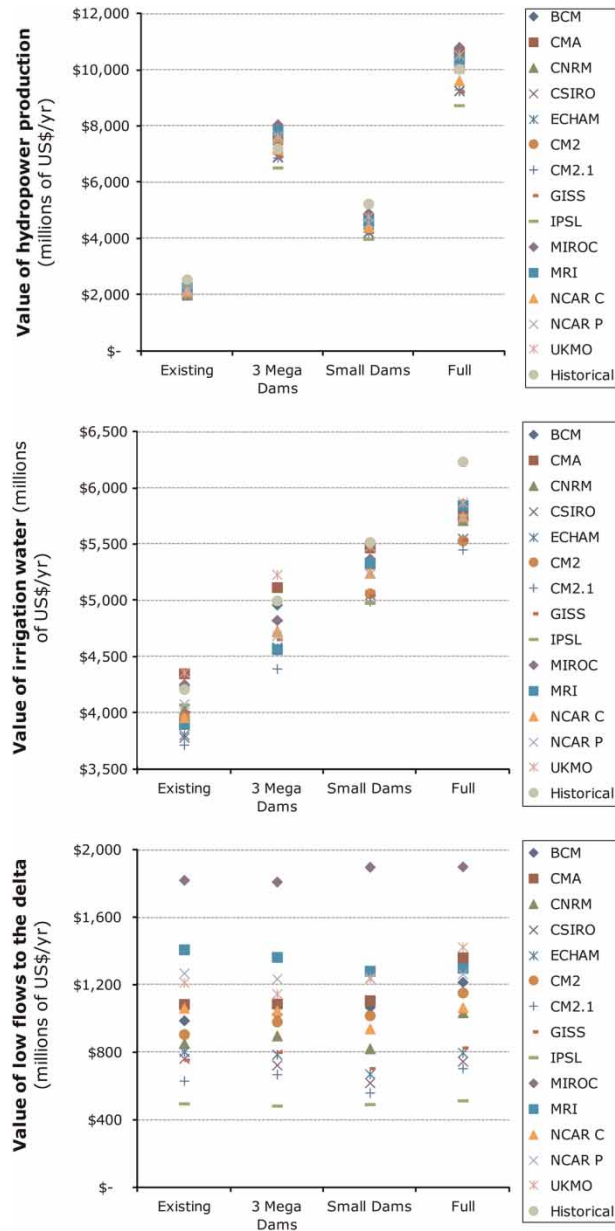


Fig. 8. Range of economic values (moderate value scenario) for optimal water allocations associated with (top) hydropower production, (middle) irrigation abstractions, and (bottom) low flow allocations to Bangladesh, using the GCM projections for the A2 emissions scenario, for 2050. Unit values are: \$0.1/kWhr (hydropower) and \$0.05/m<sup>3</sup> (irrigation water and low flows).

and associated droughts and floods, has long challenged riparians' interests in the basin. Even so, the impacts of climate change are complex and inter-connected, and there is great uncertainty in the range of predictions across models. Temperature increases, combined with uncertain precipitation changes, could greatly alter the basin's water cycle, including effects on glacier and snow melt, runoff, agricultural

water demand, and sea level rise. Study of the implications of these changes for aspects such as hydropower generation, irrigation productivity, water stress, and storm surge vulnerability has only just begun.

This paper has estimated temperature, rainfall, and runoff over the basin using 16 globally recognized GCMs for a single (A2) high emissions trajectory (IPCC, 2007). While there appears to be a clear trend towards increasing temperatures, predictions regarding rainfall and runoff vary widely and point to the possibility of increasing or decreasing overall water availability. Furthermore, these predictions vary greatly spatially. The range of model results underscores their uncertainty, and mean predictions (particularly from GCMs that are not particularly credible for simulating natural variability) can mask extremes. Nonetheless, a focus on managing current hydrological variability (whether attributable to climate change or not) is probably a good place to start in addressing and adapting to the potential future climate change challenges of the Ganges.

