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RESPONSE OF AN INDIAN CATCHMENT TO EXPECTED CLIMATIC CHANGE DUE TO GLOBAL WARMING

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PREFACE

The global climate change is expected to have profound impact on hydrological processes. The direct assessments of impacts and realistic evaluations of the climate sensitivities of water resource systems, specially on a regional scale are a matter of concern and need considerable study. One of the approaches for assessing the impacts of future climate change is the use of conceptual rainfall-runoff models.

In the present report sensitivity analyses of runoff, evapotranspiration and soil moisture on mean monthly, seasonal and annual basis for Kolar and Sher sub-basins of Narmada basin have been carried out to hypothetical yet plausible scenarios of future climate change due to doubling of CO_2 in the atmosphere.

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ABSTRACT

Global climatic changes due to increasing concentrations of greenhouse gases in the atmosphere and the possible impacts on the hydrological cycle are a matter of growing concern. The hydrologists are specifically interested in the impacts on timing and magnitude of runoff, soil moisture, and evapotranspiration and consequent temporal and spatial redistribution of regional water resources.

One of the approaches for assessing the impacts of future climate change is the use of conceptual models. An attempt has been made to study the sensitivity of runoff, evapotranspiration, and soil moisture to hypothetical scenarios of changes in temperature and precipitation for Kolar and Sher sub-basins of Narmada basin lying in Central India using a conceptual rainfall-runoff model. The observed monthly rainfall and potential evapotranspiration estimated using climatic variables have been used as input to the model. Sensitivity analysis of monthly, seasonal (pre monsoon, monsoon, post monsoon and winter months) and annual mean values of these variables has been carried out for these sub-basins. Studies show that the Sher sub-basin appears to be some what more sensitive to climatic scenarios. The influence of climatic scenarios on storage design as predicted by the model substantiates the need for consideration of effect of climate variations on the design and operation of water resource projects.

1.0 INTRODUCTION

Climate change due to increasing concentrations of greenhouse gases in the atmosphere has been a subject of concern and research in the recent years. The general circulation models have been used as a tool for projecting the changes in climate due to increase in greenhouse gases . In recent years, a number of groups in the world have carried out studies on changes in surface temperature and precipitation due to doubling of carbon dioxide based on GCMs. The results indicate that if the present trend of greenhouse gas emissions would continue, the global mean surface temperature would increase at a rate of 0.2°C to 0.5°C per decade during next few decades (IPCC, 1990). The near surface air temperature has already increased by about 0.5°C since the late 19th century (Jones et al. 1986; WMO, 1987) (Fig. 1.1). The curves show a long time scale warming trend, which is consistent with the '*hypothesized warming*' due to increased greenhouse gases.

The quantification of large scale area average precipitation changes is difficult as compared to that of temperature changes because of the higher spatial variability of the former. An upward trend for land based precipitation data from 1920 in mid to high latitudes (35-70°C) and a marked downward trend in tropical to sub-tropical latitudes (5-35°N) of the northern hemisphere has been observed by Bradley et al (1987)(Fig. 1.2). However, the confidence in prediction of regional climate changes is still low. It is expected that regionally non uniform temperature changes will develop and that precipitation will be modified regionally, with some areas receiving increased and others receiving reduced rainfall.

2.0 REGIONAL HYDROLOGICAL IMPACTS OF CLIMATE CHANGE

The global warming and climate changes would have considerable influence on hydrological regime (WMO, 1985; 1987). Hydrologists are specifically interested in regional impacts on timing and magnitude of evapotranspiration (ET), soil moisture and runoff and on their spatial and temporal redistribution. A number of studies based on various approaches to assess the impacts of climate change scenarios on hydrological parameters viz, ET, soil moisture storage, and runoff for various basins have been reported in the literature (Nemec and Schaake, 1982; Gleick, 1986, 1987; Bultot et al., 1988; Mimikov et al., 1991). However, not much work has been done in this area in India.

One of the most profound impact of climatic changes may be the major alterations in regional hydrologic cycle and changes in regional water availability. Gleick (1986) reviewed different approaches for evaluating impacts of global climatic changes on the regional hydrology . The results of some of the early studies are given in Table 2.1. These assessments have used different methods of approaches to study the climatic impact on runoff.

2.1 Approaches for evaluation of hydrological consequences of climate change

Extensive studies have been carried out on hydrologic consequences of future anthropogenic climate change for 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. is formulated statistically. Using this approach studies have been carried out for some regions of US (Stockton and Boggess, 1979; Revelle and Waggoner, 1983) and for the annual river runoff in the USSR (Anthropogenic Climatic Changes,1987).

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 by Schwartz(1977) and Glantz(1988) for the US and by Chunzhen(1989) 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 is calculated from the GCMs, based upon the increase in the concentration of greenhouse gases.

An extension to the above approach is to select some appropriate deterministic / conceptual type water balance model and input the GCMs result to it, to predict the future possible changes in hydrologic conditions. Alternatively some hypothetical set of data 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 (Nemec and Schaake, 1982; Gleick, 1986, 1987; Mather and Feddema, 1986; Cohen, 1986; Flashka et al., 1987; Bultot et al., 1988; Kuchment et al,1989; Mimikov et al., 1991).

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 by Vinnikov et al. (1989) for the USSR and Griffiths (1989) for the New Zealand and Babkin (Shiklomanov, 1988) .

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.

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 either coupled to the GCM or used independently as mentioned earlier. The concept of using these models has several advantages . First , the technique permits flexibility in identifying and choosing the most appropriate structure of the model particularly suited to any specific region. Second, hydrologic models can be tailored to fit the characteristics of available data, which is a big advantage given the diverse and sometimes questionable nature of hydrologic data. Third, regional scale hydrologic models are considerably easier to manipulate, modify and operate than the general circulation models. Fourth, such regional models can be used to evaluate the sensitivity of specific watersheds to both hypothetical changes in climate and to changes predicted by large scale GCMs. And finally, methods that can incorporate both detailed regional hydrologic characteristics and output from large scale GCMs will be well suited to take advantage of continuing improvements in the resolution, regional geography and hydrology of global climate models.

2.2 Climate change scenarios

To evaluate the hydrological effects of increasing greenhouse gases, the predictions/forecasts of changes in climatological parameters,specially air temperature and precipitation for different regions and periods of time are needed. However, the accurate forecasts of regional climatic changes are still not available. In their absence various approaches to the development of scenarios of future climatic changes are used. These are -

(a) hypothetical (or prescribed) scenarios - Many researchers prescribe hypothetical scenarios for climatic change without taking into account a particular time interval. Most of the scenarios assume an air temperature increase from 0.5° C to 4° C and precipitation change(increase or decrease) in the range of 10% to 25% .

(b) scenarios obtained by using atmospheric GCMs - These are obtained by models considering doubling of CO_2 in the atmosphere.The scenarios are usually applied to the regions for which similar simulations have been repeatedly carried out by using different methods.

(c) simulations based on paleoclimatic reconstructions - The paleoclimatic records provide information about the effects of changes in CO_2 concentrations as some aspects of past climatic changes are undoubtedly related to past changes in atmospheric CO_2 levels .

3.0 INDIAN CLIMATE

India possesses a great variety and diversity of climate. Climate changes from extreme of hot to extreme of cold, from extreme arid regions to extreme humid regions, and from drought prone areas to flood prone areas. Climatic condition govern to a great extent the operation of water resources in the country. The Himalayan rivers of India are ice fed rivers and thus are much vulnerable to climate change. Rainfall is governed by the south-west and north-east monsoons. Indian rainfall shows great temporal and spatial variations or distributions. About 80 to 90% of the total rainfall occurs during four monsoonal months. Large storage of water is required to meet the demand during the lean periods.

4.0 CLIMATE CHANGE & TRENDS OVER INDIA AND ITS IMPACTS

The mean annual temperature for India during the period 1901-1982 is shown in Figure 4.1 (Hingane et al, 1985). The trend line indicates a trend of about 0.4°C warming during recent 8 decades. In contrast to the post 1940 cooling which has been observed for the northern hemisphere, a steady increase in mean annual temperature has been observed for Indian subcontinent for the last 8 decades. Although the results can not be expressed in terms of cause and effect, a significant increase in the consumption of fossil fuel, deforestation and land use during the period can be noted.

The precipitation patterns over India have been intensively studied over the years notably at India Meteorological Department and Indian Institute of Tropical Meteorology, Pune. These studies have been centered mainly on prediction of monsoon rainfall. Analysis of data available on precipitation from 1901 onwards has not shown any definite pattern (TERI, 1989). Thapliyal and Kulshreshtha (1991) carried out studies to determine the trend of annual rainfall of India (Figure 4.2). They found that the five year running mean have fluctuated from the normal rainfall within ± one standard deviation. They did not find any long term climate change and trend.

The contributions to greenhouse effect from India is only about 4% and is due to the following factors: agricultural practices, biomass burning, power generation from thermal plants and transportation, and deforestation. India, has the largest area of paddy cultivation, and thus is the largest producer of methane in the world. India is also the fourth largest user of nitrogenous fertilizers. Within the sector of biomass burning India is seen as a significant contributor. The contribution due to power generation is from coal based thermal plants, which account for about 65% of total power generation. Out of the above parameters, deforestation is contributing least to the greenhouse effect (Hai et al, 1990).

Based upon the results from high resolution general circulation models, IPCC (1990) selected five regions, each a few million square km in area, representative of different climatological regions for particular study . Region 2 represents southern Asia (5° - 30°N , 70° - 105°E) which covers almost the entire Indian subcontinent. The report states :

"The warming varies from 1° to 2° 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% ."

Above summarizes the change in temperature, precipitation and soil moisture which is predicted to occur by year 2030 on Business

- As - Usual scenarios (BAU; if few or no steps are taken to limit greenhouse gas emissions) as an average over the region. Confidence in this estimate is low but this is the best possible estimate. There may, however be considerable variations within the region. It is expected that regionally non uniform temperature changes will develop and that precipitation will be modified regionally, with some areas receiving increased and others receiving reduced rainfall.

Lal et al (1992) studied the impact of increasing greenhouse gas concentrations on the climate of the Indian subcontinent and its variability. The monsoon region selected by Lal et al for the study was bounded by latitudes 2.8° S to 36.6° N and longitudes 61.7° E to 101.0° E , the area having 64 grid points. They used the Hamburg global coupled atmosphere - ocean circulation model which could simulate the present day climate and its inter - annual variability over the monsoon region with substantial skill. The model results obtained from the greenhouse warming experiment suggested an increase of over 2° K over the monsoon region in next 100 years under IPCC scenario A (business as usual scenarios). The model simulated an increase in total(averaged for the study area) seasonal precipitation (Figure 4.3). 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 (1992), using the results of Hamburg general circulation model (ECHAM3 T - 42) have also 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 (Figure 4.4). However the results have a low confidence because the control simulations of coupled climate models are still deficient to simulate the real climate accurately.

5.0 PURPOSE OF THE PRESENT STUDY

The information on expected changes in hydrological cycle and its components is greatly needed for understanding their impact on water resources development and management, so that plans could be made in good time and preparations made to meet the changes in streamflow regime.

There is insufficient information on regional impacts of the greenhouse effect on rainfall or other hydrological parameters currently available to allow for definite detailed statements of the potential impacts on hydrology and water resources in India.

Given that current estimates of the impacts of climate change on hydrological variables such as rainfall and soil moisture are unreliable , it is important to be aware of the sensitivity of our water resources to large changes in these parameters. Therefore the current scenarios provided by general circulation models should be used to provide estimates of the possible range of impacts. The use of a range of scenarios effectively means that sensitivity studies should be undertaken.

India's population depends to a large extent on agriculture, specially the rain fed agriculture. Keeping in view of the increasing demand of water for various activities, it becomes essential to also know with sufficient accuracy the future availability of water so as to plan and manage our resources and requirements.

It therefore becomes imperative to study the Indian climate change and its impact on hydrology on regional basis.

In this report the sensitivity of response of the Kolar and Sher sub-basins located in Narmada basin in Central India to a few scenarios of climate change, generally as predicted by large scale GCMs, has been presented.

6.0 THE CATCHMENT MODEL

As already mentioned ,one of the promising approach to study hydrological impacts of climate change is the use of the regional hydrologic models. The model used in this study is a conceptual rainfall- runoff model. The input data requirement for the model are quite modest and can be easily met with for an Indian basin.

6.1 Description of the model

The conceptual model used here operates on a monthly basis. To simulate the various processes occurring within the basin, the basin is considered to be composed of soil storage and ground water storage. For each storage, a few equations are solved, based upon some input, output variables and processes which govern moisture movement from one element to another. Model has relatively small number of parameters (7), out of which five parameters are related to soil characteristics of the basin. Model parameters can be estimated either by a optimization algorithm included in the computer program or by trial and error if, some approximate probable values of parameter is known in advance.

Model structure is finalized after several permutation and combinations of different hydrological processes of the water balance and with various parameters and according different priorities to the processes. It was also found that increased number of parameters could not improve the results much and the sequence of processes as described below represented the basins in the best way.

Monthly areal precipitation 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.

If PPTN > THRES then $\quad FSR = PPTN - THRES \quad (1)$
Otherwise $\quad FSR = 0 \quad (2)$
Final precipitation $\quad PPTN\,(f) = PPTN - FSR \quad (3)$

Second 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 :

$$QSR = PPTN(f) * IMPRM * (1 - SMD/SMQSR) \qquad (4)$$

Where, SMQSR is a constant which regulates how sensitive the impermeable area is to changes in soil moisture and,
IMPRM is the max impermeable fraction of the catchment when the soil is fully saturated and,
SMD = Soil moisture deficit at the beginning of the month and is described as :

$$SMD = FC - SMS \qquad (5)$$

SMS = Soil moisture at the beginning of the month, and
FC = Field capacity of the soil
Remaining portion of precipitation goes into the soil as infiltration (INF).

$$INF = PPTN(f) - QSR \qquad (6)$$

Soil storage : Input to this storage is infiltration (INF) and output from this storage includes evaporation (AE) and deep percolation (DP). In this storage first priority is accorded to evaporation. If soil moisture (SM) is greater than a threshold value SMAX1, evaporation occurs at potential rate (ET), otherwise at a lesser rate only from permeable portion of the catchment.

If SM > SMAX1 then AE = ET (7)
Otherwise AE = (1 - IMPRM) * ET * SM / SMAX1 (8)
SM is calculated as,
SM = 0.5 * FIN + SMS (9)

SMAX1 = A threshold value of soil moisture for potential evapotranspiration

Final soil moisture is SMF = SMS + FIN - AE (10)

The daily potential evapotranspiration (EV) is calculated using Penman's equation (Doorenbos and Pruitt, 1977). This equation has been widely used for estimation of potential evapotranspiration for locations in India. The EV is given by :

$$EV = c\,[W.R_n + (1-W).f(u).(e_a-e_d)] \qquad (11)$$

Where W is the temperature related weighting factor, R_n is the net radiation in equivalent evaporation in mm/day, f(u) the wind related function, (e_a-e_d) the difference between the saturation vapour pressure at mean air temperature and the mean actual vapour pressure of the air, both in mb and c the adjustment factor to compensate for the effect of day and night weather conditions. If the data for R_n are not available, it is calculated using the eq.

$$R_n = R_a\,(1-\alpha)\,(0.25 + 0.50\,n/N) - f(T).f(e_d).f(n/N) \qquad (12)$$

Where R_a is the amount of radiation received at the top of the atmosphere and is a function of latitude and time, α the albedo of the surface, n/N the ratio of actual (n) to maximum possible (N) sunshine hours and can be calculated knowing the cloudiness; f(T), $f(e_d)$ and f(n/N) are the functions of temperature, vapour pressure and cloudiness and their values can be obtained from standard tables, (Doorenbos and Pruitt,1977).

Daily values of EV are summed up to get monthly values:

$$ET = \sum_{1}^{ID} EV \quad \text{, Where ID = number of days in a month}$$

Now if soil moisture after satisfying demand of evapotranspiration is greater than the field capacity (FC) of the soil, the deep percolation (DP) occurs, subjected to a maximum limit defined as SMAX3. Water in excess of SMAX3 again re-appears as delayed surface runoff (DSR) or as inter flow. 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 as well as DSR are zero.

If $SMF > FC$ then $DP = SMF - FC$ (13)
and if $DP > SMAX3$ then $DSR = DP - SMAX3$ and (14)
$DP = SMAX3$ (15)

Here, SMAX3 = Maximum limit for deep percolation and,
FC = Field capacity of the soil.

Ground water storage : Input to this storage is deep percolation (DP) from the upper soil storage zone and output is base flow (GWF). This storage behaves as a linear reservoir with a time constant C_{bf}.

Computed runoff at the end of month, from the catchment is sum of QSR, FSR, DSR and GWF:

$$Q_{comp} = QSR + FSR + DSR + GWF \tag{16}$$

The input to the model consists of the values of various model parameters, period of simulation and observed runoff for period of calibration. Initial contents of various storages are specified. The rainfall and meteorological parameters, viz temperature, vapour pressure, wind speed and cloudiness to estimate potential evaporation for the period of simulation are also given as input.

6.2 Methodology adopted for calibration and validation of the model

The process by which parameters of the model are determined is called calibration of model. Present model calibration requires initial values of precipitation, runoff, potential evapotranspiration, surface and ground water storages and initial values of parameters. Though model automatically optimizes the values of parameters, for better results it is recommended to slightly change the values and see their effect on the result. Model structure is very simple and well defined conceptually and operates on only seven parameters. Several criteria are available and described in the literature to judge the performance of a rainfall-runoff model, however, none of them can be described as fully efficient one. In the present model criteria for calibration is to see the performance of model to simulate the "real world". One way is graphical comparison and another is to minimize the error. Both the approaches are followed here.

One approach is to minimize the sum of squares of error. It is determined as :

$$\min \sum_{j=1}^{N} (QHIS(j) - QCOM(j))^2 \qquad (17)$$

Where QHIS(j) and QCOM(j) are historical and computed runoff of the jth month respectively and N is total number of months.

The objective function of expression (17), in general works reasonably well, but it gives the same weight to errors regardless of whether they occur during high or low flows. This tends to produce a "better fit" for large flows as compared to low flows. Therefore alternate function, minimum of the sum of absolute error is also tried. It is determined as,

$$\min \sum_{j=1}^{N} (abs(QHIS(j) - QCOM(j)) \qquad (18)$$

These errors are minimized in the parameter optimization procedure. Search algorithm proposed by Rosenbrock (1960) is adopted here for this purpose.

For each year of calibration and validation Nash parameter (NTD) (WMO, 1986) is also computed to have an additional idea of the performance of the model. It is given by,

$$NTD = 1- \frac{\sum_{i=1}^{12}\{QHIS(i)-QCOM(i)\}^2}{\sum_{i=1}^{12}\{QHIS(i)-QBAR(j)\}^2} \qquad (19)$$

Here QBAR(j) is the mean annual runoff of the jth year.

