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Model to assess the impacts of external drivers on the hydrology of the Ganges River Basin

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Abstract Impact of climate change on the hydrology of the Ganges River Basin (GRB) is simulated by using a hydrological model – Soil and Water Assessment Tool (SWAT). Climate data from the GCM, Hadley Centre Coupled Model, version 3 (HadCM3) was downscaled with PRECIS for the GRB under A1B Special Report on Emission Scenarios (SRES) scenarios. The annual average precipitation will increase by 2.2% and 14.1% by 2030 and 2050, respectively, compared to the baseline period (1981–2010). Spatial distribution of the future precipitation shows that in the substantial areas of the middle part of the GRB, the annual precipitation in 2030 and 2050 will be reduced compared to the baseline period. Simulations indicate that in 2050 the total groundwater recharge would increase by 12%, while the increase of evapotranspiration will be about 10% compared to the baseline period. The water yield is also expected to increase in the future (up to 40% by 2050 compared to baseline), especially during the wetter months. The model setup is available for free from IWMI's modelling inventory.

Key words Ganges River Basin; climate change; Soil and Water Assessment Tool

INTRODUCTION

The River Ganges starts from the western Himalayas in the Indian State of Uttarakhand. It flows into the Bay of Bengal after covering a distance of 2525 km. The river is very important to the riparian countries, with an estimated 500 million people directly or indirectly depending on it. The Ganges River Basin (GRB) has an area of 1.09 million km^2 that spreads across India (79%), Nepal (13%), Bangladesh (4%) and China (4%). It is the most populated river basin in the world, supporting about 43% of India's population and covering about 26% of its land mass. Land and water productivity for most of the crops and fisheries in the basin are low and the agriculture dependent population (>85%) is very poor (Sharma *et al.* 2010). Although, the Ganges often floods during the monsoon season, and coastal Bangladesh is subject to cyclones, there are dry spells and even droughts in some years.

The changing climate is among the main drivers of change in the GRB. These changing circumstances have a significant impact on key social and economic sectors of the basin, largely through changes in water quantity and timing of availability. According to the latest estimations, the basin population will be about 720 million by 2025 (Hosterman *et al.* 2012). This population increase in the basin, coupled with increased demand for agricultural production, industrialization and urban water supply will contribute to increasing water demands over time. There are a number of studies on the impacts of climatic change on the water resources in the GRB and its sub-catchments (e.g. Bhutiyani *et al.* 2009, Bharati *et al.* 2011, Hosterman *et al.* 2013, Sharma 2013). Surface air temperatures are expected to increase steadily in the riparian countries of the GRB (Cruz *et al.* 2007). For instance, annual temperature has increased by 1.4°C over the last 100 years in the northwestern Himalayas (Bhutiyani *et al.* 2009) and is higher than the global average temperature increase, which is about 0.74°C (Parry *et al.* 2007). Precipitation from the southwest monsoon and the snowmelt from the mountains play a significant role in the water supply in the GRB. Therefore the changes in climatic factors such as precipitation and temperature will affect the water supply as well as the availability in the basin (Cruz *et al.* 2007, Bates *et al.* 2008).

Under these circumstances, a proper understanding about the effects of these external drivers on the hydrological flows of the Ganges Basin is very important for the future planning purposes. Therefore, this study focuses on quantifying the changes of hydrological flows in the basin due to climate change.

METHODS AND DATA

Soil and Water Assessment Tool

To simulate the streamflow and to assess the impact of various climate change on hydrology of the GRB, the Soil and Water Assessment Tool (SWAT) (Arnold *et al.* 1998) was used. This model possesses adequate representation of physical processes governing hydrology and is particularly suitable for application in large river basins. It also provides a wide range of options for testing scenarios related to agricultural water management, climate and population growth. In the SWAT model, a river basin is subdivided into a number of sub-catchments, each sub-catchment consisting of at least one representative stream. The sub-catchments are further divided into hydrologic response units (HRUs), which are lumped land areas within the catchment comprising unique land cover, soil, and slope combinations. SWAT represents the local water balance through four storage volumes: snow, soil profile, shallow aquifer and deep aquifer. The soil water balance equation is the basis of hydrological modelling. The simulated processes include surface runoff, infiltration, evaporation, plant water uptake, lateral flow and percolation to shallow and deep aquifers. The surface runoff volume is calculated by using the Soil Conservation Service (SCS) curve number equation. Potential evapotranspiration (PET) can be estimated by one of the three methods: Penman–Monteith, Priestly and Taylor or Hargreaves method. The actual evapotranspiration is estimated on the basis of simulated plant growth and soil water availability. The model calculates percolation when the soil-water content exceeds the soil-field capacity and determines the amount of water moving from one soil layer to the next by using a storage routing method. In each sub-catchment, the SWAT model simulates two groundwater aquifers: a shallow aquifer that contributes to streamflow and a deeper aquifer that does not add to streamflow within the modelled sub-catchment.

