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Climate Change and Water Resources in India: Impact Assessment and Adaptation Strategies

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1. INTRODUCTION

Climate change and climate variability has received considerable attention from the scientific community and has been the focus of a multitude of scientific investigation over past two decades (e.g., Gleick, 1986; Lettenmaier and Gan, 1990; Arnell, 1992; Xu, 1999; Nijssen et al., 2001; Rosenzweig et al., 2004; Brumbelow and Georgakakos, 2007; Akhtar et al., 2008). The Third and Fourth Assessment Reports of the Intergovernmental Panel on Climate Change (IPCC) have clearly shown that the earth's climate system has demonstrably changed on both global and regional scales since the pre-industrial era. Thus, the earth's climate system is experiencing a warmer phase. Changes in temperature and precipitation under climate variation have serious impacts on hydrologic processes and water resources availability. Improved understanding of climatic causes of hydrological variability is of paramount importance for developing strategies for the sustainable development and management of vital water resources.

Climate is the long-term average of a region's weather events lumped together. Climate change refers to "a change in the state of the climate that can be identified (e.g. using statistical tests) by changes in mean and/or variability of its properties, and that persists for an extended period, typically decades or longer" (IPCC 2007b). It is the change in climate over time whether due to natural variability or as a result of human activity (IPCC, 2007b). Changes in land use pattern and concentration of greenhouse gases (GHGs) in atmosphere are thought to be the two major anthropogenic causes of climate change and variation. Emissions of GHGs (carbon dioxide, methane, chlorofluorocarbons (CFCs) and nitrous oxide) are causing substantial increase in their concentrations in the atmosphere. This increase would enhance the greenhouse effect, resulting in additional warming of the earth's surface. The "*greenhouse effect*" is the rise in temperature that the earth experiences because certain gases (e.g., water vapor, carbon dioxide, nitrous oxide, and methane) in the atmosphere trap energy from the sun. According to the Intergovernmental Panel on Climate Change, increasing amount of carbon dioxide (CO_2) and other greenhouse gases will rise global temperatures causing what is known as "*global warming*". The increase in CO_2 concentration started in the industrial revolution with coal burning and continuing today with increasing fossil fuel consumption. The global atmospheric concentration of carbon dioxide has increased from a pre-industrial value of about 280 ppm to 379 ppm in 2005 (IPCC, 2007a). Similarly, anthropogenic nitrogen fixation has doubled as a result of increased fertilizer use, fossil fuel consumption and fixation by leguminous crops (Walker and Steffen, 1999). The atmospheric concentration of methane is reported to have increased at a rate of 1% per year (Glantz and Krenz, 1992) mainly due to wet-paddy rice

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farming and livestock farming. The global atmospheric concentration of methane has increased from a pre-industrial value of about 715 ppb to 1732 ppb in the early 1990s, and was 1774 ppb in 2005. Similarly, the global atmospheric nitrous oxide concentration increased from a pre-industrial value of about 270 ppb to 319 ppb in 2005 (IPCC, 2007a).

Global climate change induced by increases in greenhouse gas concentrations is likely to increase temperatures, change precipitation patterns and probably raise the frequency of extreme events. According to the Fourth Assessment Report of IPCC, the average global surface temperature is projected to increase by 1.1-2.9 °C for low emission scenarios and 2.4-6.4 °C at high emission scenarios during 2090-2099 relative to 1980-1999 (IPCC, 2007a). Over the same period, the global mean sea level is projected to rise by 18 to 38 cm and 26 to 59 cm for low and high emission scenarios, respectively. The projected sea level rise is extremely alarming because of the effects it will have on low-lying regions of the world. Under the worst case of IPCC modeling scenario, major coastal cities around the world could be substantially inundated and other low-lying areas of the world would also be threatened (IPCC, 2007a). Thus, continuous global warming can be expected to increase the frequency and intensity of weather-related disasters.

One of the most important impacts of future climate changes on society will be changes in regional water availability. Such hydrologic changes will affect nearly every aspect of human well being, from agricultural water productivity and energy use to flood control, municipal and industrial water supply, and fish and wildlife management (Scheraga and Grambsch, 1998; Ragab and Prudhomme, 2002; Gibson et al., 2005; Minville et al., 2008). The potential climatic impacts may have significant ramifications for decision making about water allocation and management that are likely to be made in the coming decades. The tremendous importance of water in both society and nature underscores the necessity of understanding how a change in global climate could affect regional water supplies.

In this chapter, an overview of climate change and climate variability and its impact on water resources in India has been presented, together with the role of simulation modeling in evaluating the impacts of climate change on hydrology and water resources. Finally, a case study dealing with climate change impact assessment on water resources availability in the Brahmani river basin of eastern India has been presented.

2. CLIMATE CHANGE AND CLIMATIC VARIABILITY IN INDIA

India is a land with diverse geographical and climatic endowments. The long-term average annual rainfall for the country as a whole is 116 cm and is highly variable both in space and time. 21% of the area of the country receives less than 750 mm rainfall annually while 15% area of the country receives rainfall in excess of 1500 mm (Kumar et al., 2005). Though the average rainfall is quite adequate, about 75% (88 cm with a standard deviation of ±10) of the long term average rainfall occurs during four months (June to September) of southwest monsoon season. There is considerable intra-seasonal and inter-seasonal variation as well. The mean annual temperature across the country varies from less than 10 ºC in the extreme north to more than 28 ºC in southern parts of the country. The temperature starts to increase over the country from March onwards and reaches a peak in May/June.

Possibility of increase of variability of Asian summer monsoon precipitation has been projected with increase in *Kharif* rainfall and decrease in *Rabi* rainfall in some areas. IPCC (2001) reported that GCMs show high uncertainty in the future projections of winter and summer precipitation over south Asia. The water and agriculture sectors are likely to be most sensitive to climate change-induced impacts in Asia (IPCC, 2001). Available general circulation models (GCMs) suggest that the area-averaged annual mean warming would be about 3 °C in the decade of the 2050s and about 5 °C in the decade of the 2080s over the land regions of Asia as a result of future increases in atmospheric concentration of greenhouse gases. Under the combined influence of greenhouse gas and sulfate aerosols, surface warming would be restricted to about 2.5 °C in the 2050s and about 4 °C in the 2080s (IPCC, 2001).

