CASE STUDY

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IMPACT ASSESSMENT STUDIES

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PREFACE

There has been a growing concern of the scientists and policy makers on the subject of climate change and its possible impacts on man and biosphere. The hydrologists have been specifically interested in the temporal and spatial redistribution of components of hydrologic cycle in the changed climate and the water availabilty in future for different purposes. With the initiation of various activities by WMO (including WCP - Water) in this particular area, a number of groups in the world have carried out sensitivity of different basins/regions lying in different hydroclimatic zones.

Realizing the importance of the subject area, the National Institute of Hydrology has also initiated some studies in this area. These studies pertain to impact of climate change on hydrology in Indian context. This report has been prepared to observe the sensitivity of four Indian basins to expected climatic changes, as revealed by Global Climate Models. The report has been prepared by Shri R. Mehrotra, Scientist 'C', Dr. Divya, Scientist 'C' and Dr. Ashok K. Keshari, Scientist 'B' of Atmospheric Land Surface Modelling Division.

(S. M. Seth)
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ABSTRACT

Climatic change due to increase in greenhouse gases and its impact on hydrology of different regions/basins located in various hydroclimatic zones has received considerable attention during the recent decade. The probable impact on runoff, evapotranspiration and soil moisture, and their temporal and spatial redistribution may lead to severe consequences upon water related activities such as - agriculture, drinking water supply, electric power generation etc. The impact studies are mainly based upon the application of output from the Global Climatic Models (GCMs) (either as the scenario or disaggregation of the output to the local scale) to the regional hydrologic models.

The present study deals with the sensitivity analysis of four basins namely Damanganga, Sher, Kolar and Hemavati, lying in different agroclimatic zones to expected changes in temperature and precipitation. The temperature and precitation data obtained as output from the three GCMs - CSIRO9 (resolution of $3.2^\circ \times 5.6^\circ$), ECHAM1 (resolution of $5.625^\circ \times 5.625^\circ$) and MPI (resolution of $2.812^\circ \times 2.812^\circ$) have been used for current (present day, $1 \times CO_2$) and anomaly (doubling of CO_2 or by the year 2080 under IPCC Business As Usual scenario) runs. The precipitation data obtained at GCM grid points within or near the basins has been disaggregated to the basin values using a disaggregation model. The disaggregated output has been applied to a monthly rainfall-runoff model, and the sensitivity of these basins to expected climatic changes has been studied. The sensitivity of different basins has been found to be different.

Sensitivity analyses reveal that temperature rise in different basins due to increased greenhouse gases (by the year 2080) will be within the range of 1-4 °C for all four basins. Rainfall will increase during all seasons for Damanganga, Sher and Kolar basins. Substantial increase is expected in nonmonsoon seasons. However, monsoon rainfall in Hemavati basin appears to decrease by an appreciable amount, although marginal difference is observed in annual budget. Most of the rainfall in Hemavati basin is expected to occur during the beginning of the monsoon period. Impact of climatic change on other hydrologic parameters, runoff, evapotranspiration and soil moisture establishes that basin aridity is positively associated with basin sensitivity, and the degree of sensitiveness depends upon the degree of aridity of the basin. Kolar (moist subhumid) and Sher (dry subhumid) seem to be comparatively more sensitive to climate change, whereas Damanganga (humid) seems to be the least sensitive. The reliability of the findings depends upon the uncertainties associated with the analysis and the limitations of the study, discussed in the report. No doubt, long length of data will improve the findings. Before going for more detailed impact studies on economic and socioeconomic factors, regional sensitivity studies are needed to pursue in more regions of India which vary widely in climatic condition.

1.0 INTRODUCTION

Many scientific studies warn of a rapid global climate change during the next century as a result of increased greenhouse gases in the atmosphere (NRC, 1979, 1983,1987; Ramanathan, 1988; Houghton et al., 1990; IPCC, 1990,1992). These all suggest that the effects of greenhouse warming will become dominant over the natural variability of the climate including the effects of volcanic eruptions, El Nino/Southern Oscillations (ENSO), internal atmospheric and oceanic circulation variations and possible solar variations, and all agree that surface temperature will rise, precipitation patterns will change and sea level will rise. The above findings are mainly based upon the results of the Global Climate Models (GCMs), which have been used as the tool for predicting future climate change.

Water resources and the hydrological cycle are largely controlled by climatic factors including precipitation, humidity, temperature, wind speed and solar radiation. Water supply and control system components including reservoirs, spillways, storm sewers, flood protection structures, and rules and protocols defining their management, are dependent on local climate and hydrologic patterns (Moss and Tasker, 1987; Riebsame, 1988). Changes in climate conditions can therefore affect surface water and ground water availability, quality and value for such diverse uses as irrigation, water supply, electric power production, support of aquatic ecosystems and fisheries.

Even though such projections of the future climate are relatively crude, it is important to begin the assessment of their impact on humans and the biosphere. The results of current impact analyses, even if imperfect, will be useful in design of future water resource projects. This will guide the modellers to produce parameters that will be needed by society to develop policies to minimize the impacts of climate change on hydrology and water resources in particular.

1.1 Climate change and regional hydrology

Many attempts have been made to find out the trend in the mean temperature observations over land (Diaz and Quayle, 1980; Jones *et al.*, 1982, 1986; Vinnikov *et al.*, 1980; Hansen *et al.*, 1981). The steady increase in greenhouse gases has resulted in enhancing the greenhouse effect and thus global warming. The near-surface air temperature has increased by about 0.5° C since the late 19th century (Jones *et al.*, 1986; WMO, 1987) which is roughly consistent with calculated CO_2 warming (Hansen *et al.*, 1981). The striking feature, however, is that the inter-annual variability of global temperature is much larger than the trend. According to the IPCC Business - as - Usual (BAU) scenario (scenario A), it is expected that global surface temperature may 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).

Many studies on hydrological impacts of climate change have been carried out in different parts of the world by many workers. Studies on changes in annual and seasonal runoff have pointed to a greater sensitivity of river watersheds even to insignificant changes in climatic characteristics, specially for watersheds located in arid and semi-arid regions (Lins *et al.*, 1990). Since last two decades, a period of progressive desiccation is noted over Sahel and Sudan. The available evidence supports the view that Sahelian drought is an aspect of climate variability.

The possible impacts of climate change on hydrological regime include : increase in summer evaporation, more rainstorms caused by increased convective precipitation in summer months, increased intensity of tropical storms and increased monsoon rainfall in tropics (IPCC, 1990).

1.2 Need for establishing the impacts of climate change

Changes in climatic conditions due to increasing atmospheric concentrations of radiatively active trace gases will probably alter land and water resources, their distribution in space and time, the hydrologic cycle of water bodies,. water quality, and water supply systems and requirements for water resources in different regions. Probably the most important implications of climate change for water resources arise through the effects on droughts and floods, both their frequency of occurrence and their severity. Such changes could have potentially devastating results. A gradual change in mean runoff, by comparison will probably be accompanied by a progressive adaptation by the economic sectors affected, such as agriculture. However, for such sectors as agriculture, large changes in the seasonal distribution of hydrological variables might create problems that could only be adapted to at great expense, if at all. The primary areas of impact include physical security (as related to dam safety and flood protection works), drinking water supply, agriculture, energy supply, and international (political) security (due to climate - change - induced changes in water supply, in cases where rivers cross national boundaries). The probable serious impacts of climate change have lead the scientists and the policy makers to establish the impacts of climate change for different regions.

In the present study, the sensitivity analysis of four basins namely Damanganga, Sher, Kolar and Hemavati basins lying in different agroclimatic zones to expected changes in precipitation and temperature has been made. The output of the three GCMs - ECHAM1, MPI and CSIRO9 model has been studied and most realistic one is selected and used to study the sensitivity of runoff, evapotranspiration and soil moisture to climate change due to increase in greenhouse gases in these basins. Since the GCM output considers the temporal and spatial variation of climate change, useful information on temporal redistribution of runoff, evapotranspiration and soil moisture due to changes in temperature and precipitation in these basins could be obtained in the present study.

2.0 IMPACTS OF CLIMATE CHANGE ON HYDROLOGY OVER INDIA : A REVIEW

As the problem of global warming and its impacts has received considerable attention globally, some work in this direction has been recently initiated in India also.

Groisman and Kovyneva (1989) assessed the impacts of climate change on Indian hydrology by using a set of statistical estimates for the parameters describing the relationship between changes in global climatic variables and those in local climatic characteristics for different seasons of the year. They used annual mean surface air temperature averaged over the extra tropical zone of the northern hemisphere as a global variable. They observed that increase in mean annual surface air temperature is resulted in an increasing precipitation totals over entire India, specially along the western coast of the subcontinent.

Based upon the results from high resolution general circulation models, IPCC (1990) report for Indian sub-continent states that by 2030 on Business-As-Usual (BAU) scenarios (if few or no steps are taken to limit greenhouse gas emissions) "The warming varies from 1^{o} to 2^{o} throughout the year. Precipitation changes little in winter and generally increases throughout the region by 5 to 15% in summer. Summer soil moisture increases by 5 to 10%".

Lal *et al.* (1992) studied the impact of increasing greenhouse gas concentrations on the climate of the Indian subcontinent and its variability analyzing the GCM output data of Hamburg global coupled atmosphere - ocean circulation model with a resolution of 300 x 300 km^2. The model results obtained from the greenhouse warming experiment suggested an increase of over 2^{o} K over the monsoon region in the next 100 years. The model simulated an increase in total (averaged for the study area) seasonal precipitation. However, any significant precipitation change could only be isolated over some area. Lal *et al.* did not find any evidence for a significant change in the mean monsoon onset date or in its inter - annual variability in a warmer world. Lal and

Chander (1993) have assessed that an enhanced surface warming over the Indian subcontinent by the end of next century would result in more runoff in northeast and central plains during monsoon, with no substantial change during the winter season. The results, however, have a low confidence.

Using the above model, Lal and Bhaskaran (1993) examined the possible changes on the climate of north-west India (Thar desert) due to greenhouse warming. The results point to a pronounced warming and associated enhancement in evaporation rate without any significant change in precipitation over the region over the next 100 years. This may lead to enhanced aridity over the Thar desert and could have strong implications for the hydrology and water resources in this region.

Divya and Jain (1993) carried out a sensitivity analysis of the response of a catchment situated in central India to expected climatic changes using the scenarios of climatic change and a regional model. They found that the changes in runoff were more dramatic for the months when the runoff was already very small.

Since the results of study for one catchment can not be directly applied to other catchments, more similar studies were taken up (Mehrotra and Divya, 1994 a, b, c). The sensitivity analysis indicated that basin located in comparatively drier region was more sensitive to climatic changes. Also, basin characteristics such as soil type, its moisture holding capacity and runoff coefficient play an important role in deciding the basin response. To study the effect of climate variations on the design and operation of water resources projects, the response of hypothetical reservoirs of two drainage basins, Kolar and Sher, of India to climate variations was studied (Mehrotra *et al.*, 1994). Series of streamflows under different adopted climatic variations were derived and used in modelling the influences of these variations on reservoir storage. Results of the study indicated high probability of significant effect of climate change on reservoir storage.

For more details the reader is referred to Divya and Mehrotra (1995).

3.0 EXISTING PRACTICES FOR EVALUATION OF HYDROLOGICAL IMPACTS OF CLIMATE CHANGE

Various practices have been followed for evaluating the hydrologic consequences of future anthropogenic climate change of different regions of many countries . The studies may be grouped under the following two methodological approaches :

1) Statistical approaches - In this approach, a co-relation structure among various hydrological processes such as rainfall, runoff, air temperature etc. has been formulated statistically. Using this approach studies have been carried out for some regions of US and the annual river runoff in the USSR.

In another approach , the hydrologic consequences for the past very warm or cold, wet or dry years periods have been studied. The analysis has been carried out for the US and for the northern China. Studies have also been made for some regions of the Sahelian zone using this approach.

2) Deterministic approaches - Climatic variation of large regions has been calculated from the GCMs, based upon the increase in the concentration of greenhouse gases.

The GCM results are used as an input to some appropriate deterministic / conceptual type water balance model to predict the future possible changes in hydrologic conditions. Alternatively some hypothetical set of data based upon GCM findings may be used as an input to these models to study future scenarios. This is the most popular approach and has been used by many workers for basins located in various hydroclimatic environments.

Another approach uses the water balance of a basin over a long period of time. Future total evaporation is estimated in this approach. These methods have been used for the studies in the USSR and for the New Zealand.

The results obtained in hydrologic simulations based on different GCMs results only, are inconsistent for certain important hydrologic conditions and regions. This can be attributed to the low resolution of the current generations of GCMs (resolution of approx. 500 x 500 km^2) and to the simplified description of hydrologic processes.

4.0 USE OF GCM OUTPUT FOR IMPACT ASSESSMENT STUDIES

The use of GCM output to evaluate the hydrological impacts of anthropogenic climate change has gained considerable attention in the recent years. The predictions/forecasts of changes in climatological parameters, specially air temperature and precipitation for different regions and periods of time are needed to evaluate the hydrological effects of climate change. However, the accurate forecasts of regional climatic changes are still not available. In their absence, the output from global climatic models can be used in two ways to evaluate the hydrological impacts :

(a) development of climate change scenarios and their use in hydrological models;

(b) disaggregation of GCM output for present day and anomaly runs (i.e. either at doubled CO_2 case or future projections after 100 years) to a basin.

4.1 Development of climate change scenarios

The global climate models developed by different groups namely Oregon State University (OSU), National Centre for Atmospheric Research (NCAR), Goddard Institute for Space Studies (GISS), Geophysical Fluid Dynamics Laboratory (GFDL), United Kingdom Meteorological Office (UKMO), CSIRO Australia, Max Planck Institute Germany and groups in USSR and Canada have been used for creating ranges of scenarios for studying impacts of climate change worldwide (Smith, 1989).

In order to create scenarios for individual locations, at least five related approaches have been recently suggested. Ackerman and Cropper (1988) described an overall framework for combining GCM output, local climatology, and expert judgement to create scenarios. In their procedure, if a GCM does an adequate job of simulating the current climate, or if the GCM does not do a good job but the bias is understood, the GCM information is used directly to create scenarios. Four recent papers, providing techniques to accomplish this, assume that the regional scale GCM output has some useful information, and suggest ways to go from the large GCM scale down to local scale. Wigley et al. (1990) evaluated multiple linear regression techniques for calculating sub - grid scale information. Turco (1988) suggested a method for using seasonal cycle to scale the local changes from GCM output. Karl et al. (1990) developed a statistical technique employing empirical orthogonal functions to obtain local information. Smith (1989) has actually used simple procedures, such as adding the $2 \times CO_2$ - $1 \times CO_2$ GCM results and transient GCM differences to observed data, to create scenarios for United States impact studies. However, none of these techniques provide guidance on creating scenarios if the GCMs do such a poor job that the $2 \times CO_2$ $-1 \times CO_2$ results cannot be trusted, since the model errors resulting in the poor $1 \times CO_2$ simulations are still inherent in the $2 \times CO_2$ results.

4.2 Spatial disaggregation of GCM output to a basin

Current projections of global change have been developed from large scale, physical atmospheric global climate models that attempt to describe atmospheric response to CO_2 forcing.

Presently, due to computational limitations, most GCMs operate globally with a resolution ranging from $2^{o} \times 2^{o}$ to $10^{o} \times 10^{o}$ latitude/longitude. The resulting climate projections from these models cannot be directly used as input for models at the resolution of interest to hydrologists. The hydrologic processes of interest commonly occur at scales on the order of tens to thousands of square kilometers. At these scales, spatial variability, geomorphology, and other mesoscale and local-scale processes tend to dominate resulting climatic regimes. The difficulty, then, arises in developing localized hydrologic responses to global-process changes.

In the recent years, a number of studies have been carried out on impacts of climate change using the spatial disaggregation of GCM output. Giorgi and Mearns (1991) provided a relatively complete overview of historical techniques applied to this spatial resolution problem as it pertains to catchment hydrology. The methodologies typically used for analysis of local hydrology, ranging from stochastic analysis of historical climates and paleoclimates to adjustment of historical climate by a mean change in state, frequently do not account for temporal variability in climate fields, and never account for spatial variability. More recent works (Hay et al., 1992; Barros and Lettenmaier, 1993; Bardossy and Plate, 1992) have attempted to account for scale issues. Hay et al. proposed a stochastic disaggregation model for weather-type analysis, in which precipitation fields were regressed on weather type in the Delaware basin. Barros and Lettenmaier applied multigrid methods to describe interactions between land-surface influences and large-scale circulations. In their procedure, an orographic precipitation model was coupled to a surface energy model to predict latent and sensible heat fluxes. Bardossy and Plate developed a site-specific precipitation model that accounted for spatial and temporal intermittence conditioned on large-scale circulations. In addition, limited application of cascading GCM output to mesoscale precipitation models, and then to deterministic rainfall runoff models was presented by Avery and Leavesely (1988).

Epstein and Ramirez (1994) applied directly the empirical disaggregation techniques to both temperature and precipitation data for application in resolving GCM output to regional and local climate regimes. They explored the hydrologic response of the upper Rio Grande basin to climate-change forcing by application of resulting localized climate to the Precipitation Runoff Modeling System (PRMS) of the U.S. Geological Survey (USGS). Using a two-level disaggregation scheme they used the grid data from the Canadian Climate Centre's (CCC's) GCM. Grid data overlaying the state of Colorado were first disaggregated into regions of distinctly similar seasonal climate regimes. These regions were next disaggregated into data sets corresponding to individual climate stations within Colorado.

5.0 PRESENT STUDY

5.1 Study Area

Study area comprises of four basins namely Damanganga, Sher, Kolar and Hemavati basins. General description of the study area is given in Table 5.1. The index maps of these basins showing the locations of gauge discharge and rain gauge stations are given in Figures 5.1 to 5.4.

5.1.1 Damanganga basin

The Damanganga river rises in the Sahayadri hill ranges of the Nasik district of Maharashtra at an elevation of 950 m and traverses a distances of 131 km before it drains into the Arabian sea. The catchment area of the river can be physiographically divided into five units; hill slopes, hill plateaus, upper and lower foot slopes, valley plains and local depressions, river and stream banks.

No detailed soil survey has so far been conducted in this basin. However, the information available from different sources shows that the soils of the basin can be broadly grouped into three groups viz., black soils, red soils and mixed soils.

The average forest area in the basin is about 41.4% of the geographical area. The agricultural area is about 36.3% of the total geographical area, agriculture being the main occupation of the people in the basin. The total area under irrigation is 1.97% of the total cultivable area and 0.92% of the geographical area of the basin. Irrigation is mainly from wells and minor irrigation.

