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# Sensitivity Analysis of Melt Runoff Due to Temperature and Precipitation

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# SENSITIVITY ANALYSIS OF MELT RUNOFF DUE TO TEMPERATURE AND PRECIPITATION

## Contents

Page

REFERENCES

## List of Figures

## List of Tables

# SENSITIVITY ANALYSIS OF MELT RUNOFF DUE TO TEMPERATURE AND PRECIPITATION

## Abstract

The effect of climate change on snow water equivalent, snowmelt runoff, glacier melt runoff and total streamflow and their distribution is examined for the Spiti river. It is a high altitude Himalayan river located in the western Himalayan region and total streamflow of this river has a significant contribution from snow and glacier melt runoff. Plausible hypothetical scenarios of the temperature and precipitation changes based on the simulation of climate change over Indian sub-continent by Hamburg climate model are adopted in the present study. The UBC Watershed Model was used to simulate the hydrological response of the basin under changed climatic scenarios. The adopted changes in temperature and precipitation covered a range from 1 to 3°C and -10 to +10 %, respectively.

Snow water equivalent reduces with an increase in air temperature. However, no significant change is found in the snow water equivalent of the Spiti basin by the projected increase in air temperature (T+1 to T+3°C). An increase of 2°C in air temperature reduced annual snow water equivalent in the range of 1 to 7%. Changes in precipitation caused proportional changes in snow water equivalent. It is found that annual snowmelt runoff, glacier melt runoff and total streamflow increase linearly with changes in temperature (1-3°C), but most prominent effect of increase in temperature has been noticed on glacier melt runoff for this high altitude basin. For example, an increase of 2°C in air temperature has enhanced annual snowmelt runoff, glacier melt runoff, and total streamflow in the range of 4-18%, 33-38% and 6-12%, respectively. The effect of change in precipitation (P-10 to P+10%) suggests a linear increase in snowmelt runoff and total streamflow, while in general, glacier melt runoff in inversely related to changes in precipitation. Snowmelt runoff is found more sensitive than glacier melt runoff to changes in precipitation (P-10 to P+10%). Under a warmer climate scenario, snowmelt runoff and glacier melt runoff cause an earlier response of total streamflow and change in flow distribution. The seasonal analysis of total streamflow indicates that an increase in air temperature produces an increase in the pre-monsoon season (April-June) followed by an increase in the monsoon season (July-September). Implications of such seasonal changes are also discussed in brief.

## 1.0 INTRODUCTION

The atmospheric concentration of $CO_2$ and other trace gases has increased substantially over the last century and double concentration of $CO_2$ is expected by the middle or latter part of next century, if no control measures are adopted (NAS, 1979; Pearman, 1980). This steady increase in the concentration of greenhouse gases has resulted in global warming. The global mean surface air temperature has increased by 0.3 to 0.6 °C over last 100 years (Jones et al., 1990). Further, average global surface temperature will rise by 0.2 to 0.5 °C per decade during next few decades, if human activities which cause greenhouse gas emissions continue unabated (IPCC, 1990). The striking feature, however, is that inter-annual variability of global temperature is much larger than the trend. Under the double $CO_2$ concentration scenario, precipitation may increase or decrease by as much as 15% (IPCC, 1990).

Several studies of climate variability on both short and long time scales have been carried out to establish climate changes over India (Jagannathan and Parthasarathy, 1972; Hingane et al., 1985; Sarker and Thapliyal, 1988; Thapliyal and Kulshrestha, 1991). It is observed that a warming of the Indian sub-continent by 0.4°C has taken place over the period 1901-1982 (Hingane et al., 1985). This warming 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 general circulation models (GCMs), the IPCC (1990) reports for the Indian sub-continent state that by 2030 on 'Business-as-Usual' scenarios (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% in summer. Lal et al. (1992) studied the impact of increasing greenhouse gas concentrations on the climate of Indian sub-continent 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 the model for the year 2080 is estimated to be about 25% (Lal and Chander, 1993).

The warming of the earth-atmosphere system is likely to change temperature and precipitation which may affect the quantity and quality of the freshwater resources. One of the most important impacts to society of future climatic changes is expected on the regional water availability, specifically the timing of magnitude and surface runoff and soil moisture fluctuations (Gleick, 1986; WMO, 1987). Existing global models suggest that climatic changes will have dramatic impacts on water resources leading to major alterations of regional water systems. For example, a study based on GCM indicated that streamflow from the rivers in western US will be reduced by 40 to 75% (NRC,1983). Rind and Ledederff (1984) used a GCM to assess the effect of doubling $CO_2$ on hydrological variables and concluded that precipitation would increase by about 11% and evaporation would increase proportionally, while snowpack would decrease by 20% due to higher temperatures. Because quantitative estimates of the effects of climate change on the hydrology of different regions are essential for understanding, planning and management of future water resources systems, therefore, the problems of global warming and its impact on water resources has received considerable attention in the recent years. There have been several co-ordinated efforts by World Meteorological Organisation (WMO), Inter-governmental Panel of Climate Change (IPCC), United Nations Environmental Programme (UNEP), and International Council of Scientific Union (ICSU) to bring together experts involved in projects concerned with climate variability and change, their impact on hydrology and water resources, and to identify the problems in this area. Further, WMO et al. (1991) suggested that possible effects of climate change in the design and management of water resources systems should also be examined.

The vulnerability of the Indian sub-continent to the impact of changing climate is of vital importance because major impact of climate change in this continent would be on the hydrology, affecting water resources and agricultural economy. However, very little work has been carried out in India on the impact of climate change on hydrology (Divya and Mehrotra, 1995). The major river systems of the Indian sub-continent namely Brahamaputra, Ganga and Indus which originate in the Himalayas are expected to be more vulnerable to climate change because of substantial contribution from snow and glaciers into these river systems. A review of the possible impact of climatic changes on the various aspects of hydrological cycle has shown that little emphasis has been placed to the study of the hydrological response of any Himalayan river. In the present study, attempts are made to investigate the effect of climate change on the snow water equivalent, snowmelt runoff, glacier melt runoff, total streamflow and their distribution for a high altitude Himalayan river (Spiti) which forms a part of Indus river system.

## 2.0. BASIN CHARACTERISTICS AND HYDROLOGICAL RESPONSE

Hydrological response of a catchment depends on the sources of runoff, climatic conditions and physical characteristics of the catchment. For example, streamflow distribution of a basin experiencing only rainfall will be different from a basin having contribution from rainfall, snowfall and glaciers. Further, for the basins in which temperature and precipitation characteristics are such that snowfall occurring during the preceding winter is completely melted away during next spring and summer months, will produce a different response to runoff distribution as compared to the basins where total accumulated snow is not melted and high snow fields and glaciers are formed (like the present study basin), which produce a different type of streamflow pattern. In such a complex basin melting of snow first starts and glacier melt takes over when snowmelt contribution diminishes. Cayan and Riddle (1993) also emphasized that effect of climate change on the hydrological response of the lower-elevation watershed will be different than the high-elevation watershed because of difference in their runoff distribution and original climatic regime. Recently, Chiew et al. (1995) reported that response of basins located in different region are not similar under changed climatic scenarios. Several authors have evaluated the influence of climatic changes on the basins which have input from different sources and consequently, impact of climatic changes is also different for such basins. Some studies have been carried out for snowbound basins also, but again the present study basin has glaciers and located in high altitude Himalayan region. The characteristic of the basin has allowed various aspects of the hydrological response to be studied, but at the same time this may limit comparison of the results with other basins. However, wherever possible the results have been compared with the reported studies.

## 3.0 CLIMATE CHANGE SCENARIOS

Recent advances in the ability of the global coupled atmosphere-ocean GCMs to replicate the observed atmospheric behaviour on a wide range of space and time scales are quite encouraging. The models treating the coupled ocean-atmosphere system in an interactive mode are able to provide projections of the possible perturbations in the key climatic elements in the time scales of up to 100 years for future greenhouse gas emission scenarios (Cubash et al., 1992). IPCC(1990, 1992) and several investigators (McCabe and Ayers, 1989; Nemec, 1989) recommend to construct hypothetical scenarios to study characteristics of runoff responses to climate change for particular areas. Most of the regional scale climate impact investigations related to global warming have relied on GCMs output in order to adopt scenarios for future climatic change.

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 sub-continent (Lal et al., 1992). Recently, for estimating changes in annual surface runoff over the Indian sub-continent, the output of the ECHAM3 (horizontal resolution ~ 300km x 300 km) was used by Lal and Chander (1993). Further, possible changes in the key climatological variables for a 100 year period over north-west margins of the Indian sub-continent have been examined using this model with the objective of assessing the potential climate change over the Thar desert, of which a large part lies in north-west India (Lal and Bhaskaran, 1993). Simulated changes in temperature and precipitation by the Hamburg climate model over the Indian subcontinent under "Business-as-Usual" scenario over a long time period (~ 100 years in future) are shown in Figure 1(a) and 1(b). In the present study, scenarios were adopted with a limit to changes in the approximate range provided in these Figures. 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.

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 as percent difference. Since much greater uncertainty surrounds the estimates of changes in regional precipitation, both increases and decreases in average annual precipitation are modelled in this study. The adopted changes in temperature and precipitation covered a range from 1 to 3°C and -10 to +10 %, respectively. The values chosen for hypothetical scenarios typically reflect good estimates of changes in important climatic variables (Lal et al., 1992). Both temperature and precipitation data were uniformly varied by the projected amount of changes over the simulation period. In reality changes in temperature and precipitation are likely to

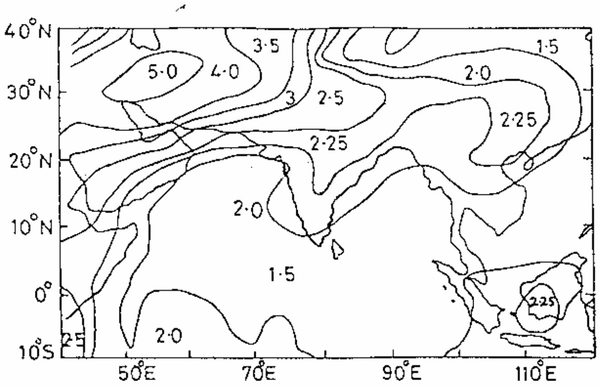

Figure 1(a) : Spatial distribution of changes in annual temperature (°C) for Indian sub-continent as simulated by Hamburg coupled climate model under 'Business-as-Usual' scenario (Lal et al., 1992).

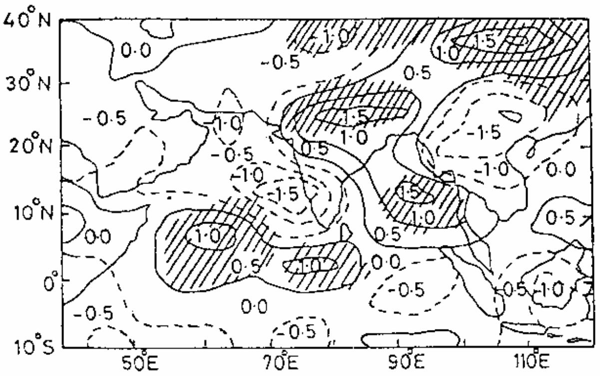

Figure 1(b): Spatial distribution of changes in annual rainfall (mm/day) for Indian sub-continent as simulated by Hamburg coupled climate model under 'Business-as Usual' scenario. The hatched area represents the significant changes at 90% level (Lal et al., 1992).

vary throughout the year and such changes may also alter seasonal temperature patterns, and consequently the distribution and frequency of precipitation events. These aspects are not considered in this study simply because of non availability of reliable information on distribution of these changes.

