Climate Change Impact and Vulnerability
in the Eastern Himalayas – Technical Report 4

ICIMOD

FOR MOUNTAINS AND PEOPLE

Modelling Climate Change Impact on the Hydrology of the Eastern Himalayas

MacArthur Foundation

Preface

Mountains are among the most fragile environments on Earth. They are also rich repositories of biodiversity and water and providers of ecosystem goods and services on which downstream communities (both regional and global) rely. Mountains are home to some of the world's most threatened and endemic species, as well as to some of the poorest people, who are dependent on the biological resources. Realising the importance of mountains as ecosystems of crucial significance, the Convention on Biological Diversity specifically developed a Programme of Work on Mountain Biodiversity in 2004 aimed at reducing the loss of mountain biological diversity at global, regional, and national levels by 2010. Despite these activities, mountains are still facing enormous pressure from various drivers of global change, including climate change. Under the influence of climate change, mountains are likely to experience wide ranging effects on the environment, natural resources including biodiversity, and socioeconomic conditions.

Little is known in detail about the vulnerability of mountain ecosystems to climate change. Intuitively it seems plausible that these regions, where small changes in temperature can turn ice and snow to water, and where extreme slopes lead to rapid changes in climatic zones over small distances, will show marked impacts in terms of biodiversity, water availability, agriculture, and hazards, and that this will have an impact on general human well being. But the nature of the mountains, fragile and poorly accessible landscapes with sparsely scattered settlements and poor infrastructure, means that research and assessment are least just where they are needed most. And this is truest of all for the Hindu Kush-Himalayas, with the highest mountains in the world, situated in developing and least developed countries with few resources for meeting the challenges of developing the detailed scientific knowledge needed to assess the current situation and likely impacts of climate change.

The International Centre for Integrated Mountain Development (ICIMOD) undertook a series of research activities together with partners in the Eastern Himalayas from 2007 to 2008 to provide a preliminary assessment of the impacts and vulnerability of this region to climate change. Activities included rapid surveys at country level, thematic workshops, interaction with stakeholders at national and regional levels, and development of technical papers by individual experts in collaboration with institutions that synthesised the available information on the region. A summary of the findings of the rapid assessment was published in 2009, and is being followed with a series of publication comprising the main vulnerability synthesis report and technical papers on the thematic topics climate change projections, biodiversity, wetlands, water resources (this publication), hazards, and human wellbeing.

Clearly much more, and more precise, information will be needed to corroborate the present findings. Nevertheless, this series of publications highlights the vulnerability of the Eastern Himalayan ecosystems to climate change as a result of their ecological fragility and economic marginality. It is hoped that it will both inform conservation policy at national and regional levels, and stimulate the coordinated research that is urgently needed.

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Modelling Climate Change Impact on the Hydrology of the Eastern Himalayas

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Introduction

Ecosystem, agriculture, water resources, wetlands, biodiversity, and other environmental services are vulnerable to climate change: the highlands of Asia, in particular, are vulnerable to any changes in the climate. The Eastern Himalayas sustain many rivers which are the lifeline of downstream provinces and countries. These rivers and landscapes provide valuable ecosystem services not only by supplying water, but also by facilitating soil retention of water, climate regulation, and carbon sequestration, and as reservoirs of pollinators, natural predators, and others. The welfare of approximately 400 million people downstream is inextricably linked with the natural resources of the Eastern Himalayas. Mountains provide opportunities for both plants and animals to migrate vertically as a coping mechanism and adaptive strategy. Species in high-altitude areas, however, will eventually have no further scope for vertical movement upwards if the climate keeps on warming. Hence species' extinction is inevitable if natural or human-induced adaptation to climate change does not take place. Erratic weather situations are already being observed in many parts of the Himalayas. Water-related hazards (glacial lake outburst floods, flash floods, and landslides) are becoming more frequent at the cost of lives, property, and natural resources, and are exacerbated by climate change (Xu et al. 2008). It has become imperative to assess the impacts of ongoing changes in the climate regime and changes that might occur in the future.

Among others, water is one of the most important sectors upon which climate change can have profound impacts. Further, climate-change impacts on water can in turn result in second order impacts on other sectors. While a consensus exists in general on the likely impacts of climate change on water resources in the Himalayas, quantitative analysis of such changes are sparse. This is mainly due to the dearth of baseline data which are essential for such analyses.

ICIMOD, in partnership with the MacArthur Foundation, has undertaken an assessment of trends, perceptions, and impacts of climate change on biodiversity in the Eastern Himalayan region and, in the process, sought a broad consensus on climate-change impacts on ecosystem and adaptation measures. The current paper is part of the broader assessment of climate change in the region and describes the results of preliminary analyses of the likely impacts of such changes on the hydrology of the Eastern Himalayas. Two study areas were considered: the Brahmaputra and Koshi basins. The results of the analyses will be useful for assessing the impacts on sectors dependent on water resources and for planning adaptation measures.

The Brahmaputra river originates in southwestern Tibet as the Yarlung river from the Chema Yundung glacier on the Tibetan plateau at an elevation of 5,300 m. The drainage area of the basin covers 651,335[1] sq.km and flows through China (50.5%), Bhutan (7.8%), India (33.6%), and Bangladesh (8.1%). It has a long journey through the dry and flat region of southern Tibet before it breaks through the Himalayas.

