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IMPACT OF GLOBAL CHANGE ON HYDROLOGICAL AND WATER RESOURCES PARAMETERS IN ARID AND SEMI-ARID AREAS

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PREFACE

Increasing gaseous pollutants in the atmosphere have enhanced the so called greenhouse effect and hence increased the relative heating of the globe. The global warming is expected to have profound impact on meteorological and hence hydrological and water resources parameters. The direct assessments of impacts and realistic evaluation of the climate sensitivities of water resources systems, specially for drought facing regions are a matter of concern and need considerable study.

A number of assessments have been made on the problem of climate changes and its impact on hydrologic regime, but there is little certainity about how meteorological and hydrological drought will be affected by future climate change. The researchers predictions indicate towards frequent and severe hydrologic events like drought, flood etc. As we have experienced the four hottest years of the century in recent past decade (i.e. 1980, 81, 83 and 1987). Also the year 1987 has been said as the second severest drought year of the century. This may be taken as the sign of the changing climate. National Institute of Hydrology has initiated some studies towards atmosphere land surface processes and impacts of climatic changes on hydrological consequences. In the present report, an attempt has been made to review the status of hydrological response of climate change with emphasis for the regions which are frequently experiencing drought.

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ABSTRACT

Global warming resulting from increasing concentration of greenhouse gases could alter hydrologic processes and cycles within many parts of the world. Current consensus is that a doubling of CO concentration will cause a 1.6 C to 4.5 C global warming and that in turn, may cause major changes in regional precipitation, evapotranspiration, annual rainfall regime and may effect water availability in some areas. A majority of scientific community believes that an abnormal planetary warming is likely. There is insufficient evidence at the moment to prove that a climate change caused by human activities is underway. Observed changes could be merely the result of normal variability. Nor is there agreement about the possible rate of change and what its impact might be on the people and nations of the world. Nor is it very much clear what effect it may have on the hydrological cycle.

A large number of research studies have been carried out on climatic change and its impact on various hydrological and meteorological aspects. The conclusions drawn from various studies are not very precise and refer only to the long-term averaged characteristics of hydrological, meteorological and water resources parameters. While reviewing the state of art on the subject, methodological approaches are considered as well as basic information/data and pre-requisites used by different scientists to evaluate and predict the effect of climatic changes on water resources and on hydrological regimes. The results obtained for different regions of the world have been discussed, including the river runoff forecasts subjected to climate changes.

There is little certainty about how meteorological and hydrological droughts will be affected by climate change. But the results from various models point towards the possibility of more frequent and severe weather events (floods, droughts, typhoons etc.). Though not uniform throughout the zone, increase in precipitation in most parts of semi-arid tropics is predicted by some models. The possibility of precipitation decrease in some areas is also indicated. Increased precipitation is expected to be in the form of convective rainfall, implying high intensity but not necessarily increased frequency of rains. Thus the seasonally dry tropics would have potentially high rainfall, high runoff and high evaporation, without necessarility having enhanced growing seasons. Some parts of semi-arid tropics already face with large variability in seasonal and annual rainfall and a trend toward decrease in precipitation could be highly sensitive even to small negative impact of greenhouse warming. As an impact of global warming, more winter precipitation and drier summers could be expected for arid and

semi-arid regions of India and Africa. The western world felt more winter precipitation as rain instead of snow and winter runoff increased while spring snowmelt runoff decreased. Increased rainfall could bring significant moisturing in arid and semi-arid regions. This may benefit agricultural practices in some regions.

This report documents the present status of knowledge in respect of climate changes and its probable effect on various hydrological and water resources characteristics. It also discusses the impact of climate changes for various regions of the world. Emphasis has been given to review the relevant studies for arid and semi-arid regions. The impact of climate changes specially on precipitation, evaporation and runoff for different regions has been reviewed.

CONTENTS

Page

LIST OF TABLES i

ABSTRACT ii

1.0 INTRODUCTION 1

2.0 DISTRIBUTION OF ARID LAND ON EARTH 3

3.0 GREEN HOUSE EFFECT ON GLOBAL CLIMATE AND DROUGHT 4

4.0 IMPACT OF CLIMATE CHANGE ON HYDROLOGICAL PARAMETERS 10

- 4.1 General 10
- 4.2 Climate Change and Hydrological Characteristics 12
- 4.2.1 Precipitation 12
- 4.2.2 Runoff 16
- 4.2.3 Evapotranspiration 23

5.0 SOME REGIONAL CLIMATIC CONSEQUENCES ON HYDROLOGY AND WATER RESOURCES 28

- 5.1 USSR 28
- 5.2 North America 30
- 5.3 North Africa 33
- 5.4 India 34
- 5.5 Northern China 35
- 5.6 Japan 36
- 5.7 Australia 38

6.0 RECOMMENDED ACTIONS AND RESEARCH NEED IN CHANGING CLIMATE 40

REFERENCES

LIST OF TABLES

Table No.	Title	Page
3.1	Climatic and other variables likely to change due to GHW and components of resource base and production environment of agriculture to be most affective by the change (first order impact).	9
4.1	Case studies of impact of climatic change on hydrology for critical or sensitive environments.	11
4.2	change in annual average precipitation (mm/day) between the experiment and the control run for different geographic regions. Also shown in the standerd deviation of the control run.	14
4.3	Effect of climatic changes on runoff some early results (Gleick,1986).	22
5.1	Probable changes of seasonal river runoff in USSR in case of global warming by 1 c (2000).	29
5.2	Water resources changes in large regions	37

1.0 INTRODUCTION

The likely occurrence of changes in climatic conditions, due to human has been a cause of serious concern during recent years. The causative factors include extensive deforestation for agricultural expansion, use of wood for energy production, industrialisation and other kinds of human interference which led to the increase of carbon-di-oxide in the atmosphere. All these factors have contributed to drought crises, soil erosion and salinization, especially in Asia and Africa.

Climate change is of global significance but its effect will be most striking at the local or regional level. Unfortunately, existing climate models are not very reliable in predicting the details of regional climate changes, specially regarding the southern hemisphere and the tropics. How would a global warming disturb rainfall patterns ? Which area would get more, which area less and by how much ? What would happen to lakes and rivers ? What about erosion and sedimentation processes ? What about drinking water, agriculture and forestry ? etc. etc. are some of the important aspects to be understood. There are now six 'general circulation models' (GCMs), which are able to provide temperature and precipitation predictions under conditions of varing concentrations of carbon dioxide. The most of GCMs are in general agreement about the amount of warming that will occur but their predictions of precipitation are quite varied.

The potential impacts associated with changing climate (warming climate) are now in the process of being assessed. Most of the studies have concentrated on impacts on North American and European regions and systems. Despite the fact that climate world, some of the major impacts will occur in developing countries. These include sea-level rise, drought, salt water intrusion, loss of forest, impact on hydrological variables, impact on human health and others. In a world experiencing rapid population growth and increased competetion for resources the most disturbing impact of global changes are environmental degradation and changes in hydrological parameters. Additionally, soil erosion and cultivation of marginal lands are further depleting the existing resource supplies, leading to economic and social disruption, regional and national insecurity and hydrological imbalances.

These uncertainties make planning for water resources management difficult. Yet if predictions of global warming are correct, then we are running out of time. What we decide to do in the next few decades, could well be critical to the future of the planet.

Most researchers prescribe climate changes for various regions or river basins in a simplified form as hypothetical scenarios without taking into account a particular time interval. As a rule, most scenarios accept an air temperature increase from 0.5° C to 4.0° C and precipitation change (increase or decrease) in the range of 10% to 25%. An increase in potential evapotranspiration has also been prescribed by some research workers. Diana et.al (1991) reported through model studies that global warming could bring warmer and drier conditions in Mexico. In their study it was found that precipitation may increase but it may not compensate for increase in potential evapotranspiration. Thus, soil moisture and water availability may decrease.

Changes in climatic conditions due to increasing atmospheric concentrations of relatively active trace gases will probably lead to alteration in land and water resources and their distribution in space and time, transformations in the hydrologic cycle , water bodies and water quality, as well as in the conditions of water supply systems and requirements of water resources in different regions. Quantitative/qualitative estimates of the hydrologic effects of climate change are essential for understanding and solving the potential water resources problems associated with drought, water supply for domestic use, irrigation, power generation, agriculture and industry, as well as for future water resource systems planning, reservoir design and management and protection of the natural environment.

The purpose of this report is to prepare a document which presents the current status of knowledge of global climate changes and their impacts on various water resources and hydrological parameters in drought affected regions of the earth and to bring out the need for research in the subject area suggested by various research workers. The information in this regard has been collected from published literature/reports.

2.0 DISTRIBUTION OF ARID LAND ON EARTH

Drought is a characteristic feature of the arid and semi-arid land. Arid areas extend along both sides of the equator in the form of two beets (Sinha, 1989). The northern beet includes the desert and semi-desert area of north America, north Africa and Asia; in the southern beet are the desert and semi-desert territories of south America, south Africa and Australia. The total area of the arid zone is about 35 million square kilometers (about 10% of the total continental area). Seventy five percent of this area comprises arid zone of Eurasia and North Africa which include the largest desert of the world. This beetwise distribution of arid zones is due to the climatic zonality of the earth. This climatic zonality acts as one of the important controls of water availability on the earth which is so important in drought management.

3.0 GREENHOUSE EFFECT ON GLOBAL CLIMATE AND DROUGHT

The greenhouse effect and potential global consequences have now been widely and frequently described in the scientific literature. A summary of major works on the subject was recently brought out by Beijer Institute (1988). All scientific studies of green house effects agree that there will be regional differences in the future climate changes but no consensus on regional pattern has emerged. Uncertainties also persist in modelled results. They relate to the rate and timing of climate changes and details of specific climatic variables. However, for semi-arid tropical regions, increase of regional temperature of the order of 0.5°-4° C is predicted. Though not uniform through the zone, increase in total amount of precipitation in most part of semi-arid tropics is predicted by some models. The possibility of precipitation decrease in some part is also indicated. Increased precipitation is expected to be in the form of convective rainfall, implying high intensity but not necessarily increased frequency of rainfall. Thus, the seasonally dry tropics would have potentially high rainfall, high runoff and high evaporation, without necessarily having enhanced growing seasons. Some parts of semi-arid tropics already face large variability in seasonal and annual rainfall and a trend toward decrease in precipitation could be highly sensitive even to the negative impact of greenhouse warming.

