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THE RUNOFF SENSITIVITY OF THE GANGES RIVER BASIN TO CLIMATE CHANGE AND ITS IMPLICATIONS

Md. Monirul Qader Mirza

Centre for Environmental and Resource Studies
University of Waikato
New Zealand

Results from General Circulation Models (GCMs) indicate that because of global warming, there is a possibility of changes in precipitation and evaporation in the future. On the other hand, increased atmospheric concentration of carbon dioxide may reduce plant evapotranspiration. These changes may significantly influence global hydrology and water resources. A runoff-climate model is used with observational and GCM data as input to investigate the sensitivity of annual runoff to climate change in the nine sub-basins of the Ganges River basin. The analysis indicates that runoff of a drier sub-basin will be more sensitive to climate change compared to a wetter sub-basin. All the sub-basins demonstrate increases in mean annual runoff. This may have wide-scale implications for the Ganges River basin where availability of the dry season flow cannot meet the demand. The possible increases in runoff may also introduce a new dimension in the water sharing problem between India and Bangladesh.

INTRODUCTION

Global warming from increasing concentrations of carbon dioxide (CO_2) and other trace gases could alter hydrologic processes and cycles. Therefore, water resources and its distribution in time and space, water quality, supply, and requirements of water in various parts of the world may be affected (Gleick, 1987; Rind, 1988; IPCC, 1990; Mimikou*et al*., 1991; Miller and Russell, 1992 and Arnell *et al*., 1996). However, there are many uncertainties with regard to climate change impacts on water resources resulting from inadequate representation of the global hydrologic processes in the General Circulation Models (GCMs) and their limited ability to accurately forecast changes in regional precipitation (IPCC, 1990; Gleick, 1993 and WMO/UNEP, 1996). Despite all these limitations, research carried out in the past few years suggests that relatively small changes in precipitation and temperature could have large effects on regional water resources (Flaschka*et al*., 1987 and Conway, 1993).

Precipitation and evapotranspiration play key roles in the runoff generation processes. In the future, increased carbon dioxide may reduce plant evapotranspiration. Rogers *et al*. (1983) experimentally demonstrated that plant stomatal closure occurs increasingly in the presence of a high atmospheric concentration of carbon dioxide. Plant evapotranspiration loss is generally reduced to about two- thirds of its original rate by a doubling of atmospheric CO_2. This results in increased soil moisture by reducing evapotranspiration and eventually generates more runoff. Based on this finding, Idso and Brazel (1984) modified Langbein's (1949) model and applied it to a river basin in Arizona, USA. The model indicated 40-60% increase in future runoff under a doubled CO_2 scenario. Wigley and Jones (1985) showed that runoff is relatively more sensitive to precipitation than evapotranspiration. Morassutti (1992) applied the Wigley and Jones (1985) model in three river basins in Australia and found significant increases in mean annual runoff.

In South Asia, water resources of major river basins such as the Ganges, Brahmaputra and the Meghna may be affected by climate change. Among these three basins, the Ganges is the most important one with a population of about half a billion people (Verghese and Iyer, 1993). Large parts of the basin are inundated every year by floods, while some parts are exposed to annual droughts. Monsoon to dry season and inter-annual variations of discharge are very high in the Ganges basin. Possible changes in climate might worsen the situation. Therefore, quantitative estimates of the hydrologic effects of climate change are essential for understanding and solving potential water resources problems associated with flooding, drought, agriculture, industry, hydro-power generation, domestic and industrial use, navigation, future water resources systems planning and management, sharing of water resources among the co-riparian countries, and protection of the natural environment.

Very few studies have been conducted on climate change impacts on water resources in South Asia (Divya and Jain, 1993; Mehrotra and Divya, 1994). These studies have ranged from statistical models to conceptual rainfall-runoff models. The study areas were concentrated in central India and the studies demonstrated significant changes in runoff during dry periods. However, the reduced evapotranspiration phenomenon was not taken into account during assessment of the effects. No study was carried out on any of the sub-basins of the Ganges River. Therefore, considering the importance of water resources of the Ganges basin to the co-riparian countries, this study focuses on the sensitivity of runoff of various sub-basins to climate change based on the Wigley and Jones (1985) model. The justification for considering the sub-basins is that the specific hydrologic changes for any given catchment would depend on local climate, physiographic, geologic and topographic characteristics, and should be investigated individually (Mimikou, 1995). The model needs two types of data input. Observational data, which include runoff ratio and forest cover, and climate change data (precipitation and evaporation) predicted by a GCM. For this study, GCM data of the Goddard Institute for Space Studies (GISS) were used.