The Sapta Koshi (or Koshi) is a transboundary river between China, Nepal, and India and is one of the largest tributaries of the Ganges. The river, along with its tributaries, drains a total area of 69,300 sq.km up to its confluence with the Ganges in India (29,400 sq.km in Tibet, 30,700 sq.km in Nepal, and 9,200 sq.km in India). Seven ('sapta') rivers join to form the Koshi river. One major tributary is the Arun, which flows through Tibet for most of its course.

Methodology

The model and its capabilities

The Soil and Water Assessment Tool (SWAT) (Arnold et al.1990; Arnold et al.1993; Neitsch et al.2002) hydrological model was used for the study. SWAT is a distributed parameter and continuous time-simulation model. The SWAT model was developed to predict the response to natural inputs as well as to human interventions on water and sediment yields in ungauged catchments. The model is (a) physically based; (b) uses readily available inputs; (c) is computationally efficient to operate; and (d) is for continuous time and capable of simulating long periods to compute the effects of management changes. The major advantage of the SWAT model is that, unlike other conventional conceptual simulation models, it does not require much calibration and therefore can be used for ungauged catchments. The model's physical base means it is capable of simulating a high level of spatial detail by allowing the watershed to be divided into a large number of sub-watersheds. In SWAT, a watershed is divided into multiple sub-watersheds, which are then further subdivided into unique soil and/or land-use characteristics called hydrologic response units (HRUs). The water balance of each HRU in SWAT is represented by four storage volumes: snow, soil profile (0-2m), shallow aquifer (typically 2-20m), and deep aquifer (>20m). Flow generation, sediment yield, and non-point-source loadings from each HRU in a sub-watershed are summed and the resulting loads are routed through channels, ponds, and/or reservoirs to the watershed outlet.

The soil percolation component of SWAT uses a storage routing technique to predict flow through each soil layer in the root zone. The surface runoff from daily rainfall is estimated by means of the modified curve number method of the United States Department of Agriculture–Soil Conservation Service, which estimates the amount of runoff based on local land use, soil type, and the antecedent moisture conditions. A provision for estimating runoff from frozen soil is also included. Snow melts on days when the maximum temperature exceeds 0°C. Melted snow is treated the same as rainfall for estimating runoff and percolation. Flow routing is simulated using the Muskingum method[2].

The snowfall-snowmelt process has a great impact on hydrologic simulation. SWAT classifies precipitation as rain or freezing rain or snow using the average daily temperature. SWAT allows the sub-basin to be split into a maximum of ten elevation bands and snow cover and snowmelt are simulated separately for each elevation band. By dividing the sub-basin into elevation bands, the model is able to assess the differences in snow cover and snowmelt caused by orographic variation in precipitation and temperature.

The SWAT model was run under HadRM2 (GHG) and HadRM3 (A2 and B2) climate change scenarios (see meteorological data and climate scenarios under the next headings) to analyse the projected changes in the hydrological regimes of the river basins. HadRM2 and HadRM3 are high-resolution, limited area atmospheric regional climate models (RCM) developed by the Hadley Centre, UK (for more details see Shrestha and Devkota 2010). The SWAT model run under HadRM2 scenarios gives the projected changes for the period from 2040-2060 with respect to the baseline period 1981-2000, whereas the model run under HadRM3 scenarios gives the projected changes in the period 2070-2100 with respect to the baseline period 1960-1990.

Data

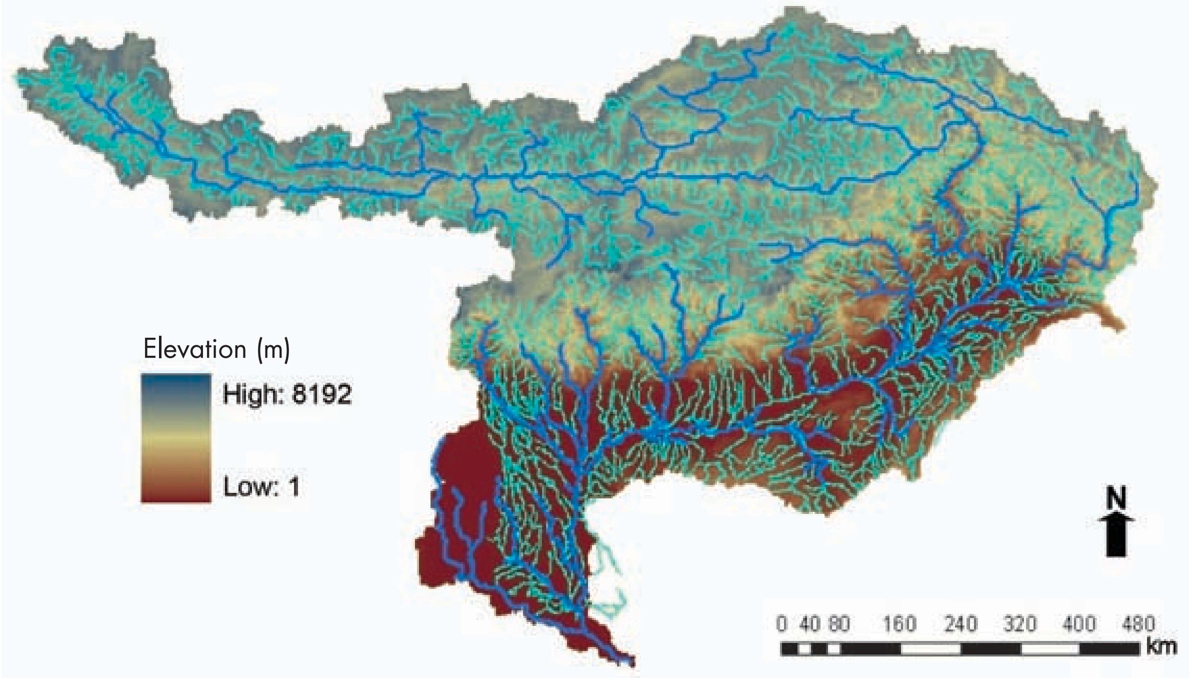
The spatial and temporal data used for the study were as follow:

