# Effect of Global Warming on the Streamflow of a High-altitude Spiti River

Pratap Singh
National Institute of Hydrology, Roorkee (U.P.), 247 667, India

## Abstract

The possible changes in seasonal and annual streamflow due to expected changes in temperature and precipitation have been studied for a high-altitude Spiti river. The plausible climatic scenarios based on the simulation of climate change over the Indian subcontinent by the Hamburg coupled atmosphere-ocean climate model were adopted in the present study. The UBC Watershed Model was used to simulate hydrological response of the basin under changed climatic scenarios. It is found that annual streamflow varies linearly with an increase in temperature and changes in precipitation. An increase of 2°C in air temperature has increased the annual streamflow of this river in the range of six to 12 per cent. In general, timings of peak runoff are not influenced by changes either in temperature or precipitation for the considered climatic scenario. However, an early response of streamflow is observed under warmer climatic scenarios. An increase in temperature produced maximum increase in streamflow in the pre-monsoon season followed by the monsoon season. No significant effect on the post-monsoon and winter streamflow was noticed due to increase in temperature in the studied range.

## Introduction

The continued accumulation of carbon dioxide ($CO_2$) and other greenhouse gases in the atmosphere is widely expected to result in global warming of the lower atmosphere over the course of the next century. Increased concentration of these greenhouse gases will cause an increase in temperature and changes in precipitation patterns and other climatic variables. The global mean surface air temperature has increased by 0.3 to 0.6°C over the last 100 years (Jones et al. 1990). Further, the average global surface temperature will rise by 0.2 to 0.5°C per decade during the next few decades, if human activities which cause greenhouse gas emissions continue unabated (IPCC 1990). The annual variability of global temperatures is expected to be much larger than the trend. Based on general circulation model (GCM) predictions, IPCC (1990) foresees (i) increased winter and spring warming in the high latitudes (above 50°) by a factor of 1.5-3.0 times the average global surface warming, (ii) summer drying in continental northern mid latitudes, (iii) the least surface temperature increases and their seasonal variations in the tropics. On a global scale, an increase in surface temperature suggests higher evapotranspiration rates and, with the increment in associated precipitable water, increases of global average precipitation are estimated somewhere in the range of three to 15 per cent over current levels. A worldwide estimation of hydrologic cycle fluxes is given by Zektser and Loaiciga (1993).

GCMs, the only available tool for detailed modelling of future climate evolution, are not well suited for providing reliable information on regional-scale hydrological variability under warmer climates. The basic reason for this limitation is their coarse resolution, with grid cells generally over 300x300km$^2$ in size, and simplification of the hydrologic cycle. Consequently, it is not possible to make reliable predictions of regional hydrological changes resulting from greenhouse warming directly from GCMs. A variety of nesting schemes and different sub-grid parameterisation schemes have been devised in an attempt to extract hydrologic information useful on river-basin scales from GCM results (Entekabi and Eagleson 1989, Giorgi and Mearns 1991). The nesting of macro-scale hydrologic models within GCMs introduces several key issues related to spatial scaling, time scaling, parameterisation of hydrological processes, and model calibration/validation etc. A comprehensive review of the current predictive capability of GCMs linked with macro-scale and land-scale hydrologic models that simulate regional and local hydrologic regimes has been provided by Loaiciga et al.(1996).

At present, the most common approach adopted to assess the impact of climatic changes on the hydrological response of a river on a regional or basin scale is the application of conceptual hydrological models combined with plausible hypothetical climate change scenarios (Gleick 1987a, Lettenmaier and Gan 1990, Cooley 1990, Nash and Gleick 1991, Rango 1992, Rango and Martinec 1994, Chiew et al. 1995). The ability of hydrologic models to incorporate projected variations in climatic variables, snowfall, and snowmelt algorithms; groundwater fluctuations; and soil moisture characteristics makes them especially attractive for studying the implications of climate change to water resources. Cayan and Riddle (1993) emphasised that the effect of climate change on the hydrological response of a lower-elevation watershed will be different from the case of a high-elevation watershed because of differences in their runoff distribution and original climatic regime. Further, Chiew et al. (1995) reported that the response of basins located in different regions is not similar under changed climatic scenarios. Hoog (1995) also concluded that changes in the discharge of a river under shifting climatic scenarios depend on the change of temperature and precipitation themselves, and on the characteristics of the catchment. The expected changes in the various hydrological components because of global warming will not be the same for all regions/basins and, therefore, investigations are under way in basins that experience different types of climate and receive contributions to streamflow from various sources such as rain, snow, and glaciers.