Also overall efficiency (EFFI) for the calibration and validation period is calculated as follows,

$$EFFI(\%) = \frac{\sum_{i=1}^{N}(QHIS(i)-QMEAN)^{2} - \sum_{i=1}^{N}(QHIS(i)-QCOM(i))^{2}}{\sum_{i=1}^{N}(QHIS(i)-QMEAN)^{2}} * 100 \qquad (20)$$

6.3 Model application and data used

6.3.1 The study area

The focus catchments of the present study are Kolar and Sher sub-basins, which lie in Narmada basin in Central India. The required input data for this catchment were readily available and their response have been studied for the present-day climate using other models (Jain et al , 1992; Kumar, 1990). The data of these sub-basins are, by no means ideal to test the performance of the model; however, these are representatives of typical Indian catchment.The index maps of the Kolar and Sher sub-basins showing the locations of gauge discharge and rain gauge stations are given in Figs. 6.1 and 6.2 respectively.

General description of two sub-basins :

Basin name	Kolar	Sher
Latitude	22°40' to 23°08'	22°25' to 23°55'
Longitude	77°01' to 77°29'	79°15' to 79°40'
Elevation	600 m to 300 m	1110 m to 450 m
Data availability	1983-88	1978-86
Area	820 sq km	1500 sq km
Region	Sub humid	Sub humid
Location	Central India	Central India

For these sub-basins under study, more than 90% of the total annual rainfall falls during the southwest monsoon season (June to September). For Kolar sub-basin, area up to Satrana gauge and discharge measurement site , and for Sher sub-basin area up to Belkheri gauging site is considered.

Kolar sub-basin :

The Kolar sub-basin is located in the latitude range of 22° 40' to 23° 08' and longitude 77° 01' to 77° 29. 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. Agriculture activity is carried out in relatively less areas. 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.

Sher sub-basin :

The Sher river 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 gauging site upstream of the confluence covering about 1500 sq km of Sher sub-basin.

The Sher sub-basin is identified with hilly terrain and is heavily intersected by streams and rivers. The vegetation of the sub-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 sub-basin.

The sub-basin lies in the districts of Narsimhapur, Chindwara and Seoni in Madhya Pradesh. The river Sher is fairly big tributary of river Narmada. About 40 kms. upstream of the confluence of river Sher with Narmada, the Narsinghpur - Jabalpur road crosses the river Sher. At this point the Belkheri gauging site is located at a distance of 16 km from Narsinghpur.

6.4 Data availability

The monthly rainfall at four stations, namely Rehti, Jholiapur, Birpur and Brijeshnagar were used to determine the weighted average rainfall for the Kolar sub-basin. The availability of rainfall data is better than can be expected in most Indian catchments (with four raingauges within or close to 820 km^2 catchment) and may be characterized as reasonable. The observed monthly discharge at Satrana was used in the analysis. One of the constraint was the availability of sufficient length of data, the complete data required being available for the period 1983-88 only.

At no station in the Kolar sub-basin the meteorological parameters necessary for ET estimation are recorded. Therefore, the data for Bhopal (class I observatory) which is about 20 km away from the catchment in the north - west direction were used. The requisite data were taken from the daily weather reports published by the India Meteorological Department. The daily mean values of temperature, wind speed, vapour pressure, and cloudiness were used for the calculation of daily values of EV. Since the solar radiation data were not available, the value of R_a (eq. 12) as a function of month and latitude was taken from the table given in Doorenbos and Pruitt (1977). The value of albedo was assumed to be 0.25 which is representative for close ground crops.

The potential evaporation was assumed to be spatially uniform within the sub-basin. In order to check whether the potential evaporation estimated at Bhopal using the available meteorological parameters can be considered to be representative for the sub-basin, the same was compared with the pan evaporation data for a station (Power Kheda) located near the southern end of the sub-basin. The variation of both these with respect to time was plotted on a graph. A visual inspection of the plot revealed that the seasonal and year-to-year variation in both the cases were in the same range of magnitude and had the same pattern. Therefore, the potential ET data at Bhopal were used for the Kolar sub-basin.

The monthly rainfall data at the recording stations at Lakhandon, Harai and Jabalpur was used to calculate the weighted average monthly rainfall for the Sher basin. The monthly discharge data at gauging site at Belkheri was used to calibrate and validate the model. As no station in the sub-basin recorded all the meteorological parameters needed for the computation of EV (using eq. 12), daily mean values of meteorological parameters at Jabalpur station were used to compute daily EV and then added to get the monthly potential evapotranspiration. This was taken as the representative value for the basin.

6.5 Model calibration

The data for the period 1978-86, for the Sher sub-basin and for the period 1983-88 for the Kolar sub-basin is utilized for model calibration.

A comparison of values of observed and simulated hydrograph for the calibration periods for Sher and Kolar sub-basins is given in Tables 6.1 and 6.2 respectively for monsoon period only. Total volume of monsoon runoff, maximum monthly runoff, Nash parameter on annual basis and over all efficiency is calculated and listed in the same Tables. Optimized value of parameters used for the various climate scenarios is also given in the Tables 6.1 and 6.2 for both sub-basins.

Observed and simulated flow hydrographs for the Kolar and Sher sub-basins are presented in Fig 6.3 and 6.4. The main hydrograph features including peaks, recession and base flow are simulated reasonably well.

6.6 Climate change scenarios adopted

Because of uncertainties in the regional prediction of temperature and precipitation, the hypothetical scenarios for temperature and precipitation changes have been considered here. Most of the workers have assumed the scenarios of precipitation change ranging from -20 to 20% in order to conduct sensitivity analysis of the hydrological systems (Nemec and Schaake, 1982; Gleick, 1986; Mimikov et al., 1991). In the present study, five scenarios of precipitation change (-20, -10, 0, 10, and 20%) and four scenarios of temperature change (0, 1, 2, and 3°C increase) have been considered. The assumption of uniform change over the months of the year is made due to uncertainties in the changes in different months. Thus a total of 19 scenarios have been analyzed to study the sensitivity of Kolar and Sher sub-basin to probable changes in temperature and precipitation. Changes in mean monthly, mean seasonal (pre monsoon (March - May), monsoon (June - September), post monsoon (October - November) and winter (December - February)) and mean annual values of ET, runoff and change in end of month soil moisture were analyzed for both sub-basins.

7.0 REGIONAL HYDROLOGICAL IMPACTS

The results with respect to sensitivity of ET, soil moisture and runoff on monthly, seasonal and annual basis for all 19 climate change scenarios compared with historical hydrological and climatological data (referred as base run) for Kolar and Sher sub-basins are discussed below .

7.1 Kolar sub-basin

Mean Monthly Runoff

Table 7.1 shows the percentage change in mean monthly runoff for temperature and precipitation change scenarios. For a given value of precipitation change, increase in temperature results in decrease of runoff in general (for June-October). During the period November-May, when the flow in river is very small, the percentage change is quite dramatic. Hence no concrete conclusion could be drawn for these months. Gleick (1986) and Mimikov et al. (1991) also found similar results for dry season.

Figures 7.1 and 7.3 show the mean monthly runoff for different temperature changes and a precipitation change of -20% and +20% respectively. Decrease in precipitation by 20% results in considerable decrease in runoff (Fig. 7.1). With increase in temperature the runoff decreases ,the monsoon months being more sensitive to these changes. With increase in precipitation by 20% the runoff increases, the increase in temperature resulting in further decrease in runoff (Fig. 7.3). The month of August, when there is ample moisture available, is most sensitive to changes in runoff. For the most extreme conditions of climate change(scenarios of temperature change of +3° C and precipitation change of -20%), there is almost 51% reduction in runoff, i.e. it is reduced to half during the month of August and on annual basis there is a reduction of 45% (Table 7.1). However, the change in the opposite scenario (no temperature change and precipitation change of 20%), runoff increases by 46% in the month of August and on annual basis its effect is moderated, the change being 38% only (Table 7.1).

Mean Seasonal and Annual Runoff

The runoff in monsoon season is most sensitive to scenarios of temperature and precipitation changes. The runoff in monsoon and post monsoon months decreases with increase in temperature for a given precipitation change. For winter and pre monsoon months when the base run value is already very small, no concrete conclusion can be drawn.

The runoff during the monsoon season is quite high as compared to the runoff in rest of the seasons. For no temperature change, runoff changes as that of precipitation on monsoonal and annual basis.

Temperature increase alone, with no change in precipitation, cause about 4% reductions of runoff for each degree rise in temperature.

For a given temperature change, the effect of change in precipitation on monsoonal (and annual runoff) is characterized by a magnification with respect to the causative factor (precipitation change) ; the magnification factor being almost the same for different temperature changes (Table 7.9). The magnification does not depend upon temperature. Figure 7.5 shows the % change in mean annual runoff for different scenarios of temperature and precipitation changes. The slopes of the parallel lines reflect to the constant magnification factor (about 1.9).

As about 95% of the annual runoff is observed during the monsoon season, the % change in monsoonal runoff due to change in precipitation and temperature is also reflected almost similarly in annual runoff.

Mean Monthly Evapotranspiration

The changes in mean monthly ET due to changes in precipitation (-20% to 20%) and temperature (1, 2 and 3° C) are given in Table 7.2. The ET increases with increasing temperature for the monsoon months, but decreases during the other months. In the months of August and September evapotranspiration increases with increasing temperature and remains the same for all precipitation change scenarios at a given temperature change. During the monsoon season the (near)saturation conditions prevailing at the ground surface result in the ET at the potential rate which is governed by meteorological parameters. However, during non-monsoon months, the ET takes place from the soil reservoir and hence the availability of moisture in successive months in the soil storage (which decreases with rise in temperature) governs the ET.

Mean Seasonal and Mean Annual Evapotranspiration

For a given precipitation change, the increase in temperature results in increase in ET for the monsoon season. However, for winter and pre monsoon seasons it decreases. As already it is at a very lesser rate, therefore small change in precipitation reflects a greater % change when compared to the base run. Evapotranspiration shows maximum sensitivity in the pre monsoon season for the scenario $\Delta t = 3^{\circ}$ C and $\Delta p = -20\%$, the condition that lead to least availability of soil moisture for evapotranspiration to occur.

Fig. 7.7 depicts the change in mean annual ET. During the monsoon season, the change in ET is positive (except for $\Delta t = 0$ and $\Delta p = -10\%$ and -20%), showing an increase for all combinations of precipitation and temperature changes studied. However, on annual basis considerable reduction in precipitation (by -20%) leads to decrease in ET.

Soil Moisture (at the end of month)

The change in moisture of soil storage at the end of each month is given in Table 7.3. The availability of soil moisture decreases with increase in temperature alone. A reduction in precipitation results in reduction of soil moisture. In the month of August when the soil moisture is at its maximum no change is observed.

During the monsoon season, the change in temperatures or precipitation or both change the soil moisture comparatively less than at the end of winter or pre monsoon season. As soil remains dry during pre monsoon, winter and summer season and there is no rainfall, change in temperature and precipitation produces dramatic results and no firm conclusion can be drawn.

7.2 Sher sub-basin

Mean Monthly Runoff

Table 7.4 shows the % change in mean monthly runoff for different scenarios of climate change. In this sub-basin also, for a given precipitation change, the increase in temperature results in lesser runoff in general. The month of July is most sensitive to temperature and precipitation change for Sher sub-basin. During the nonmonsoon months, the response is quite dramatic due to very small values of runoff in the base run.

Figures 7.2 and 7.4 show the mean monthly runoff for different temperature changes and precipitation change scenarios of extreme cases , i.e. -20% and +20% change in precipitation, respectively. Results are almost in similar lines as that of Kolar basin. For the most extreme conditions of climate change (scenarios of temperature change of 3°C and precipitation change of -20%), there is almost 62% reduction in runoff during the month of July and on annual basis it is almost 50% . This indicates that in months other than monsoon months, insufficient moisture remains available for reduction. In the opposite case of no temperature change and precipitation change of +20% , runoff increases by 77% in the month of July and on annual basis its effect is moderated, i.e. only 41% increase is observed. The reason is simple. There is very less rainfall in other months and therefore any increase in rainfall is partly compensated in fulfillment of evapotranspiration demand and partly absorbed by the soil which is already deficient in moisture and it results in almost negligible contribution to runoff.

Mean Seasonal and Mean Annual Runoff

The response of monsoon runoff of Sher sub-basin to scenarios of temperature and precipitation change is almost similar to that of Kolar sub-basin. During the post - monsoon and winter seasons, the increase in temperature results in decrease in runoff. The response of annual mean runoff for percentage changes in precipitation for different scenarios of temperature change is similar to changes in mean monsoonal runoff.(Fig. 7.6)

Mean Monthly Evapotranspiration

As for Kolar sub-basin, in this basin also, the increase in temperature results in decrease in evapotranspiration for nonmonsoon months and increases for monsoon months due to the reasons already mentioned (Table 7.5). For August and September when the evaporation is at the potential rate, the change in precipitation does not lead to any change in ET.

Mean Seasonal and Mean Annual Evapotranspiration

Sher basin also shows the increase in ET with rise in temperature at a given precipitation change scenario for monsoon season and a general decrease in winter and pre monsoon seasons. The sensitivity is seen to be maximum in the pre monsoon season for scenario $\Delta t = 3^{\circ}C$ and $\Delta p = -20\%$. The changes in mean annual

ET for different scenarios of temperature and precipitation changes are shown in Fig. 7.8.

Soil Moisture (end of month)

Table 7.6 shows the change in moisture of soil storage at end of each month. The behavior of soil moisture for different climate change scenarios is similar to that for Kolar basin in general.

Catchment Response

From the topography of both the sub-basins, it is found that Sher sub-basin is more hilly and average maximum moisture holding capacity of Sher is less than (206 mm) than that of Kolar sub-basin(269 mm) as predicted by the model. Both sub-basins lie almost at the same average mean sea level (450 m). Data study of both the sub-basins reveals that when soil is completely dry (at the beginning of monsoon) Kolar sub-basin produces approximately 5% runoff of total precipitation occured while Sher sub-basin produces 10% runoff. But when soil gets saturated response of both the sub-basin is almost similar; Kolar produces 62% of runoff and Sher 61% . Ground water lag for Kolar sub-basin is estimated as 26 days and of Sher sub-basin as 82 days by the water balance model.

Comparison of the percent deviation of climatically affected parameters namely runoff, ET and soil moisture (at the end of the month) for both sub-basins on monthly, annual and seasonal terms, using available historical hydrological and climatological data (referred as base run) and different climatic scenarios is presented in the following sections.

Comparison Of % change in mean monthly runoff, ET and soil moisture

From the Tables 7.1 and 7.4 it is clear that for Kolar basin, month of August and for Sher basin month of July is most sensitive to runoff changes. This may be attributed to the rainfall pattern of both the sub-basins. For Kolar sub-basin, as per historical series, 98%, 60% and 25% soil remains dry at the beginning of June, July and August respectively. Thus, increase in precipitation satisfy the soil moisture deficiency during the months of June and July and remaining if any in the month of August. Maximum precipitation occurs during these three months. Thus, August month generally remains saturated at the beginning of month, therefore any decrease/increase in precipitation is reflected maximum in the month of August only. In the case of Sher

ET for different scenarios of temperature and precipitation changes are shown in Fig. 7.8.

Soil Moisture (end of month)

Table 7.6 shows the change in moisture of soil storage at end of each month. The behavior of soil moisture for different climate change scenarios is similar to that for Kolar basin in general.

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For % change in ET, month of April and May should reflect maximum change as ET rate is maximum in these months. This can be observed from the Tables 7.2 and 7.5 for both the basins, though historical very deficient rainfall during these months diminishes this effect in some scenarios.

March and April months when the soil is almost dry (soil moisture is at lowest level in the month of April) have maximum sensitivity to changes in soil moisture and monsoon months, July and August are least sensitive to climate scenario for change in soil moisture for both the basins (Tables 7.3 and 7.6).

Extreme annual events : As minimum flow in the river is almost zero for both the sub-basin, only maximum annual flows are examined for temperature increase of 1°, 2° and 3° C respectively with respect to base run and are tabulated in Table 7.7.

Percentage reduction in runoff due to successive increase in temperature is almost similar for both sub-basins.

Changes in mean annual parameters namely runoff, ET and soil moisture (at the end of month): For each climate scenario, the mean annual runoff, ET and soil moisture were calculated for both sub-basins and percentage change in the value of parameter with respect to base run for each climate scenario was computed (Table 7.8).

Sher sub-basin reflects more sensitiveness to changes in precipitation as compared to Kolar sub-basin, perhaps because of regional metamorphic characteristics of sub-basin which govern the moisture retention in the sub-basin.

Runoff decreases by approximately 4% for every increase in temperature for no precipitation change for both sub-basins.

To assess effectively the sensitiveness of precipitation change on runoff, magnification factors were calculated for every change of precipitation and all temperature increase on similar lines as done by Gleick (1986), Dooge (1989) and Mimikou et al. (1991). Results are tabulated in Table 7.9.

It is obvious and clear from the Table 7.9 that magnification factors are practically independent of both temperature and precipitation changes for both sub-basins (except for extreme case of 3° temperature rise and precipitation decrease of 20% ,which will be discussed later). Also magnification factor in case of Sher sub-basin is slightly larger than Kolar sub-basin. It can be correlated as proportional to sub-basin sensitivity and inversely proportional to the moisture holding capacity of the soil.

Climate change scenarios have more accented effect on Sher sub-basin when changes in ET and soil moisture are compared with Kolar sub-basin, specially for decrease in precipitation scenarios. This may be attributed to the low moisture holding capacity of the soils of the sub-basin.(Table 7.8)

For each change in precipitation, percentage change in ET increases for successive temperature increase. While percentage in soil moisture (at the end of month) decreases.

Magnification factor decreases for adverse condition of 20% decrease in precipitation and 2° to 3° increase in temperature. With increase in temperature ET also increases which results into less soil moisture and even lesser runoff.

For Kolar sub-basin change in ET is less for decrease in precipitation by 20 % and increase in temperature by 1° - 2°C. This explains that decrease in precipitation depletes moisture availability and increased ET rate brought out by increase in temperature is not able to draw the moisture from the soil even at par of base run. However increase in temperature by 3° increases the ET on annual basis when compared to base run. In case of Sher sub-basin it is still less than base run for corresponding temperature increase. It indicates lesser availability of soil moisture in the second as compared to first.(Table 7.8)

Seasonal Effects

Runoff: During monsoon months as nearly 90 to 95 % of annual flow occurs, same annual trend is followed here. Sher sub-basin appears to be slightly more sensitive than Kolar sub-basin for monsoon season.

For winter season and for post monsoon season also Sher sub-basin shows more sensitiveness to all the climatic scenarios except for 20 % decrease in precipitation scenario where Kolar sub-basin reflects more sensitiveness during pre monsoon season. However, as there is almost zero flow during pre monsoon season in Kolar basin, no firm conclusion can be drawn.