STUDY AREA - THE GANGES BASIN

The Ganges is one of the largest river basins in the world. The entire area of the basin is 109 million hectares which is distributed over China, India, Nepal and Bangladesh. From its origin near Gangotri in the Uttar Pradesh of India to the outfall in the Bay of Bengal, numerous tributaries join the river (Figure 1). Important sub-basins of the Ganges are: Chambal, Betwa, Yamuna, Ramganga, Sone, Karnali, Gandak, Bagmati and Kosi. The first five tributaries originate in India and the last four tributaries join the Ganges from Nepal. Among these nine tributaries, the Yamuna is the most important one which drains about one-third of the entire Ganges basin. The Kosi and Karnali drain about 12 per cent and 9 per cent of the basin, respectively.

The precipitation pattern of the Ganges basin is quite diverse. Average precipitation in the basin in India varies from 350 mm on the western end to about 1000 mm along the middle course and to 1500 mm to 2200 mm near the delta (Indo-Bangladesh Task Force on Flood Management, 1990). In Nepal, the basin receives in excess of 3200 mm precipitation in the upstream portion of the Kosi basin. One-eighth of the catchment (west and the trans-Himalayan region) receives less than 1000 mm precipitation (UNESCO, 1981). About 80 per cent of the annual rainfall occurs in the Monsoon (June-October). Mean annual runoff of the Ganges River at Farakka in India and Hardinge Bridge in Bangladesh is estimated to be 362 mm and 357 mm, respectively (JRC, 1995 and BWDB, 1995).

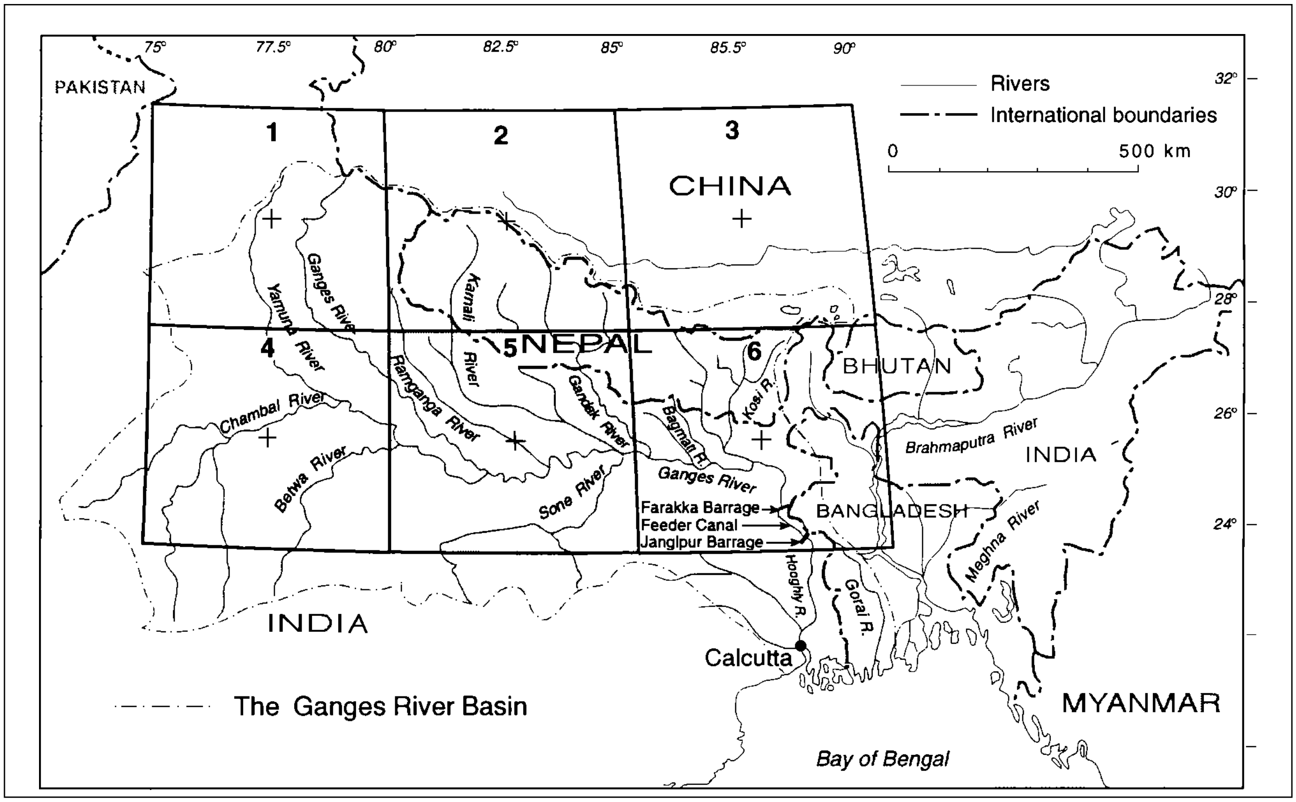

Figure 1. The Ganges River basin. Nine sub-basins considered for this research are also shown.

