

## **Modelling runoff and impact of climate change in large himalayan basins**

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### **Abstract**

The runoff regime in the basins of the rivers Ganges (917'444 km<sup>2</sup>) and Brahmaputra (547'346 km<sup>2</sup>) is modelled from precipitation, remotely sensed snow covered areas and temperatures. The runoff cycle roughly corresponds to a calendar year. In view of the small proportion of snowmelt, it is mainly governed by the distribution of rainfalls resulting in flow peaks in the summer and recession flow in the winter. The accuracy of runoff simulations is acceptable in view of the available data and because the SRM model was for the first time used in basins of this order of magnitude. In addition, for the given climate change scenario (T+1.5°, summer precipitation increased by 10%), the already high risk of floods in July-September is slightly increased.

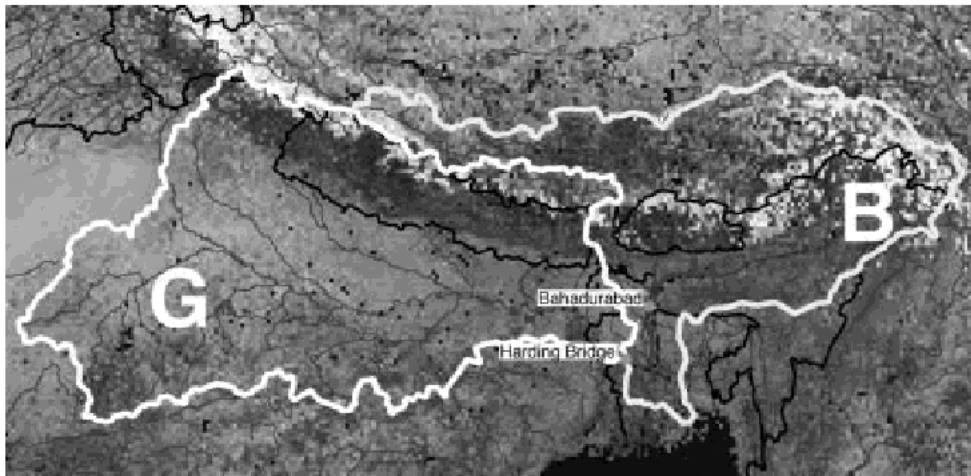
### **INTRODUCTION**

This study was conducted in the framework of the ESA-DUP SPIHRAL project with the aim to simulate runoff in the basins of the rivers Ganges and Brahmaputra, to evaluate contributions of snowmelt and to assess the effect of a climate change on runoff. The snow coverage from periodical satellite mapping and temperatures were provided only as monthly averages, precipitation only as monthly totals. Another problem was the extrapolation of precipitation by adequate altitude gradients between the sea level and 8848 m a.s.l. covering a variety of climatic zones. The results should be regarded in the light of these difficulties. In Alpine regions high accuracy runoff modelling is possible due to more detailed data available, as reported earlier (Seidel and Martinec., 1992).