From the recent investigations, there is no doubt about a naturally occurring green house effect. Carbon dioxide and water vapour in the atmosphere act like the glass in a greenhouse, allowing incoming sunlight to reach the earth but preventing the scope of most of the trapped heat back into space. Increasing concentration of greenhouse gases carbon dioxide (Co_2), Methane (CH_4), nitrous oxide (N_2O) and Chlorofluorocarbon (CFC) enhance the green house effect and result in an additional warming of the earth's surface. A number of assessments have been made on the prediction of climatic changes due to increasing greenhouse gases by various national groups, notably in United States. The changes in the future climate have been set on the basis of the changes that have occurred over the past 100 years. The green house effect is expected to cause major changes in global mean temperature, which will necessarily be accompanied by changes in various climatic variables such as absolute humidity and precipitation, annual rainfall and net terrestrial and global solar radiation. Mabbutt (1989) reviewed the pastulated effects of the Co_2 warming on semi-arid tropical climates. He mentioned that overall warming could mostly be in terms of a rise in dry season temperature, including both day time maxima and over-night minima in semi-arid tropics.

Extreme hydrological and meteorological events such as floods, droughts, typhoons, tornadoes and hurricanes could become more frequent and intense. We may even have seen the first signs of this. Current global temperatures are the highest in the period of instrumental records and the four hottest years of the past century (1980, 1981, 1983 and 1987) have all occurred in the previous decade.

Global warming could seriously affect agriculture. some key food-producing regions including the North American bread-basket may experience heat waves, drought and the loss of irrigation water.

Global warming will also affect plants and animals. Many have been forced to adapt to changing conditions in the past. But future climate changes promise to occur very quickly. Thousands and thousands of species will not be able to adapt either by evolving new characteristics, or moving to new areas quickly enough. Mass plant and animal extinctions may therefore occur. Bradley et.al (1987) have shown an upward trend for land based data from 1920 in mid to high latitudes (35°-70° N) and a marked downward trend in tropical to sub-tropical latitudes (5°-35°N) of the northern hemisphere. Barnett (1985) have concluded that it is extremely difficult to establish the trends over the ocean. On smaller spatial scales some regions of the world have experienced marked changes in precipitation on decadal time scales, for example - Sahel region of Africa.

Despite the above facts and various other observations, we are not yet in a position to answer the direct question, "Will the green house effect cause more or fewer droughts ?". But, the following paragraphs introduce the approaches in this direction.

<u>Indications from preliminary principles</u> :

Evaporation from plant and water surfaces increases by seven percent per °C temperature rise. Therefore, an increase in temperature may be expected to give rise to a more active hydrological cycle and hence more abundant rainfall. However, the local scene may be very different. For example, moisture from oceans may penetrate less far into the continents if air motion changes. As precipitation and evaporation increase, the difference between them may decrease. Indeed, it is quite reasonable to expect precipitation to lag evaporation due to the inertia in the oceans or land surface processes (Rind et.al 1989). The evidence from such events as the Sahel drought, where internal feedback prolongs initial desiccation, lends little comfort to water management in areas where the climate is already marginal. Therefore, we should not be surprised if drought incidence increases in the medium term.

Climate models predictions :

Several numerical climate models predict that there will be summer drying in middle and high latitudes (Mitchell et.al,1987 and Manabe et.al,1987). The models also show improvements to soil moisture in dry areas.

Climate models suggest that global warming could bring warmer, drier conditions to Mexico (Diana et.al,1991). Although precipitation increase is projected in some models, in most cases, they do not compensate for increase in potential evaporation. Thus, soil moisture and water availability may decrease over much of the Mexico with serious consequences for rainfed and irrigated agriculture, urban and industrial water supplies, hydropower and ecosystem, etc. However, the assessment of global warming impacts in Mexico is an uncertain task because the projections of different models vary widely, particularly for precipitation and because they are poorly reproducing the observed climate of Mexico.

Zhao and Kellogg (1988) have performed a large scale intercomparison of how the five main numerical models agree in predicting soil moisture in Asian monsoon region. Although there was no consensus, the majority indicate an intensification of the seasonal swing between high early season soil moisture in the north and summer maxima in the south. "There is an indication of a change towards drier winters and wetter summers in most India and south-east Asia".

There may be particular geographic circumstances controlling the rainfall mechanism which may simplify the forecasting problem in those areas. For example, Coleman argues for increased summer aridity in Florida, USA because of the dominance of local anticyclonic behaviour as a factor controlling ocean heating and local rainfall. This is borne out by past analogues.

Paleoclimatic evidences : There is an alternative school to how best one may estimate future climates which may base projections for future on past climates. Budyko (1988) argues that the climate in early part of the 21st century will resemble that of the climatic optimum and the climate after the middle of the century can be modelled from conditions during the "Eeemian". Paleoclimatological methods are used to reconstruct regional climates for the period. One notable conclusion is that the US Corn belt will become drier at the outset but will later become more humid than today.

Thus one of the most profound impacts of green house effect or climate changes may be major alteration of the regional hydrological cycle and changes in regional water availability and their consequences.

Table 3.1 : Climatic and other variables likely to change due to GHW and components of resource base and production environment of agriculture to be most affected by the change (First order impacts)
(SOURCE : Jodha 1989)

	Climatic and other variables							
Major components of physical resource base and production environment	Temperature	Solar radiation	Precipitation	Soil moisture	Runoff	Evapotranspi-	Atmospheric humidity	
1. Moisture regime			*		*	*		
2. Length of growing season			*	*	*		*	
3. Micro-climatic stress	*	*	*	*	*	*	*	*
4. Frequency of abharent weather	*	*						
5. Seasonality	*	*	*					
6. Disease/pest complex	*	*	*	*			*	
7. Bio-mass productivity potential	*	*	*	*		*	*	
8. Photosynthesis pattern	*	*		*		*	*	
9. Plant-input interaction		*		*		*		
10. Chemistry of soil	*	*	*	*	*			
11. Soil erosion hazard		*		*				

4.0 IMPACT OF CLIMATE CHANGE ON HYDROLOGICAL PARAMETER

4.1 General

Global warming and climate changes due to enhanced greenhouse effect could alter hydrologic processes and cycles in many parts of the world (National Academy of Sciences, 1977; Smagorinsky 1982). As a consequence of potential climate changes (Temperature and precipitation), significant impact on hydrological parameters viz. runoff, evapotranspiration, soil moisture and groundwater is expected. To assess the hydrological effects of changing climate, one needs the predictions/forecasts of changes in air temperature and precipitation for different regions and periods of time. As accurate forecasts of regional climatic changes are still not available, various scenarios of future climate changes are used. These scenarios are :

- Assume an air temperature increase (from 0.5°C to 4°C) and precipitation change (increase or decrease -10 to 25%).
- Scenarios obtained by using atmospheric GCM's.
- Past climatic changes and past changes in atmospheric CO_2 levels.

Various research workers from all over the world have made attempt to assess the impact of global climate changes on water resources and hydrological parameters using different climatic models. Also the projected climatic changes need to be regarded as the possibilities to study the sensitivity of hydrological and water resources parameters to such changes. This has been evaluated by many methods. The large scale general circulation models have been used to prescribe possible changes in the content of trace gases in the atmosphere (2 x CO_2 usually) and to directly obtain the possible changes in climate and hydrological characteristics for large regions. By using atmospheric GCM's, possible changes in runoff, soil wetness and evaporation have been estimated for USA and Canada (USEPA, 1984; Sanderson and Wong, 1987; Singh 1987; Stakhiv and Lins,1989). Some case studies of impact of climate change on hydrology for critical or sensitive environments have been summarized in Table 4.1.

Table 4.1 : Case studies of impact of climatic change on hydrology for critical or sensitivie environments

Critical or sensitive environment	Region	Future changes	Remarks
Large water bodies	Great Lakes basin (US/Canada)	decrease in precipitation	lake-levels expected to be lower and hence navigation would be affected.
		decrease in runoff	
	The Caspian Sea	The dynamics of the sea would change in 15-20 years	
Critical agricultural regions	South Platte river basin	less certain consequences of global warming, increases or very large decrease in in precipitation	
	Murray-Darling basin	precipitation increases in spring, autumn and summer	slight reduction in demand for irrigation water
Intensively urbanized areas	Delaware river basin,	Probability of occurrence of drought	
Regions of snowmelt generated runoff	The Sacramento San Joaquim river basin (USA)	Total annual runoff to remain near current levels or to increase	
		Higher runoff in winter months and considerably less in the spring snowmelt - runoff season.	

(Source : Divya 1991)

4.2 Climate Change and Hydrological Characteristics

The global hydrologic cycle is one of the principal components of our climate system. Across the global air-sea interface, there is a net flux of water out of the ocean because evaporation exceeds precipitation. Overland evaporation is less than precipitation. The long term water budgets for both continents and ocean are balanced by the continental runoff of water back to ocean.

4.2.1 Precipitation :

In a report published by Research Directorate of National Defence University, USA (1978) based on various expert opinions on climate change to the year 2000, the respondents' estimates of the probabilities of change in precipitation volume and variability indicate a high level of uncertainty not only about the amount of change but in many cases even about the direction of change. Annual precipitation levels increased slightly in the higher middle latitudes but showed little change for lower latitudinal bands. Growing season precipitation also increased slightly in the higher middle latitudes and subtropical regions but remained unchanged in lower middle latitudes. Both annual and growing-season precipitation variability remained essentially unchanged except for a slight increase in the variability of growing-season precipitation in sub tropical latitudes.

