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Climate Variability Analysis on Flow Duration Curve of a Large Himalayan River

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Abstract : The impact of climate change is projected to have different effects within and between countries. Climate change is likely to threaten food production, increase water stress and decrease its availability, result in sea level rise. Any adverse impact on water availability due to recession of glaciers, decrease in rainfall and increased flooding will affect the livelihood of large population. Information about the change is required on global, regional and basin scales for variety of purposes.

In this study, the historical daily runoff has been simulated for the Chenab river basin up to Salal Dam gauging site using a simple conceptual snowmelt model (SNOWMOD) based on the temperature index (degree-day) approach. After simulation of flow this model is used to study the impact of plausible hypothetical scenarios of temperature on daily flow duration curve of the Chenab river basin. The steeper slope of flow duration curves indicate that streamflow is fed by direct runoff and there is negligible amount of storage in the basin. The flow exceeded 50% of the time (460 m^3/s in 1996) would be exceeded 60% of the time under a warming of 2°C.

INTRODUCTION

As per IPCC (2007) eleven of the last twelve years (1995 – 2006) rank among the 12 warmest years in the instrumental record of global surface temperature (since 1850). The updated 100 – year linear trend (1906 – 2005) of 0.74 ± 0.18ºC is therefore larger than the corresponding trend for 1901 – 2000 given in the Third Assessment Report of 0.6 ± 0.2ºC. Mountain glaciers and snow cover have declined on average in both hemispheres. Widespread decreases in glaciers and ice caps have contributed to sea level rise. Global average sea level rose at an average of 1.8 mm per year over 1961 to 2003. The total 20th century rise is estimated to be 0.17 m. The frequency of heavy precipitation events has increased over most land areas, consistent with warming and observed increases of atmospheric water vapour. More intense and longer droughts have been observed over wider areas since the 1970s, particularly in the tropics and subtropics.

Snow and glaciers are considered to be key indicators for early detection of climate change signatures. Changes in the mass, volume, area, and length of the world's glaciers provide a clear signal of global warming. During last century the impact of climate change on snow and ice has been clearly observed on the global scale. Globally the extent of snow cover has decreased by about 10% on average in the Northern Hemisphere since the late 1960s (IPCC, 2001). In response to increasing temperatures over the past 100 years, mountain glaciers have generally thinned, lost mass and retreated. Studies related to changes in mass balance under changed climatic scenarios have shown significant changes towards loss in glacier mass (Oerlemans and Fortuin, 1992; Laumann and Reeh, 1993; and Dyurgerov, 2003). Many of relatively small glaciers have lost large percentages of their area during the past decades. The recent increase in the rates of ice loss over reduced glacier surface areas as compared with earlier losses related to larger surface areas becomes more pronounced and further confirms accelerating change in climatic conditions (IAHS, 2003). A warming is likely to increase the melting far more rapidly than the accumulation (IPCC, 2007).

In the last decade there has been a number of studies of the potential impact of climate changes on river flow characteristics and water resources. Gleick (1986) has reviewed various approaches for evaluating the regional hydrologic impacts of global climatic changes and presented a series of criteria for choosing among the different methods. Braun et al. (1994) examined the hydrological consequences of climatic change for the Romanche River basin (French Alps, area = 224 km2, 12.5% glaciers). They found that an increase in air temperature by 2°C would result in an increase of annual discharge by 200 mm/y from the present level of 1,050 mm/y, primarily caused by increased glacier runoff.