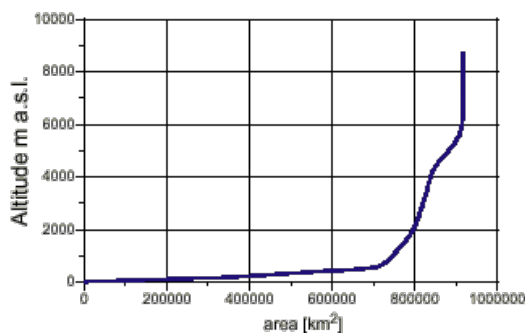
### **BASINS OF THE RIVERS GANGES AND BRAHMAPUTRA**

Published data on catchment areas and runoff vary to some extent. In an earlier publication (Chow, 1964) the combined area of Ganges and Brahmaputra river basins is given as 2'053'000 km<sup>2</sup> and the annual runoff as 630'252 . 10<sup>6</sup> m<sup>3</sup>, with the remark "subject of revision". The Water Encyclopedia (Troise and Todd, 1990) gives 1'058'852 km<sup>2</sup> and 589'000 . 10<sup>6</sup> m<sup>3</sup> for Ganges and 934'586 km<sup>2</sup> and 625'000 . 10<sup>6</sup> m<sup>3</sup> for Brahmaputra. Islam and Sado (2000a) indicate a combined area of 1'720'000 km<sup>2</sup> for the rivers Ganges, Brahmaputra and Meghna. In this study, the area of the Ganges river basin was evaluated as 917'444 km<sup>2</sup> and for Brahmaputra as 547'346 km<sup>2</sup> (Baumgartner, 1999). The situation of the basins is shown in Fig. 1. In spite of the smaller catchment area, Brahmaputra has more runoff than Ganges. This discrepancy may be better understood by inspecting the area-elevation curves in Fig. 2 and Fig. 3. As much as 75% of the Ganges basin is below 500 m a.s.l. compared with about 25% for the Brahmaputra basin.

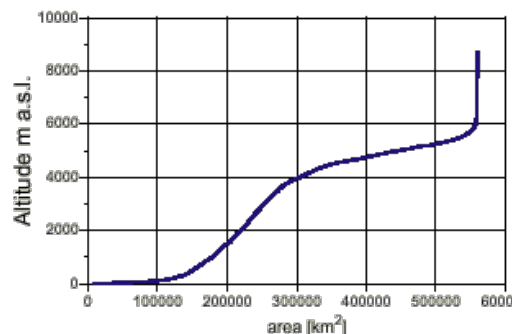
Taking into account the precipitation altitude gradient, the precipitation amounts extrapolated for higher parts of the basin are greater for Brahmaputra than for Ganges.



**Figure 1. Situation of the basins of the rivers Ganges (G) and Brahmaputra (B).**



**Figure 2. Area-elevation curve of the Ganges river basin.**



**Figure 3. Area-elevation curve of the Brahmaputra river basin.**

## HYDROMETEOROLOGICAL DATA

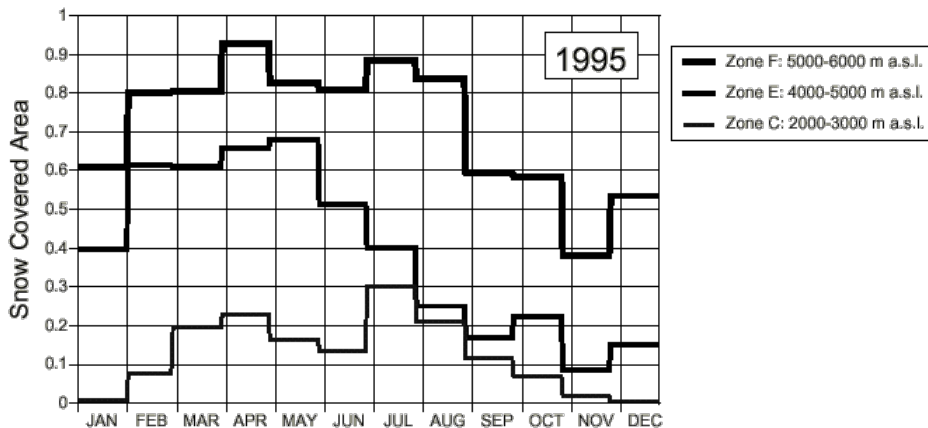
The SRM model used in this study requires temperature, precipitation and snow covered areas as input variables. These data were available for the year 1995. Temperatures for the computation of daily snowmelt depths were provided only as monthly averages. A comparison of the number of degree-days obtained from daily fluctuating values and from monthly averages carried out in a Swiss Alpine basin indicates a certain loss of degree-days if monthly averages are used. As a compensation, temperatures around 0°C can be increased as listed in Table 1.