## 4.0 APPLICATIONS OF HYDROLOGICAL MODELS TO STUDY HYDROLOGICAL RESPONSE OF A BASIN UNDER CHANGED CLIMATIC SCENARIOS

The studies carried out to demonstrate impacts of climate changes on various components of hydrologic cycle may be classified broadly into two categories; (i) studies using GCMs to predict impact of climate change scenarios (U.S. Department of Energy, 1980; Gleick, 1987a; Cohen 1986;, IPCC, 1990, Sausen et al., 1994, MacCabe, 1994, Loaiciga et al., 1996) and, (ii) studies using hydrological models with assumed hypothetical climatic inputs (Nemec and Schaake, 1982; Nemec, 1989; McCabe and Ayers, 1989; Sanderson and Smith, 1990; Thomsen, 1990; Rango, 1992, Cayan and Riddle, 1993; Burn, 1994; Rango and Martinec, 1994, Chiew et., 1995). While the GCMs are invaluable tools for identifying climatic sensitivities and changes in global climate characteristics, but their grid system is generally too large to assess the impact on major hydrological parameters, especially, on the regional scales. A single grid may encompass hundreds of square kilometers, including mountainous and desert terrain, oceans and land areas. Despite recent improvements in modelling of the climate dynamics with complex and large scale models, we are still seriously limited in evaluating regional details of climatic changes or details of the effects of such changes on hydrologic processes and water availability. Loaiciga et al. (1996) have presented a detailed review on the interaction of GCMs and hydrological cycle. Until current GCMs improve both their spatial resolution and their hydrologic parameterization, information on hydrologic effects of global climatic changes can best be studied using regional hydrological models only.

The advantages of using hydrological models for assessing the impacts of climatic change have been discussed by several investigators. Such models are considered suitable for assessing the regional hydrologic consequences due to changes in temperature and precipitation and other climatic variables. The ability of hydrologic models to incorporate projected variations in climatic variables, snowfall and snowmelt algorithms, ground water fluctuations and soil moisture characteristics makes them especially attractive for water resources studies of climatic changes. Moreover, such models can be combined with plausible hypothetical climate change scenarios to generate information on water resources implications of future climatic changes (Gleick, 1986). Various hydrologic models have been used to study the impacts of climate change scenarios, depending on the purpose of study and model availability. Gleick (1987a) used a water balance model to estimate the impact of climate on monthly water availability. Detailed studies using a deterministic model in mountain basins (National Weather Service River Forecasting System (NWSRFS) Model) are carried out (Lettenmaier and Gan, 1990; Cooley, 1990; Nash and Gleick 1991; and Panagoulia 1991). Rango (1992) used snow melt runoff model (SRM) for Rio Grande and Kings river basins to study the changes in snowmelt runoff under warmer climate scenarios. Recently Rango and Martinec (1994) examined the influence of changes in temperature and precipitation on the snow cover using SRM and their results are discussed below.

It is worth mentioning, for water resources systems dominated by snow and glacier melt runoff, vulnerability to changes in global climatic conditions can be understood better using the conceptual hydrological models which have algorithms to develop and deplete snowpack using meteorological data. This is especially true with respect to changes in snowfall and snowmelt, because climate changes will also affect the magnitude and distribution of the snowfall occurring during the preceding winters. The models with only snowmelt runoff simulation approach, but without the ability to accumulate the snowpack, may not be suitable to assess the effect on both snow water equivalent and snowmelt runoff. For example, Yeh et al. (1983) found that suddenly removing the snow cover on 15 March would bring about a significant reduction of zonal mean soil moisture for the following spring and summer seasons. They did not, however, model the effects of changes in climate on the development of the snowpack. Similarly, Rango (1989, 1992) modelled the changes in snowmelt runoff caused by temperature increase during the snowmelt period without considering the effect of climate change on snow water equivalent over the basin. Their results indicated that the warmer temperature produced an earlier hydrograph peak, but essentially the same seasonal volume since they started with the same snowpack. Rango and Martinec (1994) reported that changed temperatures of +2°C and +4°C both had a much more important effect on snow cover than doubling the precipitation occurring during the snowmelt period. Cayan and Riddle (1993) examined the influence of climate parameters on seasonal streamflow in watersheds over a range of elevations and found that temperature sensitivity of seasonal streamflow is greater in Spring and early summer. It was reported that temperature effect upon runoff in early summer is partially counteracted by the opposite effect in earlier spring, but perhaps not totally.

In this study, University of British Columbia (UBC) Watershed Model has been used to assess the impact of global warming by modelling hydrological processes including soil moisture, snowmelt, glacier melt, rainfall runoff, ground water, evaporation etc. This model was developed by Quick and Pipes (1977). The UBC Watershed Model is designed primarily for mountainous watersheds where sparse network exits. It uses daily maximum and minimum temperatures and precipitation as inputs. The basic structure of the model depends on a division of the watershed into a number of elevation bands. The model has ability to continuously monitor the hydrologic state of the catchment over extended periods of time. One of the important features of the model is developing and depleting the snowpack in the basin using meteorological data. The availability of algorithms in the model for computing contribution from snowmelt runoff and glacier melt runoff enabled us to study the influence of climatic changes on various components of the streamflow and snow water equivalent. The response of watershed model to snowmelt and rainfall is controlled by a soil moisture model. The soil moisture status of each area-elevation band controls the subdivision of the total snowmelt and rain input into the various components of watershed runoff response. The total snowmelt and rain input to each watershed band is subdivided on a priority basis. This model is used operationally for long-term and short-term forecasting in the Columbia, Peace and Fraser river systems in Canada and used for streamflow simulations of Himalayan rivers (Quick and Singh, 1992; Singh and Quick, 1993). It is not possible to discuss the model in detail here. Detailed information on this model is given by Quick and Pipes (1977).

## 5.0 PHYSICAL AND HYDROLOGICAL CHARACTERISTICS OF THE SPITI BASIN AND SIMULATION OF STREAMFLOW

The Spiti river is a major tributary of the Satluj river which forms an important part of the Indus river system. This basin has an area of 10071 km$^2$ with an elevation range from 2900 to over 7000m. However, only a small part of the basin lies above 6000m. This basin lies in the greater Himalayan range. Permanent snow fields and glaciers exist at higher altitudes in the basin. About 2.5% of this basin is covered by glaciers (Quick and Singh, 1992). The water from this river is used mainly for irrigation and hydropower generation. The location of the study basin is shown in Figure 2(a).

The weather systems coming from the west usually known as western disturbances deposit nearly all the precipitation during the winter months (October -March) and most of the precipitation falls in the form of snow in this season. The monsoon rains have only limited influence in the greater Himalayan range in which this basin is located, as compared with outer and middle Himalayan ranges (Singh et al., 1995a). The time and magnitude of snow and glacier melt runoff depends on the snowpack water equivalent accumulated in the preceding winter season and the climatic conditions prevailing in the spring- summer season over the basin. In general, maximum snow cover area exists in March when most of the snowfall had occurred and melting has not started. As the summer season advances, depletion of the snow cover takes place and temperatures follow an increasing trend. Maximum snow melt runoff is generally observed in the months of June/July. Glaciers are exposed after melting of the seasonal snow cover over them and, generally, melting of glaciers starts in late June/July, depending on the amount of seasonal snow, and the melting extends until September. Importance of the snow and glacier melt runoff in Himalayan rivers has been discussed by Singh et al. (1995a), and Singh and Kumar (1996).

Daily temperature and precipitation data of Kaza (3639m) were used to simulate the streamflow observed at the outlet of the basin. The observed mean daily temperatures at Kaza are shown Figure 2(b). The streamflow simulation was made for three years (1987-1990) starting with winter of 1987-88. The simulation was made on a daily basis and 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 the years 1987/88, 1988/89, 1989/90, respectively.

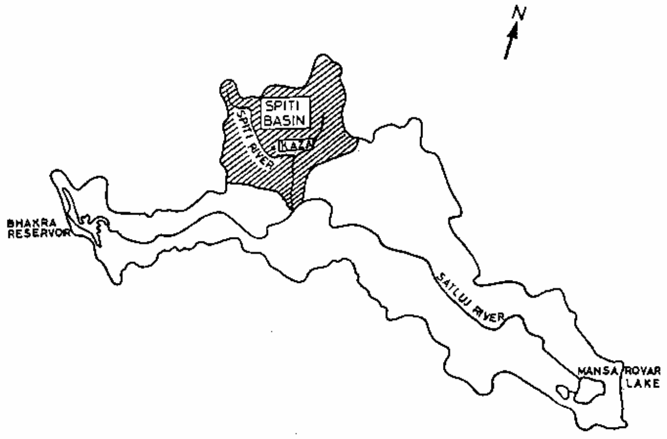

Figure 2(a):Location map of the Spiti basin

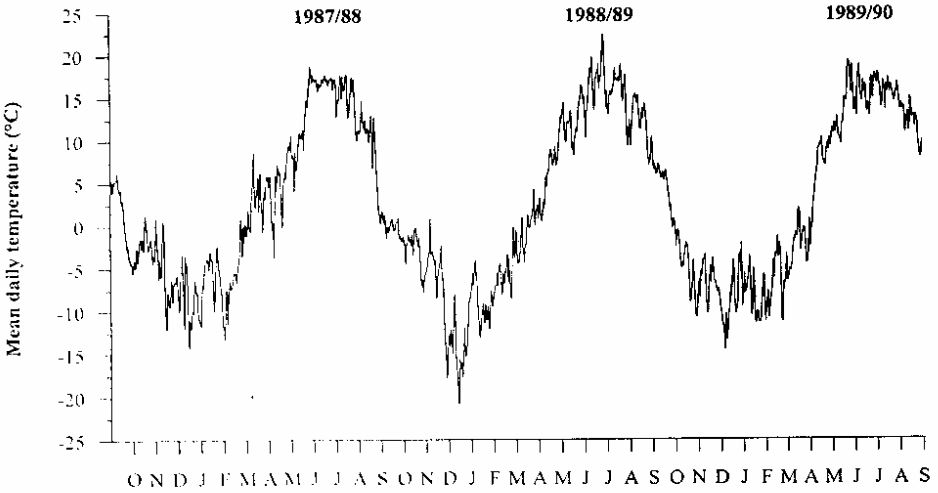

Fig. 2(b): Observed mean daily air temperature at Kaza (3639m) in the Spiti basin.

A monthly simulation is shown in Figure 3. To assess the impact of projected climate change, temperature and precipitation data were modified accordingly and the model was run continuously for a three year simulation period without changing the model parameters. In fact, model parameters will also be influenced under changed climatic scenarios and such effects should be considered in study (Becker and Serban, 1990). But, actual changes in the parameters under the warmer climatic scenarios are not well understood yet (IPCC, 1990; Chiew et al.,1995). The insufficient information/knowledge available on the changes in model parameters, has led to the use of the same parameters under both normal and changed climatic scenarios in this study. The effect of changes in the model parameters may have a significant effect on the results. More research is to be done to understand the changes in model parameters under changed climatic scenarios and to study influences of such changes on the hydrological response of the basins.

