IWMI
RESEARCH
REPORT

142

The Impacts of Water Infrastructure and Climate Change on the Hydrology of the Upper Ganges River Basin

Luna Bharati, Guillaume Lacombe, Pabitra Gurung, Priyantha Jayakody, Chu Thai Hoanh and Vladimir Smakhtin

International Water Management Institute

Research Reports

The publications in this series cover a wide range of subjects—from computer modeling to experience with water user associations—and vary in content from directly applicable research to more basic studies, on which applied work ultimately depends. Some research reports are narrowly focused, analytical and detailed empirical studies; others are wide-ranging and synthetic overviews of generic problems.

Although most of the reports are published by IWMI staff and their collaborators, we welcome contributions from others. Each report is reviewed internally by IWMI staff, and by external reviewers. The reports are published and distributed both in hard copy and electronically (www.iwmi.org) and where possible all data and analyses will be available as separate downloadable files. Reports may be copied freely and cited with due acknowledgment.

About IWMI

IWMI's mission is to improve the management of land and water resources for food, livelihoods and the environment. In serving this mission, IWMI concentrates on the integration of policies, technologies and management systems to achieve workable solutions to real problems—practical, relevant results in the field of irrigation and water and land resources.

IWMI Research Report 142

The Impacts of Water Infrastructure and Climate Change on the Hydrology of the Upper Ganges River Basin

Luna Bharati, Guillaume Lacombe, Pabitra Gurung, Priyantha Jayakody, Chu Thai Hoanh and Vladimir Smakhtin

International Water Management Institute
P O Box 2075, Colombo, Sri Lanka

The authors: Luna Bharati is a Senior Researcher and Head of the Nepal office of the International Water Management Institute (IWMI) in Kathmandu, Nepal (l.bharati@cgiar.org); Guillaume Lacombe is a Researcher based at the Laos office of IWMI in Vientiane, Lao PDR (g.lacombe@cgiar.org); Pabitra Gurung is a Research Officer at the Nepal office of IWMI in Kathmandu, Nepal (p.gurung@cgiar.org); Priyantha Jayakody was a Research Officer based at the headquarters of IWMI in Colombo, Sri Lanka, and is now a PhD student at the Mississippi State University, Agriculture and Biological Department in Starkville, Mississippi, United States (jb2038@msstate.edu); Chu Thai Hoanh is a Principal Researcher and Acting Head of the Laos office of IWMI in Vientiane, Lao PDR (c.t.hoanh@cgiar.org); and Vladimir Smakhtin is Theme Leader - Water Availability and Access at the headquarters of IWMI in Colombo, Sri Lanka (v.smakhtin@cgiar.org).

Bharati, L.; Lacombe, G.; Gurung, P.; Jayakody, P.; Hoanh, C. T.; Smakhtin, V. 2011. *The impacts of water infrastructure and climate change on the hydrology of the Upper Ganges River Basin*. Colombo, Sri Lanka: International Water Management Institute. 36p. (IWMI Research Report 142). doi: 10.5337/2011.210

/ water resources / river basins / climate change / hydrology / simulation models / precipitation / evapotranspiration / statistical methods / water balance / water yield / irrigation water / India / Ganges River /

ISSN 1026-0862
ISBN 978-92-9090-744-2

Cover picture shows Ganga River upstream of Rishikesh, Uttarakhand, India (*Photo credit:* Vladimir Smakhtin, IWMI)

Please send inquiries and comments to: IWMI-Publications@cgiar.org

A free copy of this publication can be downloaded at
www.iwmi.org/Publications/IWMI_Research_Reports/index.aspx

Acknowledgements

The authors would like to thank the Indian Institute of Tropical Meteorology (IITM) for providing regional climate change projection data (Providing REgional Climates for Impacts Studies (PRECIS)) for our analysis. We would also like to thank Nitin Kaushal, Senior Manager, World Wide Fund for Nature (WWF)-India, for helping us with data acquisition and WWF-India for funding this study.

Project

This research study was initiated as part of WWF-India's 'Living Ganga Programme'.

Collaborators

The following organizations collaborated in the research conducted for this report.

IWMI International Water Management Institute

International Water Management Institute (IWMI)

WWF

World Wide Fund for Nature (WWF)-India

Donors

Funding for this research was provided by the following organization.

WWF

World Wide Fund for Nature (WWF)-India

Contents

Summary

Provision of detailed continuous long-term hydrological time series data for any river basin is critical for estimation, planning and management of its current and future water resources. Most of the river basins in India are data poor, including its iconic river – Ganga (Ganges). This study assessed the variability of flows under present and 'naturalized' basin conditions in the Upper Ganges Basin (UGB) (area of over 87,000 square kilometers (km^2)). The naturalized basin conditions are those that existed prior to the development of multiple water regulation structures, and hence may be seen as a reference condition, a starting point, against which to evaluate the impacts of planned basin development, as well as the impacts of future climate change (CC) on basin water resources. The later impacts are also part of the study: the PRECIS regional climate model (RCM) was used to generate climate projections for the UGB, with subsequent simulations of future river flows. Results show that the annual average precipitation, actual evapotranspiration (ET) and net water yields of the whole basin were 1,192 millimeters (mm), 416 mm and 615 mm, respectively. However, there were large variations in both temporal and spatial distribution of these components. Precipitation, ET and water yields were found to be higher in the forested and mountainous upper areas of the UGB. On an annual average, present-day flows throughout the UGB are about 2-8% lower than in naturalized conditions. The percentage of flow reduction is the highest during the dry months as water is being withdrawn for irrigation. Dry and wet season flows under CC scenario A2 (scenario corresponding to high population growth with slower per capita economic growth and technological change) are lower than those in present climate conditions at upstream locations, but higher at downstream locations of the UGB. Flows under CC scenario B2 (corresponding to moderate population growth and economic development with less rapid and more diverse technological change) are systematically higher and lower than those under CC scenario A2 during dry and wet seasons, respectively. The dates of minimum daily discharges are highly variable among stations and between different CC scenarios, while the dates of maximum flow are delayed downstream as a result of the delay in the onset of the monsoon in the lower parts of the basin. The report also provides actual simulated discharge time series data for all simulated scenarios, in the overall attempt to augment the river flow data for this important river basin and to facilitate the use of these data by any interested party.

The Impacts of Water Infrastructure and Climate Change on the Hydrology of the Upper Ganges River Basin

Luna Bharati, Guillaume Lacombe, Pabitra Gurung, Priyantha Jayakody, Chu Thai Hoanh and Vladimir Smakhtin

Introduction

The Ganges River System originates in the Central Himalayas, and extends into the alluvial Gangetic Plains and drains into the Indian Ocean at the Bay of Bengal. Its basin area (1.09 million km^2) spreads across India (79%), Nepal (13%), Bangladesh (4%) and China (4%). The river is of high importance to riparian countries with an estimated 410 million people directly or indirectly depending on it (Verghese and Iyer 1993). In the upstream mountainous regions, hydropower is the main focus of development with mega and micro projects either under construction or being planned in both Nepal and India. After the main river channel reaches the plains, it is highly regulated with dams, barrages and associated irrigation canals. All this infrastructure development and abstractions affects the river's flow regime and reduces flows, which, in turn, impacts downstream water availability, water quality and riverine ecosystems. Furthermore, there are concerns that CC is likely to exacerbate the water scarcity problem in the Ganges Basin. Therefore, modeling the hydrology of the basin is critical for estimation, planning and management of current and future water resources.

To operate a hydrological model, reliable data on climatological variables such as temperature, precipitation, evaporation, etc., over space and time are necessary. For analysis of the past, such information can be derived from observational data sets. However, for assessment of the future with the possible impacts of CC, the hydrological models can be driven with the output from the general circulation model (GCM) (IPCC 1996; Akhtar et al. 2009). However, the resolutions of GCMs are currently constrained by computational and physical reasons to 200 kilometers (km) for climate change predictions and are too course for hydrological modeling at basin scale. In order to increase the spatial resolution of these predictions, one method that is used is statistical downscaling techniques, which have been developed in the last decades (e.g., Wilby et al. 1999; Bergström et al. 2001; Pilling and Jones 2002; Guo et al. 2002; Arnell 2003; Booij 2005; Benestad et al. 2008). A second option is the use of dynamical downscaling (e.g., Hay et al. 2002; Hay and Clark 2003; Fowler and Kilsby 2007; Leander and Buishand 2007). Dynamical downscaling fits output from GCMs into regional meteorological models. It involves using numerical meteorological modeling to reflect how global patterns affect local weather conditions. The high horizontal resolution of a RCM (about 10-50 km) is more appropriate for resolving the small-scale features of topography and land use. Furthermore, the high resolution of RCM is ideal to capture the spatial variability of precipitation as input into hydrological models (Gutowski et al. 2003; Akhtar et al. 2009), and provide better representation of mountain areas affected by the amount of rainfall and the location of windward rainy areas and downwind rain shadow areas (Jones et al. 2004).

Hydrological simulations using RCM output in data-sparse basins such as the Ganges involves several problems, including uncertainties in inputs, model parameters and model structure (Akhtar et al. 2009). The main disadvantages of RCMs are that they inherit the large-scale errors of their driving GCM model and require large amounts of boundary data previously archived from relevant GCM experiments. Additional uncertainties can be linked to the local scale patterns in downscaling of temperature, precipitation and evapotranspiration in a specific basin (Bergström et al. 2001; Guo et al. 2002; Akhtar et al. 2009).

Although modeling studies that analyzed the impacts of water infrastructure development on the hydrology and water resources in other parts of the world are available, studies focusing on the Ganges Basin are limited. The National Communication (NATCOM) project by the Ministry of Environment and Forests, Government of India, quantified the impact of CC on water resources of all major Indian river systems (Gosain et al. 2006). This study used the Hadley Centre Regional Climate Model 2 (HadRM2) daily weather data as input to run the Soil and Water Assessment Tool (SWAT) hydrological model to determine the spatio-temporal water availability in the river systems and to calculate basin water balances. This study suggests that precipitation, evapotranspiration and runoff will increase by approximately 10% in the Ganges Basin. The NATCOM study, however, did not consider the effect of water infrastructure development in the basin and modeled the Ganges without water abstraction and use. Furthermore, the simulations were not validated against observed flow data, making the model results uncertain.

The Water Evaluation And Planning (WEAP) model was used by de Condappa (2009) for large-scale assessment of surface water resources in the Indus and Ganges basins, with a special focus on the contribution of snow and glaciers to flow. Several, relatively simple scenarios of changes in glaciated area were simulated. Results suggest that glaciers play the role of buffers against interannual variability in precipitation, in particular, during years with a weak monsoon. However, the impacts of CC and water use in the basin were not fully assessed. Some other modeling studies examined, in detail, the hydrological regime of individual glaciers in the UGB (Singh et al. 2008), rather than the impacts of water use and CC on basin-wide water resources. Similarly, Seidel et al. (2000) modeled the runoff regime of the Ganges and Brahmaputra basins, accounting for precipitation, remotely sensed snow covered areas and temperatures using the Snowmelt Runoff Model (SRM). They found that the already high risk of floods during the period July to September is slightly increased with CC. Numerous papers can be found on the impact of water resources development and CC on downstream areas of Bangladesh (e.g., Ahmad et al. 2001; Jian et al. 2009; Mirza 2004; Rahaman 2009). These studies, however, do not assess the dynamics of water availability and use in upstream areas within Nepal and India.

Apart from the general paucity of hydrological and water resources studies with fine spatial resolution in the Ganges Basin, the inherent problem of this basin is the availability of observed discharge data, against which models can be calibrated and validated. Discharge data in the Himalayan part of the basin are scarce due to lack of measurement stations. In the downstream plains, although discharge data from gauging stations exist, these data are not accessible to the public due to national security laws in India. This leaves most of the hydrology studies of the Ganges, which are carried out by the government agencies, being classified and not accessible in the public domain. In addition, simulated data are also not widely shared, hence impeding their use in subsequent water resource applications.

The UGB (upstream of Kanpur Barrage; catchment area 87,787 km^2) (Figure 1) encompasses various physiographic conditions, is of great cultural and spiritual importance for the country, yet, it is already highly regulated with multiple water structures (with more plans on the way), and will most likely experience significant changes in hydrology (with significant economic and social implications) due to CC.

This study is part of WWF-India's "Living Ganga Programme." The main objective of this programme is to develop and promote approaches for sustainable water resources management, including environmental flows which conserve biodiversity and support livelihoods under present and changing climate scenarios (WWF 2011). In the present study, the flow variability of the catchment is characterized for four scenarios corresponding to pairwise combinations of present and future water infrastructure development and climate conditions, as detailed in the section, *Methods and Data*. Results are presented in two parts: 1) water balances for subcatchments for present and 'naturalized' conditions (prior to the development of multiple regulation structures), and 2) several indicators of hydrological variability that characterize the likely impacts of CC at both present and 'naturalized' flow regimes. For purposes of this study, naturalized flows are defined as 'free flowing flows in the mainstream without dams and barrages, and irrigation diversions'. These assessments are the prerequisites for the subsequent detailed water allocation modeling under present and future flow regimes in the UGB. In addition, the aim of the simulation modeling here is to provide freely available flow time series for the UGB, in order to enhance data availability and initiate hydrological data sharing. All simulated data are also available via IWMI's water data portal (http://waterdata.iwmi.org/).