**Expected Climate Changes over the Indian Subcontinent and the Scope of the Study**

A warming of the Indian subcontinent by 0.4°C took place over the period 1901-1982 (Hingane et al.1985), and this warming trend since 1900 is broadly consistent with observed global warming over the last century. Thapaliyal and Kulshreshtha (1991) examined the trend of annual rainfall over India and reported that the five-year running mean has fluctuated from normal rainfall within +/- one standard deviation. Based upon the results from high-resolution GCMs, IPCC (1990) reported for the Indian subcontinent that by 2030 in business-as-usual scenarios (i.e., if few or no steps are taken to limit greenhouse gas emissions), the warming varies from 1-2°C throughout the year. Precipitation changes little in winter and generally increases throughout the region by 5-15 per cent in summer. Lal et al. (1992) studied the impact of increasing greenhouse gas concentrations on the climate of the Indian subcontinent and its variability by analysing the GCM output data of the Hamburg global coupled atmosphere-ocean circulation model. The model results obtained from the greenhouse warming experiment suggested an increase of over 2°C over the monsoon region in the next 100 years. The mean annual increase in surface runoff over the Indian subcontinent simulated by this model for the year 2080 is estimated to be about 25 per cent (Lal and Chander 1993). Divya and Mehrotra (1995) have reviewed expected climatic changes over the Indian subcontinent.

As discussed above, global models suggest that climatic changes will have dramatic impacts on water. WMO et al. (1991) suggested that possible effects of climate change on the design and management of water resource systems should be examined. However, identifying the practical implications of global warming on water resources is an elusive task. The vulnerability of the Indian subcontinent to the impact of changing climate is expected to be great because such as impact would largely be on the water resources and agricultural economy. The major river systems of the Indian subcontinent, namely the Brahamaputra, Ganga, and Indus, which originate in the Himalayas, are expected to be more vulnerable to the climate change, given the substantial contribution from snow and glacier melt runoff into these river systems. Very little work has been carried out in India on the impact of climate change on hydrology. A further review of the impact of climatic changes on various hydrological concerns indicates that hardly any studies have been made on possible changes in the hydrological response of Himalayan rivers.

## Study Basin, Adopted Climatic Scenarios and Model Used for the Simulations

The Spiti River is a high-altitude river and encompasses a large catchment area, about 10,000sq.km. It originates in the greater Himalayan range of the western Himalayas, forming a major tributary of the Satlej River. The basin covers an elevation range from 2,900 to over 7,000m, with very little above 6,000m. Permanent snow fields and glaciers exist at higher altitudes in the basin. Most of the winter precipitation falls as snow in this basin. Monsoon rains have little influence in the greater Himalayan range where this basin is located, compared with outer and middle Himalayan ranges (Singh et al. 1995a). Maximum snowmelt runoff occurs in June/July. Glaciers are exposed after the melting of the seasonal snow cover. The importance of the snow and glacier melt runoff in Himalayan rivers has been discussed by Singh et al. (1995b), and Singh and Kumar (1996).

The coupled ocean-atmosphere climate model (European Community Hamburg model [ECHAM] + Large-scale Geostrophic ocean model [LSG]) has demonstrated good simulation of the characteristic features of the Asian summer monsoon as well as the broad circulation features over the Indian subcontinent (Lal et al. 1992). In the present study, scenarios were adopted with a limit to changes in the approximate range provided by Lal et al. (1992). However, the lesser variations are likely to occur when a period less than 100 years is considered. Analysis was made using a range of variation in temperature and precipitation, thus providing results for a lower order of changes also. The effect of temperature on the hydrological response of the basin has been studied independently and in combination with precipitation. The changes in temperature were applied as absolute amounts, whereas changes in precipitation were considered in terms of per cent differences. The adopted changes in temperature and precipitation covered a range from 1 to 3°C and -10 to +10 per cent respectively. Both temperature and precipitation data were uniformly varied by the projected amount of change over the simulation period.