It has been observed in several studies that there is a continuous increasing trend in mean surface air temperature over decades in most parts of the Indian subcontinent (Hingane et al., 1985; Rupa Kumar and Hingane, 1988; Govind Rao, 1993; Rupa Kumar et al., 1994). Jäger and Ferguson (1991) observed that temperature, precipitation, and humidity might increase by 1-2 ºC, 10% and 5-10%, respectively in Ganga-Brahmaputra Basin. In the above climate change scenarios, high risk of floods in the lower reaches of Ganges and Brahmaputra may further increase (Siedel et al., 2000). Based on the time series analysis of historical temperature data for different seasons over different regions of India, Chattopadhyay and Hulme (1997) reported increasing trend in temperature over most parts of south and central India in all the seasons, and entire India has shown the same trend during the post-monsoon season. The maximum extent of warming in terms of mean temperature is reported in the post-monsoon season in whole of India, except for Gujarat and some parts of west coast. The study also showed that both pan-evaporation and potential evapotranspiration have decreased in all seasons during recent years (1961-1992) in India, and the decrease in evaporation and potential evapotranspiration is strongly associated with increasing relative humidity. An analysis of seasonal and annual surface air temperatures (Pant and Rupa Kumar, 1997) has shown a significant warming trend of 0.57 ºC per hundred years. The monsoon temperatures do not show a significant trend in any major part of the country except for a significant negative trend over northwest India. Also, data analyzed in terms of day-time and night-time temperatures indicated that the warming was predominantly due to an increase in the maximum temperatures, while the minimum temperatures remained practically constant during the past century. Spatially, a significant warming trend has been observed along the west coast, in central India, the interior peninsula and over north-east India, while cooling trend has been observed in north-west India and a pocket in southern India.

Singh and Sontakke (2002) reported that in the Indo-Gangetic Plains (IGP) of India, the annual surface air temperature is having rising trend (0.53 °C/100 years, significant at 1% level) during 1875–1958 and decreasing trend (–0.93 °C/100 years, significant at 5% level) during 1958-1997. The post 1958 period cooling of the IGP seems to be due to expansion and intensification of agricultural activities and spreading of irrigation network in the region. Further, summer monsoon rainfall showed increasing trend (170 mm/100 years) from 1900 over western IGP, decreasing trend (5 mm/100 years) from 1939 over central IGP, and decreasing trend (50 mm/100 years) during 1900-1984 and increasing trend (480 mm/100 years) during 1984-99 over eastern IGP. Lal et al. (1995) presented a climate change scenario for the Indian subcontinent, taking projected emissions of greenhouse gases and sulphate aerosols into account. It predicts an increase in annual mean maximum and minimum surface air temperatures of 0.7 °C and 1.0 °C over land in the 2040s with respect to the 1980s. In another study analysis of the time series data of 125 stations distributed over whole of India, showed increase in annual mean temperature, mean maximum temperature, and mean minimum temperature at the rate of 0.42, 0.92 and 0.09 °C/100 years. The stations located in the southern and western regions showed a rising trend of 1.06 to 0.36 °C/100 years, respectively, whereas the stations located at the northern plains showed a falling trend of 0.38 °C/100 years. The seasonal mean temperature has increased by 0.94 and 1.1 °C/100 years during post-monsoon and winter season, respectively (Arora et al., 2005). Significant warming of northwestern Himalayas with rise in temperature by about 1.6 °C in the last century has been reported (Bhutiyani et al., 2007). Dash et al. (2007) reported an increase in the annual mean and maximum temperatures by about 0.7 and 0.8 °C, respectively over India. Maximum increase in the maximum temperature has been predicted in the west coast (1.2 °C) followed by north east (1.0 °C), western Himalayas (0.9 °C), north central (0.8 °C), north west (0.6 °C), east coast (0.6 °C), and interior peninsula (0.5 °C). Mean atmospheric surface temperature in India has increased by 1.0 and 1.1 °C during winter and post-monsoon months, respectively. This study also indicated small increase in rainfall during winter months of January and February, pre-monsoon months of March-May, and post-monsoon months of October-December. Pal and Al-Tabbaa (2009) reported increasing trend in winter and autumn extreme rainfall (indicating more winter and autumn floods), and decreasing trend in spring seasonal extreme rainfall with increasing frequency of dry days (indicating water scarcity in pre-monsoon period and a delaying monsoon onset) in Kerala. Thus, the studies discussed above confirm an increase in temperature and changes in rainfall pattern over India during the last century.

3. IMPACT OF CLIMATE CHANGE ON WATER RESOURCES IN INDIA: AN OVERVIEW

The UN Comprehensive Assessment of the Freshwater Resources of the World estimated that approximately one third of the world's population was living in countries deemed to be suffering from water stress in 1997 and two-thirds of the world's population would be living in water stressed countries by 2025 (WMO, 1997). Based on the SRES (IPCC **S**pecial **R**eport on **E**mission **S**cenarios) socio-economic scenarios and climate projections made using six climate models driven by SRES emission scenarios, Arnell (2004) observed that climate change increases water resources stress in some parts of the world where runoff decreases, including around the Mediterranean, in parts of Europe, central and southern America, and southern Africa. In other water stressed parts of the world, particularly in southern and eastern Asia, climate change increases runoff. However, this increase tends to appear during wet season and extra water may not be available during dry season.

The per capita surface water availability in India came down from 4944 m^3 in 1955 to 2309 m^3 in 1991 and 1902 m^3 in 2001. It is projected to reduce to 1465 m^3 and 1235 m^3 by the year 2025, and 2050, respectively under high population growth scenarios (Kumar et al., 2005). By 2050, it is projected that all the basins except Brahmaputra will be below water stress zone and most of the basins will become water scarce. The water scarcity situation for various uses such as agriculture, drinking water, domestic and industrial needs may still become worse, if anticipated impact of climate change on hydrology and water resources are taken into account. Since the major source of water in India is through rainfall, any temporal and spatial variations in rainfall have reflective effect on water availability in both irrigated and rainfed areas. There are preliminary reports that the recent trend of decline in yields of rice and wheat in Indo-Gangetic Plains could have been partly due to weather changes (Aggarwal et al., 2004). Changes in climatic conditions will affect demand, supply and water quality. In the regions that are currently sensitive to water stress (arid and semi-arid regions of India), any shortfall in water supply will enhance competition for water use for a wide range of economic, social and environmental applications. In the future, larger population will lead to heightened demand for irrigation and perhaps industrialization at the expense of drinking water. A major concern that has recently emerged globally is the impact of climate change on hydrology and water resources (e.g., Nijssen et al., 2001; Ragab and Prudhomme, 2002; Arnell, 2004) and the adaptation and preparedness strategies to meet these challenges, in case of their occurrences (e.g., Smithers and Smit, 1997; Aggarwal et al., 2004).