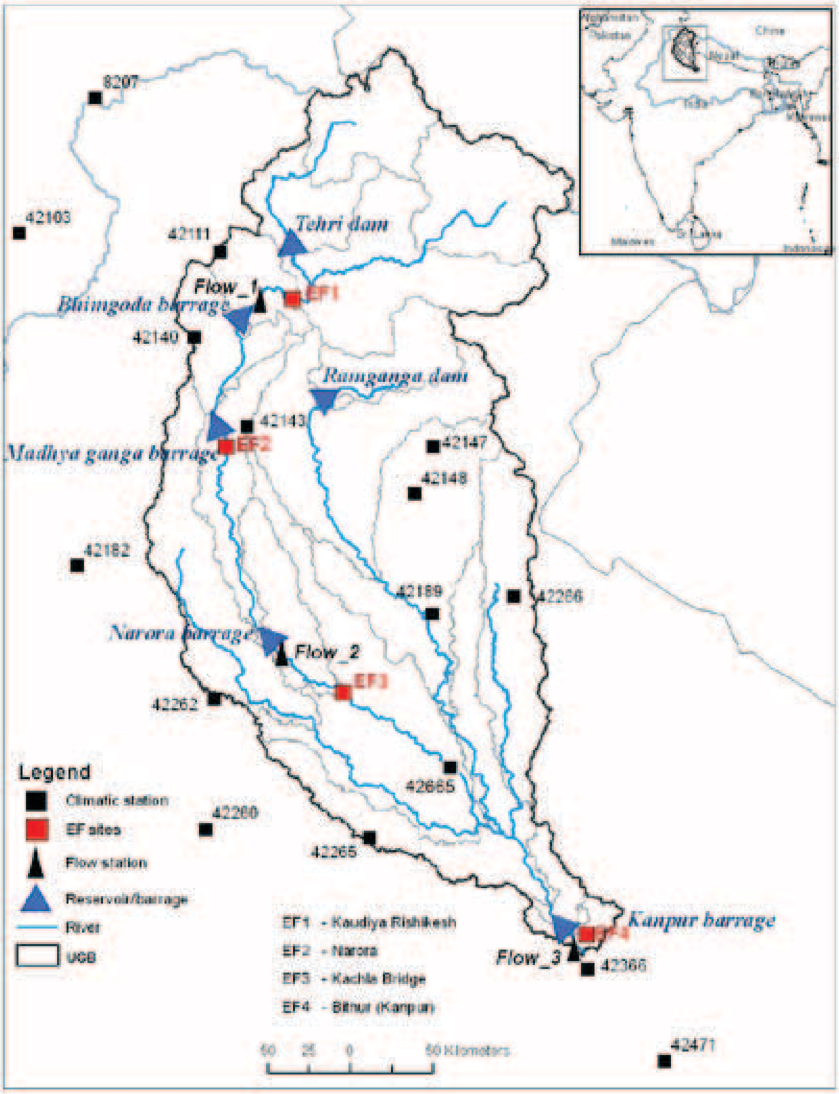


FIGURE 1. Upper Ganges Basin (UGB) with locations of barrages, reservoirs, hydrometeorological stations and 'environmental flow (EF) sites', where environmental flow assessment was undertaken under the "Living Ganga Programme."

Methods and Data

The analytical framework of the study is presented in Figure 2 and detailed in the following sections. The SWAT hydrological model is used to simulate flows.

The steps of the analytical framework are detailed below.

1. *SWAT model setup* for the UGB: a model with 21 subbasins was setup using a Digital Elevation Model (DEM), soil and land use/land cover (LULC) maps and flow data.
2. *Collection of observed climate data:* daily data for five climate variables (precipitation, maximum and minimum temperature, solar radiation, wind speed and relative humidity) measured inside and around the basin from 1971 to 2005 were collected.
3. *Calibration and validation of SWAT model* against observed flow data over the period 2000-2005.
4. *Selection of a RCM for simulation of future climate conditions:* output time series simulated by PRECIS over the periods 1961-1990 and 2071-2100 were provided by IITM.
5. *Adjustment of climate change data:* PRECIS time series data for the grid cells encompassing climatic stations were

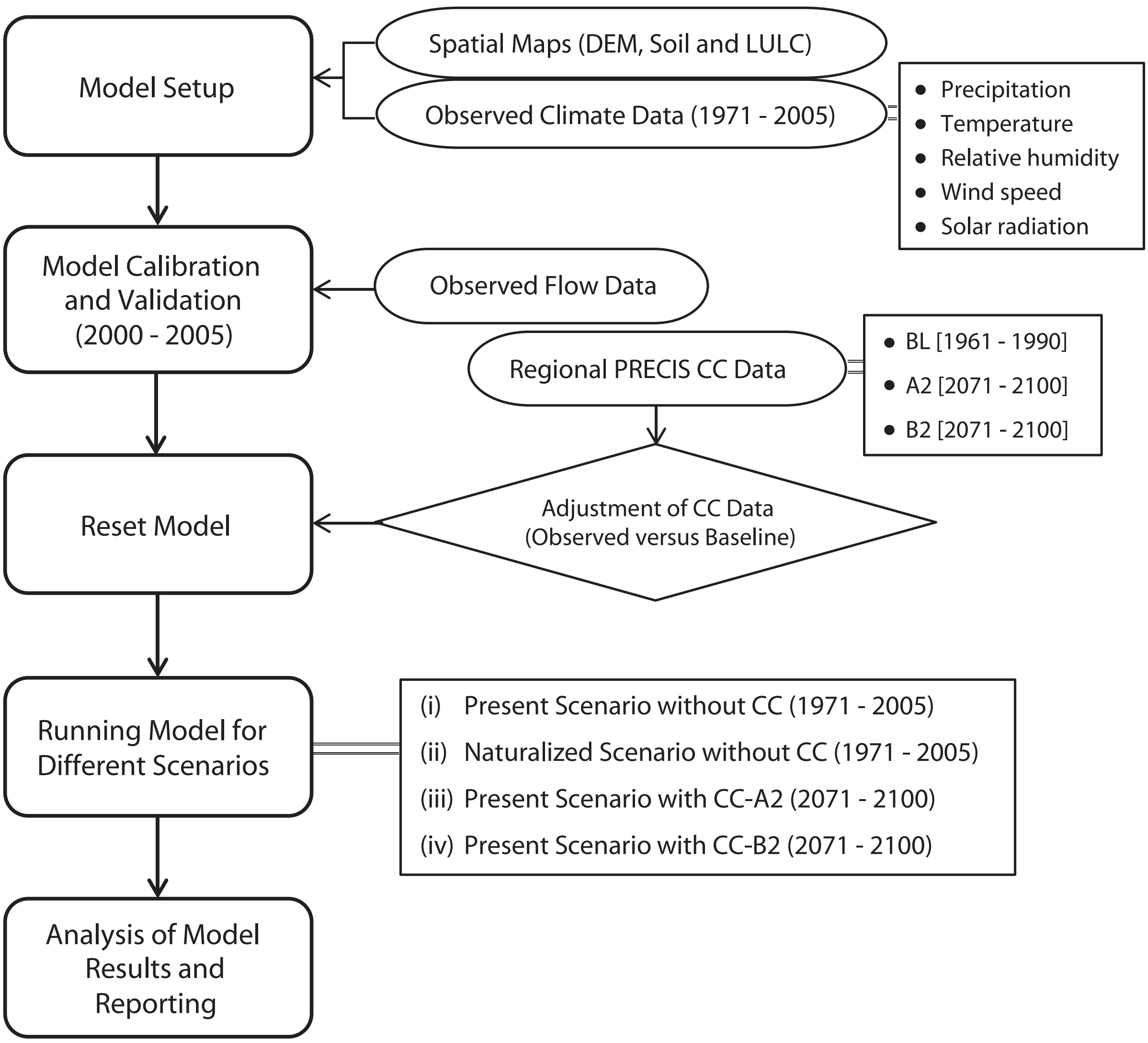


FIGURE 2. Analytical framework. *Note*: BL = baseline scenario; A2 = Climate conditions as projected by PRECIS under A2 scenarios; B2 = Climate conditions as projected by PRECIS under B2 scenarios

compared to actual records over the period 1961-1990 to statistically determine the required bias adjustments. These adjustments were then applied to the projection period 2071-2100 based on the assumption that the same bias occurs in both simulation and projection periods.

6. *Setting study scenarios:* based on the objectives of the study, four scenarios with different land and water use, and climate conditions were established. These are (i) present condition scenario (water infrastructure development as of 2005 and present climate as measured from 1971 to 2005); (ii) 'naturalized' scenario, assuming that no water infrastructure were built under present climate conditions (1971-2005); (iii) climate change scenarios, assuming that water infrastructure is that of 2005, under 2071-2100 climate conditions as projected by PRECIS under A2 scenarios; and (iv) B2 scenarios.
7. *Scenario simulation* using SWAT model.
8. *Analysis of simulated results:* simulated water balances were compared between present and 'naturalized' conditions. The impacts of climate change and water infrastructure developments on flow regimes at the four 'EF sites' were characterized using indicators of hydrological alterations. This report presents the main results of this analytical framework.

SWAT Model Description and Setup

SWAT is a process-based continuous hydrological model that predicts the impact of land management practices on water, sediment and agricultural chemical yields in complex basins with varying soils, land use and management conditions (Arnold et al. 1998; Srinivasan et al. 1998). The main components of the model include climate, hydrology, erosion, soil temperature, plant growth, nutrients, pesticides, land management, channel and reservoir routing. SWAT divides a basin into subbasins. Subbasins are connected through a stream channel. Each subbasin is further divided into Hydrological Response Units (HRU). A HRU is a unique combination of soil and vegetation types. SWAT simulates hydrology, vegetation growth and management practices at the HRU level.

The hydrological cycle is simulated by SWAT using the following water balance equation (1):

$$SW_t = SW_o + \sum_{i=1}^{n} (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw}) \qquad (1)$$

where: SW_t: Final soil water content (mm); SW_o: Initial soil water content (mm); t: Time in days; R_{day}: precipitation on day i (mm); Q_{surf}: surface runoff on day i (mm); E_a: actual evapotranspiration on day i (mm); w_{seep}: percolation on day i (mm); and Q_{gw}: return flow on day i (mm).

Basin subdivision allows differences in evapotranspiration for various crops and soils to be simulated. Runoff is predicted separately for each subbasin and routed to obtain the total runoff for the basin. This increases the accuracy and gives a much better physical description of the water balance. More detailed descriptions of the model can be found in Arnold et al. (1998), Srinivasan et al. (1998) and Neitsch et al. 2005. The SWAT model was chosen for this study because it can be used in large agricultural river basin scales to also simulate crop water use. As actual data for irrigation distribution was not available, the calculated crop water use helped determine the irrigation water requirements in the basin. The SWAT model has been extensively used in the USA and elsewhere for calculating water balances of primarily agricultural catchments (e.g., Jha 2011; Bharati and Jayakody 2011; Garg et al. 2011).

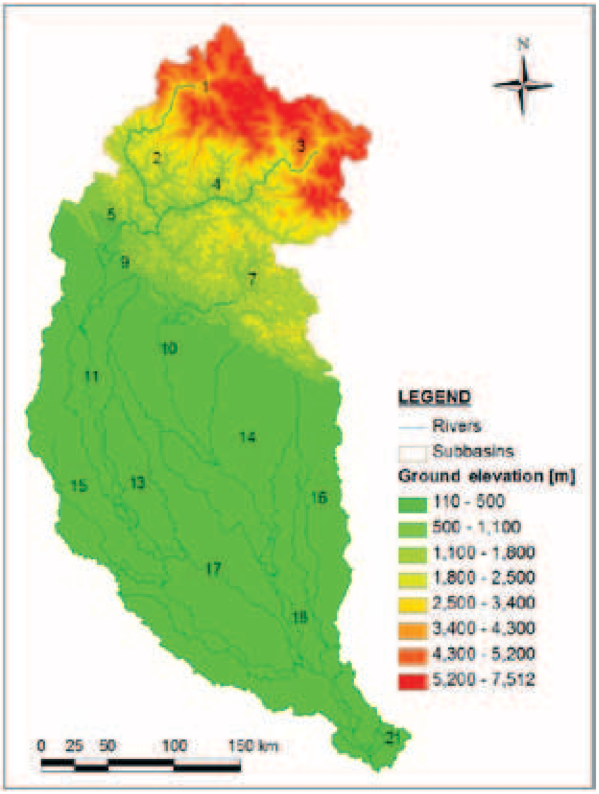
The SWAT model requires three basic files for delineating the basin into subbasins and HRUs: Digital Elevation Model (DEM), soil map and Land Use/Land Cover (LULC) map. Figure 3(a) shows the DEM for the basin using 90 m Shuttle Radar Topography Mission (SRTM) data.

The elevation in the UGB ranges from 100 m in the lower plains to 7,500 m in the upper mountain region. Some mountain peaks in the headwater basin are permanently covered by snow. Figure 3(b) shows the land use map which was developed using the LandSat image from 2003. According to this map, around 65% of the basin is occupied by agriculture. The main crop types (identified from the land use map and district statistics) are wheat, maize, rice, sugarcane, pearl millet and potato. About 25% of the area of the UGB is covered by forests, mostly in the upper mountains. For the naturalized scenarios, as there are no water provisions for irrigation, the irrigated crops such as rice and sugarcane are replaced by rainfed crops from the region, i.e., lentils and wheat.

