WATER RESOURCES IN INDIA AND IMPACT OF CLIMATE CHANGE

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ABSTRACT *There is now clear evidence for an observed change in global surface temperature, rainfall, evaporation and extreme events since the start of 20th century. In recent times, several studies around the globe have shown that climatic change is likely to have a significant impact upon fresh water resources availability. The demand for water has already increased tremendously over the years due to an increasing population, expanding agriculture, rapid industrialization, urbanization and economic development. Simultaneously, unplanned development of surface and groundwater resources, haphazard disposal of municipal and industrial wastes and application of agricultural inputs has led to the problem of water quality deterioration/pollution presenting new challenges on water management and conservation front. Today, in most agro-climatic regions and river basins of India the hydrological cycle is being modified quantitatively and/or qualitatively, by human activities such as changes in cropping pattern, land use pattern, overexploitation of water storage, irrigation and drainage. In view of the above, sustainable management of water and supporting natural environment has gained considerable importance in recent years. An assessment of the availability of water resource in the context of future national requirements taking particular account of the multiplying demands for water and expected impacts of climate change and variability is critical for relevant national and regional long-term development strategies and sustainable development. This paper examines the potential for sustainable development of surface and groundwater resources within the constraints imposed by the possible climate change and hydrologic regimes and suggests some adoptive measures and future research needs in India.*

Key words Water resources availability; climate change impact; projected climate change; water use; river basins.

INTRODUCTION

Different General Climate Models (GCM) linking atmospheric chemistry to complex atmospheric and oceanic processes is used to project climate variables such as temperatures and precipitation. Climate model projection vary widely depending upon assumptions regarding future scenarios and the sensitivity of the climate to change in atmospheric chemistry and how the models incorporate factors such as cloud cover, ocean currents and land surface characteristics. While the wide range of projection from the different models, methodologies and assumptions make it difficult to draw conclusions at river basin and watershed levels, some pattern as to the likely impacts of global warming on water resources, do emerge. IPCC (2001) using the Special Report on Emission Scenarios (SRES) projected an increase in global mean temperature of 1.4-5.8°C, global mean precipitation at regional scales (both increases and decreases) are projected in the range 5- 20% and global mean sea level rise by 0.09-0.88m over the period 1999 to 2100, but with significant regional variations. There is now clear evidence for an observed increase in global average temperatures around the world since the start of the 20th century and there is clear evidence that climatic extreme events i.e. heavy rainfall/snowfall rates have changed during the 20th century (IPCC, 2001). In India, studies by several authors have shown that there is increasing trend in surface temperature (Kothawale and Rupa Kumar, 2005; Mall et al., 2006) and no significant trend in rainfall and decreasing/increasing trends in rainfall (Mall et al., 2006).

A number of studies have been reported in the literature, to assess the impact of climate change scenarios on hydrology of various basins and regions and many others. However, few works have been done on hydrological impacts of possible climate change for an Indian region/basin (Chattopadhyay and Hulme, 1997; Mehrotra, 1999; Gosain et al., 2006; Mall et al., 2006).

Presently, more than 45 % of the average annual rainfall including snowfall in the country is going waste by natural runoff to sea. Artificial recharge/rainwater harvesting schemes are now being implemented in the country to minimize this runoff loss based on present rainfall scenarios over the country. However, for the success of this scheme it is the need of today that we focus on how the possible climate change will affect the intensity, spatial and temporal variability of the rainfall, evaporation rates and temperature in different agro-climatic regions and river basins of India.

Groundwater has been the mainstay for meeting the domestic water needs of more than 80% of rural and 50% of urban population, besides fulfilling the irrigation needs of around 50% of irrigated agriculture. The impact of rainfall variation on the region's groundwater resources is less understood, even though groundwater forms about half of the region's water supply. This is largely due to the complex interactions among land use, aquifer properties, antecedent water table levels and the actual timing and intensity of individual rainfall events. In cases where the aquifer systems are largely full, reductions in rainfall may not have an immediate effect on water tables, but a reduction in rainfall in others below a critical level could eliminate all infiltration beyond the vegetation root zone.

Water resources will come under increasing pressure in Indian subcontinent due to the changing climate. The climate affects the demand for water as well as the supply and quality. Particularly, in arid and semi-arid regions of India any shortfall in water supply multiplied with climate change will enhance competition for water use for a wide range of economic, social and environmental applications. In the future scenarios, larger population will lead to heightened demand for irrigation and perhaps industrialization at the expense of drinking water. Disputes over water resources may well be a significant social consequence in an environment degraded by pollution and stressed by climate change. UN Commission for sustainable Development, Second Session, New York, 1994 noted "As the crisis approaches and as water resources become scarcer, the risk of conflict over them will become greater. After 2025 AD climate change could also make conditions worse if rainfall amounts decrease in the major food producing regions and evaporation rates increase. Urgent and decisive action must begin now if impending water crisis of national proportions later in the 21st century are to be avoided during the next 30 years."

In view of the above, an attempt has been made in this study to give a brief resume of possible impact of climate change on India's surface and groundwater resources.