Mean seasonal evapotranspiration : On monsoon basis with increase in temperature ET increases for all the precipitation changes for both sub-basins. However, Kolar sub-basin evapotranspirates more on monsoon basis because of higher ET rate and better availability of moisture.

During pre monsoon, post monsoon and winter seasons the results are quite spectacular and no firm conclusion can be drawn.

Mean seasonal soil moisture (at the end of month): During monsoon months as soil generally remains saturated there is very little or no change in soil moisture observed for all the scenarios for both sub-basins.

For post monsoon and pre monsoon seasons Sher sub-basin reflects higher sensitiveness , specially for higher temperature increase and greater reduction in precipitation because of lesser availability of soil moisture and this may be due to low moisture holding capacity of the soil of the sub-basin. Dry period tries to extend in Sher sub-basin in case of temperature increase and reduction in precipitation.

During winter season both the sub-basin predict similar changes in soil moisture for all the scenarios.

In general Sher sub-basin appears to be more sensitive to the climate change scenarios because of its soil type, soil depth, soil cover, topography, land use and other sub-basin characteristics. From agriculture point of view rabi crops in Sher sub-basin may be more affected by climate change scenarios than Kolar sub-basin.

A characteristic of runoff which decides the storage capacity of reservoir is inter annual variability of runoff. Assuming ratio of mean annual to mean monsoon runoff as a measure of it, for all the climate scenarios, ratios are computed and tabulated in Table 7.10. Generally ratios are more sensitive to precipitation change.

If ratio is 1, it means greater variability and as it increases variability decreases. For base run Sher sub-basin shows less variability as compared to Kolar sub-basin. For precipitation change of 20% Kolar sub-basin shows 1% change while Sher sub-basin indicates 2% change in the ratio. These changes are quite nominal, but indicate clearly effect of climate variability on the storage capacity of reservoir designed in this sub-basin.

7.3 Influence of climate variation on yield and water storage of a hypothetical reservoir

The relationship between the amount of water which can reliably be taken from a reservoir and the storage capacity of the reservoir is known as the storage - yield relation. The effect of climate variations on the storage - yield relation is studied for each of the sub-basin under study. Two types of effects are considered. The first is the change in maximum possible demand which could be taken with constant reliability (75 to 90%) from a given reservoir of fixed capacity. The second is the change in storage capacity required to produce a given fixed demand at constant reliability (75 to 90%).

The storage - yield relation for each climate scenario is determined, using the simulated monthly average streamflow data from conceptual model. These monthly values are used as inputs to a very large hypothetical reservoir. The reservoir is assumed to be full at the start of the simulation. Storage deficits are then noted month by month to meet various rates of withdrawal (2, 4, 6, 8 & 10% of maf). Each year the maximum storage deficit is noted. To ensure that a reasonably constant level of reliability of yield is obtained through out and, further, the analysis and, further, to ensure that the effects of year-to-year variability for a given climate scenario are adequately considered, an amount of storage equal to mean plus one standard deviation of the annual distribution of the storage amount is used in the analyses as a standard reservoir dimension to define the storage - yield relation.

The effect of climate variations on the demand which can reliably be taken from a given storage is illustrated in Figs. 7.9 - 7.12 for 75 and 90% reliabilities for both sub-basins. The storage is taken as discussed above and it is assumed that volume available in it at the start is 0.25 times mean annual flow (maf) for all the scenarios. The values are also given in Tables 7.9 and 7.10 for both the sub-basins.

The results for the two climates represented in these figures show that 1% increase in temperature produces about 1% change in yield for both the sub-basins. Also for the scenario of one extreme temperature increase of 3°C and precipitation decrease of 20% produces the 26% and 37% change in yield for Kolar and Sher sub-basins respectively and for similar increase in temperature and 20% increase in precipitation produces 7% and 3.5% change in yield for Kolar and Sher sub-basins respectively. Therefore changes in temperature alone are greatly magnified in terms of their effect on yield. Decrease in precipitation has greater effect on the yield. Sher sub-basin is affected more than Kolar sub-basin.

The effect of climate variations on the storage required to produce a given firm yield is presented in Figures 7.13 to 7.16 and Tables 7.11 and 7.12 for Kolar and Sher sub-basins respectively. The given yield is assumed as 6% of the mean annual runoff for the historical climate data. 75% and 90% reliability levels are considered. It must be emphasized here that capacity may be increased only upto an extent such that it may be again filled up. Blanks in the figures and tables indicate insufficient availability of water to meet that particular demand at the given reliability. Results show a highly non-linear relationship. 1°C increase in temperature when coupled with decrease in precipitation, requires about 2.5% and 6% more storage for Kolar and Sher sub-basins respectively. At increased precipitation, increase in temperature has no substantial effect on storage. 20% decrease in precipitation increases the storage requirement by about 40% and 100% for Kolar and Sher sub-basins. It is obvious from the Figs. 7.13 to 7.16 that climate change has greater effect on Sher sub-basin than Kolar sub-basin.

Studies on sensitivity analysis presented here are based on the best available information. However, there are several simplifications and uncertainties associated with above analysis that need to be highlighted. Climate models predict an increase in precipitation by 5-15% during summers over India (IPCC, 1990), the regional change may be different. Studies on inter annual and long term variability of monsoon and annual rainfall have pointed out that the variations in rainfall are within the statistical limit (Thapliyal and Kulshreshtha, 1991; Srivastava, 1992). The future changes in precipitation in a warm world obtained from climate models fall within one standard deviation of the rainfall series for the last 100 years. In absence of sufficient information on variability of rainfall in the catchment, it was not considered in the present study. Indeed, without reliable statistical inference, "any climatic changes reportedly discovered (either from simulated or truly observed time series) could just as well be attributed to the chance variation of essentially unpredictable natural fluctuations" (Katz, 1980).

The direct effects of CO_2 increase on vegetation may also alter current perceptions of future consequences. Idso and Brazel (1982) estimated the changes in runoff induced by changes in temperature and precipitation for 12 drainage sub-basins in Arizona and superimposed the direct antiperspirant effect of atmospheric CO_2 enrichment. They compared the results with another study (NRC, 1983) (using identical model), which did not consider this effect. They found that inclusion of direct effect of CO_2 rise on evapotranspiration increases the streamflow by 40-60% in contrast to decrease (40%-75%) as found earlier, even in the case of adverse changes in temperature and precipitation. Since increasing concentration of the CO_2 in the atmosphere tends to induce partial stomatal closure, so reducing plant transpiration and hence conserving soil moisture and increasing runoff to stream. The role of vegetation in altering the soil moisture, availability and the possible changes in a warmer world could be studied using physically based models. However, due to extensive data requirement which is the major constraint for Indian catchments, the traditional and simple hydrological models may be more promising (Jain et al, 1992; Refsgaard et al, 1992). Off-line studies on effect of changes in CO_2 increase on vegetation and hence evapotranspiration can be included to provide information about CO_2 vegetation feedback.

The response of different catchments would be different depending upon morpho-climatic conditions in the catchments. Studies are in progress considering other catchments in different agroclimatic zones, so as to study the change in behaviour of response in a warmer world.

8.0 CONCLUSIONS AND REMARKS

Based on best available information on climatic, hydrological parameters and sub-basin characteristics the sensitivity analysis of response of two catchments lying in central India to expected climatic changes has been made. The results show that sensitivity of evapotranspiration and runoff for monsoon months is almost similar to annual values for all scenarios of climatic change. The changes in runoff are more dramatic for the months when the runoff is already very small.

The serious impact of runoff changes on storage design shown by the model further substantiates the need for considerations of these changes while formulating the project and also in the operation of the project. But to arrive at a definite conclusion longer time series of base record with finer time step is needed. It is obvious that study of these two basins are not sufficient to derive final conclusions. To incorporate the errors in deterministic analysis and stochasticity of the time series generated, split samples of long simultaneous records of climate factors and streamflow will have to be considered, covering a wide range of dry and wet periods.

Since the results of study for one catchment can not be directly applied to other catchment, more such type of studies are needed on catchments in different agroclimatic zones of India to assess the sensitivity of catchment response to climatic change. Considering the inter annual variability of Indian rainfall, only assessment of volume may not be helpful until temporal and spatial variations of climate change are assessed. Some studies have been done on the onset date of monsoon in India. Impact of climate change on extreme event also need to be given due weightage.

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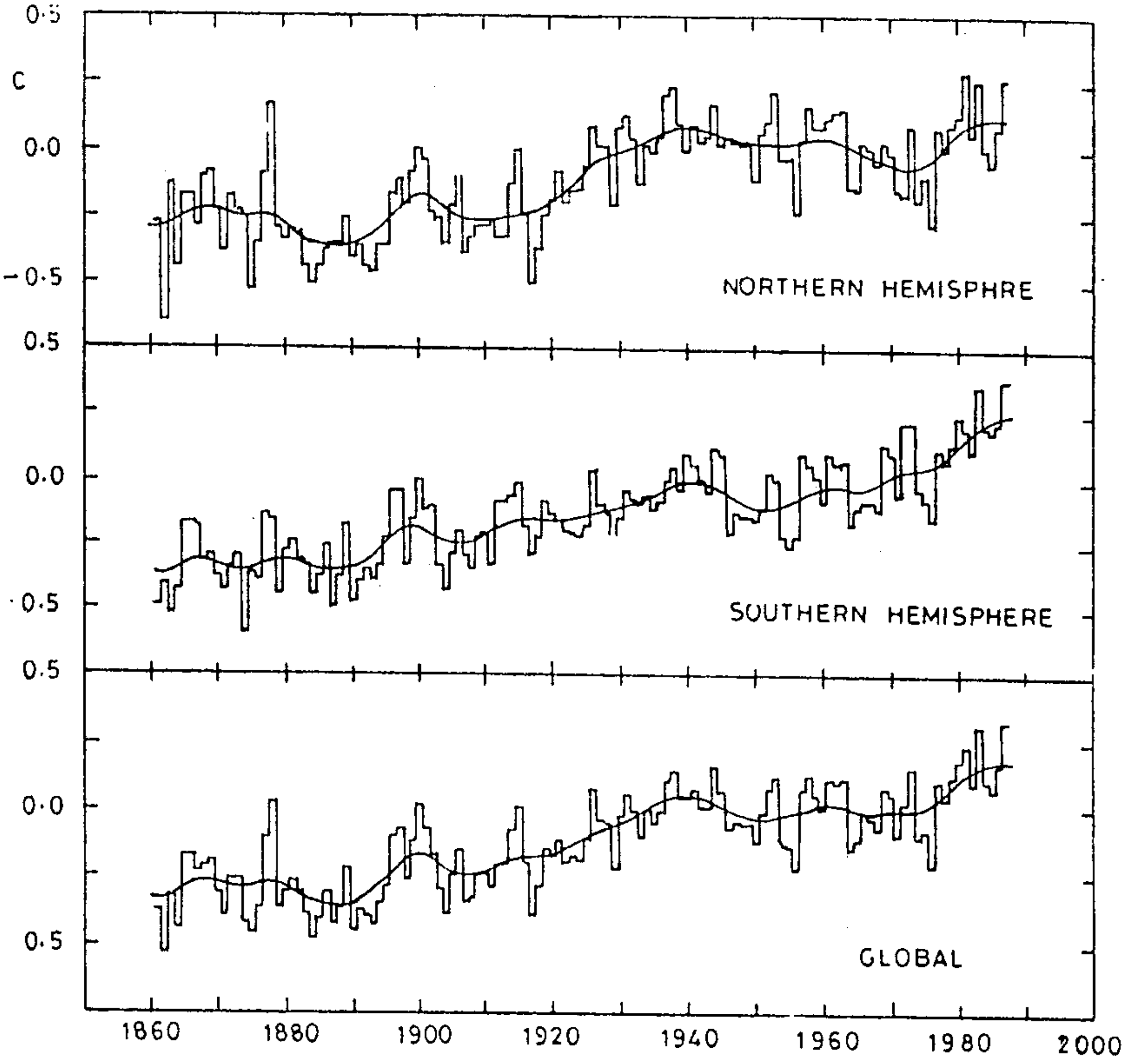


Figure 1.1 Observed changes in temperature relative to the 1950-79 period mean (WMO, 1987)

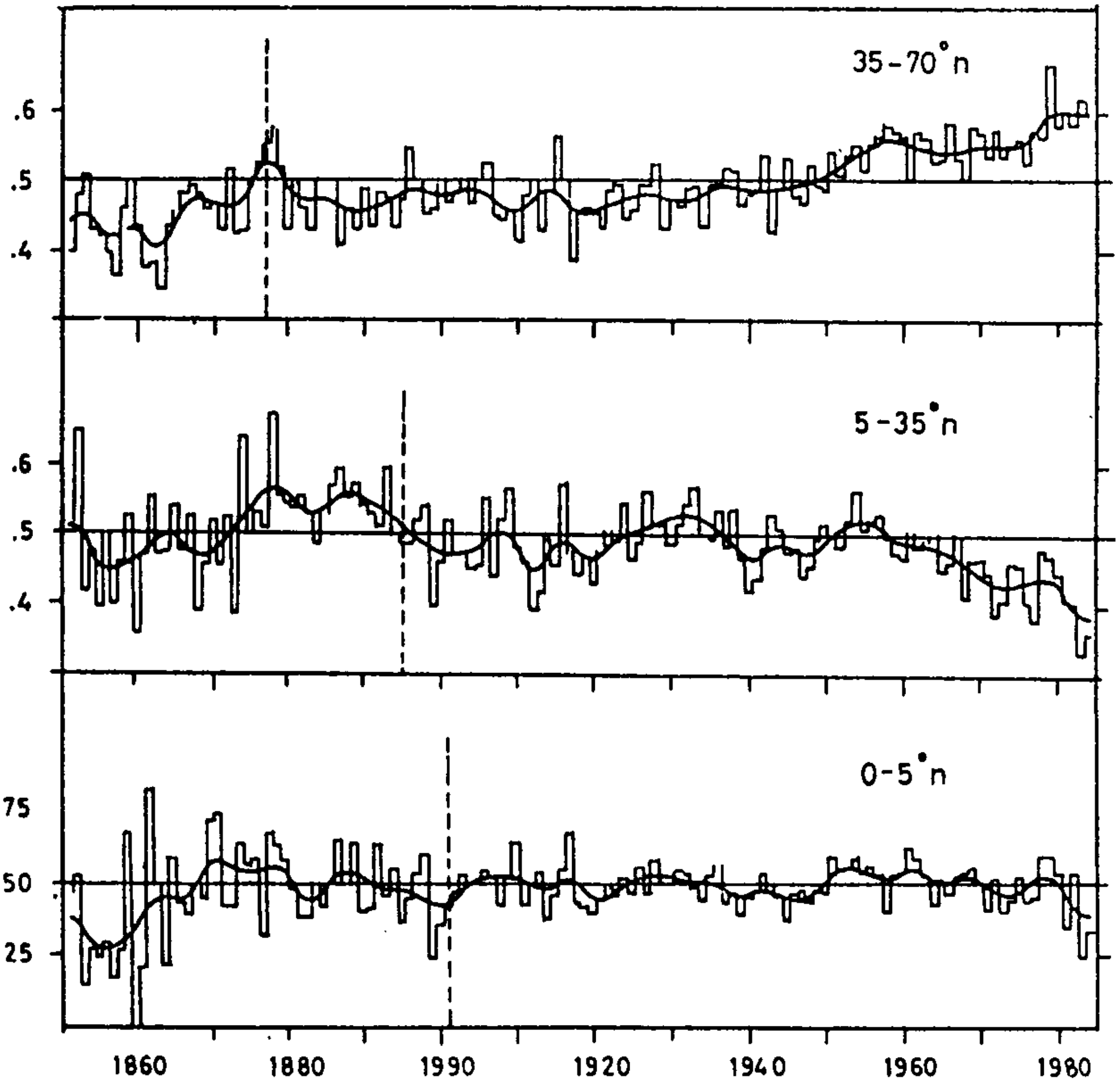


Figure 1.2 Precipitation indices showing changes in area averaged precipitation over the land areas (Bradley et al, 1987)

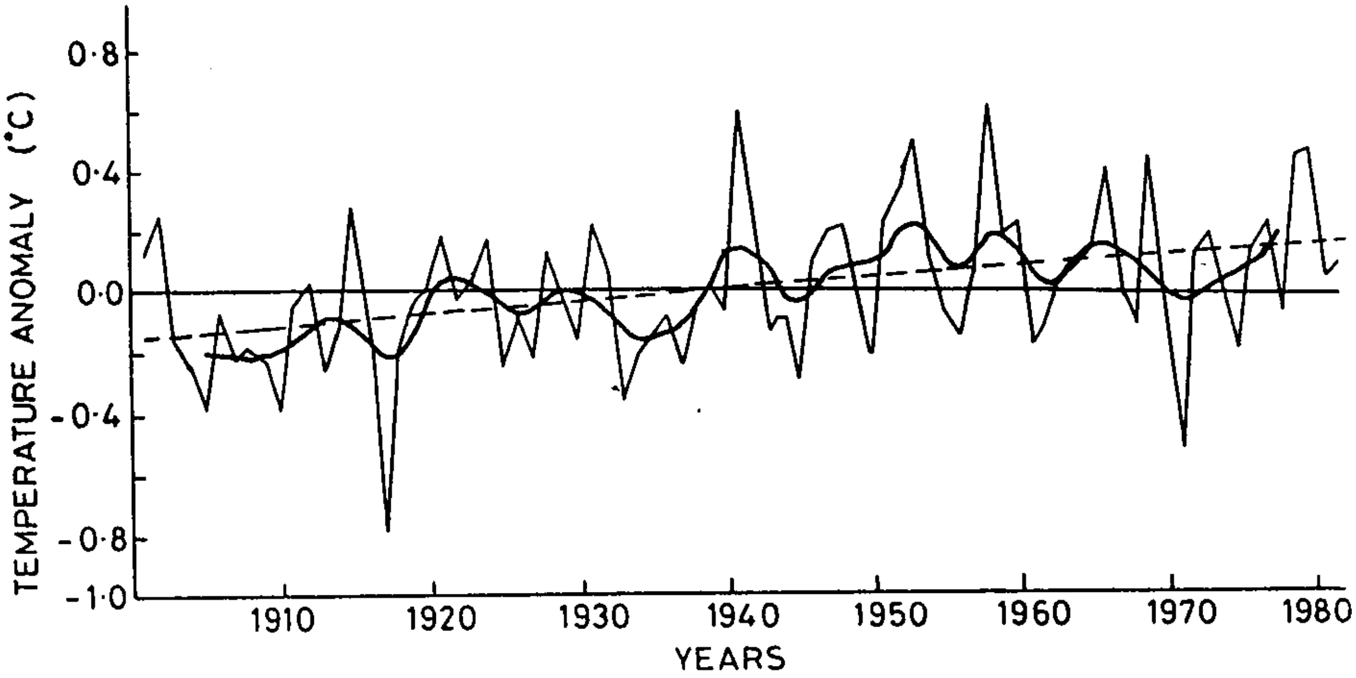


Figure 4.1 Mean annual temperature anomalies in India during the period 1901 - 1982; ——— actual, ▬▬▬ filtered values and, ----- trend line (Hingane et al, 1985)