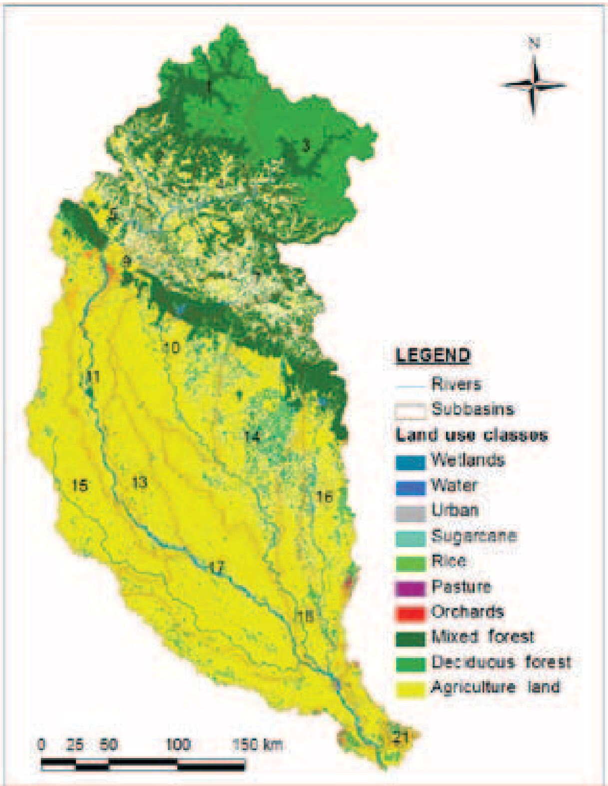
Figure 3(c) shows the soil map of the basin. There are nine soil types in the UGB. Lithosols dominate the upper, steep mountainous areas and are very shallow and erodible. Cambisols and luvisols are found in the lower areas. Cambisols are developed in medium- and fine-textured material derived from alluvial, colluvial and aeolian deposits. Most of these soils make good agricultural land. Luvisols are tropical soils mostly used by farmers because of its ease of cultivation, but they are greatly affected by water erosion and loss in fertility. Annual average precipitation in the UGB ranges from 550 to 2,500 mm (Figure 3(d)). A major part of the rainfall is due to the southwestern monsoon from July to October. Wet season corresponds to the period July to November and the dry season extends from December to June.

The UGB mainstream is highly regulated with dams, barrages and corresponding canal systems (Figure 1). The two main dams, Ramganga and Tehri, became operational in 1988 and 2008, and have total storage capacities of 2,448 and 3,540 10^6 m^3, respectively. There are three main canal systems. The Upper Ganga canal takes off from the right flank of the Bhimgoda barrage with a head discharge of 190 m^3/s, and irrigates an area of 2 million hectares (Mha). The Madhya Ganga canal provides annual irrigation water to 178,000 hectares (ha). The Lower Ganga canal from the Narora weir irrigates 0.5 Mha.

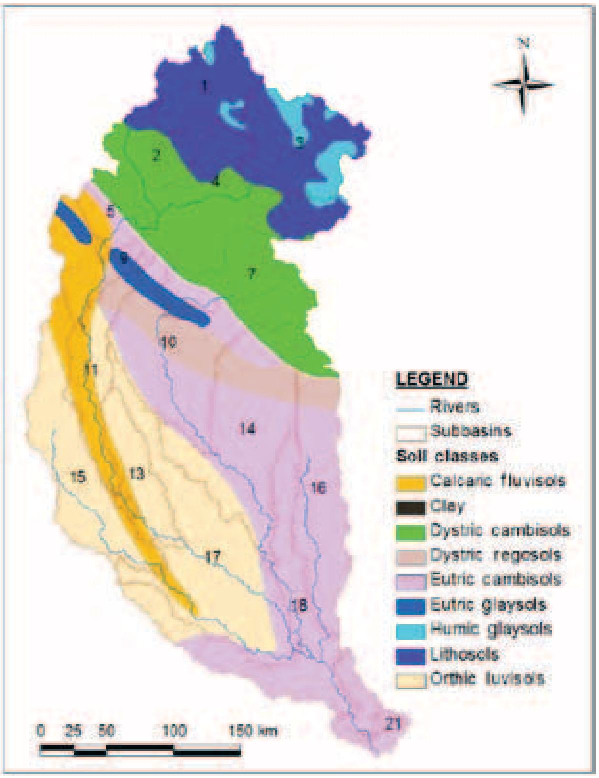
During the winter season, a part of the runoff in the basin is generated through contributions from snowmelt and glacier melt. Therefore, for this study, snowmelt was computed using the SWAT model. In the model, when the mean daily air temperature is less than the snowfall temperature, the precipitation within a HRU is classified as snow and the liquid water equivalent of the snow precipitation is added to the snowpack. The snowpack increases with additional snowfall, but decreases with snowmelt or sublimation. In the model, snowmelt is controlled by the air and snowpack temperature, the melting rate and the areal coverage of snow. Snowmelt is then included with rainfall in the calculations of runoff and percolation. Further information on snowmelt calculations can be found in Neitsch et al. 2005. Wang and Melesse (2005) evaluated the performance of snowmelt hydrology of the SWAT model by simulating streamflows for the Wild Rice River watershed (located in the USA), and found that the SWAT model had a good performance on simulating the monthly, seasonal and annual mean discharges and a satisfactory performance on predicting the daily discharges. When analyzed alone, the daily streamflows during the spring, which were predominantly generated from melting snow, could be predicted with an acceptable accuracy, and the corresponding monthly and seasonal mean discharges could be simulated very well. The Gangotri glacier is located within the UGB. Therefore, in order to include the contribution of this glacier in the present model setup, discharge data collected from a gauging site very close to the snout of the glacier (Singh et al. 2006) was added to the relevant subbasin.



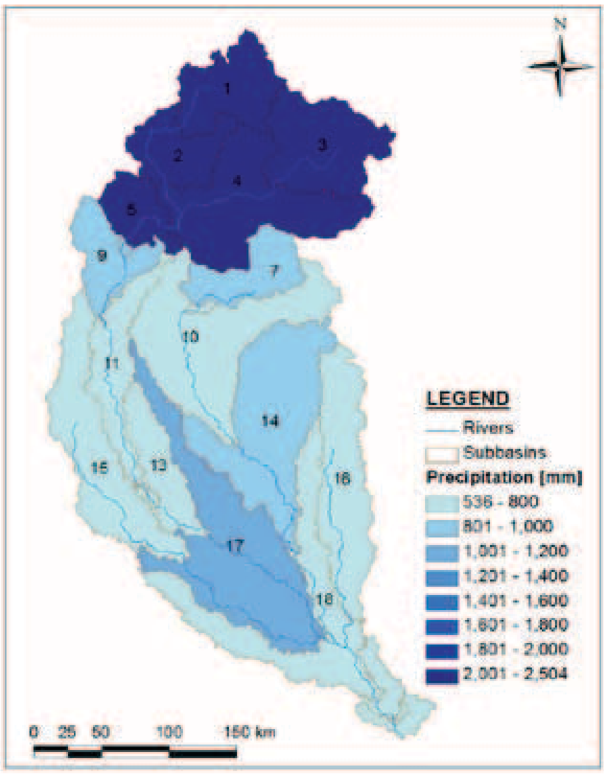
(a) Digital Elevation Model, SRTM



(b) Land use map, Land Sat TM, 2003



(c) Soil Map, FAO



(d) Mean Annual Precipitation (1971-2005)

FIGURE 3. The maps of the UGB used for modeling, with numbers and boundaries of subbasins used in hydrological simulations.
Note: FAO = Food and Agriculture Organization of the United Nations.

Available Observed Time Series Data

The SWAT model requires time series of observed climate data, including precipitation, minimum and maximum temperature, sunshine duration, wind speed and relative humidity. Table 1 lists the climate stations used in the model. The locations of stations are shown in Figure 1. The SWAT model uses the data of a climate station nearest to the centroid of each subcatchment as an input for that subcatchment (Figure 3d).

Table 2 presents details of the flow stations used for calibration and validation of the model. Locations of the flow stations are shown in Figure 1. Due to restrictions on the distribution of Ganges data from the Indian Central Water Commission (CWC), only a very short time series of data at some barrages were available. Although daily observed flow data were available from Narora, only monthly time series data were available for the other sites. As the model works with daily time steps, simulated daily flow values had to be accumulated into monthly values for calibration and validation. The existing dams, barrages and irrigation deliveries were incorporated into the model using available salient features from the relevant barrage/dam authorities.

TABLE 1. Details of the meteorological data used.

Station code[1]	Name	Available record	Available data type				
			R	T	S	W	H
42111	Dehradun[2]	1970-2005	x	x	x	x	x
42103	Ambala[2]	1970-2004	x	x	x	x	x
8207	Simla[2]	1989-2005	x	x	x	x	x
42140	Roorkee[2]	1970-1994; 2002-2005	x	x	x	x	x
42182	Delhi[2]	1970-2005	x	x	x	x	x
42366	Kanpur	1970-1974; 1986-1995	x	x			
42471	Fatehpur	1970-2005	x	x			
42189	Bareilly[2]	1970-2005	x	x	x	x	x
42260	Agra	1970-2005	x	x			
42262	Aligarh	1970-2005	x	x			
42143	Najibad[2]	1970-2005	x	x	x	x	x
42147	Mukteshwar[2]	1970-2005	x	x	x	x	x
42148	Pant Nagar[2]	1970-2005	x	x	x	x	x
42265	Mainpuri	1970-2005	x	x		x	
42665	Shajapur	1970-2005	x				
42266	Shahjahanpur	1970-2005	x	x		x	x

Notes:

[1] Station codes correspond to locations shown in Figure 1.

[2] Station has large data gaps.

R = Precipitation; T = Minimum and maximum temperature; S = Sunshine duration; W = Wind speed; H = Relative humidity.

TABLE 2. Details of flow stations and data availability for model calibration and validation.

Station code	Location	Catchment area (km^2)	Available record	Type of data
Flow_1	Bhimgoda	23,080	April 2002 - December 2005	Monthly inflow into the barrage
Flow_2	Narora	29,840	January 2000 - June 2005	Daily spill release from the dam
Flow_3	Kanpur	87,790	June 2003 - December 2005	Monthly spill release from the dam excluding dry season flows

Model Calibration and Validation

The period from January 1, 1970 to December 31, 1971 was used to warm-up the model. The available data between 2000 and 2005 from each station were divided into two sets, each of them including the same number of daily observations. The first and second sets were used for model calibration and validation, respectively. Model parameters were calibrated simultaneously for all three flow stations.

The model performance was determined by calculating the coefficient of determination (R^2) and the Nash-Sutcliffe Efficiency (NSE) criterion. R^2 and NSE values for each simulation are presented in Table 3. The model performance over calibration and validation periods is acceptable, according to the model performance ratings proposed by Liu and De Smedt (2004). In addition, comparisons were made between the measured and simulated annual water flow volumes. The differences in volume ranged from 22 to 25% and from 7 to 9% during calibration and validation periods, respectively.

Figure 4 shows observed precipitation, observed and simulated flows for inflow into the Bhimgoda barrage, outflow from Narora barrage and outflow from Kanpur barrage. Although flows are regulated at these sites, observed and simulated hydrographs match very well. This adds confidence to the results that are presented in the following sections.

Downscaling of Climate Model Data

Climate data from PRECIS were used as input to the SWAT hydrological model in order to assess future river flow scenarios. PRECIS is an atmospheric and land surface model developed at the Meteorological Office Hadley Centre, UK, for generating high-resolution climate change information for many regions of the world (Jones et al. 2004). It has a spatial resolution of 0.22° x 0.22°. Climate data from the GCM, Hadley Centre Coupled Model, version 3 (HadCM3) (Jones et al. 2004), were downscaled with PRECIS for the UGB under A2 and B2 Special Report on Emission Scenarios (SRES) scenarios (IPCC 2000) by IITM. A2 and B2 are two climate change SRES scenarios studied by the Intergovernmental Panel on Climate Change (IPCC). A2 corresponds to a story line of high population growth with slower per capita economic growth and technological change, and B2 corresponds to a story line of moderate population growth and economic development with less rapid and more diverse technological change. PRECIS data used in that study were extracted from 15 grid cells corresponding to the location of the 15 meteorological stations previously described. These time series data cover the periods 1961-1990 and 2071-2100, and include four variables: precipitation, temperature, wind speed and relative humidity. Although these PRECIS data result from a downscaled global climate model which accounts for regional climate and topographic characteristics, they still exhibit discrepancies with regard to observed meteorological data. For instance, the mean absolute relative difference in annual precipitation depths between PRECIS and observed time series over the baseline period 1970-1990 is about 55%. Therefore, PRECIS data were adjusted in such a way that, at each of the 15 station locations, the main statistical properties of adjusted PRECIS output (mean and standard deviation) match those of the historical data. This statistical downscaling approach is described in Bouwer et al. (2004).

TABLE 3. A summary of the SWAT model performance evaluation.