Drought conditions again plagued the mid-latitude areas of United States, corroborating the 20-to-22 years drought cycle hypothesis. Climatic conditions were somewhat more favourable in the Asiatic region and subtropical North Africa. The frequency of monsoon failure, specially in north west India, resembled more closely the long-term average of Sahel region. As noted earlier, the effect of increased albedo on rainfall was originally emphasized by Charney (1975) in connection with the Sahel region. Subsequent requirements of this nature have been performed by Charney et al. (1977), Chervin (1979), Rowntree (1982) and Sud and Fennessy (1982). Using different general circulation models, each work altered the albedo in different areas, generally including the Sahel area; one difference among the experiments which is thought to be significant relates to the way soil moisture is calculated, whether it is fixed at wet or dry values, or interactive. This difference has even produced opposing results in certain regions (cf. Sud and Fennessy 1982). In general, these experiments were run for the month of July. The results from these experiments are unanimous in finding decreased precipitation in the Sahel region when its albedo is increased, with values ranging from 1-4 mm/day.

Rind (1982) studied the influence of vegetation on hydrological cycle in a global climate model. Through the experiments, he emphasized the importance of vegetation in the global climate system. Table 4.2 indicates that the annual average rainfall in the Sahel decreased in this albedo experiment as well; however, in summer the rainfall over the Sahel actually increased. There are two important differences between this experiment and most of others. One is that the reduction in surface albedo occurred everywhere, not only in the Sahel area. While the surface albedo reduction was 13% in the Sahel, it was 17% in the African rainforest. It is equatorial Africa which suffers a large decrease in precipitation. Note that the land/ocean albedo contrast exists in this experiment, as in those by other experiments, only in this case it results in a land/ocean temperature contrast that is not focused but occurs for the whole continent. Rowntree (1982) also noted that regions of precipitation increase and decrease over land occur when surface albedo was altered over a wide area. The second difference is that this experiment was run for two years and thus incorporated several seasonal cycles. As noted in the previous section, the results for any month are dependent on how the hydrologic cycle and soil moisture in particular, are altered in previous months. The albedo experiment limits evaporation during spring and thereby increasing the available soil moisture in summer.

Table 4.2 : Change in annual average precipitation (mm day) between the experiments and the control run for different geographic regions. Also shown is the standard deviation of the control run.

REGION	DIFFUSION	CAPACITY	ALBEDO	STAND.DEV.
WESTERN U.S.	.06	-.72	.27	.33
MID U.S.	-.16	-.75	-.72	.11
EASTERN U.S.	-.12	.09	-.71	.63
SOUTHERN CANADA	-.78	-1.08	-.47	.07
MID EUROPE	-.19	-1.13	.35	.12
NORTHERN RUSSIA	-.13	-.31	.31	.16
WESTERN SIBERIA	-.38	-.23	.05	.06
SIBERIAN PLATEAU	.03	-.22	-.04	.06
SOUTHERN CHINA	.46	-.51	-.69	.30
CHINA DESERT	-.27	-.48	-.36	.18
INDIAN DESERT	-.09	-.59	.39	.50
AUSTRALIAN DESERT	-.33	.15	.43	.22
NORTHERN SAHARA	-.14	-.23	.22	.04
SOUTHERN SAHARA	-.02	-.27	.06	.21
AFRICAN SAHEL	-.13	-.50	-.50	.23
AFRICAN RAINFOREST	.22	-1.35	-2.33	.22
AMAZON RAINFOREST	-.07	-.60	-1.88	.21

SOURCE : Rind (1982)

The impact of soil moisture on rainfall has been studied by various modelers (ua. Manabe, 1975; Charney et al., 1977; Walker and Rowntree, 1977; Mintz, 1981; Rowntree, 1982; Rind, 1982). Results are consistent in showing that reduced soil moisture produces reduced rainfall in July in continental areas, especially in those regions without a nearby oceanic water vapor source. The effect may last for several months or even longer. Except for a few areas such as Bangladesh, southeast China, and the central portions of the United States, the regions do not overlap. Thus, in addition to indicating the effect of vegetation on climate, these experiments provide an indication of the origin and cause of rainfall in the model in different geographical locations.

Peterson and Keller (1989) evaluated the influence of temperature and precipitation changes on the irrigation requirements and the possibilities of developing future irrigated areas in arid regions of the Western US. They came to the conclusion that warming would exert an enormous effect on irrigation development in the region with unstable moistening. By increasing temperature by 3°C and decreasing precipitation by 10%, cultivated areas in the western US could decrease by 30% and efforts will be required to improve efficiency of water use and to develop new freshwater supplies (Gleick, 1989).

Linz et. al, (1990) mentioned that the analysis of annual precipitation data from stations in the Sahel region for the period 1970-85 has revealed this period to be extremely dry, the reason for Sahelian droughts being the decrease in annual precipitation. Ojo (1987), analysing the precipitation trends for 1901-85 for 60 stations of western Africa found that the average precipitation for 1970-79 and 1981-84 were 0.62 and 0.5 of the normal. Mabbutt(1989) mentioned that some indication of the hydrological consequences of rainfall decrease in the semi-arid tropics is given by the reduction in discharges and seasonal flooding in the Niger and Senegal rivers and drastic shrinkage of Lake Chad after two decades of low rainfalls in Sahelian Africa. A tendency of decrease in total annual precipitation during the period 1972-87 for arid zones of Northern Africa was observed and the total annual amounts of precipitation were found to be much lower than the normal. The succession of dry years led to a decrease in water resources in the region.

This tendency may represent a potential risk of drought which may contribute to the process of desertification and extension of deserts. The changes in precipitation due to the increase in trace gas concentration in the atmosphere may lead to changes in the future water resources, ecology and economy of the countries in Sahelian and arid and semi arid zones.

4.2.2 Runoff :

Increasing CO_2 concentration in the atmosphere may affect watershed runoff in several ways. One effect is to increase the stomatal resistance of plants; this reduces transpiration (Idso et.al 1985, Woodward 1987). Another effect is to alter air temperature and precipitation patterns, which, inturn, may affect all aspects of the hydrologic cycle.

Since the late 1970s, changes in annual and seasonal runoff have been extensively investigated and described in many publications. This is because the problem of annual and seasonal river runoff is very important owing to a determining role of the runoff in meeting water demands and providing water supply of the regions. Quantitative estimates have been obtained for many regions of the US, USSR(formerly), New Zealand, Canada, river basins in England, Wales, Belgium etc.

The investigations carried out primarily point to a great sensitivity of river watershed even to insignificant changes in climatic characteristics. The watersheds located in arid and semiarid regions are especially sensitive. In this case, two features should be taken into account. First, the annual runoff turns out to show more variations; second, for the watersheds where the main runoff is formed in the period of snowmelt, interannual runoff distribution is more vulnerable to changing air temperature than to precipitation. In middle latitudes of the Northern Hemisphere, with 1° C or 2° C warming, the winter runoff is expected to increase drastically and the spring high water to be lower, and results in more intensive winter snowmelt (due to more frequent and intense winter thaws).

It should be noted that the estimates of runoff change due to global climate warming take account of no possible direct influence of increased CO_2 on evapotranspiration (with increased CO_2 concentration, evapotranspiration usually decreases). This phenomenon is considered in Idso and Brazel (1984) for five river basins in Arizona, US, as well as in Aston (1987) for river basins in Australia. In this case, the results obtained turned out to be directly opposite to the inferences drawn by other researchers, namely, a doubling of CO_2 concentration brought about a 40% to 60% increase in annual runoff for the US rivers in question, and that for Australian rivers by 60% to 80%. Wigley and Jones (1985) and Palutikof (1987) point to the importance of taking into account the direct CO_2 effects on evapotranspiration and total evaporation, which is ignored by many researchers. This problem needs further investigation and is open to discussion.

Its solution determines profoundly the reliability of quantitative estimates of the future hydrologic cycle. The authors assume that it is necessary to take this factor into account in comprehensive studies; however, it is unlikely to lead to such significant results as have been obtained by the above authors, for total evaporation from land, as is known, is mainly determined by energy factors.

One of the important aspects in studying the hydrologic consequences of global warming is to estimate, on the one hand, possible changes in the river runoff extremes and maximum water expenditure and runoff volume during floods and, on the other hand, minimum expenditure and runoff over certain periods. The former characteristics raise the problems of runoff control and development of flood control works, as the determination of values of river runoff provides the basis for designing various hydrologic structures. Minimum water expenditure defines the water supply, in particular in the limiting periods of the year, without runoff control.

Estimation of extreme river runoff characteristics with anthropogenic climatic change is the most important modern problem in engineering hydrologic calculations, since upto the present time all over the world, design of hydrologic structures is based on the concept of stability of hydrometeorological conditions. That is, it is assumed that the observational data over many decades would reflect also hydrometeorological conditions for the next decade during the period of planning for of projected constructions. All the methods are usually used in practice for statistical calculations to estimate sizes of the constructions and their carrying capacity and to maintain stability during disastrous natural events.

In future, anthropogenic climate change exerts a pronounced effect on runoff extremes, the statistical methods for hydrologic calculations will have no scientific base. That is, the general strategy for hydrologic calculations in design work must be radically changed. At the same time, to obtain reliable quantitative estimates for maximum runoff with global warming is almost an insoluble problem at present, because of periods with very intense snowmelt in runoff formation during high water periods. The same applies to minimum water expenditure during the periods without precipitation since the indicated meteorological events are unlikely to be forecast by GCM's simulations or by using paleoclimatic analogs. In practice, quantitative regional estimates of possible changes in runoff extremes are yet unavailable. Nevertheless, there are plenty of qualitative estimates, usually based on an assumption about the proportion of changes in runoff extremes in annual, seasonal or monthly runoff. It is understandable that more reliable conclusions about the runoff extremes in various regions of the world can be drawn, based on detailed quantitative estimates of changes in meteorological characteristics over shorter periods of time.

An important component of the Earth's hydrologic cycle is river runoff. The world's 20 largest rivers account for 40% of the total continental runoff (Baumgartner and Reichel, 1975). The river runoff for a particular drainage basin depends on the precipitation and evaporation budgets within the basin and on the ability of the ground to store water, which depends on the soil type and the vegetative cover. Flow rates depend on the topography. The comparison of model generated river runoff with observations provides a useful diagnostic for climate modelers to obtain a better understanding of the parameterizations which affect the hydrologic cycle in their models. An important reason for hydrologists to study model-generated river runoff is to understand and to predict future changes in river runoff that may accompany global climatic changes. Since the prediction of future changes depends on some type of model, it is essential for hydrologists and climate modelers to develop the best possible surface parameterizations that affect model-generated river runoff.

