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Hydrologic sensitivity of some Indian basins to expected climate change and its effect on water availability using disaggregated GCMs outputs

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Abstract

Scientific studies based on General Circulation Models (GCMs) indicate a significant change in global climate during the current century. Such changes become all the more important as they may also affect the water availability of a region. However because of computational limitations, regional distributions of these changes are still not available. This paper utilises a disaggregation technique to downscale the GCMs predictions (precipitation) to catchment scale. The hydrologic sensitivity analyses of four Indian basins, namely, the Damanganga, Sher, Kolar and Hemavati, located in different agro-climatic regions are carried out using these disaggregated GCMs outputs and a catchment scale conceptual rainfall-runoff model. The study reveals that if substantial hydrologic changes materialize due to climate change predictions based on GCMs, it may have serious implications on many aspects of water resources, particularly agriculture, and thus may affect adversely the Indian economic performance and social progress as agriculture being the principal source of income for Indian economy.

INTRODUCTION

Extensive scientific studies in recent years indicate a rapid global climate change during the current century due to increased concentrations of atmospheric carbon dioxide and other radiatively active trace gases being discharged into the atmosphere in day to day life (WMO, 1986; IPCC, 1990,1992, 1995). It is believed that the effects of greenhouse warming will become predominant over the natural variability of climate, including the effects of volcanic eruptions, EINiño/southern oscillations, internal atmospheric and oceanic circulation variations and possible solar variations (Robock et al., 1993). It is almost now well accepted that the surface temperature will rise and precipitation patterns will change. Thus, such atmospheric modifications can alter the hydrologic cycle, which in turn will affect water resources systems. In this context, traditional techniques of water resources planning, development and management for various kinds of water utilization like hydropower generation, irrigation and water supply, and design of storm drains, flood protection structures and water control structures such as reservoirs, spillways etc. require to be examined. In case of large variations in hydrologic parameters, new methods may be sought for incorporating climatic information in design of long-term water resources projects and real-time water management.

Introducing the possibility of anthropogenic climate change expands the information requirement to include the effects of climate change on the availability of water. Since water has always been a determinative factor in the development of a society, recent studies show more concern over the potential implications of climate change on water resources (Gleick, 1987; Riebsame, 1988; Lettenmaier and Sheer, 1989; Lettenmaier and Gan, 1990; Cohen, 1991; Mimikou et al., 1991; Lal and Bhaskaran, 1993; Divya and Mehrotra, 1995).

The use of General Circulation Models (GCMs) outputs to evaluate the hydrological impacts of anthropogenic climate change on large scale has gained considerable attention in the recent years. However, because of computational limitations, GCMs operate at a resolution ranging from 2^o x 2^o to 10^o x 10^o (latitude, longitude). Thus, the climate projections obtained from these models cannot be directly considered as accurate forecasts of climate change for regional or local scale and further used as an input to the hydrologic models, as they operate at much smaller scale. Due to this, in the recent years, a number of studies have been carried out on impact assessment of climate change using the spatially disaggregated GCMs outputs (Avery and Leavesely, 1988; Giorgi and Mearns, 1991; Bardossy and Plate, 1992; Hay et al., 1992; Leavesley et al., 1992; Barros and Lettenmaier, 1993; Epstein and Ramirez, 1994; Mehrotra, 1999).

This paper demonstrates the application of disaggregation technique developed, and investigate the hydrologic sensitiveness of four Indian basins located in different agro-climatic regions to anthropogenic climate change derived from the GCMs. Output of three GCMs, namely, ECHAM1+LSG, MPI and CSIRO9 are used in the study. Rather than using all three GCMs output for analysing the sensitiveness of all four basins to climate change, only the GCM output which simulates the present climate of a particular basin more appropriately is chosen to assess the impact of climate change on various hydrologic components for that basin. The aim of the study is not to compare the results obtained from utilising the different GCMs, but to derive some hydrological information in a vulnerable climate condition for some Indian regions using a GCM output which describes the climate of the region under consideration more adequately. A monthly rainfall runoff model is used to assess the impact of climate change on runoff , evapotranspiration and soil moisture.

Since global climate models are still being refined by incorporating land surface heterogeneities and conceptualizing land-atmosphere interactions in a better understandable manner, and moreover various GCMs results do not conform for many regions, the results reported in this paper should not be treated as the actual predictions for the basins under consideration. Rather this paper be considered as one of the sensitivity experiments, as we do for the stochastic analysis. However, the analysis carried in this paper differs from that carried in the stochastic analysis as the former has more reliable physical basis, because global climate models follow deterministic laws based on the conservation laws of mass, momentum and energy, and thus, have a definite basis. The findings reported in this paper may crystallize, otherwise these may give sufficient feedbacks to improve the global climate models.

METHODOLOGY

The output from global climate models at grid points within/near the basin corresponding to current (present day climate or 1 x CO_2 level) and anomaly values (2 x CO_2 level or by the year 2080) are utilized to perform the sensitivity analyses of basins to the expected climate change. The precipitation output obtained from the GCMs for relevant grid points are disaggregated to obtain the representative precipitation values for the basins under consideration for both climatic conditions, current and anomaly. As climatological data is being recorded only at one station located within/near the basins, disaggregation could not be performed for temperature and other climatological data. The normal monthly grid point values for precipitation are averaged inversely proportional to the distance from the centroid of the basin to obtain the average representative values of the GCM output for that basin. These average values of precipitation corresponding to present climate run of the three GCMs are then compared with the available average basin values of precipitation as computed from the observed historical data. The predictions of the most realistic GCM, simulating the present day climate closely, are considered for the further analyses.