**Table 1. Increase of monthly average temperatures (equivalent to disaggregation).**

Monthly average temperature	Correction
-4°C to -3.01°C	+0.15°C
-3°C to -2.01°C	+0.3°C
-2°C to -1.01°C	+0.5°C
-1°C to -0.01°C	+0.85°C
0°C to 1°C	+0.9°C
1.01°C to 2°C	+0.55°C
2.01°C to 3°C	+0.3°C
3.01°C to 4°C	+0.2°C
4.01°C to 5°C	+0.1°C

Precipitation was provided only as monthly totals which is inadequate for day-to-day runoff computations. In the SPIHRAL Interim Report (Baumgartner, 1999), monthly values were empirically disaggregated by clustering the events around the dates of measured runoff peaks, taking into account the statistically determined numbers of precipitation events in each month. The daily precipitation amounts thus obtained were taken over for this study as well as the altitude gradients. Another adjustment of precipitation data was necessary in the Brahmaputra basin. While Brahmaputra has generally more precipitation than Ganges, the September total at 1250 m a.s.l. is only 9 mm against 231 mm in the Ganges basin. Evidently major rainfalls were missed, which is confirmed by inspecting the measured hydrograph. Consequently the missing precipitation was taken over from the Ganges basin.

The periodical snow cover mapping is based on 10-days composites of NOAA/AVHRR data recorded over Northern India. In each month, the best cloud-free composite was selected so that the snow coverage was evaluated in terms of monthly values. Data is available from: <http://edcwww.cr.usgs.gov/landdaac/1KM/comp10d.html>.



**Figure 4. Snow covered areas in the zones C, E and F of the Ganges river basin in terms of average values for each month, from NOAA/AVHRR data.**

In view of the great elevation range, both basins were divided into 7 elevation zones and the snow coverage was evaluated separately for each zone. A graphical example in Fig. 4 refers to the zones C, E and F in the Ganges basin. This graph differs from the usual depletion curves of the snow coverage in which temporary increases of snow covered areas due to occasional summer snowfalls are eliminated, as explained elsewhere (Hall and Martinec, 1985). The available data did not allow to recognize satellite images with short-lived snow cover from new snow and to interpolate between values referring to the seasonal snow cover. The graph indicates the estimated snow covered area in each month from January to December 1995.

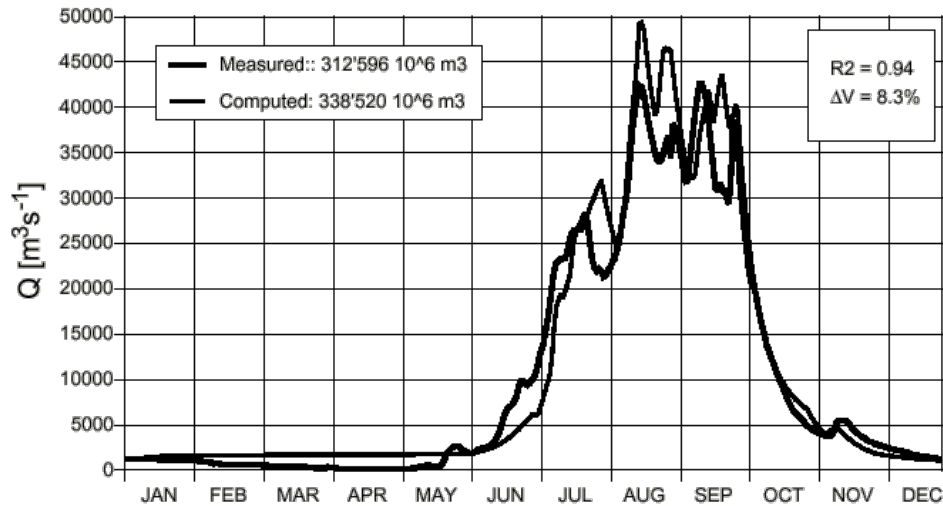


Figure 5. Measured and computed runoff in the river Ganges in 1995.