The University of British Columbia (UBC) Watershed Model was used to simulate the streamflow runoff of the study basin under current and changed climatic scenarios. The daily temperature and precipitation data of Kaza (3,639m) were used to simulate the streamflow. The model has the capability of increasing and decreasing accumulations of snow in the basin using the sparse meteorological data available from mountainous areas. This model is used operationally for long-term and short-term forecasting in the Columbia, Peace, and Fraser river systems in Canada and has been used for streamflow simulations of several Himalayan rivers (Quick and Singh 1992, Singh and Quick 1993). Before climatic influence computations were carried out on the streamflow, the simulations were made on a daily basis, and the coefficient of efficiency, $r^2$ (Nash and Sutcliffe 1970), between observed and calculated runoff was computed to be 0.90, 0.76 and 0.91 for 1987/88, 1988/89, 1989/90 respectively. To assess the impact of changed climatic scenarios, inputs to the model were modified accordingly, and it was run continuously for a period of three years.

**Simulation of Impact of Climate Change on the Streamflow**

The effect of an increase in temperature on annual total streamflow for three years is shown in Figure 1. It is observed that annual streamflow increases linearly with increase in temperature. For a temperature increase of 2°C, the variation in annual streamflow is computed to be 12, 6, and 10 per cent respectively for 1987/88, 1988/89, 1989/90. Table 1 shows the results for all seasons and annual streamflow for all the considered scenarios. An in-

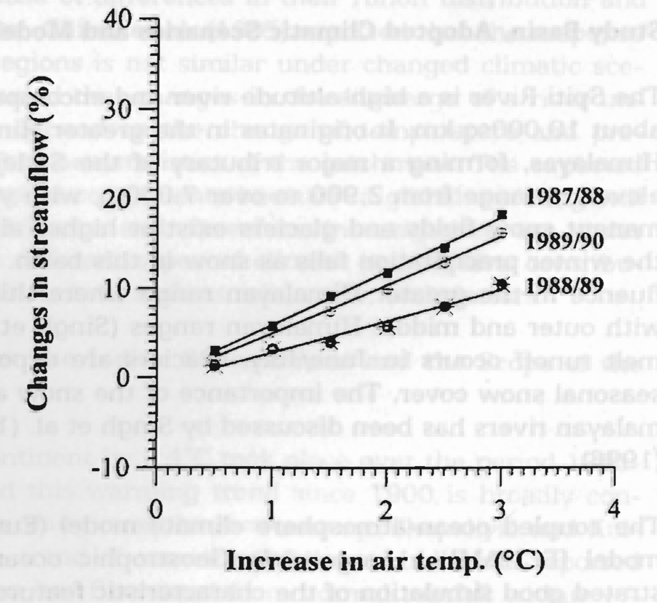


**Figure 1: Effect of Increase in Temperature on Annual Streamflow**

crease in the annual runoff of this basin is possible due to an increase in the contribution of snowmelt and glacier melt runoff to total runoff under warmer climate scenarios. It should be mentioned that the present study basin is a high-altitude basin and has snow storage characteristics. Snow storage characteristics are not found in lower-altitude basins, which reach an equilibrium state (in terms of snow storage) after the melting period every year. In high-altitude basins, by contrast, snow that has occurred in a particular year does not significantly melt during the melting period, and this remaining snow influences the melt runoff of the next year. Glaciers are found in high-altitude basins because of these snow storage characteristics. This peculiar characteristic plays an important role in augmenting the streamflow with an increase in temperature.

Table 1: Changes in Seasonal and Annual Streamflow under Warmer Climatic Scenarios (RS indicates reference scenario)