After selection of a GCM for a particular basin, the average anomaly values of the GCM output for that basin are disaggregated using the same principle as outlined earlier. The disaggregation procedure is briefly discussed in the following section, however, interested readers may refer Mehrotra and Singh (1996) for the details. The disaggregated values of precipitation corresponding to anomaly run are used as an input to a monthly rainfall-runoff model to obtain monthly values of runoff, evapotranspiration and soil moisture for various basins corresponding to the changed climate state. The rainfall-runoff model has been calibrated for the basins under consideration using the observed rainfall, runoff and climatological data. The obtained results are then compared with the present day simulations to assess the impact of climate change on various components of hydrologic cycle.

SPATIAL DISAGGREGATION OF GCMS OUTPUTS

The GCMs outputs are available at different grid points and at much larger spatial scales in comparison to the regional hydrologic models. Use of GCMs outputs at basin scale necessitate a methodology to transfer the information available at these grid points to the catchment under consideration. In this study, required information from the GCM outputs for the study area has been derived using a disaggregation technique proposed by Mehrotra and Singh (1996). This technique is the extension of the methodology originally proposed by Valencia and Schaake (1972, 1973), and is applicable for both temporal and spatial domains. The suitability of the disaggregation technique used in the study has been established on the basis of the comparison of various statistical techniques which permit the interpolation of a GCM output from grid points/centre of a basin to local scale (Mehrotra and Singh, 1996).

Disaggregation models have recently become a major technique for modeling hydrologic time series. The basic goal of any disaggregation model, either spatial or temporal, is to allow the preservation of historical statistical properties at more than one level. The statistical properties considered important at all levels include means, variances, the probability distribution of values and some covariances (or equivalently, correlations). Disaggregation modeling has two additional attributes which make it attractive. They are: (i) it often allows for a reduction in the number of parameters with little or no corresponding loss of desirable properties in the generated data, (ii) it allows for increased flexibility in the methods used for generation.

Disaggregation technique has been used by many researchers (Moreau and Pyatt, 1970; Valencia and Schaake, 1973; Mejia and Rousselle, 1976; Tao and Delleur, 1976; Hoshi and Burges, 1978, 1979; Sargent, 1979; Hay et al., 1992; Leavesley et al., 1992)). Hay et al. (1992) developed a methodology to disaggregate GCM precipitation using six weather types, classified on the basis of wind direction and cloud cover, and the precipitation characteristics of each weather type. Leavesley et al. (1992) developed a nested model approach to disaggregate large-scale model output for application in mountainous regions. Output from a coupled GCM-mesoscale atmospheric model is used as input to an orographic-precipitation model. Epstein and Ramirez (1994) utilized this technique to disaggregate the temperature and precipitation data of GCM for the Colorado river basin, USA.

The disaggregation model used in the study can be expressed as:

$$[Y] = [A]\,[X] \qquad (1)$$

where X is the grid point value of precipitation, Y is a column matrix (w x 1) containing corresponding values of precipitation at different stations (w nos) located within/near the basin, and A (w x 1) is a parameter matrix. The parameter matrix is estimated by using the method of moments, and can be expressed as:

$$A = S_{yx}\, S_{xx}^{-1} \qquad (2)$$

where S_{yx} is a matrix of covariances between the individual station precipitation values and the average basin value of precipitation, and S_{xx} is a matrix of covariances among the average values of precipitation for the basin.

The parameter matrix is estimated by using precipitation values for the present day climate at different stations, and then the average basin value of precipitation corresponding to the warmer climate obtained from GCM, is disaggregated using Equation (1).

RAINFALL-RUNOFF MODEL

The rainfall-runoff model used in the study is distributed in nature. Instead of computing the runoff based on the average precipitation over the basin, the model is applied to compute runoff from the individual station precipitation and then its average is calculated. The model is considered to be comprised of soil and ground water storage. It has seven parameters, out of which five parameters relate to the soil characteristic. 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 which govern moisture movement from one element to another. The applicability of this model to simulate the discharge of the Damanganga, Sher, Kolar and Hemavati basins has been tested by Mehrotra and Divya (1994).

DESCRIPTION OF THE STUDY AREAS

The four Indian basins; namely, Damanganga, Sher, Kolar and Hemavati basins are taken for the study. The first three basins are located in the central part and the fourth one in the southern part of India. The salient features of the study areas are given in Table 1. Fig. 1 shows the index map of various basins under consideration.

The Damanganga river rises in the Sahayadri hill ranges of Maharashtra and drains into the Arabian sea. The catchment area of the basin can be divided into five physiographic units; hill slopes, hill plateaus, upper and lower foot slopes, valley plains and local depressions, and river and stream banks. The soils of the basin can be broadly grouped into three groups; black soils, red soils and mixed soils. The average forest and agricultural areas in the basin are 41.4% and 36.3%, respectively, of the total geographical area of the basin.

The Sher and the Kolar rivers are tributaries of the Narmada river. The Narmada river is one of the two large rivers in Central India which flows westward and discharges in the Arabian sea. It is often hit by storms caused by depression originating both from the Arabian sea and the Bay of Bengal which cause heavy rains resulting in high floods. The Sher river rises in the southern Satpura range of Madhya Pradesh. Its basin is characterized by 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. The average forest area is about 66% and the agricultural area is about 31% of the total geographical area of the basin.

Table 1. Salient features of the study areas.