Hydrologic modeling of different river basins of India using SWAT (Soil and Water Assessment Tool) in combination with the outputs of the HadRM2 regional climate model for the control (1981-2000) and future/GHG (2041-2060) climate data indicated an increase in the severity of drought and intensity of floods in different parts of the country (MOEF, 2004). River basin of Luni is expected to experience acute water scarce condition; Mahi, Pennar, Sabarmati, Krishna and Tapi are likely to experience constant water scarcity; Ganga, Narmada, and Cauvery are likely to experience seasonal or regular water stressed conditions; and Godavari, Brahmani and Mahanadi are expected to experience water shortage only in few locations. The study revealed that the increase in rainfall due to climate change does not result in an increase in the surface run-off as may be generally predicted. For example, in the case of the Cauvery river basin, an increase of 2.7% has been projected in the rainfall, but the runoff is projected to reduce by about 2% and the evapotranspiration to increase by about 2% (Fig. 1). This may be either due to increase in temperature and/or change in rainfall distribution in time. Similarly, a reduction in rainfall in the Narmada is likely to result in an increase in the runoff and a reduction in the evapotranspiration, which is again contrary to the usual myth (MOEF, 2004). Using scenarios data generated from regional climatic model HadRM2, Roy et al. (2004) predicted reduced water availability due to global warming for the 2050 and 2060 scenario in five subcatchments (Talaiya, Konar, Maithon, Panchet, and Durgapur) of Damodar basin. However, the scenarios for 2041, 2045, and 2055 predicted less severe impacts on water availability due to climate change.

According to Seidel et al. (2000), there is an increased risk of summer flood in the low reaches of the rivers Ganges and Brahmaputra under climate change scenario of temperature increase by +1.5 °C, precipitation increase in summer by 10%, and increase in humidity by 5-10%. In another study on the nine sub-basins of the river Ganga, Mirza (1997) found that the changes in mean annual runoff in the range of 27-116% occurred in the sub-basins at doubled CO_2 and that the runoff was more sensitive to climate change in the drier subbasins than in the wetter subbasins. Sharma et al. (2000) reported a decrease in runoff by 2 to 8% in the Kosi basin depending upon the areas considered and models used under the scenario of contemporary precipitation and a rise in temperature of 4 °C. Mehrotra (1999, 2000) observed that basins belonging to relatively dry climatic region are more sensitive to climate change scenarios. The Kolar (moist sub-humid) and the Sher (dry sub-humid) are comparatively more sensitive to climate change, whereas Damanganga (humid) is least sensitive (Table 1). Sikka and Dhruva Narayana (1988) reported that a temperature increase of 1, 2 and 3 °C alone resulted in the reduction of runoff by 7, 12 and 19%, respectively in the Nilgiris. The simulations made through a water balance study for Bikaner indicated that the moderate scenario of 10% reduction in rainfall coupled with 8%

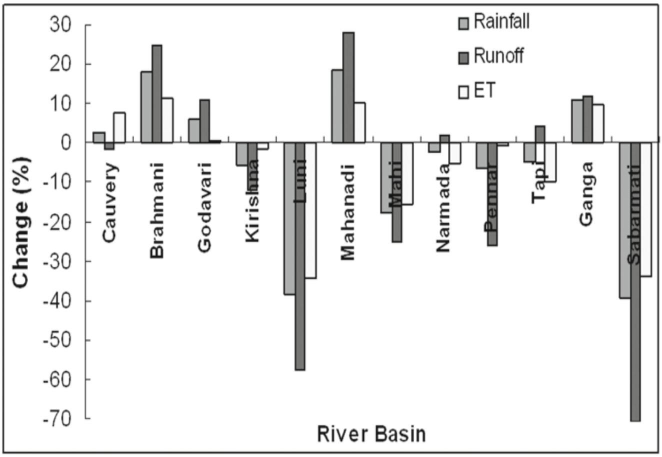

Fig. 1 Changes in water balance under control and GHG climate scenarios in different river basins of India (MOEF, 2004).

increase in PE (i.e., +2 °C temperature) resulted in the 28% reduction of runoff. The percent changes in runoff were relatively higher in arid regions compared to humid Nilgiris, which could be due to the effect of aridity. For the arid zone of Rajasthan, Goyal (2004) reported that even as small as 1% increase in temperature from the base data could result in an increase in evapotranspiration by 15 mm, which means an additional water requirement of 34.275 mcm for Jodhpur district alone and 313.12 mcm for the whole arid zone of Rajasthan. Table 2 summarizes the results of selective studies on climate change impacts on water resources over India during next century.

Table 1. Effect of climate change on different climatic and hydrological variables (Mehrotra, 1999, 2000)

Basin	*Temperature*	*Monsoon rainfall*	*Runoff*	*Evapotranspiration*
Damanganga (humid)	+1.0 °C (monsoon); +3.0 °C (pre-monsoon)	+5%	—	+13% (monsoon); +3% (annual)
Sher (dry sub-humid)	+1.5 °C (monsoon); +3.5 °C (pre-monsoon)	More than 5%	+15%	+30% (monsoon); +50% (annual)
Kolar (moist sub-humid)	+2.0 °C (monsoon); +4.0 °C (pre-monsoon)	+30%	+20%	+40% (monsoon); +55% (annual)
Hemavati	More than 2 °C in all seasons	–15%	–10%	+10% (monsoon); +20% (annual)

Table 2. Climate change impacts on water resources over India during the next century (Mall et al., 2006)

Region/Location	*Impacts*
Indian Subcontinent	Increase in monsoon and annual runoff in the central plains; no substantial change in winter runoff; and increase in evaporation and soil wetness during monsoon and on annual basis.
Orissa and West Bengal	One meter sea-level rise would inundate 1700 km^2 of the prime agricultural land.
Indian Coastline	One meter sea-level rise is likely to affect a total area of 5763 km^2 and put 7.1 million people at risk.
All India	Increase in potential evaporation across India.
Central India	Basin located in a comparatively drier region is more sensitive to climate changes.
Kosi Basin	Decrease in runoff by 2-8%.
Southern and Central India	Soil moisture increases marginally by 15-20% during monsoon months.
Chenab River	Increase in river discharge.
River Basins of India	General reduction in the quantity of available runoff, but increase in Mahanadi and Brahmani basins.
Damodar Basin	Decrease in river flow.
Rajasthan	Increase in evapotranspiration.