5.1.2 Sher basin

The river Sher is fairly big tributary of river Narmada. It rises in the southern Satpura range in the Durg district of M.P. at an elevation of 600 m above sea level. The catchment area upto the confluence point of Sher with Narmada is about 2900 sq km. However, the Central Water Commission has established a

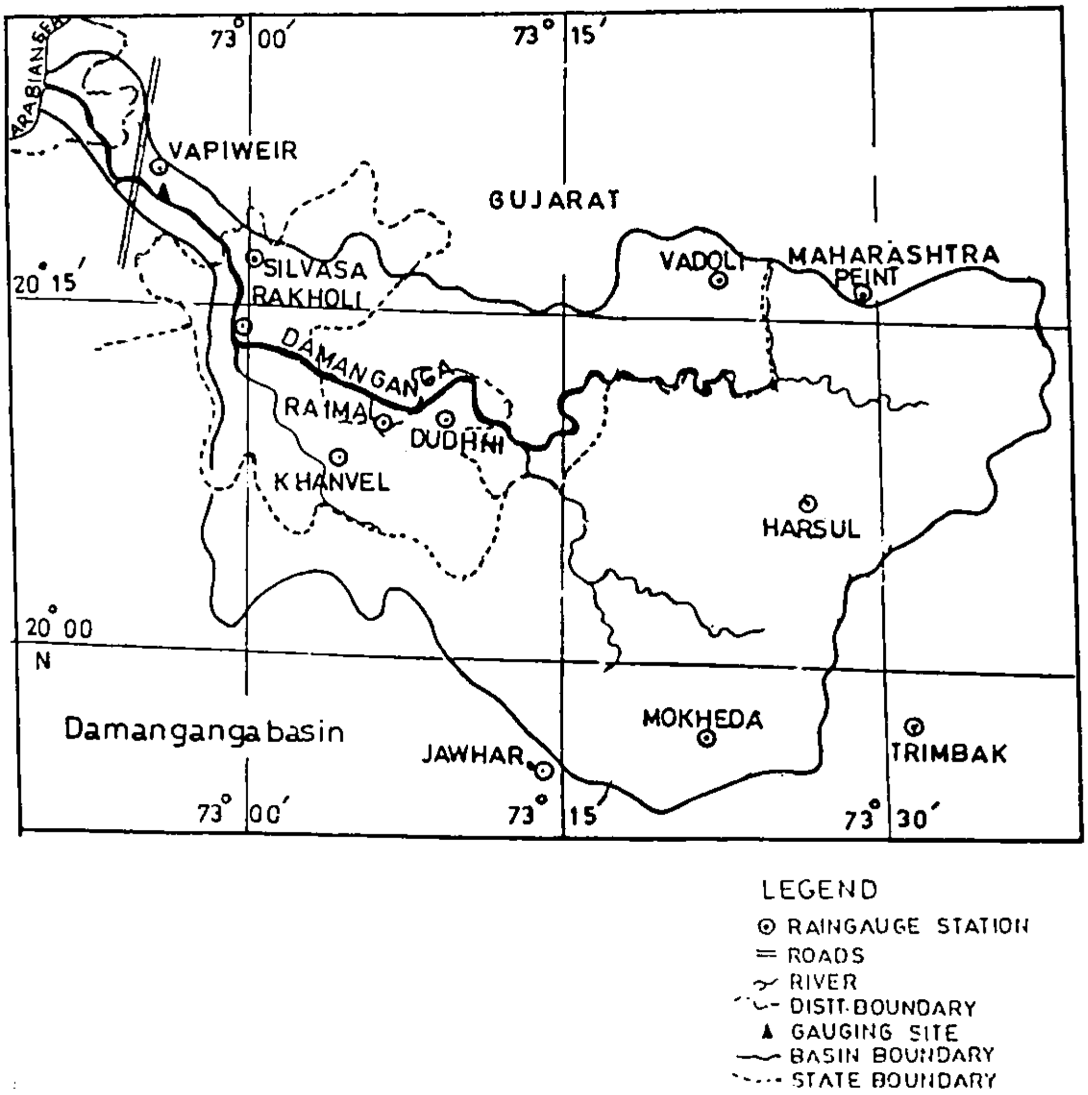
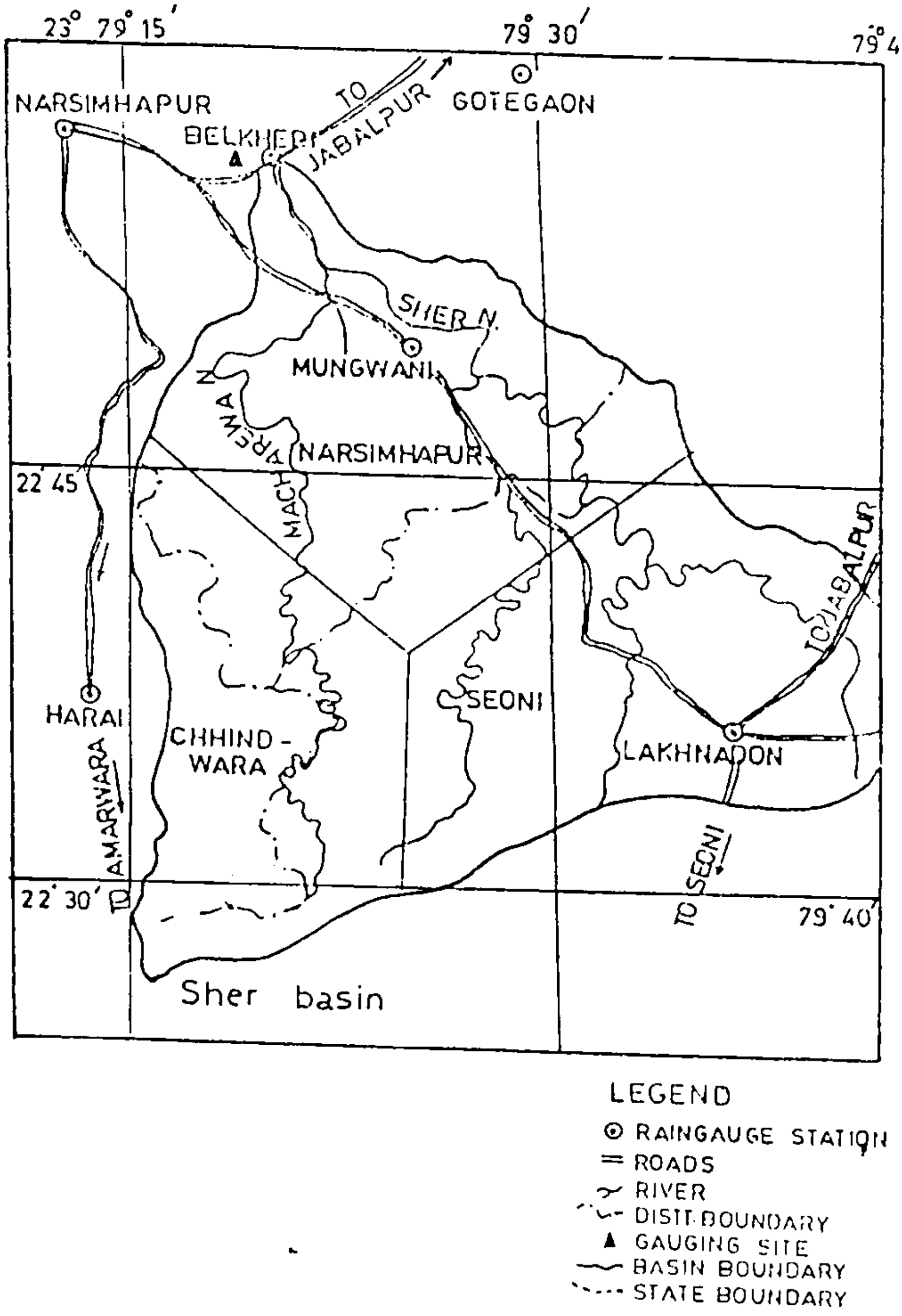


Fig. 5.1 Index map of Damanganga basin, upstream of the Vapi gauging station


23°
79° 15′
79° 30′
79° 40′
NARSIMHAPUR
TO JABALPUR
GOTEGAON
BELKHERI
SHER N.
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YREWA
NARSIMHAPUR
MACH
22° 45′
TO JABALPUR
SEONI
HARAI
CHHINDWARA
LAKHNADON
AMARWARA
TO
TO SEONI
22° 30′
79° 40′
Sher basin
LEGEND
⊙ RAINGAUGE STATION
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BASIN BOUNDARY
STATE BOUNDARY

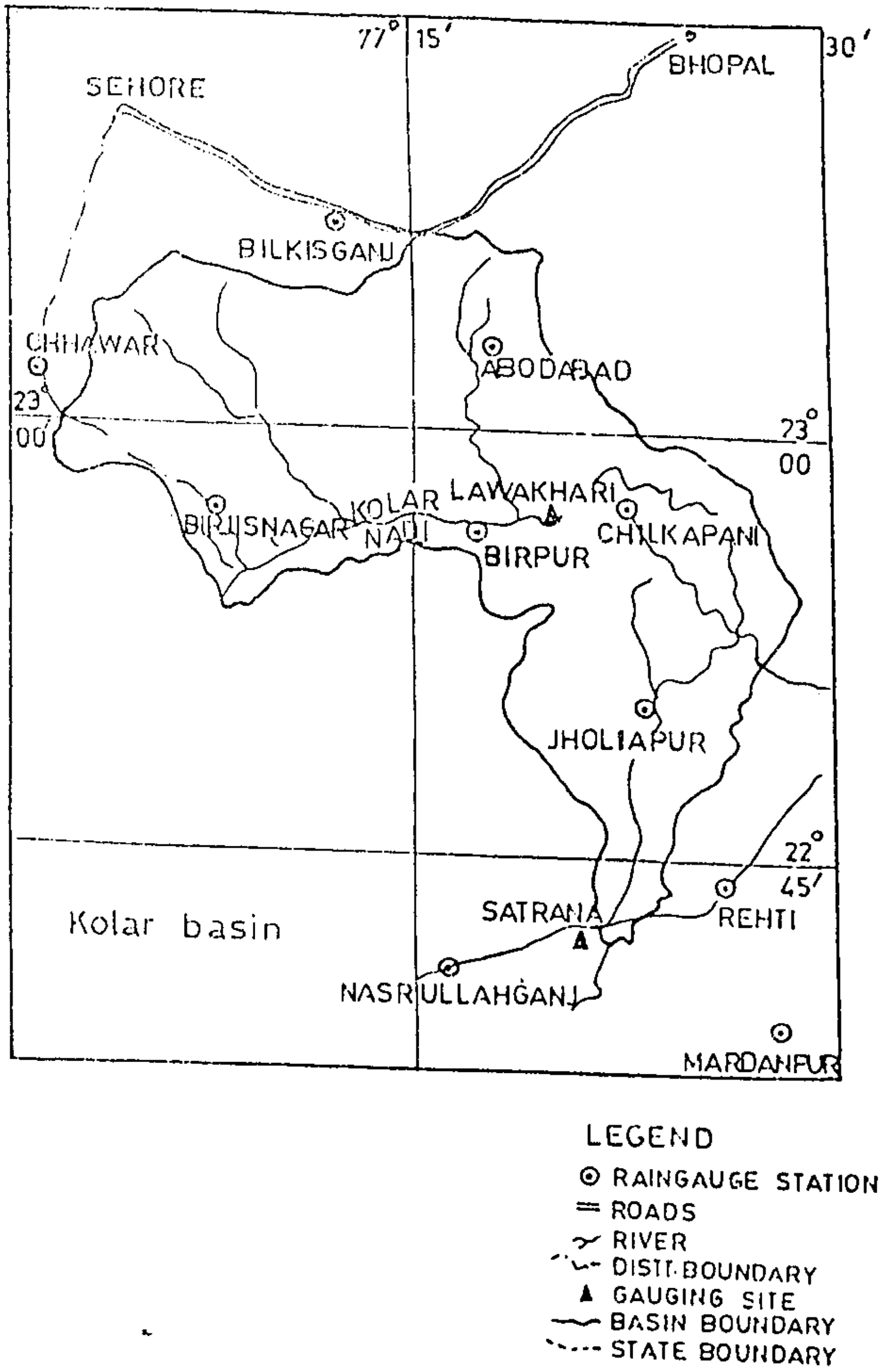

Fig. 5.3 Index map of Kolar basin, upstream of the Satrana gauging station

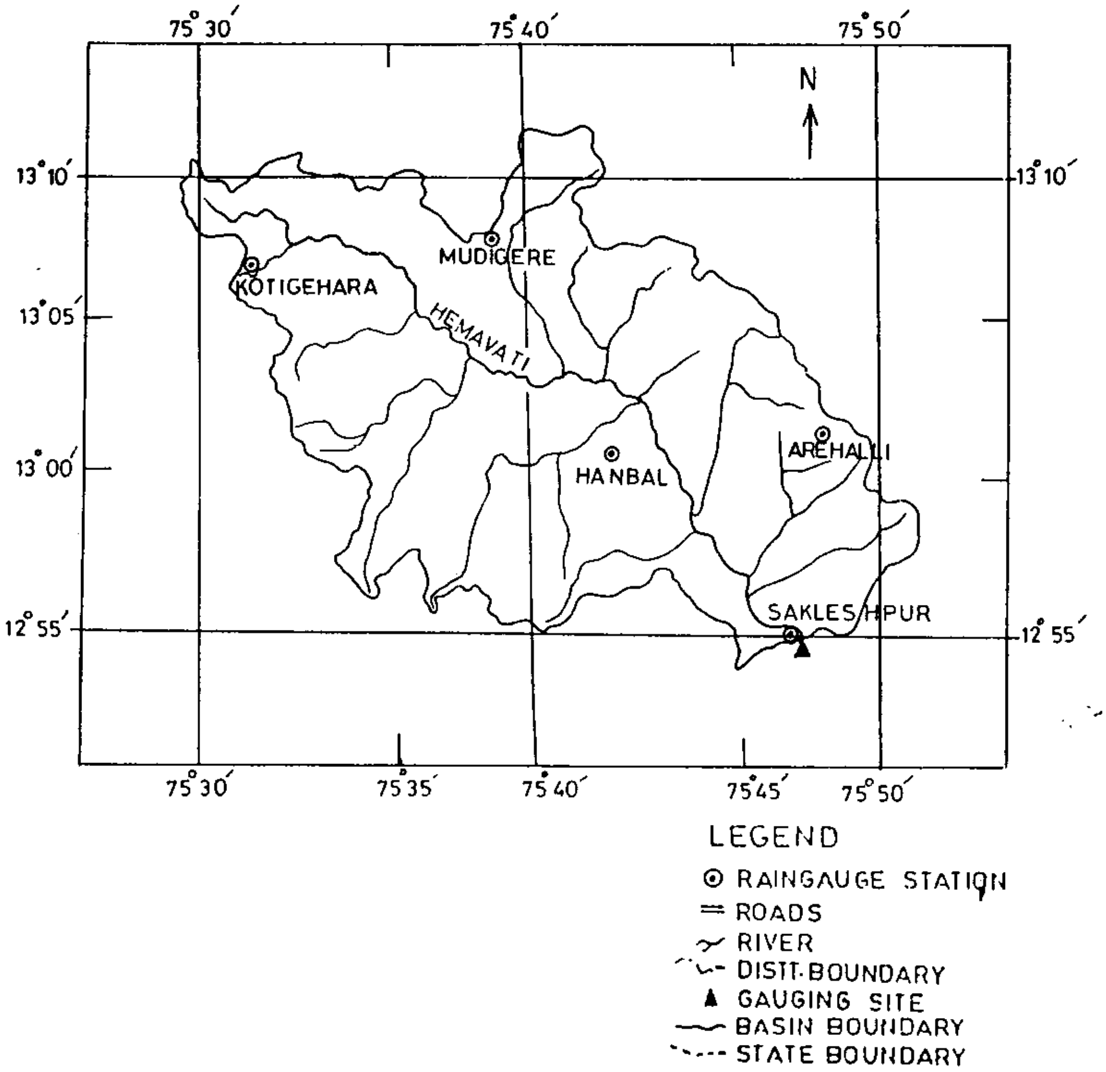

Fig. 5.4 Index map of Hemavati basin, upstream of Sakleshpur gauging station

gauging site at Belkheri, upstream of the confluence covering about 1500 sq km of Sher basin. The basin lies in the districts of Narsimhapur, Chindwara and Seoni in Madhya Pradesh.

The Sher basin is identified with hilly terrain and is heavily intersected by streams and rivers. The vegetation of the basin consists of forest of medium density, scrub land, spread pockets of cultivation on undulating land and some denuded land. At present, there is no major water resources activity in the Sher basin.

5.1.3 Kolar basin

The Kolar river originates in the Vindhyachal mountain range at an elevation of 550 m above sea level (msl) in the district Sehore of Madhya Pradesh (M.P.) state. The river, during its 100 km course first flows towards east and then towards south before joining the river Narmada near a place named Neelkanth. During its course, the Kolar river drains an area of about 1350 sq. km.

The upper four-fifth part is predominantly covered by deciduous forest. The soils are skeleton to shallow in depth except near channels, where they are relatively deep. The channel beds are rocky or graveled. Agriculture activity is carried out in relatively large areas in the north western part and in small pockets elsewhere in which the main crops are wheat and grams. The general response of this upper part of the catchment to rain appears to be quick.

Lower part of the catchment is predominantly cultivable area. The soils are deep in this area and ground slopes are flat. The response of this area to input rainfall appears to be moderate. Part of this area comes under the command of Kolar dam.

5.1.4 Hemavati basin

The Hemavati, one of the important tributaries to join river Cauvery on its northern bank, takes its origin near Javali in Mudighere taluk of Chikmagalur district in Karnataka and follows the south easterly course. The study area upto the gauging site at Sakleshpur is about 600 sq km and the total length of the Hemavati river upto the gauging site is around 55 km.

The climate during the summer months viz., March to May is generally cool, healthy and agreeable. Rainy season extends from June to October and is characterized by heavy to very heavy rainfall.

The principal soil types found in the basin are red loamy soils and red sandy soils. Soils in the forest area and coffee plantations are greyish due to high humus content. Agriculture and plantation are the main industries in the basin. Principal crops grown are coffee, paddy and cardamon. About 60% area of the basin is covered by unirrigated crop land, 29% by coffee plantations and 12% by forests. The main source for ground water in the basin is atmospheric precipitation and the agriculture is rainfed.

Table 5.1 General description of the study area

Basin name	Damanganga	Kolar	Sher	Hemavati
Latitude	19°45′ to 20°20′	22°40′ to 23°08′	22°25′ to 23°55′	12°55′ to 13°11′
Longitude	72°40′ to 73°40′	77°01′ to 77°29′	79°15′ to 79°40′	75°29′ to 75°51′
Elevation	950 m to 0 m	600 m to 300 m	1110 m to 450 m	1240 m to 890 m
Normal rainfall	2212 mm	1210 mm	1255 mm	2972 mm
Data availability	1974-83	1983-88	1978-86	1975-81
Area	2261 sq km	820 sq km	1500 sq km	600 sq km
Region	Humid	Moist sub humid	Dry sub humid	Humid
Location	Central India	Central India	Central India	Southern India

5.2 Methodology

One of the promising approach to study regional hydrological impacts of climate change particularly suited to Indian conditions, considering the climatic variability and data availability, its reliability, quality and length, also infrastructure and computing facilities available, is the use of the regional hydrologic models.

In the methodology adopted here, GCM output at various grid points within/outside the basin corresponding to current values (1 × CO_2) and anomaly values (2 × CO_2 level or by the year

2080) is collected. Output at various grid points are averaged inversely proportional to the distance to get average GCM value at centre of the basin. Only precipitation values are considered in the analysis as for all the basins, temperature is measured only at one station located mostly outside the basins. Observed normal monthly precipitation values are compared with the normal monthly values obtained from various GCMs corresponding to current values and the GCM results which are nearer to the observed values are considered for further analysis. Using the disaggregation technique a correlation between the individual station values and average value of precipitation for the basin is established. Then, using this correlation, average GCM output (for anomaly run) for the basin is disaggregated to get corresponding precipitation values of different stations. Now precipitation values corresponding to anomaly run at different stations within/outside the basin are available. A simple distributed rainfall-runoff model, which has been calibrated using existing rainfall and runoff data of the basin is taken and the results as obtained above are fed to this rainfall-runoff model to get runoff, evapotranspiration and soil moisture etc. corresponding to this input. Average temperature increase during the whole year is considered as the temperature increase in the above analysis. A brief description of the rainfall-runoff model and the disaggregation model used in the present study is given below:

5.2.1 Rainfall - runoff model

A monthly conceptual rainfall-runoff model developed at NIH is used in the present study. The model is distributed in nature in the sense that here instead of considering the average

of precipitation at different stations and then computing the runoff, runoff is computed first from the indiviudal station precipitation and then its average is calculated. The model is
(15) considered to be comprised of soil and ground water storages. Based on the given initial moisture conditions for each storage elements and input variables, the water balance equations are solved station wise conceptualizing the hydrological processes
(16) which govern moisture movement from one element to another. The monthly runoff values for each area represented by the station are obtained as one of the important outputs of the model., Model has seven parameters, out of which five parameters relate to soil characteristics. The model parameters can be calibrated from the
(17) historical records of monthly rainfall, potential evapotranspiration at each station and total runoff of the catchment. Model structure has been finalised after making several permutation and combinations while conceptualizing the different hydrological processes. It was also observed that a complex model structure consisting of a large number of parameters could not improve the simulation results much. The sequence of processes considered in the model are described here under.