| year | scenario | Oct.-Dec. change in streamflow (%) | Jan.-Mar. change in streamflow (%) | Apr.-Jun. change in streamflow (%) | Jul.-Sep. change in streamflow (%) | Annual change in streamflow (%) |
|---|---|---|---|---|---|---|
| 1987/88 | T+0°C RS | - | - | - | - | - |
| | T+1°C | 0.6 | 0.03 | 8.8 | 5.1 | 5.8 |
| | T+2°C | 1.3 | 0.06 | 18.3 | 9.9 | 11.7 |
| | T+3°C | 2.0 | 0.09 | 26.4 | 17.1 | 18.2 |
| 1988/89 | T+0°C RS | | - | - | | - |
| | T+1°C | 1.2 | 0.6 | 5.8 | 2.0 | 3.2 |
| | T+2°C | 2.4 | 0.5 | 8.2 | 5.0 | 5.7 |
| | T+3°C | 3.9 | 0.7 | 13.3 | 10.6 | 10.4 |
| 1989/90 | T+0°C RS | - | - | - | - | - |
| | T+1°C | -0.9 | -2.1 | 8.5 | 4.5 | 5.1 |
| | T+2°C | -3.6 | -6.2 | 15.6 | 10.5 | 9.9 |
| | T+3°C | -2.8 | -6.8 | 23.9 | 17.2 | 16.1 |

The maximum increase in seasonal streamflow runoff due to an increase in temperature has been computed to be in the pre-monsoon season, followed by the monsoon season. The streamflow in the pre-monsoon season has a relatively higher contribution from snowmelt runoff than other seasons. Under a warmer climate, snowmelt runoff is increased significantly, and this increase is reflected in maximum changes in pre-monsoon season streamflow. In terms of the consequences of increased runoff in the pre-monsoon season, it can be pointed out that such an increase in the pre-monsoon like this may benefit the country in meeting the higher demands of hydropower and agriculture in this season. Further, higher variation in the streamflow during the monsoon season may occur because of snowmelt runoff with glacier melt runoff from the high snowfields not to mention the contribution of rain in this season. Post-monsoon and winter flows are not affected significantly. However, some studies indicate an increase in winter discharge due to a warmer environment caused by an increase in temperature (Gleick 1987b, Bultot et al. 1988, Cooley 1990). In fact, the possible reasons for increased winter streamflow are: (i) part of the precipitation may fall as rain and responds as streamflow immediately, (ii) some snowpack may melt under warmer climatic conditions. A very low temperature regime in the basin and a projected increase in temperature do not allow either of these two possibilities to increase the winter runoff and, consequently, no significant changes are observed in the winter discharge due to increased air temperatures.

The influence of a 2°C increase in temperature on daily streamflow distribution is illustrated in Figure 2. It is seen that, in general, the timings of peak streamflow are not affected. However, there is a change in the magnitude of peak streamflow depending upon spring melting conditions. An early response of streamflow under a warmer riverine climate is observed because of the early contribution of snowmelt runoff following upon an increase in temperature.

Figure 3 shows that annual streamflow changes linearly with changes in precipitation. The effect of changes in precipitation on the distribution of daily streamflow for a T+2°C scenario is shown in Figure 4. Higher amounts of precipitation produce higher streamflow, while maintaining the same timings of peak streamflow. Details of all combined scenarios are given in Table 2. Similar results were obtained by Ng and Marsalek (1992). As expected, a higher temperature and higher precipitation scenario will result in a maximum increase of annual streamflow, the maximum increase (16-24%) in annual total streamflow runoff is produced under a T+3°C, P+10 per cent scenario.

Table 2: Simulated Changes in Streamflow due to Changes in Precipitation over Various Temperature Scenarios (RS indicates reference scenario)