4. CLIMATE CHANGE IMPACT ASSESSMENT: ROLE OF HYDROLOGIC MODELING

Hydrologic models provide a framework to conceptualize and investigate the relationship between climate, human activities and water resources. The scientific literature of the past two decades contains a large number of studies dealing with the application of hydrologic models to the assessment of the potential

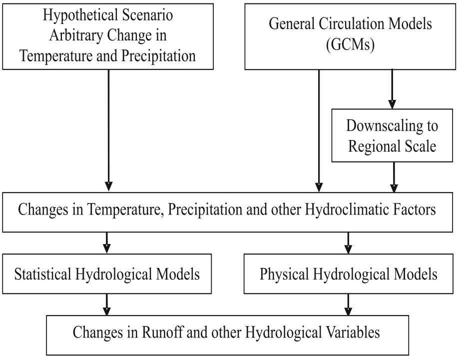

Fig. 2 Methodology for assessing climate change impact on hydrology and water resources (Vicuna and Dracup, 2007).

effects of climate change on a variety of water resource issues. The use of hydrological models in climate change studies can range from the evaluation of annual and seasonal streamflow variation using simple water balance models (Arnell, 1992) to the evaluation of variations in surface and groundwater quantity, quality and timing using complex distributed parameter models that simulate a wide range of water, energy and biogeochemical processes (Running and Nemani, 1991). The two commonly used approaches to study the effects of climate change on hydrology and water resources are: 'online approach' and 'offline approach'. The *online approach* directly uses and interprets the hydrologic outputs from the general circulation models (GCM). The *offline approach* involves employing hydrological models at the basin or watershed scale driven by climatic data obtained either directly from GCM outputs or from hypothetical or GCM-based scenarios of climate change (Fig. 2). This approach, thus, involves (i) development of climate change scenarios, (ii) modeling hydrological processes, and (iii) sensitivity analysis under different climate change scenarios. Scenario-based studies have been commonly undertaken by hydrologists.

4.1 Climate Change Scenario Generation

Climate change scenarios help to identify the sensitivity or vulnerability of the systems to climate change. A scenario is a coherent, internally consistent and plausible description of a possible future state of the world (IPCC, 1994). A climate change scenario is not a prediction of future climate but refers to a representation of the difference between some plausible future climate and the current or control climate. This is an interim step toward constructing a climate scenario. A climate scenario is the combination of the climate change scenario and the description of the current climate as represented by climate observations (IPCC, 2001).

Results from climate change studies depend critically on the climatic change scenarios used in the study. The simple and direct approach of scenario generation is to develop hypothetical scenarios of changes in temperature and precipitation. The second approach is to obtain the changes in temperature and precipitation from the general circulation models. The general circulation models (GCM) are the primary source of data for use in the assessment of climate change impact. GCMs are mathematical representation of many atmosphere, ocean, and land surface processes based on the law of physics. Such models consider a wide range of physical processes that characterize the climate systems and have been used to examine impact of increased greenhouse gas concentrations in global climate (Gates et al., 1990). Most GCMs simulate reasonable average annual and seasonal features of present climate over large geographic areas but are less reliable in simulating smaller spatial and temporal scale features that are relevant to impact assessment studies (Grotch and MacCarcken, 1991). Further, GCMs accuracy decreases from climate related variables (i.e., temperature, humidity, air pressure and wind) to precipitation, evapotranspiration, runoff and soil moisture, which are of key importance to hydrologic regimes (Xu, 1999).

There are number of GCMs available for use in impact assessment. The output from different GCMs can vary significantly for some regions, posing the problem of which GCM to consider. At least two to three GCMs should be used to create regional climate change scenarios (Benioff et al., 1996). Because, it is time consuming and expensive to run and analyze many climate change scenarios, GCMs be selected on how well they represent the current climate in the region of concern. In order to ensure that climate change scenarios are of most use for impact researchers and policy makers, guidelines prepared by the Task Group on Data and Scenario Support for Impact and Climate Assessment (TGICA) (IPCC-TGCIA, 2007) listed following five criteria to aid scenario selection:

(1) *Consistency with global projections:* The scenarios should be consistent with widely accepted global warming projections based on increased concentrations of greenhouse gases. The IPCC Third Assessment Report (IPCC, 2001) estimated 1.4 °C to 5.8 °C rise in temperature by 2100 compared with 1990.
(2) *Physical plausibility:* Scenarios should not violate the basic laws of physics, which means that not only should the changes in one region be physically consistent with those in another region and globally, but that changes in the different climate variables should also be physically consistent. For example, increase in precipitation should be correlated with increase in cloudiness.
(3) *Applicability in impact assessments:* Scenarios should describe changes in a sufficient number of climate variables on a spatial and temporal scale for impact assessment.
(4) *Representativeness:* Scenarios should be representative of the potential range of future regional climate change in order for a realistic range of possible impacts to be estimated.
(5) *Accessibility:* Scenarios should be straightforward to obtain, interpret and apply in impacts assessments.

The raw outputs from GCM simulations are inadequate for assessing hydrologic impacts of climate change at regional scale. This is because the spatial resolution of GCM grids is too coarse to resolve important catchment scale processes, and the hydrometeorological output produced by the GCMs is unreliable for individual grid points (Hostetler, 1994). A number of different methods exist to construct climate change scenarios, including techniques utilising arbitrary, analogue and global climate model (GCM) information. Synthetic scenarios (also known as 'arbitrary' or 'incremental' scenarios) are the simplest climate change scenarios to construct and apply. Their main use is in sensitivity analyses, i.e., in the determination of the response of a particular 'exposure unit' (e.g., crop yield, stream flow) to a range of climatic variations. A synthetic scenario is constructed by simply perturbing a historical record for a particular climate variable by an arbitrary amount (e.g., by increasing precipitation by 10%). In contrast to synthetic scenarios, analogue scenarios make use of existing climate information either at the site in question (temporal analogues, from paleoclimatic or instrumental information), or from another location which currently experiences a climate anticipated to resemble the future climate of the site under study (spatial analogues).

The GCM largely defines changes in mean monthly climates. Constructing scenarios from GCMs output which are at the same spatial resolution as the GCM is a relatively simple task, but construction of scenarios at finer resolutions which involves spatial and temporal downscaling is more problematic. A common method used in impact studies, known as delta change method, is to estimate average annual changes in precipitation and temperature for a region using one or more GCMs output and then apply these estimates to adjust historic time series of precipitation and temperature. In this procedure adjustment is made by adding temperature change (ΔT) to historic temperature series and by multiplying by percentage change in precipitation ($1+\Delta P/100$) to precipitation series. Hypothetical scenarios using personal estimates or historical measurements of changes, instead of GCMs output, can also be generated using this method. Applying the delta change method assumes that GCMs simulate relative changes more reliably rather than absolute values. This approach for generation of climate change scenario account for changes in the mean historic time series, but do not account for changes in variance. By varying the magnitude of precipitation and temperature changes on monthly basis, changes in variance have also been implemented in hydrologic assessments (Gleick, 1987; Arnell, 1992).