Monthly ariel precipitation at different stations is a basic input to the model. In the flow processes first priority is accorded to fast surface runoff (FSR). If precipitation (PPTN) is greater than a threshold value of soil moisture (THRES) , fast surface runoff occurs.

$$\text{If} \quad PPTN > THRES \qquad \text{then} \quad FSR = PPTN - THRES \tag{1}$$

$$\text{Otherwise} \qquad FSR = 0 \tag{2}$$

$$\text{Final moisture} \qquad PPTN\ (f) = PPTN + SFS - FSR \tag{3}$$

Where, SFS is initial surface storage available at the beginning of the month.

Second priority is accorded to infiltration (INF). For infiltration minimum and maximum infiltration rates are defined. If soil is fully saturated or moisture is available the minimum infiltration INFMIN occurs. For other conditions infiltration occurs according to exponential decaying function as under:

$$\mathrm{INF} = \mathrm{INFMIN} + (\mathrm{INFMAX} - \mathrm{INFMIN})*\mathrm{EXP}\left(- \frac{(\mathrm{SMS} * \mathrm{INFMIN})}{(\mathrm{INFLMT} - \mathrm{SMS})}\right)$$

with the condition that

INF can not exceed PPTN (f).

Where, SMS = initial soil moisture storage at the beginning of the month and INFLMT is a soil saturation capacity i.e. the maximum volume of water that a soil can hold, and INFMAX is the maximum possible infiltration.

$$\mathrm{PPTN}(f) = \mathrm{PPTN}(f) - \mathrm{INF}$$

Third priority is given to quick surface runoff (QSR). It occurs from the impermeable area of the catchment and vary with the soil moisture deficit. The algorithm which describes this process is ;

$$\mathrm{QSR} = \mathrm{PPTN} * \mathrm{IMPRM} + (1 - \mathrm{IMPRM})*(\mathrm{PPTN}**(\ \mathrm{SMS}/\mathrm{FC})$$

Where, IMPRM is the max impermeable fraction of the catchment when the soil is fully saturated and,

FC = Field capacity of the soil

If $QSR > PPTN(f)$ then $QSR = PPTN(f)$ and $SFF = 0.0$ (7)

Otherwise

$SFF = PPTN(f) - QSR$ (8)

Soil storage : Input to this storage is infiltration (INF) and output from this storage includes evapotranspiration (AE) and deep percolation (DP). In this storage first priority is accorded to evapotranspiration. If soil moisture (SM) is greater than FC, evapotranspiration occurs at potential rate (EV), otherwise at a lesser rate that too from permeable portion of the catchment.

If $SM > SMAX1$ then $AE = EV$ (9)

Otherwise $AE = (1 - IMPRM) * EV * SM / FC$ (10)

SM is calculated as,

$SM = 0.5 * FIN + SMS$ (11)

Final soil moisture is

$SMF = SMS + FIN - AE$ (12)

Now if soil moisture after satisfying demand of evapotranspiration is greater than the field capacity (FC) of the soil, the deep percolation (DP) occurs. On the other hand if soil moisture after checking or satisfying the requirement of evapotranspiration is less than the field capacity of the soil then DP is zero.

If $SMF > FC$ then $DP = SMF - FC$ (13)

and $SMF = FC$ (14)

otherwise, $DP = 0.0$

Ground water storage : Input to this storage is deep percolation (DP) from the upper soil storage zone and output is base flow (BF). BF is a percentage of ground water storage

BF = CBF * (DP/2. +GWS)

Where, CBF = a constant governing the flow of ground water and,

GWS = initial ground water storage.

Final ground water storage (GWF) is;

GWF = GWS - BF

(4) Computed runoff at the end of month, from the area represented by that station is sum of QSR, FSR, DSR and GWF.

$$Q_{comp} = QSR + FSR + DSR + GWF$$

Similarly for other stations the process is repeated. Final computed runoff of the catchment is the weighted average of the computed runoff of individual stations.

(5) The model has been successfully applied to simulate the discharge of Damanganga, Sher and Kolar basins and for carrying out sensitivity analysis of these basins using climate change scenarios (Mehrotra and Divya, 1994).

5.2.2 Disaggregation model

(6) Various statistical techniques which permit the interpolation of GCM output down to local scale are discussed in the NIH report titled 'Comparison of disaggregation techniques'(NIH, 1995). As per the discussions of the report disaggregation technique which was found to be the most suited one

is used in the present analysis. For detailed description of these techniques, above mentioned report may be referred. Here disaggregation technique is described only in brief.

Disaggregation technique was primarily proposed by Valencia and Schaake (1973). The basic goal of any disaggregation model is to allow the preservation of statistical properties at more than one level.

General form of disaggregation model used in the analysis is :

$$Y = AX$$

Here, in our context X is the grid point value and Y is column matrix (ωx1) containing corresponding (ω) values at different stations located within/outside the basin. A(ωx1) is the parameter matrix .Parameter estimation of above equation is done by using the method of moments as follows:

$$A = S_{YX} S_{XX}^{-1}$$

Here, S_{YX} is the matrix of co-variances between the station values and the average basin value and S_{XX} is the matrix of co-variances among the average basin values.

In this approach first parameter estimation of the above equation is performed using the precipitation values for present climate at different stations and then the grid point value corresponding to a warmer climate is disaggregated using the above equation.

The monthly precipitation and temperature values obtained from the three GCMs at grid points were disaggregated to obtain the temperature and precipitation values for basins for present day and anomaly scenarios.

5.3 Data Used

5.3.1 Observed data

The monthly rainfall at four stations, namely Rehti, Jholiapur, Birpur and Brijeshnagar are used to determine the weighted average rainfall for the Kolar basin. The observed monthly discharge at Satrana is used in the analyses. Meteorological data (temperature, solar radiation, vapour pressure and wind speed) for Bhopal (class I observatory) which is about 20 km away from the catchment, are used to compute evapotranspiration.

The monthly rainfall data at the recording stations at Lakhandon, Harai and Jabalpur and the monthly discharge data of Belkheri gauging site are used in the study to obtain the rainfall for Sher basin. Values of meteorological parameters at Jabalpur station are used to compute evapotranspiration.

There are 12 raingauge stations in and around the Damanganga basin. Rainfall data of all the 12 stations are used to compute the weighted average monthly rainfall of basin. Runoff data at Vapi G and D measurement site are considered in the analysis. Data of IMD observatory located at Surat are utilised to compute the value of evapotranspiration as no station in and around the basin records the meteorological parameters.

The monthly rainfall data of five stations, Mudigere, Kotigehara, Sakleshpur, Hanbal and Arehalli has been used to compute the average monthly rainfall of the basin and the discharge data of the gauging station at Sakleshpur has been used to calibrate and validate the model. Since the meteorological data for the basin was not available, the pan evapotranspiration data of Bangalore, just outside the basin was used. It was assumed that the change in temperature by 1°C corresponds to a 4% change in potential evapotranspiration (Budyko, 1980; Nemec and Schaake, 1982).

5.3.2 GCM output

In the present study the output from three global climate models have considered and the most representative one has been applied to the above mentioned four basins for present day climate (current) and the changed climate due to increase in greenhouse gases (anomaly) under IPCC's scenario A conditions. The models are ECHAM1 + LSG, MPI and CSIRO9 models. The anomaly run output for ECHAM1 + LSG and MPI have been taken as the mean of 10 years integration around the year 2080 (average of years 2075-2084). For CSIRO9 model, the anomaly run corresponds to 2 x CO_2 scenario (by the year 2030).

(a) ECHAM1 + LSG model

The European Community HAMburg (ECHAM1) + Large Scale Geostrophic ocean (LSG) model with a grid resolution of 5.625° x

5.625° is a coupled climate model in which the atmospheric component (ECHAM) of the Hamburg Climate Model (T21) is coupled to the ocean component (LSG) developed at Max Planck Institute for Meteorology, Germany. For details, the reader is referred to Cubasch et al. (1992).

(b) MPI T42 model

The MPI (Max Planck Institute) T42 model is version 3 of ECHAM models without ocean but using the ECHAM1+LSG experiment's sea surface forcing for doubled CO_2 .The model has a resolution of 2.812° x 2.812°. For further details please refer to Lal et al. (1993).

(c) CSIRO9 model

This model, with nine levels in the vertical direction was developed at the Commonwealth Scientific and Industrial Research Organization (CSIRO), Australia. A slab ocean model with prescribed heat convergence was coupled with the model to implicitly determine sea surface temperatures. The diurnal and seasonal cycles were appropriately represented in the model. The lower boundary condition of the atmosphere was determined by an interactive land-surface scheme. The model has a resolution of 3.2°x 5.6°.The annual and seasonal mean global distribution of key climatic elements simulated by the model appears to be comparable to other atmospheric GCMs. For further details on the description and performance of the model the reader is referred to McGregor et al. (1993) and Chakraborty and Lal (1994).

Figures 5.5 to 5.7 show the locations of the basins under study, namely Damanganga, Sher, Kolar and Hemavati and the GCM grid points of ECHAM1, MPI and CSIRO9 models.

6.0 RESULTS AND DISCUSSION

6.1 Application of GCM output to the basins

The actual normal values of precipitation and the disaggregated GCM outputs for Damanganga, Sher, Kolar and Hemavati basins on seasonal basis are given in Table 6.1.

It is evident from Fig. 6.1 that the monsoon and annual precipitation obtained from ECHAM1 model for the current level scenario is more close to the actual normal values for Damanganga basin. However, for nonmonsoon months, other models, CSIRO9 and MPI simulate the precipitation better than ECHAM1. Since about 90% of precipitation occurs during monsoon months; the model to investigate the possible consequences of projected climate change on hydrologic cycle components was chosen on the basis of (i) simulation of monsoon precipitation, and (ii) absolute error involved in simulating all seasonal precipitation. Therefore, ECHAM1 model was chosen for the sensitivity analysis of Damanganga basin.

MPI results appear to be more reliable for the Sher basin, as it is capable of simulating precipitation better than other models for all seasons (Fig. 6.2).

For Kolar basin, on the basis as discussed earlier ECHAM1 model seems to be more reliable for assessing the climate

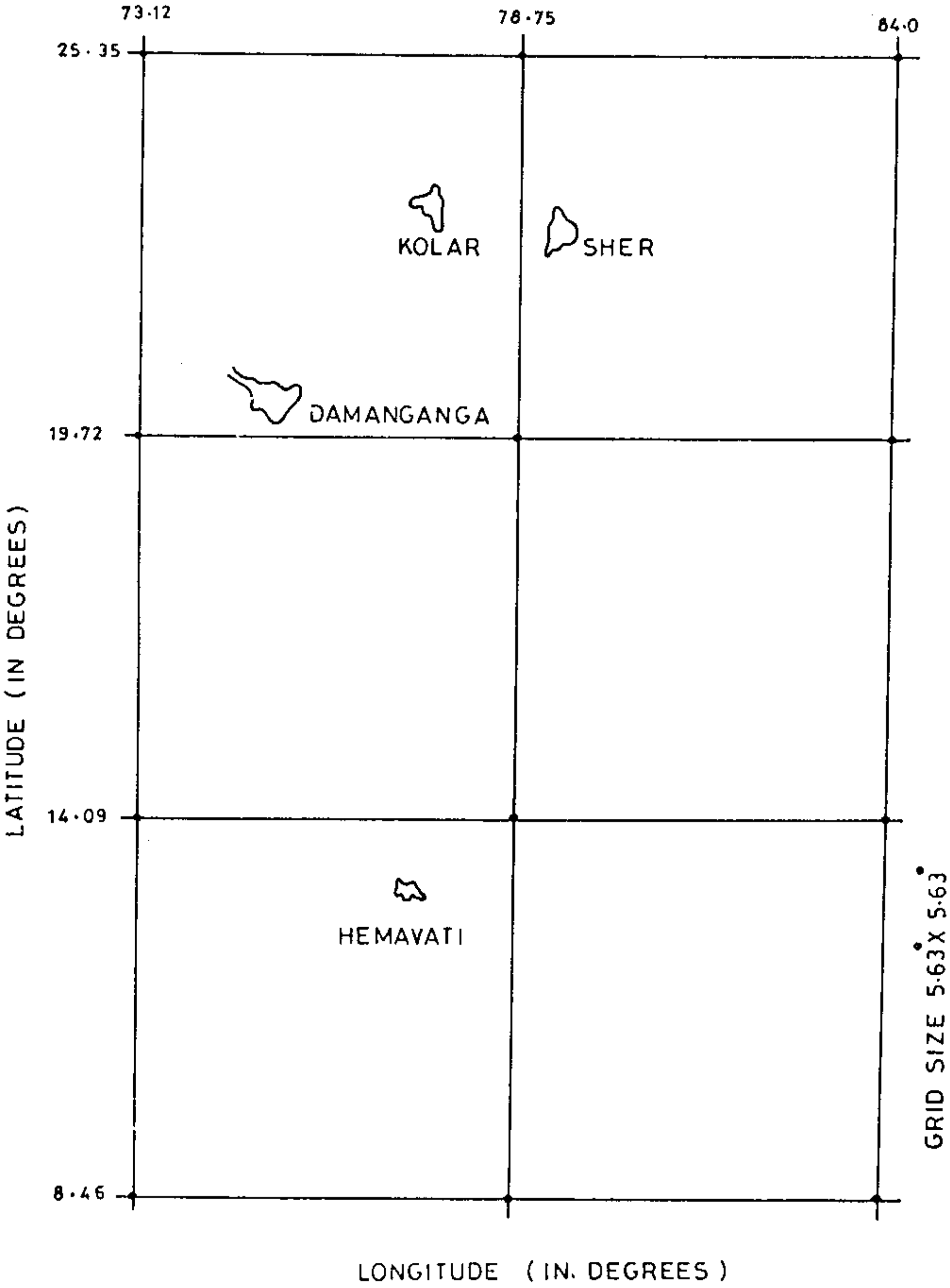

Fig. 5.5 ECHAM1 model: Locations of GCM grid points and Damanganga, Sher, Kolar, and Hemavati basins

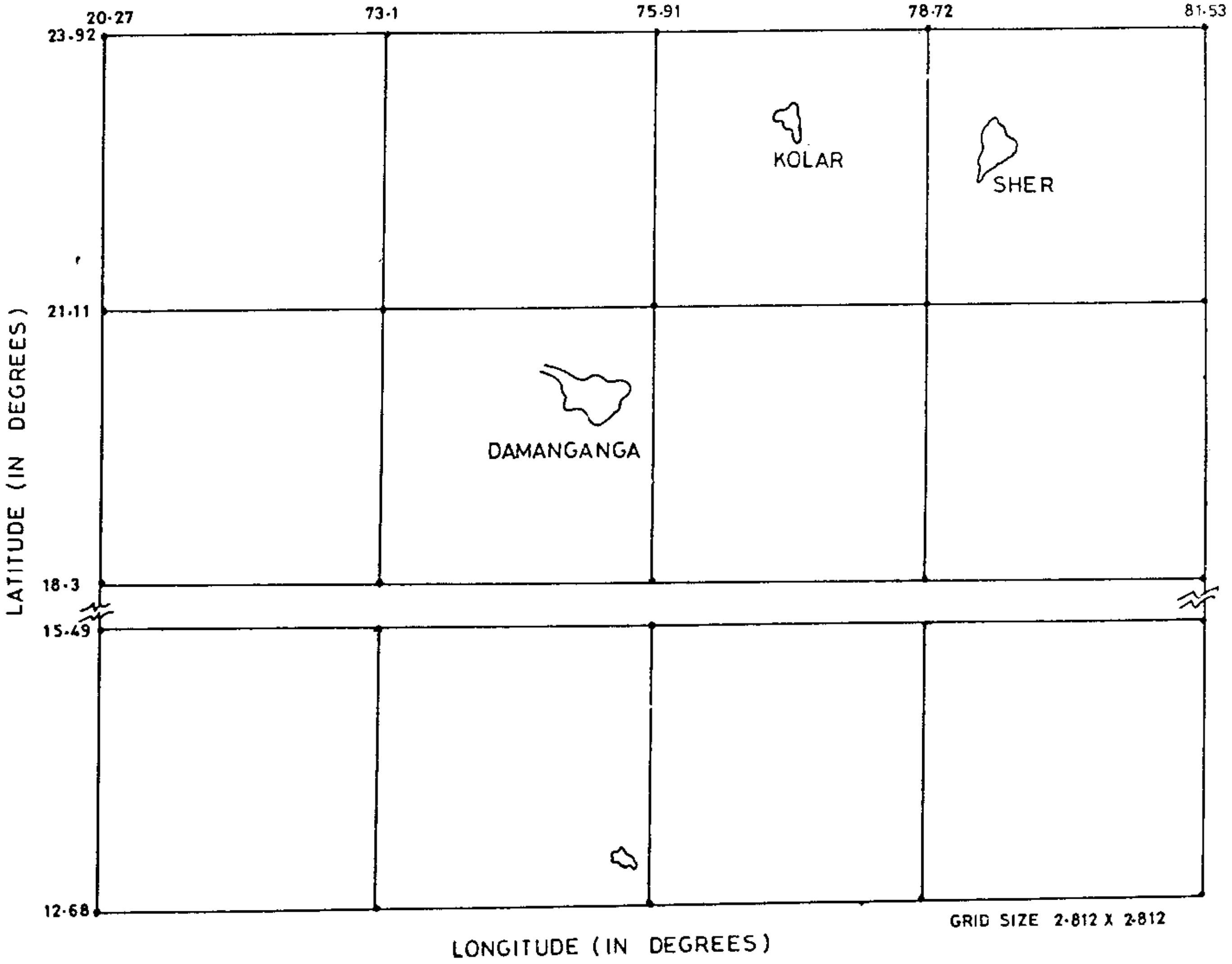

Fig. 5.6 MPI model: Locations of GCM grid points and Damanganga, Sher, Kolar, and Hemavati basins

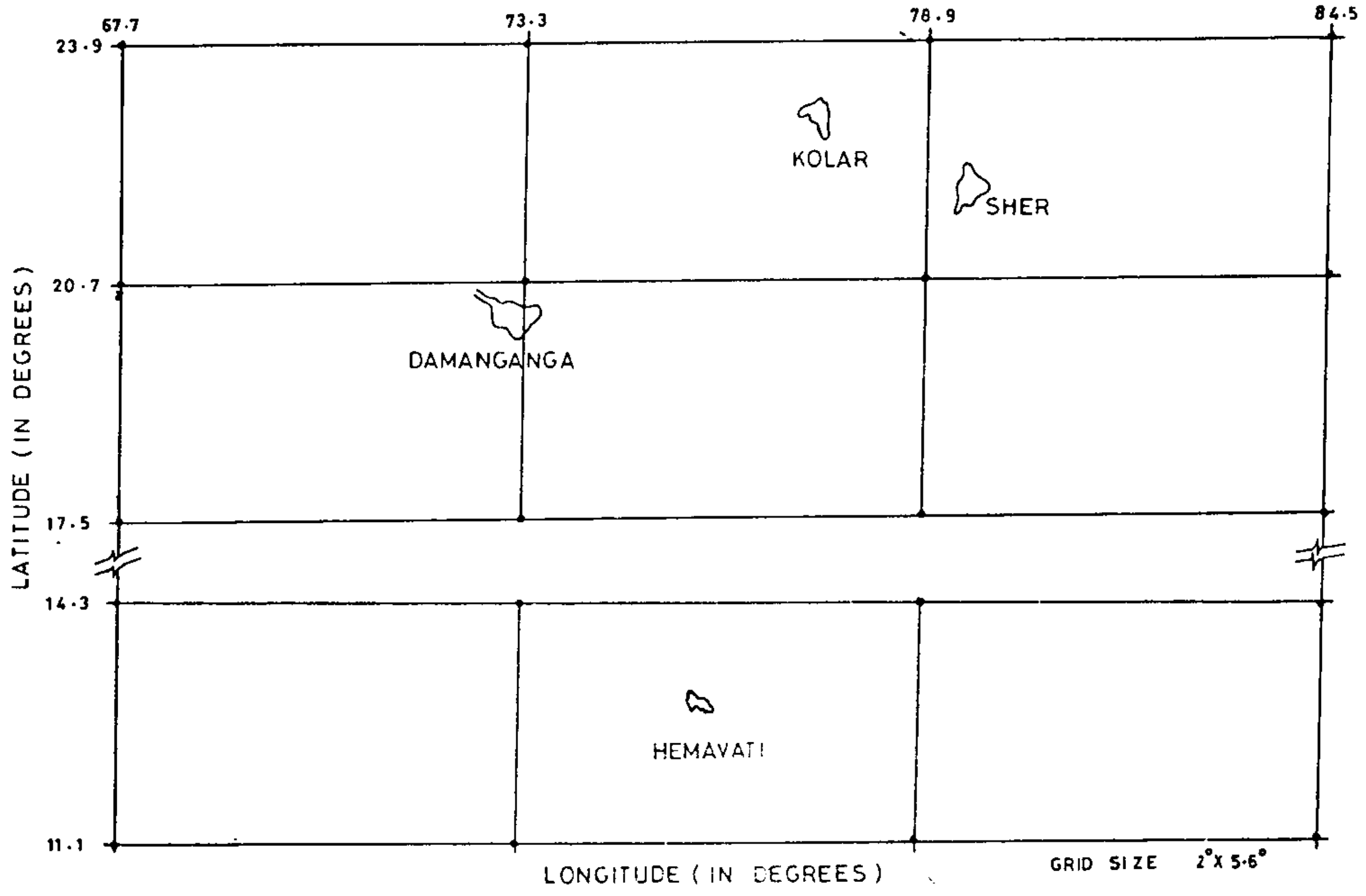

Fig. 5.7 CSIRO9 model: Locations of GCM grid points and Damanganga, Sher, Kolar, and Hemavati basins