Feature	Damanganga	Sher	Kolar	Hemavati
Latitude	19° 45′ - 20° 20′	22° 25′ - 23° 55′	22° 40′ - 23° 08′	12° 55′ - 13° 11′
Longitude	72° 40′ - 73° 40′	79° 15′ - 79° 40′	77° 01′ - 77° 29′	75° 29′ - 75° 51′
Elevation	0 - 950 m	450 - 1110 m	300 - 600 m	890 - 1240 m
Normal Rainfall	2212 mm	1255 mm	1210 mm	2972 mm
Data Availability	1974 - 1983	1978 - 1986	1983 - 1988	1975 - 1981
Area	2261 sq. km.	1500 sq. km.	820 sq. km.	600 sq. km.
Region	Humid	Dry subhumid	Moist subhumid	Humid
Location	Central India	Central India	Central India	Southern India

The Kolar river originates in the Vindhyachal mountain range of Madhya Pradesh. The upper four-fifth part of the basin is predominantly covered by deciduous forest. The soils are skeleton to shallow in depth except near channels where they are relatively deep. The lower part of the catchment is predominantly cultivable area. The soils are deep in this area, and ground slopes are flat. The average forest area is about 71% and the agricultural area is about 27% of the total geographical area of the basin.

The Hemavati river is a tributary of the Cauvery river, and follows the south easterly course. Agriculture in the Southern India is mostly dependent on the inflow to this river. The Hemavati catchment receives heavy rainfall during June to October. The principal soil types found in this basin are red loamy soils and red sandy soils. About 60% of the area of the basin is covered by crop land, 29% by coffee plantation, and 12% by forests.

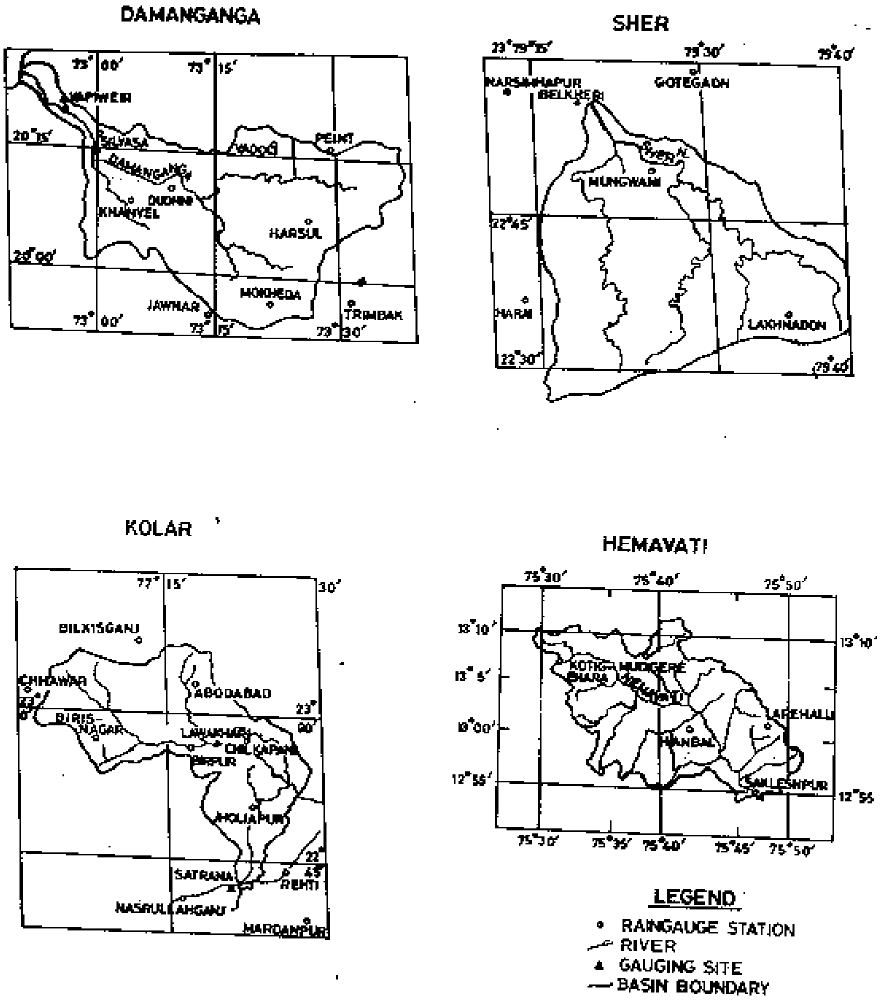

Figure 1. Index map of the study areas.

DATA USED

The observed rainfall data recorded at various raingauge stations, temperature and runoff data, and GCMs outputs from global climate models are used in this study. The rainfall measurement stations and the discharge gauging sites of the four basins under consideration are shown in Fig. 1. Monthly potential evapotranspiration values are calculated using the meteorological data of Surat, Bhopal, Jabalpur and Bangalore located near Damanganga, Kolar, Sher and Hemavati basins, respectively. These data are used as the representative values for these basins in the study as there is no station in the basins to record the meteorological parameters.

The outputs from three global climate models are utilized. The models are ECHAM1+LSG, MPI and CSIRO9 models. The precipitation and temperature values for present day climate and the changed climate due to increase in greenhouse gases under IPCC's scenario A conditions are taken for the analysis. The anomaly run outputs derived from the ECHAM1+LSG and the MPI GCMs indicate the mean of 10 years integration around the year 2080 (average of years 2075-2084). For the CSIRO9 model, the anomaly run corresponds to 2 x CO_2 scenario by the year 2030.