To circumvent the problems stated above, tools for generating the high-resolution meteorological inputs required for modeling ecohydrological processes are needed (Bass, 1996). Downscaling is a set of techniques that relate local and regional scale climate variables to large scale atmospheric forcing (Hewitson and Crane, 1996). The simplest approach to downscale from global climate model scale to finer scale involves interpolation of GCM outputs (changes in temperature and precipitation) from nearest grid boxes using some form of interpolation procedure such as inverse distance interpolation (Brumbelow and Georgakakos, 2007; Notter et al. 2007). Temporal downscaling follows spatial downscaling to convert monthly parameter values to the daily values needed by most of the hydrologic models using different stochastic weather generates such as WGEN (Rechardson, 1981), and LARS-WG (Semenov and Barrow 1997). Using stochastic weather generator, the changes in both climatic means and variability estimated by the GCM can be applied to parameters derived by the weather generator to produce multiple-year change scenarios at the daily time scale. The advantage of using a stochastic weather generator is that a number of different daily time series representing the scenario can be generated by using a different random number to control the stochastic component of the model. Hence, these time series all have the same statistical characteristics, but they vary on a day-to-day basis.

Other downscaling approaches include 'dynamic downscaling', and 'statistical downscaling'. Dynamic downscaling involves nesting of a higher resolution regional climate model (RCM) within a coarse resolution GCM (Giorgi and Mearns, 1999). Dynamic downscaling have been attempted with three approaches (Rummukainen, 1997): (a) running a regional limited area model with coarse GCM data as geographical or spectral boundary conditions (also known as 'one-way nesting'); (b) performing global scale experiments with high resolution atmospheric general circulation models (AGCM) with coarse GCM data as initial boundary conditions; and (c) use of variable resolution global model with highest resolution over the area of interest. The main advantage of RCMs is that they can resolve smaller scale atmospheric features such as orographic precipitation better than host GCMs. The limitation of the dynamic downscaling is that RCMs are computationally as demanding as GCMs. These models still cannot meet the needs of spatially explicit models of ecosystems or hydrological systems, and need to downscale the results from such models to individual sites or localities for impact assessment (Wilby and Wigley, 1997).

The *statistical downscaling* is based on developing empirical relationship between two scales using observed climate data and applies these relationships to simulated coarse scale climate data (Arnell et al., 2003). The assumption of these methods is that the statistical relationship between the large-scale and the local-scale features remains the same even under a changing climate. Empirical methods can generate a large number of realizations; it is therefore possible to assess the uncertainty of the prediction. Further local details, which cannot be examined by the dynamical models, can be considered in these models. Statistical downscaling methods can be classified according to the techniques used (Wilby and Wigley, 1997) or according to the chosen predictor variables (Rummukainen, 1997). Wilby and Wigley (1997) described three categories of statistical downscaling techniques, namely: regression methods; weather pattern-based approaches; and stochastic weather generator. Rummukainen (1997) has classified the statistical downscaling methods as follows:

(1) *Downscaling with surface variables:* This involves the establishment of empirical statistical relationships between large-scale averages of surface variables and local-scale surface variables (e.g., Kim et al., 1984; Wilks, 1989). To develop the relationships, large-scale averages

constructed from local time series are used. In application, the same local-scale surface variables will be the predictands.

(2) *The perfect prog(nosis) (PP) method:*. This involves the development of statistical relationships between large-scale free tropospheric variables and local surface variables. In this method, both the free atmospheric data and the surface data are from observations.

(3) *The model output statistics (MOS) method:* This is similar to the PP method, except that the free atmospheric variables, which are used to develop the statistical relationships, are taken from GCM output.

Wilby et al. (1998) compared six downscaling techniques, namely, weather generator technique (WGEN and SPEL models), two variants of artificial neural network (ANN1 and ANN2) and models based on airflow indices (B-Circ and C-Circ). Comparisons were made using standard set of observed and GCM-derived (i.e., HadCM2) predictor variables and by using standard suite of diagnostic statistics. The weather generator technique yielded the smallest difference between the observed and simulated precipitation, while ANN models performed poorly. In an average sense, changes in diagnostics derived directly from the GCM are generally larger in magnitude than those obtained from area-average statistical downscaling models. The study demonstrated that there are significant differences in the level of skill among the statistical downscaling methods. Wood et al. (2004) evaluated six approaches for downscaling climatic model outputs for use in hydrologic simulations. The six approaches considered for evaluation were: linear interpolation (LI), spatial disaggregation (SD), and bias correction and spatial disaggregation (BCSD) — each applied to both Parallel Climate Model (PCM) output directly, and after dynamical downscaling via a Regional Climatic Model (RCM at 0.5° spatial resolution), for downscaling the climate models output to 0.125° spatial resolution of the hydrologic model. BCSD method was found to reproduce main features of the hydrometeorology from the retrospective climatic simulation, when applied to both PCM and RCM outputs. LI produced better results using RCM output than PCM output, but both methods (i.e, PCM-LI and RCM-LI) lead to an unacceptably biased hydrologic simulation. SD of PCM output produced results similar to those achieved with RCM interpolated results. However, neither PCM nor RCM output was useful for hydrologic simulation purpose without a bias correction step. For the future climate scenarios, only BCSD method (using either RCM or PCM) was able to produce hydrologically plausible results. Further, with BCSD method, the RCM-derived hydrology was found to be more sensitive to climatic changes as compared to PCM-derived hydrology.

4.2 Hydrologic Model Selection

Hydrologic simulation models are often used together with climate scenarios generated from general circulation models to evaluate the impact of climate change on hydrology and water resources. The watershed or regional hydrologic models for assessing impacts of climate change have several attractive characteristics. The different features of regional hydrological models can be summarized as (Xu, 1999):

- A number of hydrologic models are available that are applicable to different climatic/ physiographic conditions at various spatial scales and are capable of representing dominant processes.
- These models can be tailored to fit the characteristics of the available data.
- Regional hydrologic models are considerably easier to manipulate than GCMs.
- They can be used to evaluate the sensitivity of a watershed to both hypothetical changes in climate and the changes predicted by GCMs.