Table 6.1: Actual normal values and GCM outputs (Current & Anomaly) for precipitation - Damanganga, Shar, Kolar and Hemavati basins

(Values are in mm)

Basin name	Season	Actual normal Values	CSIRO9 model			ECHAM1 model			MPI model		
			Current	Anomaly	Abs. diff. of current value with actual normal value	Current	Anomaly	Abs. diff. of current value with actual normal value	Current	Anomaly	Abs. diff. of current value with actual normal value
Damanganga	Monsoon	2027.425	953.840	984.013	1072.585	1931.863	2047.204	95.562	345.708	485.184	1681.717
	Post mon	75.455	4.535	30.033	70.920	147.841	214.074	72.386	46.718	146.823	28.737
	Winter	2.050	3.642	5.232	1.592	30.285	31.051	28.225	17.813	3.937	15.753
	Pre mon	4.245	29.194	73.003	24.949	81.204	45.613	76.959	15.230	71.189	10.985
	Annual	2109.185	991.211	1092.281		2191.193	2337.942		425.469	707.133	
	Total of abs. diff.				1171.035			273.133			1737.152
Shar	Monsoon	946.607	1277.484	1607.088	329.504	1447.780	1614.005	155.225	947.535	1097.405	149.870
	Post mon	25.367	25.093	51.957	26.865	166.026	194.825	28.799	44.510	158.671	114.161
	Winter	79.345	104.716	100.241	4.475	65.848	77.699	11.851	13.642	4.179	9.463
	Pre mon	15.413	275.101	375.659	100.556	155.959	92.405	64.554	51.015	148.813	97.798
	Annual	1066.731	1682.395	2134.944		1836.614	1978.925		1056.701	1409.068	
	Total of abs. diff.				461.500			271.429			371.292
Kolar	Monsoon	1137.833	972.015	1228.933	256.918	1329.827	1494.909	156.082	699.854	898.199	198.345
	Post mon	38.167	12.054	31.686	19.622	114.688	164.508	49.820	33.501	135.599	102.098
	Winter	16.333	65.998	63.076	2.922	41.477	44.294	2.817	9.158	2.519	6.639
	Pre mon	10.500	138.111	214.570	76.459	73.265	48.026	25.239	22.832	87.451	64.619
	Annual	1202.833	1188.188	1538.264		1558.257	1751.737		765.346	1123.769	
	Total of abs. diff.				355.921			243.958			371.701
Hemavati	Monsoon	2460.398	1229.894	1192.012	37.882	2123.132	2025.729	97.403	855.767	834.311	21.456
	Post mon	275.338	57.254	101.265	44.011	388.252	406.845	18.593	225.809	417.363	191.554
	Winter	7.662	20.506	27.851	7.345	136.843	196.359	59.516	148.115	90.586	57.529
	Pre mon	197.900	225.917	377.513	151.597	581.632	439.308	142.324	361.468	344.102	17.367
	Annual	2941.300	1533.570	1698.641		3229.859	3068.241		1591.159	1686.362	95.202
	Total of abs. diff.				240.835			317.836			287.906

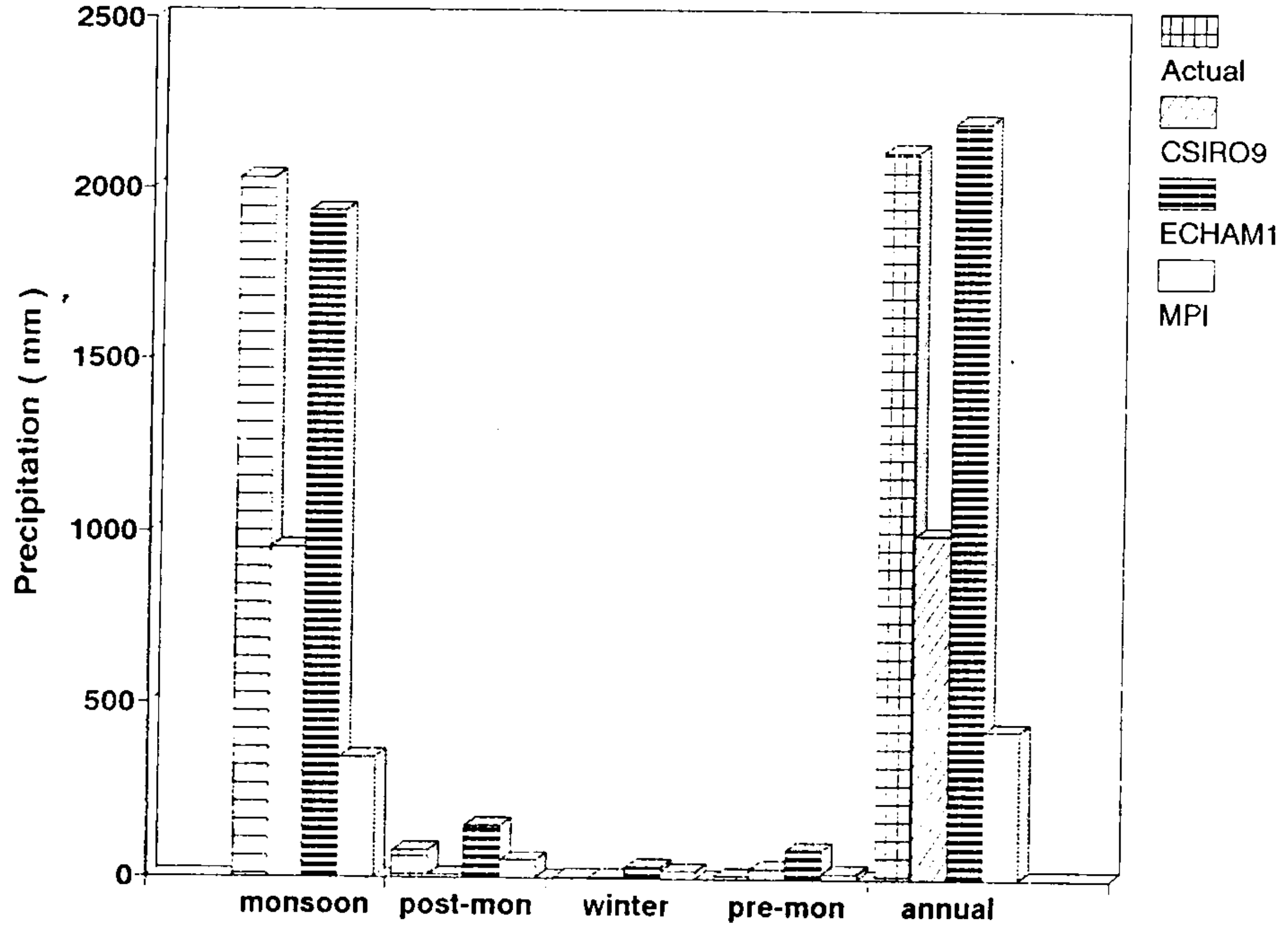

Fig. 6.1 Comparison of actual and disaggregated GCM outputs for precipitation (Damanganga basin)

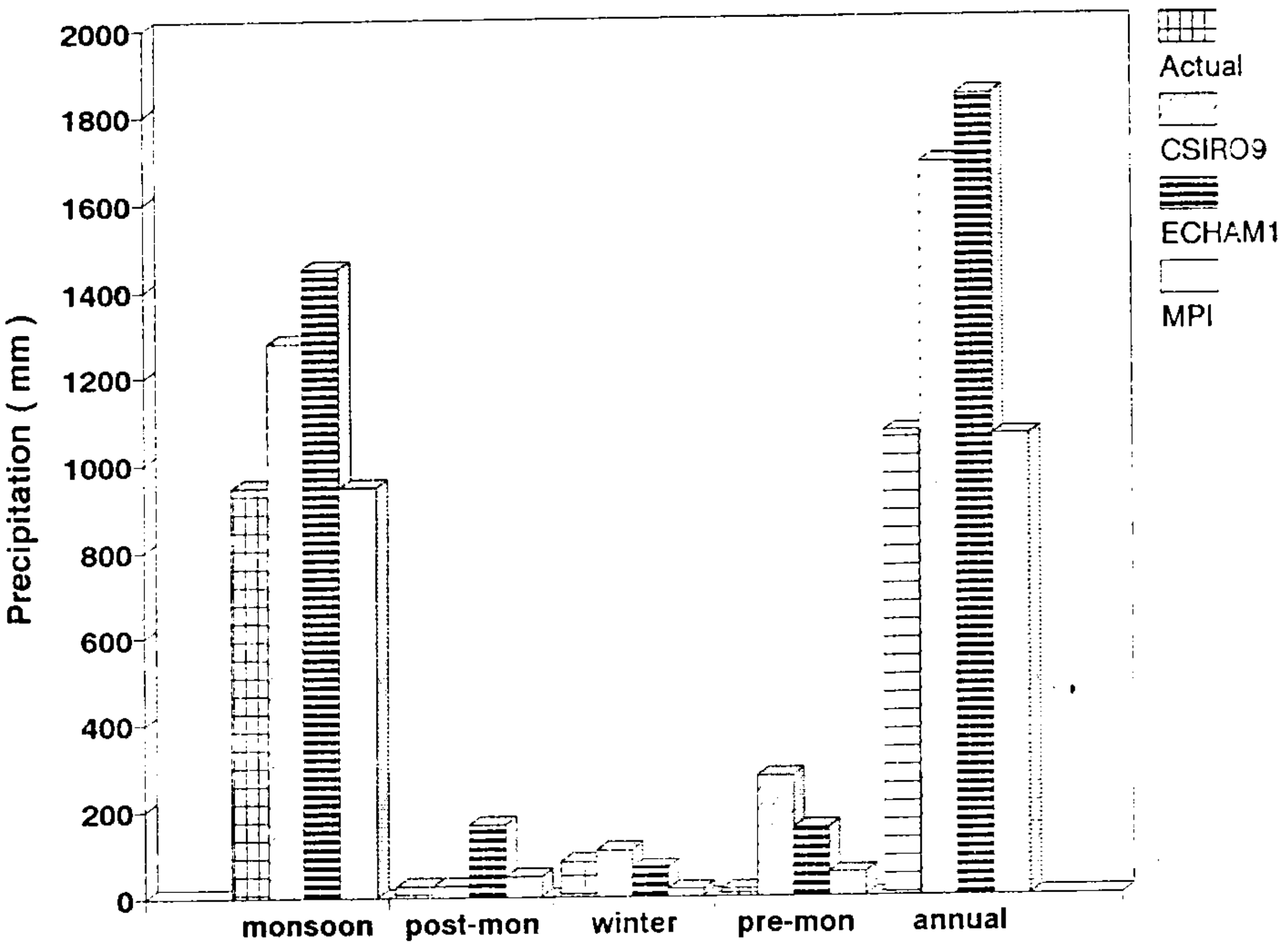

Fig. 6.2 Comparison of actual and disaggregated GCM outputs for precipitation (Sher basin)

change consequences (Fig. 6.3). However, it is observed that the ECHAM1 model overestimates the annual rainfall, and CSIRO9 model simulates the annual precipitation very closely. But the total absolute error involved in simulating all seasonal rainfall is more in case of CSIRO9 model. MPI model underestimates the precipitation values, deviating by more than 20% from the normal values. Therefore, ECHAM1 model is chosen for assessing the possible climate change consequences on hydrologic parameters.

Following the same criterion for the selection of the model, ECHAM1 model seems to be more reliable for Hemavati basin (Fig. 6.4). However, ECHAM1 results are overestimated by substantial amount during nonmonsoon periods, other two models; CSIRO9 and MPI, show completely off to the observed ones for monsoon and annual rainfall. Therefore, ECHAM1 is chosen for further analysis for Hemavati basin.

6.2 Sensitivity of basins to climate change

The sensitivity analysis of runoff, evapotranspiration and soil moisture (end of month) to expected changes in precipitation and temperature has been carried out for the above mentioned basins. Since all the models could not simulate the observed climate; only one model, which could best simulate the basin climate was chosen for the sensitivity analysis of the particular basin, as discussed in section 6.1. The results of ECHAM1 model are utilized to assess the sensitiveness of Damanganga, kolar and Hemavati basins to expected climate change. For the Sher basin, results of MPI model are taken for the analysis. The monthly runoff, evapotranspiration, and soil

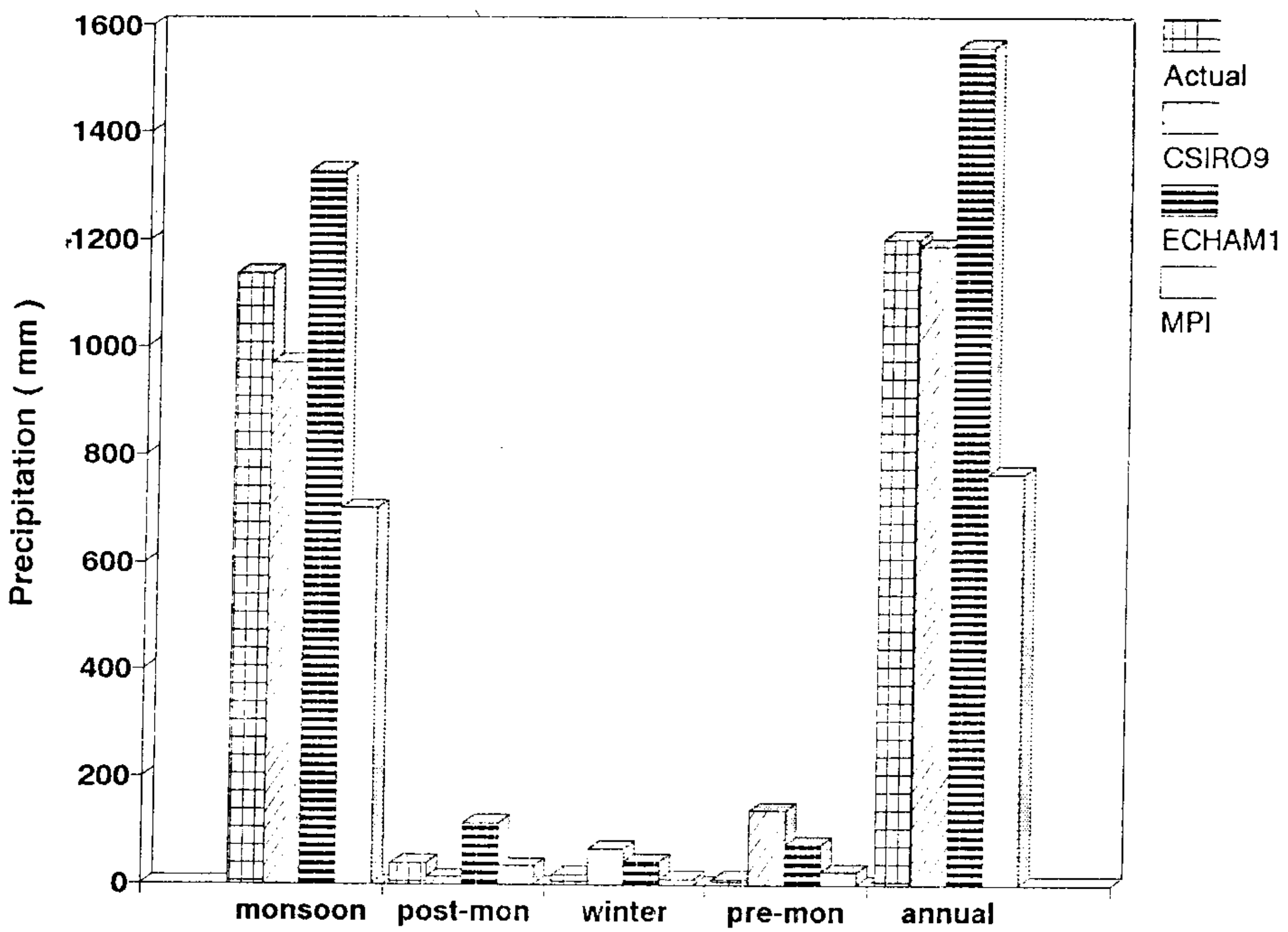

Fig. 6.3 Comparison of actual and disaggregated GCM outputs for precipitation (Kolar basin)

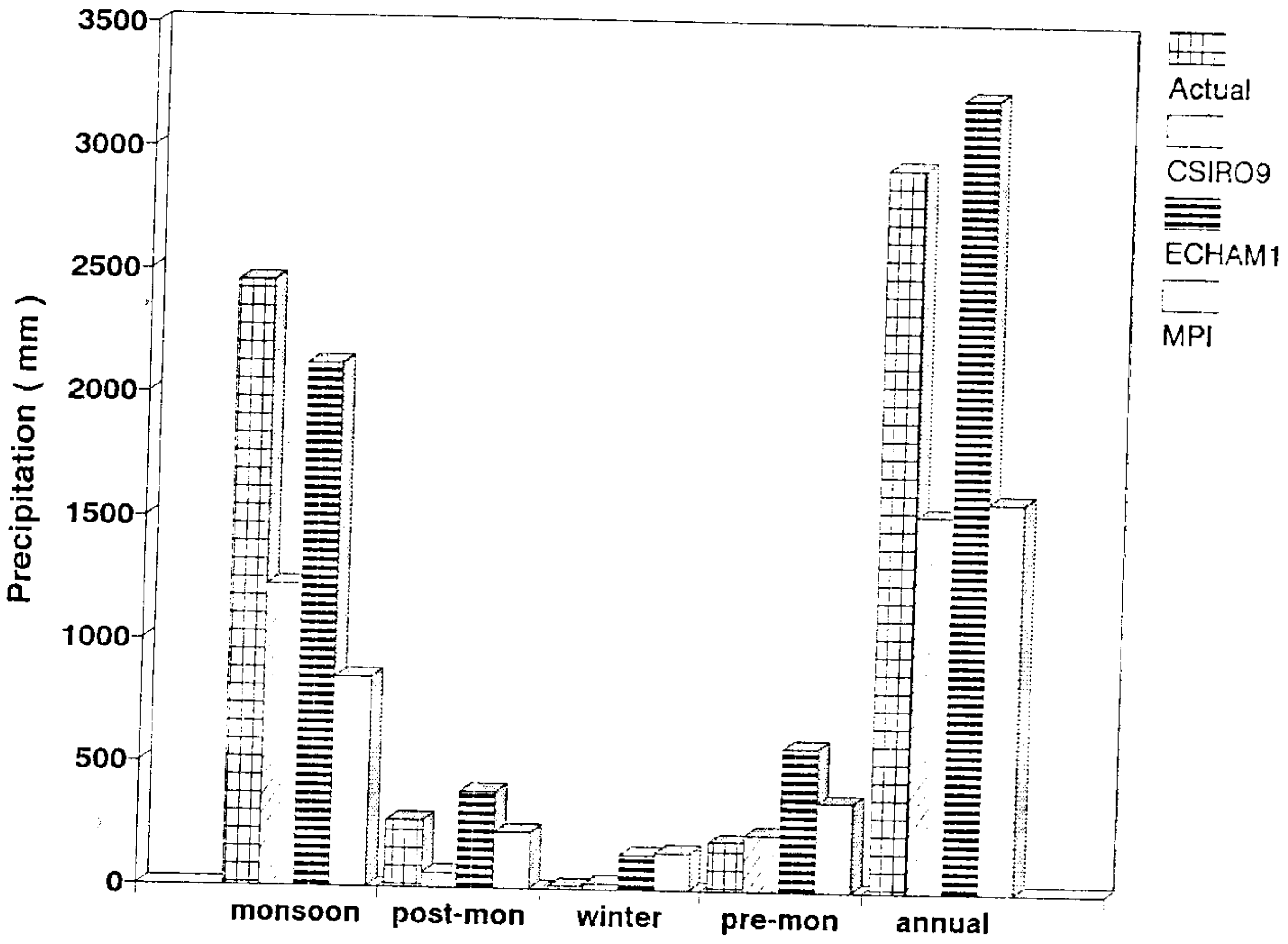

Fig. 6.4 Comparison of actual and disaggregated GCM outputs for precipitation (Hemavati basin)

moisture are computed for the current level and anomaly level of climatic conditions using the disaggregated GCM outputs for precipitation and temperature. Results of runoff, evapotranspiration, and soil moisture are reported on seasonal (monsoon: June-September; pre-monsoon: March- May; post-monsoon: October-November; and winter: December- February) and annual basis for the current and anomaly levels of climatic conditions (Table 6.2).