- A digital elevation model (DEM): the DEM from the 90m resolution from the Shuttle Radar Topography Mission (SRTM) was used. It is shown in Figure 1 together with the drainage systems of the Brahmaputra and Koshi basins to illustrate the context.

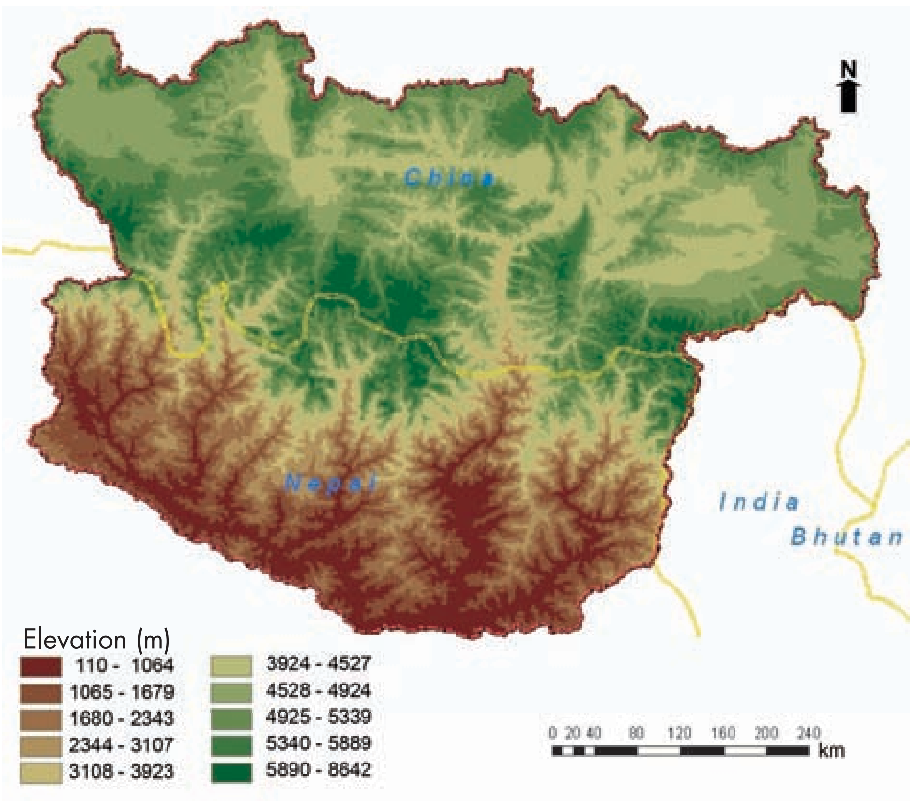
[1] Basin area calculated with Bahadurabad, Bangladesh, as the basin outlet; analyses carried out upstream from Pandu, Assam, India, basin area 526,562 km^2
[2] Flow routing determines the time and magnitude of flow at a point on a watercourse from known or assumed flow at one or more points upstream.

Figure 1: **Digital elevation model for the Brahmaputra basin (top) and Koshi basin (below) with drainage network generated based on the SRTM DEM**

Brahmaputra basin



Koshi basin



- A land-cover layer: global land use (Hansen et al. 1999) was used in the absence of actual land use data.
- A soil layer: a soil map based on the Food and Agriculture Organization's global soils (FAO 1995) was used.
- Meteorological data: the data generated in transient experiments by the Hadley Centre for Climate Prediction, UK, at a resolution of 0.44° x 0.44° latitude by longitude grid points was obtained from the Indian Institute of Tropical Meteorology (IITM), Pune (Rupa Kumar et al. 2006). The daily weather data on maximum and minimum temperature, rainfall, solar radiation, wind speed, and relative humidity from all the grid locations were processed. The regional climate model (RCM) scenario grid was superimposed on the sub basins to derive the weighted means of the inputs for each of the sub basins. The centroid of each sub basin was then taken as the location for the weather station to be used in the SWAT model.
- Climate scenarios: The study used IPCC IS92 scenarios for predicting emission, based on which climate scenario-control (CTL; 1981-2000) and greenhouse gas (GHG; 2041-2060) were developed using the HadRM2 climate model. Further, the Intergovernmental Panel on Climate Change's Special Report on Emission Scenarios (IPCC SRES) A2 (2071-2100) and B2 (2071-2100) scenarios (IPCC 2000) were used in the HadRM3 (also known as PRECIS or Providing Regional Climates for Impacts Studies) climate model to generate climate scenarios for baseline (BL; 1961-1990), and the future GHG scenarios (A2 and B2 for the period 2071-2100). The scenarios used did not incorporate the impact of sulphur. (For more details see Shrestha and Devkota 2010.)