The choice of a particular hydrological model depends on many factors. In general, model should be sufficiently detailed to capture the dominant processes and natural variability, but not unnecessarily refined that computation time is wasted or data availability is limited. For assessing water resources management on regional scale, monthly rainfall-runoff/water balance models have been found useful for identifying consequences in changes in precipitation, temperature and other climatic variables (Gleick, 1986; Mimikou et al., 1991; Arnell, 1992; Xu and Singh, 1998). The conceptual lumped parameter models have been widely used for detailed assessment of surface flows. The Sacramento Soil Moisture Accounting Model, a lumped parameter model, has been widely used by many researchers (Nemec and Schaake, 1982; Gleick, 1987; Lettenmaier and Gan, 1990; Nash and Gleick, 1991) for assessing the impact of climate change. For simulating the spatial patterns of hydrological response within a basin, process based distributed parameter models have been found useful (Beven, 1989; Bathurst and O'Connell, 1992). According to Larson et al. (1982), averaging a certain parameter 'averages' (implicitly) the process being represented. Because of the distributed nature of the climatic inputs and watershed parameters, distributed parameter hydrologic models are more suitable for studying the effect of changes in climate, land use and vegetation on the watershed hydrology (Sikka, 1993). The partitioning of a watershed/basin into smaller homogeneous units in terms of a certain combination of soils, land use, elevation, slope, and aspect is one of the prerequisites for the application of distributed hydrologic models. Spatial variability in the basin characteristics in most distributed models is often captured by partitioning a watershed/basin into smaller homogeneous units in terms of a certain combination of soils, land use, elevation, slope, and aspect. These small sub-basin elements are called *Hydrologic Response Units* (HRUs) (Leavesley and Stannard, 1990) or *Representative Elemental Areas* (REAs) (Wood et al., 1988), or *Grouped Response Unit* (GRU) in a regular grid system (Kouwen et al., 1993). Hydrological modeling at the basin scale using distributed hydrological models requires large input data to describe the spatial variability of watershed characteristics. Manual collection of input data for such models is often difficult and tedious due to level of aggregation and the nature of spatial distribution. GIS has been proven to be an excellent tool to aggregate and organize input data for distributed parameter hydrologic models (Srinivasan and Arnold, 1994; Rosenthal et al., 1995). Passcheir (1996) compared 5 "event" (single runoff event) models and 10 continuous hydrological models for rainfall-runoff modeling of the Rhine and Meuse basin for land use impact modeling, climate change impact modeling, real-time flood forecasting and physically based flood frequency analysis. Four continuous models, namely, Precipitation Runoff Modeling System (PRMS), SACRAMENTO, HBV and SWMM and one event model (HEC-1) were evaluated as the best ones. The HEC-1 and HBV models were found to be the most appropriate for flood frequency analysis, the HBV and SLURP models for climate change impacts on peak discharges, and the PRMS and SACRAMENTO models for assessment of climate change impact on discharge regimes.

Table 3 summarizes the hydrologic models, climate change scenarios and downscaling method used in the selected studies for assessing the impact of climate change on hydrology and water resources. It is apparent from this table that hypothetical scenarios were used in the earliest studies and even in some recent studies because of its simplicity in representing a wide range of alternative scenarios. One major limitation in using GCMs output is its spatial and temporal resolution which does not match with the resolution needed for the hydrologic models. Though several downscaling methods have been developed to downscale GCMs output, the delta change (perturbation) method of modifying the historical time is the preferred method due to its simplicity and limited studies have attempted to use more complex statistical and dynamical downscaling methods. As there is a considerable uncertainty in the GCM simulation of future climate, many studies attempted to use various GCMs output to bracket the plausible changes. Though the application of watershed models ranges from simple regression models to distributed hydrological models, conceptual rainfall-runoff (semi-distributed/distributed) models have been used in most of the studies.

Table 3. Summary of selected studies on climate change impact assessment on hydrology and water resources

Authors	*Climate change scenario*	*Downscaling technique*	*Hydrologic models*	*Application area*
Akhtar et al. (2008)	PRECIS RCM	No downscaling	HBV model	Hunza, Gilgit, and Astore river basins of Hindukush-Karakoram-Himalaya region
Minville et al. (2008)	HadCM3, ECHAM4, CSIRO, CCSR/NIES and CGCM3	No downscaling (changed factor approach)	Lumped parameter conceptual rainfall-runoff model HSAMI	Chute-du-Diable watershed, Quebec, Canada
Jiang et al. (2007)	Hypothetical	NA	Monthly water balance models (Thornthwaite-Mather, Vrije University Brussel, Xinanjiang, Guo, Schaake, and WatBal)	Dongjiang basin, south China
Lenderink et al. (2007)	HadRM3H	No downscaling	Spatially distributed water balance model RhineFlow	River Rhine
Notter et al. (2007)	ECHAM4	GCM outputs are interpolated using inverse distance interpolation	Semi-distributed grid-based water balance model (NRM3 Streamflow model)	Upper Ewaso Ng'iro basin, Mt. Kenya
Andersson et al. (2006)	HadCM3, CCSR/NIES, CCCma-CGCM2 and GFDL-R30	No downscaling	Pitman hydrological model	Okavango River basin, Africa
Charlton et al. (2006)	HadCM3	Statistical downscaling	HYSIM	Ireland
Toth et al. (2006)	CGCM, CSIRO, ECHAM, GFDL, HadCM2, NCAR and CCSR	No downscaling	Distributed hydrological model (WATFLOOD)	Peace and Athabasca catchment
Booij (2005)	Three GCMs (CGCM1, HadCM3, CSIRO9) and two RCMs (HadRM2, HIRHAM4)	Stochastic precipitation model generated synthetic series	HBV model (HBV96)	Meuse basin
Dibike and Coulibaly (2005)	CGCM1	Statistical downscaling using SDSM and stochastic weather generator LARSWG	HBV-96 (Semi-distributed conceptual model) and CEQUEAU (distributed hydrological model)	Chute-du-Diable sub-basin of Saguenay watershed in northern Quebec, Canada