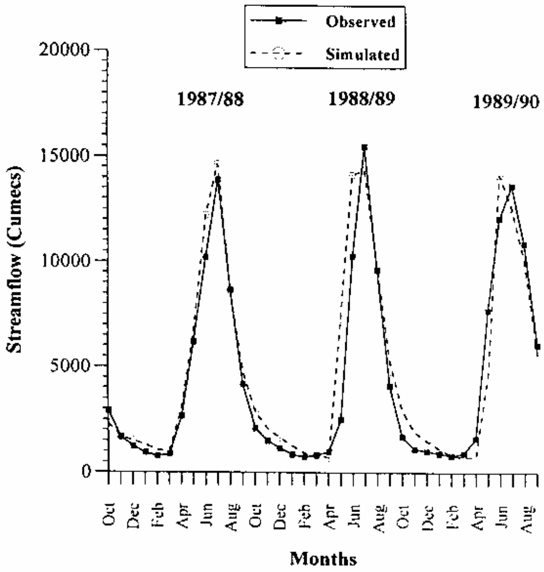

Fig. 3 : Observed and simulated monthly streamflow of the Spiti river using UBC Watershed Model.

## 6.0 EFFECT OF CLIMATE CHANGE ON HYDROLOGICAL RESPONSE OF THE SPITI RIVER

### 6.1 Snow water equivalent

*Temperature scenarios*

The changes in monthly and annual snow water equivalent (SWE) of the Spiti basin with projected increase in air temperature (1-3°C) for 1987/88, 1988/89 and 1989/90 are shown in Figure 4(a) and (b), respectively. The increase in temperature has slightly reduced the amount of annual snow water equivalent (SWE) falling in the winter period, because in a particular period, if air temperature is nearer to the critical/threshold temperature (usually 2°C), SWE is significantly reduced because the form of precipitation changes to rain. Therefore, in such cases a minor increase in temperature can reduce the snow water equivalent significantly because precipitation falls as rain. On the other hand when air temperatures are already very warm or cold, moderate changes in temperature will not change the rain or snow amounts. In the present study basin air temperatures are far below the critical threshold temperature in the winter period (Fig. 2(b)) and projected global warming changes in temperature cannot affect snow accumulation very much. Air temperatures in the starting and ending months of the winter season are closer to the critical temperature and therefore, an increase in the air temperature in those months reduces snowfall. Figure 4(a) also shows that snowpack build-up time of the snowpack is not influenced significantly by the projected increase in air temperature, because it is very high altitude basin. Vehvilainen and Lohvansuu (1991) found that snow accumulation period is greatly reduced in the Finland due to an increase in temperature by about 5-6°C, but in our case the projected increase in temperature is lower than they adopted.

Figure 4(c) shows the distribution SWE in the basin with an increase in temperature. It can be seen that an increase in temperature up to 3°C did not melt the whole accumulated snow in the basin i.e. snow remains in the basin after melt period under normal as well as the warmer climatic scenarios. However, the magnitude of this remaining snow in the basin decreases as the temperature increases. This shows the snow storage characteristics of the basin which influences the snowmelt runoff.

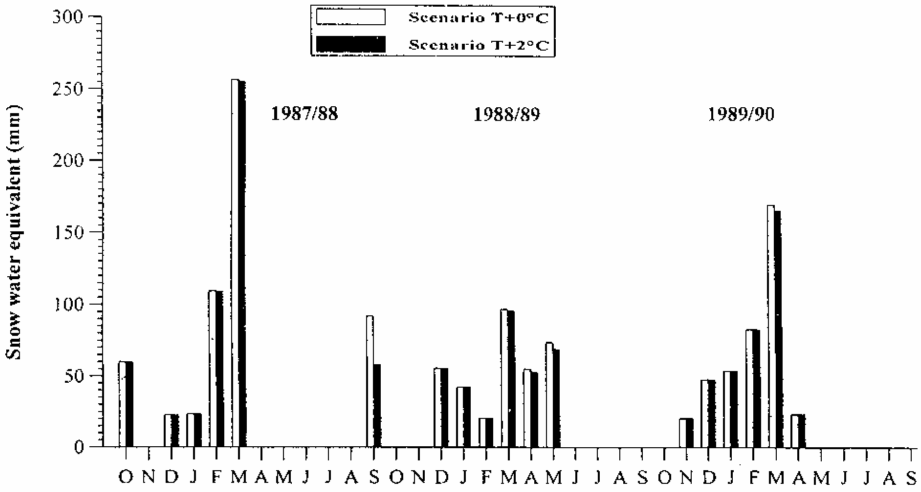

Fig. 4(a):Effect of increase in temperature on monthly snow water equivalent

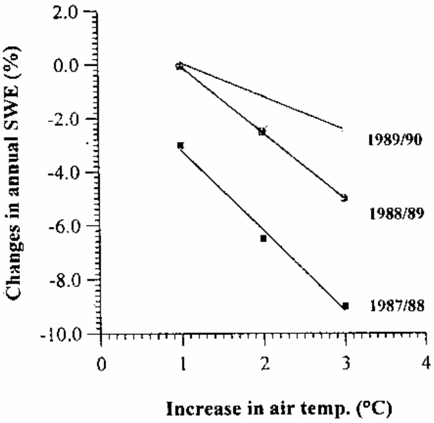

Fig. 4(b): Effect of increase in temperature on annual snow water equivalent

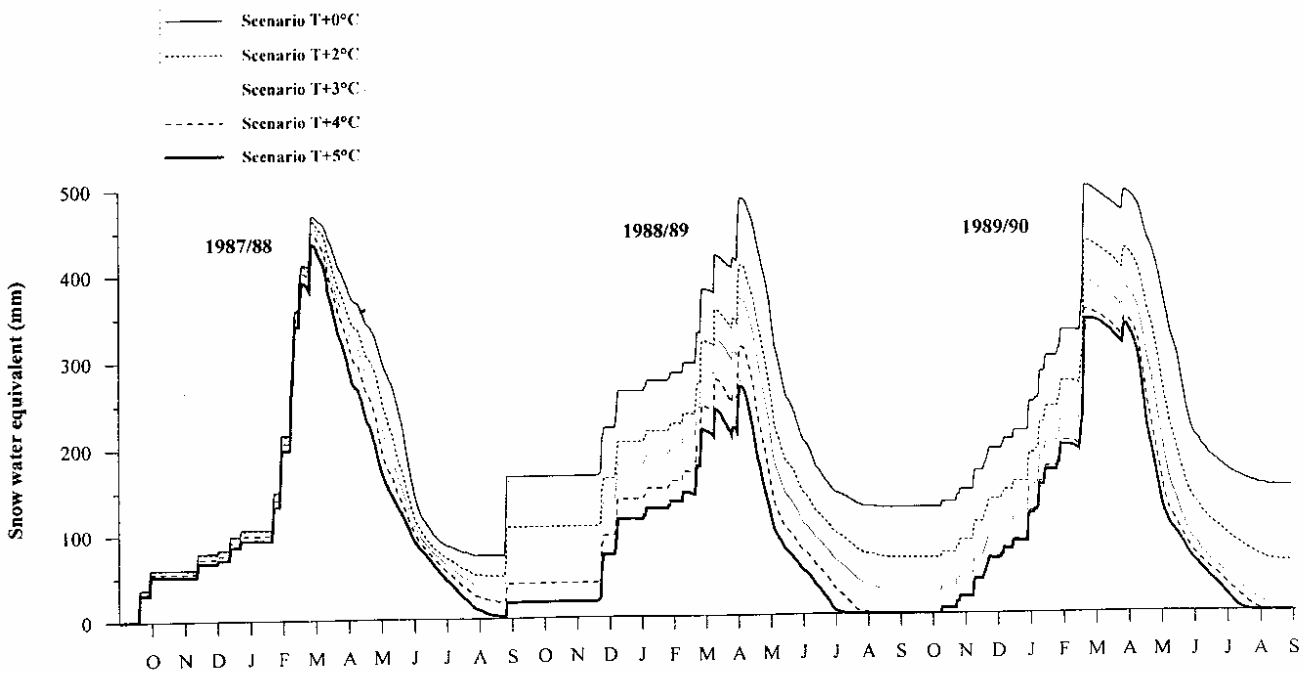

Fig. 4(c) :Effect of increase in temperature on the distribution of snow water equivalent in the basin

Details of simulated annual SWE under different temperature scenarios are summarized in Table 1(a). Annual SWE is reduced by 1-7% for an increase in air temperature of 2°C for the studied years. Reduction in annual SWE for 1987/88 is slightly higher because of occurrence of sizeable snowfall in the months of September and October. There is no snowfall in these months for the other years. As discussed above, in these months air temperature are closer to the critical temperature so that rainfall is increased, in total precipitation which results in reduction of SWE. Similarly, Lettenmaier and Gan (1990) reported a marked reduction in SWE under $2xCO_2$ scenario.

### *Temperature and precipitation scenarios*

The possible impact of precipitation scenarios on monthly and annual SWE is presented in Figure 5(a) and (b), respectively. These results suggest that changes in SWE are proportional to the changes in precipitation. It can also be seen from the Table 2 that for all the projected temperature scenarios, the variation in annual SWE due to specific change in precipitation is found to be of the same order. Table 3 shows variation in annual SWE under various temperature and precipitation scenarios with respect to original simulations. It can be observed from Table 3 that out of the studied scenarios, maximum reduction (13-18%) in annual SWE is produced under T+3°C, P-10% scenario.