Gary et.al (1990) used global atmospheric model of Hansen et.al to calculate the annual river runoff for the world's major rivers. The model has a horizontal resolution of 4° x 5°, but the runoff from each grid box within a particular river's drainage basin is summed on a resolution of 2° x 2.5° to obtain the runoff at the river mouth. The mean annual runoff is calculated and compared with observations for 33 of the world's largest rivers. The runoff depends on the model's precipitation and parameterizations of groundwater storage and evapotranspiration, which are affected by soil type and vegetation.

Forecasting the effects of climate change on watershed runoff has two important sources of uncertainty. First, uncertainty in how the climate will change creates variability in the expected implications of increasing CO_2 . For the Delaware River basin, the effects on runoff characteristics range from increasing trends to decreasing trends, depending on which climate-change scenario is used. Second, the lack of knowledge of the actual time sequence of future precipitation and temperature causes uncertainty. Different simulations of the future climate with the same statistical properties (i.e., the same gradual changes in climate variables) produce differences in the detectability of changes in runoff characteristics. The underlying natural variability in precipitation and temperature caused many simulations of future climate with dramatic changes to induce no statistically detectable trend in runoff characteristics.

Wolock et al (1989) used a deterministic hydrological model, "TOPMODEL" to derive the runoff forecasts with stochastic inputs of temperature and precipitation. The results indicated that the direction and magnitude of the changes in watershed runoff are dependent on the relative magnitude of the induced changes in precipitation, temperature and stomatal resistance. Natural variability in temperature and precipitation obscured the changes in watershed runoff even when the simulated changes in precipitation, temperature and stomatal resistance were substantial.

The hydrological sensitivities of the medium-sized mountainous catchments in the Sacramento and San Joaquim River basins to long term global warming were analysed. The hydrological response of these catchments, all of which are dominated by spring snowmelt runoff, were simulated by the coupling of the snowmelt and the soil moisture accounting models of U.S. National Weather Service River Forecast System. The global warming pattern, which was indexed to CO_2 doubling scenarios simulated by three (global) general circulation models, produced a major seasonal shift in the snow accumulation pattern. Under the alternative climate scenarios more winter precipitation fell as rain instead of snow and winter runoff increased while spring snowmelt, snowmelt runoff decreased (Lettenmeir 1990).

Schaake (1988) applied prescribed (+10 and -10 percent) changes of precipitation and evapotranspiration to monthly water balance model of south eastern united states. He estimated a 20 to 36 percent decrease in average annual runoff for the 10% decrease in precipitation and a 10 to 22 percent decrease for the 10 percent increase in evapotranspiration. The percent change in runoff consistently was less in the eastern, more humid part of the south-east than in the western, more arid part. Some early results showing effect of climatic changes on runoff are given in Table 4.3

Table 4.3 : Effects of climatic changes on runoff : some early results (Gleick, 1986)

Author[*1]	Region	Scale (km^2)	Climatic change	% Change in runoff[*2]
Stockton and Boggess (1979)	Average for seven western U.S. regions	10^5	+20;-10% precip.	-40 to -76
Nemec and Schaake (1982)	Arid basin	10^4	+10 +10% precip. +10;-10% precip.	+50 -50
	Humid basin	10^3	+10;+10% precip. +10;-10% precip.	+25 -25
Revelle and Waggoner (1983)	Colorado River Basin	10^5	+20;+10% precip. +20;-10% precip.	-18 -40 +7.4
Plaschka (1984)	Great Basin	10^5	+20;-10% precip.	-17 to -38
U.S. EPA (1984)	Central U.S.	10^5	Doubled atmospheric carbon dioxide	-26
	NW U.S.	10^5		+10 to +60

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

*2 annual average changes in runoff

4.2.3 Evapotranspiration

Evapotranspiration becomes an increasingly important water-balance component during summer when climatic and biologic demand for water is high. Atmospheric warming will cause an increase in potential evapotranspiration and, unless precipitation increases, will result in decrease in soil moisture during summer (Mather and Feddema 1988). With increased CO_2 concentration in the atmosphere, evaporation usually increases (Idso and Brazel, 1984).

There are three necessary prerequisites for the evapotranspiration to occur. These are - a source of water, energy to drive the phase change and a sink for water or moisture deficit in the air above ground. With the changing climate, the increase in temperature is making last two requisites more active.

The surface warming due to enhanced greenhouse effect is likely to alter the evapotranspiration patterns. However, the way in which ET may change due to climatic change is rather complicated. This is because the greenhouse effect is accompanied by changes in cloudiness and hence radiation, windiness and humidity besides temperature; which affect the above three prerequisites. The climatic changes may alter the plant growth, plant cover of the ground and also the deeper or shallower rooting, which, in turn, also affect ET. Furthermore, it is important to note that carbondioxide affects the plant physiological conditions specially the plant growth and the resistance to the passage of water to the atmosphere through plant.

Evapotranspiration changes as a consequence of climatic changes have been studied by different workers. In these studies, ET has been considered as a function of temperature (Revelle and Waggoner, 1983; Gleick, 1987) or a function of the carbondioxide effects on plant resistance (Idso and Brazel, 1984) and using micrometeorological and physiological measurements (Martin et al. 1989).

Aston (1984) used a distributed deterministic process model WATSIM (Aston and Dunin, 1980) to simulate the effects of changed stomatal resistance (the stomatal resistance rises with CO_2 increase) on streamflow of a 5 ha experimental catchment. The evaporation was computed using the combination formulae (Statver and Mc Ilnoy, 1961; Monteith, 1965). The months with small to intermediate yields were relatively more sensitive to CO_2 increase as the evaporation process was limited by the soil moisture.

$$EP = S/(S+\gamma)\ (R-G) + (\rho Cp/ra)\ (T-T_w) \qquad .....(i)$$

and

$$ET = EP/[1+\gamma/(s+\gamma)\ (r_c\ /r_a)] \qquad .....(ii)$$

Where ; EP - potential evaporation,
ET - actual evaporation,
s - slope of the saturation vap. pressure curve
γ - psychrometric constt.
R - net radiation
G - ground heat flux
ρ - air density
C - heat capacity of air at constt. pressure
T & Tw - ambient dry & wet bulb temp.
ra & rc - aerodynamic and canopy resistances respectively

Also Aston simulated a large catchment area (417 sq.km) using a hydrological model SHOLSIM evolved from WATSIM. The major difference between the two was in the formulation of evapotranspiration. In SHOLSIM, ET was expressed as a ratio of class. A pan evaporation and related to the absolute values of soil moisture content :

$$ET/Pan = S\rho\ (\theta - \theta_w) \qquad .....(iii)$$

Where, $S\rho$ is the empirically derived slope of the relationship between pan ratio and moisture content for a given vegetation type, θ and θ_W are the volumetric soil moisture content and moisture content at 15 atm. respectively and Pan is the evaporation from the class A pan evaporimeter. A doubling of resistance in Eq.(ii) resulted in a reduction of ET of around 20-40%, depending on ambient conditions. The present level of water yield of both small and large catchments can significantly increase due to doubling of CO_2 concentrations.

Bultot et.al (1988) evaluated quantitatively the impact of the CO_2 doubling on the annual regime of the effective evapotranspiration and other energy balance components. They used IRMB conceptual daily step model (Bultot and Dupriez, 1976 a, b, 1985) to simulate the daily effective evapotranspiration for a drainage basin in Belgium. Besides daily effective evapotranspiration, the model quantitatively estimated the annual regimes of net terrestrial radiation and net radiation for the 2 x CO case on the basis of a ten year period daily data for the Semois drainage basin.

The compared regimes of the evapotranspiration and of other climate and hydrological variables under the present climatic conditions (scenario 0) and assuming a doubling of the atmospheric CO_2 concentration (scenario 1), as studied by Bultot et.al (1988) are given in Appendix I. The potential evapotranspiration increases in all seasons, as one goes from scenario 0 to scenario 1; the maximum and minimum being during April (0.3 mm d^{-1}) and January (0.06 mm d^{-1}) respectively. However, in relative values, the rise is greatest during winter months, the reason being the smallness of the corresponding present day ETP values. In response to the increased potential evapotranspiration, the effective evapotranspiration also augments, though not in the same ratio. This is because in scenario 1, the rainfall is lowered during the late spring and summer and the water supply from the soil cannot meet fully the evapotranspiration requirements.

Martin et.al (1989) studied the sensitivity of evapotranspiration in a wheat field, a forest and a grassland to changes in climate and direct effects of carbon dioxide. They used the Penman Monteith equation (Monteith, 1965) to estimate the evapotranspiration, which has been successfully used to evaluate the ET from crops and forests by Rosenberg et.al (1983). The P-M approach incorporates micro meteorological and physiological parameters and is best used at local level and with the time scales of the order of a day. It has been found suitable for simulation studies as well (Stewart, 1984). The P-M equation for the latent heat flux, LE, as used by Martin et.al (1989), is expressed as

$$LE = \frac{S\ (Rn + s) + \rho a\ Cp\ (es - e)/ra}{s + \gamma\ (ra+rc)/ra} \qquad \text{........(iv)}$$

Where L is the latent heat of vaporization in J/kg , E the flux of evaporated water in kg m^{-2} s^{-1} , R_n the net radiation in W m^{-2} , S the soil heat flux in W m^{-2} , ρa the density of dry air in kg m^{-3} , ra and rc , the aerodynamic and canopy resistances in sm^{-1} , Cp the specific heat of dry air at constant pressure in J kg^{-1} K^{-1} , es the saturation partial pressure of water vapour at leaf temperature, e the actual vapour pressure in the air above the canopy, both in Pa, and, s and γ are the derivatives of the saturation vapour pressure with respect to temperature and the pyschrometric constt. respectively, both in Pa K^{-1}.