THE MODEL

The Wigley and Jones (1985) model has some advantages in determining sensitivity of runoff to climatic changes such as possible changes in precipitation and evapotranspiration. These changes are expected to be introduced by an increased concentration of CO_2. The model also incorporates the reduced evapotranspiration phenomenon. Less evapotranspiration may result in increased runoff the streams and rivers.

The basic structure of the Wigley and Jones (1985) model follows the water-balance principle. In a catchment, the water-balance over a selected time period can be evaluated as follows:

$$P - R - G - \Delta S - E - = 0 \tag{1}$$

where P is precipitation, R is runoff, G is groundwater runoff, E is evapotranspiration and ΔS is change in storage. In many cases it is assumed that the catchment is watertight and that no inflow or outflow of groundwater occurs. On an annual basis it is often assumed that no change in storage takes place from year to year. Therefore, equation (1) reduces to:

$$R = P - E \tag{2}$$

Runoff ratio γ_0, is expressed as R_0 / P_0 (3)

where R_0 and P_0 are present day values for runoff and precipitation, respectively.

There may be changes in precipitation under climate change. So, if P_1 denotes future precipitation

$$P_1 = \alpha P_0 \tag{4}$$

where α is the fractional change in precipitation under climatic change scenarios.

Changes in evapotranspiration can be expressed as

$$E_1 = \beta E_0 \tag{5}$$

where E_0 and E_1 denote present day and future evapotranspiration, respectively. β is the fractional change in evapotranspiration due to climatic change which can be expressed as the product of three parameters.

$$\beta = \beta_1 \beta_2 \beta_3 \tag{6}$$

In equation (6), β_1 denotes change in evapotranspiration due to a change in climate, β_2 expresses the change due to a change in the area of vegetation cover (due to either climatic change or direct effects of CO_2 on plant growth), and β_3 is the direct CO_2 effect on evapotranspiration. Wigley and Jones (1985) used the algorithm cited in Idso and Brazel (1984) for β_3 which is

$$\beta_3 \approx 1 - 0.3a \tag{7}$$

where a represents the area of the drainage basin covered by vegetation. Thus, if there is no vegetation ($a = 0$) there would be no change in vegetative effect.

The ratio of future and present day runoff can be expressed as

$$R_1 / R_0 = \frac{\alpha - (1 - \gamma_0)\beta}{\gamma_0} \tag{8}$$

(the derivation is given in Appendix 1).

Differentiating equation (8) with respect to α and β yields

$$\frac{\partial}{\partial \alpha}\left(\frac{R_1}{R_0}\right)=\frac{1}{\gamma_0} \tag{9}$$

and

$$\frac{\partial}{\partial \beta}\left(\frac{R_1}{R_0}\right)=\frac{1-\gamma_0}{\gamma_0} \tag{10}$$

Therefore, the relative sensitivity can be expressed as

$$\frac{\frac{\partial}{\partial \alpha}\left(\frac{R_1}{R_0}\right)}{\frac{\partial}{\partial \beta}\left(\frac{R_1}{R_0}\right)}=\frac{1}{1-\gamma_0} \tag{11}$$

Wigley and Jones (1985) discuss the following constraints that apply to their model: (i) when α= 0.7 and a = 1(no other changes in evapotranspiration, i.e. $\beta_1 = \beta_2 = 1$), equation (8) reduces to $R_1 = 0.7R_0$, making changes in runoff independent of runoff ratio, (ii) when $0.7 < \alpha < 1.0$, γ_0 determines changes in runoff; and (iii) for $\alpha > 1.0$, runoff always increases because precipitation and evapotranspiration changes are directly proportional.

DATA

Application of the Wigley and Jones model in any river basin requires values of two observed parameters γ_0 and β_3. γ_0 can be determined from historical precipitation and runoff values. β_3 is a function of vegetation cover (a). For the Ganges basin, runoff ratios and vegetation cover data for the seven sub-basins were taken from Kothyari and Garde (1991). These sub-basins are: Chambal, Betwa, Yamuna, Ramganga, Sone, Gandak, and Bagmati. Precipitation, runoff ratio and forest cover in the Karnali and Kosi basins in Nepal were received from Dixit (1996, personal communication) (Table 1).