## 6.2 Snowmelt runoff

### *Temperature scenarios*

The simulated daily snowmelt runoff under a T+2°C temperature scenarios is shown in Figure 6(a). As expected, an early response for the snowmelt runoff is noticed under the warmer climate along with change in distribution. In the water year 1987/88 the original temperatures were warmer in the spring months and produced a significant increase in melt runoff under the warmer climate scenario, and has reduced peak runoff significantly in the month of June 1988 because a significant melting occurred in the spring months from the basin. Examination of the simulation results for the year 1988/89, shows that the peak runoff is not reduced but slightly increased, because significant melting could not occur in the

**Table 1(a):** Effect of increase in temperature on annual snow water equivalent, snowmelt runoff, glacier melt runoff and total streamflow. All the changes in temperature are in °C. RS indicates reference scenario.

| year | scenario | snow water equiv. (mm) | change (%) | snow melt runoff (cum.) | change (%) | glacier melt runoff (cum.d) | change (%) | Total stream flow (cum.d) | change (%) |
|---|---|---|---|---|---|---|---|---|---|
| 1987/88 | T+0 RS | 564 | - | 17504 | - | 9072 | - | 58808 | - |
| | T+1 | 545 | -3.4 | 18513 | 5.8 | 10681 | 17.7 | 62212 | 5.8 |
| | T+2 | 528 | -6.4 | 19914 | 13.8 | 12490 | 37.7 | 65681 | 11.7 |
| | T+3 | 512 | -9.2 | 21414 | 22.3 | 14338 | 58.0 | 69518 | 18.2 |
| 1988/89 | T+0 RS | 343 | - | 21014 | - | 10451 | - | 61171 | - |
| | T+1 | 342 | -0.3 | 21426 | 2.0 | 12102 | 15.8 | 63141 | 3.2 |
| | T+2 | 335 | -2.3 | 21822 | 3.8 | 13873 | 32.7 | 64645 | 5.7 |
| | T+3 | 326 | -5.0 | 23051 | 9.7 | 15640 | 49.6 | 67516 | 10.4 |
| 1989/90 | T+0 RS | 398 | - | 17784 | - | 9598 | - | 56649 | - |
| | T+1 | 397 | -0.3 | 19389 | 9.0 | 11283 | 17.6 | 59451 | 4.9 |
| | T+2 | 394 | -1.0 | 21022 | 18.2 | 13029 | 35.7 | 62257 | 9.9 |
| | T+3 | 388 | -2.5 | 22733 | 27.8 | 14903 | 55.3 | 65791 | 16.1 |

**Table 1(b):** Effect of increase in temperature on annual snow water equivalent and snowmelt runoff. All the changes in temperature are in °C. RS indicates reference scenario.

| year | scenario | snow water equiv. (mm) | change (%) | snow melt runoff (cum.d) | change (%) |
|---|---|---|---|---|---|
| 1987/88 | T+0 RS | 564 | - | 17504 | - |
| | T+1 | 545 | -3.4 | 18513 | 5.8 |
| | T+2 | 528 | -6.4 | 19914 | 13.8 |
| | T+3 | 512 | -9.2 | 21414 | 22.3 |
| | T+4 | 480 | -14.9 | 23259 | 32.8 |
| | T+5 | 463 | -17.9 | 24667 | 40.9 |
| 1988/89 | T+0 RS | 343 | - | 21014 | - |
| | T+1 | 342 | -0.3 | 21426 | 2.0 |
| | T+2 | 335 | -2.3 | 21822 | 3.8 |
| | T+3 | 326 | -5.0 | 23051 | 9.7 |
| | T+4 | 314 | - 8.5 | 21797 | 3.7 |
| | T+5 | 295 | -14.0 | 19021 | -9.4 |
| 1989/90 | T+0 RS | 398 | - | 17784 | - |
| | T+1 | 397 | -0.3 | 19389 | 9.0 |
| | T+2 | 394 | -1.0 | 21022 | 18.2 |
| | T+3 | 388 | -2.5 | 22733 | 27.8 |
| | T+4 | 381 | -4.3 | 21007 | 18.1 |
| | T+5 | 370 | -7.0 | 20973 | 17.9 |

**Table 2:** Effect of precipitation variation on annual snow water equivalent, snowmelt runoff, glacier melt runoff, and total streamflow over various temperature scenarios for 1987/88, 1988/89, 1989/90. The changes in temperature and precipitation are in °C and percent, respectively. RS indicates reference scenario in this table.

| year | scenario | snow water equiv. (mm) | change (%) | snow melt runoff (cum.d) | change (%) | glacier melt runoff (cum.d) | change (%) | total stream flow (cum.) | change (%) |
|---|---|---|---|---|---|---|---|---|---|
| 1987/88 | T+1,P+0 RS | 545 | - | 18513 | - | 10681 | - | 62212 | - |
| | T+1,P-10 | 490 | -10.1 | 16235 | -12.3 | 11198 | 4.8 | 58829 | -5.4 |
| | T+1,P-5 | 518 | -4.9 | 17339 | -6.3 | 10938 | 2.4 | 60498 | -2.8 |
| | T+1,P+5 | 572 | 5.0 | 19757 | 6.7 | 10467 | -2.0 | 63941 | 2.8 |
| | T+1,P+10 | 600 | 10.1 | 21040 | 13.6 | 10283 | -3.7 | 65768 | 5.7 |
| | | | | | | | | | |
| | T+2,P+0 RS | 528 | - | 19914 | - | 12490 | - | 65681 | - |
| | T+2,P-10 | 475 | -10.0 | 17629 | -11.5 | 12989 | 4.0 | 62249 | -5.2 |
| | T+2,P-5 | 501 | -5.1 | 18766 | -5.8 | 12742 | 2.0 | 63948 | -2.6 |
| | T+2,P+5 | 554 | 4.9 | 21089 | 5.9 | 12256 | -1.9 | 67325 | 2.6 |
| | T+2,P+10 | 580 | 9.8 | 22297 | 11.9 | 12053 | -3.5 | 69192 | 5.4 |
| | | | | | | | | | |
| | T+3,P+0 RS | 512 | - | 21414 | - | 14338 | - | 69518 | - |
| | T+3,P-10 | 460 | -10.2 | 19168 | -10.5 | 14836 | 3.5 | 66109 | -4.9 |
| | T+3,P-5 | 486 | -5.1 | 20249 | -5.4 | 14599 | 1.8 | 67805 | -2.5 |
| | T+3,P+5 | 537 | 4.9 | 22547 | 5.3 | 14117 | -1.5 | 71245 | 2.5 |
| | T+3,P+10 | 563 | 10.0 | 23740 | 10.9 | 13928 | -2.9 | 73087 | 5.1 |
| 1988/89 | T+1,P+0 RS | 342 | - | 21426 | - | 12102 | - | 63141 | - |
| | T+1,P-10 | 307 | -10.2 | 18973 | -11.5 | 12333 | 1.9 | 58925 | -6.7 |
| | T+1,P-5 | 324 | -5.3 | 20324 | -5.1 | 12267 | 1.4 | 61177 | -3.1 |
| | T+1,P+5 | 358 | 4.7 | 22537 | 5.2 | 11953 | -1.2 | 64935 | 2.8 |
| | T+1,P+10 | 375 | 9.6 | 23690 | 10.6 | 11810 | -2.4 | 66815 | 5.8 |
| | | | | | | | | | |
| | T+2,P+0 RS | 335 | - | 21822 | - | 13873 | - | 64645 | - |
| | T+2,P-10 | 301 | -10.1 | 19767 | -9.4 | 14185 | 2.3 | 61069 | -5.5 |
| | T+2,P-5 | 318 | -5.1 | 20751 | -4.9 | 14032 | 1.2 | 62854 | -2.8 |
| | T+2,P+5 | 351 | 4.8 | 22818 | 4.6 | 13732 | -1.0 | 66379 | 2.7 |
| | T+2,P+10 | 369 | 10.0 | 23854 | 9.3 | 13599 | -2.0 | 68221 | 5.5 |
| | | | | | | | | | |
| | T+3,P+0 RS | 326 | - | 23051 | - | 15640 | - | 67516 | - |
| | T+3,P-10 | 294 | -9.8 | 21079 | -8.6 | 15950 | 2.0 | 64126 | -5.0 |
| | T+3,P-5 | 309 | -5.2 | 22025 | -4.5 | 15796 | 1.0 | 65812 | -2.5 |
| | T+3,P+5 | 342 | 4.9 | 24031 | 4.3 | 15490 | -0.9 | 69150 | 2.4 |
| | T+3,P+10 | 359 | 10.1 | 25081 | 8.8 | 15346 | -1.9 | 70836 | 4.9 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1989/90 | T+1,P+0 RS | 397 | - | 19389 | - | 11283 | - | 59451 | - |
| | T+1,P-10 | 356 | -10.3 | 17312 | -10.7 | 11644 | 3.2 | 55661 | -6.4 |
| | T+1,P-5 | 376 | -5.3 | 18214 | -5.7 | 11470 | 1.7 | 57307 | -3.6 |
| | T+1,P+5 | 416 | 4.8 | 20601 | 6.3 | 11977 | 6.2 | 62589 | 5.3 |
| | T+1,P+10 | 436 | 9.8 | 21612 | 11.5 | 11809 | 4.7 | 64527 | 8.5 |
| | T+2,P+0 RS | 394 | - | 21022 | - | 13029 | - | 62257 | - |
| | T+2,P-10 | 353 | -10.4 | 18862 | -10.3 | 13411 | 2.9 | 58585 | -5.9 |
| | T+2,P-5 | 372 | -5.6 | 19878 | -5.4 | 13225 | 1.5 | 60166 | -3.4 |
| | T+2,P+5 | 412 | 4.6 | 22259 | 5.9 | 13731 | 5.4 | 65325 | 4.9 |
| | T+2,P+10 | 432 | 9.6 | 23341 | 11.0 | 13554 | 4.0 | 67214 | 7.9 |
| | T+3,P+0 RS | 388 | - | 22733 | - | 14903 | - | 65791 | - |
| | T+3,P-10 | 348 | -10.3 | 18197 | -19.9 | 15276 | 2.5 | 59578 | -9.4 |
| | T+3,P-5 | 367 | -5.4 | 20466 | -9.9 | 15094 | 1.3 | 62627 | -4.8 |
| | T+3,P+5 | 406 | 4.6 | 24007 | 5.6 | 15583 | 4.6 | 68785 | 4.6 |
| | T+3,P+10 | 425 | 9.8 | 25130 | 10.5 | 15415 | 3.4 | 70439 | 7.1 |

**Table 3:** Variation in annual SWE, snowmelt runoff, glacier melt runoff, and total streamflow under various temperature and precipitation scenarios with respect to simulation obtained using original temperature and precipitation data for 1987/88-1989/90. Changes in temperature and precip. are in °C and percent, respectvely. RS indicates reference scenario.