Station code and location	Calibration period	Validation period	Performance statistics (Fraction)					Annual water flow volume					
			Statistic	Calibration		Validation		Calibration			Validation		
				Value	Ratings	Value	Ratings	Observed	Simulated	Difference	Observed	Simulated	Difference
Flow_1 (Bhimgoda)	April 1, 2002 - December 31, 2003	January 1, 2004 - December 31, 2005	R^2	0.86	> 0.85	0.84	(0.65 - 0.85)	1,152	1,437	24.7%	1,017	1,090	-7.2%
					Excellent		Very good						
			NSE	0.67	(0.65 - 0.85)	0.81	(0.65 - 0.85)						
					Very good		Very good						
Flow_2 (Narora)	January 1, 2000 – December 31, 2002	Jan 1, 2003 - June 30, 2005	R^2	0.92	(> 0.85)	0.88	(> 0.85)	905	1,103	21.8%	694	754	8.6%
					Excellent		Excellent						
			NSE	0.90	(> 0.85)	0.85	(0.65 - 0.85)						
					Excellent		Very good						
Flow_3 (Kanpur)	June 1, 2003 - October 31, 2003	June 1, 2005 – December 31, 2005	R^2	0.86	(> 0.85)	0.60	(0.60 - 0.64)	756	923	22.1%	622	663	6.7%
					Excellent		Good						
	and		NSE	0.82	(0.65 - 0.85)	0.66	(0.65 - 0.85)						
	June 1, 2004 - October 31, 2004				Very good		Very good						

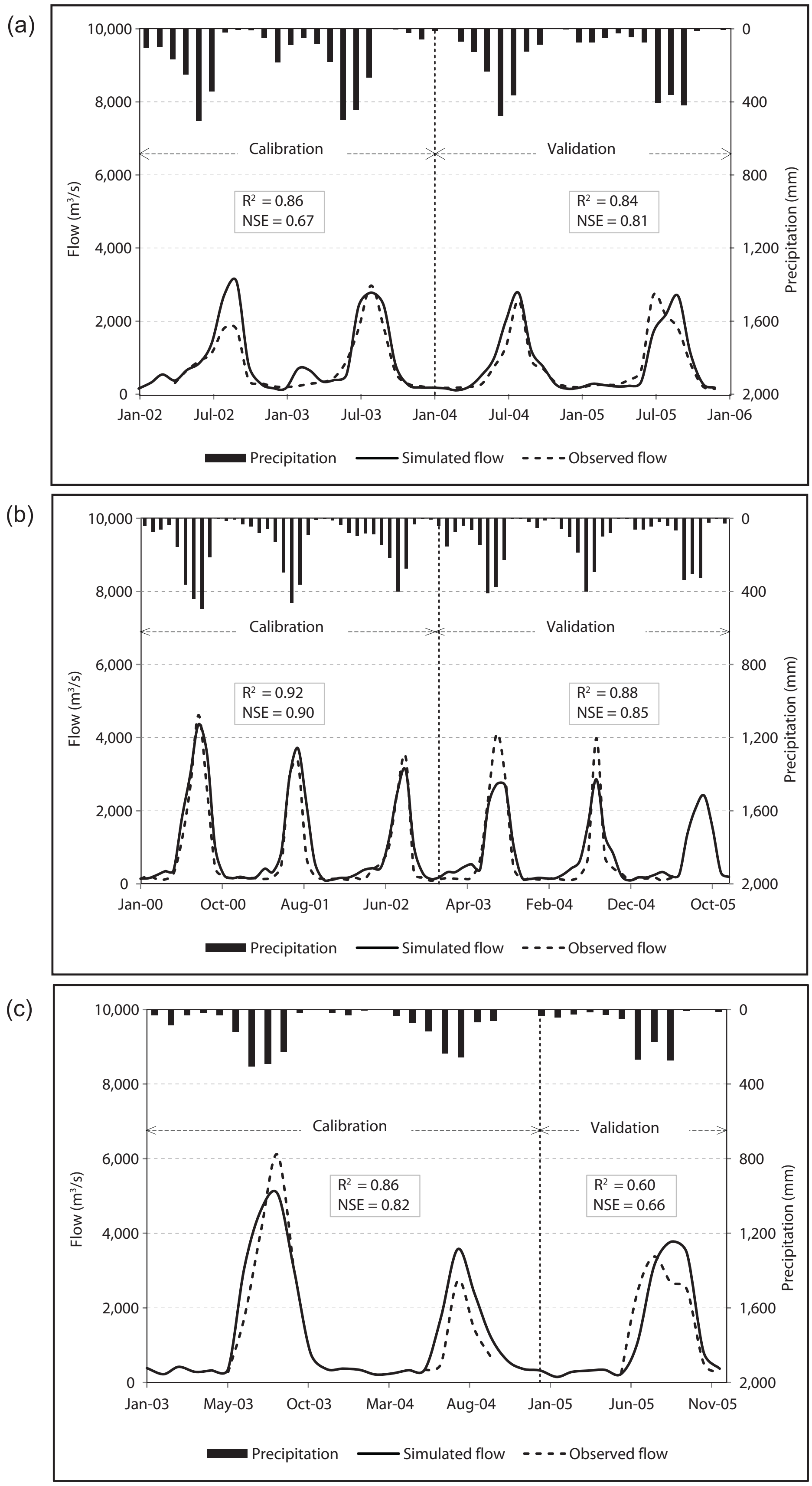


FIGURE 4. Observed and simulated flows at (a) Bhimgoda barrage, (b) Narora barrage, and (c) Kanpur barrage.

The period 1961-2008 was used to calculate the standard deviation, and average of PRECIS and observed data. For each of the four downscaled climate variables, specific adjustment rules were defined and are detailed below.

Precipitation

It is assumed that, for each month of the year, the proportion of dry days (daily precipitation = 0 mm) should be identical in both data sets (PRECIS and observation). In order to meet this hypothesis, the distribution of non-rainy days in the original PRECIS data set was modified before it was statistically downscaled, as described in Bouwer et al. (2004). The successive steps of the calculations are described below.

i) The average proportion (P) of rainy days (> 0 mm) for each month of the year was determined for both PRECIS and observed data sets for each meteorological station. P was found to be significantly higher for PRECIS data, i.e., PRECIS data include fewer dry days than observations. This difference is explained by the fact that observed data are point-based while PRECIS data are grid-based (each cell extends over an area of 0.22 x 0.22 square degrees - about 25 x 25 km^2). Thus, the probability of having a dry day over this area is much lower than that of having a dry day at a point location.

ii) For each month of the year, a daily precipitation threshold H (mm/day) is determined in such a way that P% of PRECIS daily precipitation values are higher than H.

iii) For each month of the year and for both data sets (all observed values and PRECIS values higher than H), the means, $M_{OBSERVATION}$ and M_{PRECIS}, and standard deviations, $ST_{OBSERVATION}$ and ST_{PRECIS}, respectively, of rainy day depths (> H) were calculated.

iv) For each month of the year, adjusted PRECIS daily values '*y*' were calculated from the original PRECIS data '*x*' as shown in Equation (2) below.

If $x < H$, then $y = 0$

$$\text{If } x > H, \text{ then } y = (x - M_{PRECIS}) \frac{ST_{OBSERVATION}}{ST_{PRECIS}} + M_{OBSERVATION} \quad (2)$$

Temperature

As the PRECIS data set does not include maximum and minimum temperature but only daily averages, data adjustment was based on mean observed daily temperature calculated from observed maximum and minimum values. For each month of the year, average and standard deviation of daily temperatures were calculated for observed and PRECIS data using available daily values for the period 1961-2008. Data adjustment was performed similarly to precipitation data, although the first step of precipitation adjustment (threshold definition) was not necessary in the case of temperature.

Furthermore, the SWAT model required maximum and minimum temperature as an input and the adjusted PRECIS temperatures were in daily average (x_{AVG}). Therefore, the observed daily data were used to calculate monthly averages and standard deviations of maximum, minimum and average temperature ($M_{OBS,\,MAX}$, $M_{OBS,\,MIN}$, $M_{OBS,\,AVG}$, $ST_{OBS,\,MAX}$, $ST_{OBS,\,MIN}$, and $ST_{OBS,\,AVG}$), and then the following equations were used to calculate the maximum daily PRECIS temperature (T_{MAX}) (Equation (3)) and minimum daily PRECIS temperatures (T_{MIN}) (Equation (4)).

$$\text{Maximum daily PRECIS temperature, } T_{MAX} = (x_{AVG} - M_{OBS,AVG}) \frac{ST_{OBS,MAX}}{ST_{OBS,AVG}} + M_{OBS,MAX} \quad (3)$$

$$\text{Minimum daily PRECIS temperature, } T_{MIN} = (x_{AVG} - M_{OBS,AVG}) \frac{ST_{OBS,MIN}}{ST_{OBS,AVG}} + M_{OBS,MIN} \quad (4)$$

Wind speed

In the data set of observations, wind speed values are measured 2 meters above the ground surface. In contrast, PRECIS data correspond to wind speeds 10 meters above the ground surface. This difference in elevations results in higher PRECIS wind velocities, as wind is slowed down by frictional resistance close to the surface. As this difference is observed for each month of the year, a unique reduction coefficient (0.38) was applied to all PRECIS daily values. This coefficient was calculated by dividing the mean observed daily wind speed value averaged over the period 1961-2008 by that obtained from PRECIS data. Further adjustment steps consisted of applying Equation (1) to PRECIS wind speed daily values, similarly to other climate variables.

Relative humidity

The adjustment of relative humidity is similar to that of temperature and includes the same steps. A further adjustment, when required, consisted of replacing values exceeding 100% by ‘100%’. Such cases (less than 1% of adjusted values), was due to the following reasons: in some cases, the range of observed relative humidity values over the baseline period was found to exceed that of the PRECIS data. This resulted in higher monthly averages and/or standard deviations for observed values, in comparison with those of PRECIS data. The latter, when used for the data adjustment, could produce daily relative humidity values exceeding 100%.

Scenario Setting

Four scenarios were simulated. In scenario 1, the water infrastructure system up until the year 2005 was included. This scenario includes water abstractions from dams and barrages. The Tehri Dam (Figure 1), which became operational in 2008, is not included in this scenario. Irrigated crops such as rice, wheat, corn, finger millet, sugarcane and potato represent the major crop types during present conditions. Scenario 2 represents the ‘naturalized’ condition without any artificial flow regulation. Simulated flows for this scenario were produced after having removed all water infrastructures from the calibrated model. In this scenario, farming areas were characterized by rainfed crops such as mung bean and wheat. Most of the non-agricultural land is covered by natural forest. Scenarios 3 and 4 correspond to the present conditions of water infrastructure development, abstraction (up until 2005) with CC scenario adjusted from PRECIS time series data under SRES A2 and B2, respectively. Table 4 provides a detailed description of the scenarios.

TABLE 4. Description of simulated scenarios.

No.	Water infrastructure development	Climate input data
1	Present (as of 2005)	Observed data 1971-2005
2	Naturalized conditions	Observed data 1971-2005
3	Present (as of 2005)	Adjusted PRECIS data over period 2071-2100 under A2 scenario
4	Present (as of 2005)	Adjusted PRECIS data over period 2071-2100 under B2 scenario

Results and Discussion

Water Balance Under Present Conditions and Natural Conditions (Scenarios 1 and 2)

Figure 5 shows the annual average water balance for all 21 subbasins of the UGB, and Figure 6 shows the mean monthly water balance of the whole basin, both under Scenario 1. Four hydrological components are considered, i.e., precipitation, actual evapotranspiration (ET), net water yield (which is a routed runoff from the subbasin) and balance closure. The term ‘balance closure’ includes groundwater recharge, change in soil moisture storage in the vadose zone and model inaccuracies.

Annual average precipitation, actual ET and net water yield of the whole basin were 1,192, 416 and 615 mm, respectively. However, there was a large variation in the spatial distribution of these components. Precipitation, ET and water yield were found to be higher in the forested and mountainous upper areas. In the upper subbasins, water yield is higher than ET. However, in some of the lower subbasins dominated by agriculture, ET values were higher than water yield. Water balances from the lower part of the catchment, containing irrigated areas, are affected by water regulation through barrages, dams and canals. The large network of canals is transferring water from one subbasin to irrigate crops in another subbasin. Therefore, it is difficult to determine the accuracy of the runoff calculations from each subbasin. However, the ET and precipitation figures are useful in characterizing the water availability and use in each of the subbasins. The maximum precipitation of 2,504 mm occurred in subbasin 3 and minimum precipitation of 536 mm occurred in subbasins 8 and 11 (see also Figure 3(d)). Furthermore, the maximum ET of 671 mm occurred in subbasin 7 and the minimum ET of 177 mm occurred in subbasin 10.

The mean monthly results from 1971 to 2005 (Figure 6) show that there are large temporal variations in the water balance components. The maximum precipitation of 338 mm occurred during August and a minimum of 7 mm occurred in November. Similarly, water yields are also much higher during the monsoon months as compared to the dry season. ET, however, which is more related to land cover, was found to be lowest during the winter months, i.e., November-January (post-rice harvest).

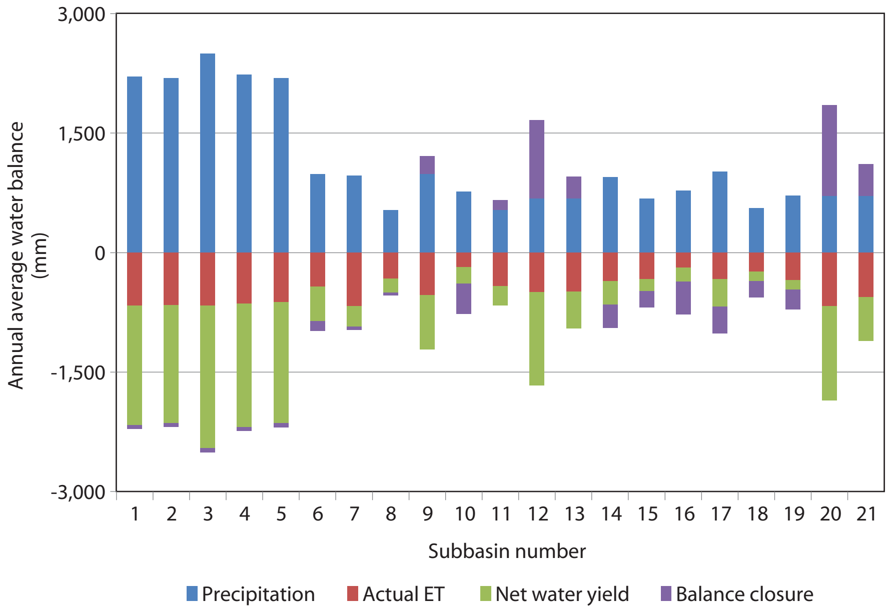


FIGURE 5. Annual average water balance results of model simulation at the subbasin level (1971-2005). The subbasin numbers are given in Figure 3.