GISS GCM data on precipitation change (α) and fractional evaporation change (β_1) were received from Russell (1996, personal communication). The GCM has a 4 x 5° resolution. The GCM has a base CO_2 concentration of 315 ppm. For increased CO_2 simulation, 1% per annum compound increase was assumed. Therefore, the concentration of CO_2 doubles after 74 years. Results from this GCM were used in the second assessment report of the IPCC (IPCC, 1996). The grid boxes for deriving the values α and β_1 for various sub-basins are shown in Figure 1. For the runoff sensitivity assessment, data for doubled CO_2 were used (Table 2).

ASSESSMENT OF RUNOFF CHANGES

Runoff changes for the various sub-basins were calculated by equation (8) with the input of required data. Calculated results are presented in Figures 2, 3 and 4. The results indicate wide ranging

Table 1. Hydro-meteorological and Forest Cover Data for Various Sub-basins of the Ganges River Basin

Sub-basin	Precipitation (mm)	Evaporation (mm)	Mean annual runoff (mm)	Runoff Ratio Col. 4/Col.2	Forest Cover (%)
Yamuna	809	520	289	0.35	20.0
Chambal	871	697	174	0.19	18.0
Betwa	1138	787	351	0.30	24.0
Ramganga	1073	500	573	0.53	30.0
Sone	1308	714	594	0.45	40.0
Karnali	2570	1833	737	0.29	43.0
Gandak	1241	269	972	0.78	26.0
Bagmati	1265	289	976	0.77	33.0
Kosi	1670	892	778	0.46	43.0

Table 2. Value of Precipitation and Evaporation Changes for Various Sub-Basins of the Ganges River Basin under Doubled CO_2 as Predicted by the GISS GCM

	Box No	Box centered at	Precipitation Change (α)	Evaporation Change (β_1)
Yamuna	1,4	26°N, 30°N	1.20	1.06
Chambal	4	26°N	1.18	1.00
Betwa	4	26°N	1.18	1.00
Ramganga	2,5	30°N, 26°N	1.24	1.10
Sone	5	26°N	1.18	1.11
Karnali	2,5	30°N, 26°N	1.24	1.22
Gandak	2,5	30°N, 26°N	1.24	1.22
Bagmati	6	26°N	1.26	0.99
Kosi	6	26°N	1.26	0.99

change in runoff in the various sub-basins of Ganges basin under the doubling of carbon dioxide and reduced evapotranspiration.

Effect of Runoff Ratio

Figure 2 illustrates the comparison of percentage change in runoff to runoff ratio (γ_0). It shows that changes in runoff vary linearly with runoff ratio. The lower the runoff ratio, the more changes in runoff. Wigley and Jones (1985) also maintained a similar view. Among the nine sub-basins, the Chambal sub-basin has the lowest runoff ratio (Table 1). Under the doubling of CO_2 and reduced evapotranspiration, this sub-basin may experience a 116% change in mean annual runoff. Changes