| year | scenario | snow water equiv. (mm) | change (%) | snow melt runoff (cum.d) | change (%) | glacier melt runoff (cum.d) | change (%) | total stream flow (cum.d) | change (%) |
|---|---|---|---|---|---|---|---|---|---|
| 1987/88 | T+0,P+0 RS | 564 | - | 17504 | - | 9072 | - | 58808 | - |
| | T+1,P-10 | 490 | -13.1 | 16235 | -7.2 | 11198 | 23.4 | 58829 | 0.04 |
| | T+1,P-5 | 518 | -8.2 | 17339 | -0.9 | 10938 | 20.6 | 60498 | 2.8 |
| | T+1,P+0 | 545 | -3.4 | 18513 | 5.8 | 10681 | 17.7 | 62212 | 5.8 |
| | T+1,P+5 | 572 | 1.4 | 19757 | 12.8 | 10467 | 15.4 | 63941 | 8.7 |
| | T+1,P+10 | 600 | 6.4 | 21040 | 20.2 | 10283 | 13.4 | 65768 | 11.8 |
| | T+2,P-10 | 475 | -15.8 | 17629 | 0.7 | 12989 | 43.2 | 62249 | 5.9 |
| | T+2,P-5 | 501 | -11.2 | 18766 | 7.2 | 12742 | 40.5 | 63948 | 8.7 |
| | T+2,P+0 | 528 | -6.4 | 19914 | 13.8 | 12490 | 37.7 | 65681 | 11.7 |
| | T+2,P+5 | 554 | -1.8 | 21089 | 20.5 | 12256 | 35.1 | 67375 | 14.6 |
| | T+2,P+10 | 580 | 2.8 | 22297 | 27.4 | 12053 | 32.9 | 69192 | 17.7 |
| | T+3,P-10 | 460 | -18.4 | 19168 | 9.5 | 14836 | 63.5 | 66109 | 12.4 |
| | T+3,P-5 | 486 | -13.8 | 20249 | 15.7 | 14599 | 60.9 | 67805 | 15.3 |
| | T+3,P+0 | 512 | -9.2 | 21414 | 22.3 | 14338 | 58.0 | 69518 | 18.2 |
| | T+3,P+5 | 537 | -4.8 | 22547 | 28.8 | 14117 | 55.6 | 71245 | 21.2 |
| | T+3,P+10 | 563 | -0.17 | 23740 | 35.6 | 13928 | 53.5 | 73087 | 24.3 |
| 1988/89 | T+0,P+0 RS | 343 | - | 21014 | - | 10451 | - | 61171 | - |
| | T+1,P-10 | 307 | -10.5 | 18973 | -9.7 | 12333 | 18.0 | 58925 | -3.7 |
| | T+1,P-5 | 324 | -5.5 | 20324 | -3.3 | 12267 | 17.4 | 61177 | 0.01 |
| | T+1,P+0 | 342 | -0.3 | 21426 | 2.0 | 12102 | 15.8 | 63141 | 3.2 |
| | T+1,P+5 | 358 | 4.4 | 22537 | 7.3 | 11953 | 14.4 | 64935 | 6.2 |
| | T+1,P+10 | 376 | 9.6 | 23690 | 12.7 | 11810 | 13.0 | 66815 | 9.2 |
| | T+2,P-10 | 301 | -12.2 | 19767 | -5.9 | 14185 | 35.7 | 61069 | -0.2 |
| | T+2,P-5 | 318 | -7.3 | 20751 | -1.3 | 14032 | 34.3 | 62854 | 2.8 |
| | T+2,P+0 | 335 | -2.3 | 21822 | 3.8 | 13873 | 32.7 | 64645 | 5.7 |
| | T+2,P+5 | 351 | 2.3 | 22818 | 8.6 | 13732 | 31.4 | 66379 | 8.5 |
| | T+2,P+10 | 369 | 7.6 | 23854 | 13.5 | 13599 | 30.1 | 68221 | 11.5 |
| | T+3,P-10 | 294 | -14.3 | 21079 | 0.3 | 15950 | 52.6 | 64126 | 4.8 |
| | T+3,P-5 | 309 | -9.9 | 22025 | 4.8 | 15796 | 51.1 | 65812 | 7.6 |
| | T+3,P+0 | 326 | -5.0 | 23051 | 9.7 | 15640 | 49.6 | 67516 | 10.4 |
| | T+3,P+5 | 342 | -0.3 | 24031 | 14.4 | 15490 | 48.2 | 69150 | 13.0 |
| | T+3,P+10 | 359 | 4.6 | 25081 | 19.4 | 15346 | 46.8 | 70836 | 15.8 |

| | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| 1989/90 | T+0,P+0 RS | 398 | - | 17784 | - | 9598 | - | 56649 | - |
| | T+1,P-10 | 356 | -10.6 | 17312 | -2.7 | 11644 | 21.3 | 55661 | -1.7 |
| | T+1,P-5 | 376 | -5.5 | 18284 | 2.8 | 11470 | 19.5 | 57307 | 1.2 |
| | T+1,P+0 | 397 | -0.3 | 19389 | 9.0 | 11283 | 17.6 | 59451 | 4.9 |
| | T+1,P+5 | 416 | 4.5 | 20601 | 15.8 | 11977 | 24.8 | 62589 | 10.5 |
| | T+1,P+10 | 436 | 9.5 | 21612 | 21.5 | 11809 | 23.0 | 64527 | 13.9 |
| | T+2,P-10 | 353 | -11.3 | 18862 | 6.1 | 13411 | 39.7 | 58585 | 3.4 |
| | T+2,P-5 | 372 | -6.5 | 19878 | 11.8 | 13225 | 37.8 | 60166 | 6.2 |
| | T+2,P+0 | 394 | -1.0 | 21022 | 18.2 | 13029 | 35.7 | 62257 | 9.9 |
| | T+2,P+5 | 412 | 3.5 | 22259 | 25.2 | 13731 | 43.1 | 65325 | 15.3 |
| | T+2,P+10 | 432 | 8.5 | 23341 | 31.2 | 13554 | 41.2 | 67214 | 18.7 |
| | T+3,P-10 | 348 | -12.6 | 18197 | 2.3 | 15276 | 59.2 | 59578 | 5.2 |
| | T+3,P-5 | 367 | -7.7 | 20466 | 15.1 | 15094 | 57.3 | 62627 | 10.6 |
| | T+3,P+0 | 388 | -2.5 | 22733 | 27.8 | 14903 | 55.3 | 65791 | 16.1 |
| | T+3,P+5 | 406 | 2.2 | 24007 | 35.0 | 15583 | 62.4 | 68785 | 21.4 |
| | T+3,P+10 | 426 | 7.0 | 25130 | 41.3 | 15415 | 60.6 | 70439 | 24.3 |

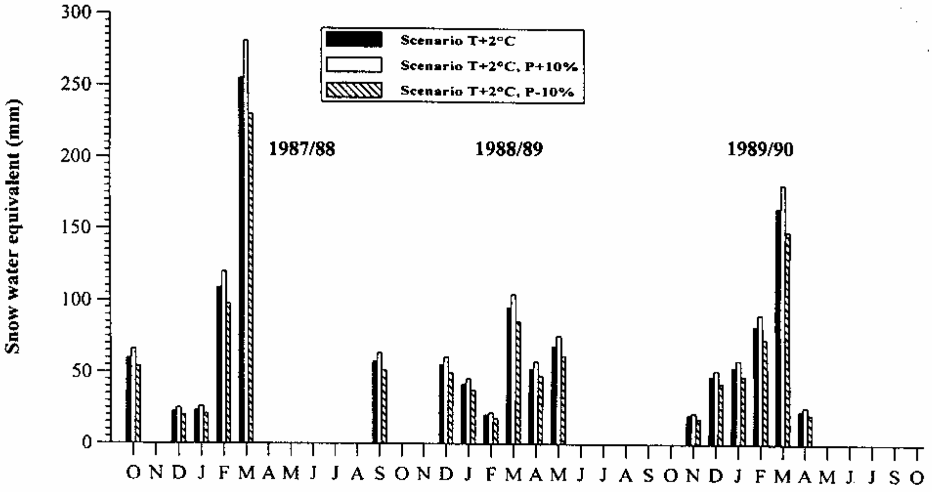

Fig. 5(a): Effect of changes in precipitation on monthly snow water equivalent over a T+2°C scenario.

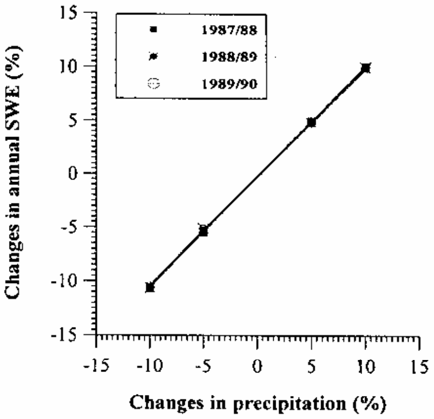

Fig. 5(b) : Effect of changes in precipitation on annual snow water equivalent over a T+2 °C scenarios.

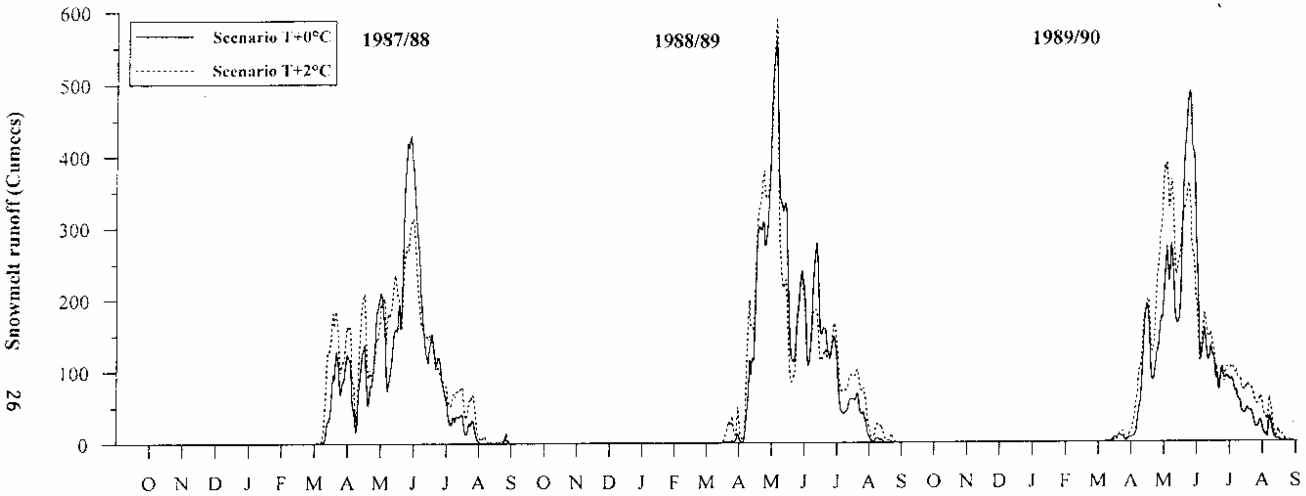

Fig. 6(a) :Effect of increase in temperature on daily snowmelt runoff spring months because of lower temperatures during this time. Again in 1989/90 a substantial melting occurred in May under the warmer climate and it resulted in the shift of peak runoff. Therefore, melting pattern in the spring months also controls the snowmelt runoff distribution. Such effects also have been noticed by Cayan and Riddle (1993), and they have also reported that the temperature effect on runoff in early summer is partially counteracted by the opposite effect in the early spring.

Figure 6(b) illustrates that for all the years, snowmelt runoff increased linearly with increase in temperature. However, the magnitude of changes in snow melt runoff for a particular year depends on the snow water equivalent storage and climatic conditions over the basin in that year. Based on three years projected climatic simulations, temperature increase from 1-3°C increased snowmelt runoff from 2-28%. For a 2°C increase in temperature this range was found to be from 4-18% (Table 1(a)). These results indicate that the reduced built up snow under warmer climate will not always decrease the annual snow melt runoff for all snowbound basins. If snow available in the basin does not melt completely, under normal and warmer climate scenarios (Fig. 4(c)), then reduced snow water equivalent (SWE) will not decrease annual snowmelt runoff, but will increase the annual snowmelt runoff. However, in other situation, when snow accumulated in the basin is melted in total, then reduced SWE will decrease annual snowmelt runoff. Such results are not reported before, therefore, in order to test this concept, snowmelt runoff and SWE were computed for a higher temperature scenarios (T+4°C, T+5°C). It can be noticed that annual snowmelt runoff starts decreasing for T+4°C and T+5°C temperature scenarios Table 1(b). Fig. 4(c) shows that SWE in the basin decreases under all the warmer climatic scenarios because a higher increase in temperature builds up lesser snow in the basin. The important point to be noted is that an increase in temperature up to 3°C did not melt the whole accumulated snow in the basin i.e. snow remains in the basin after melt period under normal and these warmer climatic scenarios. However, the magnitude of this remaining snow in the basin decreases as the temperature increases, but an increase up to 3°C has not depleted the snow completely for any year (1987/88 or 188/89 or 1989/90) and snow is always available for melting under warmer scenarios (T+1 to T+3°C) throughout the melt period. Therefore, higher melt rate under the warmer climate (T+1 to T+3°C) and broadened melt period would increase the annual snow melt runoff. But, for more higher temperature scenarios (T+4, T+5°C) snow storage in the basin approaches to nil, and therefore, annual snow melt

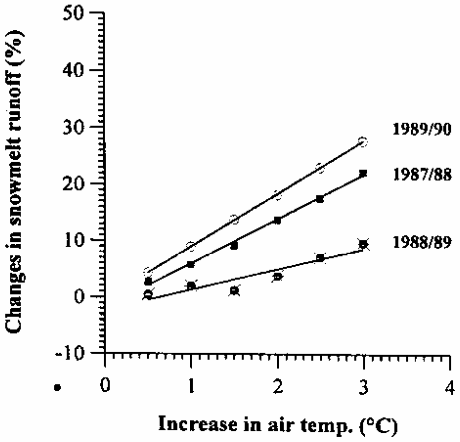

Fig. 6(b):Effect of increase in temperature on annual snowmelt runoff

runoff decreased for this temperature range.