| year | scenario | change in streamflow (%) |
|---|---|---|
| 1987/88 | T+1°C, P+0% RS | - |
| | T+1°C, P-10% | -5.4 |
| | T+1°C, P-5% | -2.8 |
| | T+1°C, P+5% | 2.8 |
| | T+1°C, P+10% | 5.7 |
| | T+2°C, P+0% RS | - |
| | T+2°C, P-10% | -5.2 |
| | T+2°C, P-5% | -2.6 |
| | T+2°C, P+5% | 2.6 |
| | T+2°C, P+10% | 5.4 |
| | T+3°C, P+0% RS | - |
| | T+3°C, P-10% | -4.9 |
| | T+3°C, P-5% | -2.5 |
| | T+3°C, P+5% | 2.5 |
| | T+3°C, P+10% | 5.1 |
| 1988/89 | T+1°C, P+0% RS | - |
| | T+1°C, P-10% | -6.7 |
| | T+1°C, P-5% | -3.1 |
| | T+1°C, P+5% | 2.8 |
| | T+1°C, P+10% | 5.8 |
| | T+2°C, P+0% RS | - |
| | T+2°C, P-10% | -5.5 |
| | T+2°C, P-5% | -2.8 |
| | T+2°C, P+5% | 2.7 |
| | T+2°C, P+10% | 5.5 |
| | T+3°C, P+0% RS | - |
| | T+3°C, P-10% | -5.0 |
| | T+3°C, P-5% | -2.5 |
| | T+3°C, P+5% | 2.4 |
| | T+3°C,P+10% | 4.9 |
| 1989/90 | T+1°C, P+0% RS | - |
| | T+1°C, P-10% | -6.4 |
| | T+1°C, P-5% | -3.6 |
| | T+1°C, P+5% | 5.3 |
| | T+1°C, P+10% | 8.5 |
| | T+2°C, P+0% RS | - |
| | T+2°C, P-10% | -5.9 |
| | T+2°C, P-5% | -3.4 |
| | T+2°C, P+5% | 4.9 |
| | T+2°C, P+10% | 7.9 |
| | T+3°C, P+0% RS | - |
| | T+3°C, P-10% | -9.4 |
| | T+3°C, P-5% | -4.8 |
| | T+3°C, P+5% | 4.6 |
| | T+3°C, P+10% | 7.1 |