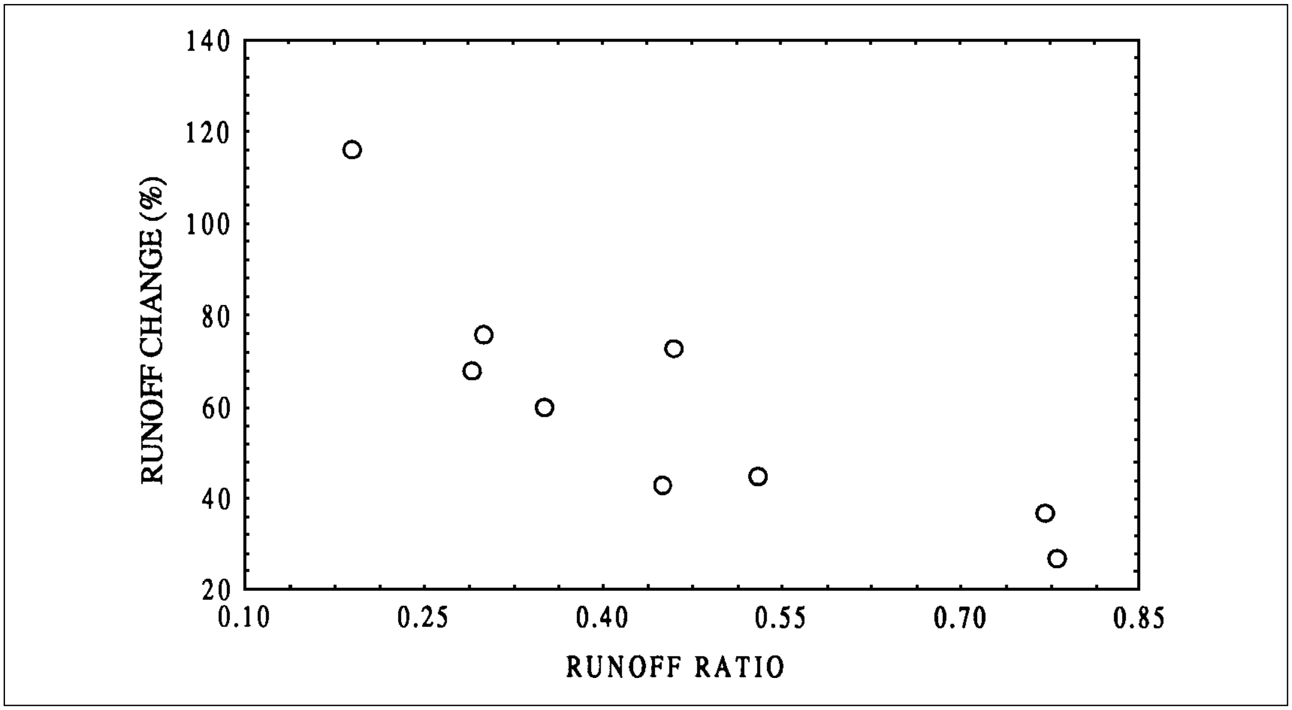

Figure 2. Percentage runoff change versus runoff ratio for the nine sub-basins of the Ganges.

in runoff in the Betwa sub-basin may be 76%. The Gandak sub-basin has the highest (0.78) runoff ratio. This sub-basin may experience the lowest (27%) increase in runoff. Other sub-basins may experience 27-68% changes in runoff. The nine sub-basins constitute about 61% of the Ganges River basin. If these sub-basins are considered together to be representative of the entire Ganges River basin, the area weighted average change in runoff in the basin may be 69%.

Effect of Precipitation and Evaporation Changes

Prediction of changes in precipitation by the GISS GCM is not very diverse in the Ganges basin. In other words, changes can be termed rather homogeneous. Precipitation changes for five Indian sub-basins: Yamuna, Chambal, Betwa, Ramganga and Sone are within a range of 18-24%. Projected precipitation changes for the sub-basins of the tributaries originating in Nepal are slightly higher. The projected range is 24-26%.

Figure 3 shows the effects of precipitation changes on runoff. Three sub-basins, Sone, Betwa and Chambal, having equal values (1.18), indicate runoff changes from 43-116%. This is caused by the influence of β values and low runoff ratios. Five sub-basins with values between 1.24-1.26 show a runoff change from 27-73%. Runoff changes in these five sub-basins were influenced by β values and high runoff ratios. However, runoff changes are found to be more sensitive to precipitation changes.

Figure 4 illustrates the effect of evaporation (β) on runoff changes. Note that β is the product of $\beta_1\beta_2\beta_3$. The value of β_2 is kept constant at 1. From Figure 4, it is seen that (with two exceptions), runoff change is almost proportional to evaporation change. These exceptions are the Chambal and Bagmati sub-basins. With a β value of 0.95, Chambal's high runoff resulted from the influence of low runoff ratio. The case of Bagmati ($\beta = 0.89$) is just the opposite (high runoff ratio).