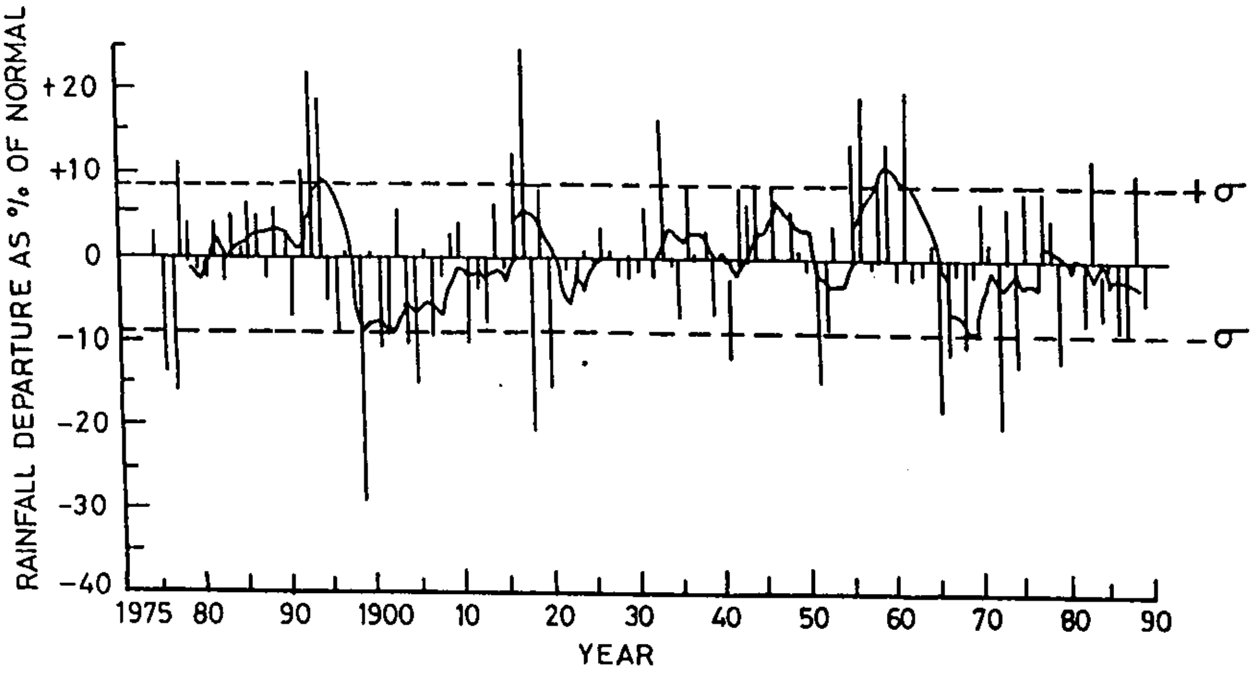
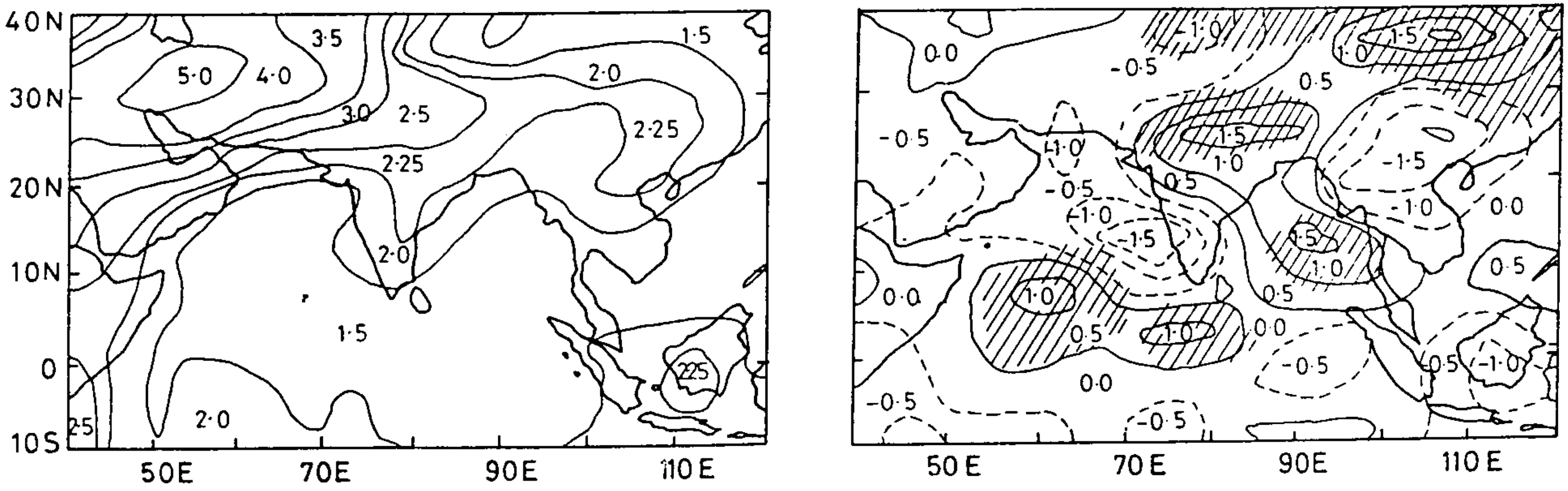


Figure 4.2 Annual rainfall of India for the period 1875 - 1989. The curve shows 5- year running mean ; the dotted lines indicate the upper and lower limits of ±one standard deviation (Thapliyal and Kulshreshtha, 1991)



(a)

(b)

Figure 4.3 Spatial distribution of changes in a) temperature, and b) rainfall for the monsoon region as simulated by Hamburg coupled climate model under Business As Usual Scenario. Hatched area represents the significant

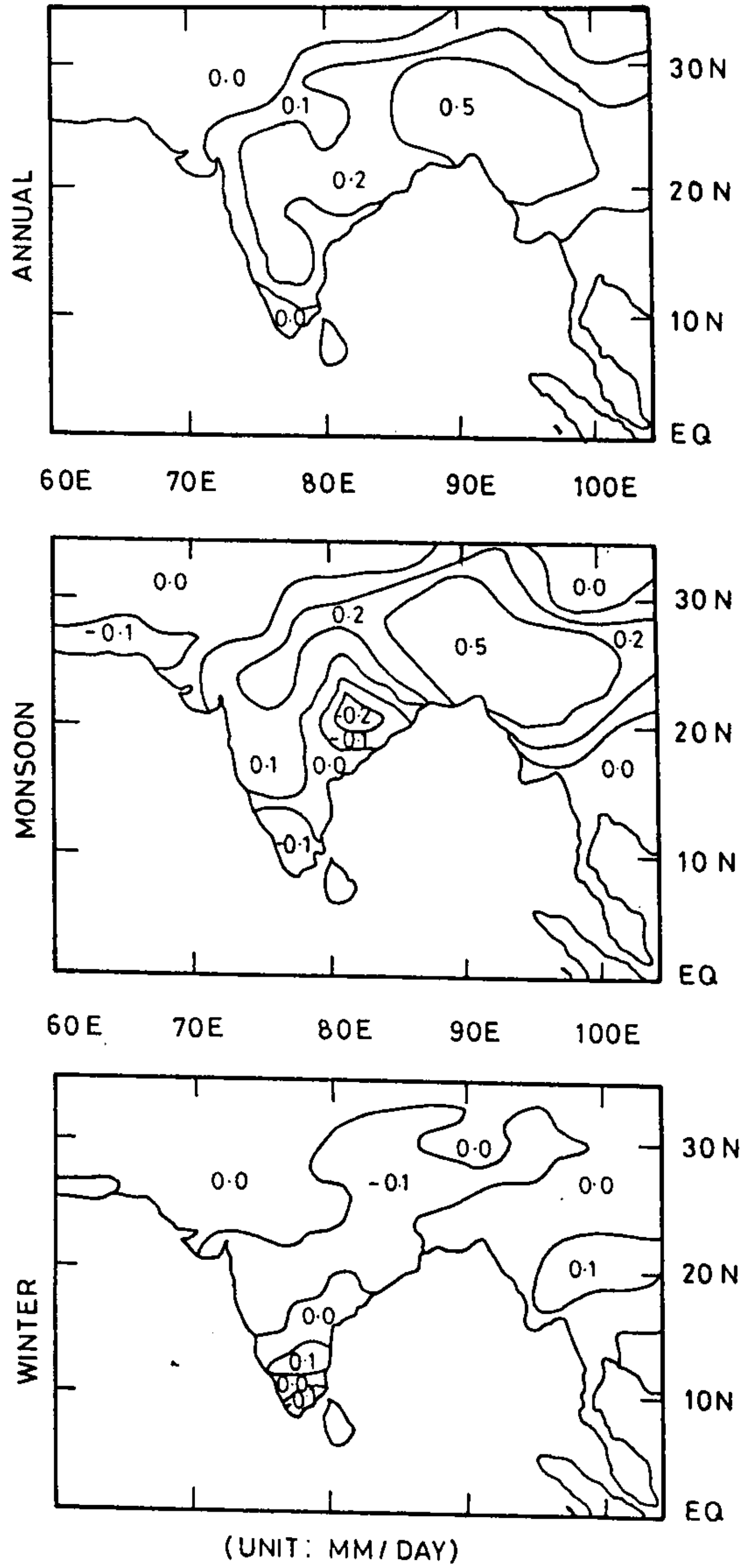


Figure 4.4 Annual and seasonal changes in surface runoff due to global warming for Indian subcontinent as simulated by ECHAM3 T - 42 model (Lal and Chander, 1992)

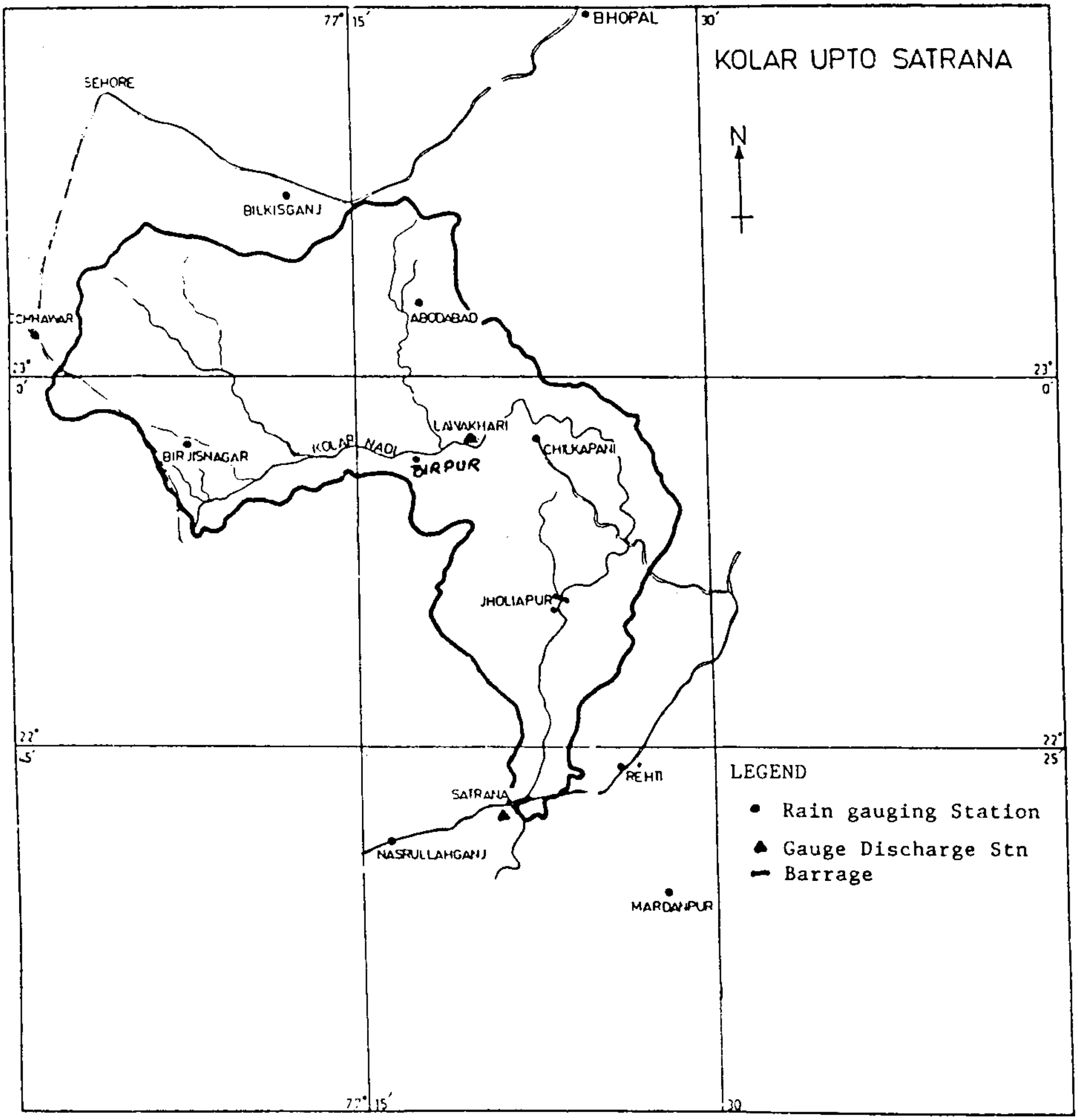


Figure 6.1 Index map of the Kolar sub-basin upstream of the Satrana gauging station