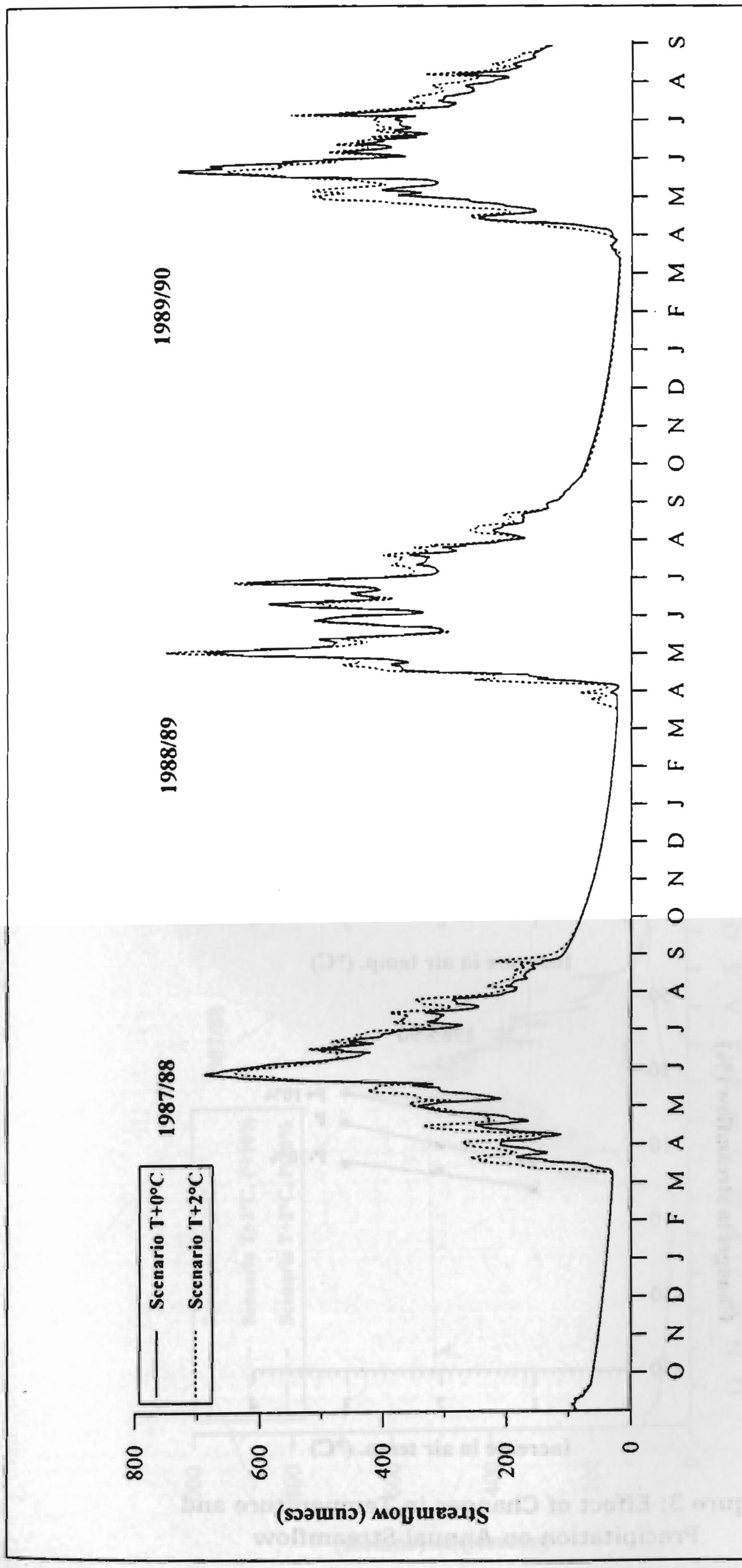


Figure 2: Effect of Changes in Air Temperature by 2°C on Daily Streamflow Distribution

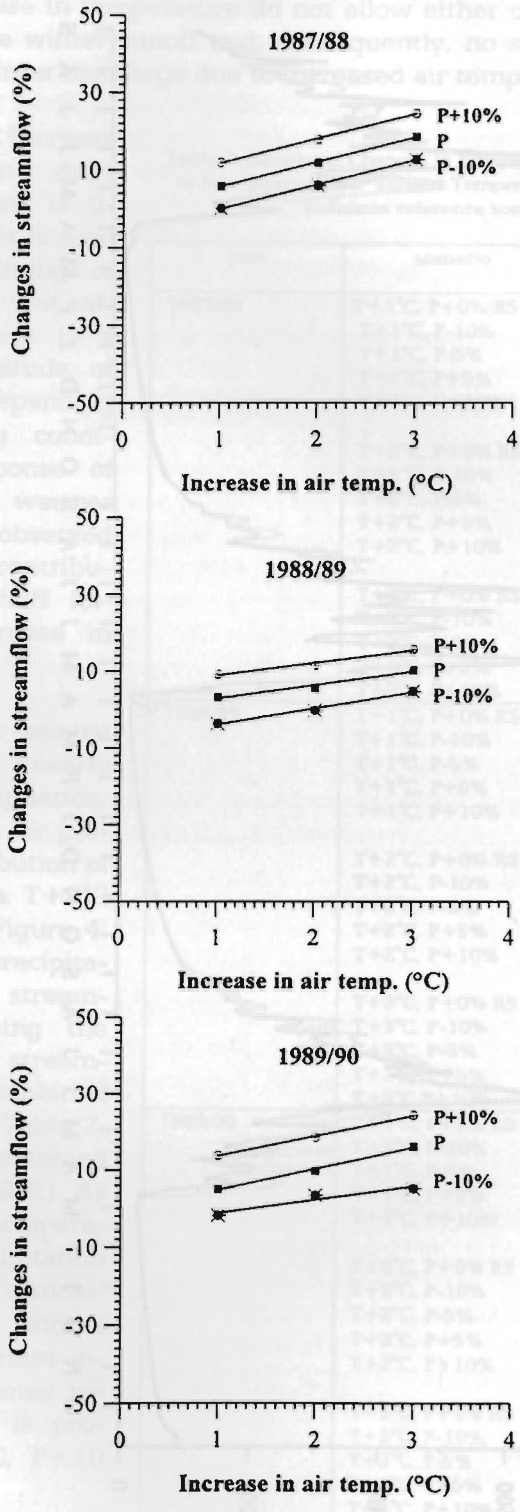


Figure 3: Effect of Changes in Temperature and Precipitation on Annual Streamflow