The European Community HAMburg (ECHAM1)+Large Scale Geostrophic ocean (LSG) model with a grid resolution of 5.625^o x 5.625^o 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 the details, interested readers may refer Cubasch et al. (1992). The MPI (Max Planck Institute) T42 model is a version 3 of the ECHAM models without ocean component, but using the ECHAM1+LSG experiment's sea surface forcing for doubled CO_2. The model has a resolution of 2.812^o x 2.812^o. The details are available in Lal et al. (1993).

The CSIRO9 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 is coupled with the model to implicitly determine sea surface temperatures. The diurnal and seasonal cycles are appropriately represented in the model. The lower boundary condition of the atmosphere is determined by an interactive land-surface scheme. The model has a resolution of 3.2^o x 5.6^o. The annual and seasonal mean global distributions of key climatic elements simulated by the model appear to be comparable to other atmospheric GCMs. For further details on the description and performance of the model, readers may refer McGregor et al. (1993), and Chakraborty and Lal (1994).

RESULTS AND DISCUSSION

Precipitation is used as an index in the selection of a particular GCM for a basin as discussed earlier. The actual normal values of precipitation and the disaggregated GCM outputs (Current and Anomaly levels) for the Damanganga, Sher, Kolar and Hemavati basins on seasonal basis are shown in Fig.2.

It is evident from Fig. 2 that the monsoon and annual precipitation obtained from the ECHAM1 model for the current level scenario are more close to the actual normal values for the Damanganga basin. However, for non-monsoon months, other models, the CSIRO9 and the MPI, simulate the precipitation better than the 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 is chosen on the basis of (i) simulation of monsoon precipitation, and (ii) absolute error involved in simulating all seasonal precipitation. Based on these criteria, the ECHAM1 model output was chosen for the sensitivity analysis of the Damanganga basin.

The MPI model results appear to be more close for the Sher basin as it is capable of simulating precipitation better than the other models for all seasons (Fig. 2).

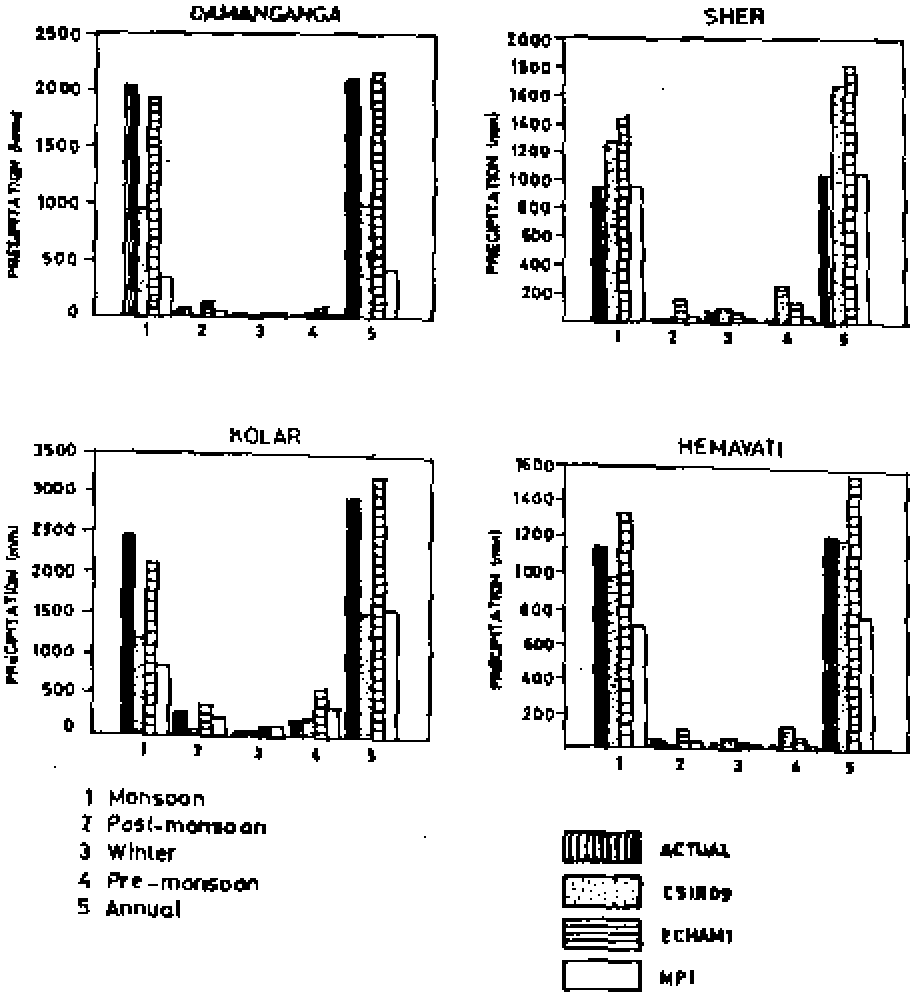

Figure 2. Comparison of observed and disaggregated GCM precipitation for current level.

On the same basis as discussed earlier, the ECHAM1 model seems to be more reliable for assessing the climate change consequences for the Kolar basin (Fig. 2). However, it is observed that the ECHAM1 model overestimates the annual rainfall, whereas the CSIRO9 model simulates the annual precipitation very closely. But the total absolute error involved in simulating all seasonal rainfall is more in case of the CSIRO9 model. The MPI model underestimates the precipitation values, deviating by more than 20% from the normal values. Therefore, the ECHAM1 model is chosen for assessing the possible climate change consequences on hydrologic parameters for the Kolar basin.