An understanding of the runoff regimes of the glaciers in the context of climate change is important because they contribute significantly to water resources. Changes in glacier melt runoff under warmer climate in some areas will experience increases in water supply and flood risk, while others would experience opposite impact. Effect of climate change in the Himalayan region will be more vulnerable where glacier fed rivers supply water to one third of the world's population. Snow and glacier melt have significant contribution in the Himalayan Rivers (Singh et al., 1995b and Singh and Kumar, 1996) and therefore, it is very likely that changes in climate would change the runoff regime of Himalayan basins. Singh and Kumar (1997) studied the effect of climate change on snow water equivalent, snowmelt runoff, and total streamflow and their distribution on a high altitude Himalayan River. They found that annual snowmelt runoff, glacier melt runoff and total streamflow for the Himalayan basin increased linearly with changes in temperature, but the most prominent effect of increase in temperature was noticed on glacier melt runoff. The effect of change in precipitation suggested a linear increase/decrease in snowmelt runoff and total streamflow, while; in general, glacier melt runoff was inversely related to changes in precipitation. Singh et al (2006) studied the impact of climate change on the monthly distribution of runoff and total summer runoff has been studied with respect to plausible scenarios of temperature and rainfall, both individually and in combined scenarios. The analysis included six temperature scenarios ranging between 0·5 and 3°C, and four rainfall scenarios (-10%, -5%, 5%, 10%). The combined scenarios were generated using temperature and rainfall scenarios. The combined scenarios represented a combination of warmer and drier and a combination of warmer and wetter conditions in the study area. The results indicate that, for the study basin, runoff increased linearly with increase in temperature and rainfall. For a temperature rise of 2°C, the increase in summer streamflow is computed to be about 28%. Changes in rainfall by ±10% resulted in corresponding changes in streamflow by ±3·5%. For the range of climatic scenarios considered, the changes in runoff are more sensitive to changes in temperature, compared with rainfall, which is likely due to the major contribution of melt water in runoff.

Studies for snow and glacier fed river basins or for rain fed basins over Indian sub-continent related to investigation of the effect of climatic change on water resources are limited. The status of studies shows that very few studies related to climate change have been reported for Himalayan region, while this area is one of the most vulnerable area in respect of climate change and their impact on Himalayan water resources. Globally there have been many studies into the effect of climate change on monthly river flow regimes; only a few of these have considered changes in high and low flow extremes. Such studies on basin and regional scale are needed for the Himalayan region.

STUDY AREA

The Chenab River is one of the main five tributaries of the great Indus River system. The

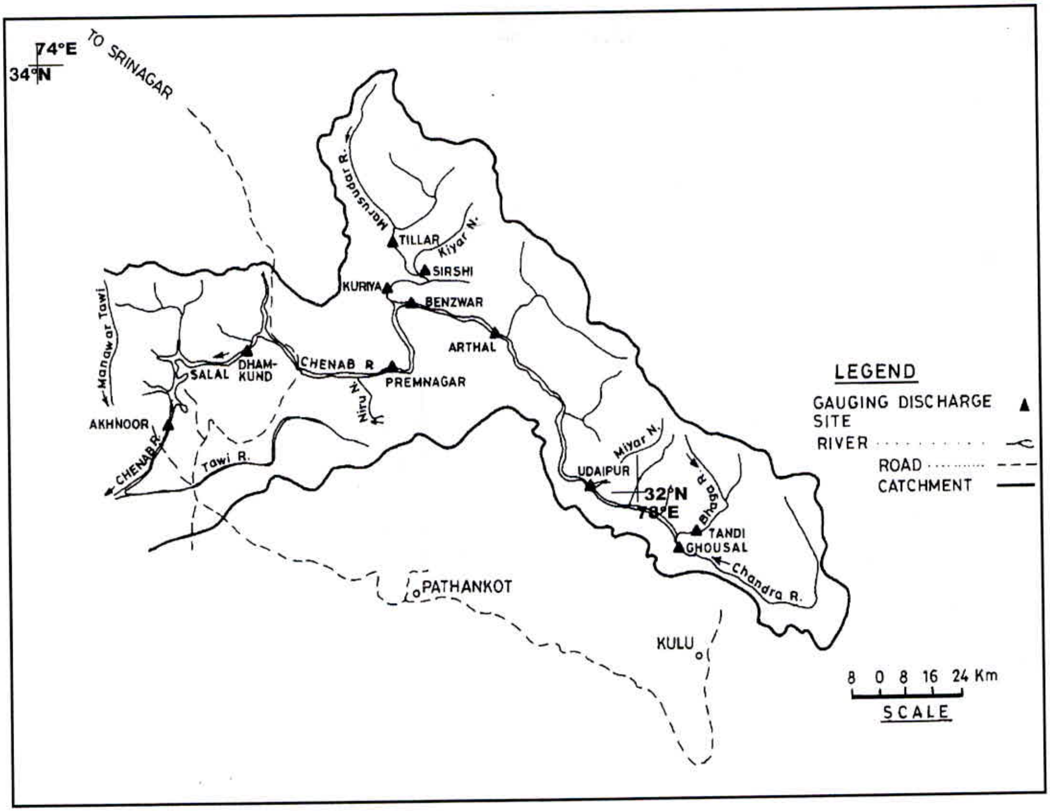

Fig. 1 : Chenab River basin with location of gauging sites.