Martin et al (1989) calculated the LE flux using actual weather and plant parameter values as temperature, net radiation, air humidtity, wind speed, leaf area index, characteristic leaf dimension and stomatal resistance. Then, to test the sensitivity of ET to each individual climate and plant factor, each factor was changed one at a time, twice at a time and then in groups. The range of changes in climatic parameters was obtained from Schneider et.al (1989) and for the physiological changes, the values found in Rosenberg et al (1983) were chosen. These changes were; temperature from -10K to + 10K, net radiation from -30 to +30%, absolute humidity from -20 to +20%, wind speed from -20 to +20%, leaf area index from -30 to +30% and stomatal resistance from -60 to +60% . Appendix II gives the simulated effects of climatic change on LE, when various parameters are changed simultaneously. These studies showed that when all the climatic and plant factors are considered, evaporation estimates can differ greatly from those that consider only temperature.

5.0 SOME REGIONAL CLIMATIC CONSEQUENCES ON HYDROLOGY AND WATER RESOURCES

As applied to up-to-date hydrological and water resources problems, it is interesting as well as important to predict regional characteristics of water resources and hydrological regime for the near and remote future due to anthropogenic changes in climate. The results obtained by various research workers for different physiographic regions of the world have been presented in this section.

5.1 USSR (Formerly)

According to the climatological forecasts, if air temperature in winter and summer still rise after 2000, we may expect much more precipitation over the whole territory of USSR, which is quite important for the southern regions. The most unfavourable change in water resources can be expected in the forest-steppe and in the south of the forest zones of the European USSR and west Siberia where, with a considerable increase in air temperature, precipitation does not change or even slightly decrease is likely. Here annual runoff can reach 10-20% of the normal (upto 20-25 mm) Budyko 1988). The winter runoff in the basins of the water deficit zones tends to increase by several times as experienced in case of large vogla basin. Possible annual changes in runoff are shown in Table 5.1.

Table 5.1 : Probable Changes of Seasonal River Runoff in the USSR in Case of Global Warming by 1°C (2000)

River	Drainage area, thou km	Zone	Runoff, mm			
			Year	Winter	Spring	Summer-
Volga at Volgograd	1360	forest	187	22	107	58
		forest-steppe	165	35	94	36
Sosna at Elets	16.3	forest-steppe	144	30	102	12
			129	53	63	13
CHir at Oblivskoje	8.47	steppe	47	3.0	43	1.0
			70	22	45	3.0

Note : Numerator indicates mean long-tern natural conditions; denominator indicates computed values in case of the global warming by 1°C.

The model calculations show that even such insignificant changes in climatic characteristics can lead to a considerable modification of Interannual runoff pattern. The main consequence of such a modification is a drastic increase of winter runoff, due to more intense snowmelt in winter (increasing the amount and intensity of winter thaws) and correspondingly a decrease in the spring runoff. The seasonal runoff changes averaged over a long-term period for the same river basins, the winter runoff for the zone with insufficient moistening (steppe) increases many-fold and rises considerable even for such a vast river basin as that of the Volga River. It is very interesting to note that, as observational data shows, on the rivers of the European USSR since the second half of the 1980s, the winter runoff has tended to increase noticeably, probably owing to developing global climate warming.

While comparing runoff regime for every year obtained in case of observed and computed meteorological characteristics, it is possible to evaluate all expected changes of the hydrological regime within every basin. It appeared that even a very insignificant change of climatic characteristics might lead to a significant transformation of stream flow distribution during a year in the basins located in the zone of water deficit or variable water availability. The maximum effect of transformation is due to a higher intensity of snow-melting in winter. (A greater number of thaws in winter and a higher rate of thaws) and as a result lower spring snowmelt discharge (Budyko 1988).

5.2 North America

Starting in the end of 1970's a number of studies have been performed on the quantitative evaluation of climatic variation effect on hydrological and water resources parameters related to specific or hypothetic basins located under various physiographic conditions.

The scientist from North America used all possible meteorological approaches to evaluate hydrological consequences. For example, regression dependence on annual runoff on air temperature and precipitation was used by Stockton et.al (1979), Revelle et.al (1983) for the west areas of USA and for Colorado basin. The detailed and reliable conclusions on assessment of basin sensitivity to climatic parameter changes have been obtained from the application of deterministic hydrological models for short term periods.

Most of the conclusions drawn from the studies show significant changes (for arid and semi-arid regions, in particular) which may be expected even in case of insignificant climatic characteristic changes, e.g., at the rise of annual air temperature by 1-2° C and precipitation by 10%, it is possible to expect annual runoff decrease in the water deficit areas by 40-70%. As shown by recent climatological studies, these changes of climatic characteristics caused by anthropogenic factors are quite probable in some regions in nearest decades (Shiklomanov 1989).

Gleick (1986, 1987) was one of the first to apply this approach for estimating global warming effects on the seasonal runoff of the Sacramento River (California). As the basis, Gleick accepted the climate change scenarios (monthly air temperature and precipitation) developed with the help of the three most advanced GCM's with 2 x CO_2 in the atmosphere. Simulation of changing hydrological characteristics was carried out by the water-balance basin model built by Gleick with a month as time interval. Simulations by the three GCMs showed increasing winter runoff from 16% to 81% and decreasing summer runoff from 30% to 68%, which can physically be explained by a drastic change (due to rising air temperature) in the snowfall and snowmelt conditions. A similar approach has been used by other authors. In particular, with doubling CO_2 concentration, the Great Lakes Basin runoff has been found to decrease by 12-13% (Sanderson and Wong, 1987) and the water amount of large rivers in the Province of Quebec, Canada, to increase by 7-20% (Singh, 1987).

Most important results obtained from practically all the scenarios are : a continuous decrease of soil moisture content in summer, great decrease of summer discharges and great increase of winter water discharges, transformation of streamflow distribution during a year. For example, higher mean monthly air temperatures by 2° C and lower precipitation by 10% lead to summer runoff decrease by 32% and by 9% - in winter. This change in air temperatures with unchanged precipitation will lead to summer runoff decrease by 22% and to winter runoff increase by 8%. In case of air temperature rise by 4° C, annual streamflow distribution during a year is transformed completely. On the basis of investigations performed, Gleick concluded that the problem of studying anthropogenic climate changes required an assessment of future hydrological basin characteristics, for solution of regional problems on runoff control and water supply, for a development of measures on elimination or reduction of probable negative results was very important and top-urgent for hydrologists and hydraulic engineers. These conclusions may be fully translated to other regions and river basins, especially in the zones of water deficit.

Various conclusions drawn by different researchers to show the following most probable tendencies in the changes of water resources for certain U.S. regions with global warming :

Pacific Northwest : some increase in annual runoff and floods;

California : a considerable increase in winter and decrease in summer runoff with insignificant rise in annual runoff;

Colorado and Rio Grande River Basins, the Great Basin : decreasing runoff;

Great Lakes Basin : decreasing runoff;

Great Plains, northern and southeastern states: uncertain changes in water resources.

The above qualitative inferences obtained by the atmospheric GCMs do not contradict in general the results obtained by Soviet climatologists (Anthropogenic Climatic Changes, 1987) based on paleo-climatic analogs. These data show that with global warming a considerable decrease in general moistening south of 55° N and noticeable increase in precipitation in northward regions of North America are to be expected.

Looking very broadly at the impact of climatic warming on the water resources on Canada in aggregate, the general climate may be somewhat favourable. With temperature rises generally in the 2° C to 4°C range and precipitation generally increasing across the country from 11% to 54%, runoff could be expected to increase in all major regions by 10% to 23% (Ripley 1987).

5.3 North Africa

Winstanley (1973) has come out with the theory that since the late 1920's, the summer rainfall in the Sahel zone of Africa and north-western India has been showing a declining trend, with a corresponding increase in the winter spring precipitation of the Middle East and of regions to the Sahara along the Mediterranean coast. There was a temporary reversal in the 1950's but from 1960's, the summer-monsoon rainfall in the Sahel and Rajasthan (India) is once again at the low point of irregular fluctuation with a decreasing trend, where as the cold season precipitation of the countries around the Mediterranean Sea is at a higher point of an irregular fluctuation with an increasing trend. Linz et al (1990) mentioned that the analysis of annual precipitation data from stations in the Sahel region for the period 1970-85 has revealed this period to be extremely dry; the reason for Sahelian droughts being the decrease in annual precipitation. Ojo (1987), analysing the precipitation trends for 1901-85 for 60 stations of western Africa found that the average precipitation for 1970-79 and 1981-84 were 0.62 and 0.5 of the normal. Mabbutt (1989) mentioned that some indication of the hydrological consequences of rainfall decrease in the semi-arid tropics is given by a reduction in discharges and seasonal flooding in the Niger and Senegal rivers and drastic shrinkage of

Lake Chad after two decades of low rainfalls in Sahelian Africa.

5.4 India

Summer rainfall in the north-western India has been showing a declining trend with increase in winter-spring precipitation trend (Winstanley 1973). One striking point in Winstanley analysis is that he has combined the data of different stations sometimes even stations having totally different regimes. For example, Marrakesh, Tunis, Tripolis, Jerusalem, Beirut, Masul, Shiaz and Jodhpur are tropical, with rains concentrated in summer.

The stir caused by the Winstanley (1973) that India was getting progressively drier, led to several studies ruling out this possibility (Agarwal 1976, Chawdhury and Abhyankar 1976, Legirs and Meher Homji 1976; Mukherjee and Singh 1978). Beijer Institute (1988) described in the literature of scientific studies of greenhouse effect that there will be regional differences in the future climate changes. For arid and semi-arid tropical regions (Indian sub-continent), increases in regional temperature of the order of 0.5° to 4°C is predicted. Though not uniform throughout the zone, increase in precipitation in most parts of the semi-arid tropics is predicted by some models. The possibilities of precipitation decrease in some areas is also indicated. Increased precipitation is expected to be in the form of convective rainfall, implying high intensity but not necessarily increased frequency of rain storms. Thus the seasonally dry tropics would have potentially high rainfall, high runoff and high evaporation, without necessarily having enhanced growing seasons. Some parts of semi-arid tropics already faced large variability in seasonal and annual rainfall and a trend toward decrease in precipitation could be highly sensitive even to a small negative impact of green house warming. A study was conducted by Steven et al (1991) for forest region of Montana to study regional climate change induced hydrologic and forest response. In general, an increase of 10-20% in LAI and 20-30% in evapotranspiration (ET) and photosynthesis were projected. Snowpack duration decreased by 19-69 days, depending on location and growing season length increased proportionally. However, hydrologic outflow, primary fed by snowmelt in this region was projected to decrease by as much as 30% which could virtually dry up rivers and irrigation water in future.