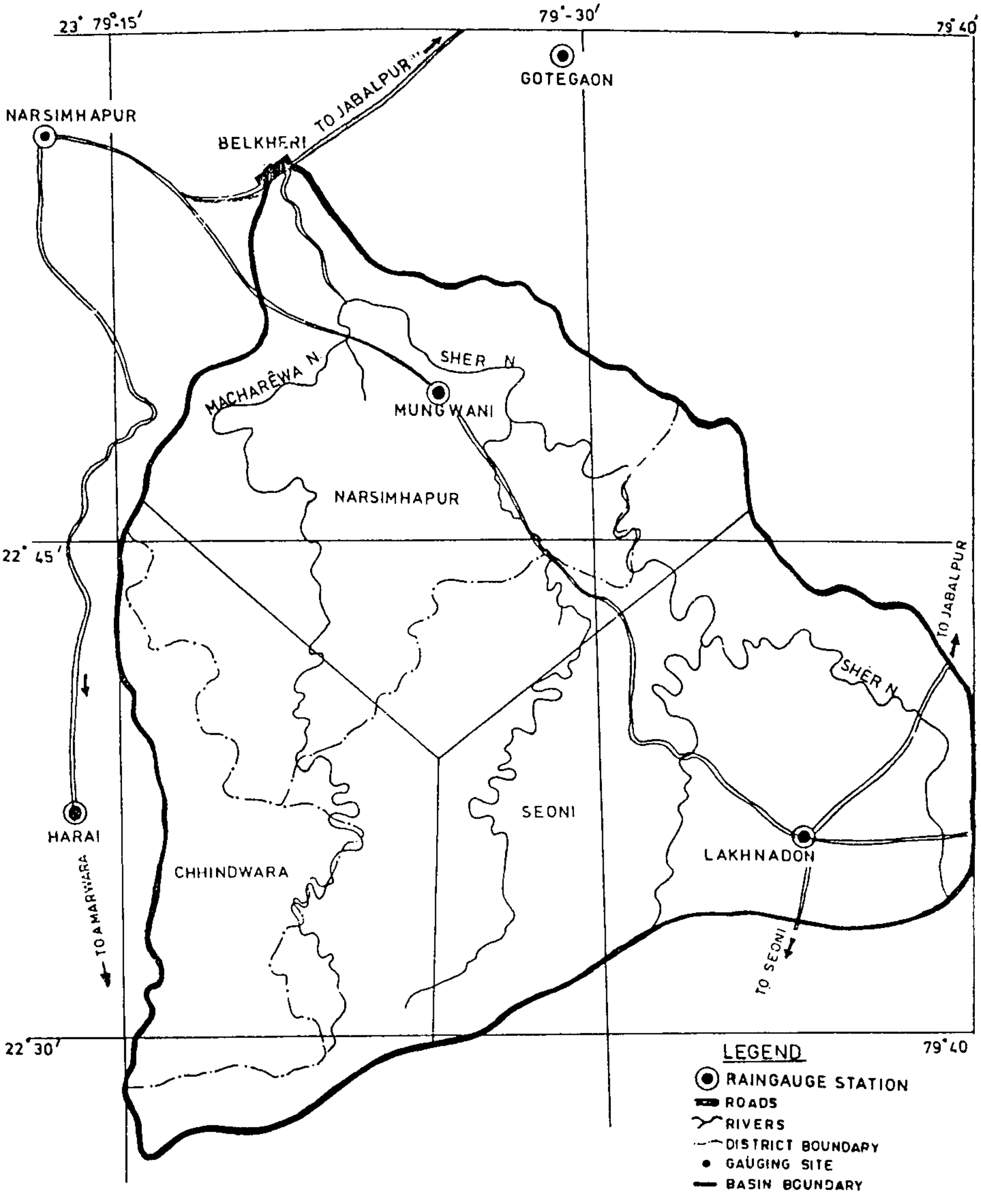


Figure 6.2 Index map of Sher sub-basin upstream of Belkheri gauging station

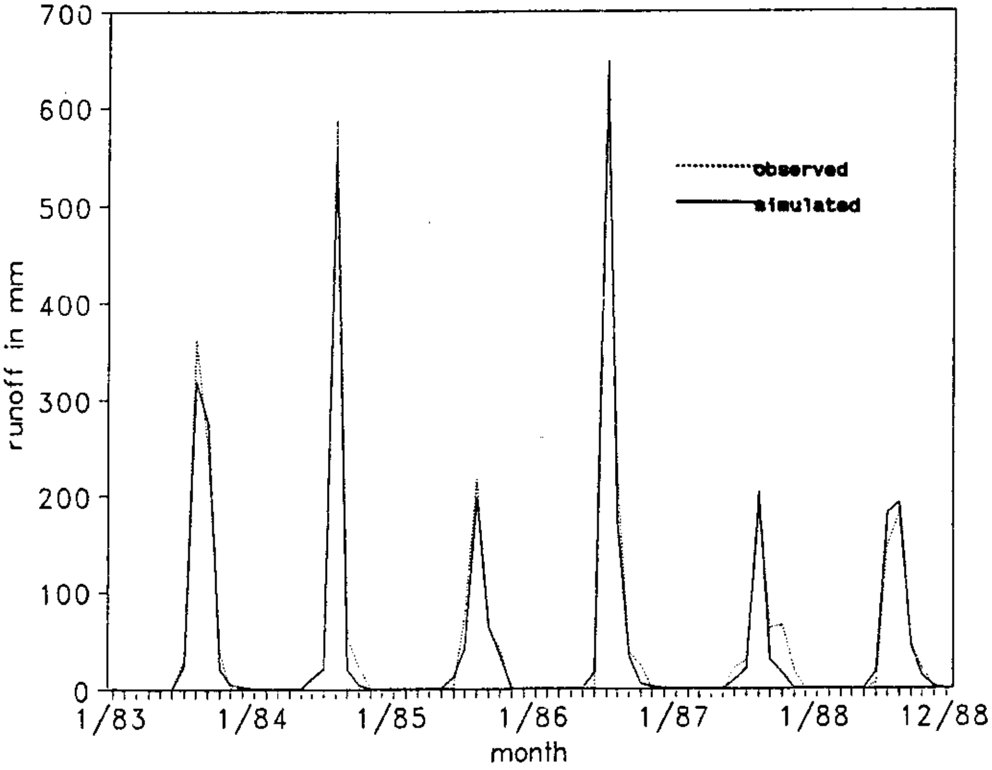


Figure 6.3 Observed and simulated flow hydrographs for Kolar sub-basin

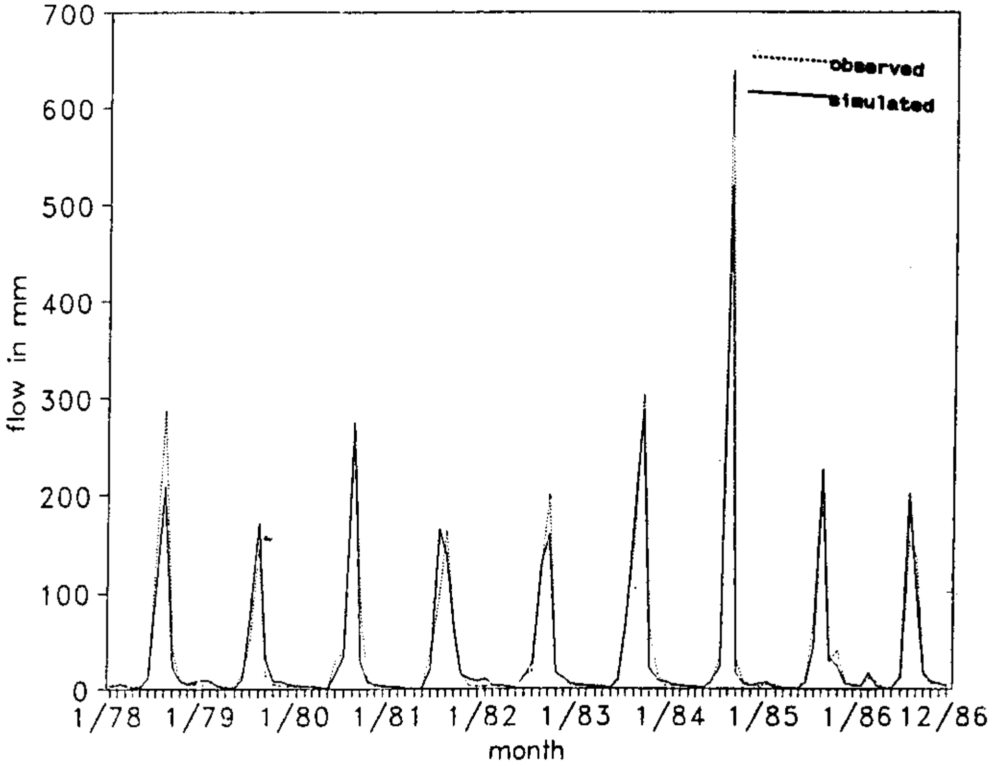


Figure 6.4 Observed and simulated flow hydrographs for Sher sub-basin

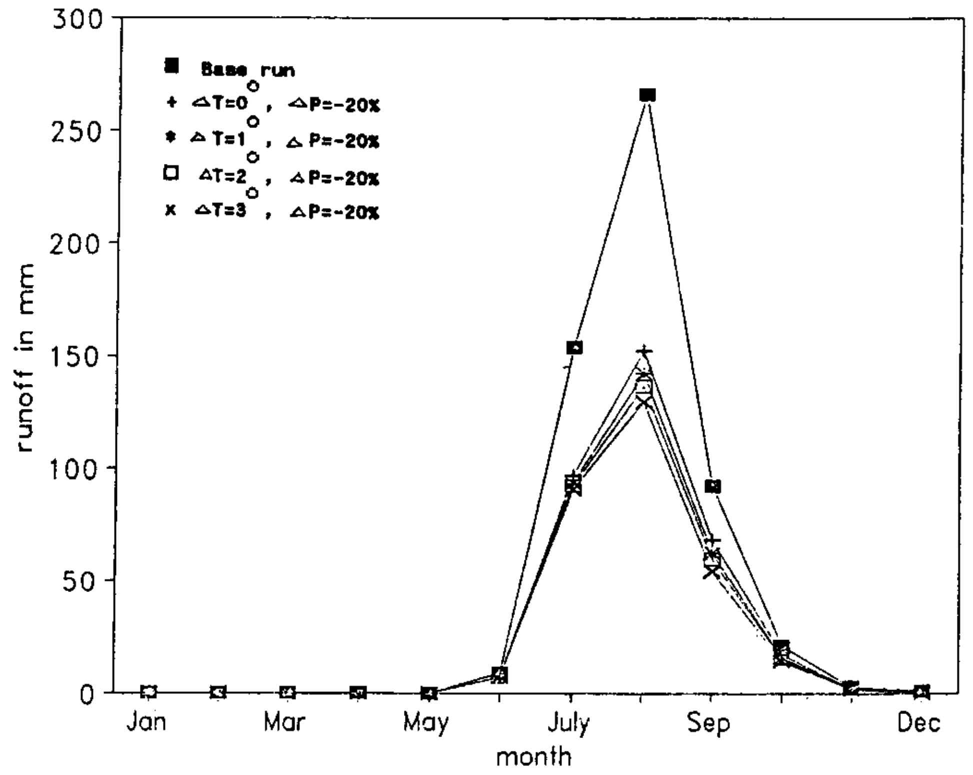


Figure 7.1 Change in mean monthly runoff as a function of change in temperature and 20% decrease in precipitation - Kolar sub-basin

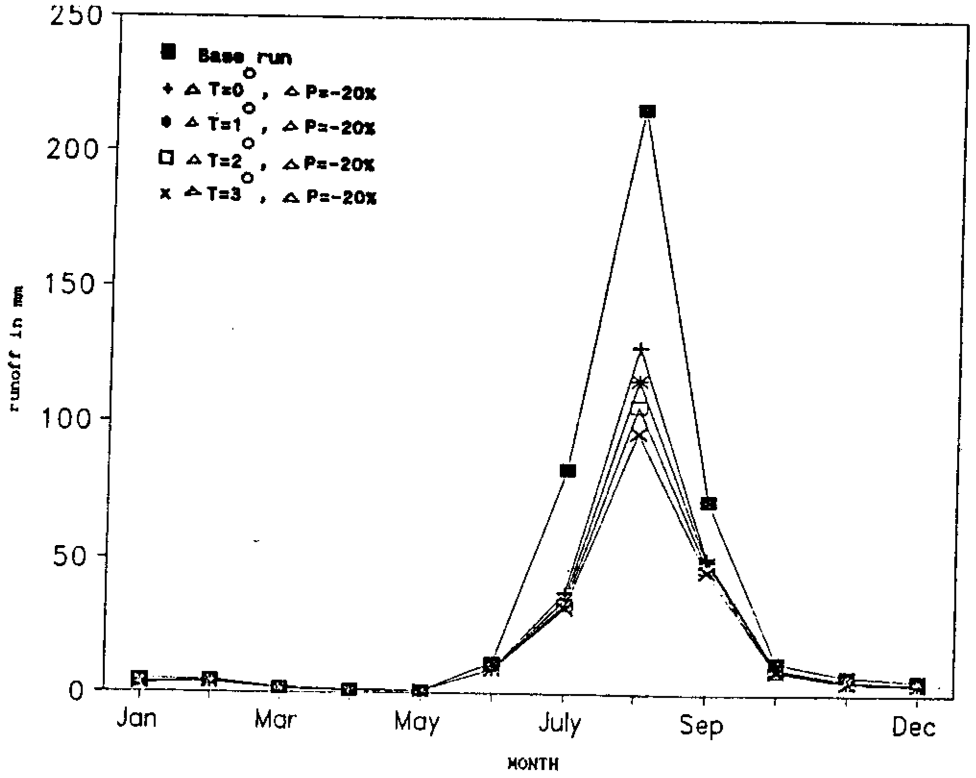


Figure 7.2 Change in mean monthly runoff as a function of change in temperature and 20% decrease in precipitation - Sher sub-basin

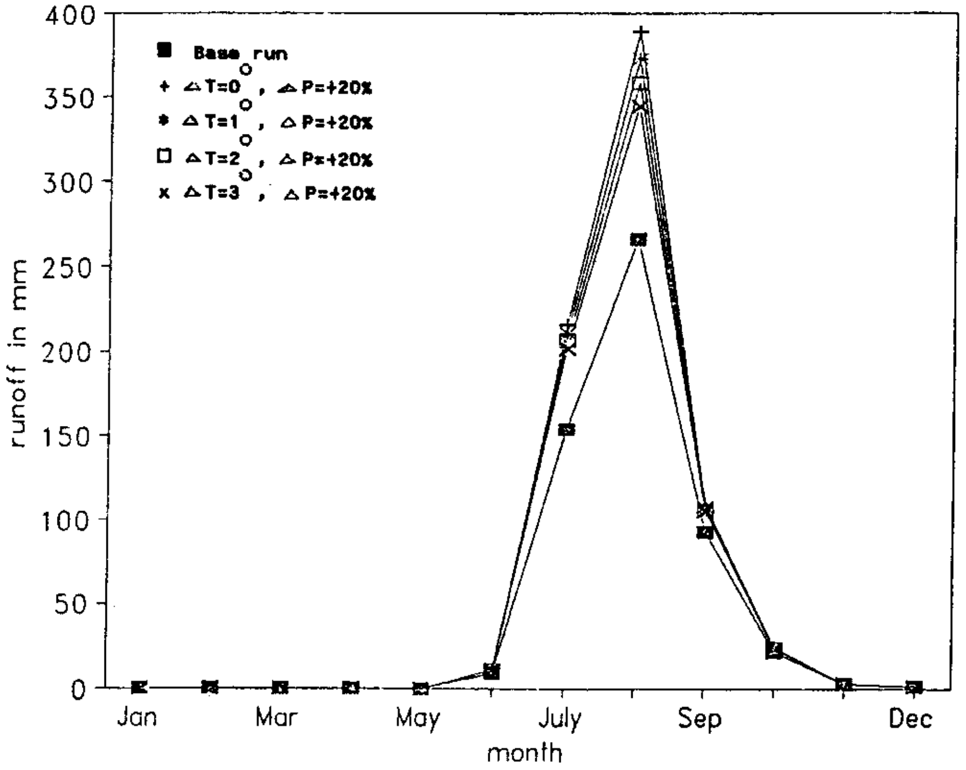


Figure 7.3 Change in mean monthly runoff as a function of change in temperature and 20% increase in precipitation - Kolar sub-basin

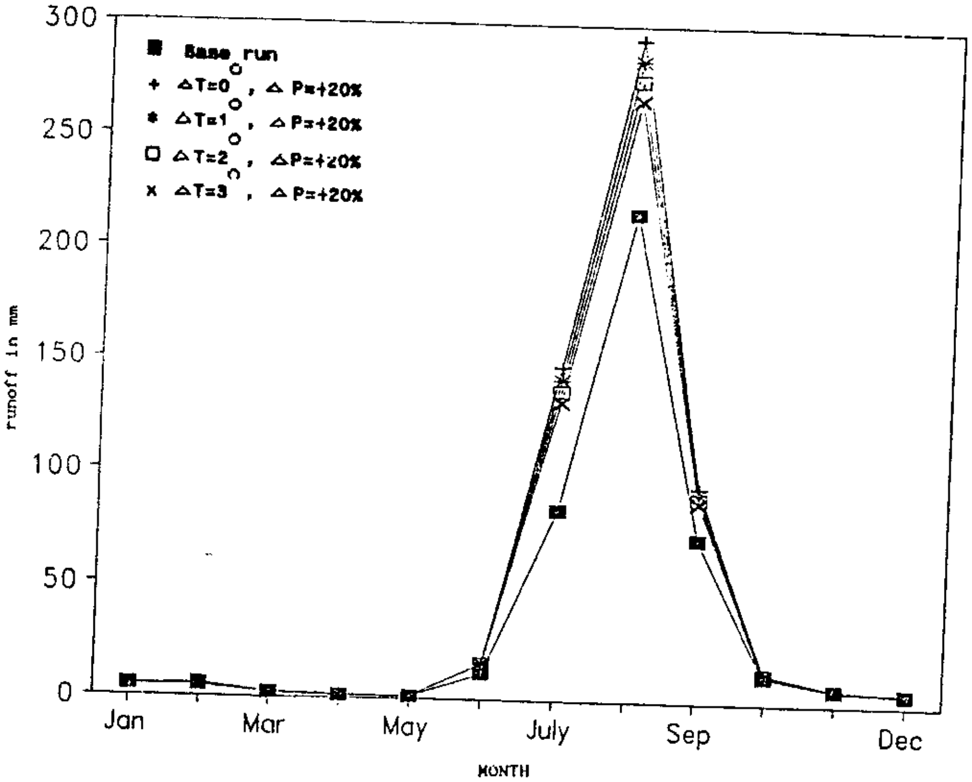


Figure 7.4 Change in mean monthly runoff as a function of change in temperature and 20% increase in precipitation - Sher sub-basin

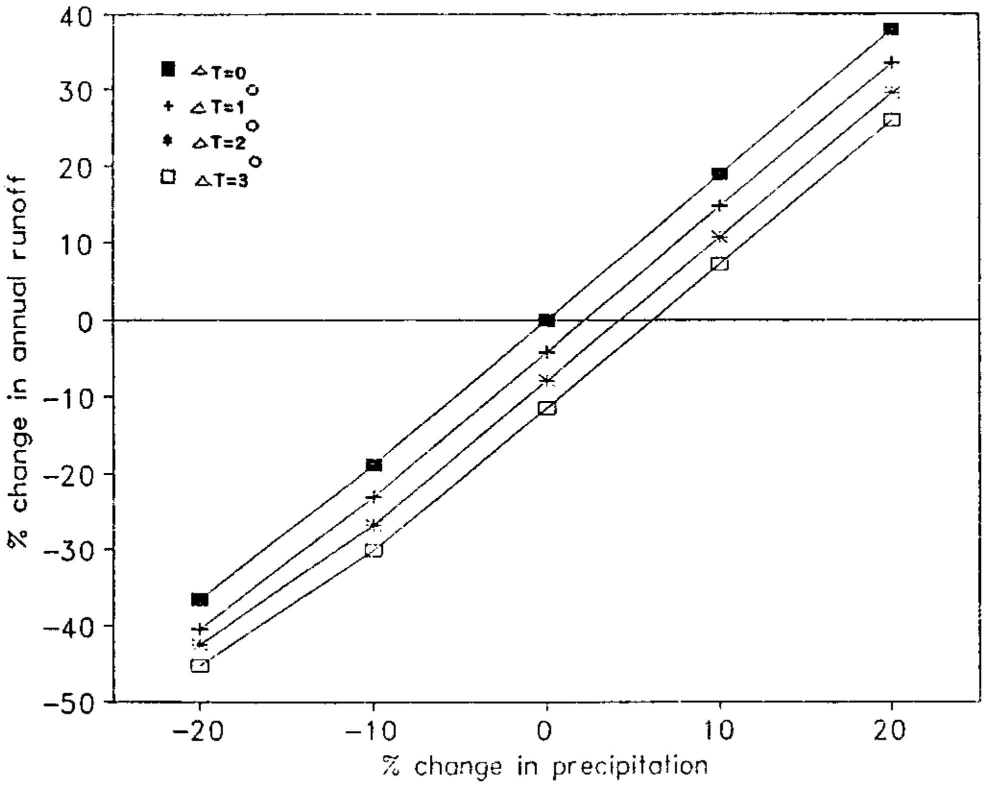


Figure 7.5 % Change in mean annual runoff as a function of change in temperature and precipitation - Kolar sub-basin

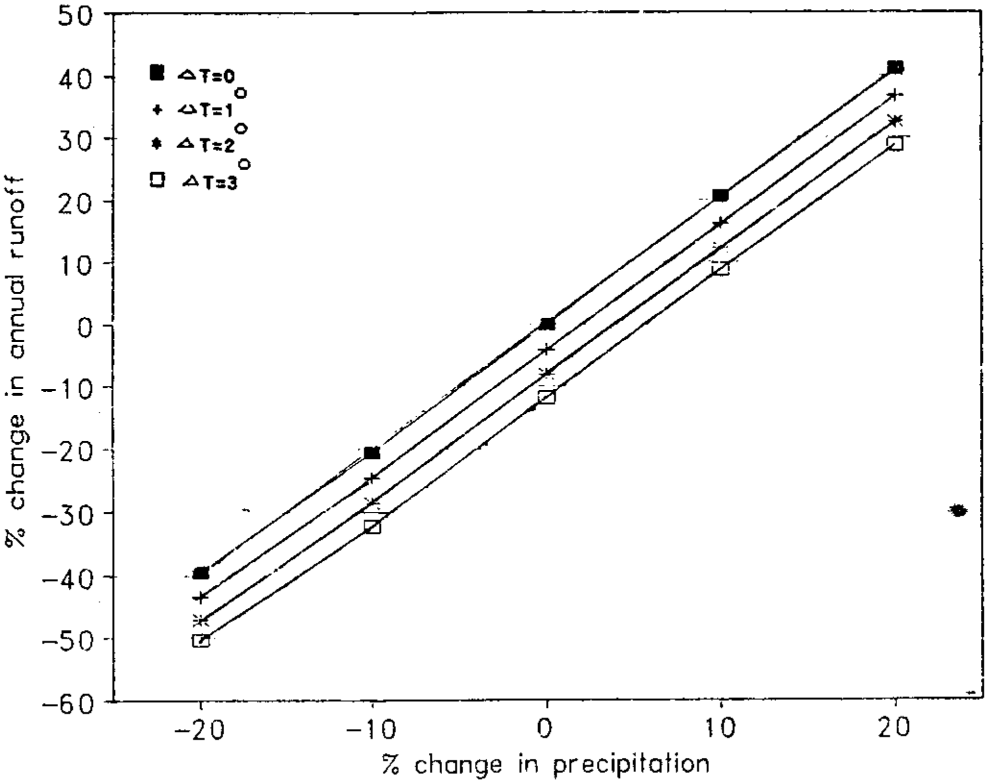


Figure 7.6 % Change in mean annual runoff as a function of change in temperature and precipitation - Sher sub-basin