Following the same criterion for the selection of the model, the ECHAM1 model seems to be more reliable for the Hemavati basin (Fig. 2). However, the ECHAM1 results are overestimated by substantial amount during non-monsoon periods. Other two models, the

CSIRO9 and the MPI, show completely off to the observed ones for monsoon and annual rainfall. Therefore, the ECHAM1 model is chosen for the Hemavati basin to carry out the further analysis.

SENSITIVITY OF BASINS TO CLIMATE CHANGE

The disaggregated GCM outputs for precipitation and temperature are used as the input to the rainfall-runoff model to obtain the monthly runoff , evapotranspiration and soil moisture for the current and anomaly levels of climatic condition. Results of runoff , evapotranspiration, and soil moisture are reported on seasonal and annual basis for the current and anomaly levels of climatic condition. The seasonal results are grouped into five categories. They are monsoon (June-September), pre-monsoon (March-May), post-monsoon (October-November), and winter (December-February). Since all the models could not simulate the observed climate, the sensitivity analysis of a basin is carried out using the output of a global climate model which could best simulate the basin climate as discussed earlier. The possible consequences of climate change on the temperature, precipitation, runoff, evapotranspiration and soil moisture patterns of the basins, interpreted on the basis of results obtained from the rainfall-runoff model for the current and anomaly runs, are discussed in the following sections.

Temperature

Due to increase in greenhouse gases, the average temperature of the Damanganga basin is expected to increase by more than 2.5 ^{o}C during winter, 3.0 ^{o}C during pre-monsoon, 1.0 ^{o}C during monsoon, 2.0 ^{o}C during post-monsoon and 2.8^{o}C annually. The monthly average increase in temperature is expected to be more than 2.5 ^{o}C.

The surface temperature of the Sher basin is expected to increase by more than 3.5 ^{o}C during winter and pre-monsoon periods, and 1.5 ^{o}C during monsoon period. The monthly average increase in temperature is expected to be more than 2.5 ^{o}C. Similar results have been reported by Lal and Chander (1993).

The average surface temperature of the Kolar basin is expected to increase by more than 3.5 ^{o}C during winter, 4.0 ^{o}C during pre-monsoon and post-monsoon, 2.0 ^{o}C during monsoon and 3.55 ^{o}C annually. The monthly average increase in temperature is expected to be more than 3.5 ^{o}C.

In case of the Hemavati basin, increase in surface temperature appears to be more than 2.0 ^{o}C during all seasons. The analysis shows that the seasonal temperature of the Kolar basin seems to be comparatively more sensitive to the vulnerability of the atmospheric composition.

Precipitation

The precipitation over the Damanganga basin 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. 3). The maximum rainfall appears to occur in the same month, July, as it is occurring in the present climate.

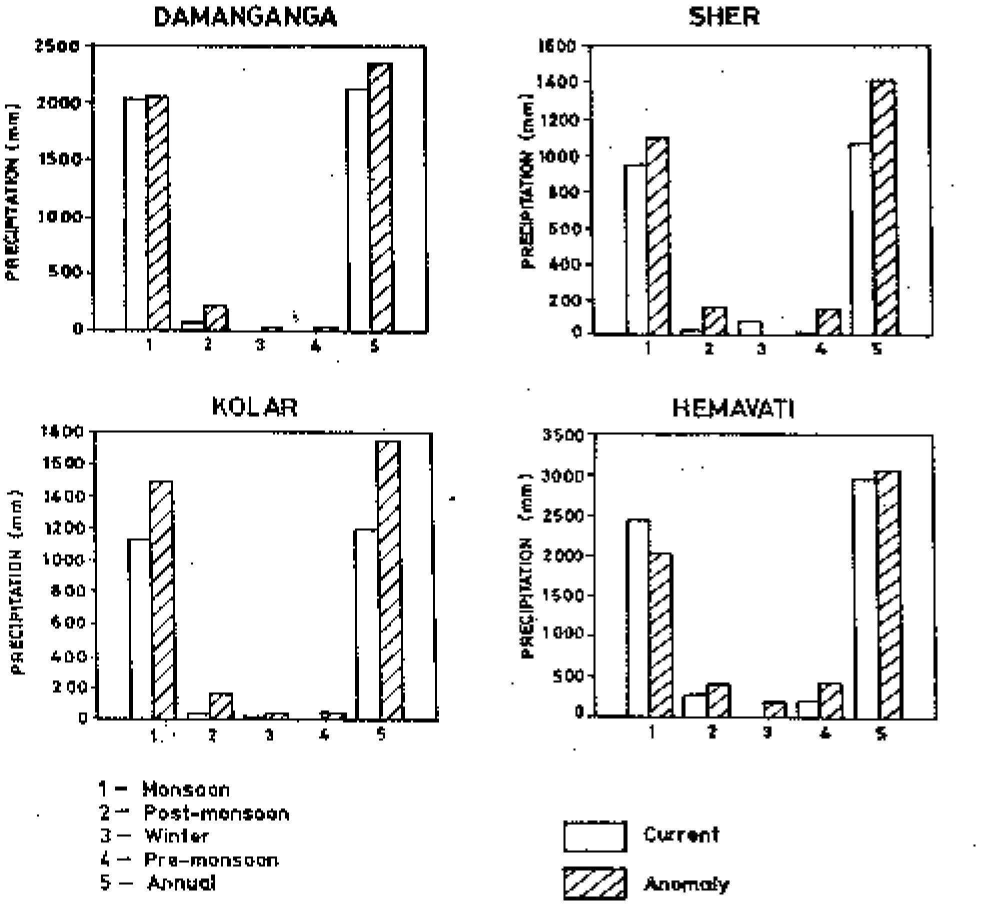

Figure 3. Seasonal and annual precipitation for current (present day) and anomaly (CO_2 doubling, obtained from the GCM) levels.