WATER RESOURCES

Surface Water Resources

India has a large and intricate network of river systems of which the most prominent are the Himalayan river systems draining the major plains of the country. Apart from this, the numerous water bodies present in the subcontinent make it one of the wettest places in the world after South America. The annual precipitation including snowfall, which is the main source of the water in the country, is estimated to be of the order of 4000 km^3. The resources potential of the country, which occurs as natural run off in the rivers is about 1869 km^3 as per the basin wise latest estimates of Central Water Commission, considering both surface and groundwater as one system. Ganga-Brahmaputra-Meghna system is the major contributor to total water resources potential of the country. Its share is about 60 percent in total water resources potential of the various rivers. Based on 2001 census, the per capita freshwater availability of water works out to 1820 m^3 . Due to various constraints of topography, uneven distribution of resource over space and time, it has been estimated that only about 1122 km^3 of total potential of 1869 km^3 can be put to beneficial use, 690 km^3 being due to surface water resources. Again about 40 percent of utilisable surface water resources are presently in Ganga-Brahmaputra-Meghna system. In majority of river basins, present utilisation is significantly high and is in the range of 50% to 95% of utilisable surface resources. But in rivers such as Narmada and Mahanadi percentage utilisation is quite low. The corresponding values for these basins are 23% and 34%, respectively.

Unfortunately, distribution of water resources in space and time is highly uneven. Majority of the runoff occurs in the 3-4 months. Further, Brahmaputra, Barak and Ganga account for as much as 60% of the total flow causing recurring floods. At the same time large areas in Rajasthan, Gujarat, Andhra Pradesh, Karnataka and Tamilnadu get scanty rainfall and face drought like condition. While per capita gross water availability in Brahmaputra and Barak basin is of the order of 14057 M m^3 per annum it is as low as 307 m^3 in the Sabarmati basin and about 579 m^3 in Kutch and Saurastra region (MoWR, 2003).

Average water yield per unit area of the Himalayan rivers is almost double that of south peninsular river system indicating the importance of snow and glacier melt contribution from high mountains. The average intensity of mountain glaciation varies from 3.4% for Indus to 3.2% for Ganges and 1.3% for Brahmaputra. The tributaries of these river systems show maximum intensity of glaciation (2.5 to 10.8%) for Indus followed by Ganges (0.4 to 10%) and Brahmaputra (0.4 to 4%); the average annual and seasonal flows of these systems give a different picture thereby demonstrating that the rainfall contributions are greater in eastern region while the snow and glacier melt contributions are more important in the western and central Himalayan region. Apart from monsoon rains, India has been using the Himalayan Rivers for over a century for its water resource development. In recent decades, the hydrological characteristics of the watersheds in this region seems to have undergone substantial change as a result of extensive land use (e.g., deforestation, agricultural practices and urbanization) leading to more frequent hydrological disasters, enhanced variability in rainfall and runoff, extensive reservoir sedimentation and pollution of lakes etc (Ramakrishnan, 1998). The global warming and its impact on the hydrological cycle and nature of hydrological events have posed an additional threat to this mountainous region of the Indian subcontinent. Extreme precipitation events have geomorphological significance in the Himalayas where they may cause widespread slope failures (Ives and Messerli, 1989). The response of hydrological systems, erosion processes and sedimentation in this region could alter significantly due to climate change.

It is estimated that Himalayan mountains cover surface area of permanent snow and ice in the region is about 97,020 km^2 with 12,930 km^2 volumes. In these mountains, it is estimated that 10 to 20% of the total surface area is covered by glaciers while an additional area ranging from 30 to 40% has seasonal snow cover (Upadhyay, 1995; Bahadur, 1999). These glaciers provide the snow and the glacial-melt waters keep our rivers perennial throughout the year. Bahadur (1999) reported that a very conservative estimate gives at least 500 km^3/yr from snow and ice melt water contributions to Himalayan streams, while another study reports about 515 km^3/yr from the upper mountains. The most useful facet of glacial runoff is the fact that glaciers release more water in a drought year and less water in a flood year, thus ensuring water supply even during the lean years. The snow line and glacier boundaries are sensitive to changes in climatic conditions. Almost 67% of the glaciers in the Himalayan mountain ranges have retreated in the past decade (Ageta and Kadota, 1992; Yamada et al., 1996). The mean equilibrium line altitude at which snow accumulation is equal to snow ablation for glacier is estimated to be about 50-80 m higher relative to the altitude during the first half of the 19^{th} century (Pender, 1995). Available records suggest that Gangotri glacier is retreating about 28 m per year. A warming is likely to increase the melting far more rapidly than the accumulation. Glacial melt is expected to increase under changed climate conditions, which would lead to increased summer flows in some river systems for few decades, followed by a reduction in flow as the glaciers disappear (IPCC, 1998).

Most of the rivers in south peninsular India like the Cauvery, the Narmada and the Mahanadi are fed through groundwater discharges and are supplemented by the monsoon rains. Therefore, these rivers have very limited flow during the non-monsoon period. The importance of these rivers lies not just in the size of their basins but also on the quantity of water they can carry. The flow rate in these rivers is independent of the water source of the river and depends upon the precipitation rate in the region. Therefore, in spite of being smaller, the rivers flowing west have a higher flow rate due to higher precipitation over that region.