### *Temperature and precipitation scenarios*

The impact of precipitation changes over a T+2°C on daily snow melt runoff is shown in Figures 7(a). No changes are observed in the snowmelt period and timing of peak snow melt runoff, but magnitude of peak runoff is higher under higher precipitation scenario and vice-versa. It is evident from Figure 7(b) that for all the years, annual snowmelt runoff increased linearly with changes in precipitation. Changes in precipitation by -10 and +10 % have varied annual snowmelt runoff over the T+2°C scenario by -11.5 and 11.9, -9.4 and 9.3%, -10.3 and 11.0% respectively for 1987/88, 1988/89, 1989/90. Combined temperature and precipitation scenarios influence both snow water equivalent and melting conditions over the basin. In the warmer conditions snow cover will deplete faster if precipitation is not changed. In case both temperature and precipitation increased, temperature will cause faster melt, but precipitation will enhance the snowpack. Figure 7(b) illustrates that higher snowmelt runoff is observed with a higher amount of precipitation, because increase in precipitation provides higher snow water equivalent and in addition snow is stored in the catchment at high altitudes which melts in the following snowmelt season or later as snowmelt runoff. Consequently, it causes an increase in annual snowmelt runoff (Table 1(a)). Results for changes in annual snowmelt runoff corresponding to various temperature and precipitation scenarios are given in Table 2 and 3. Maximum increase (19-41%) in annual snowmelt runoff has occurred under a T+3°C, P+10% scenario.

## 6.3 Glacier melt runoff

### *Temperature scenarios*

The study basin includes glaciers, however, the magnitude of glacier contribution to the total flow is much less as compared to that due to snowmelt runoff. Normally their major contribution to the streamflow occurs in the months of July and August after the snow cover on the glacier has been melted. Effect of a T+2°C temperature scenario on daily glacier melt runoff is shown in Figure 8(a). As expected, contribution from the glacier starts earlier under the warmer climate. There is systematic increase in the glacier melt runoff with

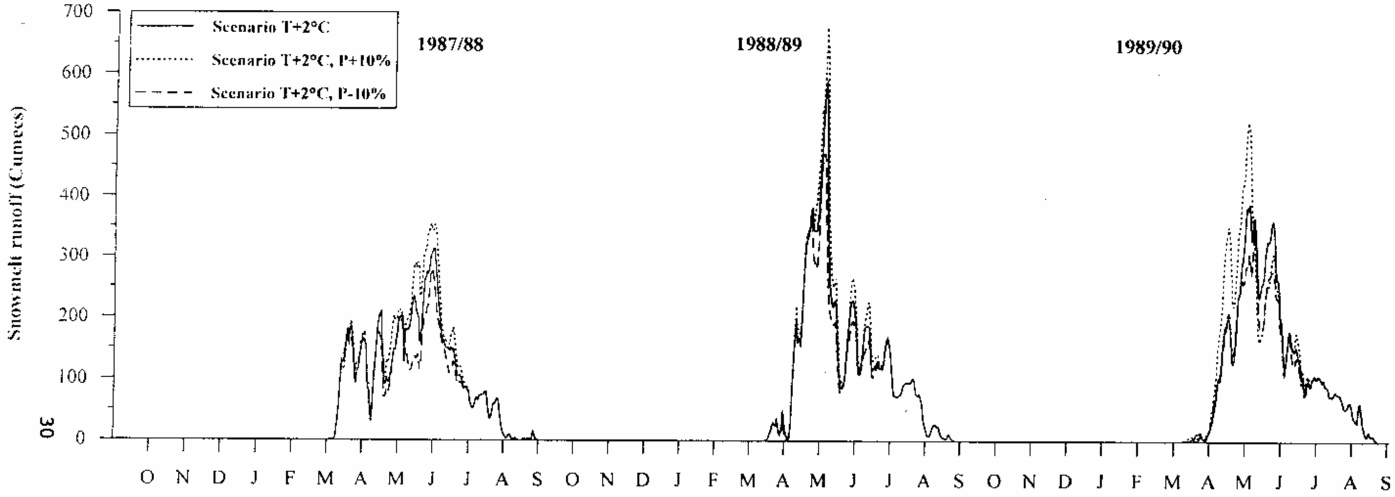

Fig. 7(a):Effect of changes in precipitation on daily snowmelt runoff over a T+2°C scenario

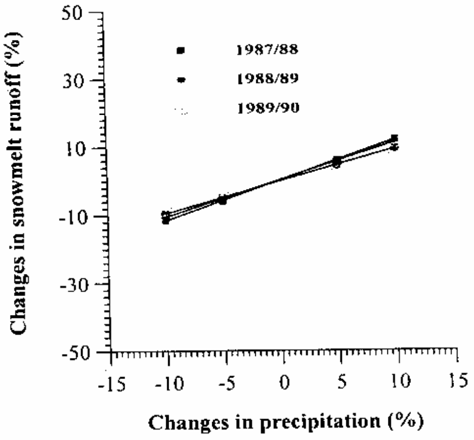

Fig. 7(b): Effect of changes in precipitation on annual snowmelt runoff over a T+2°C scenario.

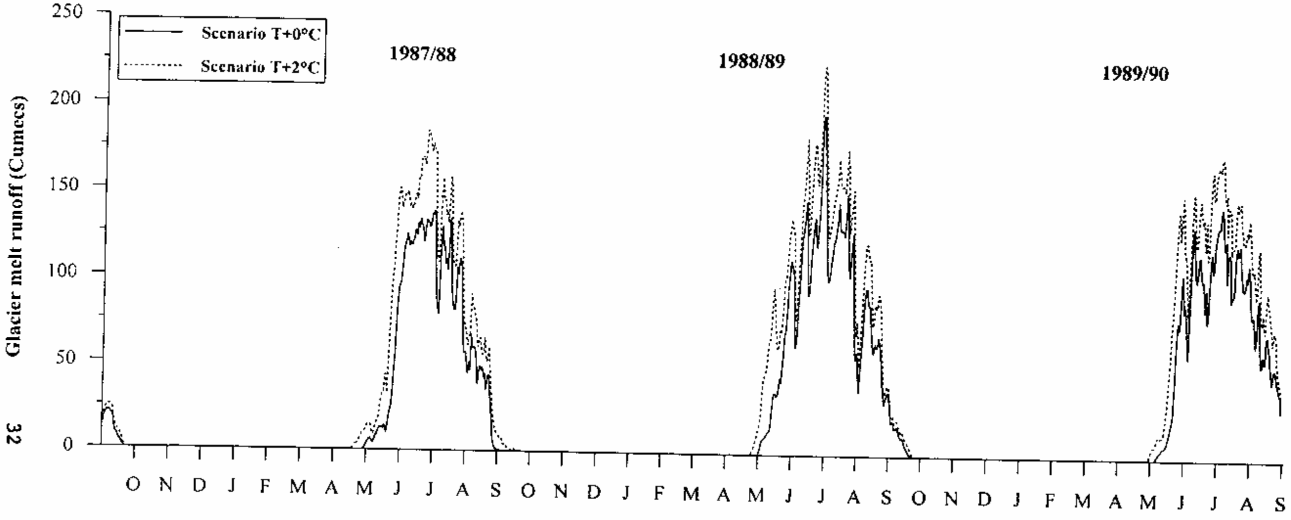

Fig. 8(a): Effect of increase in temperature on daily glacier melt runoff increase in temperature, which is expected, because total glaciated area does not change significantly from year to year , and therefore, would tend to produce higher runoff under a warmer climate. In contrast, for snowmelt runoff, as the snowline moves up, the lower part of the basin becomes snowfree and no contribution is obtained from the bare area in terms of snow melt runoff irrespective of the change in temperature conditions.

Variations in total annual glacier melt runoff for different temperature increase scenarios are shown in Figure 8(b), and it is seen to increase linearly with projected range of temperature. A significant increase is found in the glacier melt runoff under warmer climate as compared with other components of runoff. For an increase of 2°C in air temperature, the glacier melt runoff has increased 38, 33 and 36%, respectively, for 1987/88, 1988/89, 1989/90 (Table 1(a)). Like other components of streamflow, the magnitude of glacier melt runoff also depends on the original temperature regime during a particular year.

### *Temperature and precipitation scenarios*

Figure 9(a) presents the results of precipitation variation from -10% to +10% on daily glacier melt runoff over a T+2°C scenario. The effect of changes in temperature and precipitation on annual glacier melt runoff is illustrated in Figure 9(b). It is noticed that projected changes in precipitation does not change glacier melt runoff very significantly. In general, it has the inverse effect to the changes in precipitation i.e. an increase in precipitation reduces the glacier melt runoff and vice-versa. The increase in precipitation results in a higher snowpack over the glaciers. The glaciers are therefore exposed relatively later because snowmelt runoff due to the excess snowcover lasts for a longer duration. This results in less contribution of glacier melt runoff when precipitation is increased. For the lower precipitation scenario, the glaciers are exposed for longer duration producing more glacier melt runoff. The details of results obtained for combined temperature and precipitation are shown in Table 2 and 3. The present investigations indicate that the maximum increase in annual glacier melt runoff (53-64%) is obtained under a T+3°C, P-10% scenario, which in the long-term might lead to accelerated glacier depletion and consequent retreat of glaciers to higher elevations.