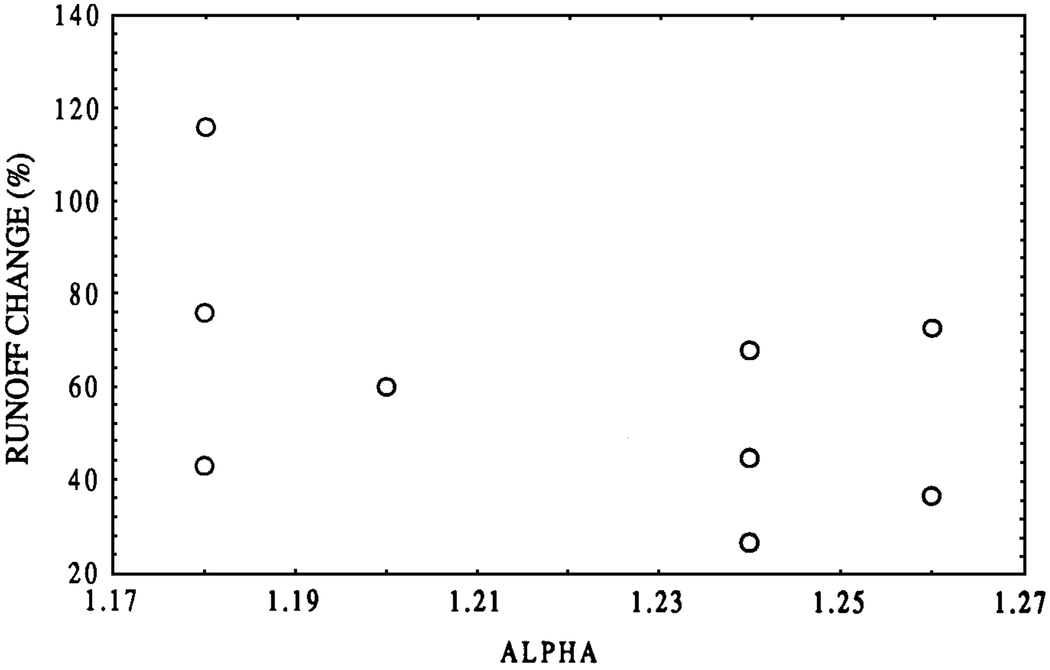

Figure 3. Percentage runoff change versus precipitation change (α) for the nine sub-basins of the Ganges (α values were derived from the GISS GCM).

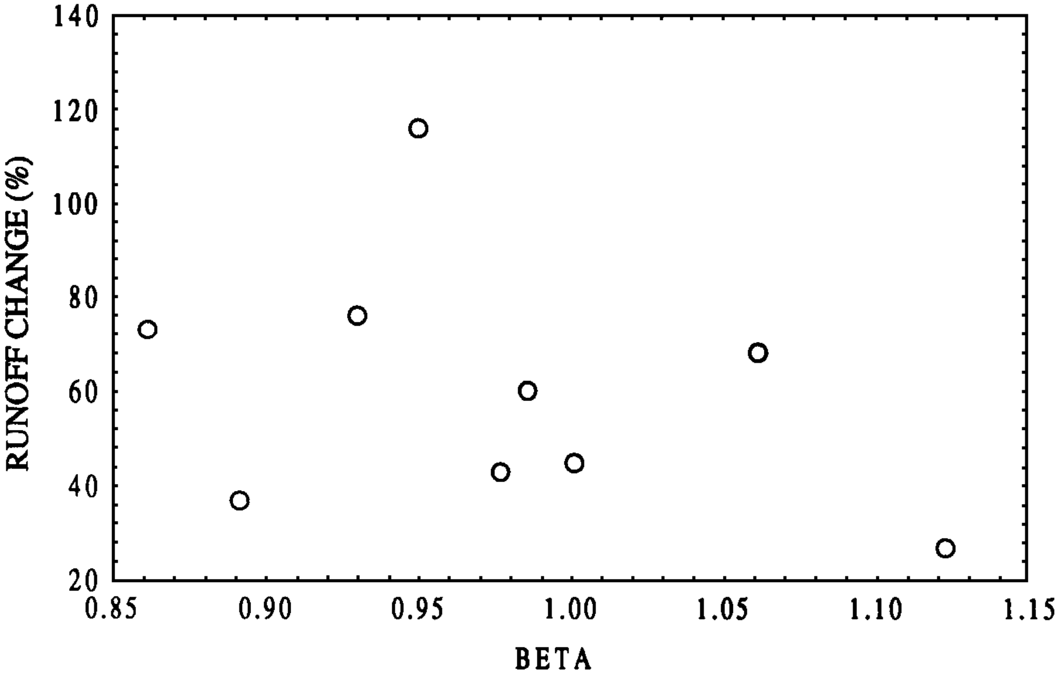

Figure 4. Percentage runoff change versus evaporation change (β) for the nine sub-basins of the Ganges.

LIMITATIONS OF THE ASSESSMENT

All GCMs show changes in global mean temperature and precipitation under climate change scenarios. However, on continental and regional scales (10^5-10^7 km^2), climate changes produced by GCM equilibrium experiments were not satisfactory (IPCC, 1992 and 1996). Various reasons were attributed to this. They were: coarse resolution, limitations in model physics representations, errors in model simulation of the present day regional climate features, etc. (Kattenberg *et al*., 1996). With these limitations, all GCMs predicted increases in precipitation in South Asia where the Ganges River Basin is located. Considering uncertainty, the predicted precipitation and evaporation changes considered in this study may vary with the real world situation in the future. Similarly, the runoff may also vary.