Results and Discussion

Validation of model performance

Model validation for the Brahmaputra basin was carried out using the baseline climate data available from HadRM3. This was compared with the actual observed flow data at the Pandu, Assam, station in India (many data were unavailable). The results are shown in Figure 2. In fact ideal validation requires actual observed precipitation and other weather parameters, and these were not available. Even by using the simulated baseline weather data to generate the simulated flow series, however, the validation is reasonably good.

Model validation for the Koshi basin was also carried out using the baseline climate data available from HadRM3. This was compared with the actual observed flow data at the station in Chatara, Nepal, for the period from 1977-1990. The results ae shown in Figure 2.

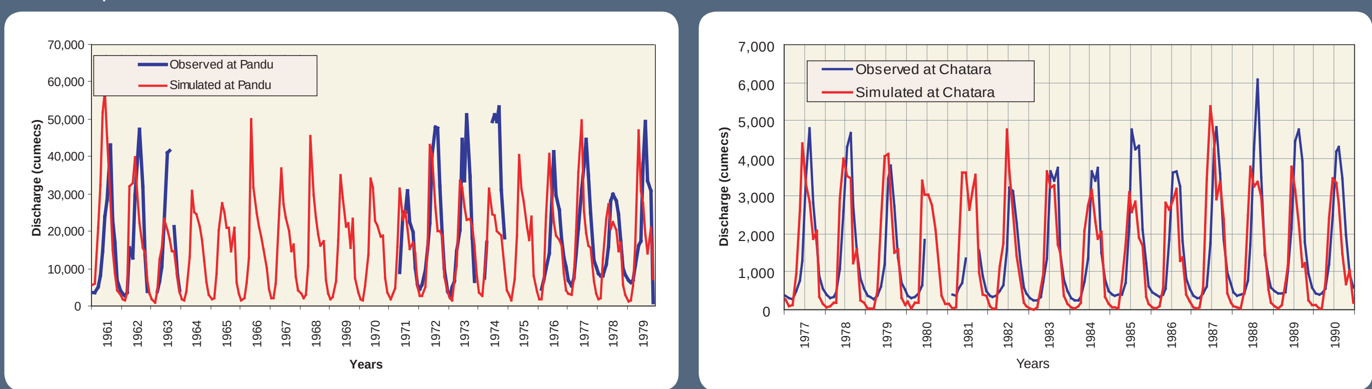
In both the Brahmaputra and Koshi validations, the simulated flow series were plotted with the observed ones but were not expected to have the same chronology.

Hydrological simulation of climate-change scenarios

The subcomponents of the water balance identified for use in analyses are total flow (water yield) consisting of surface runoff, lateral, and base flow; soil water recharge; and actual evapotranspiration (actual ET). These components are expressed in terms of average annual depth of water in millimetres (mm) over the total watershed area. In other words, the total water yield is the equivalent depth in mm of flow past the outlet of the watershed on an average annual basis

Figure 2: **Observed and simulated discharge for HadRM3 IPCC baseline scenarios**

Brahmaputra basin Koshi basin



Water-balance components for the Brahmaputra basin

The simulation of the Brahmaputra was carried out in two parts: the results are presented first for the upper Brahmaputra basin and then for the entire Brahmaputra basin (Figure 3). The analysis was carried out for the HadRM2 and HadRM3 models for the periods from 2041-2060 and 2071-2100 respectively.

Upper Brahmaputra

The major components of the water balance; namely, precipitation, runoff, groundwater, water yield, and actual evapotranspiration were selected and depicted for the upper Brahmaputra basin using HadRM2 under control (CTL; 2041-2060) and GHG scenarios (2071-2100), respectively (Figure 4a). On the annual time-scale, there is an increase of about 27% in the water yield in the GHG scenario compared to the CTL. The analysis of water-balance components as long-term mean monthly values suggests a 40-50% increase in water yields in the winter months, whereas in the monsoon months the increase is about 10%.

A similar analysis was carried out using data from HadRM3. The major components of the water balance for the upper-Brahmaputra basin under HadRM3 BL (1961-1990) and GHG (A2, B2) scenarios (2071-2100) are presented in Figure 4b. Approximate increases of 40 and 50% in water yield are expected under the GHG scenarios B2 and A2 respectively.

In long-term mean monthly values, a 17% increase in future precipitation simulated by the HadRM3 A2 scenario produced a 12% decrease in snowfall, a 33% increase in snowmelt, a 32% increase in surface runoff, and a 57% increase in groundwater recharge, resulting in a 42% net increase in total water yield in the upper Brahmaputra basin on an annual basis. Similarly, a 9% increase in future precipitation simulated by the HadRm3 B2 scenario produced a 7% decrease in snowfall, a 30% increase in snowmelt, a 19% increase in surface runoff, and a 36% increase in groundwater recharge, resulting in a 26% net increase in total water yield in the upper Brahmaputra basin on an annual basis.