At anomaly level of climatic condition, the precipitation over the Sher basin is expected to increase by more than 5% during the monsoon period (Fig. 3). Total annual rainfall may increase substantially. Lal and Chander (1993), assessing the potential impacts of climate change on hydrology for Indian subcontinent analysing the MPI (T-42) model results, have found similar results for the region in which the Sher basin is located. Their findings include an increase in rainfall during monsoon and pre-monsoon periods, and an increase in annual rainfall. The results of this study show that there is decrease in rainfall during winter periods, whereas no change was reported by Lal and Chander (1993) for this period. The results indicate that the maximum rainfall appears to occur in the same month, August, as it is occurring in the present climate.

Rainfall over the Kolar basin is expected to increase by more than 30% during monsoon, and 45% annually (Fig. 3). Substantial increase in post-monsoon rainfall is expected. In other seasons also, precipitation is expected to increase. In case of the Kolar basin, the maximum rainfall appears to occur earlier by two months (June instead of August).

The analysis indicates that monsoon rainfall over the Hemavati basin is liable to decrease by more than 15%, whereas more rainfall is expected during other seasons (Fig. 3). Rainfall during winter and pre-monsoon seasons may increase substantially. Although considerable increase in precipitation is expected during winter and pre-monsoon months, annual rainfall appears to hardly increase by more than 3%. The heavy rainfall is expected over the Hemavati basin in the beginning of the monsoon period, however, its intensity will decrease at a faster rate in subsequent months.

Runoff

The results show that the numerical quantification for monthly balance is difficult for the Damanganga basin. However, qualitative assessment can be done for the annual and monsoon runoff. Furthermore, quantitative analysis of GCM results is difficult for less rainy periods; pre-monsoon, post-monsoon and winter, because model may not be able to simulate the basin precipitation accurately in these periods. This finding seems to be true for the Sher basin and moderately for the other basins also.

For the 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 monsoon season, and increase in non-monsoon seasons at anomaly level of climatic condition (Fig. 4).

In case of the Sher basin, it is observed that the annual and monsoon runoff may exceed by 15% at anomaly level scenario (Fig. 4). However, during winter period, runoff seems to decrease. The similar results, increasing trend in annual and monsoon runoff , and decreasing trend in runoff during winter period, were also reported 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.

Runoff for the Kolar basin appears to increase by more than 20% during monsoon season and annually (Fig. 4). However, runoff during low flow periods show hardly any difference except during post-monsoon season in which it will increase. Similar characteristics were also reported by Mehrotra and Divya (1994).

In case of the Hemavati basin, the flow appears to decrease more than 10% during the monsoon period, whereas there is increasing trend during the low flow periods. The annual runoff also is expected to decrease by 10% (Fig. 4).

Evapotranspiration

The analysis for the Damanganga basin shows that the evapotranspiration is likely to increase by 13% and 3% for monsoon months and on annual basis, respectively (Fig. 5). However, this is on lowerside when compared to the earlier results reported by Mehrotra and Divya (1994) which was based on the sensitivity experiments using hypothetical climate change scenarios utilizing historical data. 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 were reported by Mehrotra and Divya (1994) corresponding to 3 °C rise in temperature and 5-10% increase in precipitation. Increase in evapotranspiration during the monsoon period 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.