The effects of precipitation change and vegetation change may reinforce each other. Therefore, in some regions large increases in mean annual runoff are expected unless they are compensated by large climate related increases in evapotranspiration.

> *"The extent of this compensation is difficult to estimate because the magnitudes of climate-related changes in evapotranspiration due to increasing CO_2 are unknown. Over the land, evapotranspiration changes will result from several competing factors: warmer temperatures, changes in the length of the growing (evaporative) season, changes in wind speed, changes in cloudiness, and so on. Some of these factors may cause either increases or decreases in evapotranspiration" (Wigley and Jones, 1985).*

The assessment only considered the change in annual runoff. However, for the assessment of changes in runoff, seasonality is more important than annual variation where seasonal variation of runoff is very high. In the Ganges River basin, the ratio of monsoon and dry season runoff is 5.7:1. This indicates a very high seasonal variation in runoff. Therefore, a seasonal model may be more useful than an annual one. Despite this limitation, the annual model is used because it is simple and the data requirement is minimum.

IMPLICATIONS OF THE RUNOFF CHANGES

Compared to relative changes in runoff, net changes will have a substantial effect on the availability of water resources. For example, runoff in the Chambal sub-basin is now only 174 mm. Under climate change this quantity may be increased to 383 mm. On the other hand, mean annual runoff in the Gandak sub-basin is of the order of 972 mm. With a 27% increase in runoff under climate change, the net runoff may increase to 1234 mm. So, in the future under the climatechange scenario, a sub-basin with high current runoff may play a vital contributing role to the annual runoff of the entire Ganges basin. Sub-basins with low runoff may compensate the Ganges deficit with increased runoff in future. Present day runoff and possible future runoff for the nine sub-basins are shown in Figure 5. If the predicted runoff changes are consistent with the actual changes under the doubling of CO_2 scenario, there may be a substantial increase in mean annual runoff. Considering the 69% increase for the entire Ganges basin, mean annual runoff of the Ganges at Farakka may be increased to 612 mm from the current 362 mm.

The projected increase will have significant impacts on various water use sectors such as agriculture, industry, navigation, and domestic. Agriculture may be the principal beneficiary compared to other sectors with regard to the water requirement. However, seasonal availability may play a major role instead of gross annual availability. For example, in a large part of the Ganges basin,