Inland water resources of the country are classified as rivers and canals; reservoirs; tanks and ponds; beels, oxbow lakes, derelict water; and brackish water.

Other than rivers and canals, the water bodies cover a total area of about 7 M ha. Of the rivers and canals, Uttar Pradesh occupies the first place with the total length of rivers and canals as 31.2 thousand km, which is about 17% of the total length of rivers and canals in the country. Other states following Uttar Pradesh are Jammu & Kashmir and Madhya Pradesh. Among the remaining forms of the inland water resources, tanks and ponds have maximum area (2.9 M ha) followed by reservoirs (2.1 M ha). More than 77% of area under beels, oxbow, lakes and derelict water lies in the states of Orissa, Uttar Pradesh and Assam. Orissa ranks first as regards the total area of brackish water and is followed by Gujarat, Kerala and West Bengal. The total area of inland water resources is, thus, unevenly distributed over the country with five states namely Orissa, Andhra Pradesh, Gujarat, Karnataka and West Bengal accounting for more than half of the country's inland water bodies.

Most of the area under tanks and ponds lies in Southern States of Andhra Pradesh, Karnataka and Tamil Nadu. These states along with West Bengal, Rajasthan and Uttar Pradesh, account for 62 percent of total area under tanks and ponds in the country. As far as reservoirs are concerned, major states like Andhra Pradesh, Gujarat, Karnataka, Madhya Pradesh, Maharashtra, Orissa, Rajasthan and Uttar Pradesh account for larger portion of area under reservoirs. During lean season, these reservoirs are the key source of water. For example, a large dam in Mettur over Cauvery River has a reservoir with a storage capacity of about 10 km^3.

The existence of promising potentials of freshwater lies in our rivers. However, due to lack of proper management of rivers in India, the country is already on the brink of water stress. The reintroduction and the recent emphasis which is being laid on the traditional ideas of rain water harvesting and augmenting recharging of groundwater using defunct bore wells holds immense potential and will definitely assist in alleviating water stress. But sole reliance on these options may not completely solve the problem of water at the present or in the future as these options too have their drawbacks such as availability of large land areas and also their dependence on precipitation, which is subject to large intraseasonal and interannual fluctuations. Despite environmental and social disturbances caused by big dams, we may not be able to ensure food security and a reliable water supply for the country without implementation of large hydrological projects. The fallout of these projects can be managed, damages may be minimized, and feasibility of such projects entertained through cost benefit analysis including environmental and social costs.

On the average, the area actually affected by floods every year in India is of the order of 10 million hectares of which about half is cropland. Rashtriya Barh Ayog (RBA) constituted by the Government of India in 1976 carried out an extensive analysis to estimate the flood-affected area in the country. RBA in its report has assessed the area liable to floods as 40 million hectares, which is nearly 1/8 of the country's area (Mall et al., 2006)

According to CWC (2002) as many as 99 districts spread over 14 states were identified as drought prone districts in the country. Most of theses drought prone areas are concentrated in the states of Rajasthan, Karnataka, Andhra Pradesh, Maharashtra and Gujarat. Human factors that influence drought include demand of water through population growth and agricultural practices, and modification of land use that directly influences the storage conditions and hydrological response of catchments and thus its vulnerability to drought. As pressures on water resources grow so does vulnerability to meteorological drought (WMO, 2002).

Sinha Ray and She wale (2001) used rainfall data from 1875 to 1998 and give the percentage area of the country affected by moderate and severe drought.

It may be noted that during the complete 124 years period there were three occasions i.e. during the years 1877, 1899 and 1918 when percentage of the country affected by drought was more than 60%. It may be noted that during recent times there has been no occasion when the percentage area of the country affected by drought has been more than 50%. It also confirms the finding of Sen and Sinha Ray (1997), which showed a decreasing trend in the area affected by drought in the country. During the 124 years period, probability of occurrence of drought was found maximum in Rajasthan (25%), Saurashtra & Kutch (23%), followed by Jammu & Kashmir (21%) and Gujarat (21%) region. The drought of 1987 in various parts of the country was of "unaprecedented intensity" resulting in serious crop damages and an alarming scarcity of drinking water. Only 12 of 35 meteorological sub-divisions in the country had received normal rains (Mall et al., 2006). With the decreased rainfall contributing to drought, the water levels in major reservoirs in the country, meant for agricultural irrigation purposes and hydroelectric power, naturally declined.

Groundwater Resources

India is a vast country having diversified geological climatological and topographic set-up, giving rise to divergent groundwater situations in different parts of the country. The prevalent rock formations, ranging in age from Archaean to Recent, which control occurrence and movement of groundwater, are widely varied in composition and structure. Similarly, not too insignificant are the variations of landforms, from the rugged mountainous terrains of the Himalayas, Eastern and Western Ghats to the flat alluvial plains of the river valleys and coastal tracts, and the aeolian deserts of Rajasthan. The rainfall pattern, too, shows similar region-wise variations. The topography and rainfall virtually control runoff and groundwater recharge.