## RUNOFF MODELLING

The SRM snowmelt runoff model has been already successfully applied for runoff forecasts in Himalayan mountain basins (Kumar et al., 1991). The model structure is relatively simple:

$$Q_{n+1} = [c_{S_n} a_n T_n S_n + c_{R_n} P_n] \cdot \frac{A \cdot 10000}{86400} (1 - k_{n+1}) + Q_n k_{n+1} \quad (1)$$

where

- Q average daily discharge [ $m^3 s^{-1}$ ]
- $c_S, c_R$  runoff coefficient ( $c_S$  for snow,  $c_R$  for rain)
- a degree-day factor [ $cm \text{ } ^\circ C^{-1} d^{-1}$ ]
- T number of degree-days [ $^\circ C d$ ] (extrapolated by a lapse rate)
- S ratio of snow covered area to total area
- $P_R, P_S$  precipitation as rain or snow [cm] according to the critical temperature (snow contributes to runoff with a delay when temperatures rises above  $0^\circ C$ )
- A area of the basin or zone [ $km^2$ ]
- k recession coefficient indicating the decline of discharge in a period without snowmelt or rainfall as a daily ratio

n sequence of days  
 10000 conversion from [cm km<sup>2</sup> d<sup>-1</sup>] to [m<sup>3</sup> s<sup>-1</sup>]  
 86400

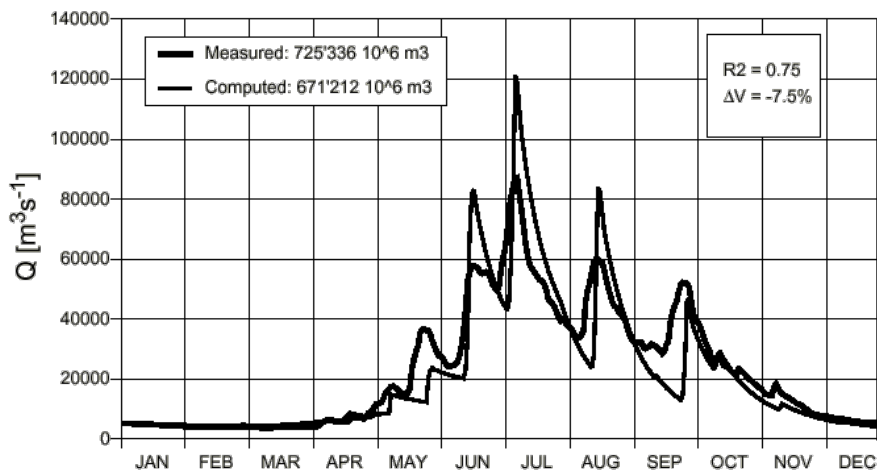
The model is described in detail elsewhere (Martinec et al., 1998). Eq. 1 refers to a basin as a whole. It is recommended to divide basins into several elevation zones and to compute the run-off input for each zone separately. In the given case, about 15 zones would be adequate with regard to the altitude difference of 8840 m which is the largest in the world. However, this is outside the capacity of the SRM computer program version 4. This version had to be used because it can also evaluate the effect of the climate change. Consequently, the number of elevation zones was reduced to 7 which put the model under strain.

Also, the model requires daily values of the input variables T, S, P. However, even by sub-stituting monthly average temperatures and snow covered areas as well as disaggregated pre-cipitation (as outlined in the previous section), acceptable runoff simulations have been obtained. Fig. 5 shows the measured and computed runoff in the year 1995 for the river Ganges and Fig. 6 for the river Brahmaputra. The measured runoff of the river Ganges is in March and April unusually low and could not be very well simulated with the pre-selected runoff coefficients. The respective yearly runoff volumes are given in the figures, as well as coefficients of determination R<sup>2</sup> and volume differences ΔV.

It should be noted that the SRM model was for the first time applied in a basin of this size. Therefore a special attention had to be paid to the recession coefficient which governs the trans-formation of input of a basin to the outflow. The recession formula reads

$$K_{n+1} = x \cdot Q_n^{-y} \quad (2)$$

where x, y are constants to be predetermined for the given basin. Taking into account the size of both basins (Martinec et al., 1998), x = 1.118 and y = 0.015 were used..