Various data sets were accumulated from global and local sources. The major data sets used in this study are listed in Table 1. The ArcSWAT interface was used to pre-process the spatial data for the Ganges River system.

Table 1 An overview of main data sets used in this study.

Category	Data	Data source
Topography	Digital elevation model (DEM) (90 m×90 m)	Shuttle Radar Topography Mission (acquired from http://srtm.csi.cgiar.org/)
Land use	Land use map (500 m × 500 m)	IWMI data base – Satellite based landuse map – 2000
Soils	Digital map of the soils and soil Properties (10 km×10 km)	FAO soil map of the world–1995
Climate	Rainfall, temperature, relative humidity, sunshine hours, wind speed	Meteorological organization in Bangladesh, Re-Analysis data, Indian meteorological department
Hydrology	River discharge	IWMI data base

Daily climate data from the GCM, Hadley Centre Coupled Model, version 3 (HadCM3) were downscaled with PRECIS for the Ganges River Basin under A1B Special Report on Emission Scenarios (SRES) scenarios. The A1B scenario provides a middle-impact scenario at the global level, lying between extremes produced by other emission scenarios.

Model set-up and calibration

The GRB was delineated using 3000 ha as the minimum “area threshold”, resulting in 1684 sub-catchments. The “area threshold” was selected by trial-and-error in an attempt to match the SWAT sub-catchments as close as possible to capture all the tributaries of the GRB. The land-use map used has 16 classes and these classes were assigned to comparable SWAT land-use classes. The GRB has mixed land use with the agriculture as a major class (about 66%). A large portion of these areas are under irrigation, while the rainfed areas cover only 4.4% of the basin area. Forest area in the basin is about 22% and the rest includes wetlands, water bodies, deserts, built-up areas and rangelands. There are 80 types of soils in GRB. In terms of soil texture (i.e. Clay, Loam and Sandy), Loam is the most prevalent soil class. The physical characteristics of the soils, required by the SWAT model, were extracted for each soil texture class from the MWSWAT database (http://swat.tamu.edu/-software/mwswat/). For the calibration of the model, the SWAT Calibration and Uncertainty Program (SWATCUP) (Abbaspour 2009) was used. Two indicators, Nash-Sutcliffe efficiency (NS) (Nash and Sutcliffe 1970) and the coefficient of determination (R^2), were used to evaluate model performance.

RESULTS AND DISCUSSION

The model was initially calibrated and validated for the monthly discharge data collated at the Harding Bridge (Fig. 1). The calibration period was selected from 1981 to 1990 and the validation period was selected as 1991–2000. The performance indicators, NS and R^2 are 0.69 and 0.73, respectively, for the calibration period and indicate reasonable agreement between observed and simulated streamflow time series. For the validation period, NS and R^2 are 0.75 and 0.81. Additionally the model simulations were compared with the observed flow data at another seven locations (Fig. 1), for which the observed data were available. Table 2 presents the model performance indicators for these seven locations.