6.2.1 Damanganga basin

Temperature:

Due to expected climate change, the average temperature is expected to increase by more than 2.5 °C during winter, 3.0 °C during pre-monsoon, 1.0 °C during monsoon, 2.0 °C during post-monsoon and 2.8°C annually. Monthly average increase in temperature is expected to be more than 2.5 °C.

Precipitation:

Due to expected climate change, precipitation is expected to increase by 5 % during the monsoon period. Total annual rainfall is also expected to increase by 5 %. Rainfall during post-monsoon period may increase, whereas during pre-monsoon and winter periods, almost no change in precipitation is expected (Fig. 6.5).

Maximum rainfall will occur in the same month, July, as it is occurring in the present climate.

Runoff:

The results show that the numerical quantification for monthly balance is difficult for Damanganga basin. Qualitative

Table 6·2 Values of Precipitation, runoff, Evapo-transpiration and soil moisture (end of month) on seasonal and annual basis for present and anomaly scenarios for - Damanganga, Sher, Kolar and Hemavati basins

(Values are in mm)

Season	Precipitation			Runoff			Evapo-transpiration			Soil moisture		
	At current level	At anomaly level	Absolute difference	At current level	At anomaly level	Absolute difference	At current level	At anomaly level	Absolute difference	At current level	At anomaly level	Absolute difference
Damanganga basin												
Monsoon	2027.425	2047.204	19.779	1326.811	1234.110	92.701	421.516	450.550	29.034	1081.510	1162.460	80.950
Post-mon	75.455	214.074	138.619	64.511	147.120	82.509	230.291	261.320	31.029	467.795	496.790	28.995
Winter	2.060	31.051	28.991	3.194	12.810	9.616	137.035	95.720	41.315	295.475	190.590	104.885
Pre-mon	4.245	45.613	41.368	1.724	3.450	1.726	54.589	32.370	22.219	53.061	43.950	9.111
Annual	2109.185	2337.942	228.757	1396.240	1397.490	1.250	843.431	839.960	3.471	1897.841	1893.790	4.051
Sher basin												
Monsoon	946.607	1097.405	150.798	446.921	521.480	74.559	349.778	459.910	110.132	585.787	666.730	80.943
Post-mon	25.367	158.671	133.304	12.770	23.170	10.400	115.856	213.240	97.384	118.787	259.110	140.323
Winter	79.345	4.179	75.166	21.272	6.310	14.962	63.059	102.860	39.801	139.307	149.460	10.153
Pre-mon	15.413	148.813	133.400	4.764	13.100	8.336	56.354	107.380	51.026	26.118	86.510	60.392
Annual	1066.731	1409.068	342.337	485.727	564.060	78.333	585.047	883.390	298.343	869.999	1161.810	291.811
Kolar basin												
Monsoon	1137.833	1494.909	357.076	545.116	652.090	106.974	418.644	599.410	180.766	596.454	704.430	107.976
Post-mon	39.157	164.508	125.341	28.529	42.330	13.801	137.108	279.480	142.372	121.887	263.870	141.983
Winter	16.333	44.294	27.961	2.162	3.650	1.488	40.002	59.110	19.108	63.174	89.960	26.786
Pre-mon	10.500	48.026	37.526	0.344	0.000	0.344	23.556	50.970	27.414	7.103	19.210	12.107
Annual	1202.833	1751.737	548.904	576.151	698.070	121.919	619.310	988.970	369.660	788.618	1077.470	288.852
Hemavati basin												
Monsoon	2460.398	2025.729	434.669	1901.720	1489.080	412.640	260.530	289.400	28.870	1711.290	1705.400	5.890
Post-mon	275.338	406.845	131.507	198.740	339.120	140.380	128.260	139.470	11.210	867.460	878.400	10.940
Winter	7.663	196.359	188.696	64.620	92.670	28.050	202.000	248.730	46.730	914.120	1072.860	158.740
Pre-mon	197.900	439.308	241.408	6.870	36.930	30.060	193.400	283.050	89.650	620.020	781.460	161.440
Annual	2941.300	3068.241	126.941	2171.950	1957.800	214.150	784.190	960.650	176.460	4112.890	4439.120	325.230

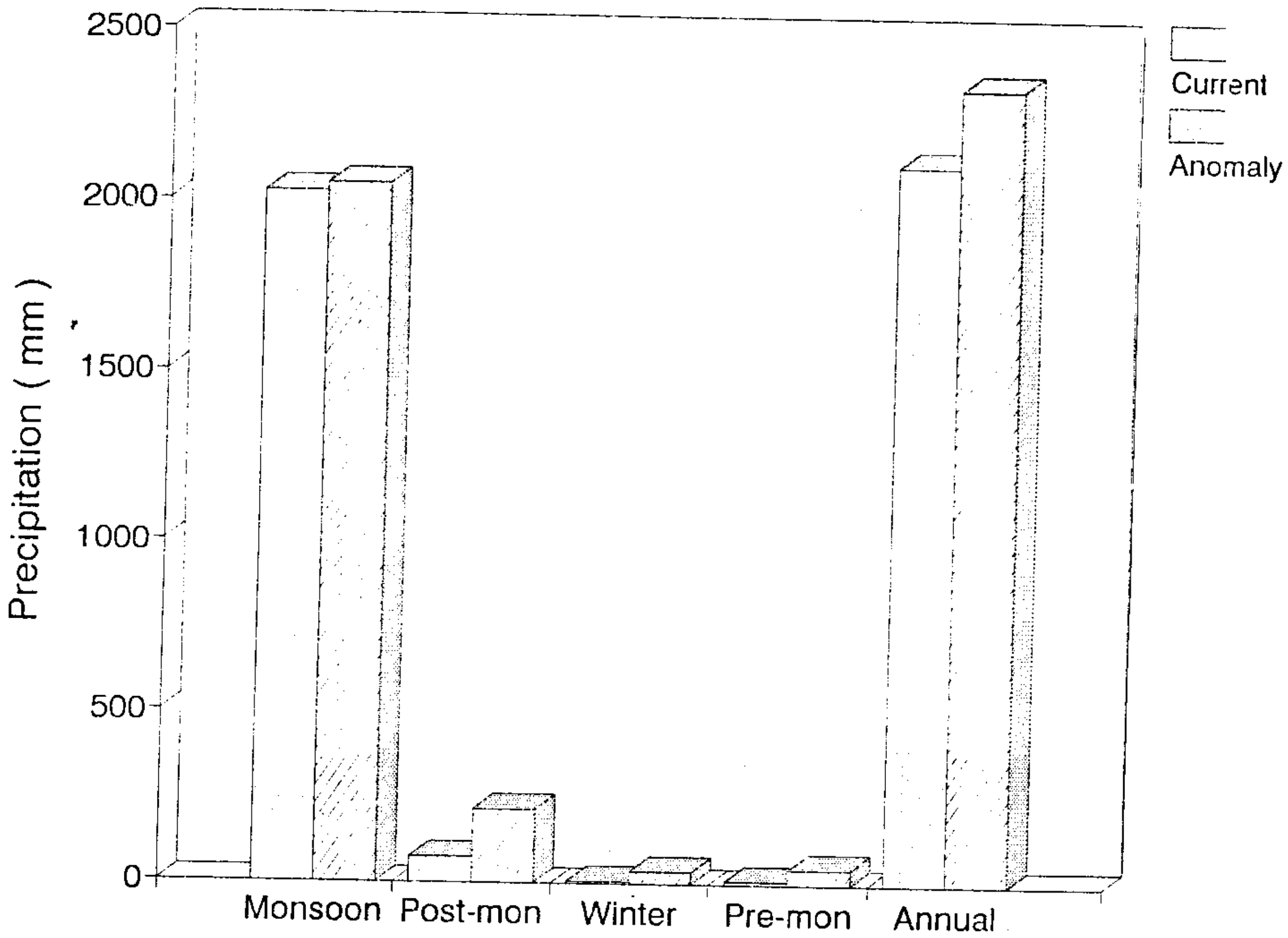

Fig. 6.5 Seasonal and annual precipitation for Damanganga basin for current (present day) and anomaly (by year 2080 due to greenhouse warming) level of climatic conditions

assessment can be done for annual and monsoon months. Analysis of GCM results is difficult for less rainy periods; pre-monsoon, post-monsoon and winter, because model is not able to simulate precipitation accurately in these periods.

For Damanganga basin, peak in runoff occurs earlier, but its intensity is moderately reduced, although there is hardly any difference in annual budget. There is a shift of one month (from August to July) in the occurrence of peak. The runoff is expected to decrease during monscon season, and increase in nonmonsoon seasons at anomaly level of climatic condition (Fig. 6.6).

Evapotranspiration:

The evapotranspiration is likely to increase by 13% and 3% for monsoon months and on annual basis (Fig. 6.7). However, this is underestimated when compared to the results of sensitivity analysis using observed data for the climate change scenario of 3°C increase in temperature and precipitation increase between 5% and 10% (Mehrotra and Divya, 1994).

Increased temperature and expected change in precipitation cause 15 % increase in evapotranspiration during post-monsoon period. However, there is appreciable decrease in evapotranspiration during winter and pre-monsoon period. Similar results are observed by the analysis of sensitivity experiments carried out by Mehrotra and Divya (1994), in which 3°C rise in temperature and precipitation increase between 5% and 10% was considered for the basin.

Increase in evapotranspiration during the monsoon period

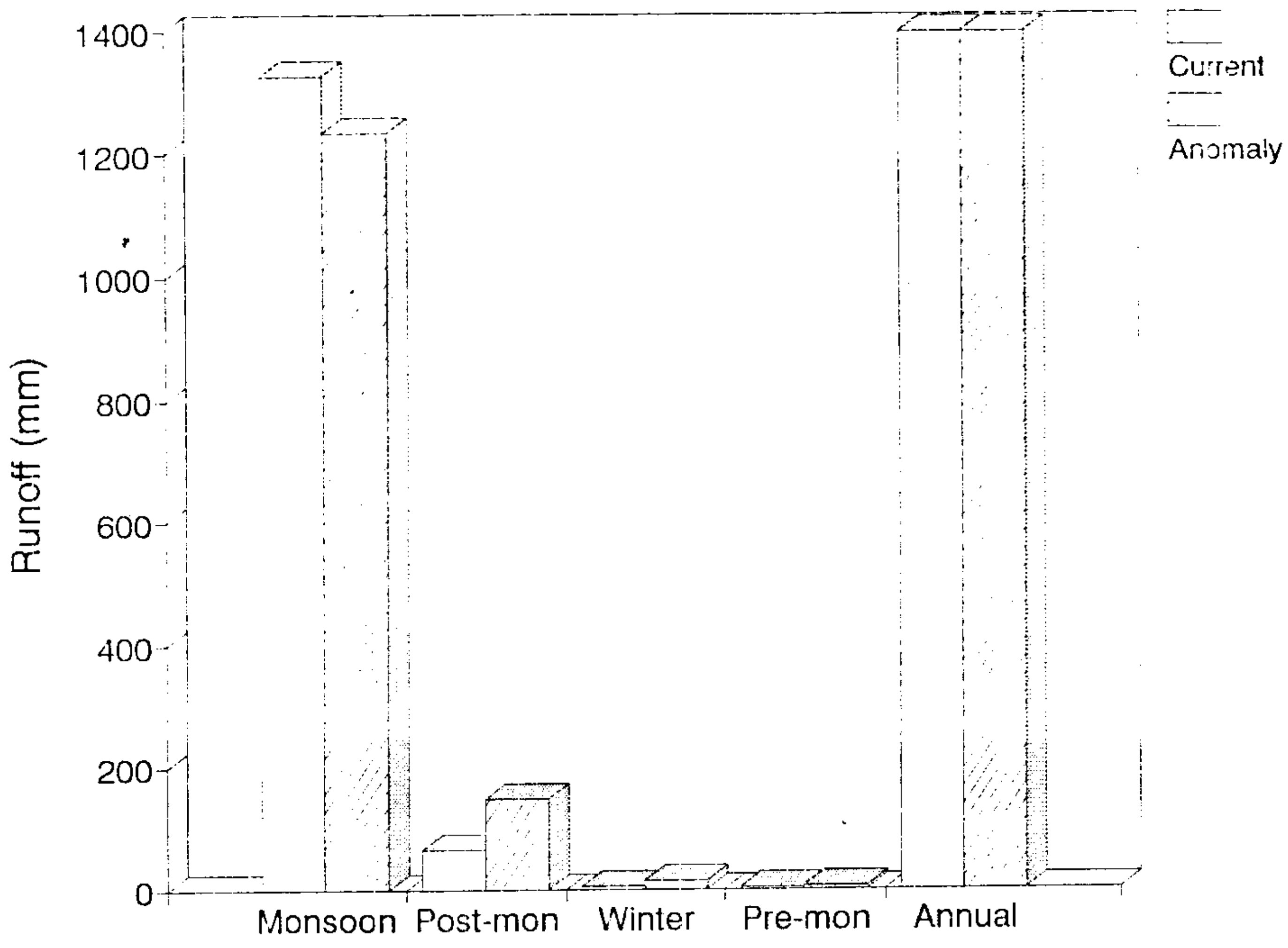

Fig. 6.6 Seasonal and annual runoff for Damanganga basin for current (present day) and anomaly (by year 2080 due to greenhouse warming) level of climatic conditions

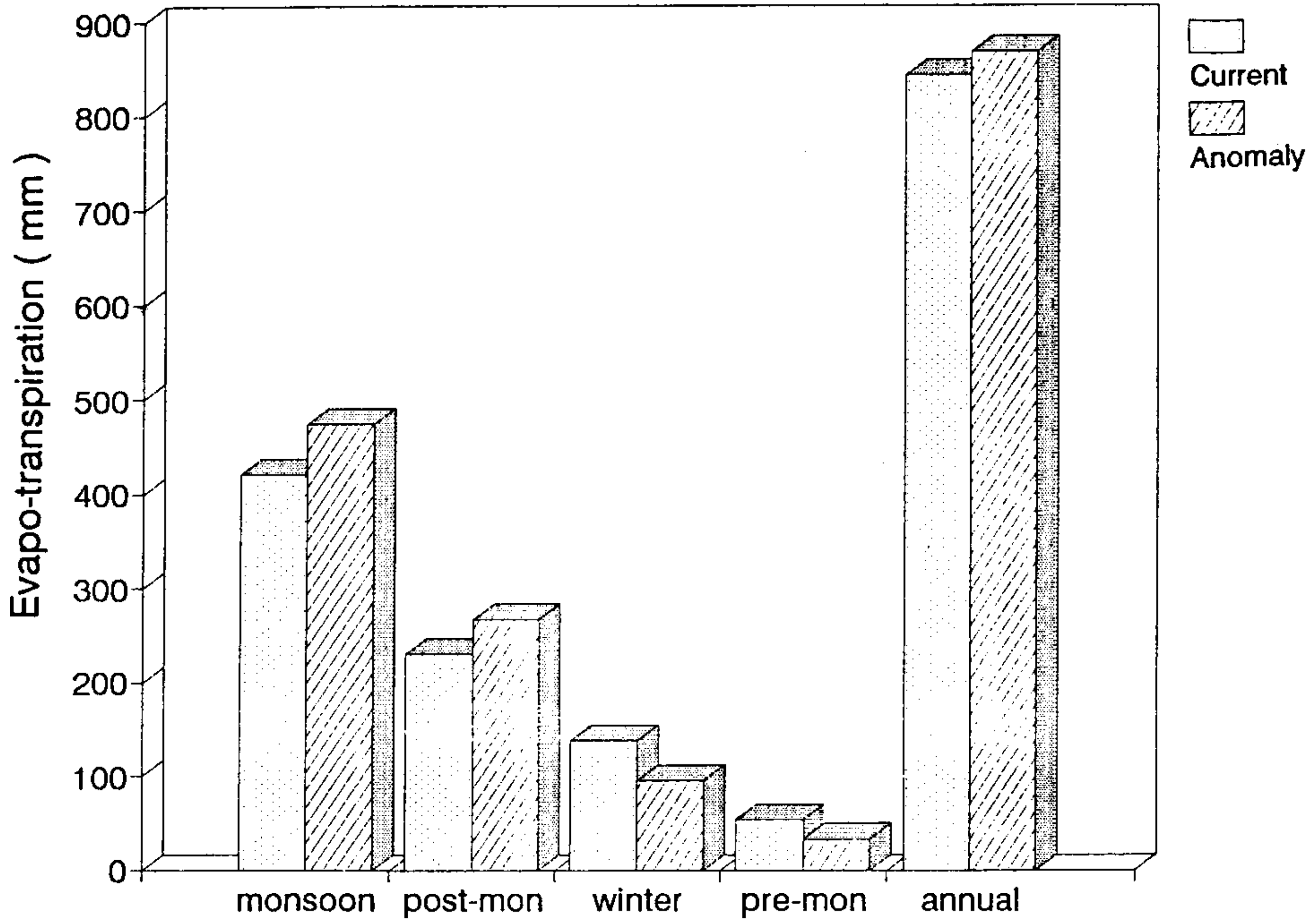

Fig. 6.7 Seasonal and annual evapotranspiration for Damanganga basin for current (present day) and anomaly (by year 2080 due to greenhouse warming) level of climatic conditions

is caused by the increase in temperature as evapotranspiration takes place at potential rate. However, decrease in evapotranspiration during winter and pre-monsoon periods is due to decrease in availability of soil moisture.

Soil moisture:

The results show that the soil moisture is expected to increase during monsoon and post-monsoon seasons (Fig. 6.8). However, it may decrease during winter and pre-monsoon seasons, and annually.

6.2.2 Sher basin

Temperature:

Surface temperature is expected to increase by more than 3.5 °C during winter and pre-monsoon periods, and 1.5 °C during monsoon period. Monthly average increase in temperature is expected to be more than 2.5 °C. Similar results have been reported by Lal and Chander (1993).