**Figure 6. Measured and computed runoff in the river Brahmaputra in 1995.**

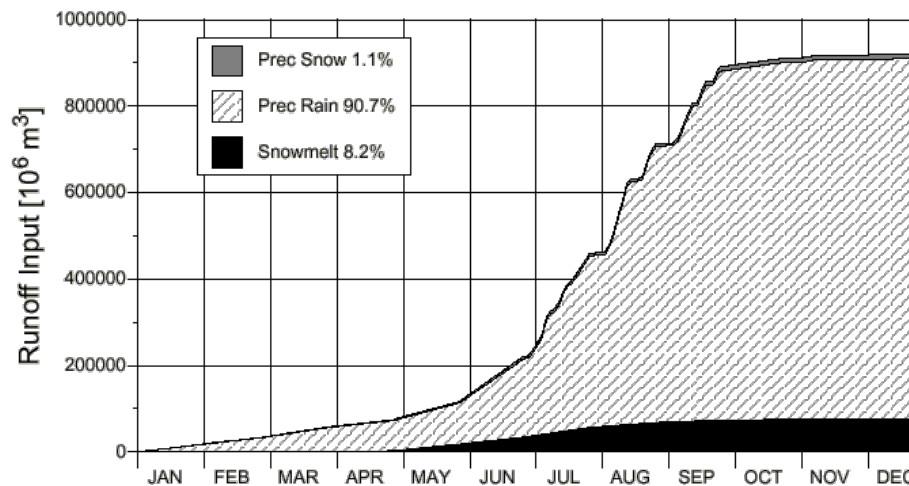
As for the other model parameters, similar values were predetermined as in a previous study (Kumar et al., 1991). The seasonally variable degree-day factor ranged from 0.3 to 0.75, the run-off coefficients  $c_S$  from 0.6 to 0.85,  $c_R$  from 0.5 to 0.7 and the critical temperature from 0.75 to 2°C. The lapse rate was 0.6° per 100 m altitude difference.

Fig. 7 and Fig. 8 show computed cumulative curves of the runoff input from the seasonal snow cover, temporary snowfalls and rain. The temporary snowfalls refer to the hitherto snow free areas while their remaining part is integrated into the seasonal snow cover. Numerical totals are listed in Table 2.

**Table 2. Computed proportions of runoff components in the year 1995.**

Basin	Seasonal snow cover [%]	Temporary snow [%]	Rain [%]	Total [%]
Ganges	8.2	1.1	90.7	100
Brahmaputra	24.0	2.6	73.4	100

From the satellite imagery, snow occurs above 2500 m a.s.l. Recalling the area-elevation curves in Fig. 2 and Fig. 3, this represents 57% of the Brahmaputra basin and 12% of the Ganges basin. Consequently, the proportion of snow in the runoff as indicated in Table 2 is much smaller for Ganges than for Brahmaputra. Almost the whole snowmelt contribution occurs in April through August. It also includes icemelt because it was not possible to map glaciers separately. The contribution of rain is more equally distributed and reflects the yearly precipitation regime.