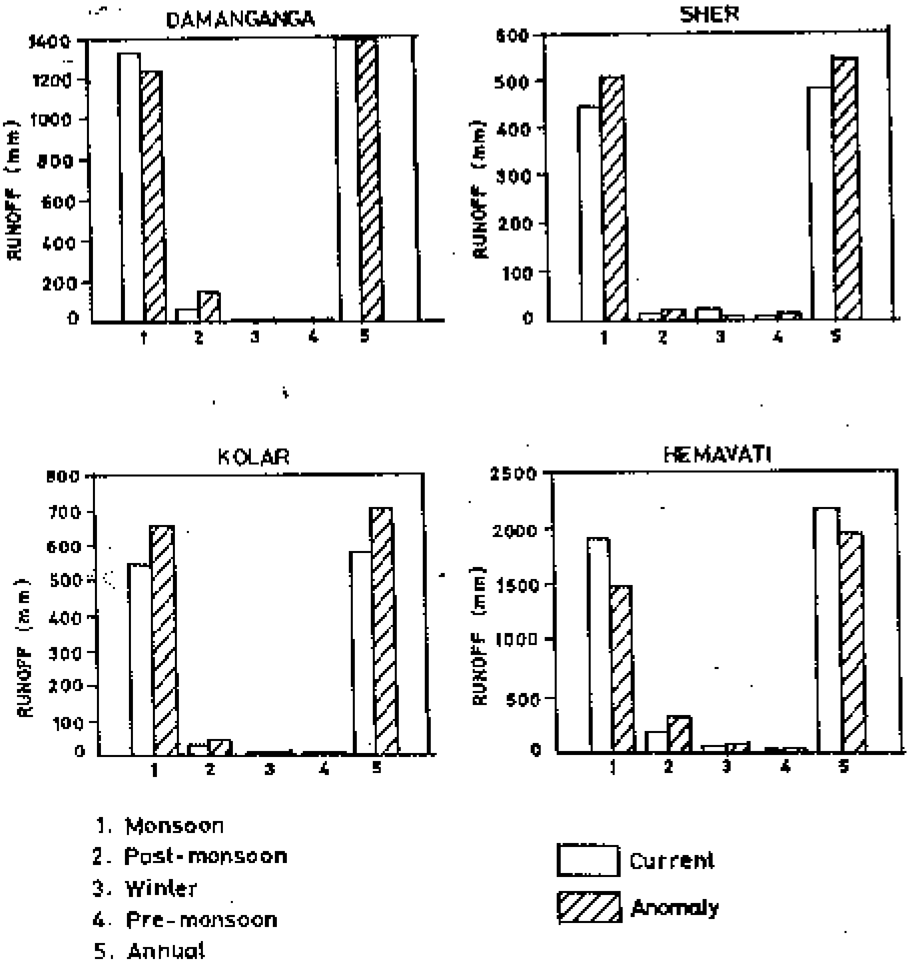

Figure 4. Seasonal and annual runoff for current (present day) and anomaly (CO_2 doubling, obtained from the GCM) levels.

In case of the Sher basin, the evapotranspiration is likely to increase by 30% and 50% for monsoon months and on annual basis, respectively (Fig. 5). However, these values seem to be on higherside when compared with the results reported by Mehrotra and Divya (1994) corresponding to a temperature increase of 3 °C and precipitation increase of about 20%. The evapotranspiration 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 the evapotranspiration. 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.

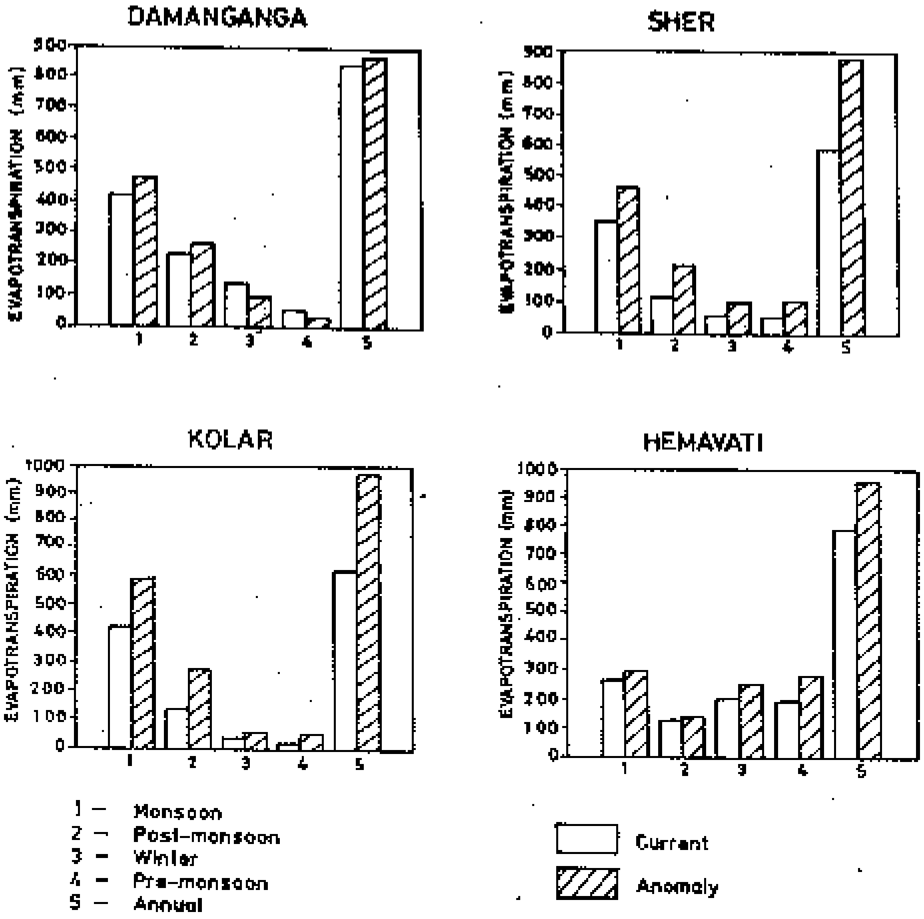

Figure 5. Seasonal and annual evapotranspiration for current (present day) and anomaly (CO_2 doubling, obtained from the GCM) levels.

The evapotranspiration is expected to increase in all seasons for the Kolar basin (Fig. 5). Substantial increase is observed in monsoon, post-monsoon and annual evapotranspiration. This increase may be more than 40% during monsoon and 55% annually due to increased temperature.

The results for the Hemavati basin indicate that the evapotranspiration may increase by 10% during monsoon and post-monsoon seasons. During winter season and annually, the evapotranspiration is expected to increase by more than 20% (Fig. 5). The pre-monsoon evapotranspiration shows a significant increase by more than 40%.

Soil moisture

Fig. 6 shows the state of the soil moisture pattern in different seasons for various basins at current and anomaly levels of climatic condition. It is evident from this figure that the soil moisture increases during monsoon and post-monsoon seasons for the Damanganga basin due to increased greenhouse gases. However, it may decrease during winter and pre-monsoon seasons, and annually.