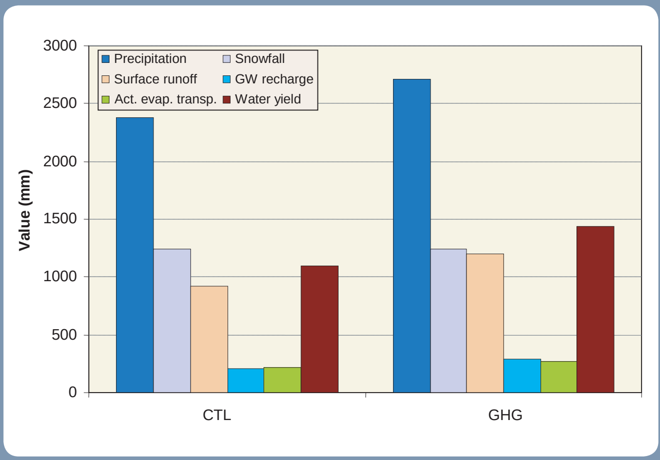
Complete Brahmaputra basin

Figure 5a presents the components of the water balance as long-term annual averages for the complete Brahmaputra basin using HadRM2 under the CTL and GHG scenarios respectively. An increase in water yield of about 35% from the CTL to the GHG scenario is suggested by this analysis.

Figure 3: **Map showing modelled parts of Brahmaputra - Upper and Lower Brahmaputra**

Figure 4: **Average annual water-balance component values for the upper Brahmaputra basin**

a) HadRM2 IPCC IS92 scenarios



b) HadRM3 IPCC SRES scenarios

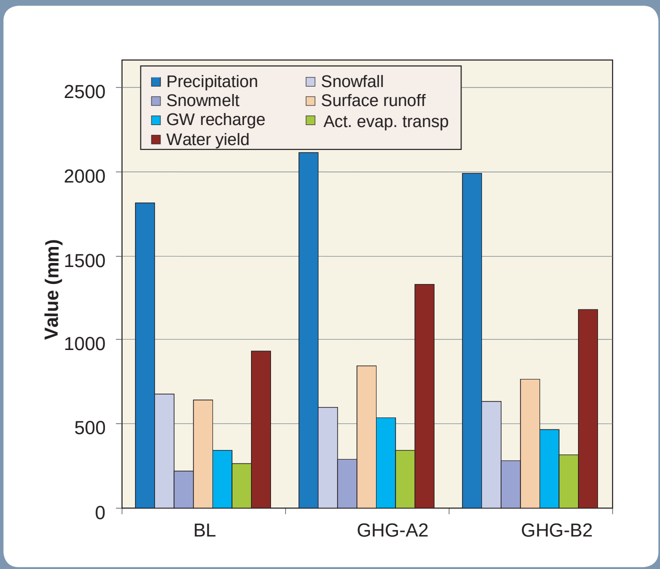
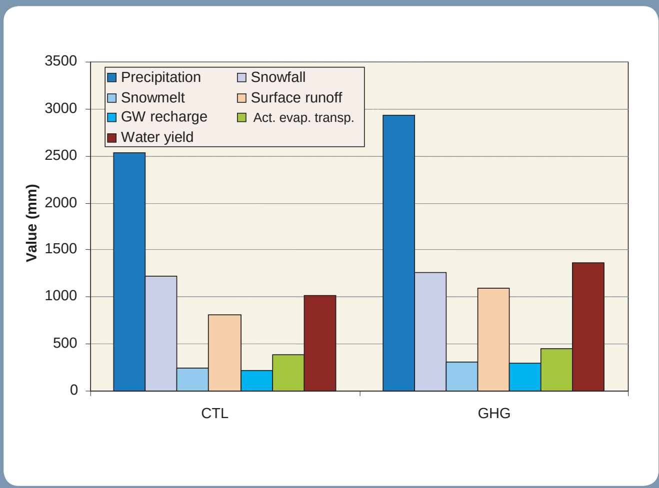


Figure 5: **Average annual water-balance component values of the complete Brahmaputra basin**

a) HadRM2 IPCC IS92 scenarios



b) HadRM3 IPCC SRES scenarios

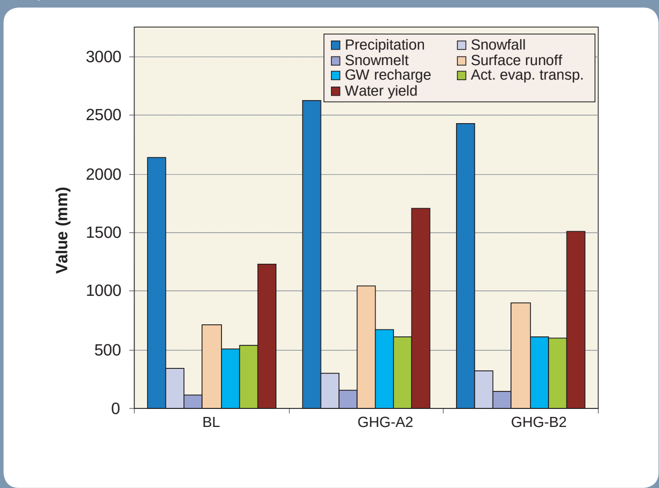
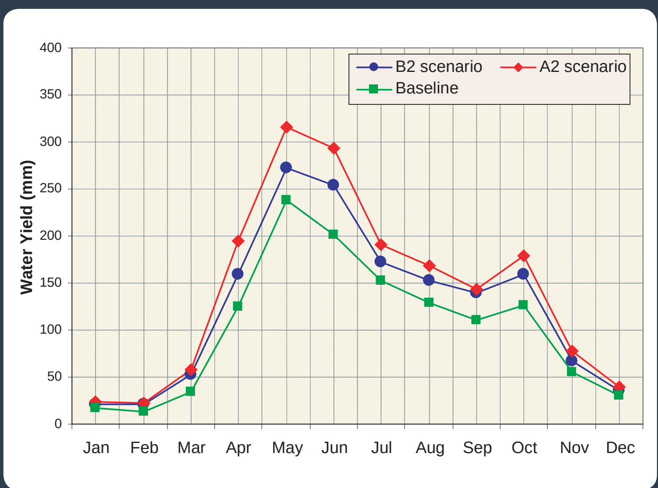