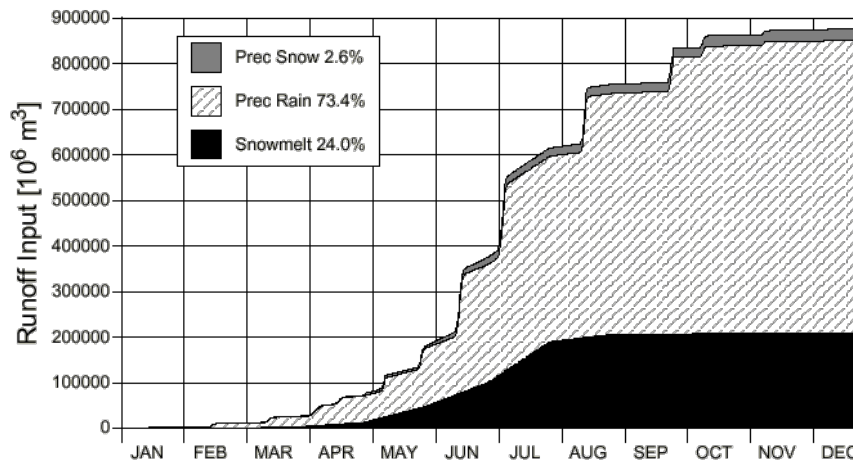


**Figure 7. Computed cumulative curves of the runoff input components: seasonal snow cover, temporary snowfalls and rain, for the river Ganges.**

## EFFECT OF CLIMATE CHANGE ON RUNOFF

The low reaches of the Ganges and Brahmaputra rivers have a history of catastrophic floods. In 1988, large areas of Bangladesh were inundated. The highest flood peak in the

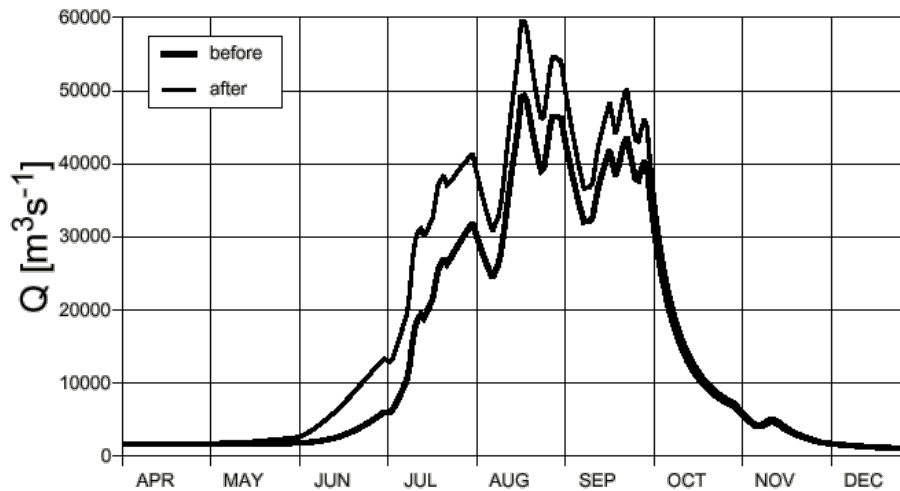
Brahmaputra basin reached  $99'500 \text{ m}^3 \text{ s}^{-1}$ . In the Ganges basin, the peak reached  $72'300 \text{ m}^3 \text{ s}^{-1}$  (Islam and Sado, 2000b). In the studied year 1995, the respective values were  $87'000 \text{ m}^3 \text{ s}^{-1}$  and  $42'600 \text{ m}^3 \text{ s}^{-1}$ , as can be seen in Fig. 5 and Fig. 6. The question arises how this situation will be influenced by a changed climate.



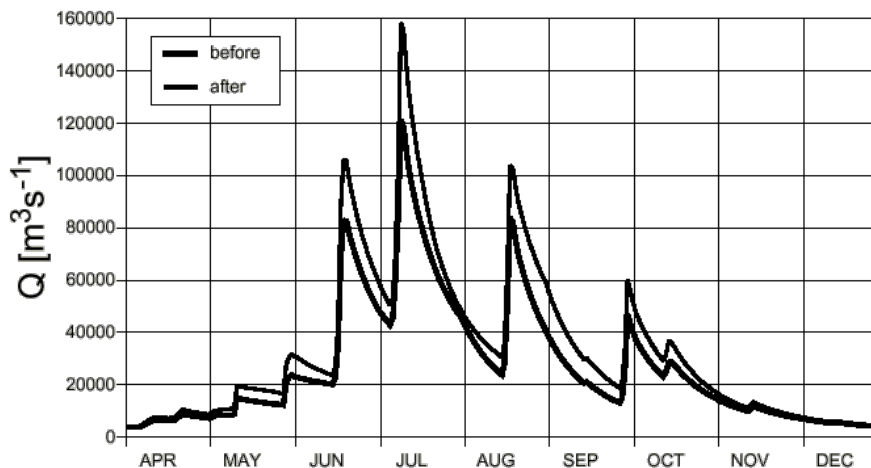
**Figure 8. Computed cumulative curves of the runoff input components: seasonal snow cover, temporary snowfalls and rain, for the river Brahmaputra.**