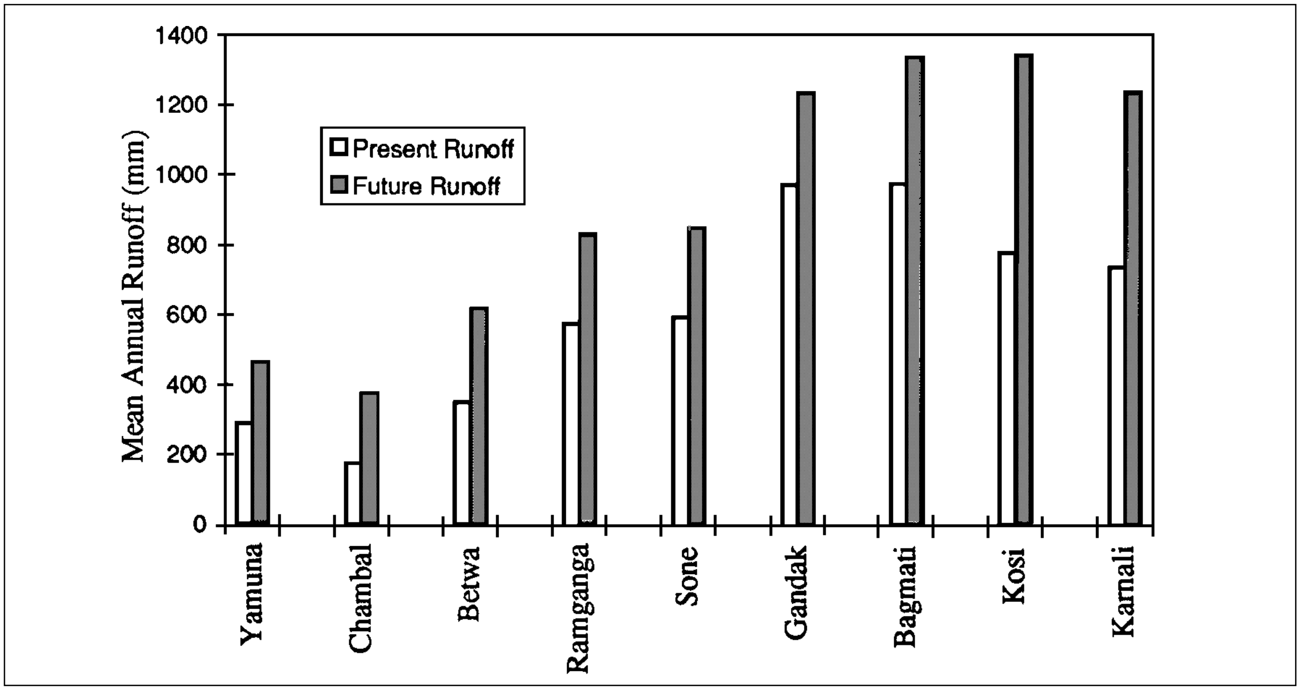

Figure 5. Present and future runoff of the nine sub-basins of the Ganges.

the water requirement for dry season irrigation is higher than the supplementary irrigation requirement in the monsoon.

The increase in mean annual runoff may increase the dry season availability of water, although the future monthly runoff pattern is unknown. This may introduce a new dimension in the water negotiation problem between India and Bangladesh. Therefore, an estimate of future dry season discharge for the Ganges River at Farakka was made (Table 3). This will give an idea about the possible changes in the magnitude of monthly discharge.

Three assumptions were made for the estimation: (1) current fractional monthly runoff (in percent of the mean annual runoff) will remain the same; (2) the calculated future change in runoff will remain valid; and (3) there will be no change in dry season water withdrawal upstream of Farakka. Although changes indicated (Table 3) in the dry season discharge of the Ganges River are only scenarios, possible increases in discharge may help in compensating the increased future water demands in the

Table 3. Present and Possible Future Dry Season discharge (in Cumecs) of the Ganges River at Farakka

	November	**December**	**January**	**February**	**March**	**April**	**May**
Runoff	4.5%	3.2%	1.8%	1.4%	1.3%	1.2%	1.5%
Present discharge	6822	4677	2733	2335	1922	1769	2142
Possible future discharge	11158	7904	4602	3564	3248	2893	3619
Increase in discharge	4336	3227	1869	1229	1326	1124	1477

co-basin countries. Countries involved in the water sharing negotiation will have to design the modalities to share the increased resources under the framework of a long-term water sharing agreement. Unless mechanisms for incorporating climatic changes in the water sharing agreement can be worked out, changes in future dry season discharge may provoke further conflicts between India and Bangladesh.

CONCLUDING REMARKS

The sensitivity analysis with the GISS GCM scenarios for precipitation and evaporation indicates substantial changes in the mean annual runoff in the various sub-basins of the Ganges. The calculated changes also demonstrate that under climate change in future, runoff of the relatively drier areas will be more sensitive to climatic change than the wetter areas. The analysis further shows that thewetter sub-basins will continue to contribute significantly to the annual runoff of the Ganges River.

The possible increased runoff will have many implications for the highly populated water hungry Ganges River basin. Current availability of dry season water is inadequate to meet requirements for various sectors such as agriculture, navigation, domestic and industry. In the future, the water requirement in the co-basin countries will be multiplied. Therefore, increases in the dry season flow may compensate the future increased water demands in the basin. However, the possible increased flow may complicate the water sharing problem between India and Bangladesh unless the climate change issue is adequately addressed under the framework of a long-term water sharing agreement.

APPENDIX 1

We know $R=P-E$ (1)

with R_0, P_0 and E_0 as present day runoff, precipitation and evapotranspiration.

Therefore, $R_0 = P_0 - E_0$ (2)

We know $R_0 = \gamma_0 P_0$ (3)

$P_1 = \alpha P_0$ (4)

$E_1 = \beta E_0 = \beta_1 \beta_2 \beta_3 E_0$ (5)

We can write $R_1 = P_1 - E_1$ (6)

From equation (2) and (6),

$$R_1 / R_0 \frac{P_1 - E_1}{P_0 - E_0} \tag{7}$$

Substituting the value of P_1, E_1, P_0 and E_0 in equation (7) yields

$$R_1 / R_0 = 1/\gamma_0 \left(\alpha - \beta E_0 / P_0\right) \tag{8}$$

Substituting the value of E_0 from equation (2) reduces equation (8) to

$$R_1 / R_0 = \frac{\alpha - (1-\gamma_0)\beta}{\gamma_0} \tag{9}$$

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ADDRESS FOR CORRESPONDENCE

Md. Monirul Qader Mirza
Centre for Environmental and Resources Studies (CEARS)
University of Waikato
Private Bag 3105, Hamilton
New Zealand

e-mail: mirza@waikato.ac.nz