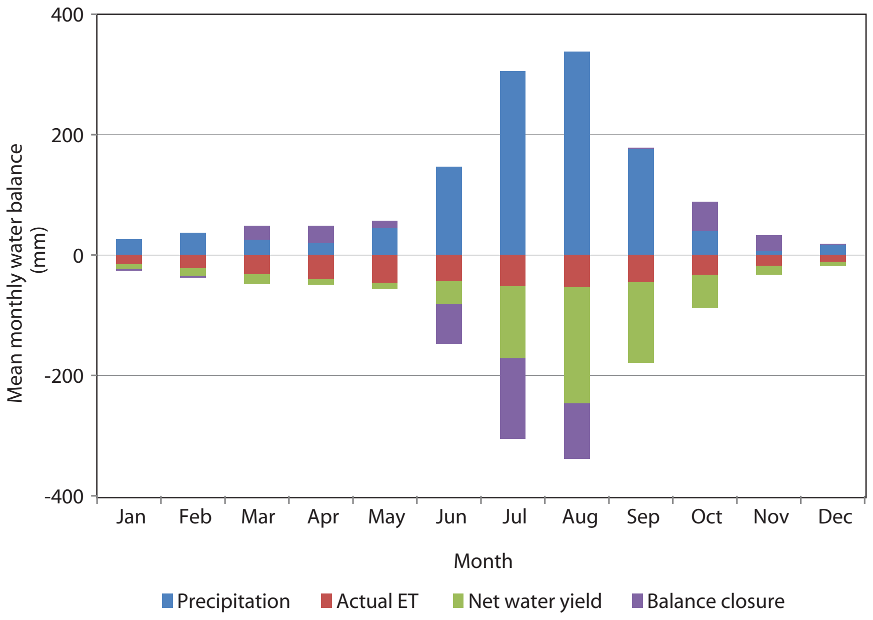


FIGURE 6. Mean monthly water balance results of model simulation (1971-2005) for the entire UGB - at Kanpur.

Simulation of Natural Flow Conditions for the Four EF Sites (Scenario 2)

Simulating non-regulated, pre-development flow regimes is important to determine the reference hydrology, against which flow changes in a basin can be measured. Strictly speaking, this constitutes the assessment of water actually available for all uses and development – a starting point in sustainable basin planning and management. Natural flow simulations are also required to assess EF – the flow regimes that are required for the ecological health of the river. Results from the EF assessment for the UGB are beyond the scope of this paper and are discussed in another report (WWF 2011).

Natural flows for four locations (sites EF1-EF4, coordinates in Table 5) are presented in the following sections. Although natural flows have been simulated for the whole basin, these four locations were chosen for this study as they are representative of different agroecological zones in the river stretch used for this study. These locations were also sites for the EF assessment study and are, therefore, referred to as EF sites in this report.

Simulated daily flow data at the four EF sites under scenarios 1 and 2 were summed up to monthly and annual time steps, and are presented in the tables and figures below. As already mentioned above, the modeling period only went up to 2005, so the effect of the Tehri Dam, which became operational in 2008, was not considered. Therefore, for site EF1, only natural flows have been reported because water is neither stored in dams nor abstracted for agriculture upstream of this site.

TABLE 5. Location and names of representative sites along the UGB (see also Figure 1).

Site code	Name	Latitude	Longitude
EF1	Kaudiyala Rishikesh	30°04’29” N	78°30’09” E
EF2	Narora	29°22'22” N	78°2'20” E
EF3	Kachla Bridge	27°55'59” N	78°51’42” E
EF4	Bithur (Kanpur)	26°36'59” N	80°16'29” E

Figure 7 shows the plots of annual water flow volume and monthly water flow volume at site EF4, Bithur (Kanpur), which is located near the outlet of the UGB. Table 6 shows simulation flow results for the four EF sites including simulated present flows for EF sites 2-4. Comparison between natural and present flows showed that, on average, the present annual water volume is 7%, 2% and 8% lower than in the natural conditions at EF sites 2, 3 and 4 (Narora, Kachla Bridge and Bithur (Kanpur)), respectively. At all sites, the percentage of flow reduction is highest during the dry months as water is being withdrawn for irrigation. At Narora (site EF2), maximum flow reduction is 70% in February. Similarly, at site EF3, the maximum flow reduction is 35% in February and at site EF4, the maximum flow reduction is 58% also in February (Table 6). In April, and some other months, mean flow volume of the present conditions exceeds the flow volume of the natural conditions. This is caused by the basin flow transfer from Ramganga Dam. Although high percentages of flow reduction occur in the dry season, the contribution of flow in this season to annual flow is low (less than 10%).

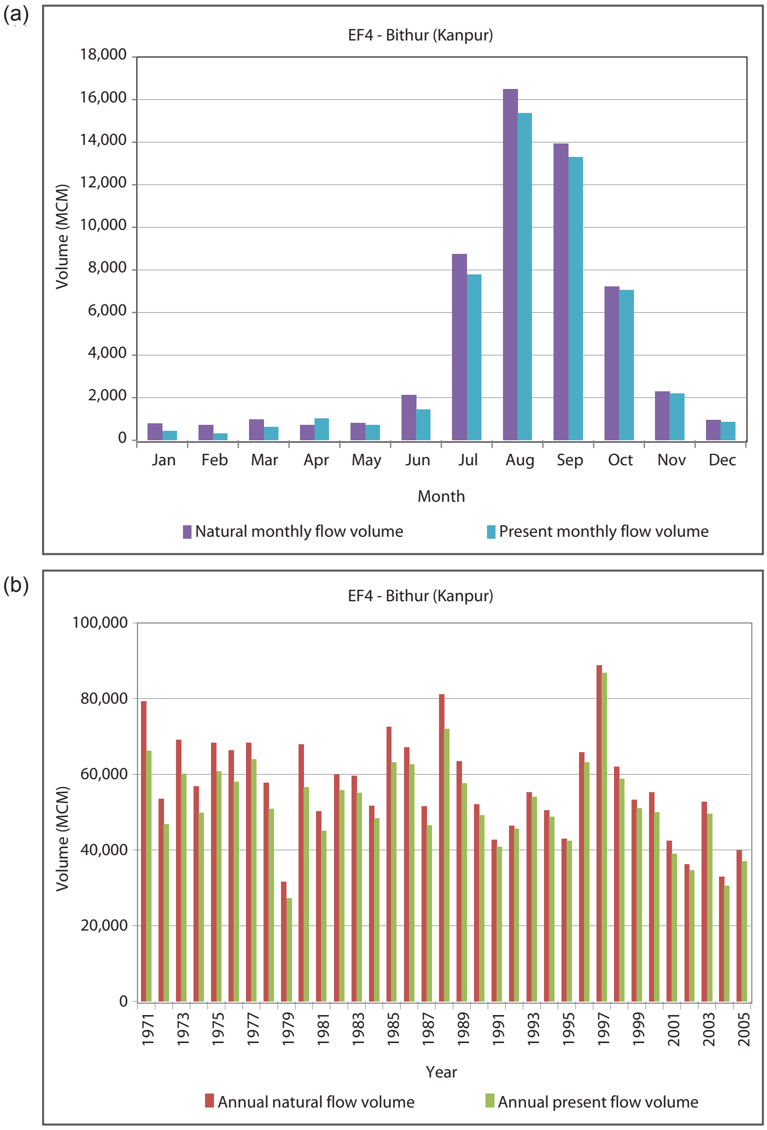


FIGURE 7. (a) Annual flow totals, and (b) average monthly flow distribution for Bithur (Kanpur).

TABLE 6. Simulated flow results at EF sites.

EF sites	Annual simulated flow volume (MCM)		Annual reduction in flows (volume (%))	Percentage of monthly reduction in flows (%)											
	Natural	Present		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
EF1 (Kaudiyala/ Rishikesh)	38,445	38,445*	0 (0%)	0	0	0	0	0	0	0	0	0	0	0	0
EF2 (Narora)	42,608	39,632	2,976 (7%)	68	70	44	-10	30	24	0	0	2	4	19	18
EF3 (Kachla Bridge)	42,909	42,165	774 (2%)	27	35	14	-60	7	16	-1	-1	0	2	12	18
EF4 (Bithur (Kanpur))	57,061	52,268	4,793 (8%)	44	58	35	-44	12	31	11	7	5	2	4	10

Note: * No reduction compared with natural conditions, because there was no water use upstream of this site during the study period.

Figure 8 shows the comparison of water yield (runoff from subbasin) distribution at the subbasin level for the natural condition as well as the present condition. As can be expected, water yield or runoff, from the upper forested subbasins, have not changed. However, there are reduced flows during the present condition from the lower subbasins, mainly due to water withdrawals for agricultural production. There are a few subbasins in the lower catchment where water yields have increased and this is a result of water transfers from the Upper and Madhya Ganga canals.

Figure 9 shows flow duration curves (FDC) in present and natural conditions at the EF sites. These curves indicate that flows are lower in the present condition in comparison with natural conditions.

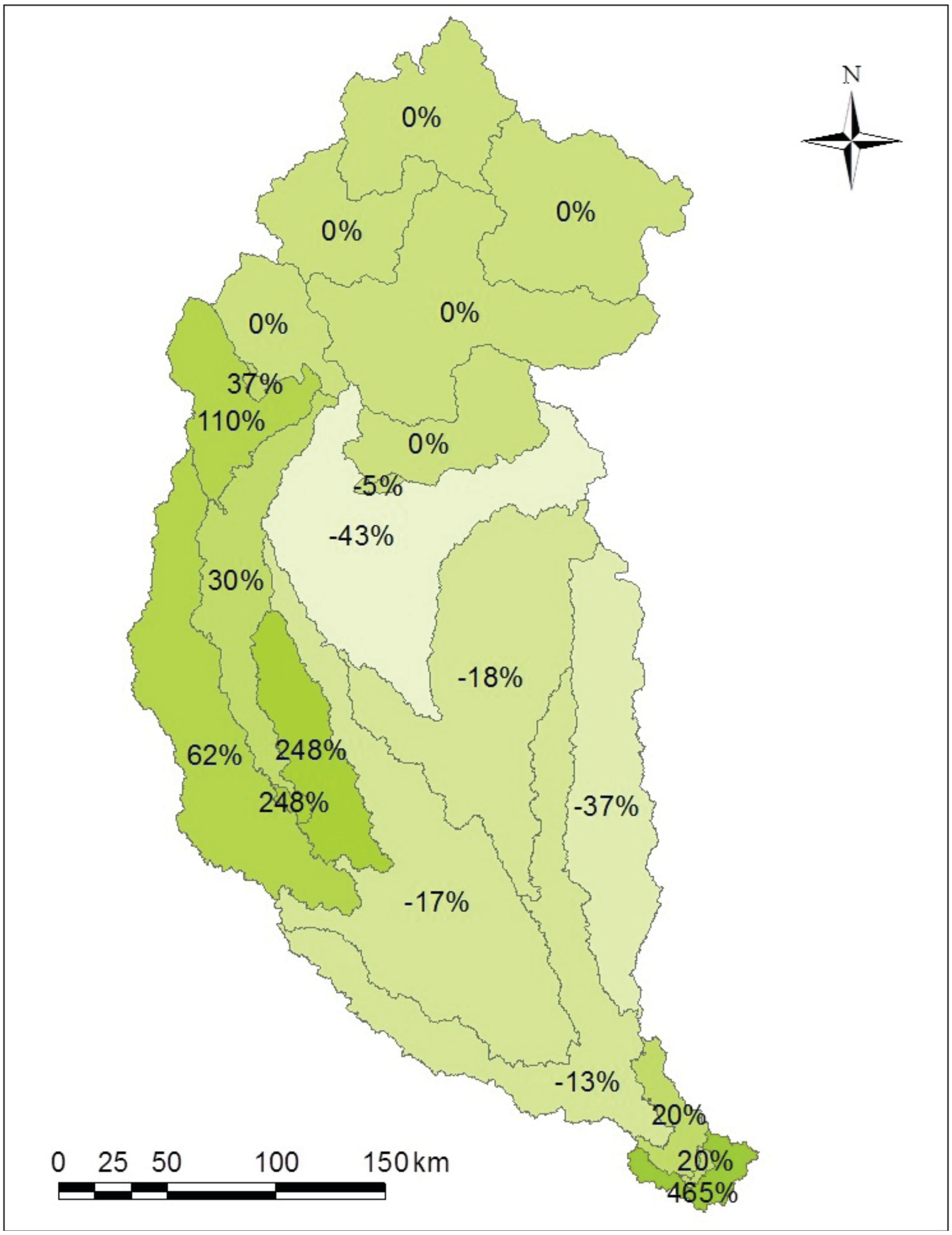


FIGURE 8. Percentage change in mean annual net water yields at present condition in comparison to natural condition of model simulation at subbasin level (i.e., present-natural).