river Chenab rises in two streams – Chandra and Bhaga. The Chandra starts from a large snow bed on the south-eastern side, while Bhaga rises in the north-western slopes of Baralacha Pass at an elevation of 5639 m above sea level (asl). The major part of the Chenab River basin lies in India, while the lower part including its outfall into main Indus River lies in Pakistan. The total length of the Chenab River up to Akhnoor is about 535 km. In India the Chenab basin is located in western Himalayas between latitudes 32° to 34° N and longitudes 74° to 78° E. The shape of Chenab basin is elongated and its elevation varies from about 305m to 7500m. The mean elevation of the basin is 3600 m asl. The catchment area of the Chenab River up to Akhnoor, the lowermost rain and gauge site in India is 22,400 km^2.

It spreads over two states viz. Himachal Pradesh and Jammu and Kashmir. Upper half of this basin is located between the Zanskar and the Pir-panjal ranges whereas the lower half is located between the Pir-panjal and the Dhauladhar ranges. In this way the basin covers outer, middle and greater Himalayas.

METHODOLOGY

The snowmelt model (SNOWMOD) (Singh and Jain, 2003) was applied to simulate the daily streamflow for Chenab River. Model variables are derived from actual observations of temperature, precipitation and snow covered area. The temperature in a particular elevation zone determines the form of precipitation and the model handles it accordingly. A critical temperature, T_c is specified in the model to determine whether the measured precipitation was rain or snow. In the present study T_c is considered to be 2°C. The algorithm used in the model to determine the form of precipitation is:

if $T_m \geq T_c$, all precipitation is considered as rain

if $T_m \leq 0^\circ C$ all precipitation is considered as snow

Where Tm is mean air temperature. In the cases $T_m \geq 0^\circ C$ and $T_m \leq T_c$ the precipitation is considered as a mixture of rain and snow ans the portion is determined as follows:

$$Rain = (\frac{T_m}{T_c}) \times P$$

$$Snow = P - Rain$$

The basin is divided into a number of elevation zones and various hydrological processes relevant to snowmelt and rainfall runoff are evaluated for each zone. The model deals with snowmelt and rainfall runoff by performing the following three operations at each time step: (i) available meteorological data are extrapolated to the different elevation zones, (ii) rates of snowmelt and/or rainfall are calculated at different points, and (iii) snowmelt runoff from SCA (snow covered area) and rainfall runoff from SFA (snow free area) are integrated, and these components are routed separately with proper accounting for baseflow to the outlet of basin. Computation of different runoff components of streamflow is discussed below.

Computation of runoff from different components

The computation of runoff for its each component was made for each elevation zone separately and then the total runoff from the basin was obtained by arithmetic sum of output from each zone.

Surface runoff from snow covered area

The runoff from snow-covered area consists of: (a) snowmelt caused due to prevailing air temperature, (b) under rainy conditions, snowmelt due to heat transferred to the snow from rain, and (c) runoff from rain itself falling over the SCA. The runoff from snow-covered area is computed as follows:

Snowmelt runoff for each elevation zone of the basin is

$$M_{s,i,j} = C_{s,i,j} D_{i,j} T_{i,j} S_{c,i,j} \quad (1)$$

where M_s is the snowmelt in terms of depth of water (mm day^{-1}); C_s is the runoff coefficient for snowmelt; D is the degree-day factor (mm °C^{-1} day^{-1}); T is temperature (°C); and S_c is the ratio of SCA to the total zone area. Subscripts i and j refer to day and zone, respectively.

(a) Runoff depth due to snowmelt from the heat transferred to snow by the rain falling on the SCA in an elevation zone is given by

$$M_{r,i,j} = 4.2 T_{i,j} P_{i,j} S_{c,i,j} / 325 \quad (2)$$

where M_r is the snowmelt due to rain on snow (mm day^{-1}); and P is rainfall on snow (mm day^{-1}).