Precipitation:

At anomaly level of climatic condition, precipitation is expected to increase by more than 5 % during the monsoon period (Fig. 6.9). Total annual rainfall may increase substantially. Lal and Chander (1993), assessing the potential impacts of climate change on hydrology for Indian sub continent analysing the MPI (T-42) model results have found similar results for the region corresponding to latitude and longitude of Sher basin. Their findings include: an increase in rainfall during monsoon and pre-monsoon periods, and an increase in annual rainfall. However,

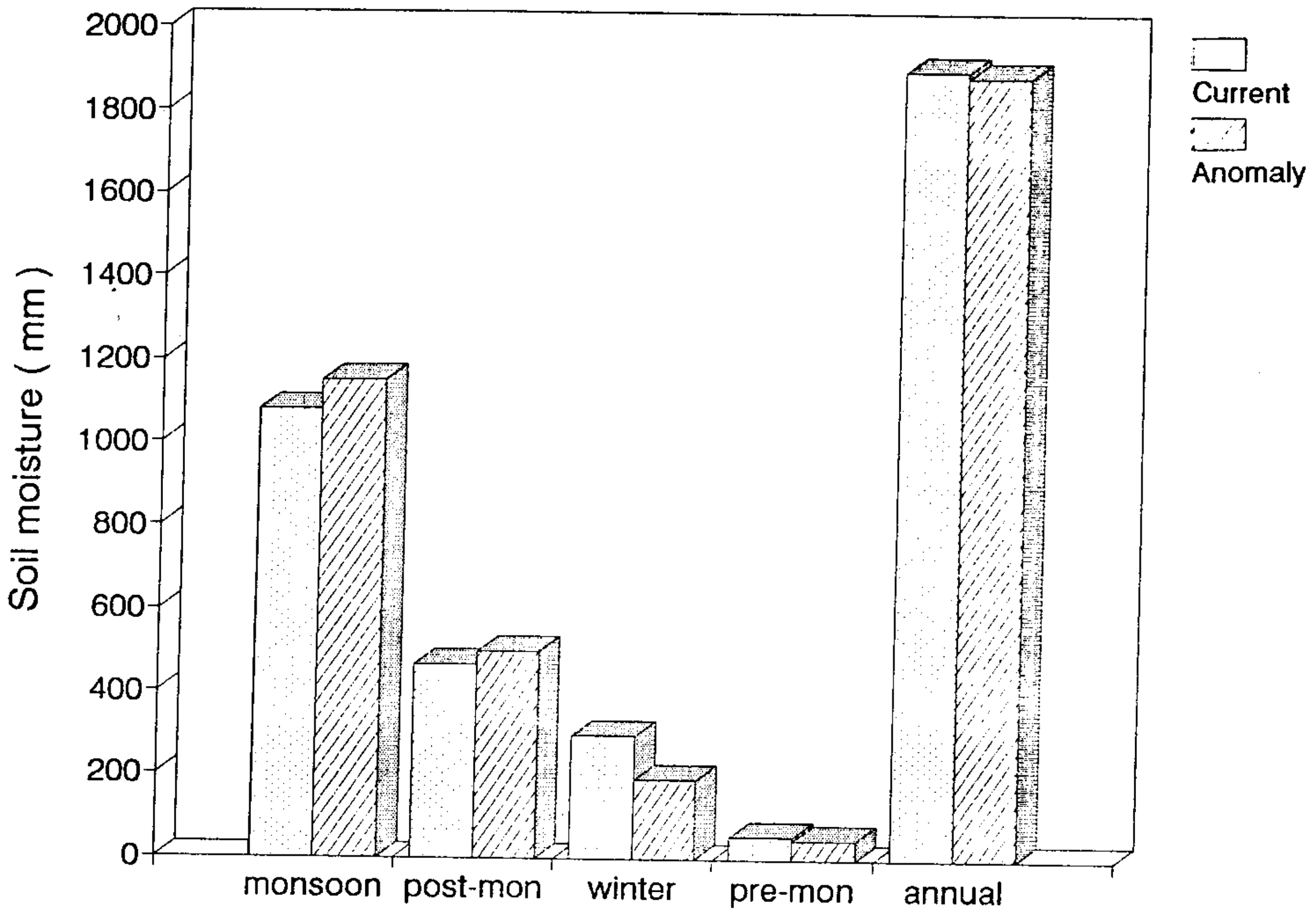

Fig. 6.8 Seasonal and annual soil moisture for Damanganga basin for current (present day) and anomaly (by year 2080 due to greenhouse warming) level of climatic conditions

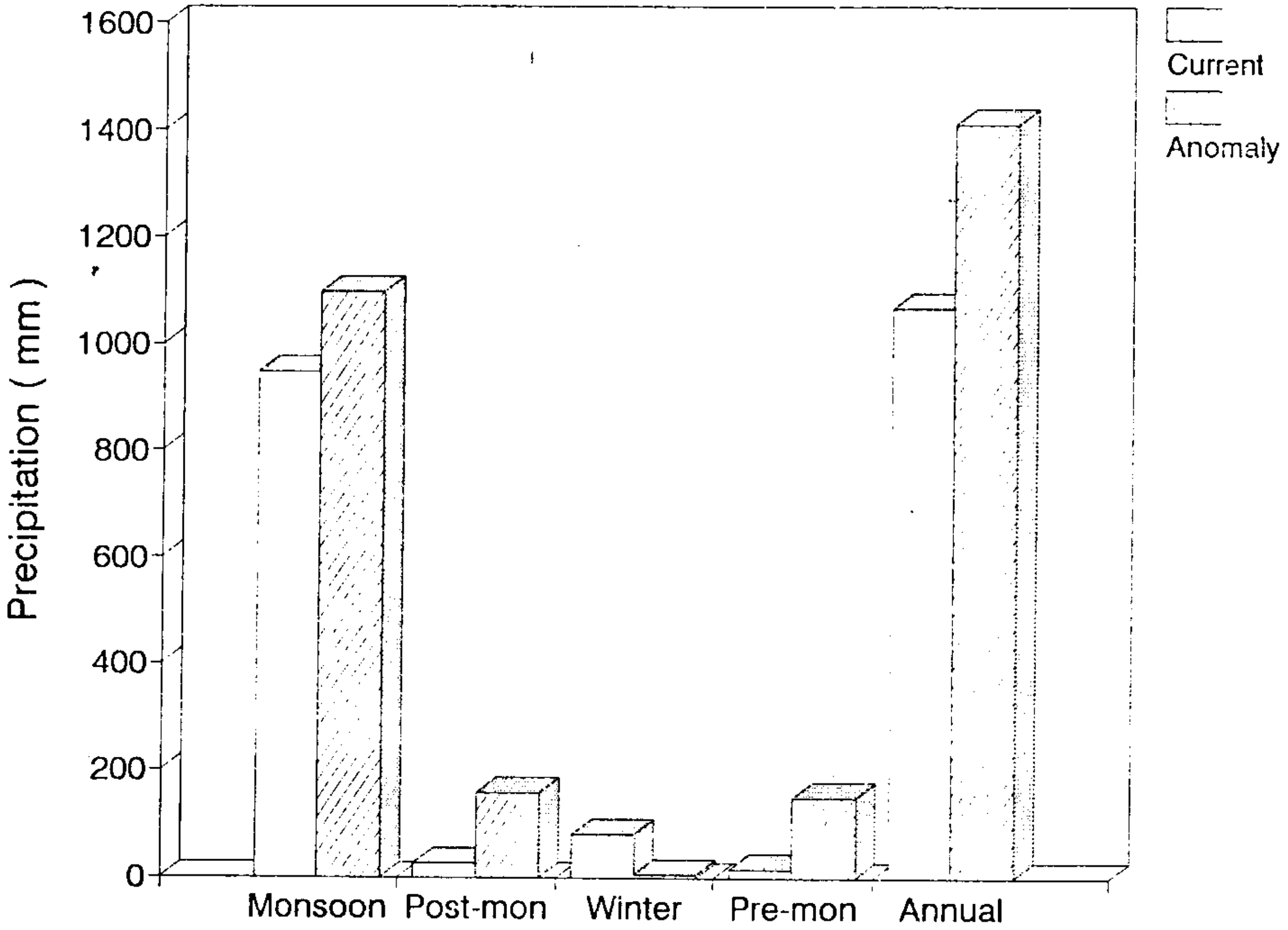

Fig. 6.9 Seasonal and annual precipitation for Sher basin for current (present day) and anomaly (by year 2080 due to greenhouse warming) level of climatic conditions

our results show that there is decrease in rainfall during winter periods, whereas no change was reported by Lal and Chander (1993).

The results indicate that the maximum rainfall will occur in the same month, August, as it is occurring in the present climate.

Runoff:

The results for Sher basin, like Damanganga also show that the monthly runoff values can not be numerically quantified and qualitative assessment can be done for annual and monsoon months. Furthermore, analysis of GCM results is difficult for pre-monsoon, post-monsoon and winter, when precipitation is less, because model is not able to simulate precipitation accurately in these periods.

Runoff during monsoon season, and annually may exceed by 15% at anomaly level scenario (Fig. 6.10). During winter period, runoff seems to decrease. Similar results; increasing trend in annual and monsoon runoff, and decreasing trend in runoff during winter period; were also observed by Lal and Chander (1993).

Pattern of runoff shows that time to peak remains same, but peak intensity is slightly reduced; although annual runoff is expected to increase due to increased global warming.

Evapotranspiration:

The evapotranspiration for monsoon months and annual value is likely to increase by 30% and 50% (Fig. 6.11). However, these values seem to be overestimated when compared with the

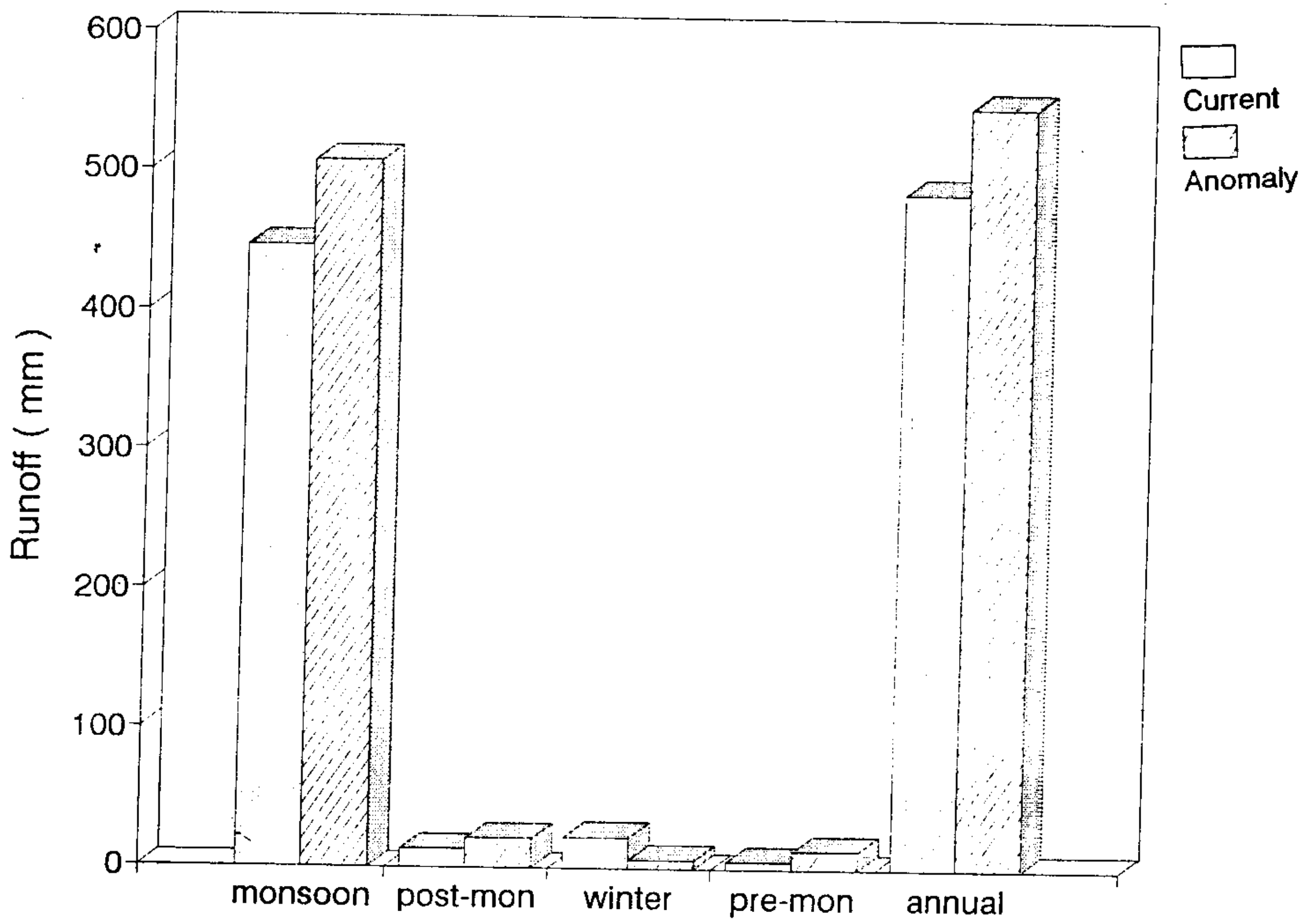

Fig. 6.10 Seasonal and annual runoff for Sher basin for current (present day) and anomaly (by year 2080 due to greenhouse warming) level of climatic conditions

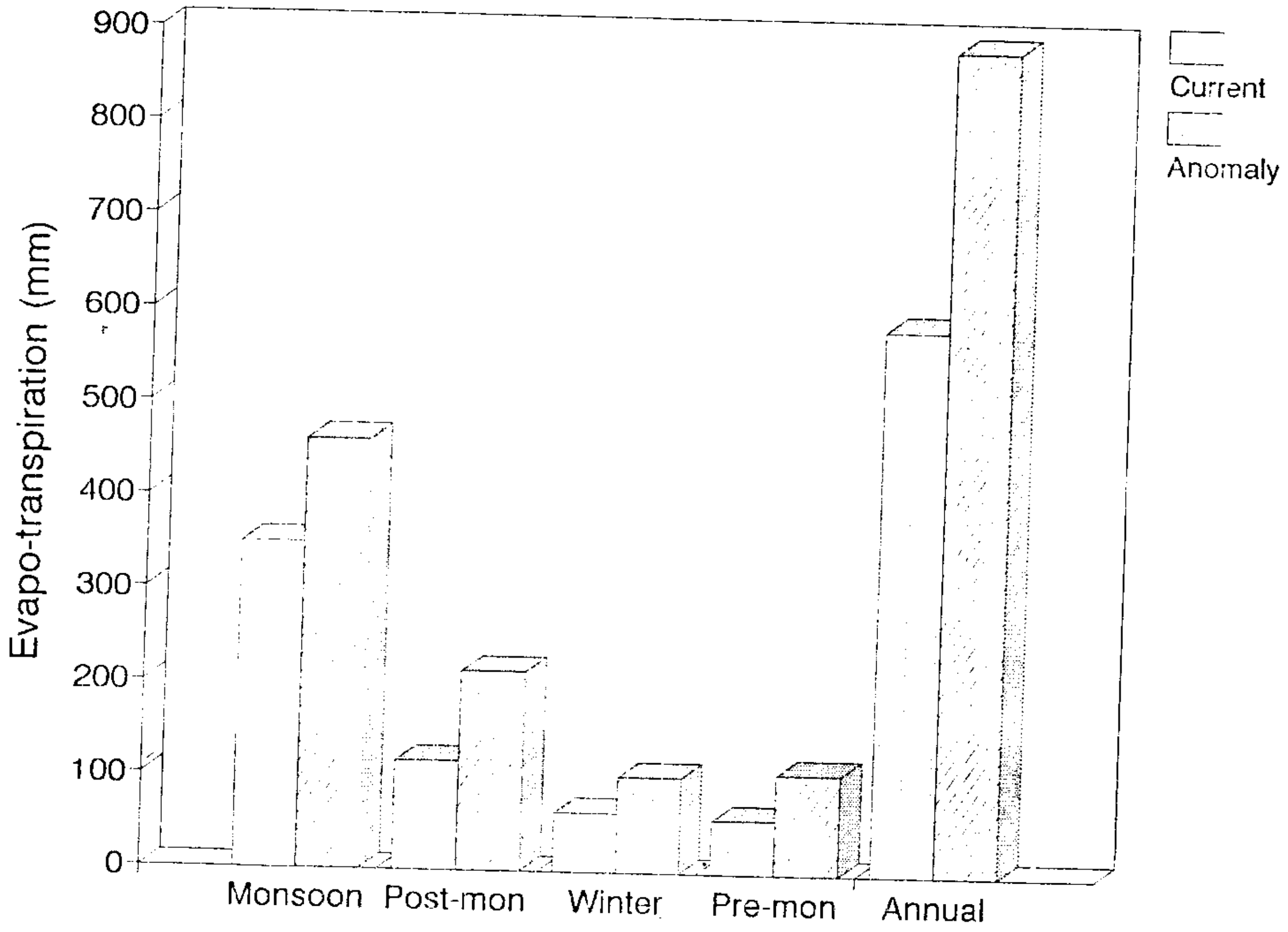

Fig. 6.11 Seasonal and annual evapotranspiration for Sher basin for current (present day) and anomaly (by year 2080 due to greenhouse warming) level of climatic conditions

sensitivity experiments using climate change scenarios (a temperature increase of 3°C and precipitation change of about + 20%) (Mehrotra and Divya, 1994).

ET increases in all seasons for the Sher basin. It is expected to increase by more than 10% per °C increase in temperature. During post-monsoon and pre-monsoon periods, there is substantial increase in ET. These results are also supported by earlier findings (Mehrotra and Divya, 1994). Lal and Chander (1993) also showed increase in evapotranspiration.

The increase in evapotranspiration is observed due to increase in temperature and availability of soil moisture during all the seasons.

Soil moisture:

Soil moisture is expected to increase during all seasons (Fig. 6.12). However, Lal and Chander (1993) concluded that soil moisture increases during monsoon season and annually, whereas no change was observed during pre-monsoon and winter periods.

6.2.3 Kolar basin

Temperature:

Average surface temperature is expected to increase by more than 3.5 °C during winter, 4.0 °C during pre-monsoon and post-monsoon, 2.0 °C during monsoon and 3.55°C annually. Monthly average increase in temperature is expected to be more than 3.5°C.