As a consequence of regional climate changes, projected rise in temperature and uncertainity of precipitation may cause decrease in effective yield of major crops (rice and wheat) in India (Sinha 1992). Dr. Meher Homji brought out through his studies that deforestation seems to be responsible for the decreasing trend of rainfall, particularly in Kerala and Orissa. In order to bring out deforestation-linked declining trend of precipitation, the rainfall and number of rainy days of the meteorological stations in the western ghats retaining their forest wealth were compared with those stations having witnessed large scale deforestation. Historical records of Udhagamandalam and Chotanagpur plateau also support the decreasing tendency (Meher-Homji 1989).

5.5 Northern China

The analysis of hydrometeorological data for Northern China shows that the mean air temperature over 1981-1987 became 0.5° C above the normal and precipitation was somewhat lower than the normal (for Beijing by 4%). The studies of natural climate variation for 100 years indicate that warming has begun in China and will continue upto the next century. As for the scales of potential influence on Northern China climate of increasing CO_2 in the atmosphere, estimates are as yet unavailable. At the same time, it is obvious that even with insignificant climate characteristic changes, the hydrologic consequences can be considerable in these regions. Simulations by the Hinangchzang Hydrological model show that in semi-arid regions, with a 10% increase in precipitation and a 4% decrease in evaporation, the runoff will increase by 27%: with increasing precipitation by 10% and evaporation by 4%, the runoff will rise by 18%; provided that these modifications in climatic characteristics take place in semi-arid regions, the runoff changes will make up 30-50% (Chunzhen, 1989).

5.6 Japan

A number of agencies and institutes within Japan have begun to focus on how climate warming would affect the water resources and related environment systems of that country. To date, the studies have emphasised the empirical description and characterisation of effects and problem areas with the aim of identifying how to derive quantitative estimates of likely impacts. To estimate the potential hydrological consequences of the global warming, the long-term series of meteorological observations in different regions of the country have been analysed. In particular, the precipitation and runoff characteristics have been compared over the coldest and the warmest 10-year periods with the mean temperature difference of 0.074° C. Precipitation over the warmest period turned out to increase by 10%, the incidence of heavy rains (more than 300 mm for two days) becoming much more frequent. At the same time, precipitation sums for 60 to 90 days with minimum rains during the warm period have been noticeably smaller than in the cold period (Yamada, 1989). This empirical data analysis makes it possible to assume that with global warming in most regions of Japan, maximum precipitation and river runoff volume are expected to grow somewhat, especially during the periods of rain storms. At the same time in dry seasons the runoff can decrease, thus exacerbating the problems of water supply. Because of the lack of data, it is impossible to estimate quantitatively the corresponding values. The use of GCM output is particularly troublesome in Japan since precipitation is generated by typhoons and convective storms, which are not resolved by the GCMs, as well as by frontal storms, which are resolved by GCMs. Accuarate accounting of water resource impacts would, therefore, need to consider, for example, how typhoon frequency, magnitude and intensity would be affected.

Table 5.2 : Water Resources changes in large regions

Sl. No.	Region	Impact of climate change
1.	Pacific Northwest	some increase in annual runoff and floods
2.	California	increase in winter and decrease in summer runoff with insignificant rise in annual runoff
3.	Colorado and Rio Grande river basins, the great basin	decreasing runoff
4.	Great Lakes basin	decreasing runoff
5.	Great Plains, northern and southeastern States	uncertain changes in water resources
6.	Northern Africa, Sahel, Westelrn Eruasia, USSR, most regions of Australia and New Zealand	increasing runoff
7.	Central European USSR and western Siberia	decreasing trend

5.7 Australia

As a result of increasing concentration of CO_2 and other gases in the atmosphere, significant climatic changes are probable over the next 50 years. In this respect Pittock (1981) has studied the change in mean precipitation in Australia in two consecutive periods of 33 years between 1913-45 and 1946-78. The main changes observed are as follows :

- Decreased winter rainfall in the later period in southwest Australia, western New South Wales, and north-central Queensland. There has been increased winter rainfall in eastern New South Wales.
- Increased spring rainfall in inland New South Wales, with decreased spring rainfall in southwest Western Australia.
- Increased summer rainfall in north-central New South Wales, with small decreases along the south coast of Australia.
- Increased autumn rainfall in western New South Wales, inland central Queensland, and Tasmania, with decreases in a considerable area of inland Western Australia.

Pittock (1988) concluded that, with global climatic change, summer-maximum rainfall regions will intensify and shift further south. This has already happened in central New South Wales where average spring, summer and autumn rainfall has increased by 30-40 per cent since early this century. On the other hand, the winter-maximum rainfall belt is expected to shift further south leading to reduced rainfall especially in the southwest of Western Australia. Observed decreases in this region so far this century are 10-12 per cent. Such trends are expected to continue as the greenhouse effect intensifies, although local impacts may be marked by periodical natural climatic changes such as those due to the El Nino-Southern Oscillation Phenomenon (Pittock 1988).

There is some evidence from climatological studies that the pattern of Australian rainfall changed from the period 1913-45 to the period 1946-73. Rainfall increased in many areas, with the exception of Perth where rainfall decreased. There was a southwards shift in the region of summer-dominated rainfall. Postulated climatic change due to the accrual of greenhouse gases from fossil fuel burning and other anthropogenic sources indicate that these trends will continue.

Climatic change of this nature will have major effects on the groundwater resources of the continent. Effects will be beneficial in the arid and semi-arid zones and in areas where aquifers are under stress due to overdevelopment, such as many of the alluvial aquifers of New South Wales and Queensland. Effects will be detrimental in some other important areas, such as the Perth and Murray Basins. Also, rises in sea level will increase the intrusion of sea water in coastal aquifers and will reduce the sustainable yield of fresh water in such aquifers.

The costs of the negative effects of climatic change, such as the development of new sources of water supply for Perth, management of coastal aquifers affected by sea water intrusion and control of salinity problems in the Murray Basin could be substantial (Fereidoum et al 1991).

6.0 Recommended Actions and Research Needs in Changing Climate

Among the most important impacts of climatic change will be its effect on hydrologic cycle and water management systems and through these, on socio-economic systems. Therefore, there is a need to acquire an adequate understanding of the potential impact of the predicted climate change on availability and reliability of water resources, on water demand, on the incidence of floods and droughts and on the consequences for efficient management and safety of existing and future water-related projects. This will facilitate the planning and implementation of effective counter-measures in the case of deleterious consequences and revised policies in the event of beneficial consequences. Efforts should be directed through both national and international programmes involving comprehensive monitoring, research and policy-review.

As discussed under various sections of this report, most of the researchers have been using General Circulation Models (GCMs) for assessing and predicting changes in the climatic situations and water resources. However, hydrological process are not well described in general circulation models for climate simulation. Particular problems result from special averaging within the large GCM grid-cell size, mostly more than 10,000 sq.km . As a result, fine-scale effects, caused by local variability in topography and land cover, are excluded, contributing to the often poor regional match between GCM results and observations for present day patterns of rainfall and river runoff. This mismatch seriously limits the utility of such models in predicting the behaviour of water cycle under different climate and land use scenarios.

To improve the realism of GCMs in respect of evaluation of hydrological effects of climatic changes, there is a need to incorporate hydrological parameters such as soil moisture, vegetation evapotranspiration etc. in the GCMS.

Despite considerable literature, there is little certainity about how meteorological and hydrological drought will be affected by future climate change. The state of art models are unable to answer the most urgent question. Will climatic change produce more or fewer droughts, but they are good enough to alert us to the real possibility of more frequent severe events. Extreme weather events such as floods, droughts, typhoons, tonadoes and hurricanes may become more frequent and intense. We may have even seen the signs of this. Current global temperatures are the highest in the period of instrumental records, and the four hottest years of the century (1980, 1981, 1983 and 1987) have all occurred in one decade. Also, droughts have been experienced during all these years in Indian subcontinent.

The highest priority from the point of view of drought studies should go to the quantification the land atmosphere interactions so that land management practices can be set in place that avoid desertification.

Though, studies have been carried out on hydrological impacts of climatic changes in different countries, studies in this direction in India have yet to start. Some studies have been initiated at National Institute of Hydrology, Roorkee to examine the sensitivity of evaporation and evapotranspiration to the expected climatic changes for different agroclimatic zones of India.

Keeping in view all the discussions presented in this report on climatic fluctuations observed in the past, the potential impacts of climatic changes that may occur in the future and their implications to water planning and management, the following recommendations can be made :

1. There is an urgent need to establish and/or expand reliable and cost-effective data collection systems for hydrological and hydrometeorological data, especially for rainfall, runoff, evapotranspiration and temperature, in most of the developing countries. A reliable long-term data base is essential not only for efficient planning, management and operation of water resource systems but also to determine in the future, the extent of climatic changes, if any, and how to deal with them effectively.

Data collected should be easily available to all parties requiring that information. This is especially important for international river basins where exchange of data between co-basin countries is essential for optimal water management.

2. There is an urgent need to critically re-examine the existing methodologies used for water planning and management. On the basis of climatic fluctuations observed in many countries and basins during the past 30-70 years, it is becoming increasingly clear that many of the present hydrological techniques used to generate synthetic streamflow for design of water resources projects leave much to be desired. Even when 30 years of continuous hydrological time series data are available, it is currently assumed that they define hydro-climatic averages. Current analyses from many parts of the world indicate that this assumption may not necessarily be accurate. For many water

projects in developing countries, even 30 years of data are aften not available. Under these conditions, elasticity of water projects to deal with unexpected risks from climatic fluctuations could become an important consideration. Accordingly, development of new and more effective methodologies which would enable us to plan, design and operate water projects more efficiently than at present has become an urgent necessity.

3. Increasing attention should be paid to improve the existing monitoring and forecasting methods which could facilitate more effective consideration of climatic fluctuations in water management. Equally, facilities available for such activities in developing countries should be significantly increased. International organizations should make a special effort to assist developing countries to establish effective forecasting centres and also to improve the operational capabilities of existing centres.