Groundwater Availability and Development Scenarios

The groundwater resources have two components viz., static and dynamic. The static fresh groundwater reserves (i.e., aquifer zones below the zone of groundwater table fluctuation) of the country have been estimated as 10812 billion m^3. The dynamic component is replenished annually, which has been assessed as 432 billion m^3. As per the National Water Policy, development of groundwater resources is to be limited to utilization of the dynamic component groundwater. The present development policy, therefore, forbids utilization of the static reserve to prevent groundwater mining. The total annual replenishable groundwater resource is about 43 million-hectare metres (Mham). After making a provision of 7 Mham for domestic, industrial and other uses, the available groundwater resource for irrigation is 36 Mham, of which the utilisable quantity is 32.6 Mham. The stage of groundwater development for the country as a whole, works out to be 37%. The utilisable irrigation potential has been estimated as 64 Mha based on crop water requirement and availability of cultivable land. Out of this, the potential from natural rainfall recharge is 50.8 Mha and augmentation from irrigation canal systems is 13.2 Mha. Based on crop water requirement and availability of cultivable land, utilizable irrigation potential has been estimated as 64.05 Mha excluding 6.4 Mha kept as reserve for any eventuality. The irrigation potential created till March, 1997 is estimated as 45.73 Mha (CGWB, 2002).

During the past four decades, there has been a phenomenal increase in the growth of groundwater abstraction structures due to implementation of technically viable schemes for development of the resource, backed by liberal funding from institutional finance agencies, improvement in availability of electric power and diesel, good quality seeds, fertilizers, government subsidies, etc. During the period 1951-97, the number of dugwells increased from 3.86 million to 10.50 million, shallow tubewells from 3000 to 6.74 million and public bore/tubewells from negligible to 90,000. Electric pump sets have increased from negligible to 9.34 million and diesel pumps from 66,000 to about 4.59 million (Chadha and Sharma, 2000). There has been steady increase in area irrigated by groundwater from 6.5 Mha in 1951 to 41.99 Mha in 1997. During VIII Plan, 1.71 million dug wells, 1.67 million shallow tubewells and 114,000 deep tubewells have been added (CGWB, 2002).

Growing demands of water in agriculture, industrial and domestic sectors, has brought problems of over-exploitation of the groundwater resource, continuously declining water levels, seawater ingress in coastal areas and groundwater pollution in different parts of the country. The falling groundwater levels in various parts of the country have threatened the sustainability of groundwater resource, as water levels have gone deep beyond the economic lifts of pumping. Central Ground Water Board has established about 15000 network monitoring stations in the country to monitor the water level and its quality. The water level in major parts of the country generally do not show any significant rise/ fall. However, significant decline in the levels of groundwater has been observed in certain pockets of 289 districts in the States of Andhra Pradesh, Assam, Bihar, Chhattishgarh, NCT Delhi, Jharkhand, Gujarat, Haryana, Karnataka, Kerala, Madhya Pradesh, Maharashtra, Orissa, Punjab, Rajasthan, Tamilnadu, Tripura, Uttar Pradesh and West Bengal.

The groundwater in most areas of the country is fresh. Brackish groundwater occurs in the arid zones of Rajasthan, close to coastal tracts in Saurashtra and Kutch, and in some zones in the east coast and certain parts of Punjab, Haryana, Western Uttar Pradesh, etc., which are under extensive surface water irrigation. The fluoride levels in the groundwater are considerably higher than the permissible limit in vast areas of Andhra Pradesh, Haryana and Rajasthan and in some parts of Punjab, Uttar Pradesh, Madhya Pradesh, Karnataka and Tamil Nadu. In the northeastern regions, groundwater with iron content above the desirable limit occurs widely. Pollution due to human and animal wastes and fertilizer application have resulted in high levels of nitrate and potassium in groundwater in some parts of the country. Groundwater contamination in pockets of industrial zones is observed in localised areas. The over-exploitation of the coastal aquifers in the Saurashtra

Kutch regions of Gujarat has resulted in salinisation of coastal aquifers. The excessive groundwater withdrawal near the city of Chennai has led to seawater intrusion into coastal aquifers. Artificial recharge techniques can be utilized in improving the quality of groundwater and to maintain the delicate equilibrium between fresh water and salt water in coastal aquifers (CGWB, 2002).

WATER DEVELOPMENT USE SCENARIOS

At present, available statistics on water demand show that the agriculture sector is the largest consumer of water in India. About 83% of the available water is used for agriculture alone. The quantity of water required for agriculture has increased progressively through the years as more and more area was brought under irrigation. Since 1947, irrigated area in India rose from 22.60 Mha to 80.76 Mha upto June 1997. The contribution of surface and groundwater resources for irrigation has played a significant role in India attaining self-sufficiency in food production during the past 3 decades and is likely to become more critical in future in the context of national food security. According to available estimates, the demand on water in this sector is projected to decrease to about 68% by the year 2050 though agriculture will remain the largest consumer. In order to meet this demand, augmentation of existing water resources by development of additional sources of water or conservation of the existing resources through impounding more water in the existing water bodies and its conjunctive use will be needed (Mall et al., 2006).