Precipitation:

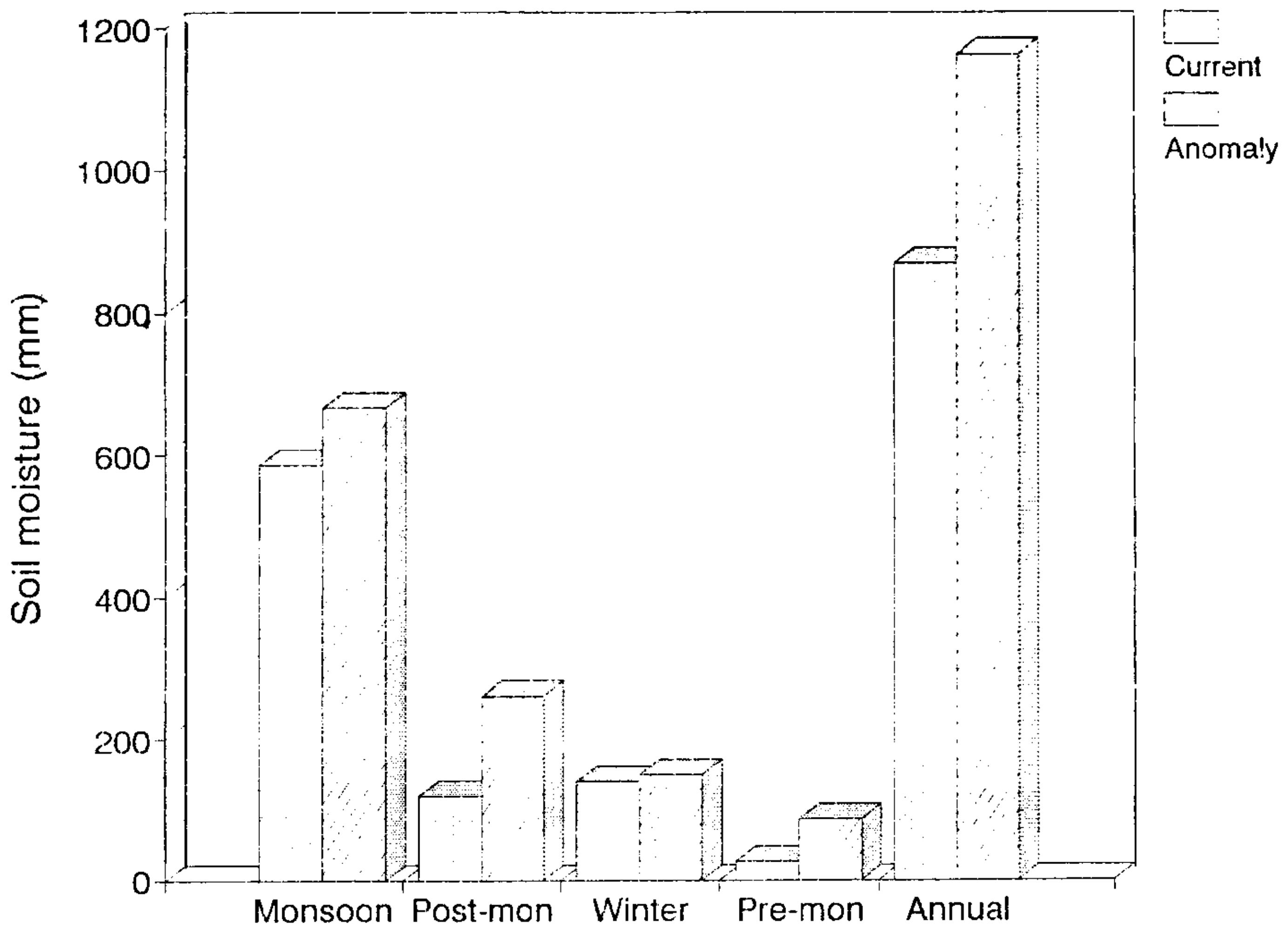

Fig. 6.12 Seasonal and annual soil moisture for Sher basin for current (present day) and anomaly (by year 2080 due to greenhouse warming) level of climatic conditions

Rainfall is expected to increase by more than 30%, during monsoon, and 45% annually (Fig. 6.13). Substantial increase in post-monsoon rainfall is expected. In other seasons also, precipitation is expected to increase.

Maximum rainfall appears to occur earlier by two months (June instead of August).

Runoff:

Runoff appears to increase by more than 20% during monsoon season and annually (Fig. 6.14). Runoff during low flow periods will hardly differ except during post-monsoon season in which it will increase. Similar characteristics were also reported by Mehrotra and Divya (1994).

Evapotranspiration:

ET is expected to increase in all seasons (Fig. 6.15). Substantial increase is observed in monsoon, post-monsoon and annual evapotranspiration. Increase in ET is expected to be more than 40 % during monsoon and 55 % annually due to increased temperature.

Soil moisture:

Soil moisture increases annually and also during winter, pre-monsoon, monsoon and post-monsoon seasons (Fig. 6.16). Appreciable increase in soil moisture is observed in annual, monsoon and post-monsoon balance. Soil moisture may increase more than 18% annually and 36% during monsoon period in a changed climatic conditions.

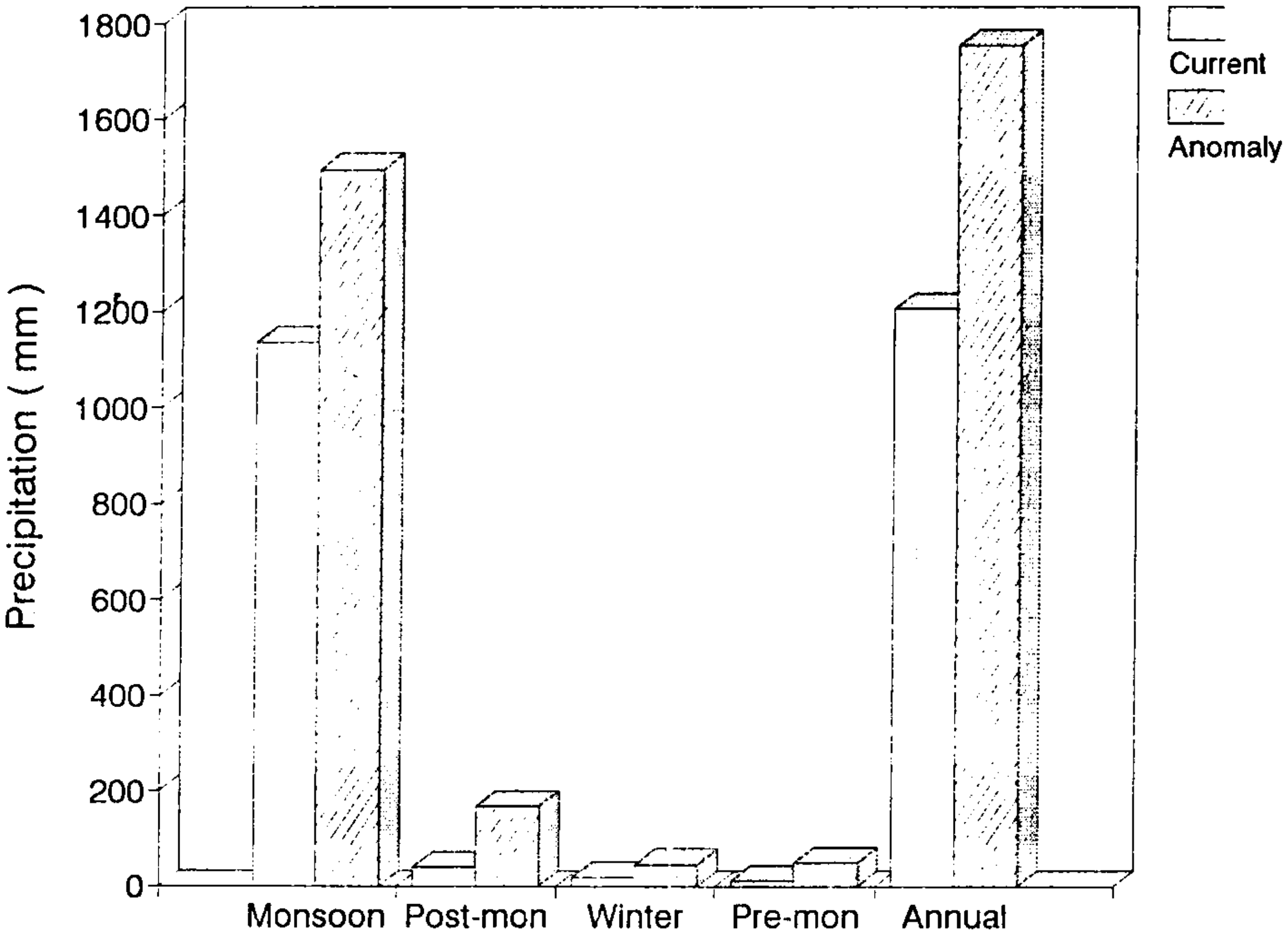

Fig. 6.13 Seasonal and annual precipitation for Kolar basin for current (present day) and anomaly (by year 2080 due to greenhouse warming) level of climatic conditions

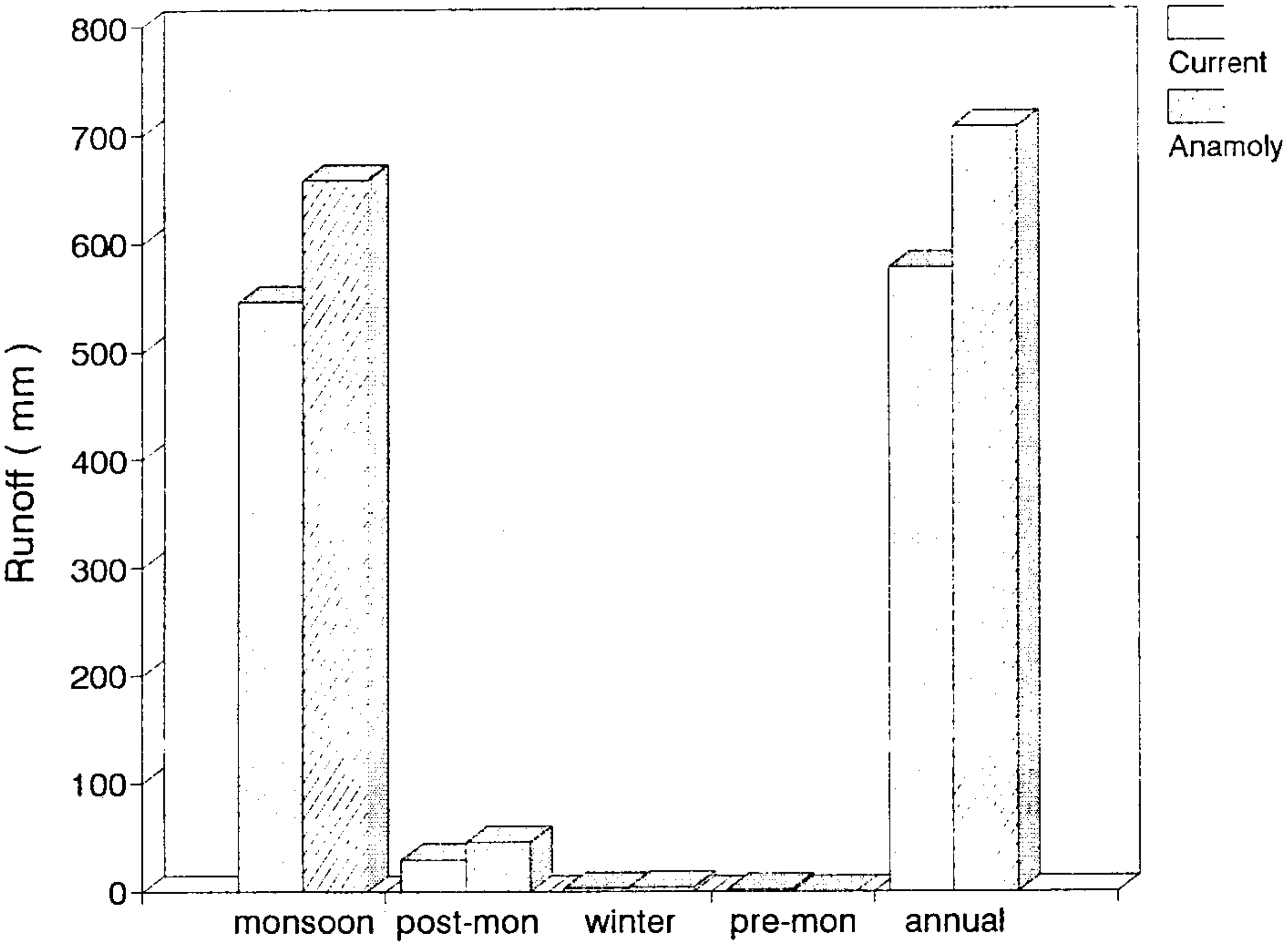

Fig. 6.14 Seasonal and annual runoff for Kolar basin for current (present day) and anomaly (by year 2080 due to green-house warming) level of climatic conditions

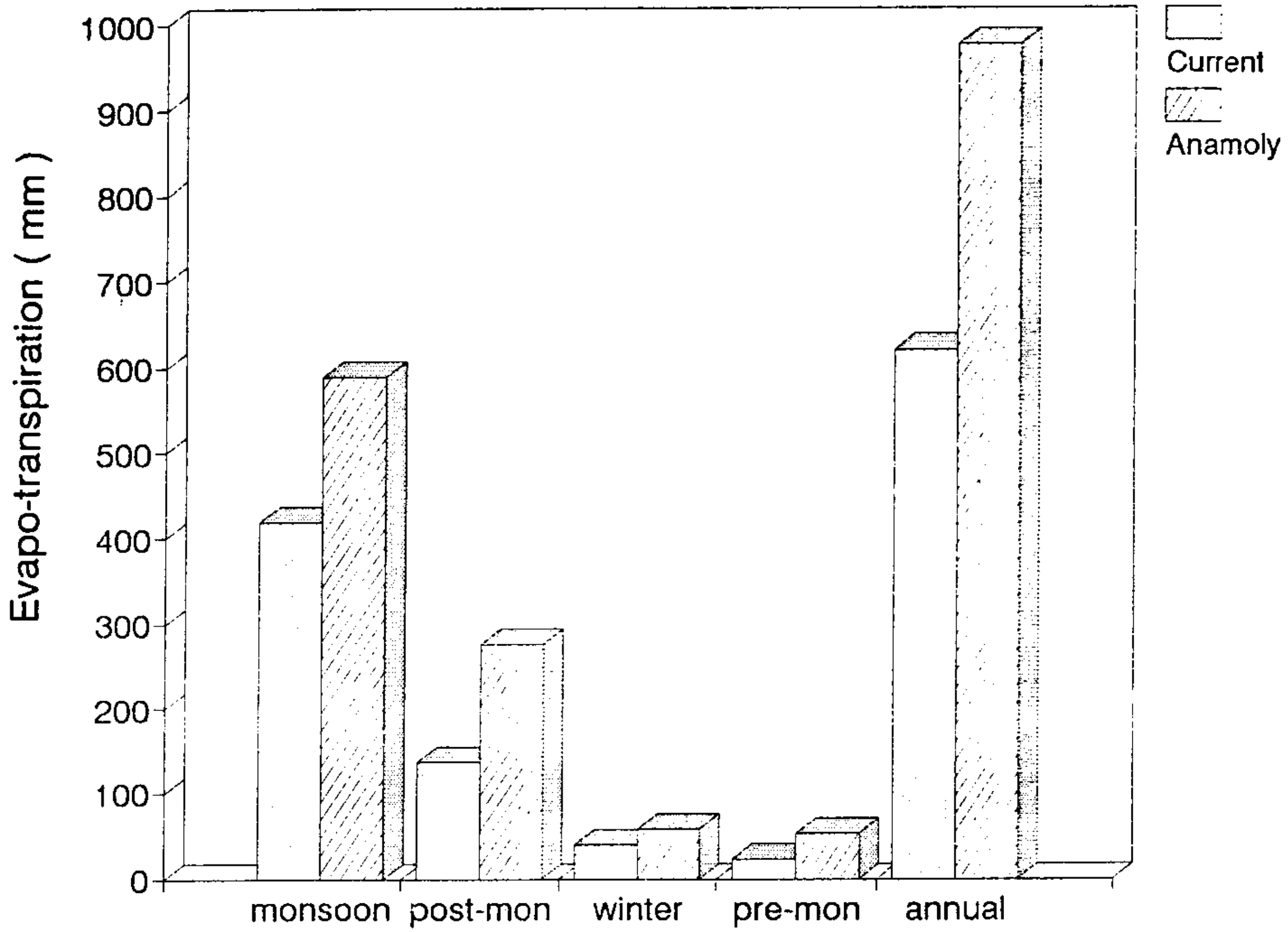

Fig. 6.15 Seasonal and annual evapotranspiration for Kolar basin for current (present day) and anomaly (by year 2080 due to greenhouse warming) level of climatic conditions

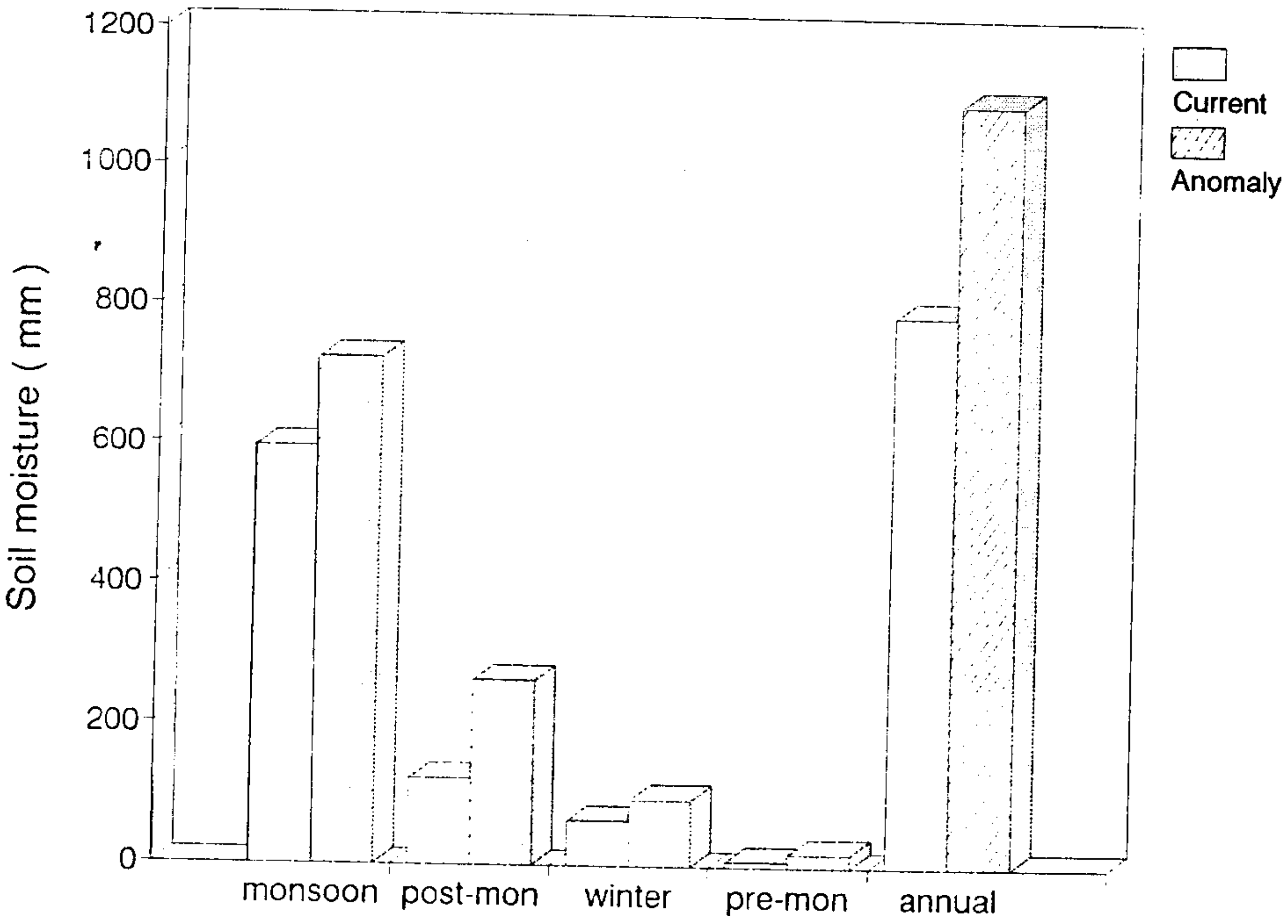

Fig. 6.16 Seasonal and annual soil moisture for Kolar basin for current (present day) and anomaly (by year 2080 due to greenhouse warming) level of climatic conditions

6.2.4 **Hemavati basin**

Temparature:

Surface temperature is expected to increase more than 2 °C during all seasons.

Precipitation:

The analysis indicates that monsoon rainfall seems to decrease by more than 15% (Fig. 6.17). During other seasons, more rainfall is expected. Substantial increase in rainfall is expected during winter and pre-monsoon seasons. Although considerable increase in precipitation is expected during winter and pre-monsoon seasons, annual rainfall appears to hardly increase more than 3%.

Heavy rainfall is expected in the beginning of monsoon period, but its intensity decreases at a faster rate in subsequent months.

Runoff:

During the monsoon period, flow decreases more than 10 %, whereas it increases during the low flow periods. Annual runoff is expected to decrease by 10 % (Fig. 6.18).

Time to peak remains the same, but peak magnitude is retarded.