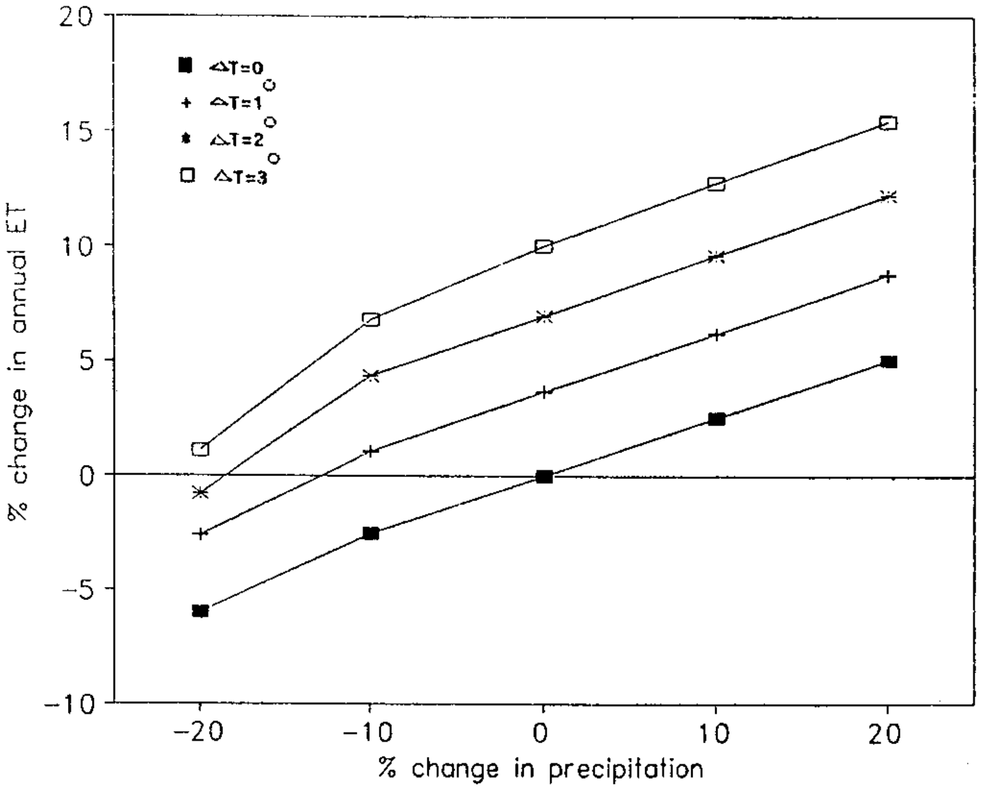


Figure 7.7 % Change in mean annual ET as a function of change in temperature and precipitation - Kolar sub-basin

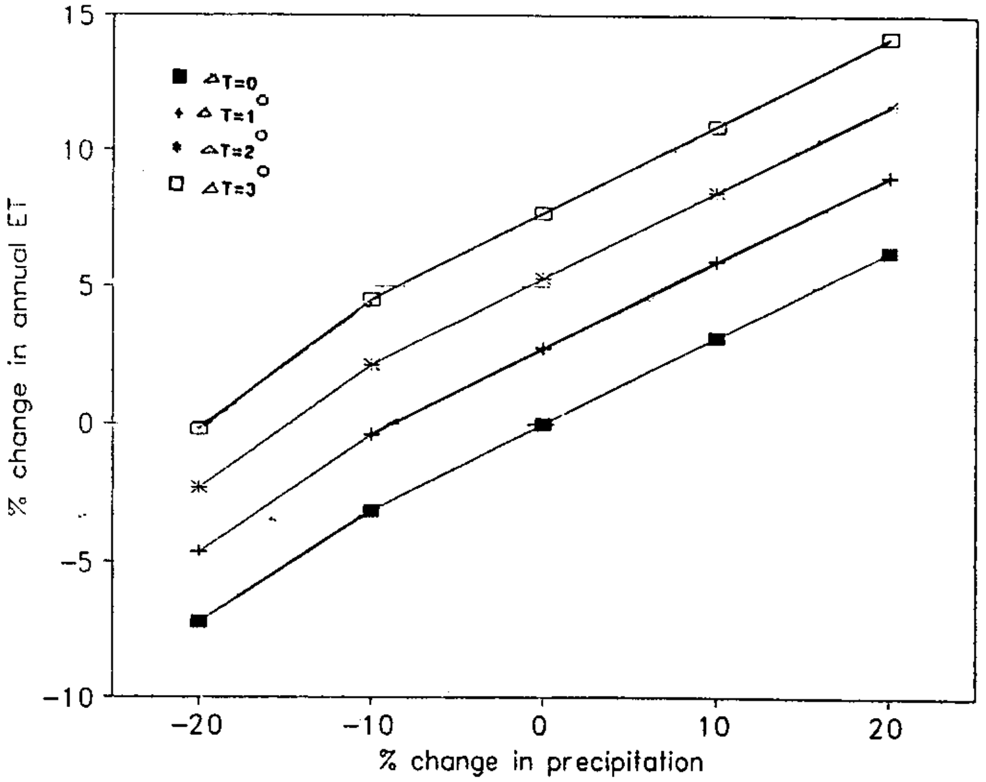


Figure 7.8 % Change in mean annual ET as a function of change in temperature and precipitation - Sher sub-basin

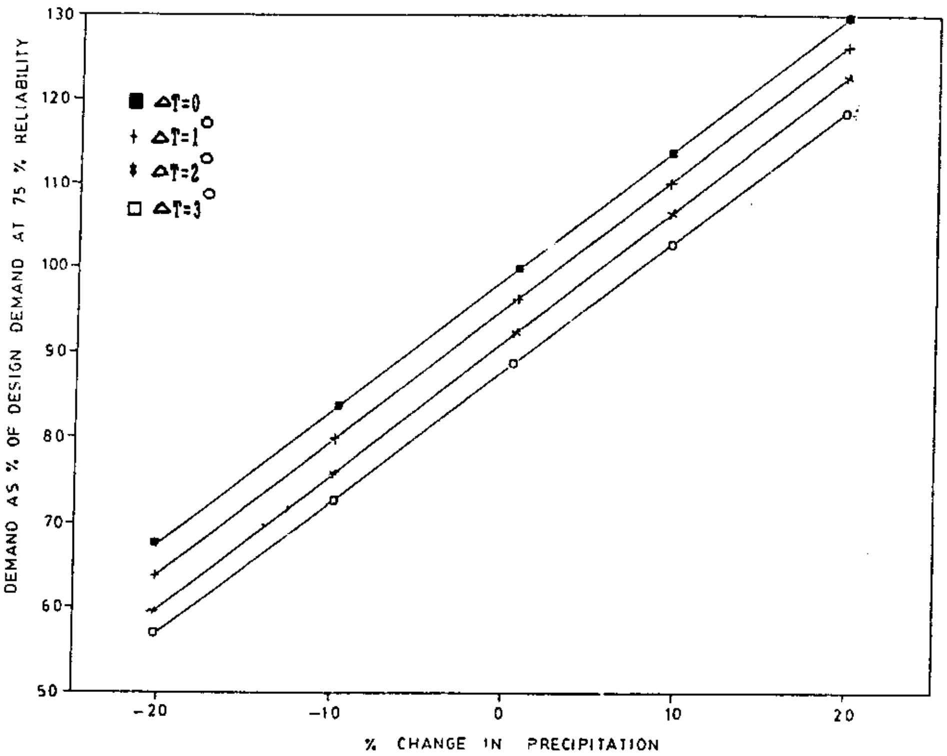


Figure 7.9 Maximum constant firm demand available as % of historic firm demand at 75% reliability - Kolar sub-basin

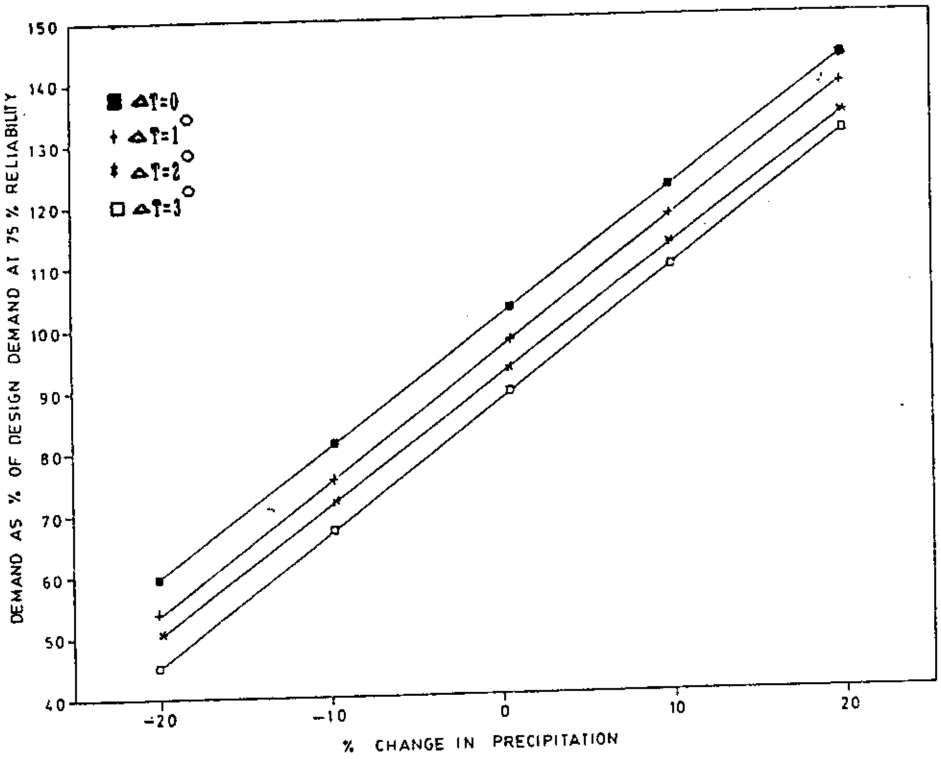


Figure 7.10 Maximum constant firm demand available as % of historic firm demand at 75% reliability - Sher sub-basin

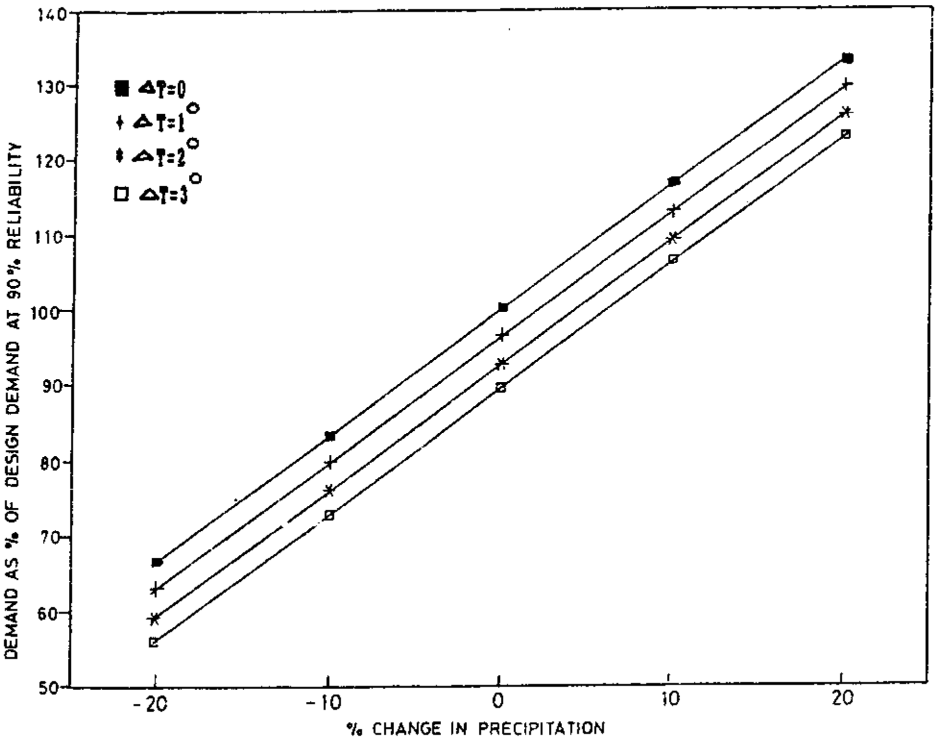


Figure 7.11 Maximum constant firm demand available as % of historic firm demand at 90% reliability - Kolar sub-basin

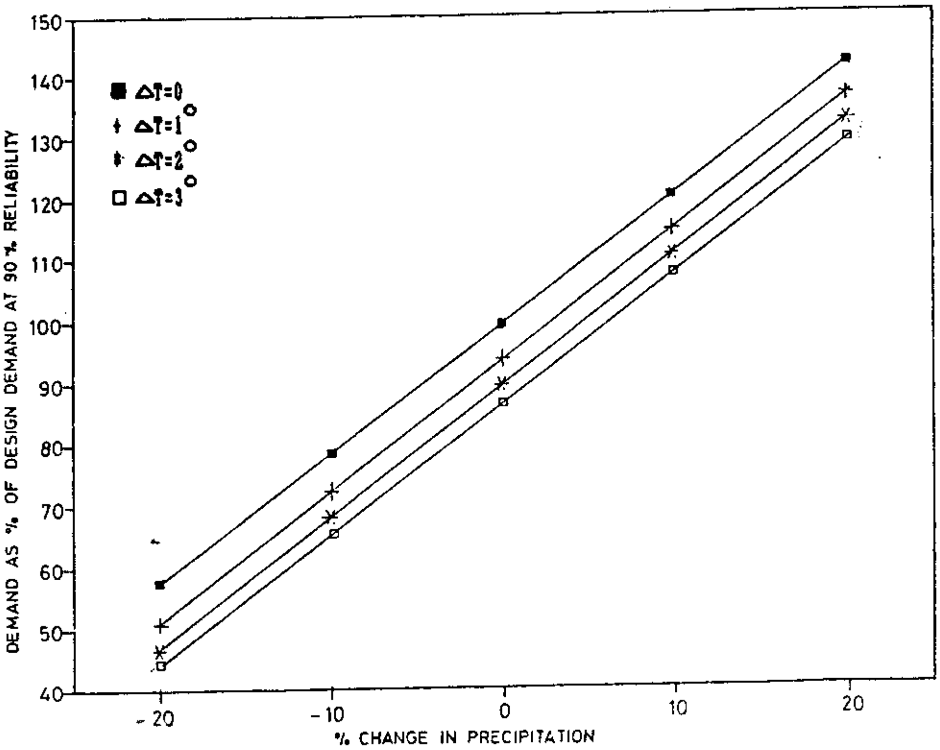


Figure 7.12 Maximum constant firm demand available as % of historic firm demand at 90% reliability - Sher sub-basin

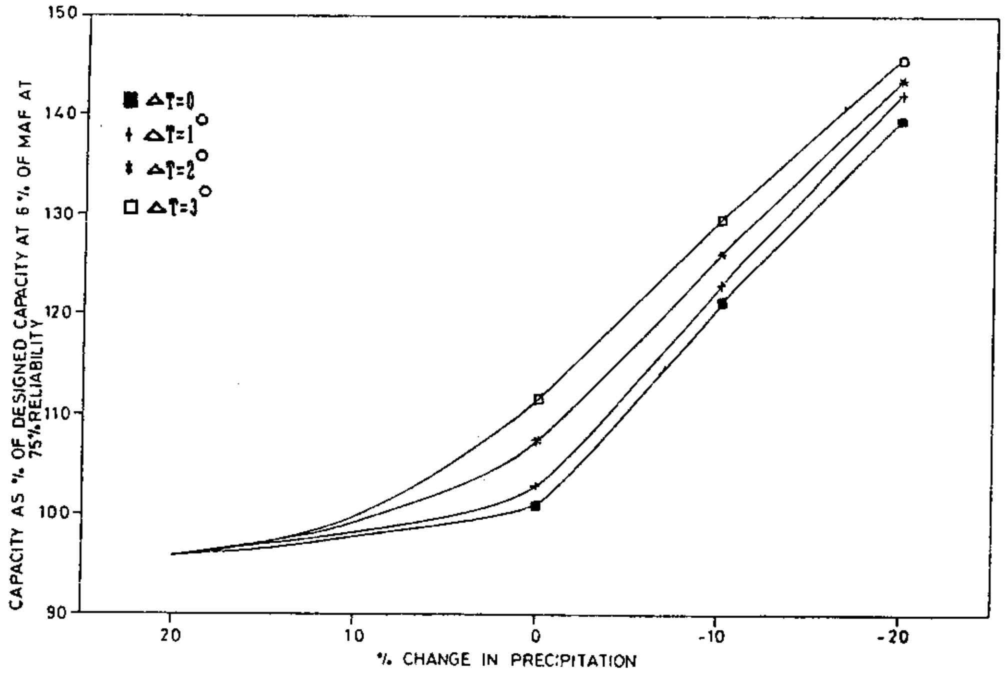


Figure 7.13 Change in capacity to produce a fixed demand (6% of maf) at 75% reliability - Kolar sub-basin

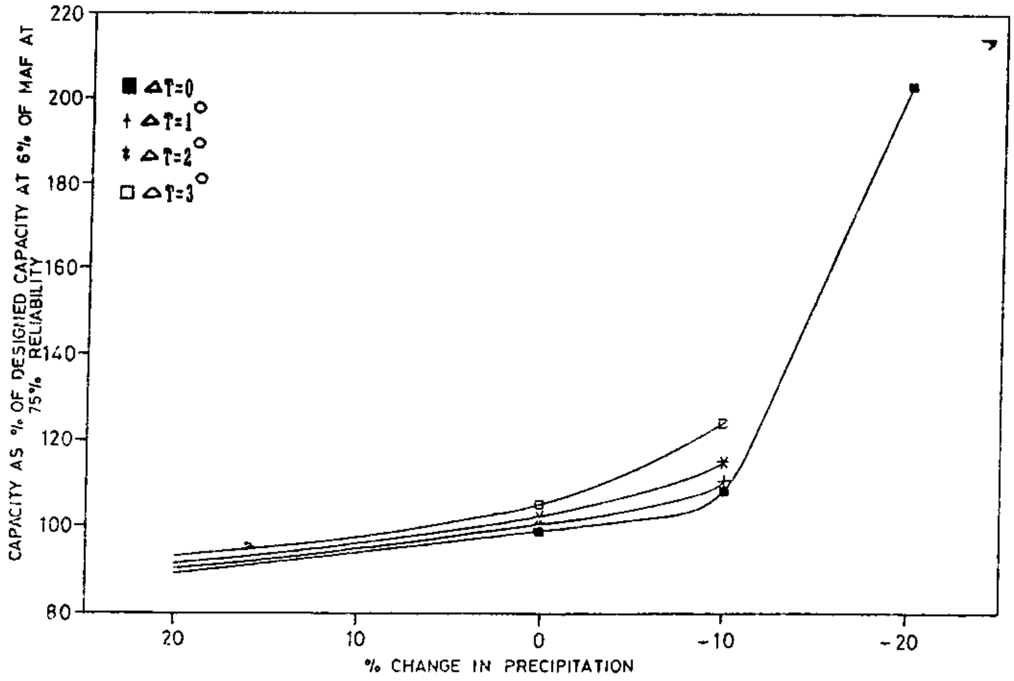


Figure 7.14 Change in capacity to produce a fixed demand (6% of maf) at 75% reliability - Sher sub-basin