One common strategy for managing variability is investment in storage or irrigation infrastructure. Our analysis shows that dams could deliver significant energy and dry season water supply benefits in the region, worth US\$4–8 billion/yr (US\$4–6 billion/yr from hydropower) depending on the GCM and on the assumed value of downstream flows. Also, the reduction in snow accumulation and melt may increase the value of seasonal storage. The value of additional irrigation investments is less clear. At present, the value of downstream flows in the basin would seem to be very low; however, research is lacking on the economics of dry season flows in Bangladesh, and modernization of irrigation schemes or changes in groundwater availability could raise the marginal productivity of water in the Gangetic plain. Indeed, other work suggests that irrigation investments can reduce losses due to dry weather, but that this effect varies with groundwater availability and temperature (Fishman, 2011).

Dams are also much more limited in their ability to measurably reduce peak flows, particularly in the mainstem of the Ganges. This is because the active storage that would be added in the system – roughly 40 BCM – represents only a small fraction of peak flows, even for the driest GCMs. Plus, much of the flooding in the basin occurs as a result of local rainfall or because of failures in embankment protection; major embankments are rarely overtopped (World Bank, 2013). Thus, an effective strategy to cope with climate variability and change, particularly with respect to extreme floods, must also include soft measures: strengthened information, forecasting and warning systems, regional management institutions, and tailored local and national interventions. In fact, such solutions are already urgently needed, as evidenced by the fact that extreme and localized floods sometimes occur even when the overall flow in the Ganges is low. Improvements such as better management of conjunctive use of surface water and groundwater would similarly improve the ability of basin riparians to cope with drought conditions. The logic behind the development of greater adaptive capacity and the enabling of ‘soft’ responses only increases with greater variability and climate extremes. Several GCMs project large changes that may be of concern in either the monsoon or dry season for this region, and which generally point to the need for improved flexibility in water management systems to deal with a new range of hydrological variability. As climate models improve for this part of the world, there may be more convergence of results with respect to water availability, but water managers must today prepare for a wide range of possibilities and make decisions based on current information.

There is also a need for continued research on the potential impacts of climate and other changes in this region, and for engagement with local institutions and governments on the diverse outcomes of this research. Shifts in ‘green’ water availability will impact land cover, rainfed agriculture and livestock, while those in ‘blue’ water will alter the reliability of irrigation, hydropower, water supply, and environmental services. This paper reviewed the state of knowledge and only began to address these

complexities. The hydrology of the Himalaya and the value of water in the delta are poorly understood and, amazingly, there are no publicly available streamflow records for the rivers in the Gangetic plain in India. Specific areas of research should thus target these issues and aim to improve understanding of climate to hydrology, extreme events (droughts and floods), and long-term climate and demographic trends beyond 2050, and collect and share basic climatic and hydrological data. The framework developed in this paper could also be used to estimate climate damages through changes in water resources, by characterizing the range of losses under a range of scenarios.

This scale of uncertainty leaves water planners in a difficult position as they may not be able to discern which information in the climate change domain they can trust. Because GCM and hydrological predictions are so varied across a range of credible models, we would argue that it is impossible to define a ‘most likely’ future for which policies could be targeted. A framework for managing climate uncertainty based on specific predictions is therefore not likely to be a robust approach for adaptation and development planning. Given the extreme uncertainty over future hydrology, emphasis should be placed on flexible approaches that avoid costly mistakes and accommodate adaptive management as more information becomes available. Policy-makers should favor robust development strategies that perform well over a wide range of potential conditions and/or deliver immediate benefits regardless of climate change.

## Acknowledgements

This work was undertaken as part of the World Bank’s Ganges Strategic Basin Assessment, supported by the South Asia Water Initiative, a partnership of the World Bank and the Governments of Australia, Norway, and the United Kingdom. Thanks are due to the efforts and inputs of the many members of the assessment team, including Sylvia Lee, Ranu Sinha, Genevieve Connors, Dale Whittington, Xun Wu, Hrishii Patel, and Lauriane Cayet, who helped the co-authors to assess the broader implications of this work. The Institute for Water Modeling in Dhaka, Bangladesh, and a team from the INRM (including faculty from the Indian Institute of Technology, Delhi, and University of Texas A&M), as well as RMSI Ltd in Delhi, helped develop the knowledge base used in this study. A large group of other individuals also provided useful critiques, including Peter Rogers, David Grey, Glenn Jenkins, Mark New, Winston Yu, and two anonymous reviewers.

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