OBSERVED CLIMATE CHANGE AND ITS IMPACTS DURING THE PAST CENTURY

Temperature

Hingane et al. (1985) have prepared for the first time, an all India (and regional) mean series of seasonal and annual surface air temperature for long-term trend studies, using data during 1901-82 for a well-distributed network of 73 stations. Their study indicated a significant warming of 0.4^0C/100 years in the mean annual temperatures for the country as a whole. Temperature fluctuation however is not showing increasing trend over the entire country; in northeast and northwest India the temperatures show cooling trends also. While Hingne et al. (1985) have explained this trend because of rise in the maximum temperature; later studies by Sinha Ray et al. (1997) have shown that the trend is partly due to rise in the minimum temperature related to urbanization.

The study of Srivastava et al. (1992) on the decadal trends of maximum and minimum temperature over India using a large number of stations gave the first indications that the diurnal asymmetry of temperature trends over India is quite different from that observed over many other parts of the globe. They found that the maximum temperatures have shown much larger increasing trends than the minimum temperatures, over a major part of the country. Rupa Kumar et al. (1994) analyzed that the increase in the all India mean temperature is largely contributed by the increase in maximum temperatures (0.6^oC/100 yrs) significant at 1% level, with the minimum temperature remaining practically trend less. Consequently, there is a general increase in the diurnal range of temperatures. Pant and Hingne (1988) found significant surface cooling associated with significant rainfall increase in the peripheral regions of Rajasthan desert and proposed the increased area under irrigation as one of the main causal factors. Pant et al. (1999) analyzed the available long term climatic record on rainfall and temperature at some observatories in and around the western Himalayas and observed that during winter season some station show increasing trend (0.5°C/100 year), of which Srinagar, Mussoorie and Mukteswar experience significant increasing trend. During the monsoon season, Srinagar, which is beyond the monsoon regime, shows significant increasing trend, whereas Mussoorie and Dehradun which are at the foothills of Himalaya show significant decreasing trend.

Since 1980s, climatic anomalies on global scale have been monitored closely. Globally speaking, the decade of 1980s was the warmest decade; warming continues into the 1990s (De and Mukhopadhyay, 1998). The year 1995 was characterized by severe heat wave conditions over north India during which 550 people lost their lives. The years 1998 and 1999 saw severe heat wave conditions over India during which the number of deaths was more than that 1995 (De, 2001).

Singh and Sontakke (2002) studied that the annual surface air temperature of the Indo-Gangetic Plain Region (IGPR) showed rising trend (0.53°C/100 yrs, significant at 1% level) during 1875-1958 and decreasing trend (-0.93°C/100 yrs, significant at 5% level) during 1858-1997. They concluded that the post 1958 period cooling of IGPR seems to be due to expansion and intensification of agricultural activities and spreading of irrigation network in the region. Lateral shift in the river courses is an environmental hazard of serious concern in the IGPR.

Recently, Kothawale and Rupakumar (2005) found that, while all India mean annual temperature has shown significant warming trend of 0.05 °C/10 year during the period 1901-2003, the recent period 1971-2003 has seen a relatively accelerated warming of 0.22 °C/10 yr, which is largely due to unprecedented warming during the last decade. The recent accelerated warming over India is manifested equally in day time and night time temperatures.

Rainfall

Monsoon rainfall displays predominant interannual variability being considerably below and above normal over large areas of the Indian subcontinent in several years, leading to widespread droughts and flood situations. Years of large-scale deficient and excess monsoon rainfall are usually identified with the criteria of the all-India monsoon rainfall being below and above 10% of the long-term mean respectively. Most of the studies during the last four decades have clearly pointed out that the monsoon rainfall is trendless and is mainly random in nature over a long period, particularly on all-India scale (Mooley and Parthasarathy, 1984; Thapliyal and Kulshrestha, 1991). However, some workers did report the presence of pockets of significant long-term rainfall changes (Koteswaram and Alvi, 1969; Jagannathan and Parthasaathy, 1973; Raghavendra, 1974). Studies by Rupa Kumar et al. (1992) have shown that areas of north-east and north-west peninsula show widespread significant decreasing trend in the Indian summer monsoon rainfall (-6 to 8% of normal/100 years) while statistically significant increasing trend was noticed along the west coast and over central peninsula (+10 to 12 % of normal/100 years). Later studies by Srivastava et al. (1998) have supported the existence of a definite trend in rainfall over smaller spatial scale.

Recently, Sen and Sinha Ray (1997) have found a decreasing trend in the drought affected areas in India, which are located over northwest India, parts of central peninsula and southern parts of Indian peninsula. The long-term time series of summer monsoon rainfall have no discernible trends, but decadal departures are found above and below the long time averages alternatively for three consecutive decades (Kothyari and Singh, 1996). The western Himalayas get more snowfall than the eastern Himalayas during winter. There is more rainfall in the eastern Himalayas and Nepal than in the western Himalayas during the monsoon season (Kripalani et al., 1996). The seasonal as well as annual scale trend analysis of rainfall does not show any significant increasing or decreasing tendency for last 100 years over the Western Himalayan region (Pant et al., 1999). Stephenson et al. (2001) concluded that observed all India rainfall index contained no significant trend since 1958, and that there is little consensus between various GCM studies concerning the possible trend in South East Asian rainfall.