Evapotranspiration:

Evapotranspiration may increase by 10 % during monsoon and post-monsoon seasons. During winter season and annually,

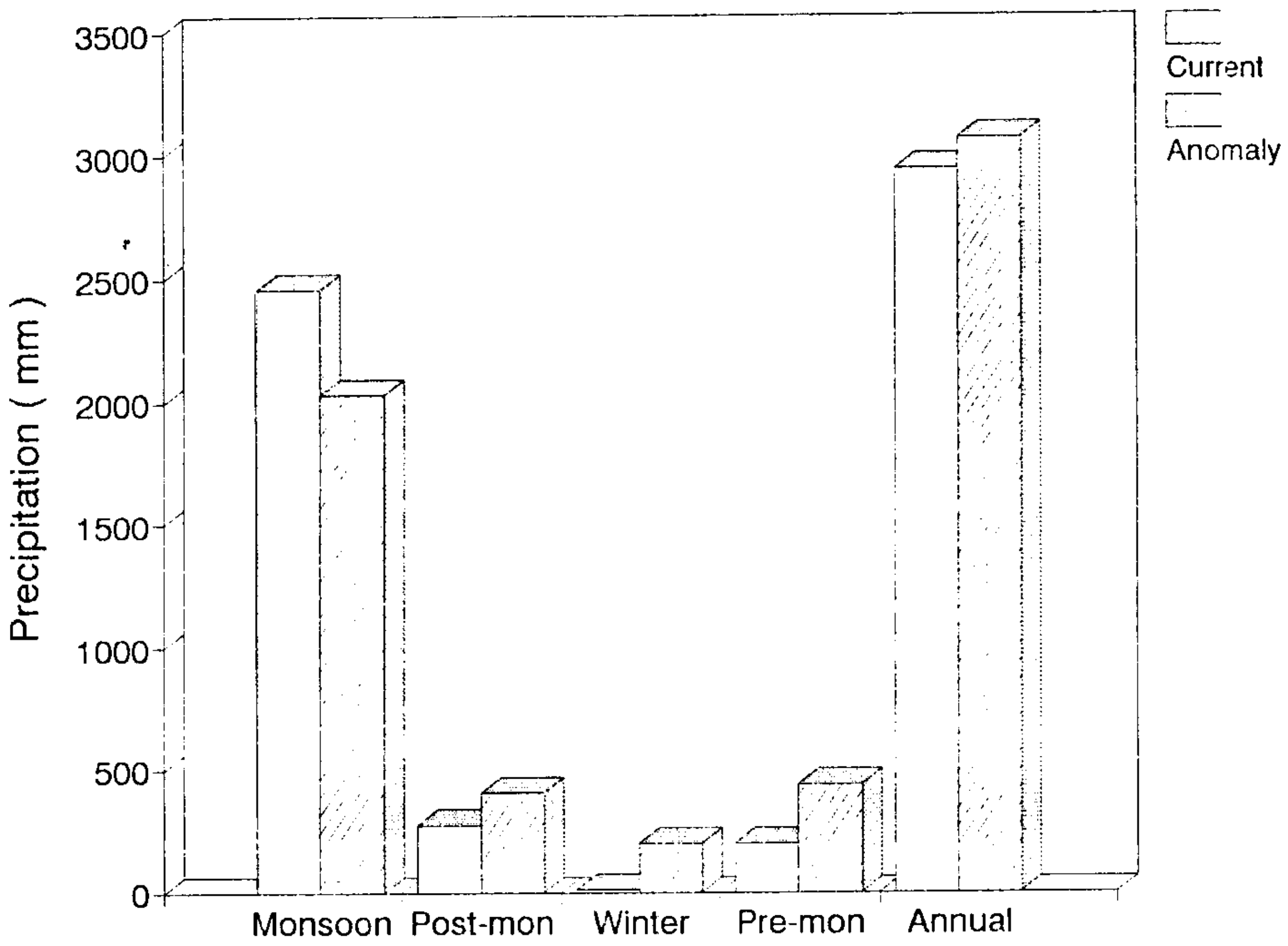

Fig. 6.17 Seasonal and annual precipitation for Hemavati basin for current (present day) and anomaly (by year 2080 due to greenhouse warming) level of climatic conditions

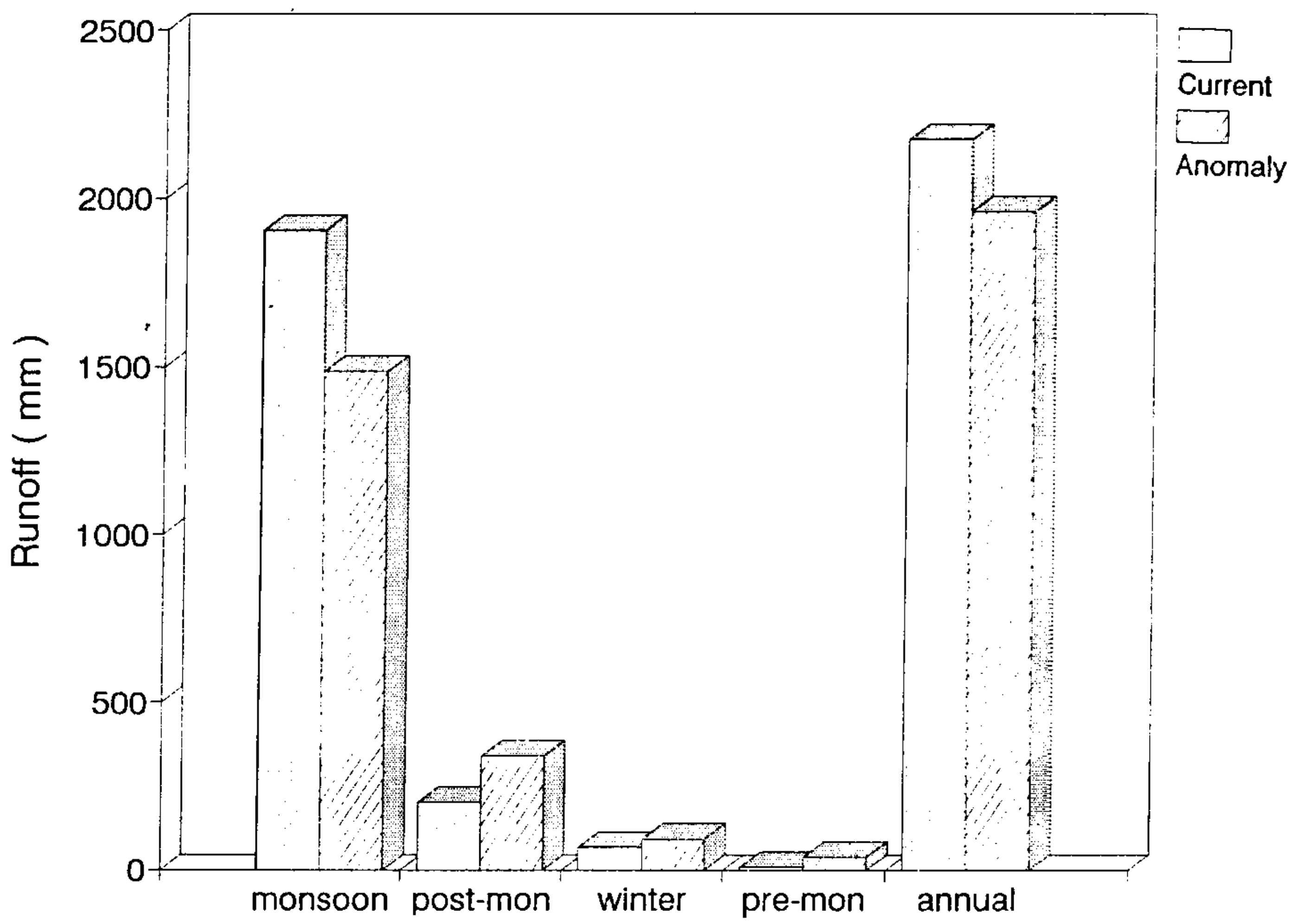

Fig. 6.18 Seasonal and annual runoff for Hemavati basin for current (present day) and anomaly (by year 2080 due to greenhouse warming) level of climatic conditions

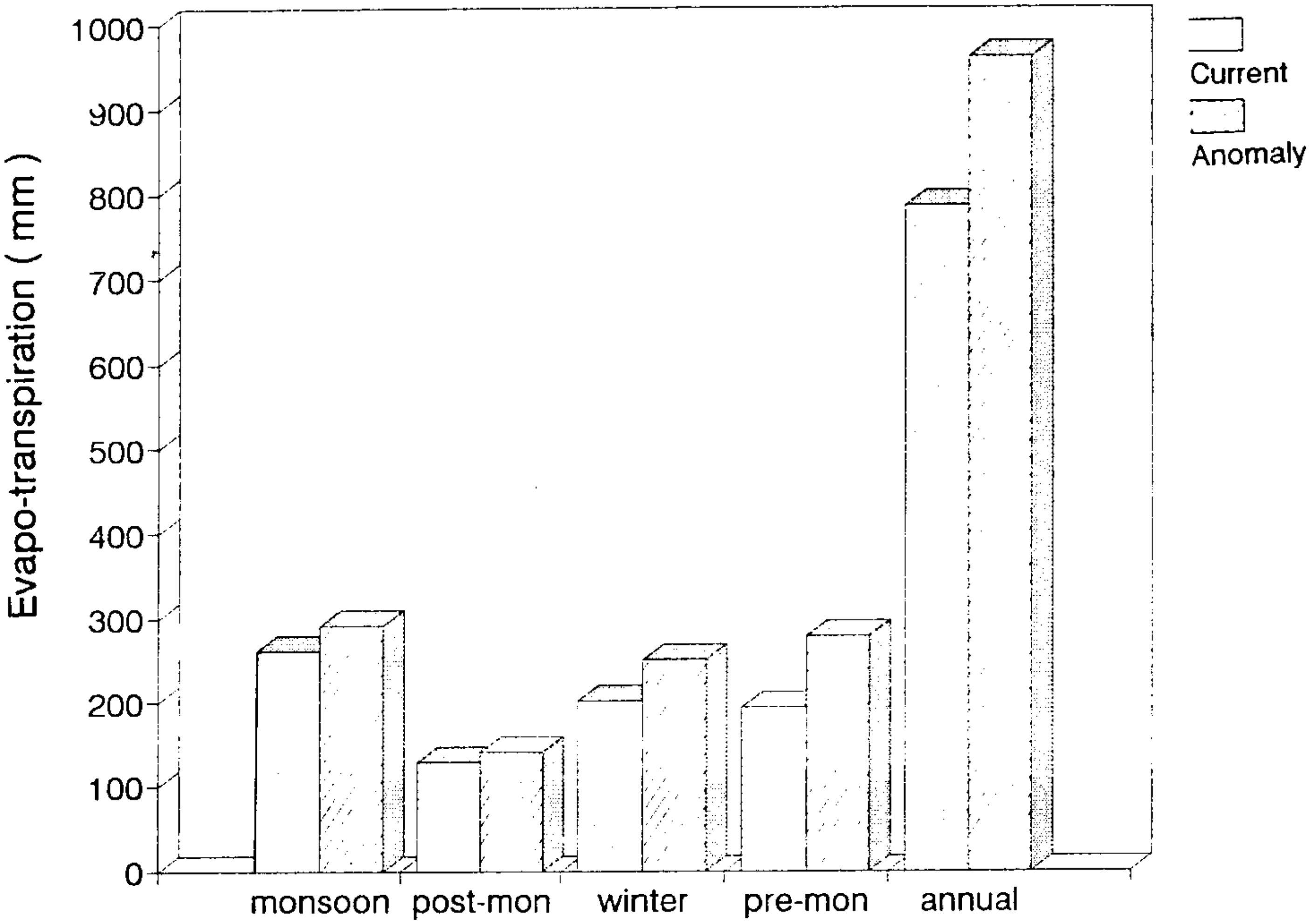

Fig. 6.19 Seasonal and annual evapotranspiration for Hemavati basin for current (present day) and anomaly (by year 2080 due to greenhouse warming) level of climatic conditions

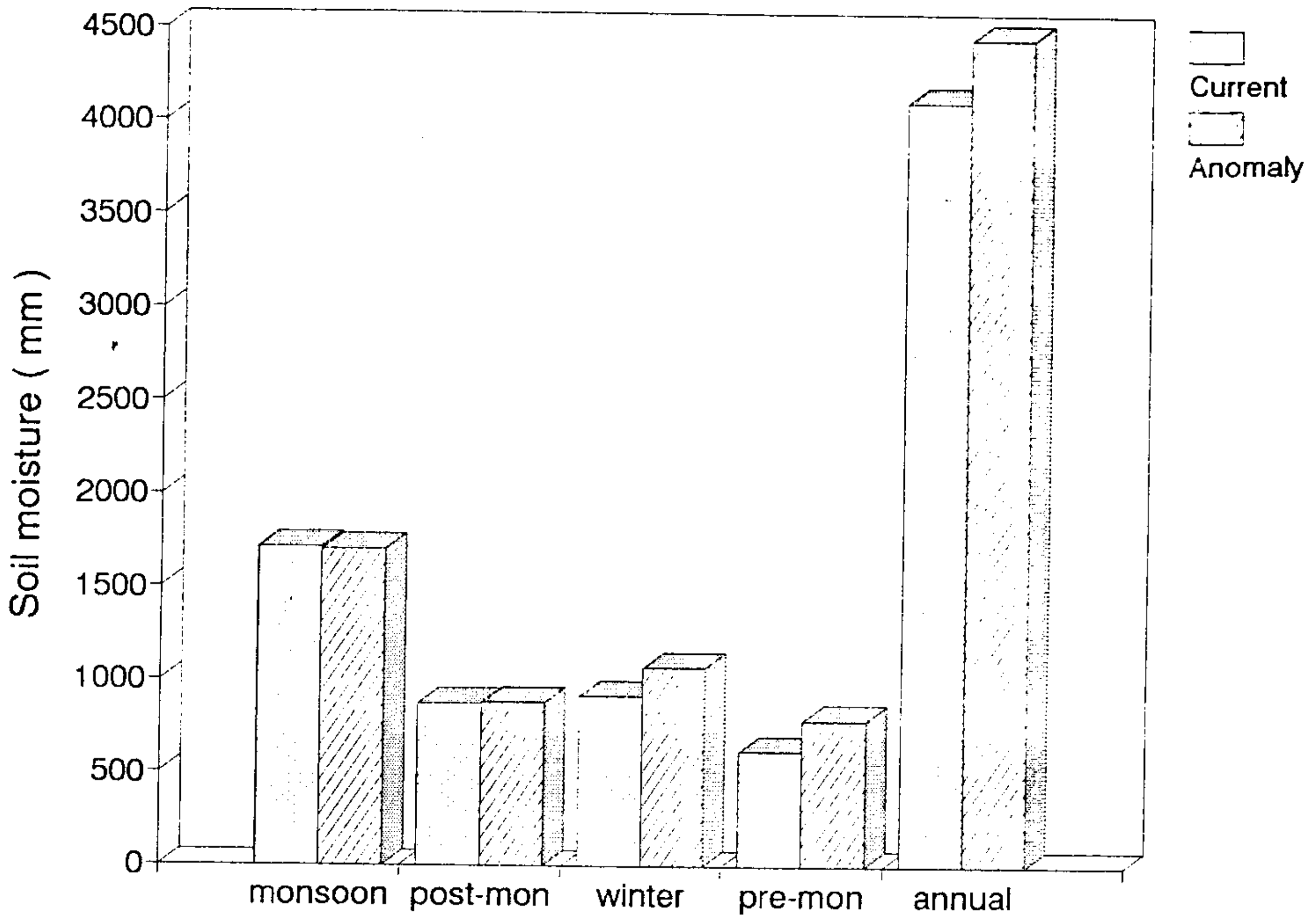

Fig. 6.20 Seasonal and annual soil moisture for Hemavati basin for current (present day) and anomaly (by year 2080 due to greenhouse warming) level of climatic conditions

evapotranspiration is expected to increase more than 20 % (Fig. 6.19). Pre-monsoon ET may increase more than 40%.

Soil moisture:

Soil moisture is expected to increase in all seasons except monsoon and post-monsoon (Fig. 6.20). In monsoon and post-monsoon seasons, no change in soil moisture is observed. Increased precipitation in the winter months increase the winter soil moisture storage, and make more moisture available for evapotranspiration during pre-monsoon period (Figs. 6.19 and 6.20). Increased temperature causes increase in pre-monsoon evapotranspiration.

7.0 CONCLUSIONS AND REMARKS

The sensitivity analysis for the four basins, viz. Damanganga, Sher, Kolar and Hemavati to expected changes in temperature and precipitation as revealed by different GCMs has been carried out in the present study. The findings are based on the best possible information available. However, there are several simplifications and uncertainties associated with the results that need to be highlighted. One of the major bottleneck in the present study was the availability of complete set of meteorological data for a limited period only, which is one of the major constraint for carrying out impact studies for Indian basins. A longer set of data may provide better results.

The study is based on the results from the GCMs, which are still in the developmental stage. The incorporation of hydrologic parameterizations in GCMs is still crude and the grid resolution is less. With increasing improvements in GCMs and more realistic GCM output for present day and future climate, the regional evaluations of impacts on hydrology may provide important insights. Although, the best GCM output was chosen for the analysis of climate change impact on a particular basin, some errors in the analysis are encountered because of incapability of simulating the present day climate of particular basin adequately. The studies reported here point towards a need for improvement of climate models/ development of regional models so as to obtain more realistic information on regional climate change that can be used for impact studies.

With the above limitations the general conclusions of the study for the regional scale assessment are enumerated below:

1. The sensitivity of different basins is different. The specific conclusions of the study pertaining to different basins have been discussed earlier.

2. It is to be pointed out that the conclusions made in the present study should be interpreted as qualitative assessment only.

3. Temperature rise in different seasons due to increase in greenhouse gases (by the year 2080) is expected to be within the range 1-4° C for the Damanganga, Sher, Kolar and Hemavati basins. Monthly average increase in temperature is expected to be more in Kolar basin than in other basins.

4. In Hemavati basin, heavy rainfall is expected in the

beginning of monsoon period, but its intensity decreases at a faster rate in subsequent months.

5. Numerical quantifications for analysis of precipitation, runoff, evapotranspiration and soil moisture may not be proper, and realistic prediction of these variables on monthly basis in a warmer world may not be accurate.

6. Rainfall over the Damanganga and Sher basins is expected to be more than 5% during monsoon and annually. Substantial increase in monsoon, pre-monsoon and annual rainfall is expected for Kolar basin, whereas Hemavati basin shows a decrease of more than 15% in monsoon and 3% increase in annual rainfall.

7. Runoff appears to decrease during monsoon season and annually for Damanganga and Hemavati basins; whereas it seems to increase for the Sher and Kolar basins.

8. Evapotranspiration is expected to increase during the monsoon season and annually for all the basins, as ample moisture for evapotranspiration is available during monsoon.

9. Soil moisture is expected to increase during all seasons for Sher and Kolar basins. For Damanganga basin, soil moisture will increase during monsoon and post-monsoon seasons, whereas it will decrease during winter and pre-monsoon seasons. In case of Hemavati basin, soil moisture appears to increase in all seasons except monsoon and post-monsoon in which no change is observed.

10. It is observed that basins belonging to relatively dry climatic region are more sensitive to climate change scenarios. Kolar (moist sub humid) and Sher (dry sub humid) are comparatively more sensitive to climate change, whereas Damanganga (humid) is the least sensitive. The similar characteristic, the arid regions are more sensitive to climate change, are reported by many researchers. Thus, basin aridity appears to be positively associated with basin sensitivity, the same has been also reported by Dooge (1989). The degree of sensitiveness seems to be dependent on the degree of aridity of the basin.

A very wide climate variability exists within India, and thus climatic change may have serious implications on many aspects of water resources including agricultural water supply, flooding and drought probabilities, groundwater potential, water quality, and reservoir design and operation. If substantial hydrologic changes materialize due to climate change predictions inferred from GCMs, it may affect adversely the Indian economic performance and social progress. Agriculture, a principal source of the national economy, and industrial growth may have acute consequences due to drastic change in temporal and spatial distributions of hydrologic parameters. Besides the crop production and industrial growth, flood and drought aspects need special attention, because these are common phenomena in India. However, before going for more detailed impacts studies on economic and socioeconomic factors, regional sensitivity studies are needed to pursue in more regions of India.

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