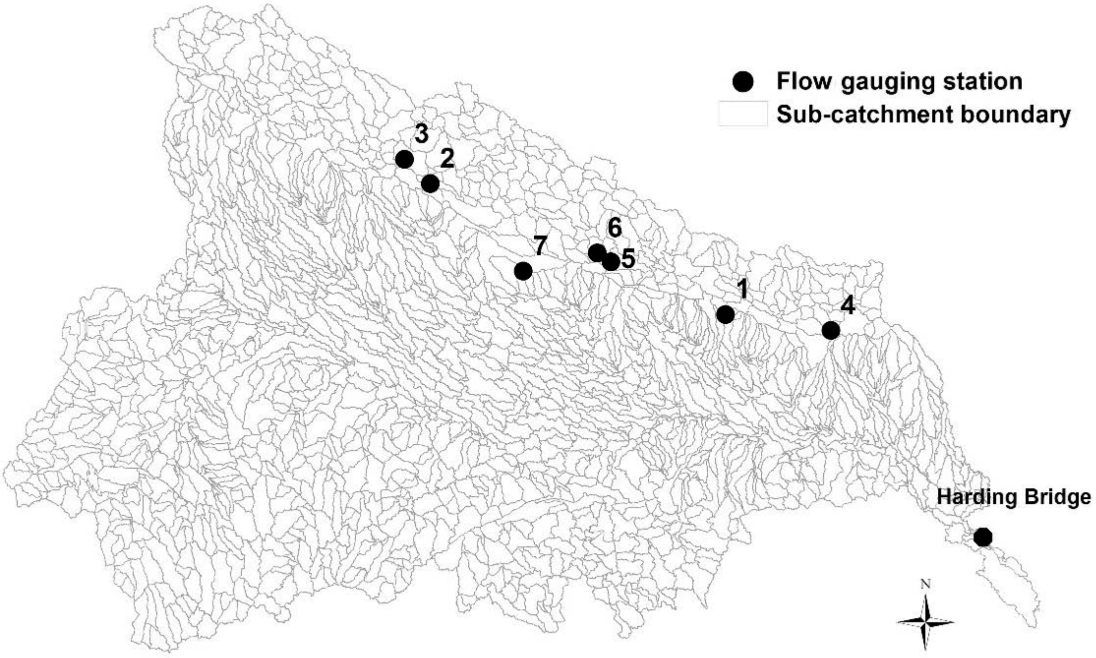

Fig. 1 Modelled sub-catchments of GRB and the streamflow gauges.

Table 2 Model performance indicators for seven locations in GRB.

Number	River	Latitude	Longitude	Period	R^2	NS
1	Baghmati	27.15	85.49	1981–2006	0.83	0.82
2	Karnali	28.96	81.12	1981–2006	0.79	0.61
3	Seti	29.30	80.78	1986–2006	0.76	0.54
4	Arun	26.93	87.15	1986–2006	0.63	0.64
5	Kali Gandaki	27.88	83.80	1996–2006	0.75	0.62
6	Kali Gandaki	28.00	83.61	1987–1995	0.58	0.58
7	Kali Gandaki	27.75	82.35	1984–2006	0.76	0.66

At these locations, as presented in Table 2, the performance indicators show reasonable values. Figure 2 shows the observed and simulated hydrographs at Pandhera Dobhan gauging station (Latitude: 27.15, Longitude: 85.49) on the Bagmati River.

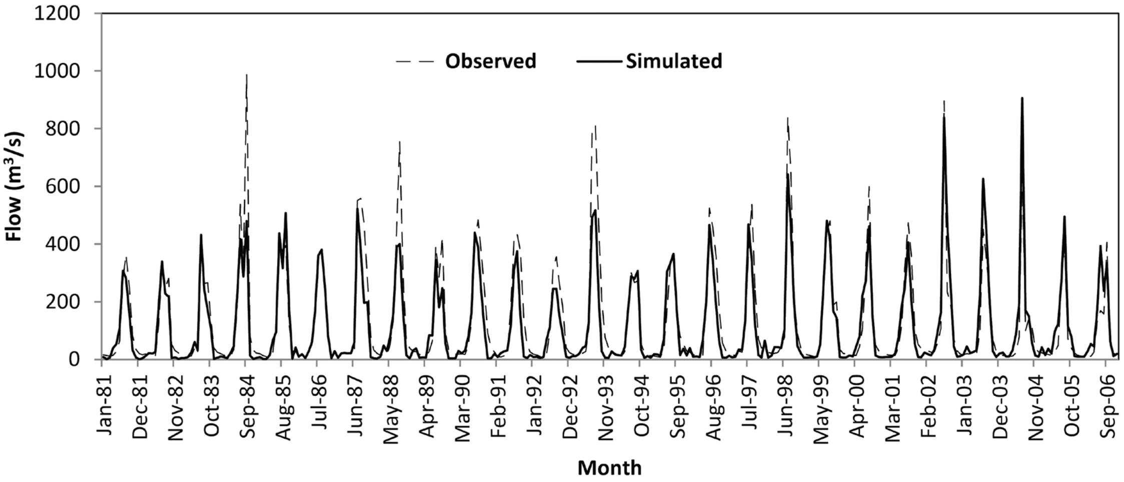

Fig. 2 Observed and simulated hydrographs at the Pandhera Dobhan gauging station.