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Authors	*Climate change scenario*	*Downscaling technique*	*Hydrologic models*	*Application area*
Wurbs et al. (2005)	CCCMA	No downscaling	Soil and Water Assessment Tool (SWAT)	Brazos River basin, USA
Brekke et al. (2004)	HadCM2 and PCM	Statistical downscaling	Sacramento Soil Moisture Accounting Model (SAC-SMA)	San Joaquin River basin, California, USA
Ministry of Environment and Forest (2004)	HadRM2	No downscaling	Soil and Water Assessment Tool (SWAT)	Different river basins of India
Rosenzweig et al. (2004)	GCM of GFDL, GISS, MPI, CCC (CGCM2) and HC (HadCM2)	No downscaling	WATBAL, CERES-Maize, SOYGRO, CROPWAT and WEAP	Argentina, Brazil, China, Hungary, Romania and the US
Roy et al. (2004)	HadRM2	No downscaling	Hydrologic Engineering Center's Hydrologic Modeling Systems (HEC-HMS)	Damodar basin (Talaiya, Konar, Maithon, Panchet, and Durgapur sub-catchments), India
Miller et al. (2003)	HadCM2, PCM and hypothetical scenarios	Statistical downscaling	Sacramento Soil Moisture Accounting Model (SAC-SMA)	Smith, Sacramento, Feather, American, Merced and Kings basins of California, USA
Mirza et al. (2003)	CSIRO9, UKTR, GFDL and LLNL	No downscaling	Statistical regression model and MIKE11-GIS hydrodynamic model	Ganges, Brahmaputra, and Meghna (GBM) rivers in Bangladesh
Burlando and Rosso (2002)	HadCM2GHG and HadCM2SUL	Stochastic downscaling	Precipitation-Runoff Modeling System (PRMS)	Arno River basin, Central Italy
Evans and Schreider (2002)	CSIRO9	Stochastic weather generator	Conceptual rainfall-runoff model (CMD-IHACRES)	Major tributaries of Swan River, Perth, Western Australia
Menzel and Burger (2002)	ECHAM4/OPYC3	Expanded downscaling (EDS) method	HBV-D (semi-distributed conceptual rainfall-runoff model)	Mulde catchment, Southern Elbe, Germany
Pilling and Jones (2002)	HadCM2	Statistical downscaling	Lumped runoff simulation model (HYSIM)	Upper Wye Experimental catchment, mid-Wales, U.K.
Prudhomme et al. (2002)	HadCM2	No downscaling	Semi-distributed rainfall-runoff model CLASSIC (Climate and landuse scenario simulation catchment)	Severn at Haw Bridge, Wales, Western England
Fontaine et al. (2001)	Hypothetical	NA	SWAT	Spring Creek basin, USA

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Limaye et al. (2001)	HadCM2	Interpolated using VEMAP	SWAT	Dale Hollow Watershed, Southeastern United States
Mohseni and Stefan (2001)	GISS and CCC	No downscaling	Deterministic monthly runoff model (MINRUN96)	Baptism and Little Washita River of North-central and South-central US
Nijssen et al. (2001)	HCCPR-CM2, HCCPR-CM3, MPI-ECHAM4 and DOE-PCM3	No downscaling	Variable infiltration capacity (VIC) macroscale hydrological model (MHM)	Nine large continental river basins (Amazon, Amur, Mackenzie, Mekong, Mississippi, Severnaya Dvina, Xi, Yellow, and Yenisei)
Stone et al. (2001)	CSIRO GCM	Regional Climate Model (RegCM) nested within CSIRO GCM	SWAT	Missouri River basin, USA
Tung (2001)	CGCM, GFDL and GISS	Weather generation model	Generalized watershed loading function (GWLF) model	Tsengwen Creek watershed, Taiwan
Muller-Wohlfeil et al. (2000)	ECHAM4/OPYC3	Expanded downscaling (EDS)	Distributed hydrological model (ARC/EGMO)	Upper Stör basin, Germany
Stonefelt et al. (2000)	Hypothetical	NA	SWAT	Upper Wind River basin, northwestern Wyoming
Hamlet and Lettenmaier (1999)	CGCM1, GFDL-CGCM, HadCM2 and ECHAM4	No downscaling	Variable Infiltration Capacity (VIC) Hydrology Model, Columbia Simulation (ColSim)	Columbia River basin
Jose and Cruz (1999)	CCCM, UKMO, GFDL and Hypothetical	No downscaling	Lumped conceptual model (WATBAL)	Angat and Lake Lanao reservoirs, Philippines
Mehrotra (1999)	Hypothetical	NA	Conceptual rainfall-runoff model	Damanaganga, Sher, and Kolar sub-basins of central India
Yates and Strzepek (1998)	GFDL (steady and transient state), GISS, UKMO, MPI and CCC	GCM outputs are interpolated using IDRISI	Monthly water balance model (WBNILE)	Nile basin
McCabe and Hay (1995)	Hypothetical	NA	Precipitation-Runoff Modeling System (PRMS)	East River basin, Colorado, USA
Duell (1994)	Hypothetical	NA	Regression model	American, Carson and Truckee River basins, USA
Sikka (1993)	Hypothetical	NA	Distributed Climate Vegetation Hydrologic Model (CVHM) based on Precipitation Runoff Modeling Systems (PRMS)	Causey watershed in the Weber basin, USA
Wolock et al. (1993)	Hypothetical	NA	Modified Thornthwaite water balance model	Delaware River basin, USA
Nash and Gleick (1991)	Hypothetical and scenarios from GISS, GFDL and UKMO GCM	No downscaling	Conceptual model of NWSRFS	Upper Colorado River basin, USA

Note: NA = Not Applicable.

5. HYDROLOGICAL MODELING FOR CLIMATE CHANGE IMPACT ASSESSMENT IN THE BRAHMANI RIVER BASIN: A CASE STUDY

This section presents a case study for assessing water resources availability in the Brahmani river basin under HadCM3 and PRECIS (Providing REgional Climates for Impact Studies) generated climate scenarios.

5.1 Study Area Description

Brahmani river basin (longitude: 83°52′55″-87°00′38″E, latitude: 20°30′10″-23°36′42″N) is located in the eastern part of India and spreads over the states of Orissa, Jharkhand and Chattisgarh. It has a total catchment area of 39,313.50 km^2 and is composed of four distinct sub-basins, namely Tilga, Jaraikela, Gomali and Jenapur (Fig. 3). The basin has a sub-humid tropical climate with an average annual rainfall of 1305 mm, most of which is concentrated during southwest monsoon season. The Brahmani river rises near Nagri village in Ranchi district of Jharkhand at an elevation of about 600 m and travels a total length of 799 km before it outfalls into the Bay of Bengal.