A scenario recommended for this area and expected to take place around the year 2030 consists of a temperature increase of  $+1 - 2 \text{ }^\circ\text{C}$  throughout the year, a precipitation increase of 10% in the summer and of a humidity increase by 5 to 10% (Jäger and Ferguson, 1991). It has been stated on several occasions (for example Klemes, 1985) that calibration models are not adequate for climate change studies since the parameters cannot be meaningfully adapted to the new conditions. The SRM model does not use calibration and so the predetermined values of the runoff coefficient for rain were increased by 5% in the summer in line with the mentioned increase of the humidity. After this adjustment, the model was run with  $T+1.5^\circ$  throughout the year and with the summer precipitation  $P \times 1.1$ . The precipitation data which were available only as monthly totals make the evaluation difficult. With an estimated disaggregation, it was possible to simulate the runoff peaks (Fig. 5 and Fig. 6) and to compare this simulation with the climate run, as illustrated in Fig. 9 for the river Ganges and in Fig. 10 for the river Brahmaputra. It appears that in the new climate, the flood peaks will be increased by about 20% for Ganges and by 30% for Brahmaputra as compared with the year 1995. It is of course uncertain whether a precipitation increase by 10% should be interpreted as a proportional increase of each daily amount or as a corresponding increase of days with precipitation.

The actual yearly runoff volume from April until December will increase by about 25% in both basins. It is further uncertain to what extent the year 1995 can be considered as representative for the present climate. Therefore the effect of a changed climate on runoff could be evaluated only in terms of relative differences rather than in absolute numbers. At all events, the risk of floods will be further accentuated should the mentioned climate scenario materialize.



**Figure 9.** Comparison of the runoff in the Ganges river computed with the data of 1995 and with the climate scenario recommended for the region: Temperature in-crease of  $+1.5^{\circ}\text{C}$ , precipitation increase in the summer by 10%, increase of hu-midity by 5 to 10%.



**Figure 10.** Comparison of the runoff in the Brahmaputra river computed with the data of 1995 and with the climate scenario recommended for the region (the same as for Ganges).

## CONCLUSIONS

The study reveals that the SRM snowmelt runoff model can handle very large river basins which were so far considered to be outside the range of applicability.

Runoff from the basins of the rivers Ganges and Brahmaputra was simulated with an acceptable accuracy although temperatures and snow cover areas were available only as monthly averages and precipitation as monthly totals. In particular, this data did not en-



able the temporary snow cover from occasional summer snowfalls to be excluded from the periodical satellite snow cover mapping. Therefore the depletion curves of the snow coverage could not be derived in the usually required way.

Even so, it can be concluded that the proportion of snow in the runoff was about 27% for Brahmaputra and about 9% for the Ganges. The different participations of snowmelt are in line with the respective area-elevation curves of the basins.

For the given scenario of a climate change (temperature increase of +1.5°C, precipitation increase in summer by 10%, increase of humidity by 5 to 10%), it appears that the already high risk of summer floods in the low reaches of the rivers Ganges and Brahmaputra will be further increased. The presently available climate scenario is not specific enough to allow answering the question whether the increased risk of floods will consist in an increase of flow peaks (as evaluated) or in an increased frequency of flood events.

The spatial resolution of NOAA/AVHRR is sufficient for the size of the elevation zones, even if the new computer program enables the basins to be divided into 15 zones. The accuracy of results could be improved should daily measured values of the model input variables instead of monthly ones become available.

### **Acknowledgment**

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