(a) Runoff depth from rain itself falling over the snow-covered area, R_s, is given by:

$$R_{s,i,j} = C_{s,i,j} P_{i,j} S_{c,i,j} \quad (3)$$

For the computation of runoff from the rain, the coefficient C_s is used (not the rainfall runoff coefficient, C_r), because the runoff from the rain falling on the SCA behaves like the runoff from the melting of snow.

The daily total discharge from the SCA is computed by adding the contribution from each elevation zone. Thus, discharge from the SCA, Q_{SCA}, for all the zones is given by

$$Q_{SCA} = \alpha\sum_{j=1}^{n}(M_{s,i,j} + M_{r,i,j} + R_{s,i,j})A_{SCA,i,j}$$

where n is the total number of zones; A_{SCA} is the snow-covered area (km^2); and μ is a factor (1000/86400 or 0.0116) used to convert the runoff depth (mm day^{-1}) into discharge (m^3 s^{-1}).

Surface runoff from snow-free area Runoff from the SFA is computed for each zone using the following expression:

$$R_{f,i,j} = C_{r,i,j}P_{i,j}S_{f,i,j} \quad (5)$$

where S_f is ratio of SFA to the total zone area. Because SCA and SFA are complimentary, $S_{f,i,j}$ is directly calculated as 1-$S_{c,i,j}$. The total runoff from SFA, Q_{SFA} for all the zones is thus given by

$$Q_{SFA} = \alpha\sum_{j=1}^{n}R_{f,i,j}A_{SFA,i,j} \quad (6)$$

where A_{SFA} is the snow-free area.

Estimation of subsurface runoff It is assumed that half of the water percolates down to shallow groundwater and contributes to baseflow. The depth of runoff contributing to base flow from each zone is given by

$$R_{b,i,j} = \beta[(1 - C_{r,i,j})R_{f,i,j} + (1 - C_{s,i,j})M_{t,i,j}] \quad (7)$$

where $M_{t,i,j} = M_{s,i,j} + M_{r,i,j} + R_{s,i,j}$ and is 0.50. The baseflow, Q_b, is computed by multiplying the depth of runoff by the conversion factor a and area, and is given as

$$Q_b = \alpha\sum_{j=1}^{n}R_{b,i,j}A_{i,j} \quad (8)$$

Where A is the total area (km^2) and represents the sum of A_{SCA} and A_{SFA}.

Total Streamflow

The daily total streamflow from the basin is calculated by adding the three different routed components of discharge each day

$$Q = Q_{SCA} + Q_{SFA} + Q_b \quad (9)$$

Flow Duration Curve

Mean daily river discharge data can be summarized in the form of a flow duration curve (FDC) which relates flow to the percentage of the time that it is exceeded in the record. A flow duration curve is plotted using Flow on a logarithmic scale as the ordinate and Percentage of Time Discharge Exceeded on a probability scale as the abscissa. The flow duration curve was prepared from the simulated values of the flows and impact of the temperature increase on the behavior of flow duration curve was estimated.

RESULTS AND DISCUSSION

The shape of the flow duration curve characterizes the variability in flows from day-to-day and largely defines catchments low flow properties. The shape of the flow-duration curve is determined by the hydrologic and geologic characteristics of the basin. A curve with a steep slope throughout results from streamflow that varies markedly and is largely fed by direct runoff, whereas a curve with flat slope results from streamflow that is well sustained by surface releases or groundwater discharges. The slope of the lower end of the duration curve, i.e. low flow characteristics, shows the behavior of the perennial storage in the basin; a flat slope at the lower end indicates a large amount of storage and a steep slope indicates a negligible amount.

The above discussed conceptual hydrological model, SNOWMOD was used to simulate the runoff of the Chenab River from 1997 to 2002. The temperature was increased by 2°C. The flow duration curves with different scenarios and baseline scenario are shown in Fig. 2. From