4. Special attentiona and support should be given to international river basins and aquifers in terms of their more efficient management due to climatic fluctuations. In this context, authorities in charge of international water bodies may be provided with increasing support to improve their capacity to :

i) monitor and predict patterns of rainfall, runoff, temperature, and evapotranspiration;

ii) plan, manage and operate water projects efficiently in the light of potential climatic fluctuations;

iii) analyse and forecast environmental impacts of climatic fluctuations and steps that can be taken to effectively manage such impacts; and

iv) estimate environmental, social and economic costs due to both natural changes and planned hydraulic interventions.

5. The International Water Resources Association should consider the establishment of a network of researchers studying climatic fluctuations and water resources issues as a Specialty Group, with full support and active collaboration of UNEP and other appropriate international organisations like WMO and FAO. Such a Group could :

i) compile, maintain and disseminate a comprehensive, annotated bibliography on climatic fluctuations and water management;

ii) critically evaluate the present techniques of assessing time series, and develop new and more improved methodologies;

iii) provide a better understanding to identify and integrate the effects of climatic fluctuations and possible future climatic changes;

iv) encourage dissemination of climatic change scenarios derived from GCMs, historical analyses and other methods;

v) examine the need for an international institute on climate and water management, and if considered desirable, explore the possibilities of establishing such an institute.

vi) Increasing the co-operation between climatological and hydrological communities in developing predictions of climate change for individual seasons and for specific regions;

vii) Strengthening capabilities to collect, store and process water-related data, including data related to climate change;

viii) Developing research programmes at national level and contributing to regional and international research projects on the question of climate change, its early detection and its impact on the hydrological regime. These should address the situation in developing as well as developed countries and could involve case studies designed to develop and test specific methodologies for impact assessment;

ix) Assessing the likely socio-economic and environmental impacts of such changes, developing response strategies and funding and implementing these strategies.

6. Training of water resources professionals on how to effectively incorporate climatic fluctuations in planning, management and operation of water resources systems is needed. The training programmes should emphasize practical and

operational aspects of water projects. At present, such effective training programmes do not exist. Universities, training centres and international organizations should work together to develop such training courses.

7. International organizations like the United Nations Environment Programme, FAO, International Irrigation Management Institute, WMO and other appropriate organizations should give more attention on how to effectively incorporate climatic fluctuations in water management. They should also assist selected developing countries to establish new centres for studies on climate and water management.

REFERENCES

1. Anthropogenic Climatic Changes, 1987. Ed. (Budyko M. and Izrael Yu.) L. Gidrometeoizdat, p. 406, The Univ. of Arizona Press, 1990.

2. Aston A.R., 1984. The effect of doubling atmospheric CO_2 on streamflow : A simulation, J. Hydrol., 67, 273-280.

3. Barnett, T.P., 1985. Long term change in precipitation patterns, in detecting the climatic effects of increasing carbon-dioxide, DOE/ER-02335, Dec. 1985.

4. Baumgartner, A and Reichel, E., 1975. The world water balance. Elsevier, Amsterdam, Chan, S.O. and Engleson, P.S.1980. Water balance studies of the Bhar E.L. Ghazal swamp Rep.No.161. Ralph M. Parson Lab., Water Resources Hydrology, MIT Cambridge, M.A.

5. Beijer Institute, 1988. Developing policies for responding to climate change, Mimeo. The International Institute for Energy, Resources and human environment, The Royal Swedish Academy of Sciences, Stockholm.

6. Beran Max. 1989. Drought processes and future. Paper presented in "International symposium on Groundwater Resources and Management in Drought Prone Areas", Nov. 27-Dec.1, New Delhi.

7. Bradley, R.S., H.F. Diaz, J.K. Eischeid, P.D. Jones, P.M. Kelly and C.M. Goodess, 1987. Precipitation fluctuations over Northern Hemisphere land areas since the mid-19th century. Science, 237, 171-175.

8. Budyko, M.I. 1988. Climate of the end of the 20th century. Soviet Meteorology and Hydrology, 10, 5-24. Allerton press translation, pp.1-33.

9. Bultot, F. and G.L. Dupriez, 1976a. Conceptual hydrological model for an average sized catchment area, I. Concepts and relationships, J. Hydrol., 29, 251-272.

10. Bultot, F. and G.L. Dupriez, 1976b. Conceptual hydrological model for an average sized catchments area, II. Estimate of parameters, validity of model, applications, J. Hydrol., 29, 273-292.

11. Bultot, F. and G.L. Dupriez, 1985. Daily effective evapotranspiration from a river basin, in Casebook on operational assessment of areal evaporation, operational hydrology report no.22 (WMO-No.635), 80-105.

12. Bultot, F., G.L. Dupriez and D. Gellens, 1988. Estimated annual regime of energy balance components, evapotranspiration and soil moisture for a drainage basin in the case of a CO_2 doubling, Climatic Change, 12, 39-56.

13. Bultot F. et al. Repercussions of a CO_2 doubling on the water cycle and on the water balance - a case study for Belgium. J. of Hydrology, 1988, 99, N 3-4, p.319-347.

14. Carter, T.R., J.K. Porter and M.L. Parry, 1991. Global warming and crop potential in Europe. Jour. of Global Warming and Environmental Change : Prospective and conditions. Vol. 1 No.4. pp.291.

15. Charney, J.G., 1984. Dynamics of desert and drought in Shahel, Quart. Jour. Roy. Met. Soc., 101, 193-202.

16. Charney, J.G., W. Quirk, S.H. Chow and J. Kornfield, 1977. A comparative study of the effect of albedo change on drought in semi-arid regions, Jour. Atm. Sci., 34, 1366-1385.

17. Charvin, R.M., 1979. Response of NCAR General Circulation Model to changed land surface albedo. Report of JOC study Conference on Climate Models. Performance intercomparison and Sensitivity studies, Vol.1, 563-581.

18. Chaturvedi, G.S., P.K. Agarwal, A.K. Singh and S.K. Sinha 1985. Effect of late sowing on the relative behaviour of mother shoot and tillers in wheat. Indian Jour. Agri. Sci.55, pp.87-98.

19. Chitale, M.A. 1987. Water Management in drought prone areas. Water supply, 5, pp.121-130.

20. Dennis P. Lettenmaier, 1990. Hydrological sensitivities of the Sacramento - San Joaquim River Basin California to Global Warming. Water Resources Research, Vol. 26 No.1, pp.66-86.

21. Diana, M. Liverman and Karen L.O. Brien 1991; Global warming and climate changes. Journal of Global Environmental changes : Human and policy dimension, vol.1, No.5, pp.381-395.

22. Fereidoum Ghassemi, Garry Jacobson and Anthony J. Jakeman, 1991. "Major Australian aquifers : potential climatic change impacts", Water International, Vol.16, No.1, pp.38-44.

23. Gary L. Russell and James R. Miller, 1990. Global river runoff calculated from a global atmospheric general circulation model. Journal of Hydrology, 113 (1990) 241-254.

24. Gleick P.H., 1986. Methods for evaluating the regional hydrologic effects of global climate changes. Journal of Hydrology, 88 : pp.97-116.

25. Gleick P.H. Regional Hydrologic consequences of Increases in Atmospheric CO_2 and other Trace-Gases. Climate change 10 : pp.137-161.

26. Gleick, P.H., 1987. The development and testing of a water balance model for climate impact assessment : modelling the Sacramento Basin, Water Resources Research, 23, 1049-1061.

27. Gregory J. McCabe, Jr. and Mark A. Ayers, 1989. Hydrologic effects of climate change in the Delaware river basin. Water Resources Bulletin American Water Resources Association, vol. 25, No.6, 1231-1442.

28. Idso, S.B. and A.J. Brazel, 1984. Rising atmospheric carbon 30.dioxide concentration may increase streamflow, Nature, 312, 51-53.

29. Linz, H., I. Shiklomanov and K. Mostefa Kara, 1990. Hydrology and water resources, Ch. 4, Draft rept. of WG of IPCC.

30. Mabbutt, J.A., 1989. Impacts of carbondioxide warming on climate and man in the semi-arid tropics, Climatic change, 15, 191-221.

31. Manabe, S. and R.T. Wetherald, 1975. The effects of doubling the CO_2 concentration on the climate of a general circulation model, J. Atmos. Sci., 32, 3-15.

32. Martin P., N.J. Rosenberg and M. S. Mc. Kenney, 1989. Sensitivity of evapotranspiration in a wheat field, a forest and a grassland to changes in climate and direct effects of carbon dioxide, Climatic change, 14, 117-151.

33. Mather, J.R. and J. Feddema, 1988. Hydrologic consequences of Increases in Trace Gases and CO_2 in the atmosphere. In : Effect of changes in strulospheric ozone and global climate, Vol.3-climate change, U.S. Environmental protection Agency, pp.251-271.

34. Meher-Homji, V.M. 1989. Deforestation and probable climatic changes : a review, proceedings of International symposium on Global warming and climate changes, held at New Delhi, Feb.21-23.

35. Mostafa K. Tolba, 1989. A seminar repot : International seminar on climatic fluctuations and water management, Cairo, Egypt, Dec. 11-14.

36. National Academy of Sciences, 1977, climate, climate change and water supply overview and recommendations, Washington D.C. pp.1-23.

37. Jodha, N.S. 1989. Global warming and climate change : Impacts and adaptations in agriculture. Proceedings of International symposium on Global warming and climate change held at New Delhi, Feb. 21-23.

38. Pittock, A.B., 1983, "Recent climatic change in Australia : implications for a CO_2 - warmed earth" climatic change, Vol.5, pp.321-340.

39. Pittock, A.B., 1988, "Actual and anticipated changes in Australia's climate" in : Greenhouse, planning for climate change, E.J. Publishing Co., Leiden, Netherlands. PP.35-51.

40. Revelle, R.R., and P.E. Waggoner, 1983. Effects of a carbon dioxide induced climatic change on water supplies in the western United States, In Changing Climate, National Academy Press, Washington, D.C., 419-432.

41. Rind, D. 1982. The influence of ground moisture conditions in North America on summer climate as modelled in the GISS GCM, Mon. Wea. Rev. 110, 1487-1494.