Figure 6: **Simulated average monthly water yield for the complete Brahmaputra basin** (for explanation see text)



A similar analysis was carried out using data from HadRM3. The major components of the water balance were depicted for the Lower Brahmaputra basin under HadRM3 BL and GHG (A2, B2) scenarios and combined with the upper basin results. The components of the water balance are depicted as long-term averages for the complete-Brahmaputra basin under CTL and GHG scenarios in Figure 5b.

In this simulation, a 23% increase in future precipitation simulated by the HadRM3 A2 scenario produced a 12% decrease in snowfall, a 32% increase in snowmelt, a 48% increase in surface runoff, and a 31% increase in groundwater recharge, resulting in a 38% net increase in total water yield in the Brahmaputra basin on an annual basis.

Similarly a 14% increase in future precipitation simulated by the HadRM3 B2 scenario produced a 7% decrease in snowfall, a 29% increase in snowmelt, a 28% increase in surface runoff, and a 19% increase in groundwater recharge, resulting in a 22% net increase in total water yield in the Brahmaputra basin on an annual basis.

Intra-annual trends in the Brahmaputra basin

The mean monthly simulated water yields for baseline, A2, and B2 scenarios are shown in Figure 6. It can be seen that there is a marked change in the water yield relative to the baseline. The variation in changes between B2 and A2 scenarios is also appreciable, revealing the sensitivity of the basin to changing conditions under various scenarios. The A2 and B2 scenarios show a warming up in the Brahmaputra basin by about 3-4°C and 2.5-3.5°C respectively. Two key effects of the increased temperature appear to be a decrease in snowfall and an increase in snowmelt runoff resulting in increased flows. It can be inferred from the simulation that the average annual water yields predicted by SWAT would increase by 40 and 25% respectively for the A2 and B2 scenarios.

The results indicate that the Brahmaputra hydrological system is very sensitive to climatic variations, both on a seasonal basis and over longer time periods. However, it is clear that the HadRM2 scenarios are not very reliable since the baseline is very much over estimated. Therefore, only the HadRM3 scenarios were used for the analyses. The scenario outcomes indicate that precipitation and increased temperature shifts would have a much greater impact on future flow changes. The analyses also show that the effects will vary spatially across the basin in A2 and B2 scenarios relative to baseline conditions (Figure 7). The climatic scenarios that were simulated here were simulated with an adequate level of validation of the base scenario within the context of the data available. These SWAT predictions provide an insight into the potential magnitude of streamflow changes that could occur as a result of future changes in climate, but with the assumptions such as no land-use and/or land-cover changes will take place over the time period.

Water-balance components for the Koshi basin

The simulation for the Koshi basin was carried out in the same way as for the Brahmaputra basins described previously; however, the simulation was not carried out for the whole basin and for its parts, but rather the simulation was carried out for the basin up to Chatara.

Figure 8a depicts the annual values for the selected water-balance components for the CTL (1981-2000) and GHG (2041- 2060) scenarios using HadRM2 data. There is a dramatic increase in water yield of about 80% from the CTL to the GHG scenario. This is due to increases in precipitation, snowmelt, and surface runoff. On monthly time scales an increase in water yield for all months in the range of 35 to 50% is expected.

A similar analysis was carried out using data from the HadRM3 BL and A2 and B2 scenarios. The results are shown in Figure 8b. An increase in water yield of 49% for B2 and and 70% for A2 scenarios is expected.

The components of the water balance are depicted as long-term averages for the Koshi basin under CTL (BL) and GHG (A2 and B2) scenarios. HadRM3 suggests a 10% increase in future precipitation simulated by the HadRM3 A2 scenario, which produced a 23% decrease in snowfall, a 76% increase in snowmelt, a 66% increase in surface runoff, and a 79% increase in groundwater recharge, resulting in a 70% net increase in total water yield in the Koshi basin on an annual basis. Similarly, a 2% increase in future precipitation simulated by the HadRM3 B2 scenario produced a 19% decrease in snowfall, a 74% increase in snowmelt, a 48% increase in surface runoff, and a 48% increase in groundwater recharge, resulting in a 49% net increase in total water yield in the Koshi basin on an annual basis.

Figure 7: **Spatial distribution of 30-year average annual water yield – Complete Brahmaputra basin**