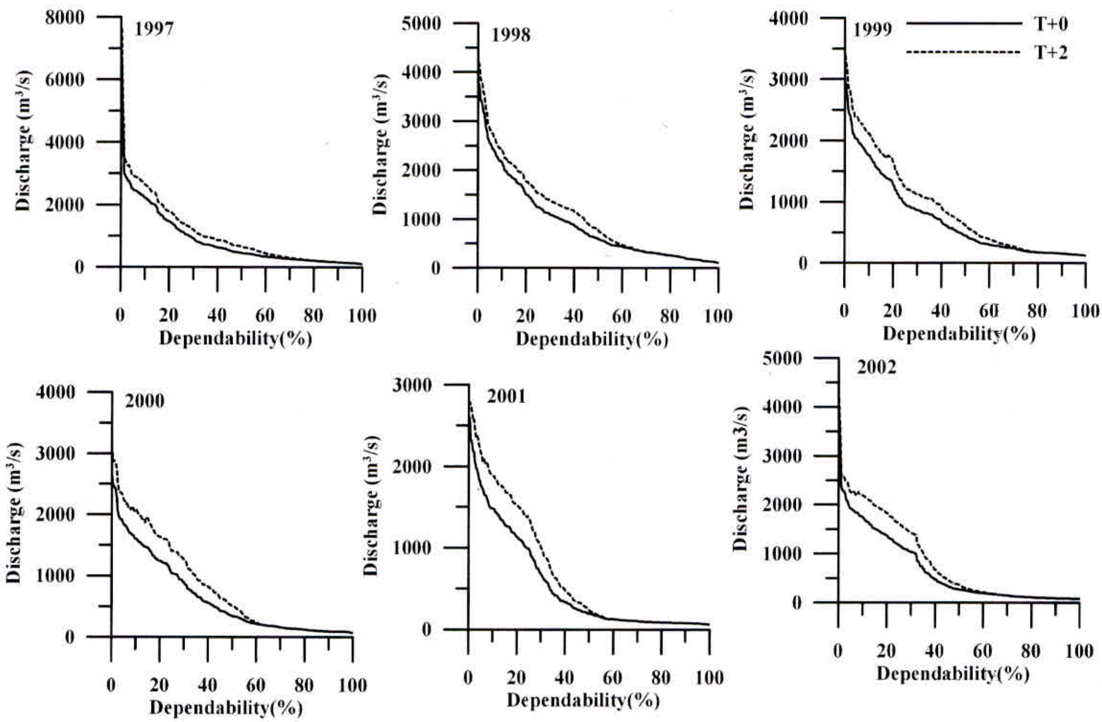

Fig. 2 : Flow duration curve of River Chenab at Salal : baseline and T+2^{0}c scenario

the figure it can be seen that the slope is steep indicating that streamflow has major contribution by direct runoff though there is significant contribution from rainfall and baseflow also. The shape of the flow duration curve suggests that there is not much amount of storage in the basin. As the flow has major contribution from glacier melt runoff there is marked variability in flows because of rise in temperature in comparison to changes in rainfall.

In the case of warming the future flow duration lies above the present curve, indicating that a given magnitude of flow would be exceeded more frequently in the future. For example, the flow exceeded 50% of the time (460 m^3/s in 1996) would be exceeded 60% of the time under a warming of 2°C. The steeper curve under the change scenario indicates greater variability in flow through the year.

CONCLUSIONS

Popular accounts of global warming frequently suggest an increase in he snow and glacier melt in the runoff as a result of the enhanced greenhouse effect. It is important to distinguish between rain generated high flows and those associated with increased snowmelt/glacier melt contributions in runoff. An understanding of changes in melt runoff due to climate change is essential and important because glaciers feed a number of rivers. The present study is carried out to study the impact of warmer climatic scenarios on the flow duration curve of a large Himalayan river. The study basin is dominated by presence of snow and ice. The total catchment area of this basin is about 22,400 km^2. There are about one thousand glaciers of different sizes located in the head waters of the basin. Nearly 70% area of the basin is covered with snow during winters.

The study first involves the simulation of runoff of Chenab river for six year (calibration on the data of 1997 to 1999 and validation on the data of 2000 to 2002) and then to study the effect of climate change on the flow duration curve. The runoff of Chenab river was simulated using a conceptual snowmelt model (SNOWMOD). Different temperature (T+0°C, T+1°C, T+2°C & T+3°C) were incorporated into the model to study the impact on flow duration curves. The steeper slope of flow duration curves indicated that streamflow is fed by direct runoff and there is negligible amount of storage in the basin. Also there is marked variability in flows because of rise in temperature. The flow exceeded 50% of the time (460 m^3/s in 1996) would be exceeded 60% of the time under a warming of 2°C. Such study will be useful for the effective planning and management of the major and medium water resources projects being planned in the Himalayan region.

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