Singh and Sontakke (2002) studied that the summer monsoon rainfall over western IGPR shows increasing trend (170 mm/100 yrs, significant at 1% level) from 1900; over central IGPR it shows decreasing trend (5 mm/100 yrs, not significant) from 1939; over eastern IGPR decreasing trend (50 mm/100 yrs, not significant) during 1900-1984 while an insignificant increasing trend (480 mm/100 yrs, not significant) during 1984-1999. Broadly it is inferred that there has been a westward shift in rainfall activities over the IGPR. These spatial changes in rainfall activities are attributed to global warming and associated changes in the Indian summer monsoon circulation and the general atmospheric circulation.

Course Change by Rivers

Course change by the rivers is an environmental problem of serious concern in the IGPR. During various time periods in the past, different rivers changed their course a number of times. During the period 1731-1963, the course of the Kosi river (the sorrow of Bihar) has shifted westward by about 125 km, the courses of Ganga, Ghaghara and Son at their confluence have shifted by 35 to 50 km since epic period dating around 1000 BC (Singh, 1971) and that of Indus and its tributaries by 10-30 km in the 1200 years in the same period (Wilhelmy, 1967). Between 2500 BC and 500 AD the course of the Yamuna river shifted westward to join Indus and then east to join Ganga thrice (Raikes, 1968).

Sea Level Rise

Das and Radhakrishnan (1991) reported a rising trend in the sea level at Mumbai during the period 1940-86 and Chennai during the period 1910-33, based on the annual mean of tide gauge observations. Srivastava and Balakrishnan (1993) studied the atmospheric and tide gauge data and confirmed a rise of sea level by 8 cm with a corresponding fall in the pressure during the period 1901-40.

By above studies it is clear that the global warming threat is real and the consequences of the climate change phenomena are many, and alarming. The impact of future climatic change may be felt more severely in developing countries such as India which has an economy largely dependent on agriculture and is already under stress due to current population increase and associated demands for energy, fresh water and food. In spite of the uncertainties about the precise magnitude of climate change and its possible impacts particularly on regional scales, measures must be taken to anticipate, prevent or minimize the causes of climate change and mitigate its adverse effects.

PROJECTIONS OF FUTURE CLIMATE CHANGE

Climate change is no longer a distant scientific prognosis but is becoming a reality.The anthropogenic increases in emissions of greenhouse gases and aerosols in the atmosphere result in a change in the radiative forcing and a rise in the Earth's temperature. The bottom-line conclusion of the Third Assessment Report of the Intergovernmental Panel on Climate Change (IPCC, 2001) is that the average global surface temperature will increase by between 1.4^0C and 3^0C above 1990 levels by the year 2100 for low emission scenarios and between 2.5^0C and 5.8^0C for higher emission scenarios of greenhouse gases (GHG) and aerosols in the atmosphere.

The UKMO GCM model (Bhaskaran et al., 1995) predicts a total precipitation increase of approximately 20% and increase in winter or rabi crop season temperature by 1–4◦C with increased Carbon dioxide (CO_2) concentration; specific humidity increases by 19%, indicating that the increased monsoon rainfall is largely due to increased water content of the atmosphere. The model also predicts a greater number of heavy rainfall days during the summer monsoon or kharif period, and an increased interannual variability. Lonergan (1998) estimates that India's climate could become warmer under conditions of increased atmospheric CO_2. The average temperature change is predicted to be in the range of 2.33°C to 4.78°C with a doubling in CO_2 concentrations.

Lal et al. (2001) estimated that CO_2 level will increase to 397-416 ppm by 2010s from the present CO_2 level of 371 ppm and this would further increase by 605–755 by 2070s. They projected between $1\text{-}1.4^0$C and $2.23\text{-}2.87^0$C area-averaged annual mean warming by 2020 and 2050 respectively. Comparatively, increase in temperature is projected to be more in winter season than in summer.

A large uncertainty is associated with projected winter rainfall than monsoon rainfall in 2050s. Moreover, the standard deviation of future projections of area-averaged monsoon rainfall centered around 2050s is not significantly different relative to the present-day atmosphere implying thereby that the year-to-year variability in mean rainfall during the monsoon season may not significantly change in the future.

More intense rainfall spells are, however, projected over the land regions of the Indian subcontinent in the future thus increasing the probability of extreme rainfall events in a warmer atmosphere. Rupa Kumar and Ashrit (2001) have projected 13% increase in monsoon or kharif season rainfall in India using ECHAM4 model, while HadCM2 suggests reduction in kharif rainfall by 6% in the greenhouse gas simulation. Both GCMs suggest an increase in annual mean temperature by more than 1°C (1.3°C in ECHAM4 and 1.7°C HadCM2). Rupa Kumar et al. (2003) concluded that under future scenarios of increased GHG concentrations indicate marked increase in both rainfall and temperature into the 21st century, particularly becoming conspicuous after the 2040s in India. Over the region south of 25°N latitude (south of cities such as Udaipur, Khajuraho and Varanasi) the maximum temperature will increase by 2-4◦C during 2050s.

In the northern region, the increase in maximum temperature may exceed 4°C. This study also indicates a general increase in minimum temperature up to 4°C all over the country, which may however be more over the southern peninsula, northeast India and some parts of Punjab, Haryana and Bihar.