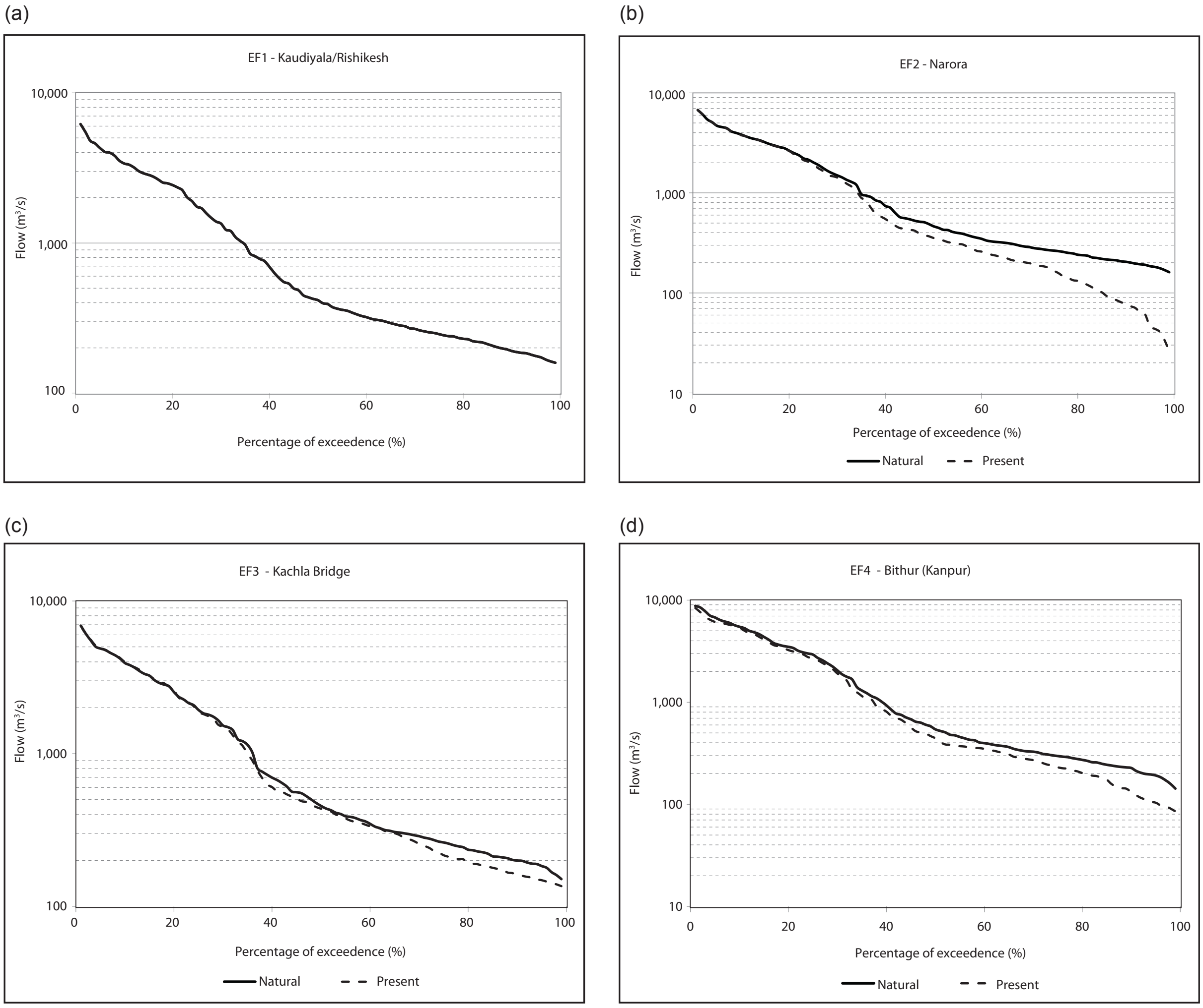


FIGURE 9. Flow duration curves (FDC) for (a) Kaudiyala/Rishikesh, (b) Narora, (c) Kachla Bridge, and (d) Bithur (Kanpur) sites.

Table 7 shows the difference in flow rates between simulations of natural and present conditions for 40% to 90% of percentile of exceedence. Usually, water-related infrastructure such as hydropower plants or irrigation systems are designed taking into consideration a design discharge corresponding to 40% to 90%. The difference in flows affects any future planning of water resources development as well as allocations for environmental flows in the river.

TABLE 7. Difference in flows between simulations of the natural and present conditions at EF sites.

	Difference in flows (natural-present) (m^3/s)		
Percentage of exceedence	EF2 (Narora)	EF3 (Kachla Bridge)	EF4 (Bithur (Kanpur))
40%	232	99	156
50%	120	28	115
60%	93	17	48
70%	89	25	54
80%	114	41	68
90%	126	37	88

Analysis of Changes in Specific Flow Characteristics Under Different Simulation Scenarios Including CC (Scenarios 1-4)

Five indicators of hydrological variability were derived from simulated time series: mean daily dry season flows, mean daily wet season flows, the date of maximum flow, the date of minimum flow and the number of reversals reflecting the rate of change in river discharge.

Hydrological Variability and Alteration Caused by Dams Under Present Climate Conditions

The analysis first focuses on flows simulated from observed precipitation, either under the present conditions of water infrastructure development or in naturalized conditions. Figure 10 displays mean dry and wet season discharges computed from mean monthly discharge values. In natural conditions, dry season flows remain stable all along the river stream, with values ranging from 302 to 340 m^3/s. This flow regime indicates that river flow mostly originates from the melting of glacier and snow cover while the flow contribution from the water table drainage is negligible. During the wet season, mean daily discharge consistently increases from upstream to downstream, reflecting the successive flow contributions of the tributaries, and collecting surface runoff produced by monsoon rainstorms. While the impact of water infrastructure remains moderate during the wet season (flows under present condition are 6% lower than flows produced in natural conditions), relative flow changes during the dry season are of a higher magnitude, especially at EF sites 2, 3 and 4, as no dam exists in the EF1 headwater catchment. Between the sites EF1 and EF4, the dams have induced a 25% flow decrease as a result of dry season irrigation.

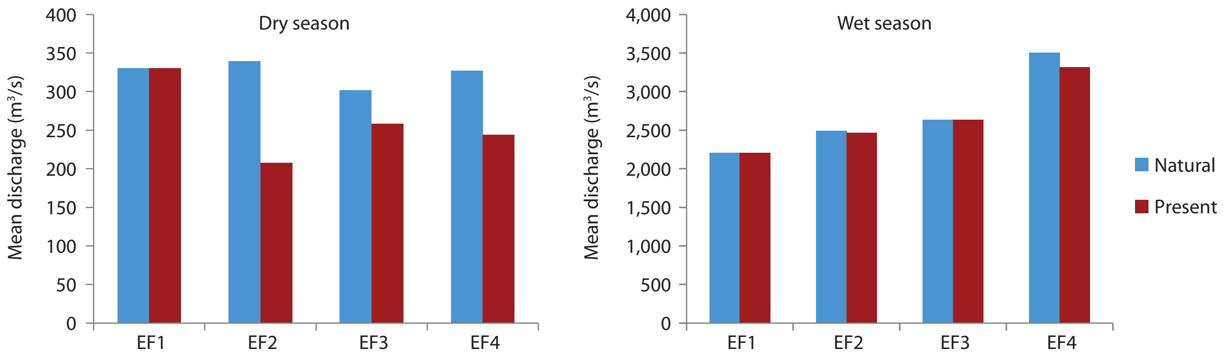


FIGURE 10. Mean dry and wet season daily discharge for the period 1971-2005 at four EF sites, under naturalized (natural) and present conditions.

Figure 11 displays the mean Julian date of 1-day minimum and maximum flow at four EF sites, under natural and present conditions. In natural conditions, 1-day minimum and maximum flow conditions are delayed downstream. This shift in the flow regime results from the difference in the onset of the monsoon between upstream and downstream parts of the basin. First rains of the wet season occur in the upper part of the basin (Figure 12). Under the present conditions, the downstream shift in the date of the 1-day maximum flow is similar to that observed under natural conditions. In contrast, the 1-day minimum flow does not follow this pattern. Dates at sites EF1 and EF3 are similar (dates = 22) while the 1-day minimum flow occurs much earlier at sites EF2 and EF4 (date = 1 for EF2; date = 2 for EF4). This alteration of the natural flow regime results from the operation of the dams located upstream of the sites EF2 and EF4, storing flows at the beginning of the year. The impact of these dams on the date of the 1-day maximum flow is imperceptible, as the range of flow variations caused by the operation of the dams is much lower than the mean river discharge during this period of the year.

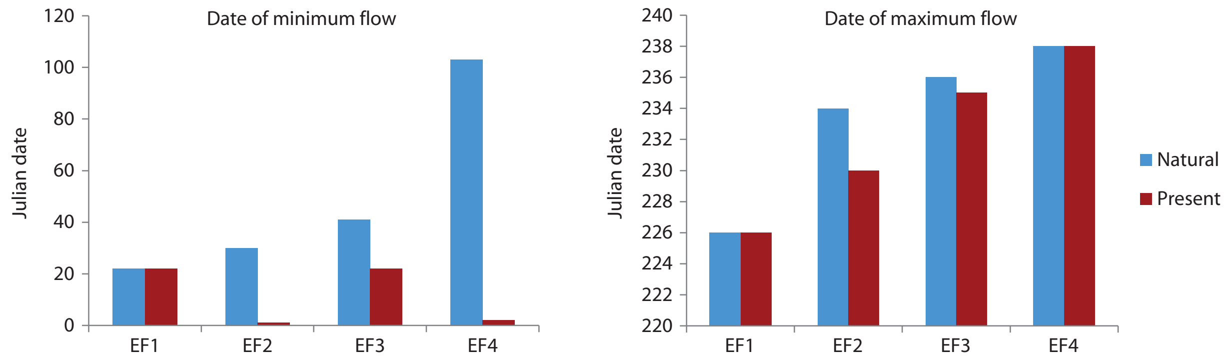


FIGURE 11. Timing of annual extreme water conditions.

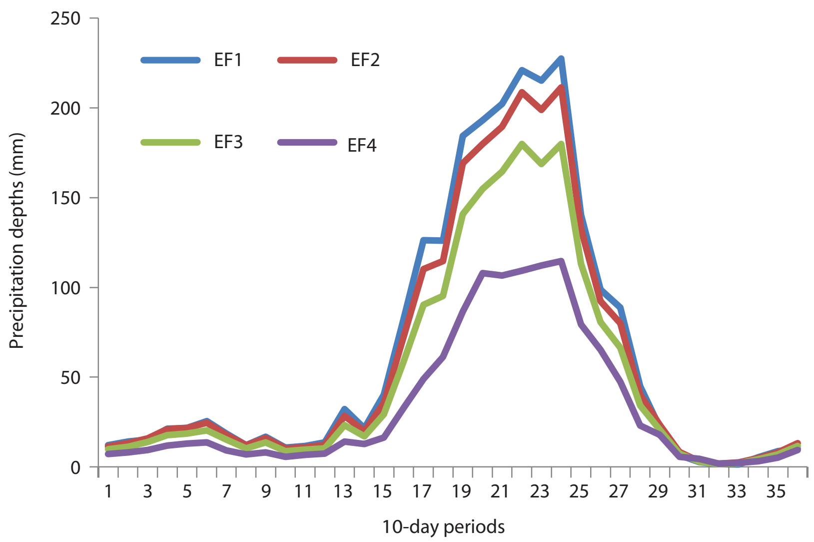


FIGURE 12. Mean observed precipitation (1971-2005) in the subcatchments of four EF sites.

The number of reversals is calculated by dividing hydrological records into 'rising' and 'falling' periods in which daily changes in flows are either positive or negative, respectively. The annual average number of reversals indicates whether a flow regime is influenced only by precipitation input or includes anthropic alterations. Figure 13 displays the mean annual number of reversals at four EF sites, under natural and present conditions. In natural conditions, the number of reversals decreases downstream, reflecting the lower temporal variability of the natural flow regime, mostly caused by the mainstream's integration of flow fluctuations of the tributaries. Under present conditions, the number of reversals at site EF2 is greater than the number of reversals recorded at site EF1. The increase in the flow variability between sites EF1 and EF2 reflects the great impact of dams located between the two stations. As flows are still moderate in the upper part of the basin, the operation of dams can significantly alter the natural river regime, unlike in the downstream areas where the greater river discharge is less impacted by dam operation.

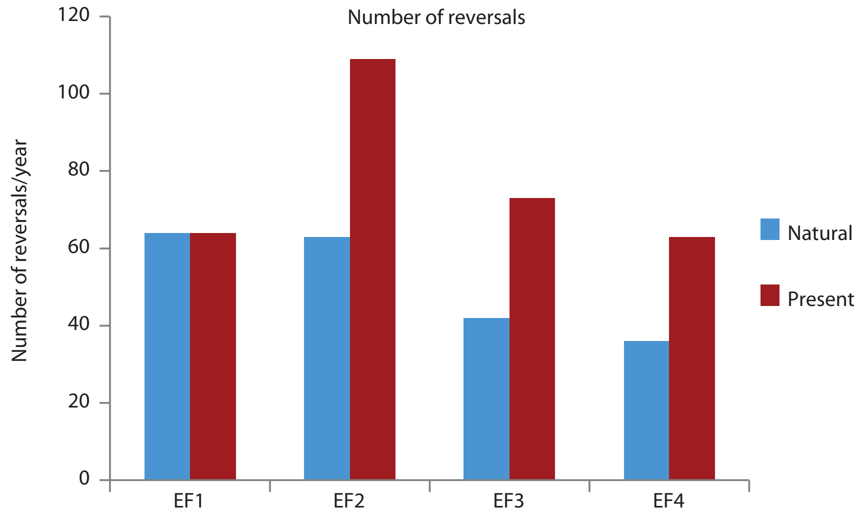


FIGURE 13. Mean annual number of reversals recorded at four EF sites and at the basin outlet, under natural and present conditions.

Hydrological Changes Caused by 'Climate Change' Scenarios Under Present Water Infrastructure Development

Figure 14 displays the mean dry and wet season flows at the four EF sites under present climate conditions, and climate change projections from the PRECIS RCM under A2 (PRECIS-A2) and B2 (PRECIS-B2) scenarios. Upstream of site EF3, dry and wet season flows produced by PRECIS under the A2 scenario, precipitation is lower than that in present climate conditions. This tendency inverts downstream of the site EF3, with higher dry and wet season flows at site EF4 under PRECIS-A2 precipitation, in comparison with flows produced by present climate conditions. Similar patterns are observed for precipitation (Figure 15), suggesting that spatial variations in flow patterns originates from the precipitation distribution over the subcatchments of the four EF sites. Flows produced by PRECIS-B2 precipitation are systematically higher and lower than those produced by PRECIS-A2 precipitation during the dry season and wet season, respectively. These flow differences most likely result from the difference of PRECIS-A2 and PRECIS-B2 precipitation as displayed in Figure 15.