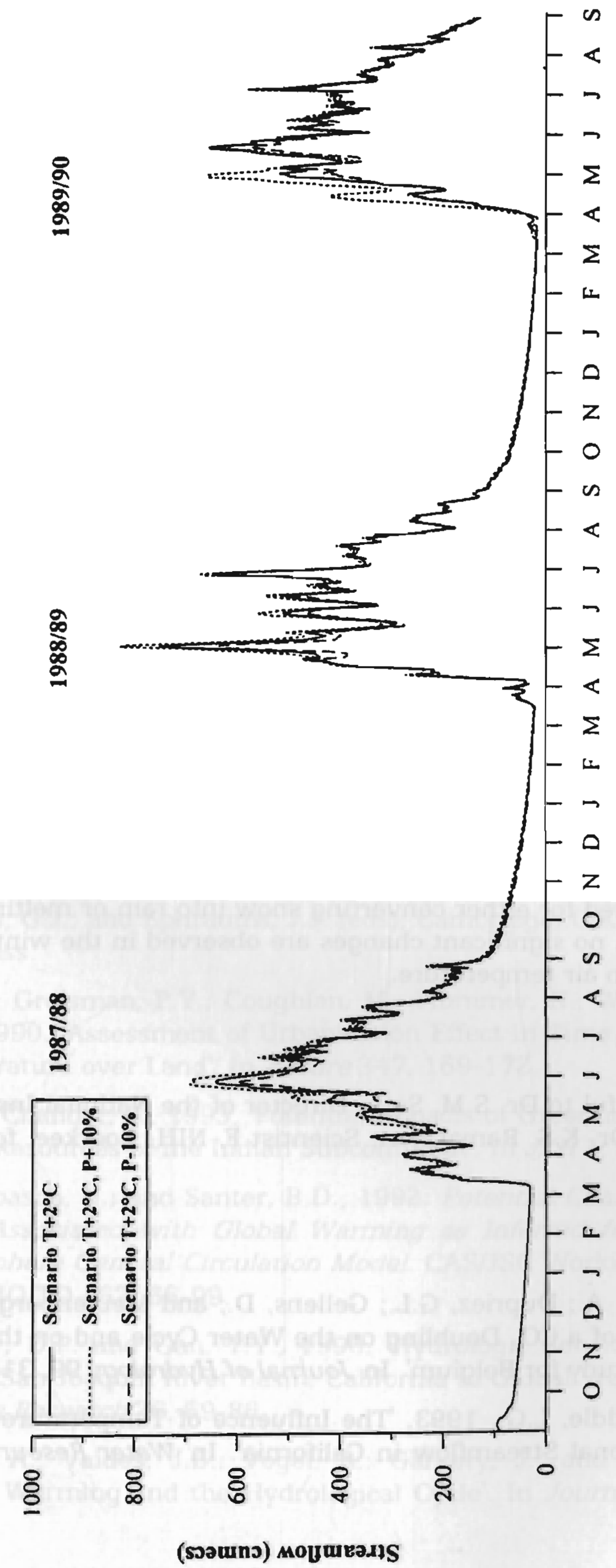


Figure 4: Effect of Changes in Precipitation on Daily Streamflow Distribution over a T+2°C Scenario

## Conclusions

This paper describes the possible consequences of various climate scenarios on the seasonal and annual streamflow of the high-altitude Spiti River in the Himalayas. The adopted climatic scenarios for this study were constructed on the basis of simulations of the Hamburg coupled atmosphere-ocean climate model for the study region. The UBC watershed model was used to study the changes in runoff. The following conclusions are drawn from this study.

Annual streamflow increases linearly with an increase in temperature (1-3°C) and precipitation (-10 to 10%). An increase of 2°C in air temperature has increased the annual streamflow of this river in the range of 6-12 per cent. A higher contribution from snow and glacier runoff to annual streamflow under a warmer climate leads to an increased annual streamflow. In general, the timings of peak streamflow are not affected, however, an early response of snowmelt runoff under a warmer climate resulted in early streamflow in the river. Maximum increases in annual streamflow (16-24%) were observed under a T+3°C, P+10 per cent scenario.

The seasonal analysis of total streamflow indicates that an increase in temperature produced a maximum increase in the pre-monsoon streamflow, followed by the monsoon season. For example, for a T+2°C scenario, streamflow increased in the range of 8-18 and 5-10 per cent for the pre-monsoon and monsoon seasons, respectively. Possibly a higher snowmelt runoff under a warmer climate is the reason for the significant increase in the pre-monsoon season. Post-monsoon and winter streamflows are not affected significantly by an increase in temperature. The projected increase in temperature during winter, when the study basin experiences very cold temperatures (far below 0°C), is not sufficient to bring on the temperatures required for either converting snow into rain or melting the snowpack. Consequently, no significant changes are observed in the winter discharge due to an increase in air temperature.

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