There is an overall decrease in number of rainy days over a major part of the country. This decrease is more in western and central part (by more than 15 days) while near the foothills of Himalayas (Uttarakhand state) and in northeast India the number of rainy days may increase by 5-10 days. However, increase in GHG may lead to overall increase in the rainy days intensity by 1-4 mm/day except for small areas in the northwest India where the rainfall intensities decrease by 1 mm/day.

Rupa Kumar et al. (2006) projected that warming is monotonously widespread over the country, but there are substantial spatial differences in the projected rainfall changes. Extreme precipitation shows substantial increases over a large area, particularly over the west coast of India and west central India. Extremes in maximum and minimum temperatures are also expected to increase in future, but the night temperatures are increasing faster than the day temperatures.

Table 1 shows the selective reports about projected climate changes over India during later part of 21st century using GCMs and Regional Climate Models (RCMs). Generally, all reports show changing patterns in rainfall and an increase in temperature during different crop season or annual basis.

IMPACTS OF PROJECTED CLIMATE ON WATER RESOURCES

Table 2 shows the selective reports on impact on water resources during next century over India. The enhanced surface warming over the Indian subcontinent by the end of the next century would result in an increase in pre-monsoonal and monsoonal rainfall and no substantial change in winter rainfall over the central plains. This would result in an increase in the monsoonal and annual runoff in the central plains with no substantial change in winter runoff. These studies also indicate an increase in evaporation and soil wetness during the monsoon and on an annual basis (Lal and Chander, 1993).

A case study of Orissa and West Bengal estimates that in the absence of proper protection, 1 m sea level rise would inundate 1700 km^2 of predominantly proper agricultural land (IPCC, 1992). From GCM simulation of climate, Chattopadhyay and Hulme (1997) show an increase in potential evaporation across India that may be largely related to vapor pressure deficit resulting from higher temperature.

Table 1 Selective reports on projected climate change during next century over India.

Region	Temperature	Rainfall	Reference
All India	Increase in winter temperature by 1-4°C with increased CO_2 concentration.	• Precipitation increase of approximately 20% Increase in heavy rainfall days during the summer monsoon period, and an increased inter annual variability	Bhaskaran et al., 1995
All India	Average temperature change is predicted in the range 2.33-4.78°C with a doubling in CO_2 concentration.	Increase in the frequency of heavy rainfall events	Lonergan, 1998
All India	• Annual mean surface temperature rise is projected to range between 3.5°C and 5.5°C by the end of century. • More warming in winter season.	• Increase of about 7 to 10% in annual mean precipitation. • Decline of 5-25% in winter precipitation. • Increase in monsoon precipitation is 10-15%. • Monsoon season, over northwest India, an increase of 30% or more in rainfall by 2050s. • Higher than normal rainfall in western semi-arid regions of India. • Decrease between 10-20% in winter precipitation over central India by 2050s.	Lal et al., 2001
All India	• Over the region south of 25°N (south of cities such as Udaipur, Khajuraho and Varanasi) the maximum temperature will increase by 2-4° C during 2050s. In the northern region, the increase in maximum temperature may exceed 4°C. • A general increase in minimum temperature up to 4°C all over the country.	• Decrease in number of rainy days over a major part of the country. This decrease is more in western and central part (by more than 15 days) while near the foothills of Himalayas (Uttaranchal state) and in northeast India the number of rainy days may increase by 5-10 days. • Overall increase in the rainy days intensity by 1-4 mm/day except for small areas in the northwest India where the rainfall intensities decrease by 1 mm/day.	Rupa Kumar et al., 2003
All India	• Increase in extremes in maximum and minimum temperatures • Night temperatures are increasing faster than the day temperatures.	Increase over large area, especially substantial over west coast and west central India	Rupa Kumar et al., 2006

Table 2 Selective reports on impact on water resources during next century over India.

Region/Location	Impact	Reference
Indian subcontinent	• Increase in monsoonal and annual runoff in the central plains • No substantial change in winter runoff. • Increase in evaporation and soil wetness during the monsoon and on an annual basis.	Lal and Chander, 1993
Orissa and West Bengal	1 m sea level rise would inundate 1700 km^2 of prime agricultural land.	IPCC, 1992
Indian coastline	1 m sea level rise on the Indian coastline is likely to affect a total area of 5763 km^2 and put 7.1 million people at risk.	JNU, 1993
All India	Increases in potential evaporation across India.	Chattopadhyay and Hulme, 1997
Central India	Basin located in a comparatively drier region is more sensitive to climatic changes.	Mehrotra, 1999
Kosi basin	Decrease in runoff by 2-8%.	Sharma et al., 2000 a, b
Southern and Central India	Soil moisture increase marginally by 15-20% in monsoon months.	Lal and Singh, 2001
River basins of India	General reduction in the quantity of the available runoff, increase in Mahanadi and Brahmini basin.	Gosain and Rao, 2006
Damodar basin	Decreased river flow.	Roy et al., 2003
Rajasthan	Increase in ET.	Goyal, 2004

The hydrologic sensitivity of the Kosi Basin to projected land use, and potential climate change scenarios has been analyzed by Sharma et al. (2000 a, b) It was found that runoff increase was higher than precipitation increase in all the potential climate change scenarios related to contemporary temperature. The scenario of contemporary precipitation and a rise in temperature of 4°C caused a decrease in runoff by 2-8% depending upon the areas considered and model used. It is also projected that soil moisture increase marginally by 15-20% over parts of Southern and Central India. This increase is confined to the monsoon months of June through September. During the rest of the year, there is either no change in soil moisture, or a marginal decline possibly due to the increase in temperature leading to enhanced ET (Lal and Singh, 2001).