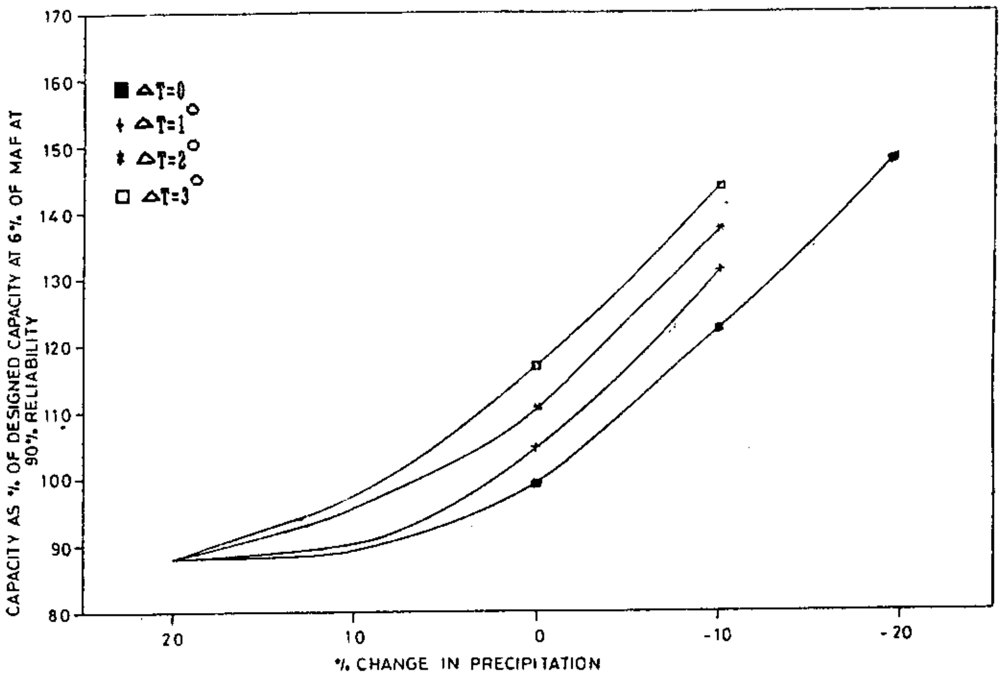


Figure 7.15 Change in capacity to produce a fixed demand (6% of maf) at 90% reliability - Kolar sub-basin

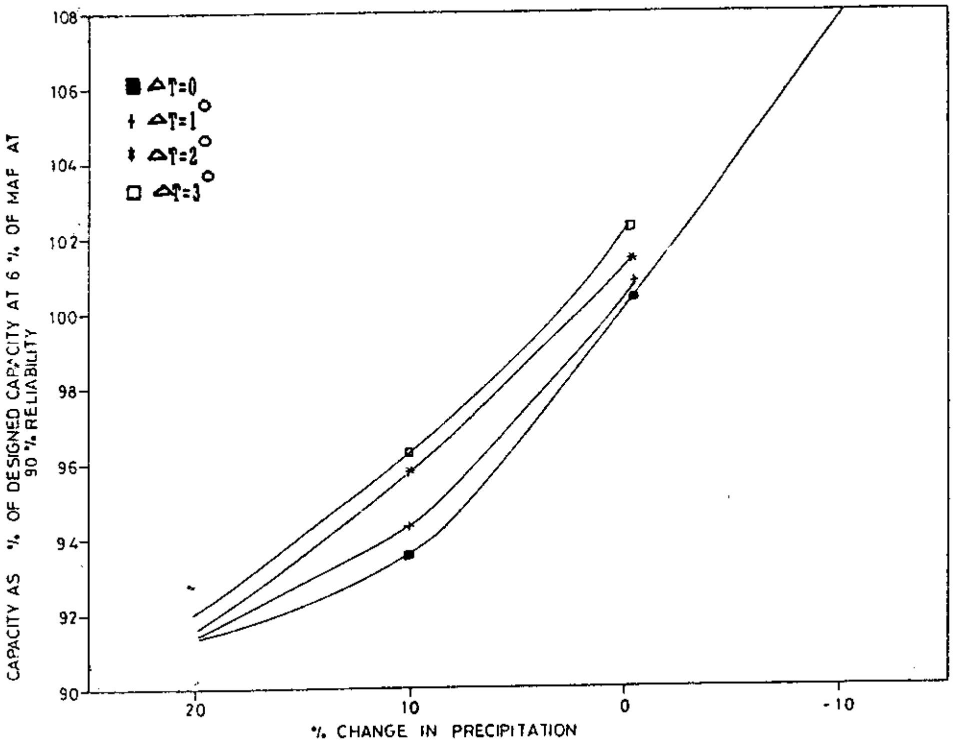


Figure 7.16 Change in capacity to produce a fixed demand (6% of maf) at 90% reliability - Sher sub-basin

Author*	Region	Scale (Km^2)	Climatic change	%Change in runoff (annual average)
Stockton and Boggess (1979)	Average for seven western U.S.regions	10^5	+2C;-10% precip.	-40 to -76
Nemec and Schaake(1982)	Arid basin	10^4	+1C +10% precip. +1C;-10% precip.	+50 -50
	Humid basin	10^3	+1C;+10% precip. +1C; -10% precip.	+25 -25
Revelle and Waggoner (1983)	Colorado river basin	10^5	+2C;+10% precip. +2C;-10% precip.	-18 -40 + 7.4
Idso and Brazel(1984)	12 drainage basins of Arizona	__	+2C;-10% precip.	+40 to +60
Flaschka (1984)	Great Basin	10^5	+2C;-10% precip.	-17 to -38
U.S. EPA (1984)	Central U.S.	10^5	Doubled atmospheric carbon dioxide	-26
	NW U.S.	10^5		+20 to +60
Mc Cabe and Ayers(1989)	Delaware river basin	10^5	+2C;-10% precip.	-30
Mimikou et al	Greek Basins:			
(1991)	Mesohora	10^3	+2C; +20% precip. +2C; -20% precip.	27 -31
	Sykia	10^3	+2C; +20% precip. +2C; -20% precip.	27 -30
	Pyli	10^2	+2C; +20% precip. +2C; -20% precip.	25 -24
Cohen (1991)	Saskatchewan river basin	10^5	+2C; -20% precip. +2C; +20% precip.	-51 +40

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* Each assessment uses different method,hence the direct comparison results is not possible.

Table 2.1 Expected changes in runoff due to climate change

Sher sub-basin of river Narmada

Year 1978

Month	Pptn	Obs runoff	Comp runoff
Jun	166.56	10.76	11.15
Jul	328.81	144.74	104.32
Aug	309.73	285.75	208.25
Sep	53.99	42.41	22.20
Total	859.09	483.66	345.92
NTD	0.90		

Year 1979

Month	Pptn	Obs runoff	Comp runoff
Jun	134.13	14.04	9.23
Jul	328.03	51.03	79.35
Aug	302.10	144.09	170.92
Sep	93.05	13.79	30.08
Total	857.31	222.95	289.58
NTD	0.90		

Year 1980

Month	Pptn	Obs runoff	Comp runoff
Jun	212.73	28.30	14.44
Jul	199.81	39.16	33.90
Aug	388.47	262.56	274.54
Sep	97.67	84.88	28.27
Total	898.68	414.90	351.15
NTD	0.94		

Year 1981

Month	Pptn	Obs runoff	Comp runoff
Jun	279.06	39.78	19.76
Jul	326.45	90.74	165.31
Aug	250.83	162.33	137.40
Sep	182.25	65.57	59.32
Total	1038.59	358.42	381.79
NTD	0.76		

Year 1982

Month	Pptn	Obs runoff	Comp runoff
Jun	153.38	12.91	11.86
Jul	201.23	18.38	25.96
Aug	281.22	124.74	126.89
Sep	303.74	198.09	159.32
Total	939.57	354.12	324.03
NTD	0.96		

Year 1983

Month	Pptn	Obs runoff	Comp runoff
Jun	131.39	8.67	9.24
Jul	346.46	73.17	72.59
Aug	306.91	157.59	184.60
Sep	396.12	302.15	284.73
Total	1180.88	541.58	551.16
NTD	0.97		

Year 1984

Month	Pptn	Obs runoff	Comp runoff
Jun	91.24	6.59	6.68
Jul	216.40	32.20	22.73
Aug	671.18	638.84	520.26
Sep	49.17	31.27	16.75
Total	1027.99	708.90	566.42
NTD	0.96		

Year 1985

Month	Pptn	Obs runoff	Comp runoff
Jun	95.74	12.08	6.54
Jul	320.12	72.23	44.36
Aug	351.82	220.45	225.76
Sep	106.68	28.74	31.99
Total	874.36	333.50	308.65
NTD	0.97		

Year 1986

Month	Pptn	Obs runoff	Comp runoff
Jun	186.55	10.68	12.78
Jul	403.03	152.84	202.25
Aug	226.98	134.84	100.49
Sep	26.43	14.05	16.75
Total	842.99	312.41	332.27

Optimised value of parametres for Sher sub-basin

IMPRM	0.20	¦	SMAX3	25.80
Cbf	2.77	¦	SMAX1	166.00
FC	206.50	¦	SMQSR	307.30
THRES	312.00	¦		

Table 6.1 Observed and simulated monthly runoff and other parameters for monsoon period

Kolar sub-basin of river Narmada

Year 1983

Month	Pptn	Obs runoff	Comp runoff
Jun	7.00	0.00	0.00
Jul	270.00	29.38	35.10
Aug	548.00	361.12	324.65
Sep	382.00	245.64	269.54
Total	1207.00	636.14	629.29
NTD	0.99		

Year 1984

Month	Pptn	Obs runoff	Comp runoff
Jun	141.00	10.00	18.33
Jul	141.00	20.11	18.33
Aug	851.00	586.07	551.13
Sep	27.00	52.16	38.69
Total	1160.00	668.34	626.48
NTD	0.99		

Year 1985

Month	Pptn	Obs runoff	Comp runoff
Jun	139.00	0.00	18.07
Jul	293.00	75.52	38.09
Aug	386.00	216.63	178.01
Sep	181.00	62.35	58.71
Total	999.00	354.50	292.88
NTD	0.97		

Year 1986

Month	Pptn	Obs runoff	Comp runoff
Jun	201.00	0.00	26.13
Jul	958.00	606.31	657.91
Aug	302.00	217.73	164.14
Sep	60.00	36.35	51.91
Total	1521.00	860.39	900.09
NTD	0.98		

Year 1987

Month	Pptn	Obs runoff	Comp runoff
Jun	105.00	21.00	13.65
Jul	160.00	27.90	20.80
Aug	509.00	184.74	198.79
Sep	58.00	61.51	42.72
Total	832.00	295.15	275.96
NTD	0.90	Efficiency	98.45

Year 1988

Month	Pptn	Obs runoff	Comp runoff
Jun	195.00	5.00	25.35
Jul	494.00	147.78	190.59
Aug	527.00	181.67	185.24
Sep	92.00	43.47	56.07
Total	1108.00	377.92	457.25
NTD	0.94		

Optimised value of parametres for Kolar sub-basin

IMPRM	0.13	SMAX3	78.21
Cbf	0.64	SMAX1	257.41
FC	258.20	SMQSR	258.61
THRES	591.61		

Table 6.2 Observed and simulated monthly runoff and other parameters for monsoon period

Month	Base run	d(t) = 0				d(t) = 1				
		p = -10%	p = -20%	p = 10%	p = 20%	p = 0%	p = -10%	p = -20%	p = 10%	p = 20%
Jan	0.153	1	-11	1	1	1	-1	-20	1	1
Feb	0.037	0	-14	0	0	0	-5	-18	0	0
Mar	0.012	0	-29	0	0	0	0	-43	0	0
Apr	0.002	0	0	0	0	0	0	0	0	0
May	0.000	-	-	-	-	-	-	-	-	-
Jun	9.020	-10	-21	10	21	-0	-10	-21	10	21
Jul	153.487	-20	-37	20	41	-3	-24	-39	17	37
Aug	266.163	-23	-43	23	46	-6	-28	-46	17	40
Sep	92.153	-9	-26	9	18	-2	-12	-32	8	17
Oct	21.523	-5	-18	6	12	-1	-8	-24	4	10
Nov	2.830	1	-13	1	1	1	-2	-22	1	1
Dec	0.680	2	-12	2	2	2	-1	-22	2	2
monsoon	520.823	-20	-38	20	39	-4	-24	-41	15	35
post-mon	24.353	-5	-18	5	11	-1	-7	-24	4	9
winter	0.870	2	-12	2	2	2	-1	-21	2	2
pre-mon	0.013	-0	-25	-0	-0	-0	-0	-38	-0	-0
annual	546.060	-19	-37	19	38	-4	-23	-41	15	34

Month	d(t) = 2					d(t) = 3				
	p = 0%	p = -10%	p = -20%	p = 10%	p = 20%	p = 0%	p = -10%	p = -20%	p = 10%	p = 20%
Jan	1	-7	-20	1	1	-3	-15	-25	1	1
Feb	0	-9	-18	0	0	-5	-14	-27	0	0
Mar	0	-29	-57	0	0	-14	-57	-57	0	0
Apr	0	0	0	0	0	0	0	0	0	0
May	-	-	-	-	-	-	-	-	-	-
Jun	-0	-10	-21	10	21	-0	-10	-21	10	21
Jul	-7	-26	-40	14	34	-8	-27	-41	11	31
Aug	-11	-32	-49	12	34	-16	-36	-51	6	29
Sep	-3	-17	-35	6	15	-7	-25	-41	4	14
Oct	-2	-13	-27	3	9	-6	-20	-33	2	8
Nov	1	-8	-24	1	1	-4	-19	-32	1	1
Dec	1	-8	-23	2	2	-3	-19	-31	1	2
monsoon	-8	-27	-43	11	31	-12	-31	-46	8	27
post-mon	-2	-12	-27	3	8	-6	-20	-33	2	7
winter	1	-8	-22	2	2	-3	-18	-30	1	2
pre-mon	-0	-25	-50	-0	-0	-13	-50	-50	-0	-0
annual	-8	-27	-42	11	30	-11	-30	-45	7	26

Table 7.1 % change in mean monthly runoff - Kolar sub-basin

Month	Base run	d(t) = 0				d(t) = 1				
		p = -10%	p = -20%	p = 10%	p = 20%	p = 0%	p = -10%	p = -20%	p = 10%	p = 20%
Jan	15.975	9	4	8	16	-0	4	-1	8	9
Feb	15.615	4	-2	8	16	-3	-2	-9	5	7
Mar	16.978	2	-5	8	17	-5	-6	-13	3	7
Apr	7.527	-1	-8	8	16	-9	-12	-19	-2	3
May	4.810	-8	-18	10	19	-1	-11	-20	8	17
Jun	35.433	-10	-20	10	20	3	-7	-18	13	23
Jul	79.610	-5	-18	5	10	9	4	-10	15	20
Aug	117.183	0	0	0	0	10	10	10	10	10
Sep	149.350	0	0	0	0	7	7	7	7	7
Oct	137.117	-7	-8	0	1	-5	-6	-6	-4	3
Nov	51.977	-7	-12	3	6	5	-12	-17	7	2
Dec	22.195	8	2	8	16	-2	1	-5	6	7
monsoon	381.577	-2	-6	2	4	8	6	2	10	12
post-mon	189.093	-7	-9	1	2	-2	-7	-9	-1	3
winter	53.785	7	1	8	16	-2	1	-5	6	7
pre-mon	29.315	-1	-8	9	17	-6	-9	-16	2	8
annual	653.770	-3	-6	3	5	4	1	-3	6	9

Month	d(t) = 2					d(t) = 3				
	p = 0%	p = -10%	p = -20%	p = 10%	p = 20%	p = 0%	p = -10%	p = -20%	p = 10%	p = 20%
Jan	5	-0	-8	1	9	1	-5	-14	7	3
Feb	-2	-8	-15	-3	5	-8	-14	-22	-1	-1
Mar	-6	-13	-20	-5	3	-12	-19	-27	-6	-4
Apr	-15	-21	-28	-12	-5	-23	-29	-36	-17	-14
May	-3	-13	-22	6	16	-4	-14	-23	5	15
Jun	6	-5	-15	16	27	8	-3	-13	19	30
Jul	18	12	-3	23	29	25	20	3	31	37
Aug	20	20	14	20	20	29	29	22	29	29
Sep	13	13	13	13	13	18	18	18	18	18
Oct	-4	-5	-5	-3	-2	-3	-11	-13	-2	-1
Nov	-11	-16	-22	5	7	-15	-12	-20	-10	5
Dec	0	-6	-13	-3	5	-6	-2	-10	-0	-3
monsoon	15	13	7	17	20	22	20	13	24	26
post-mon	-6	-8	-10	-1	1	-6	-11	-15	-4	1
winter	1	-5	-12	-2	6	-5	-6	-15	1	-1
pre-mon	-8	-15	-23	-5	3	-14	-21	-28	-7	-3
annual	7	4	-1	10	12	10	7	1	13	15

Table 7.2 % change in mean monthly evapotranspiration - Kolar sub-basin

Month	Base run	d(t) = 0				d(t) = 1				
		p = -10%	p = -20%	p = 10%	p = 20%	p = 0%	p = -10%	p = -20%	p = 10%	p = 20%
Jan	32.588	5	-1	8	15	-7	-5	-11	0	3
Feb	23.803	1	-5	8	16	-7	-9	-15	0	5
Mar	7.660	-0	-7	8	16	-11	-14	-20	-4	0
Apr	1.805	-6	-15	9	18	-8	-16	-24	1	7
May	4.990	-10	-20	10	20	-1	-11	-21	9	19
Jun	91.870	-10	-20	10	20	-1	-11	-21	9	19
Jul	232.712	-5	-11	5	11	-1	-7	-12	4	9
Aug	309.500	-0	-0	-0	-0	-0	-0	-0	-0	-0
Sep	224.970	-2	-4	2	4	-4	-6	-8	-2	1
Oct	116.060	2	-4	6	11	-1	-7	-12	4	2
Nov	64.247	8	2	8	16	-6	-3	-8	2	3
Dec	44.218	8	1	8	17	-8	-5	-11	0	2
monsoon	859.052	-3	-6	3	6	-1	-4	-8	2	5
post-mon	180.307	4	-2	7	13	-3	-5	-11	3	3
winter	100.610	5	-1	8	16	-7	-6	-12	0	3
pre-mon	14.455	-4	-13	9	18	-7	-13	-21	1	7
annual	1154.423	-1	-5	4	8	-2	-5	-9	2	4