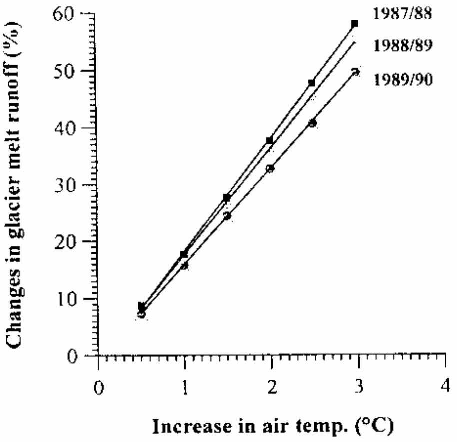

Fig. 8(b): Effect of increase in temperature on annual glacier melt runoff

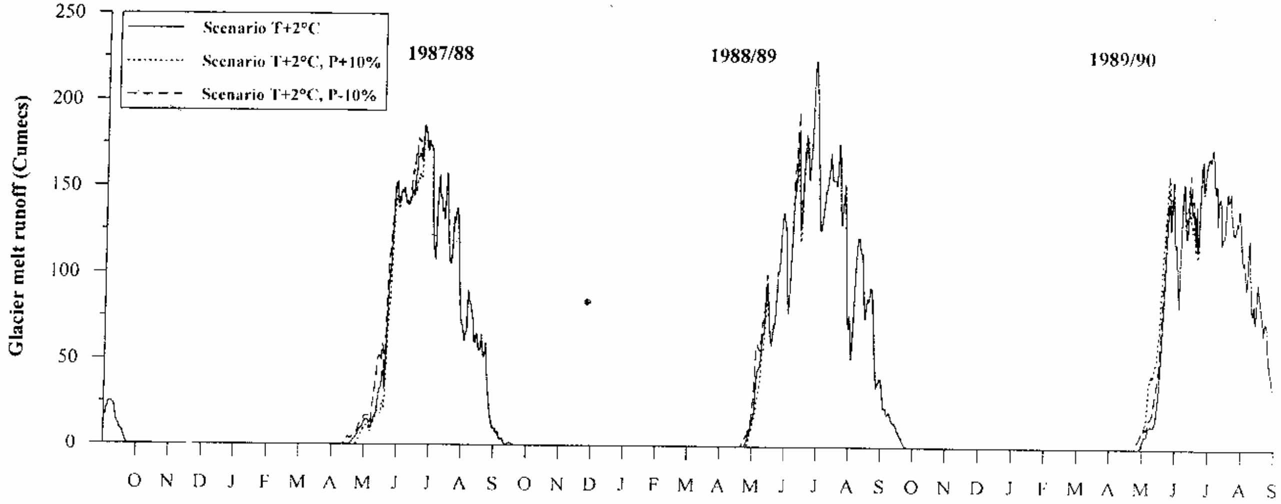

Fig. 9(a): Effect of changes in precipitation on daily glacier melt runoff over a T+2°C scenario

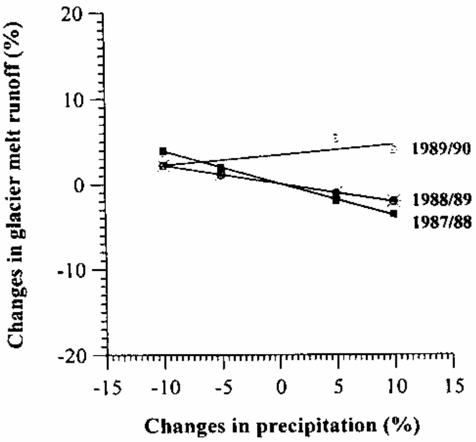

Fig. 9(b): Effect of changes in precipitation on annual glacier melt runoff over a T+2°C scenario.

In addition to the climatic conditions in a current year over a glacier, melting of the glacier is also governed by the accumulation and ablation patterns of the snowpack of the previous years. If some snow is left in a preceding year over the glacier, it is added to the snowpack built up in the current year and even years before, so that the period of exposure of the glaciers and their melt water contributions are influenced by the status of the snowpack left in preceding years. Changes in the glacier melt runoff for year of 1989/90 for projected temperature and precipitation scenarios are well supported by this concept. For example, both 1988/89 and 1989/90 experienced less precipitation in comparison to 1987/88. In addition, changes in precipitation are considered as absolute percentage of precipitation. For a low precipitation year, the change in precipitation with a specific projected percentage will be less than the change in a high precipitation year due to same projected percentage. For example in the low precipitation year of 1989/90 even an increase in precipitation could not decrease the glacier melt runoff because the glaciers were exposed earlier.

## 6.4 Total streamflow

### *Temperature scenarios*

As discussed above, snow and glacier contribution forms a major part of the total runoff in this basin and therefore changes in the snow and glacier melt runoff due to various climatic scenarios are reflected in the changes of total streamflow. For a basin having precipitation storage characteristics, an increase in total streamflow is expected under a warmer climate because runoff both from snow and glaciers is accelerated. Changes in daily streamflow distribution for temperature increase of 2°C are illustrated in Figure 10(a). In general, the timing of peak streamflow is not affected, however, there is change in the magnitude of peak streamflow depending upon the spring melting condition. Figure 10(a) also indicates that no significant change in the winter streamflow could be produced for this watershed by the T+2°C temperature scenarios, while several authors have suggested that winter discharge would increase when temperature is increased. This is discussed in the next section. Like annual snow and glacier melt runoff, annual total streamflow runoff also linearly varies with increase in temperature (Fig.10(b)). For a temperature increase of 2°C, the variation in annual streamflow is computed to be 12, 6 and 10%, respectively for 1987/88, 1988/89, 1989/90. Changes in total annual streamflow for other temperature

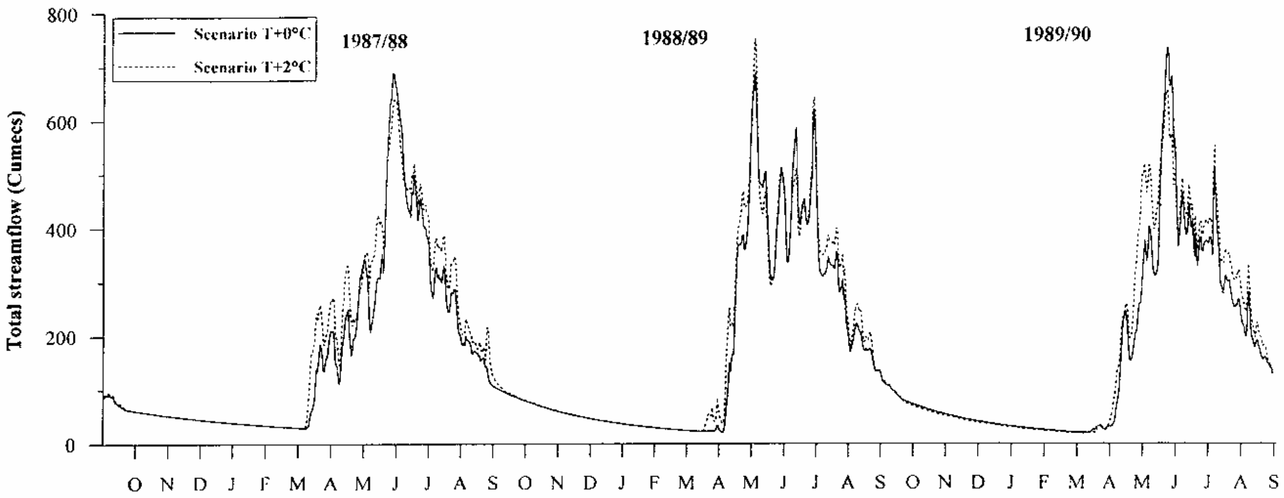

Fig. 10(a): Effect of increase in temperature on daily total streamflow

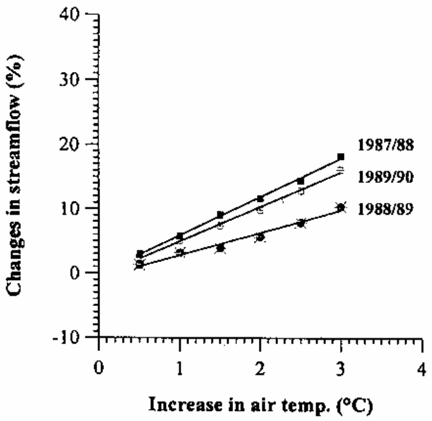

Fig. 10(b): Effect of increase in temperature on annual total streamflow

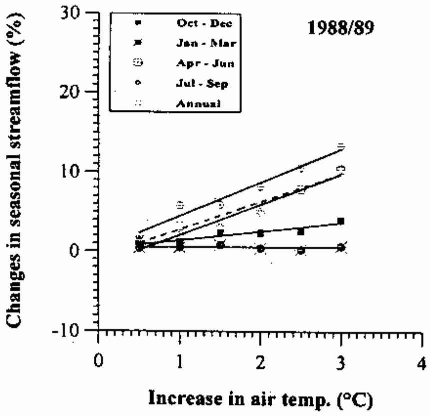

Fig. 10(c): Effect of increase in temperature on seasonal and annual streamflow scenarios are given in Table 1(a).

To understand the seasonal variation in total streamflow, a seasonal analysis was carried out. For this purpose a year was divided into four seasons namely snowmelt season or pre-monsoon season (April-June), monsoon season (July-September), post-monsoon season (October-December) and winter season (January-March). Relative changes in each season with increase in temperature for the year 1988/89 are depicted in Figure 10(c) and details for other years are given in Table 4. Changes in the streamflow for all the seasons are linearly related with the increase in temperature. Maximum increase in streamflow runoff is computed to be in the pre-monsoon season followed by the monsoon season which correspond to the spring and summer seasons respectively. Cayan and Riddle (1993) also reported that temperature sensitivity seems to be confined to spring and early summer. Larger increase in pre-monsoon season is possible because of higher amount of snowmelt runoff due to warmer climate. It is to be mentioned that higher flows in the pre-monsoon season may benefit the country because demand of water both for hydropower and domestic uses is very high in this season. Further, higher variation in the streamflow during monsoon season may occur because of snowmelt runoff from the high snowfields along with glacier melt runoff and rain contribute in this season. Post-monsoon and winter flows are not affected significantly as melt contribution from snow and glacier is either negligible or nil in these seasons. However, some studies indicate increase in winter discharge due to a warmer environment caused by increase in temperatures (Gleick, 1987b; Bultot et al., 1988; McCabe and Ayers, 1989; Cooley, 1990). It is understood that increase in winter discharge is possible either because due to increase in winter temperature the precipitation may fall as rain or some snowpack may melt under warmer climatic conditions. The combination of these two processes can increase streamflow during the winter period. For the study basin both conditions are found not applicable because of very low temperatures regime and, therefore, no significant changes are observed in the winter discharge due to increase in air temperatures. Based on the three years, it is seen that magnitude of the changes in the annual streamflow is very close to the variation in magnitude noted for the monsoon season. During the monsoon season streamflow consists of rain, snow and glacier melt from higher altitudes.