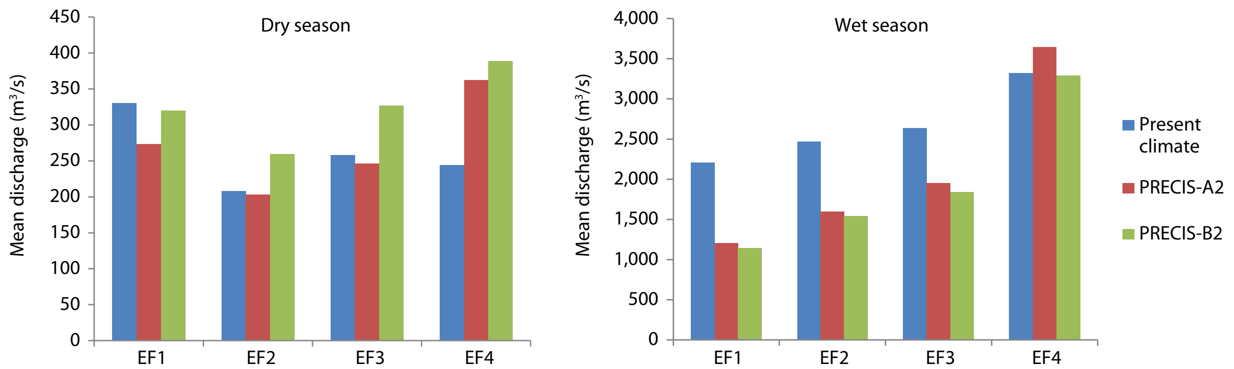


FIGURE 14. Mean dry and wet season daily discharge under present climate conditions (for the period 1971-2005), and for future climate conditions under scenarios A2 and B2 (for the period 2071-2100).

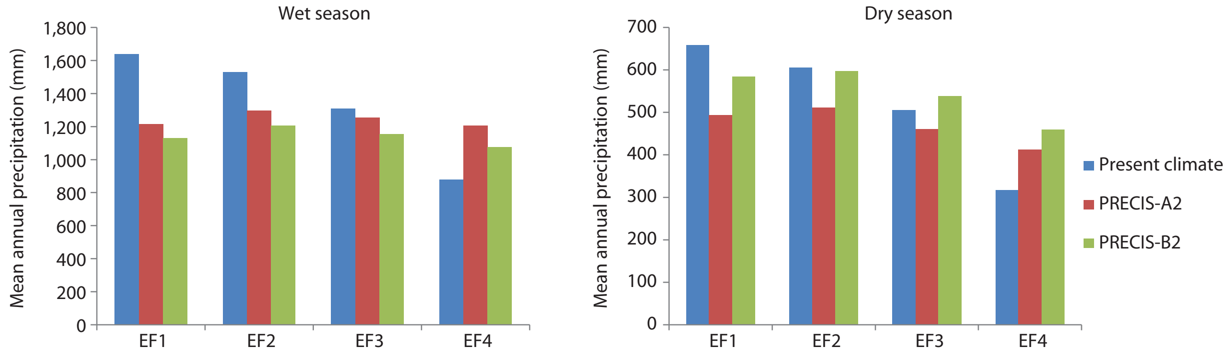


FIGURE 15. Mean dry and wet season precipitation under present climate conditions (observed precipitation averaged over period 1971-2005), and for future climate conditions under scenarios A2 and B2 (for the period 2071-2100).

Figure 16 displays the average Julian dates of minimum and maximum 1-day flow at four EF site under present and future climate conditions. The dates of minimum 1-day flow are highly variable among stations and between different climate scenarios. This variability is caused by the operation of the dams, as the volume of controlled outflow is of the same order of magnitude as natural flow. As a result, a slight change in the dam outflow results in a significant change in the date of the minimum flow. The same phenomenon explains the delay of the minimum flows under scenarios A2 and B2. Julian dates of maximum flows are delayed downstream as a result of the delay in the onset of the monsoon in the lower parts of the basin (Figure 12 and Figure 17). Maximum flows simulated from PRECIS-A2 precipitation occur later than maximum flows simulated from PRECIS-B2 precipitation. This time lag is caused by the slight difference in the timing of the wettest period, which occurs earlier in the case of PRECIS-B2.

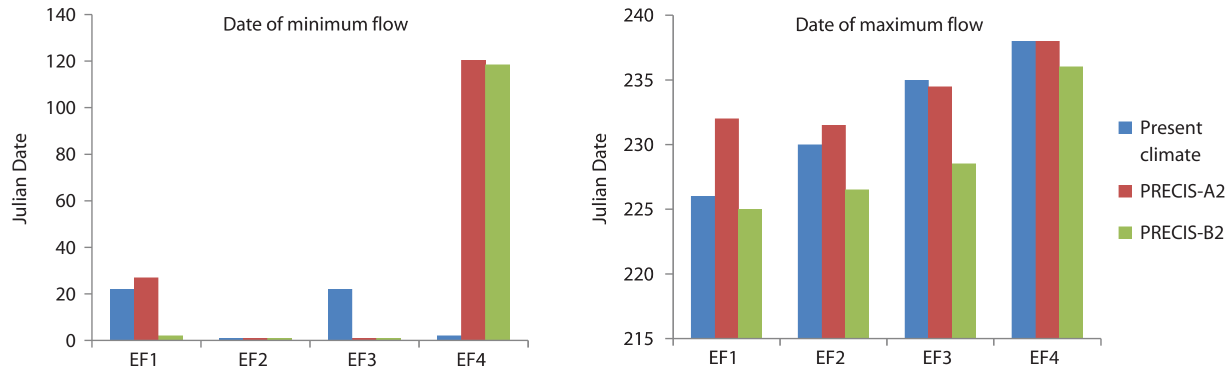


FIGURE 16. Occurrence of annual extreme flow conditions.

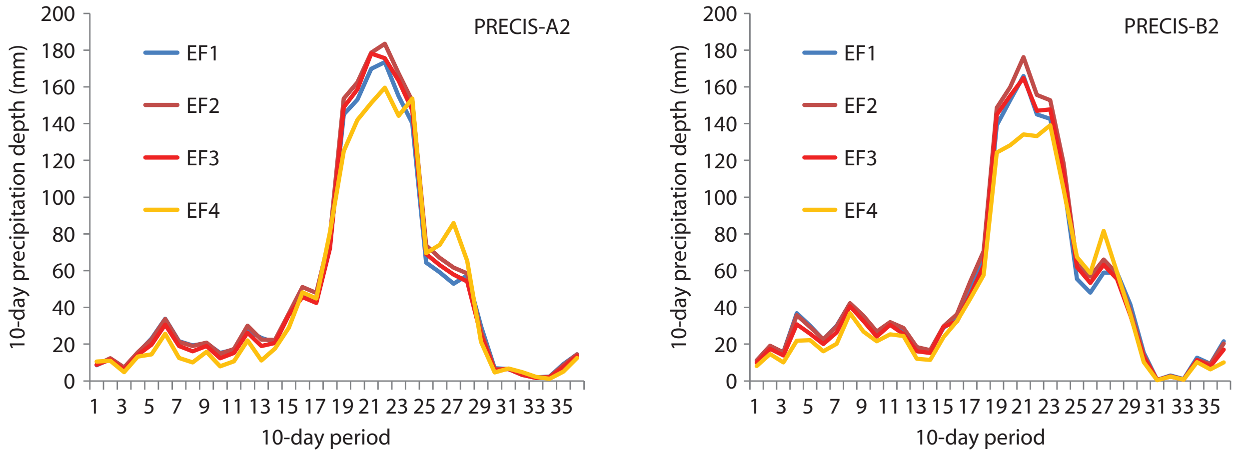


FIGURE 17. Mean precipitation in the subcatchments of four EF sites, as predicted by PRECIS A2 and B2 scenarios. Averages computed over the period 2071-2100.

Figure 18 displays the number of reversals at four EF sites. At sites EF1, EF2 and EF3, the number of reversals under climate change conditions (PRECIS-A2 and PRECIS-B2) is lower than the number of reversals observed under present climate conditions. At site EF4, this tendency reverses and the number of reversals becomes greater under climate change conditions. The greater number of reversals under climate change conditions in the downstream part of the catchment is caused by the higher variability of precipitation. At each EF site, the number of reversals is greater under PRECIS-B2 in comparison with PRECIS-A2. This difference results from the greater temporal variability of PRECIS-B2 precipitation.

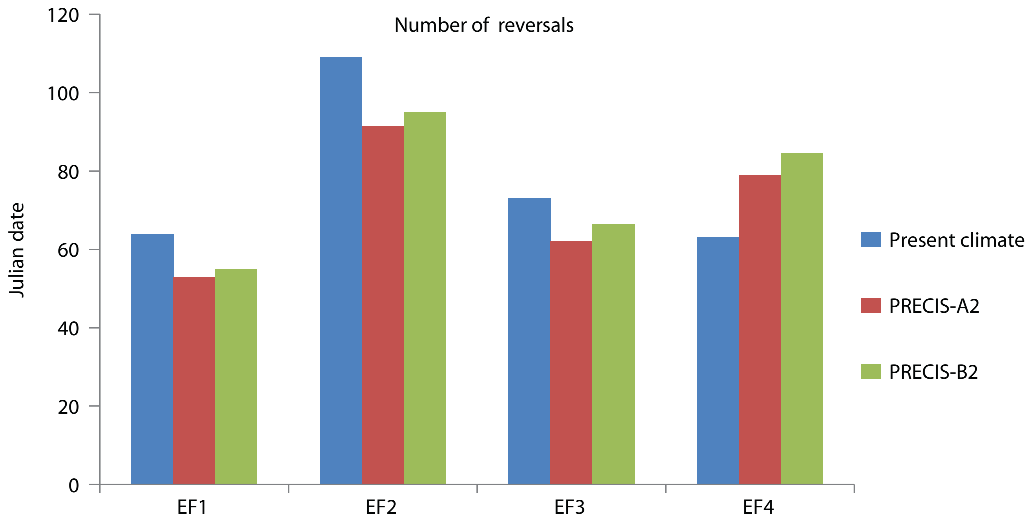


FIGURE 18. Mean annual number of reversals recorded at four EF sites, under present and future climate conditions.

Conclusions

This report explains the results of the first (known to authors) attempt to analyze the impacts of water infrastructure development in the entire UGB, by comparing flow changes under natural and present conditions. The analysis shows that, on average, annual flows at present are 2-8% lower than under naturalized conditions. Higher flow reduction in the dry season (up to 70% in February) is detected, compared to just a small percentage change in the wet season. Therefore, various dams and barrages constructed to date have reduced mainly the flows during the dry season – when irrigation water demands are the highest. Flow regulation through dams and barrages has also changed the timing of annual extreme water conditions such as the date of minimum and maximum flows. The change in the timing of the minimum flow date is, however, affected more than the maximum flows. Future water resources development plans need to take this into serious consideration in order to avoid further detrimental impacts on the river ecology.

Also, the study simulated the impacts of CC on water infrastructure development in the UGB. The results suggest that both dry and wet season flows under CC scenario A2 (scenario corresponding to high population growth with slower per capita economic growth and technological change) are lower than that under present climate conditions at upstream locations, but higher at downstream locations and at the basin outlet. Flows simulated under CC scenario B2 (corresponding to moderate population growth and economic development with less rapid and more diverse technological change) are found to be higher during the dry season, and lower during the wet season than that under CC scenario A2. Under CC scenario B2, the timing of the maximum flow period is earlier than that under present conditions. This basically means that the monsoon might start earlier. Furthermore, greater temporal variability of precipitation was found in the lower basin under both the A2 and B2 scenarios. All these results are very relevant to future water management in the basin. In the upper parts of the basin, especially in the Uttarkhand District, plans for further hydropower development are underway. Decrease in precipitation and flows will affect water availability in the planned projects. Similarly, change in the timing of the monsoon as well as increased variability in precipitation, especially in the lower parts of the basin, will affect the current irrigation water regulation practices. Therefore, some adjustment to agricultural practices such as early sowing might be necessary if the projected changes under the B2 scenario become a reality.

The present modeling study did not consider scenarios of future water resources development under future climate scenarios. As mentioned above, in the UGB, especially in upper parts of the basin, several hydropower dams are being planned or operationalized. The impacts of the already constructed Tehri Dam are now coming into effect. The combined impact of future water infrastructure development and climate on river flow in the UGB and the availability of water for agriculture and other uses, as well as the impacts of CC on operation of infrastructure itself, is a subject of a subsequent ongoing study.

It could be argued that precipitation scenarios used to anticipate hydrological change under CC are not reliable as they originate only from one climate model: PRECIS RCM forced by HadCM3. It is now accepted that climate models are not able to accurately simulate precipitation, mostly because of their inability to simulate actual climate dynamics. For instance, Kingston et al. (2011) showed that uncertainty in precipitation is the main source of error in hydrological projections. Even the use of averaged precipitations projected by several climate models cannot reduce this uncertainty as the variability between different climate projections from different models is high. However, Rupa Kumar et al. (2006), who assessed the biases in PRECIS simulation over India by comparing simulated and observed precipitation, found that this RCM is able to reasonably predict the climate over India, both in terms of means and extremes. A second source of uncertainty in the PRECIS precipitation projections originates from the SRES scenarios, associated with specific gas emission conditions that may result in various precipitation conditions. In the present study, two very contrasting scenarios are used to cover the whole range of possible precipitation changes. Consequently, even if the CC projections used in this study are biased because of the use of only one climate model, it is moderated by the use of the two contrasting SRES emission scenarios - A2 and B2.

The main constraint in this study (as well as in all research carried out on water resources in the Ganga Basin) is the availability of *observed* data (on climate, hydrology, etc.). This limitation severely affects model calibration and validation, and, in the end - simulations of future scenarios. The authorities responsible for observed hydrological data management and sharing should seriously consider opening their archives for water research needs. Without more open policies on observed data access, proper planning of water resources development in the Himalayan parts of India is impossible. The uncertainty in climate projections is another major issue associated with studies like this one. Improvement in CC projections as well as access to more climate data would certainly enhance the accuracy of the simulations, and in the end – planning for the future.