Month	d(t) = 2					d(t) = 3				
	p = 0%	p = -10%	p = -20%	p = 10%	p = 20%	p = 0%	p = -10%	p = -20%	p = 10%	p = 20%
Jan	-9	-14	-20	-10	-3	-16	-22	-29	-11	-12
Feb	-10	-17	-24	-9	-2	-18	-24	-31	-12	-10
Mar	-18	-24	-30	-16	-9	-28	-33	-39	-22	-20
Apr	-16	-23	-31	-8	0	-21	-28	-36	-13	-6
May	-2	-12	-22	7	17	-3	-13	-23	6	16
Jun	-2	-12	-22	7	17	-3	-13	-23	6	16
Jul	-3	-8	-13	2	8	-4	-9	-14	1	6
Aug	-0	-0	-1	-0	-0	-0	-0	-1	-0	-0
Sep	-7	-9	-12	-5	-3	-10	-12	-16	-8	-6
Oct	-9	-14	-21	-3	2	-15	-12	-20	-10	-5
Nov	-7	-12	-19	-10	-2	-15	-11	-19	-10	-12
Dec	-10	-15	-22	-12	-5	-19	-16	-24	-14	-16
monsoon	-3	-6	-9	0	3	-4	-7	-11	-1	2
post-mon	-8	-13	-20	-6	1	-15	-12	-19	-10	-7
winter	-10	-15	-22	-11	-3	-18	-20	-27	-12	-13
pre-mon	-13	-20	-28	-7	1	-18	-26	-33	-11	-6
annual	-4	-8	-12	-2	2	-7	-9	-14	-4	-1

Table 7.3 % change in mean monthly soil moisture (end of month) - Kolar sub-basin

Month	Base run	d(t) = 0				d(t) = 1				
		p = -10%	p = -20%	p = 10%	p = 20%	p = 0%	p = -10%	p = -20%	p = 10%	p = 20%
Jan	4.524	-10	-22	7	18	-3	-13	-24	5	17
Feb	4.830	-10	-22	13	22	-2	-13	-24	7	19
Mar	1.981	-10	-31	7	12	-3	-13	-33	5	11
Apr	0.962	-9	-21	4	5	-4	-13	-24	2	3
May	0.667	-8	-21	4	5	-4	-12	-24	2	4
Jun	11.298	-10	-20	10	41	-0	-10	-21	10	41
Jul	83.419	-33	-55	38	77	-5	-38	-58	32	69
Aug	216.568	-20	-41	18	36	-4	-25	-46	14	31
Sep	72.157	-15	-29	16	31	-3	-17	-32	13	28
Oct	12.161	-9	-21	6	10	-3	-12	-23	4	8
Nov	6.793	-8	-27	5	7	-4	-15	-29	2	5
Dec	5.116	-9	-20	5	12	-3	-12	-23	3	11
monsoon	383.441	-22	-41	22	44	-4	-26	-45	17	39
post-mon	18.954	-9	-23	6	9	-3	-13	-25	3	7
winter	14.470	-10	-21	8	17	-3	-12	-24	5	15
pre-mon	3.610	-9	-27	6	9	-4	-13	-29	4	7
annual	420.476	-20	-40	21	41	-4	-25	-43	16	37

Month	d(t) = 2					d(t) = 3				
	p = 0%	p = -10%	p = -20%	p = 10%	p = 20%	p = 0%	p = -10%	p = -20%	p = 10%	p = 20%
Jan	-5	-15	-26	3	15	-7	-18	-29	1	13
Feb	-4	-14	-26	5	17	-6	-17	-27	3	17
Mar	-6	-15	-35	3	9	-8	-19	-37	0	7
Apr	-7	-16	-27	-1	1	-10	-21	-30	-4	-1
May	-7	-15	-27	-1	1	-10	-21	-30	-4	-1
Jun	-0	-10	-21	10	41	-1	-11	-21	10	40
Jul	-10	-41	-60	26	63	-14	-44	-62	21	57
Aug	-9	-30	-51	10	27	-13	-34	-55	6	23
Sep	-6	-19	-34	10	25	-8	-22	-36	7	22
Oct	-6	-15	-26	1	6	-8	-19	-30	-1	4
Nov	-7	-18	-33	-1	2	-9	-23	-37	-3	0
Dec	-6	-14	-26	0	8	-8	-19	-30	-2	6
monsoon	-8	-30	-49	13	35	-12	-33	-52	9	31
post-mon	-6	-16	-29	1	5	-8	-20	-32	-2	3
winter	-5	-14	-26	3	13	-7	-18	-29	0	12
pre-mon	-6	-15	-31	1	5	-9	-20	-34	-2	3
annual	-8	-29	-47	12	33	-12	-32	-50	9	29

Table 7.4   % change in mean monthly runoff - Sher sub-basin

Month	Base run	d(t) = 0				d(t) = 1				
		p = -10%	p = -20%	p = 10%	p = 20%	p = 0%	p = -10%	p = -20%	p = 10%	p = 20%
Jan	17.744	-8	-14	5	14	-1	-8	-15	7	12
Feb	27.390	-9	-17	8	17	-0	-9	-18	9	17
Mar	41.142	-5	-14	5	10	-1	-7	-17	4	9
Apr	8.160	-31	-43	30	62	-12	-38	-45	19	48
May	2.989	-10	-20	10	20	0	-10	-20	10	20
Jun	51.357	-10	-20	10	18	3	-7	-18	13	22
Jul	104.922	-1	-8	1	3	6	6	-2	7	10
Aug	98.611	0	0	0	0	8	8	8	8	8
Sep	121.822	0	0	0	0	5	5	5	5	5
Oct	124.257	-2	-5	1	3	1	-2	-4	2	3
Nov	33.626	-7	-8	13	15	-5	-10	-15	2	14
Dec	15.352	-7	-10	2	11	-5	-11	-17	2	4
monsoon	94.178	-2	-5	2	3	6	4	0	7	9
post-mon	78.941	-3	-6	4	6	-1	-4	-7	2	6
winter	20.162	-8	-14	6	14	-2	-9	-17	7	12
pre-mon	17.430	-10	-19	9	19	-3	-12	-21	7	15
annual	53.948	-3	-7	3	6	3	-0	-5	6	9

Month	d(t) = 2					d(t) = 3				
	p = 0%	p = -10%	p = -20%	p = 10%	p = 20%	p = 0%	p = -10%	p = -20%	p = 10%	p = 20%
Jan	-1	-9	-17	7	10	-2	-9	-18	6	13
Feb	-0	-9	-19	9	16	-0	-9	-19	9	17
Mar	-2	-10	-19	3	7	-3	-12	-21	2	6
Apr	-23	-40	-47	7	36	-32	-41	-48	-3	27
May	0	-10	-20	10	20	-0	-10	-20	10	20
Jun	5	-5	-16	16	25	8	-3	-14	19	28
Jul	12	11	3	13	16	18	17	9	19	22
Aug	15	15	15	15	15	21	21	21	21	21
Sep	9	9	9	9	9	13	13	13	13	13
Oct	1	-2	-3	3	4	1	-1	-3	3	5
Nov	-9	-14	-23	-3	11	-15	-21	-29	-7	-0
Dec	-10	-15	-23	-3	-5	-15	-21	-28	-8	-1
monsoon	11	9	5	13	15	16	14	10	18	20
post-mor	-1	-4	-7	2	6	-2	-5	-9	1	4
winter	-3	-11	-19	5	9	-4	-12	-21	4	11
pre-mon	-5	-15	-24	4	13	-7	-17	-25	2	10
annual	5	2	-2	8	12	8	4	-0	11	14

Table 7.5 % change in mean monthly evapotranspiration - Sher sub-basin

Month	Base run	d(t) = 0				d(t) = 1				
		p = -10%	p = -20%	p = 10%	p = 20%	p = 0%	p = -10%	p = -20%	p = 10%	p = 20%
Jan	30.599	-9	-17	8	16	-5	-13	-22	3	10
Feb	39.442	-10	-19	9	18	-4	-13	-22	5	14
Mar	6.672	-36	-49	34	71	-15	-45	-51	20	54
Apr	0.643	-10	-20	10	20	-5	-14	-24	5	14
May	1.969	-10	-20	10	20	-2	-12	-22	8	18
Jun	100.977	-10	-20	10	18	-1	-11	-21	8	17
Jul	195.874	-4	-9	2	4	-1	-6	-11	2	3
Aug	206.510	0	0	0	0	0	0	0	0	0
Sep	160.464	-2	-5	2	5	-2	-5	-7	0	2
Oct	51.666	-6	-7	7	12	-8	-13	-18	-2	5
Nov	24.266	-7	-8	-0	10	-11	-15	-20	-5	-4
Dec	25.824	-8	-14	6	15	-7	-14	-22	1	6
monsoon	663.826	-3	-7	3	5	-1	-4	-8	2	4
post-mon	75.931	-6	-8	5	12	-9	-13	-18	-3	2
winter	95.866	-9	-17	8	17	-5	-14	-22	4	11
pre-mon	9.284	-29	-41	27	56	-12	-36	-43	16	43
annual	70.409	-4	-8	4	8	-2	-7	-11	2	5

Month	d(t) = 2					d(t) = 3				
	p = 0%	p = -10%	p = -20%	p = 10%	p = 20%	p = 0%	p = -10%	p = -20%	p = 10%	p = 20%
Jan	-10	-18	-26	-2	5	-14	-21	-29	-6	1
Feb	-7	-16	-25	2	10	-10	-19	-28	-1	7
Mar	-29	-47	-53	6	39	-41	-49	-55	-7	27
Apr	-10	-19	-28	-1	8	-15	-23	-32	-6	2
May	-3	-13	-23	6	16	-5	-14	-24	5	14
Jun	-3	-13	-22	7	15	-4	-14	-23	6	14
Jul	-2	-7	-13	1	2	-3	-9	-16	0	1
Aug	0	0	0	0	0	0	0	0	0	0
Sep	-4	-7	-10	-2	0	-6	-9	-12	-4	-2
Oct	-15	-20	-28	-10	-4	-23	-28	-35	-17	-11
Nov	-20	-24	-31	-15	-18	-29	-33	-39	-23	-18
Dec	-13	-20	-28	-5	-2	-18	-25	-33	-11	-4
monsoon	-2	-6	-10	1	3	-3	-7	-11	-0	2
post-mon	-16	-21	-29	-11	-8	-25	-30	-36	-19	-13
winter	-10	-18	-26	-1	5	-13	-21	-30	-5	2
pre-mon	-22	-38	-45	5	32	-32	-40	-47	-5	22
annual	-4	-9	-14	-0	3	-7	-11	-16	-2	1

Table 7.6 % change in mean monthly soil moisture (end of month) - Sher sub-basin

	Kolar		Sher	
	Max	Min	Max	Min
Base run (mm)	676	0	520	0
Δ T=1	-0.03	0	-0.03	0
Δ t=2	-0.05	0	-0.05	0
Δ t=3	-0.07	0	-0.07	0

Table 7.7 Percent changes of extreme annual flow under different temperature changes.

KOLAR SUB-BASIN

% change in mean annual runoff

% change in pptn	-20	-10	0	10	20
t=0	-36.67	-18.89	0.00	18.91	37.83
t=1	-40.52	-22.95	-4.13	14.70	33.55
t=2	-42.49	-26.68	-7.93	10.83	29.62
t=3	-45.28	-30.15	-11.47	7.24	25.97

% change in mean annual evapotranspiration

% change in pptn	-20	-10	0	10	20
t=0	-5.98	-2.53	0.00	2.51	5.01
t=1	-2.59	1.04	3.64	6.22	8.78
t=2	-0.79	4.32	6.97	9.61	12.23
t=3	1.08	6.79	10.06	12.75	15.43

% change in mean annual soil moisture (at the end of month)

% change in pptn	-20	-10	0	10	20
t=0	-5.10	-1.27	0.00	4.14	8.25
t=1	-8.59	-4.82	-2.27	1.72	4.13
t=2	-12.20	-7.97	-4.29	-1.73	2.17
t=3	-13.87	-9.04	-7.15	-3.54	-0.97

SHER SUB-BASIN

% change in mean annual runoff

in pptn	-20	-10	0	10	20
t=0	-39.54	-20.49	0.00	20.55	41.00
t=1	-43.47	-24.69	-4.20	16.26	36.66
t=2	-47.00	-28.55	-8.10	12.31	32.61
t=3	-50.33	-32.20	-11.79	8.57	28.81

% change in mean annual evapotranspiration

% change in pptn	-20	-10	0	10	20
t=0	-7.22	-3.14	0.00	3.10	6.27
t=1	-4.66	-0.40	2.74	5.90	9.11
t=2	-2.34	2.11	5.28	8.48	11.74
t=3	-0.16	4.49	7.68	10.91	14.22

% change in mean annual soil moisture (at the end of month)

% change in pptn	-20	-10	0	10	20
t=0	-8.38	-4.43	0.00	3.81	7.59
t=1	-11.04	-6.65	-2.32	1.71	5.06
t=2	-13.63	-8.86	-4.43	-0.45	2.56
t=3	-15.83	-10.99	-6.62	-2.43	0.96

Table 7.8 % change in mean annual runoff, evapotranspiration and soil moisture for Kolar and Sher sub-basins

	% change in runoff magnification factors			
% change in pptn	-20 to -10	-10 to 0	0 to 10	10 to 20
Kolar basin				
t=0	1.8	1.9	1.9	1.9
t=1	1.8	1.9	1.9	1.9
t=2	1.6	1.9	1.9	1.9
t=3	1.5	1.9	1.9	1.9
Sher basin				
t=0	1.9	2.0	2.1	2.0
t=1	1.9	2.0	2.0	2.0
t=2	1.8	2.0	2.0	2.0
t=3	1.8	2.0	2.0	2.0

Table 7.9 Magnification factors for Kolar and Sher sub-basins

Precipitation scenarios		-20%	-10%	0%	10%	20%
Kolar sub-basin	t=0	1.06	1.06	1.05	1.04	1.04
	t=1	1.06	1.06	1.05	1.04	1.04
	t=2	1.06	1.06	1.05	1.04	1.04
	t=3	1.06	1.06	1.05	1.05	1.04
Sher sub-basin	t=0	1.13	1.11	1.10	1.08	1.08
	t=1	1.13	1.11	1.10	1.09	1.08
	t=2	1.14	1.12	1.10	1.09	1.08
	t=3	1.14	1.12	1.10	1.09	1.08

Table 7.10 Mean annual to mean monsoon runoff ratios

Table 7.11 Maximum possible demand at a fixed capacity - Kolar sub-basin

Demand in mm						
capacity = 880 mm	Temperature change in degree C	% change in percipitation				
		-20%	-10%	0%	10%	20%
At 90% reliability	0	34.5	42.7	51.2	60.2	66.6
	1	33.2	40.8	49.3	58.2	65.1
	2	31.7	39	47.5	56.4	63.3
	3	30.2	37.4	45.9	54.6	62.5
At 75% reliability	0	40.9	49	60.9	68.2	77.8
	1	38.7	46.9	58.6	68.2	75.8
	2	36.3	45.5	55.1	67	73.9
	3	34.7	44	53.1	65	72

Table 7.12 Maximum possible demand at a fixed capacity - Sher sub-basin

	Demand in mm					
capacity = 770 mm	Temperature change in degree C	% change in percipitation				
		-20%	-10%	0%	10%	20%
At 90% reliability	0	19.5	25.5	33.5	40.5	47.5
	1	18.5	24	31.5	38.5	45.5
	2	17	22.5	30	37.5	45
	3	15.5	22	28.5	36	43.5
At 75% reliability	0	25.5	35	43	53	61.5
	1	23	32.5	41.5	50.5	59
	2	22	30	40	49	56.5
	3	21	28.5	38	47	56.5

Table 7.13 Capacity required at different reliabilities and demands for precipitation and temperature scenarios - Kolar sub-basin

		Capacity in mm																			
		Precipitation change																			
% relia-bility	Demand in mm	+20%				+10%				0%				-10%				-20%			
		Temperature change in degree C																			
		0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3
75	54.6	426	430	430	454	458	474	488	496	504	510	638									
	43.7	286	286	294	294	300	306	328	338	350	354	370	380	390	390	396	488				
	32.8	188	188	188	188	194	194	194	194	196	196	218	218	238	250	252	254	274	276	278	286
	21.8	106	108	108	108	108	108	108	108	120	120	120	120	120	120	120	122	120	132	142	144
	10.9	42	42	42	42	42	42	42	42	44	44	44	44	44	44	44	44	44	44	46	46
90	54.6	600	630	650	670	688	710	732	778												
	43.7	376	386	394	410	432	448	468	486	506	524	544	562								
	32.8	250	250	250	250	252	252	270	270	284	296	314	332	352	372	390	406	408	470		
	21.8	144	144	144	144	144	144	144	144	152	152	152	152	154	154	162	176	176	184	202	214
	10.9	64	64	64	64	64	64	64	64	64	64	64	64	64	64	64	66	64	66	66	66

Note: Blanks indicate insufficient availability of water to meet that demand at that reliability

Table 7.14 Capacity required at different reliabilities and demands for precipitation and temperature scenarios - Sher sub-basin

		Capacity in mm																			
		Precipitation change																			
		+20%				+10%				0%				-10%				-20%			
% reliability	Demand	Temperature change in degree C																			
		0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3	0	1	2	3
75	42	242	244	246	250	254	272	296	338	480											
	33.6	178	178	184	184	186	188	192	192	190	198	226	264	384							
	25.2	116	116	118	120	126	126	126	126	128	128	132	134	134	140	144	160	264			
	16.8	62	62	62	62	68	68	70	70	70	72	72	74	76	76	76	76	78	78	84	84
	8.4	14	16	16	16	16	18	18	18	20	20	20	20	22	22	22	24	24	26	26	26
90	42	326	326	336	370																
	33.6	242	244	244	244	246	252	252	262	324											
	25.2	159	159	159	160	163	164	167	169	174	175	176	176	188							
	16.8	92	92	92	92	94	94	94	94	94	94	94	96	98	100	100	104	106	116	126	
	8.4	28	28	28	30	32	32	32	32	34	34	34	34	34	36	36	38	38	38	40	42

Note: Blanks indicate insufficient availability of water to meet that demand at that reliability

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