### *Temperature and precipitation scenarios*

**Table 4:** Effect of increase in temperature on seasonal and annual total streamflow. All the changes in temperature are in °C. RS indicates reference scenario.

| year | scenario | Oct.-Dec. | | Jan.-Mar. | | Apr.-Jun. | | Jul.-Sep. | | Annual | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | flow (cum.d) | change (%) | flow (cum.d) | change (%) | flow (cum.d) | change (%) | flow (cum.d) | change (%) | flow (cum.d) | change (%) |
| 1987/88 | T+0 RS | 5501 | - | 3353 | - | 21907 | - | 28047 | - | 58808 | - |
| | T+1 | 5536 | 0.6 | 3354 | 0.03 | 23832 | 8.8 | 29491 | 5.1 | 62212 | 5.8 |
| | T+2 | 5572 | 1.3 | 3355 | 0.06 | 25912 | 18.3 | 30842 | 9.9 | 65681 | 11.7 |
| | T+3 | 5608 | 2.0 | 3356 | 0.09 | 27699 | 26.4 | 32856 | 17.1 | 69518 | 18.2 |
| 1988/89 | T+0 RS | 6559 | - | 3030 | - | 22095 | - | 29486 | - | 61171 | - |
| | T+1 | 6639 | 1.2 | 3047 | 0.6 | 23377 | 5.8 | 30079 | 2.0 | 63141 | 3.2 |
| | T+2 | 6717 | 2.4 | 3044 | 0.5 | 23913 | 8.2 | 30972 | 5.0 | 64645 | 5.7 |
| | T+3 | 6821 | 3.9 | 3051 | 0.7 | 25041 | 13.3 | 32604 | 10.6 | 67516 | 10.4 |
| 1989/90 | T+0 RS | 6340 | - | 2624 | - | 19416 | - | 28239 | - | 56649 | - |
| | T+1 | 6283 | -0.9 | 2600 | -2.1 | 21062 | 8.5 | 29506 | 4.5 | 59451 | 5.1 |
| | T+2 | 6109 | -3.6 | 2489 | -6.2 | 22444 | 15.6 | 31215 | 10.5 | 62257 | 9.9 |
| | T+3 | 6165 | -2.8 | 2473 | -6.8 | 24047 | 23.9 | 33106 | 17.2 | 65791 | 16.1 |

The effect of changes in precipitation on the daily streamflow for a T+2°C scenario is shown in Figure 11(a). Higher amount of precipitation produces higher streamflow maintaining the same timings of peak streamflow. Results indicate that streamflow changes linearly with changes in precipitation (Fig.11(b)). Impact of combined scenarios is given in Table 2. Similar results were obtained by Ng and Marsalek (1992). For the studied scenarios, the maximum increase (16-24%) in annual total streamflow runoff is produced under a T+3°C, P+10% scenario (Table 3).

## 7.0 COMPARISON OF CLIMATE CHANGE IMPACT ON SNOWMELT RUNOFF, GLACIER MELT RUNOFF AND TOTAL STREAMFLOW

To compare the changes in annual snowmelt, glacier melt and total runoff due to projected climatic scenarios, they are shown together for 1988/89 in Fig.12(a)&(b). For other years results are in Tables. It is clear that maximum effect of increase in temperature is found on the glacier melt runoff as compared with snow melt runoff and total runoff. For this basin, an increase in 2°C in air temperature increased snowmelt runoff, glacier melt runoff and total streamflow ranging from 4-18%, 33-38% and 6-12%, respectively. Maximum variation in snowmelt runoff (19-41%) and total streamflow (16-24%) is found when both temperature and precipitation are high (T+3°C and P+10%), whereas maximum variation in glacier melt runoff (53-64%) is obtained when temperature is high but precipitation is low (T+3°C and P-10%). Changes in the snow and glacier melt runoff are also reflected in changes in total streamflow. For example, in 1988/89, the variation in snowmelt runoff is relatively lower, which results in less variation in total streamflow in that year. Further, it is noticed that snowmelt runoff is more sensitive than glacier melt runoff to the projected changes in precipitation and sensitivity of total streamflow lies between these two (Fig. 12(b)).

A long-term effect of temperature and precipitation changes on the physical characteristics of the glacier can be addressed on the basis of these results. An increase in air temperature for a longer time will reduce the size of glaciers due to higher melting rate. Similar effects are expected under the less precipitation scenarios. They will retreat because of their faster depletion under these situations. Moreover, a combination of these two scenarios, increase in temperature and decrease in precipitation, for longer time will have the

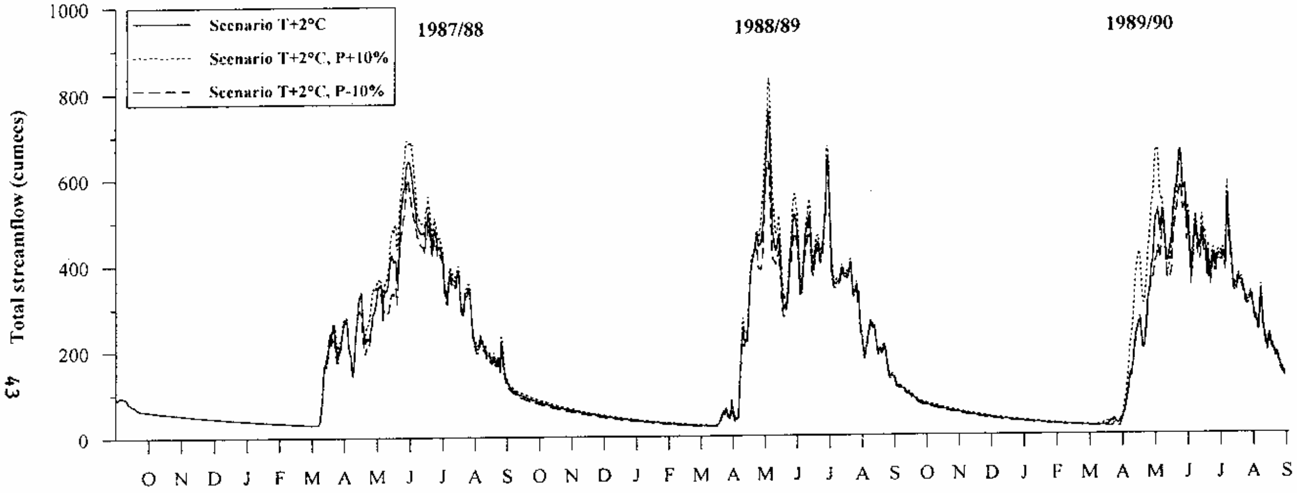

Fig. 11(a): Effect of changes in precipitation on daily total streamflow over a T+2°C scenario

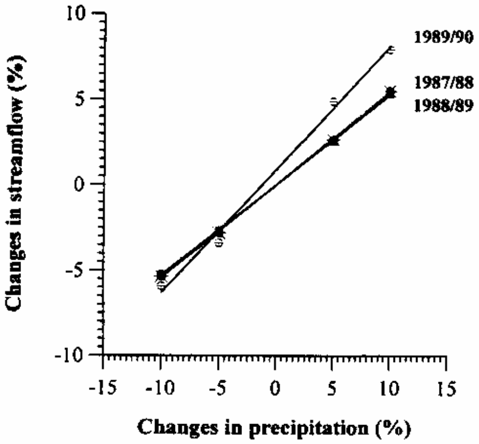

**Fig. 11(b):** Effect of changes in precipitation on annual total streamflow over a T+2°C scenario

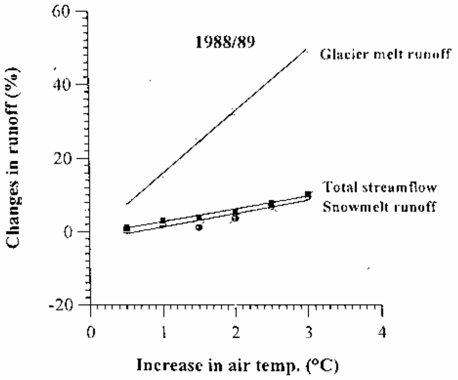

Fig. 12(a): A comparison of effect of increase in temperature on annual snowmelt runoff, glacier melt runoff and total streamflow

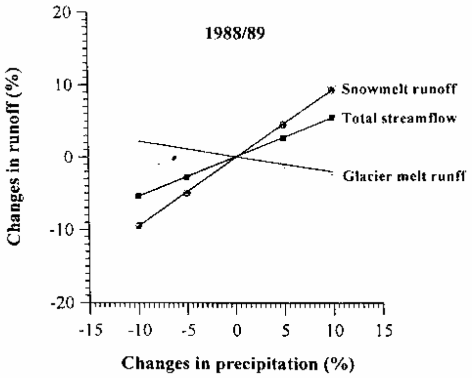

Fig. 12(b): A comparison of changes in precipitation on annual snowmelt runoff, glacier melt runoff and total streamflow.

compound effect in reducing them in size. On the other hand, the glaciers can grow in size and chances of their advancement will be higher when precipitation increases and temperature does not change.

## 8.0 CONCLUSIONS

The basic objective of this study is to assess the impacts of various climate scenarios on the hydrological response of the high altitude Spiti river in the Himalayas. The climatic scenarios were constructed on the basis of simulations of the Hamburg coupled atmosphere-ocean climate model for the study region. The influence of these scenarios on the snow water equivalent, snowmelt runoff, glacier melt runoff, total streamflow and their distribution have been studied. The adopted changes in temperature and precipitation ranged from 1 to 3°C and -10 to +10 %, respectively. The following conclusions are drawn from this study:

*1.* Snow water equivalent over the study basin reduces with an increase in air temperature (T+1, T+2, T+3°C; P+0%). However, no significant reduction in annual SWE is observed for these projected increases in air temperature over the basin. It seems the high altitude and low temperature regime of the basin limited the reduction in SWE. An increase of 2°C in air temperature reduced annual SWE in the range of 1 to 7% (T+2°C, P+0%). The changes in SWE are found proportional to the changes in precipitation. Maximum reduction in annual SWE (13-18%) is found under a T+3°C, P-10% scenario.

*2.* Under warmer climate scenarios (T+1, T+2, T+3°C; P+0%), snowmelt runoff, glacier melt runoff and total streamflow indicate early response along with change in their runoff distribution over time. All these hydrological components linearly increase with an increase in temperature from 1-3°C. The most prominent effect of temperature increase has been noticed on glacier melt runoff as compared to snowmelt runoff and total streamflow. An increase of 2°C in air temperature has increased annual snowmelt runoff, glacier melt runoff and total streamflow ranging from 4-18%, 33-38% and 6-12%, respectively. Maximum increase in snowmelt runoff (19-41%), glacier melt runoff (53-64%) and total streamflow (16-24%) are observed corresponding to (T+3°C, P+10%), (T+3°C, P-10%), (T+3°C, P+10%) scenarios, respectively.

*3.* The snowmelt runoff and total streamflow increases linearly with changes in precipitation, but glacier melt runoff is inversely related to changes in precipitation (P-10 to P+10%) for different temperature scenarios (T+1,T+2,T+3°C). It is found that snowmelt runoff is more sensitive than glacier melt runoff to changes in precipitation. A general long-term effect of temperature and precipitation changes on the glaciers can be addressed on the basis of present results. An increase in air temperature or decrease in precipitation for a longer time will reduce the size of glaciers due to higher melt runoff from them. They may retreat because of their faster depletion under warmer climate. The study suggests that a combination of increase in temperature and decrease in precipitation will provide a compound effect in reducing their size. However, under higher precipitation scenarios, the glaciers might grow in size and result in their advancement.

*4.* The seasonal analysis of total streamflow indicates that increase in temperature, (T+1,T+2,T+3°C; P+0%), can produce a large increase in the pre-monsoon season streamflow followed by an increase in the monsoon season. Post-monsoon and winter streamflow are not affected significantly by increase in temperature. No significant changes in the winter streamflow are found for this river.

*5.* Similar studies should be carried out on basins located in different geographic and climatic regions to investigate potential impacts of projected climate warming on hydrology and water resources in India.

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