42. Rind, D., 1984. The influence of vegetation on the hydrologic cycle in a global climate model. Climate processes and climate sensitivity, Geophysical Monograph 29, Maurice Ewing Vol. 5, 73-91.

43. Rind, D., R.Goldbery, J. Hansen, C. Rosenzweig and R. Ruedy, 1989. Potential evapotranspiration and the likelihood of future drought. In press.

44. Sanderson, M. and L. Wong, 1987. Climate changes and Great Lakes water levels. The influence of climate change and climatic variability on the hydrologic regime and water resources, IAHS publ. No.168, 477-487.

45. Schaake, J.S. 1988. From climate to flow American Association for the advancement of the science, climate and water panel report on climatic variability. Climate change and U.S. Water Resources, Chapter II-D.

46. Shiklomanov I.A., Markova O.L.,1987. Problemy Vodoobespechenia perebroski rechnogo stoka v mire (Problems of water availability and water transfers in the world). - Leningrad, Gidrometeoizdat, p. 293.

47. Shiklomanov I.A.,1988. Issledovanie vodnykh resursov sushi itogi, problemy, perspektivy (Studies of land water resources : results, problems and prospects). - Leningrad, Gidrometeoizdat, 170 p.

48. Shiklomanov I.A. 1989. Anthropogenic changes of climate, water resources and water management problems. Conference on climate and water. Helsinki, Finland. Sept. 11-15.

49. Singh, B. 1987. The impact of CO_2 induced climate change on hydro-electric generation potential in the James Bay Territory of Quebec, The influence of climatic variability on the hydrologic regime and water resources, IAHS publ. No.168, 403-418.

50. Sinha, B.P.C. 1989. Ground water in Drought-Review of Indian scene; International symposium on Ground Water Resources Management in Drought Prone Areas, held at New Delhi, Nov.27-Dec.1.

51. Sinha, S.K. 1989. Global warming and food security in developing countries. Proceedings of International Conference on Global warming and climate change, held at New Delhi Feb. 21-23.

52. Stakhiv, E.Z. and H. Lins, 1989. Impact of climate change on U.S. Water resources (with ref. to Great Lakes basin, USA), presented at IPCC workshop at Geneva.

53. Steven, W.R. and K.N. Ramakrishnan 1991,'Regional hydrologic and carbon balance response of forests resulting from potential climate change' climate change, Vol.19, No.4.

54. Stockton C.W., Bogges W.R. 1979. Geohydrological Implication cf Climate Change on Water Resource Development. U/S. Army Coastal Engineering Research Center. Port Belvoir Va.

55. U.S. Environmental protection agency, 1984. Potential climatic impacts of increasing atmospheric CO_2 with emphasis on water availability and hydrology in the United States, EPA 230-04-84-006, USEPA, Washington, D.C. 96 pp.

56. Wolock, D.M., M.A. Ayers, L.E. Hay and G.J. McCabe, 1989. Effect of climate change on watershed runoff, proceedings of National Seminar on Hydraulic Engineering Hy Div/ASCE LA/Aug.14-18, New Orleans.

57. Zhao, Z.C. and W.W. Kellogg, 1988. Sensitivity of soil moisture to doubling of carbon dioxide in climate model experiments : The Asian Monsoon region - Journal of climate, 1, 367-378.

APPENDIX-I

: Climatic and hydrological variables under scenario 0 and scenario 1 (Bultot et al, 1988)

	J	F	M	A	M	J	J	A	S	O	N	D	Year
Potential evapotranspiration (mm d^{-1})													
ETP_0	0.149	0.373	0.805	1.768	2.744	3.130	3.132	2.721	1.881	0.890	0.258	0.167	1.507
ETP_1	0.211	0.551	1.061	2.069	2.950	3.377	3.337	2.997	2.015	0.995	0.359	0.233	1.685
ΔETP	0.062	0.178	0.256	0.301	0.206	0.247	0.204	0.276	0.134	0.105	0.101	0.067	0.178
$\Delta ETP/ETP_0$	42%	48%	32%	17%	8%	8%	7%	10%	7%	12%	39%	40%	12%
Effective evapotranspiration (mm d^{-1})													
ET_0	0.149	0.370	0.793	1.690	2.608	2.778	2.766	2.266	1.611	0.834	0.255	0.167	1.362
ET_1	0.211	0.546	1.042	1.965	2.773	2.936	2.868	2.391	1.655	0.920	0.353	0.233	1.496
ΔET	0.062	0.176	0.249	0.275	0.165	0.158	0.102	0.125	0.044	0.086	0.098	0.066	0.134
$\Delta ET/ET_0$	42%	48%	31%	16%	6%	6%	4%	6%	3%	10%	38%	40%	10%
ET_0/ETP_0	100%	99%	99%	96%	95%	89%	88%	83%	86%	94%	99%	100%	90%
ET_1/ETP_1	100%	99%	98%	95%	94%	87%	86%	80%	82%	92%	98%	100%	89%
Water vapour pressure (hPa)													
e_0	5.96	5.98	6.58	7.46	10.14	12.62	14.09	13.98	11.89	9.55	7.46	6.38	9.36
e_1	7.42	7.60	8.32	9.21	12.19	15.00	16.51	16.18	13.82	11.44	9.05	7.99	11.25
Δe	1.46	1.62	1.74	1.75	2.05	2.38	2.42	2.20	1.93	1.89	1.59	1.61	1.89
$\Delta e/e_0$	24%	27%	26%	23%	20%	19%	17%	16%	16%	20%	21%	25%	20%
Temperature (°C)													
t_0	0.7	1.4	3.4	6.1	10.9	14.0	15.7	15.3	11.8	8.0	3.9	1.6	7.8
t_1	3.8	4.8	6.8	9.2	13.7	16.7	18.2	17.6	14.1	10.7	6.7	4.3	10.6
Δt	3.1	3.4	3.4	3.1	2.8	2.7	2.5	2.3	2.3	2.7	2.8	3.2	2.8
Precipitation (mm d^{-1})													
P_0	3.47	3.42	3.35	2.37	3.07	2.62	2.74	2.12	2.71	2.31	4.77	3.77	3.06
P_1	3.77	3.79	3.67	2.71	3.03	2.53	2.69	2.05	2.71	2.48	5.04	4.05	3.21
ΔP	0.30	0.37	0.32	0.34	-0.04	-0.09	-0.05	-0.07	0.00	0.17	0.27	0.28	0.15
$\Delta P/P_0$	9%	11%	10%	14%	-1%	-3%	-2%	-3%	0%	7%	6%	7%	5%
ET_0/P_0	4.3%	10.8%	23.7%	71.2%	84.9%	106.0%	100.9%	106.9%	59.4%	36.1%	5.3%	4.4%	44.6%
ET_1/P_1	5.6%	14.4%	28.4%	72.5%	91.5%	116.0%	106.6%	116.7%	61.1%	37.1%	7.0%	5.8%	46.7%
Water content of the upper layer of the unsaturated zone (percentage of values at saturation) – Maximum water capacity: $WSX = 23$ mm													
WS_0/WSX	100%	98%	91%	71%	66%	54%	54%	54%	59%	82%	98%	100%	77%
WS_1/WSX	100%	96%	88%	69%	63%	50%	51%	49%	56%	80%	97%	99%	75%
Water content of the lower layer of the unsaturated zone (mm and percentage of values at saturation)													
WIX	194.1	194.1	195.1	198.7	203.6	208.5	211.1	210.0	205.3	201.0	196.8	193.9	201.0
WI_0/WIX	100%	100%	100%	97%	91%	83%	78%	74%	72%	80%	93%	100%	89%
WI_1/WIX	100%	100%	99%	96%	89%	79%	73%	68%	65%	74%	90%	100%	86%

APPENDIX-II

Sensitivity of evapotranspiration to climate change and direct effects of CO_2 in a wheat field, a forest and a grassland (Martin et al, 1989)

	Change in					Wheat		Forest (avg. all days)		Grassland		Notes
Line no.	T (K)	R_n (%)	e (%)	r_s (%)	LAI (%)	LE ($W\ m^{-2}$)	Change (%)	LE ($W\ m^{-2}$)	Change (%)	LE ($W\ m^{-2}$)	Change (%)	
												Climate Change Scenario I
1	3	10	−10	0	0	562	33	350	40	302	29	1) Climate change only
2	3	10	−10	20	0	528	25	321	28	276	18	2) Climate change + stomatal resistance increase
3	3	10	−10	40	0	499	18	298	19	254	9	
4	3	10	−10	60	0	473	12	277	11	235	1	
5	3	10	−10	0	15	589	39	372	49	321	38	3) Climate change + leaf area index increase decrease
6	3	10	−10	0	−15	530	25	324	30	279	20	
7	3	10	−10	20	15	556	31	343	37	295	27	4) Climate change + change in stomatal resistance and leaf area index
8	3	10	−10	20	−15	496	17	297	19	253	9	
9	3	10	−10	40	15	527	24	319	27	273	17	
10	3	10	−10	40	−15	466	10	273	9	232	−1	
11	3	10	−10	60	15	501	18	298	19	254	9	
12	3	10	−10	60	−15	440	4	254	1	214	−8	
												Climate Change Scenario II
13	3	−10	10	0	0	455	7	272		246	6	1) Climate change only
14	3	−10	10	20	0	428	1	250	0	225	−3	2) Climate change + stomatal resistance increase
15	3	−10	10	40	0	404	−5	232	−7	207	−11	
16	3	−10	10	60	0	383	−10	216	−14	192	−18	
17	3	−10	10	0	15	477	13	290	16	262	12	3) Climate change + leaf area index increase/ decrease
18	3	−10	10	0	−15	429	1	253	1	227	−2	
19	3	−10	10	20	15	450	6	267	7	241	3	4) Climate change + change in stomatal resistance and leaf area index
20	3	−10	10	20	−15	401	−5	231	−8	206	−11	
21	3	−10	10	40	15	427	1	248	−1	223	−4	
22	3	−10	10	40	−15	377	−11	213	−15	189	−19	
23	3	−10	10	60	15	406	−4	232	−7	208	−11	
24	3	−10	10	60	−15	356	−16	197	−2	174	−2	

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