References

Ahmad, Q.K.; Ahmed, A.U.; Khan, H.R.; Rasheed, K.B.S. 2001. GBM regional water vision: Bangladesh perspectives. In: *Ganges-Brahmaputra-Meghna region: A framework for sustainable development,* (eds.), Ahmad, Q.K.; Biswas, A.K.; Rangachari, R.; Sainju, M.M. Dhaka: University Press Limited. pp. 31-78.

Akhtar, M.; Ahman, N.; Booij, M.J. 2009. Use of regional climate model simulations as input for hydrological models for the Hindukush-Karakorum-Himalaya region. *Hydrology and Earth System Sciences* 13: 1075-1089.

Arnell, N.W. 2003. Relative effects of multi-decadal climatic variability and changes in the mean and variability of climate due to global warming: Future streamflows in Britain. *Journal of Hydrology* 270(3-4): 195–213.

Arnold, J.G.; Srinivasan, R.; Muttiah, R.S.; Williams, J.R. 1998. Large area hydrologic modeling and assessment. Part I: Model development. *Journal of the American Water Resources Asso*ciation 34(1): 73–89.

Benestad, R.E.; Hanssen-Bauer, I.; Chen, D. 2008. *Empirical-statistical downscaling*. Singapore: World Scientific Publishing Co. pp. 300.

Bergström, S.; Carlsson, B.; Gardelin, M.; Lindström, G.; Pettersson, A.; Rummukainen, M. 2001. Climate change impacts on runoff in Sweden-assessments by global climate models, dynamical downscaling and hydrological modelling. *Climate Research* 16: 101-112.

Bharati, L.; Jayakody, P. 2011. Hydrological impacts of inflow and land-use changes in the Gorai River catchment, Bangladesh. *Water International* 36(3): 357-369.

Booij, M.J. 2005. Impact of climate change on river flooding assessed with different spatial model resolutions. *Journal of Hydrology* 303(1-4): 176-198.

Bouwer, L.M.; Aerts, J.C.J.H.; van de Coterlet, G.M.; van de Giesen, N.; Gieske, A.; Mannaerts, C. 2004. Evaluating downscaling methods for preparing Global Circulation Model (GCM) Data for Hydrological Impact Modelling. In: *Climate Change in Contrasting River Basins,* (eds.) Aerts, J.C.J.H.; Droogers, P. Wallingford, UK: CABI Publishing.

de Condappa, D. 2009. WEAP modeling for Indus and Ganges basin. Unpublished Report.

Fowler, H.J.; Kilsby, C.G. 2007. Using regional climate model data to simulate historical and future river flows in northwest England. *Climatic Change* 80(3-4): 337-367.

Garg, K.K.; Bharati, L.; Gaur, A.; George, B.; Acharya, S.; Jella, K.; Narasimhan, B. 2011. Spatial mapping of agricultural water productivity using the SWAT model in Upper Bhima Catchment, India. *Irrigation and Drainage* (article first published online).

Gosain, A.K.; Rao, S.; Basuray, D. 2006. Climate change impact assessment on hydrology of Indian river basins. *Current Science* 90(3): 346-353.

Guo, S.; Wang, J.; Xiong, L.; Yin, A.; Li, D. 2002. A macro-scale and semi-distributed monthly water balance model to predict climate change impacts in China. *Journal of Hydrology* 268(1-4): 1-15.

Gutowski, W.J.; Decker, S.G.; Donavon, R.A.; Pan, Z.; Arritt, R.W.; Takle, E.S. 2003. Temporal-spatial scales of observed and simulated precipitation in central U.S. climate. *Journal of Climate* 16(22): 3841-3847.

Hay, L.E.; Clark, M.P. 2003. Use of statistically and dynamically downscaled atmospheric model output for hydrologic simulations in three mountainous basins in the western United States. *Journal of Hydrol*ogy 282(1-4): 56-75.

Hay, L.E.; Clark, M.P.; Wilby, R.L.; Gutowski, W.J.; Leavesley, G.H.; Pan, Z.; Arritt, R.W.; Takle, E.S. 2002. Use of regional climate model output for hydrological simulations. *Journal of Hydrometeorol*ogy 3(5): 571–590.

Jian, J.; Webster, P.J.; Hoyos, C.D. 2009. Large-scale controls on Ganges and Brahmaputra river discharge on intraseasonal and seasonal time-scales. *Quarterly Journal of the Royal Meteorological Society* 135(639): 353-370.

IPCC (Intergovernmental Panel on Climate Change). 1996. *Climate change 1995: Impacts, adaptation, and mitigation of climate change: Scientific-Technical analyses. The contribution of working group II to the second assessment report of the Intergovernmental Panel on Climate Change*, (eds.), Watson, R.T.; Zinyowera, M.C.; Moss, R.H. Cambridge, UK: Cambridge University Press.

IPCC. 2000. IPCC special report on emission scenarios. Summary for policymakers. A special report of working group III of the Intergovernmental Panel on Climate Change (IPCC. Geneva, Switzerland: Intergovernmental Panel on Climate Change (IPCC). 20p.

Jha, M.K. 2011. Evaluating hydrologic response of an agricultural watershed for watershed analysis. Water 3(2): 604-617.

Jones, R.G.; Noguer, M.; Hassell, D.C.; Hudson, D.; Wilson, S.S.; Jenkins, G.J.; Mitchell, J.F.B. 2004. *Generating high resolution climate change scenarios using PRECIS*. Met Office Hadley Centre, Exeter, UK. 40p. Available at http://precis.metoffice.com/docs/PRECIS_Handbook.pdf (accessed on October 4, 2011).

Kingston, D.G.; Thompson, J.R.; Kite, G. 2011. Uncertainty in climate change projections of discharge for the Mekong River Basin. *Hydrology of Earth System Sciences* 15(5): 1459-1471.

Leander, R.; Buishand, T.A. 2007. Resampling of regional climate model output for the simulation of extreme river flows. *Journal of Hydrol*ogy 332: 487-496.

Liu, Y.B.; De Smedt, F. 2004. *WetSpa Extension, Documentation and User Manual.* Department of Hydrology and Hydraulic Engineering, Vrije Universiteit Brussel, Belgium. 108p.

Mirza, M.M.Q. (ed.). 2004. *The Ganges water diversion: Environmental effects and Implications*. Dordrecht, the Netherlands: Kluwer Academic Publishers.

Neitsch, S.L.; Arnold, J.G.; Kiniry, J.R.; Williams, J.R. 2005. *Soil and Water Assessment Tool – Theoretical documentation (version 2005)*. Temple, Texas: Grassland, Soil and Water Research Laboratory, Agricultural Research Service, Blackland Research Center, Texas Agricultural Experiment Station.

Pilling, C.G.; Jones, J.A.A. 2002. The impact of future climate change on seasonal discharge, hydrological processes and extreme flows in the Upper Wye experimental catchment, mid-Wales. *Hydrological Proc*esses 16(6): 1201-1213.

Rahaman, M.M. 2009. Integrated Ganges basin management: Conflict and hope for regional development. *Water Policy* 11(2): 168-190.

Rupa Kumar, K.; Sahai, A.K.; Krishna Kumar, K.; Patwardhan, S.K.; Mishra, P.K.; Revadekar, J.V.; Kamala, K.; Pant, G.B. 2006. High-resolution climate change scenarios for India for the 21st century. *Current Science* 90(3): 334-345.

Seidel, K.; Martinec, J.; Baumgartner, M.F. 2000. *Modelling runoff and impact of climate change in large Himalayan basins*. International Conference on Integrated Water Resources Management (ICIWRM), December 19-21, 2000, Roorkee, India.

Singh, P.; Haritashya, U.K.; Kumar, N. 2008. Modelling and estimation of different components of streamflow for Gangotri Glacier basin, Himalayas. *Journal of Geophysical Research* 53(2): 309-322.

Singh, P.; Haritashya, U.K.; Kumar, N.; Singh, Y. 2006. Hydrological characteristics of the Gangotri Glacier, central Himalayas, India. *Journal of Hydrology* 327(1-2): 55-67.

Srinivasan, R.; Ramanarayanan, T.S.; Arnold, J.G.; Bednarz, S.T. 1998. Large area hydrologic modeling and assessment Part II: Model application. *Journal of the American Water Resources Association* 34(1): 91-101.

Verghese, B.G.; Iyer, R.R. 1993. *Harnessing the eastern Himalayan rivers: Regional cooperation in South Asia*. New Delhi: Konark Publishers.

Wang, X.; Melesse, A.M. 2005. Evaluation of the SWAT Model's snowmelt hydrology in a Northwestern Minnesota watershed. *Transactions of the American Society of Agricultural Engineers* 48(4): 1359-1376.

Wilby, R.L.; Hay, L.E.; Leavesley, G.H. 1999. A comparison of downscaled and raw GCM output: Implications for climate change scenarios in the San Juan River Basin, Colorado. *Journal of Hydrology* 225(1-2): 67-91.

WWF (World Wide Fund for Nature)-India. 2011. Assessment of environmental flows for Upper Ganga Basin. New Delhi, India: World Wide Fund for Nature (WWF)-India. 21p. Available at *http://wwfindia.org/about_wwf/reducing_footprint/living_ganga2/* (accessed on October 31, 2011).

IWMI Research Reports

142 *The Impacts of Water Infrastructure and Climate Change on the Hydrology of the Upper Ganges River Basin*. Luna Bharati, Guillaume Lacombe, Pabitra Gurung, Priyantha Jayakody, Chu Thai Hoanh and Vladimir Smakhtin. 2011.

141 *Low-Cost Options for Reducing Consumer Health Risks from Farm to Fork Where Crops are Irrigated with Polluted Water in West Africa.* Philip Amoah, Bernard Keraita, Maxwell Akple, Pay Drechsel, Robert C. Abaidoo and Flemming Konradsen. 2011.

140 *An Assessment of Crop Water Productivity in the Indus and Ganges River Basins: Current Status and Scope for Improvement*. Xueliang Cai, Bharat R. Sharma, Mir Abdul Matin, Devesh Sharma and Sarath Gunasinghe. 2010.

139 *Shallow Groundwater in the Atankwidi Catchment of the White Volta Basin: Current Status and Future Sustainability.* Boubacar Barry, BenonyKortatsi, Gerald Forkuor, Murali Krishna Gumma, Regassa Namara, Lisa-Maria Rebelo, Joost van den Berg and Wolfram Laube. 2010.

138 *Bailout with White Revolution or Sink Deeper? Groundwater Depletion and Impacts in the Moga District of Punjab, India.* Upali A. Amarasinghe, Vladimir Smakhtin, Bharat R. Sharma and Nishadi Eriyagama. 2010.

137 *Wetlands, Agriculture and Poverty Reduction*. Matthew McCartney, Lisa-Maria Rebelo, Sonali Senaratna Sellamuttu and Sanjiv de Silva. 2010.

136 *Climate Change, Water and Agriculture in the Greater Mekong Subregion*. Robyn Johnston, Guillaume Lacombe, Chu Thai Hoanh, Andrew Noble, Paul Pavelic, Vladimir Smakhtin, Diana Suhardiman, Kam Suan Pheng and Choo Poh Sze. 2010.

135 *Impacts of Climate Change on Water Resources and Agriculture in Sri Lanka: A Review and Preliminary Vulnerability Mapping*. Nishadi Eriyagama, Vladimir Smakhtin, Lalith Chandrapala and Karin Fernando. 2010.

134 *Evaluation of Current and Future Water Resources Development in the Lake Tana Basin, Ethiopia*. Matthew McCartney, Tadesse Alemayehu, Abeyu Shiferaw and Seleshi Bekele Awulachew. 2010.

133 *Mapping Drought Patterns and Impacts: A Global Perspective*. Nishadi Eriyagama, Vladimir Smakhtin and Nilantha Gamage. 2009.

Related Publications

Bartlett, R.; Bharati, L.; Pant, D.; Hosterman, H.; McCornick, P. G. 2010. ***Climate change impacts and adaptation in Nepal.*** Colombo, Sri Lanka: International Water Management Institute (IWMI). 35p. (IWMI Working Paper 139)

www.iwmi.org/Publications/Working_Papers/working/WOR139.pdf

Cai, X.; Sharma, B. R.; Matin, M. A.; Sharma, D.; Gunasinghe, S. 2010. ***An assessment of crop water productivity in the Indus and Ganges River Basins: current status and scope for improvement***. Colombo, Sri Lanka: International Water Management Institute (IWMI). 30p. (IWMI Research Report 140)

www.iwmi.org/Publications/IWMI_Research_Reports/PDF/PUB140/RR140.pdf

Jha, R.; Smakhtin, V. 2008. ***A review of methods of hydrological estimation at ungauged sites in India***. Colombo, Sri Lanka: International Water Management Institute (IWMI). 24p. (IWMI Working Paper 130)

www.iwmi.org/Publications/Working_Papers/working/WOR130.pdf

Smakhtin, V.; Gamage, M. S. D. N.; Bharati, L. 2007. ***Hydrological and environmental issues of interbasin water transfers in India***: ***A case of the Krishna River Basin***. Colombo, Sri Lanka: International Water Management Institute (IWMI). 35p. (IWMI Research Report 120)

www.iwmi.org/Publications/IWMI_Research_Reports/PDF/PUB120/RR120.pdf

Venot, J. P.; Turral, H.; Samad, M.; Molle, F. 2007. ***Shifting waterscapes: Explaining basin closure in the Lower Krishna Basin, South India***. Colombo, Sri Lanka: International Water Management Institute (IWMI). 60p. (IWMI Research Report 121)

www.iwmi.org/Publications/IWMI_Research_Reports/PDF/PUB121/RR121.pdf

Postal Address
P O Box 2075
Colombo
Sri Lanka

Location
127 Sunil Mawatha
Pelawatta
Battaramulla
Sri Lanka

Telephone
+94-11-2880000

Fax
+94-11-2786854

E-mail
iwmi@cgiar.org

Website
www.iwmi.org

IWMI International Water Management Institute

ISSN 1026-0862
ISBN 978-92-9090-744-2