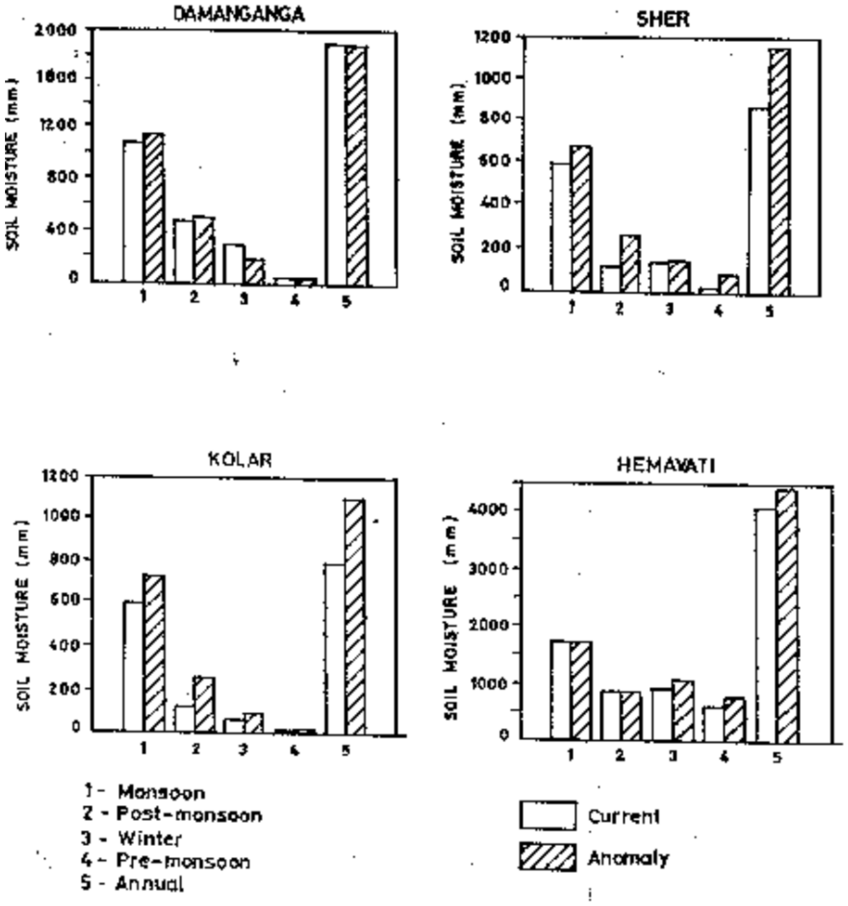

Figure 6. Seasonal and annual soil moisture for current (present day) and anomaly (CO_2 doubling, obtained from the GCM) levels.

The soil moisture of the Sher basin is expected to increase during all seasons (Fig. 6). 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.

The soil moisture of the Kolar basin increases annually and also during winter, pre-monsoon, monsoon and post-monsoon seasons (Fig. 6). 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 condition.

The soil moisture of the Hemavati basin is expected to increase in all seasons except monsoon and post-monsoon (Fig. 6). In monsoon and post-monsoon seasons, no change in soil moisture is observed. Increased precipitation in the winter months increases the winter soil moisture storage, and thus, more moisture becomes available for the evapotranspiration during pre-monsoon period (Figs. 5d and 6d). Increased temperature causes increase in pre-monsoon evapotranspiration.

CONCLUSIONS AND REMARKS

The sensitivity analyses are carried out using the disaggregated GCM output and a conceptual regional rainfall-runoff model for the Damanganga, Sher, Kolar and Hemawati basins located in different agro-climatic regions to expected change in temperature and precipitation patterns as revealed by different GCMs. 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 is 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 poor. In addition, the outputs from different GCMs can vary significantly for some regions, posing the problem of which GCM to consider as correct. With increasing improvements in GCMs and thus, more realistic GCM output for present day and future climate, the regional evaluations of impacts on hydrology may provide important insights. Although in this study, the best GCM output is 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 results reported here also 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 derived for the regional scale assessment are enumerated below, as detailed specific conclusions pertaining to different basins need not to be repeated:

1. The findings reported in this paper should be interpreted as qualitative assessment only. Numerical values should not be taken granted as numerical quantification for the 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.
2. Temperature rise in different seasons due to increase in greenhouse gases (by the year 2080) is expected to be within the range of 1-4 ^{o}C for all the four basins.

The monthly average increase in temperature is expected to be more in the Kolar basin than in other basins.

3. Rainfall over the Damanganga and Sher basins is expected to be more than 5% during monsoon and annually. Also, substantial increase in monsoon, pre-monsoon and annual rainfall is expected for the Kolar basin, whereas the Hemavati basin shows a decrease of more than 15% in monsoon and 3% increase in annual rainfall.
4. Runoff appears to decrease during monsoon season and annually for the Damanganga basin; whereas it is expected to increase for the Sher and Kolar basins.
5. Evapotranspiration is expected to increase during the monsoon season and annually for all the basins, as ample moisture for evapotranspiration is available during monsoon.
6. Soil moisture is expected to increase during all seasons for the Sher and Kolar basins. For the Damanganga basin, soil moisture will increase during monsoon and post-monsoon seasons, whereas it will decrease during winter and pre-monsoon seasons.
7. It is observed that basins belonging to relatively dry climatic region are more sensitive to climate change scenarios. The Kolar (moist subhumid) and the Sher (dry subhumid) are comparatively more sensitive to climate change, whereas the 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 the 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, there is need to improve global predictions and methodologies for regional impact assessment, and to pursue regional sensitivity studies for more Indian regions, especially for the regions differing significantly in hydrometeorlogical and hydrological characteristics. No doubt, uncertainties associated with modeling and data gaps adhere to the findings.

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