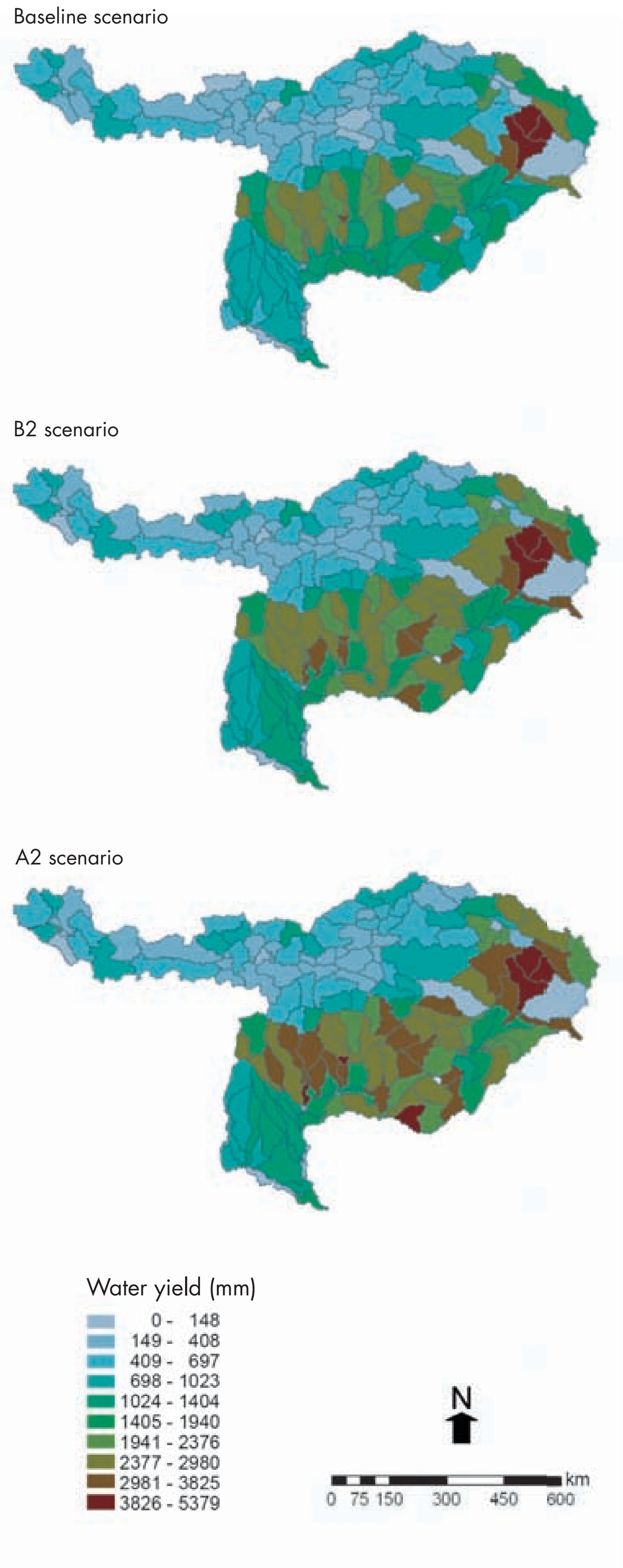
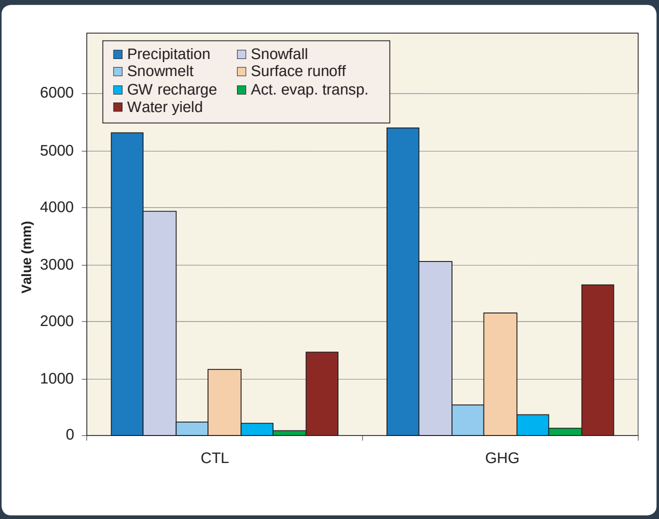


Figure 8: **Average annual water-balance component values of the Koshi basin**

a) HadRM2 IPCC IS92 scenarios



b) HadRM3 IPCC SRES scenarios

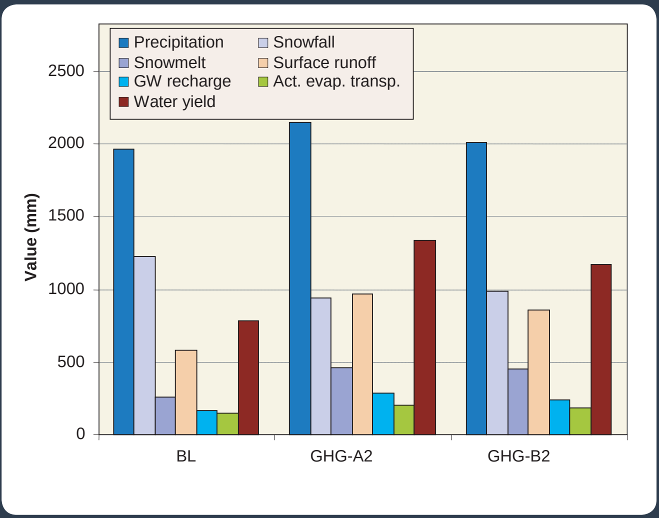
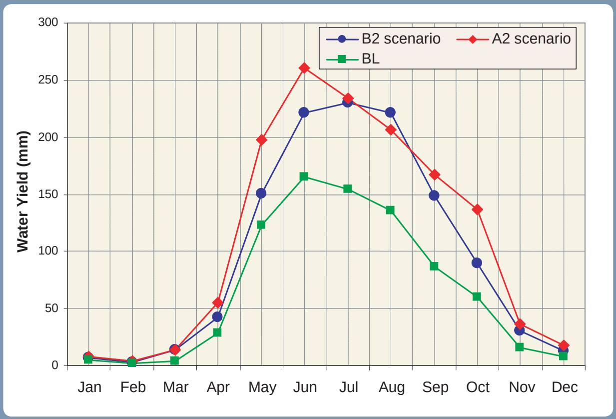