Gosain et al. (2006) and Gosain and Rao (2003) projected that the quantity of surface runoff due to climate change would vary across the river basins as well as sub basins in India. However, there is general reduction in the quantity of the available runoff. An increase in precipitation in the Mahanadi, Brahmini, Ganga, Godavari and Cauvery is projected under climate change scenario; however, the corresponding total runoff for all these basins does not increase. This may be due to increase in ET because of increased temperature or variation in the distribution of the rainfall. Sabarmati and Luni basin shows drastic decrease in precipitation and consequent decrease of total runoff to the tune of 2/3rd of the prevailing runoff. This may lead to severe drought conditions in future. The analysis has revealed that climate change scenario may deteriorate the condition in terms of severity of droughts and intensity of floods in various parts of the country. There have been few more studies on climate change impacts on Indian water resources (Roy et al., 2003; Chadha, 2003; Tangri, 2003).

Goyal (2004) studied the sensitivity of ET to global warming for arid regions of Rajasthan and projected an increase of 14.8% of total ET demand with increase in temperature, however ET is less sensitive to increase in solar radiation, followed by wind speed in comparison to temperature. Increase in water vapor has a negative impact on ET (-4.3%). He concluded that a marginal increase in ET demand due to global warming would have a larger impact on the resource poor, fragile arid ecosystem of Rajasthan.

Problems in groundwater management in India have potentially huge implications for global warming. The most optimistic assumption suggests that an average drop in groundwater level by one meter would increase India's total carbon emissions by over 1%. More realistic assumption reflecting the area projected to be irrigated by groundwater in 2003, suggests that the increase in carbon emission could be 4.8% for each meter drop in groundwater levels. Chadha (2003) recommended studying the aquifer geometry and establishing the saline fresh interfaces within 20 km of the coastal area, the effect of glaciers melting on the recharge potential of the aquifer in the Ganga basin together with its effects on the transboundary aquifer system particularly of the arid and semi-arid regions.

These studies are still in infancy and a lot more data both in terms of field information is to be generated. This will also facilitate the appropriate validation of the simulation for the present scenarios.

SUMMARY

The current simulation results from GCMs are still considered uncertain. Present GCM ability in predicting the impact of climate change on rainfall are still not promising. In addition, the uncertainty involved in predicting extreme flood and drought events by the models are large. While climate models predict an increase in precipitation by -24 to 15 % over India (Lal et al., 2001), the regional change may be different (Rupakumar et al., 2006). Kripalani et al. (2003) analyzed observed data for the 131-year period (1871-2001) and suggest no clear role of global warming in the variability of monsoon rainfall over and suggest India. Therefore, it is difficult, at this juncture, to convince the water planning and development agencies to incorporate the impact of climate change into their projects and water resources systems. However, given the potential adverse impacts on water resources as a consequence of climate change, it is worthwhile for the authorities to conduct more in-depth studies and analyse to gauge the extent of problems that the country may face. For this, Mehrotra (1999) suggests that more studies are needed on basins in different agro climatic regions of India to assess the sensitivity of the basin response to climate change. Considering the interannual variability of rainfall in India, only assessment of volume may not helpful until temporal and spatial variations of climate change are assessed. Adel (2002) studied man-made climate changes in the Ganges basin and found that a reduction in the Ganges discharge by 60% over 25 years has led to about 50% drop in water availability in surface water resources, drop in groundwater table, and generation of new surface features having different thermal properties.

Agricultural demand, particularly for irrigation water, which is major share of total demand of the country, is considerably more sensitive to climate change. The potential effects, include, a change in field-level climate that may alter the need for and timing of irrigation; increased dryness may leads to increased demands, but demand could be reduced if soil moistures content rises at critical times of the year (IPCC, 2001). Doll and Sibert (2001) concluded global net irrigation requirements would increase relative to the situation without climate change by 3.5 to 5% by 2025, and 6-8% by 2075.

From the above, it can be concluded that the Indian region is highly sensitive to climate change. The elements/sectors currently at risk are likely to be highly vulnerable to climate change and variability and uncertainties exist in dealing with vulnerabilities associated with climate change and variability. It is urgently required to intensify in-depth research work with following objectives:

- Analyze recent experience in climate variability and extreme events, and their impacts on regional water resources and groundwater availability.
- Assess the impacts of projected climate change and variability and associated hydrological events in India.
- How climate changes might affect groundwater aquifers, including quality, recharge rates, and flow dynamics. New studies on these issues are needed.
- Effect on groundwater recharge, which is dependent on individual sustained rainfall events as well as on the changes in land use pattern.
- How sea level rise might affect the coastal groundwater?
- Determine vulnerability of regional water resources to climate change and identifying key risks and prioritizing adaptation responses.
- Evaluate the efficacy of various adaptation strategies or coping mechanisms that may reduce vulnerability of the regional water resources.

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