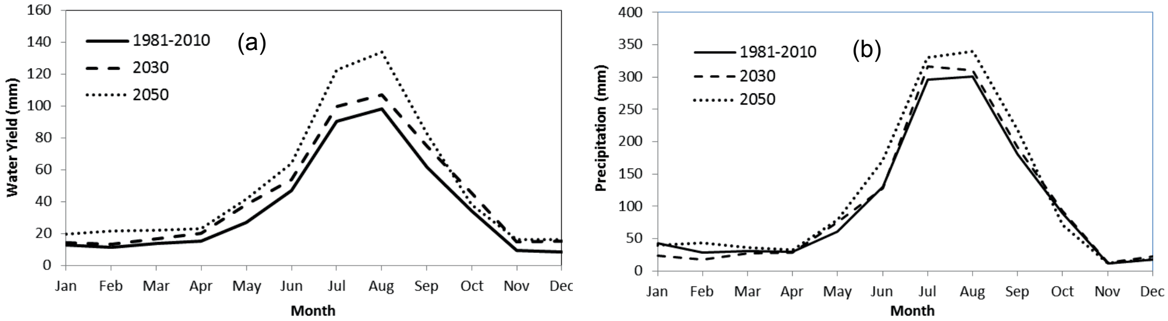

Fig 3 Monthly variations of precipitation and water yield for the three time periods.

The calibrated model was used to simulate the hydrological system of the GRB. The model provides detailed daily, monthly and annual outputs for the key components of water balance within each sub-catchment. Simulations were carried out for the baseline period (1981–2010), near future (2025–2035) and the distant future (2045–2050). To represent the hydrological variables in 2030, the average values between 2025 and 2035 were taken. The average values of the hydrological variables between 2045 and 2055 were used to represent the values in the year 2050.

The climate change scenario indicates a basin-wide increase in annual average precipitation. This increase will be of 2.2% and 14.1% by 2030 and 2050, respectively, compared to the baseline period. The average annual precipitation over the basin is about 1218 mm/year in the baseline period and it increases to 1389 in 2050. There is no significant change in the monthly patterns of precipitation in three time periods (Fig. 3(a)). However, the precipitation amounts for 2030 and 2050, especially in wetter months, show considerable difference compared to the baseline period. Although the average precipitation over the GRB will increase, substantial areas of the middle plains of the GRB will receive less precipitation compared to the baseline period, as shown in Fig. 4(a)–(c). This would lead to less water availability for agriculture in these areas. On the other hand, the hilly areas will have more precipitation in the future compared to the baseline period.

As presented in Table 3, water yield will be increased by 40% in 2050 compared to the baseline period. During the baseline period, average shallow groundwater recharge is about 228.2 mm/year and it will increase to 255.2 mm/year by 2050, which is about 12%. Analysis further reveals that due to the increase of mean daily temperature in future, PET will increase by about 15% and 12 % in 2030 and 2050 respectively. Because of the increased precipitation, the available water for soil evaporation and plant transpiration will increase in future, leading to increased actual evapotranspiration (ETa) by 4.1% and 10.3% in 2030 and 2050, respectively, compared to the baseline period.