Figure 9: **Average monthly water yield – Koshi basin up to Chatara** (for explanation see text)



Intra-annual trends in the Koshi basin

The average monthly, simulated water yield for baseline, A2, and B2 scenarios is plotted in Figure 9. There is a marked change in the water yield from the baseline. The variation in change between B2 and A2 scenarios is also appreciable, revealing the sensitivity of the basin to changing conditions under various scenarios. The A2 and B2 scenarios show a warming in the Koshi basin by about 3-4°C and 2.5-3.5°C respectively. Two key effects of the increased temperature appear to be a decrease in snowfall and an increase in snowmelt runoff resulting in the increased flows. The impact on the individual segments of water balance has already been discussed in the previous section. The change in the response of water yield to the A2 and B2 scenarios can be attributed to the changes in precipitation from the baseline for different months. It can be inferred from the simulation that the average annual water yields predicted by SWAT would increase by 60% for A2 and 43% for the B2 scenario.

As with the Brahmaputra basin, the hydrological system of the Koshi is sensitive to climatic variations on both a seasonal basis and over longer time periods. According to HadRM3, precipitation and increased temperature shifts would have a marked impact on future flow changes. The results also show that the effects will vary spatially across the basin in A2 and B2 scenarios, relative to baseline conditions.

Uncertainties and assumptions

The analyses were carried out with many limitations. All these limitations result in uncertainties at various levels and ultimately reduce the accuracy of the model results. Some of the limitations encountered in the study are given in the following paragraphs.

Limitations in the climate and hydrological models – There are various assumptions related to the climate scenarios. Firstly, the emission scenarios are themselves assumptions and it is not clear how much they reflect reality. Next, the ability of the general circulation model (GCM) to translate GHG emissions into the future global climate scenario is limited. The downscaling of the coarse GCM outputs to regional climate scenario adds another layer of uncertainty. A further level of uncertainty arises from the limited ability of the hydrological models to reflect the real conditions.

Limitations of the data – The study has been carried out in areas for which data availability is a major problem. Due to lack of high resolution spatial data, we have used coarse resolution global data (e.g., land use, soil type, snow cover, glaciers, and so on). Further, the future dynamics of spatial data are not available and therefore have not been considered. Time series data, such as meteorological and hydrological data, are not accessible in the region. As a result, validation of the model results could not be carried out to the extent desired.

Conclusion

The current attempt to study the impacts of climate change in the Brahmaputra and Koshi basins is a preliminary one only, considering the lack of important data sets. Nevertheless, the exercise provides insights into possible changes which could occur in future. The study shows, in general, a significant increase in water yield and surface runoff. The increases could be as high as 20 to 40% from the baseline and can be attributed to both increases in precipitation as well as in snowmelt. The predicted increase is significantly more in the Koshi basin than in the Brahmaputra basin. Furthermore, the predicted increases in water yield and surface runoff are much higher during the wet months and not so much or even absent in dry months, suggesting possible increases in flood frequency and magnitude. This problem is shown to be more prominent in the lower parts of the basins.

Associated with the increase in water yield, predicted sediment yield is also found to increase with climate change. Under no land-use and/or land-cover change, climate-change scenarios are likely to result in 25 to 40% more sediment. This could mean serious management problems for water resource projects and could cause degradation of wetlands.

As indicated, the study was carried out under many constraints and, therefore, the results should be seen as preliminary rather than conclusive. Similar studies need to be carried out using better spatial and temporal data when they become available.

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Acronyms and Abbreviations

BL	baseline
CTL	control
DEM	digital elevation model
ET	evapotranspiration
FAO	Food and Agriculture Organization
GCM	general circulation model
GHG	greenhouse gas
GW	groundwater
HRU	hydrologic response unit
ICIMOD	International Centre for Integrated Mountain Development
IPCC	Intergovernmental Panel on Climate Change
PRECIS	Providing Regional Climates for Impacts Studies
RCM	regional climate model
SRES	Special Report on Emissions Scenarios
SRTM	Shuttle Radar Topography Mission
SWAT	soil and watrer assessment tool

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About ICIMOD

The International Centre for Integrated Mountain Development, ICIMOD, is a regional knowledge development and learning centre serving the eight regional member countries of the Hindu Kush-Himalayas – Afghanistan, Bangladesh, Bhutan, China, India, Myanmar, Nepal, and Pakistan – and based in Kathmandu, Nepal. Globalisation and climate change have an increasing influence on the stability of fragile mountain ecosystems and the livelihoods of mountain people. ICIMOD aims to assist mountain people to understand these changes, adapt to them, and make the most of new opportunities, while addressing upstream-downstream issues. We support regional transboundary programmes through partnership with regional partner institutions, facilitate the exchange of experience, and serve as a regional knowledge hub. We strengthen networking among regional and global centres of excellence. Overall, we are working to develop an economically and environmentally sound mountain ecosystem to improve the living standards of mountain populations and to sustain vital ecosystem services for the billions of people living downstream – now, and for the future.

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