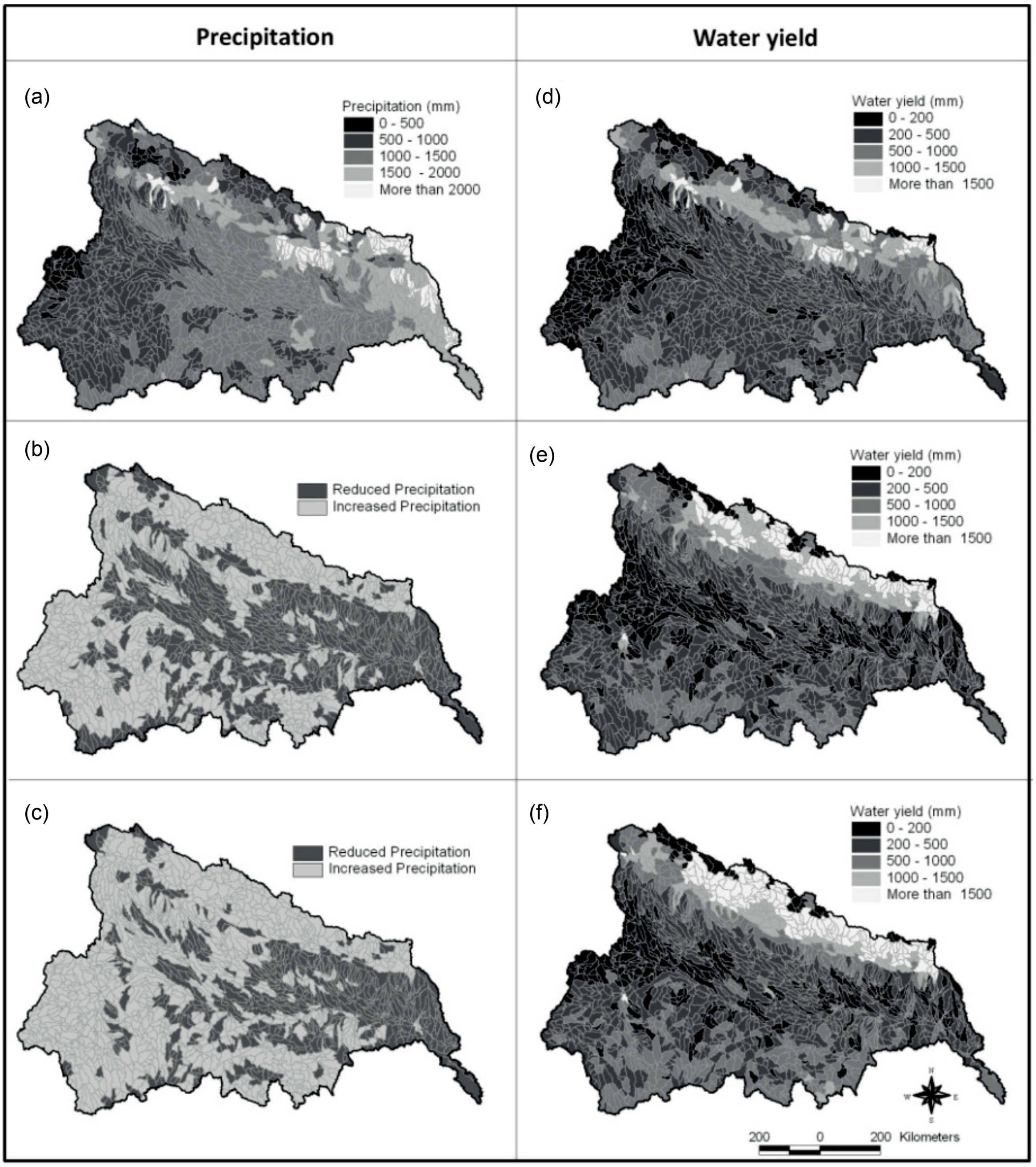

Fig. 4 Sub-catchment scale precipitation changes and water yield for three time periods.

Table 3 Average values of key hydrological variables for the three time periods in mm.

	1981–2010	2025–2035	2045–2055
Total Water Yield*	427.9	511.2	600.0
GW recharge (Shallow)	228.2	226.0	255.2
GW recharge (Deep)	12.0	11.9	13.4
ETa	580.9	605.2	640.8

*Water yield (measured in mm) is defined as the net amount of water that leaves the sub-basin and contributes to the streamflow in the reach (surface runoff + lateral flow + groundwater flow – transmission losses – pond abstraction) (Neitsch *et al*. 2002).

Figure 3(b) shows the monthly variations of water yield for three time periods considered in this study. Figure 4 (d)–(f) presents the sub-catchment scale average water yields for the baseline period, 2030 and 2050. Owing to the increased rainfall in 2050, the water yield also significantly increases during wetter months, especially between July and August. Analysis of the river flow data shows an increase in outflow at the Harding Bridge by 19% for 2030 and by 41% for 2050 compared to the average flow values during the baseline period.

CONCLUSIONS

In the A1B scenario considered in this study, both precipitation and temperature are projected to increase. This would lead to higher PET and increased ETa in 2030 and 2050 compared to the baseline period. For the agriculture sector, this could mean a higher demand for irrigation water. In future, the average water yield over the GRB will increase by about 172 mm and the average shallow aquifer recharge will increase by about 27 mm in 2050 compared to the baseline period. This is attributed to the higher precipitation in some parts of the basin, especially during the wet season. Therefore, according to the model simulations, the A1B climate change scenario will have a positive effect in terms of the water availability in the GRB. But the average numbers hide a lot of spatial and temporal variability within the basin. This implies an increase in extreme events in the basin. To manage the increased variability within the basins, a holistic approach of developing infrastructure to capture the increased flow in the river due to the higher water yield in the hilly areas, along with enhanced groundwater recharge techniques and improved rainwater harvesting to enhance soil moisture should be a priority in the GRB. Such an approach also requires a sustainable development of the groundwater resource in the basin such that it can act as an underground storage for access water in the wet season and a source of water in the dry season. This will help in mitigating adverse effects of climate change in the future.

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