5.2 Methodology

The impact of climate change on the hydrology and water availability in the Brahmani river basin has been studied using USGS (United States Geological Survey) MMS/PRMS (Modular Modeling Systems/ Precipitation-Runoff Modeling Systems) model. MMS (Leavesley et al., 1996) is an integrated system

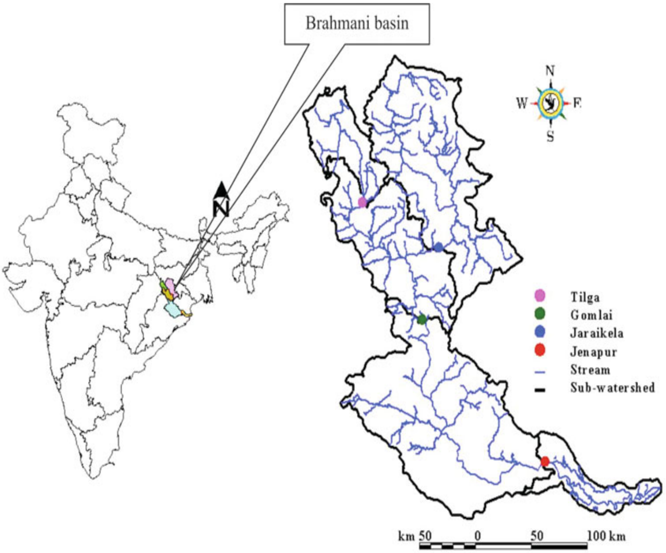


Fig. 3 Location map of Brahmani basin.

of computer software developed to provide a framework for the development and application of models to simulate various hydrological processes. Existing models can be modularized and brought into MMS.

The PRMS (Leavesley et al., 1983) is a deterministic, process-based, distributed parameter modeling system designed to analyze the effects of precipitation, climate, and landuse on streamflow and other general basin hydrology. Distributed parameter capabilities of the model are provided by partitioning the basin into homogenous units, using characteristics such as slope, elevation, aspect, vegetation type, soil type, and precipitation distribution. Each unit, termed as hydrologic response unit (HRU), is assumed to be homogenous with respect to its hydrological response and to the above listed characteristics. In PRMS, the basin is conceptualized as a series of reservoirs (Fig. 4). These reservoirs include interception storage in the vegetation canopy, storage in the soil zone, subsurface storage between surface of watershed and the water table, and groundwater storage. Model considers subsurface flow as relatively rapid movement of water from the unsaturated zone to a stream channel. The subsurface reservoir routes soil-water excess to the ground-water reservoir. Groundwater reservoir is considered as the source of all base flows.

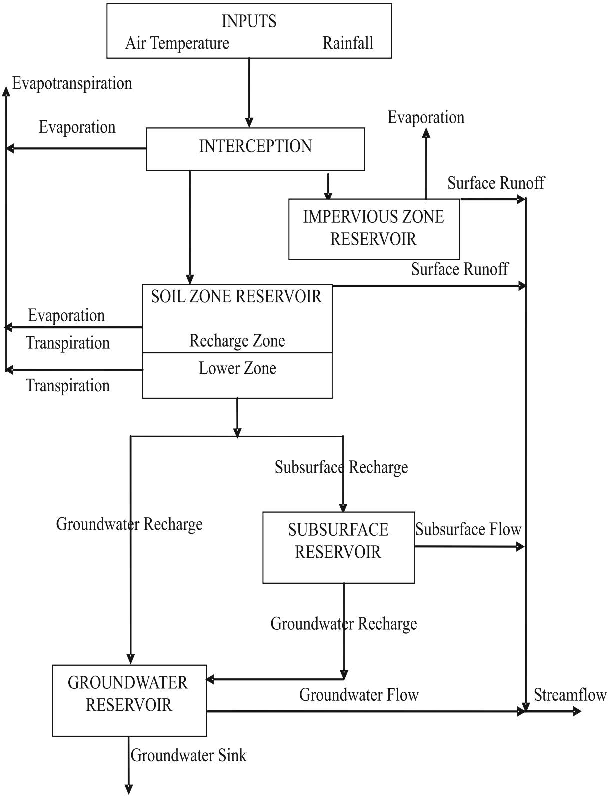


Fig. 4 Conceptual diagram of Precipitation-Runoff Modeling System (Leavesley et al., 1983).

Streamflow is the sum of the various reservoir contributions. Systems inputs included are daily precipitation, and daily minimum and maximum temperature. The model can be operated in two modes—daily and storm mode.

For distributed hydrological modeling using MMS/PRMS, the delineation of basin into different HRUs was done using Digital Elevation Model (DEM) of 30 m resolution. By overlaying elevation, landuse and soil layers, nineteen different classes of hydrological response units were generated (Fig. 5) and basin was divided into 66 HRUs. Different characteristics (such as area, mean and median elevation, slope, land use and soil type etc.) of each HRUs were extracted and used as input to the PRMS model. The model inputs were daily rainfall, maximum and minimum temperature.

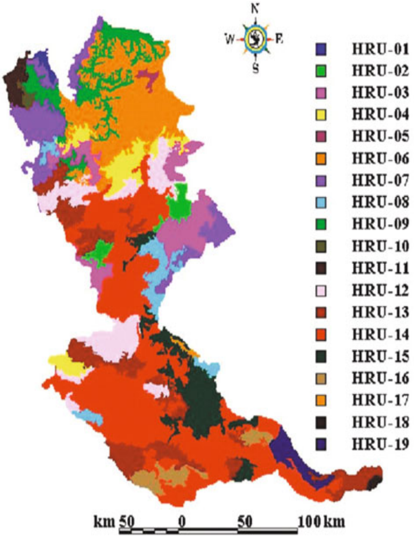


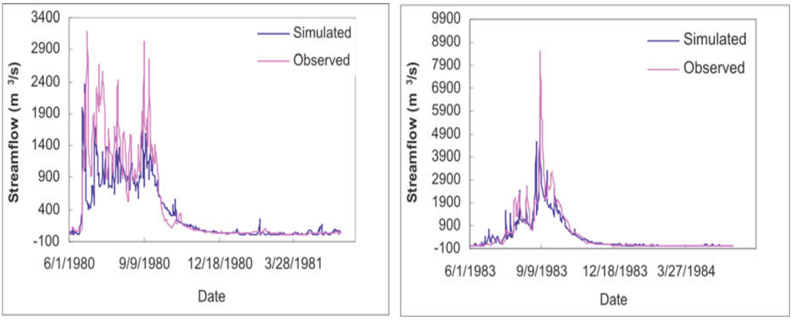
Fig. 5 HRU of Brahmani basin.

For assessing the sensitivity of streamflow to climate change scenarios, hypothetical scenarios were generated by varying the temperature from 0 to 4 °C and rainfall from ± 10 to 30%. For assessing water resources availability in the basin under the climate change scenarios derived from the output of HadCM3 climate model, the HadCM3 predicted mean monthly rainfall and temperature from six nearest grid boxes were extracted. They were then interpolated using inverse distance interpolation method for different periods (i.e., 1980, 2020, 2050 and 2080) and changes were estimated for generation of climate change scenarios. Historical time series of rainfall and temperature were then adjusted by adding monthly changes in temperature (ΔT) to historic temperature series, and by multiplying by monthly changes in rainfall ($1+\Delta P/100$) to precipitation series.

5.3 RESULTS

Calibration of MMS/PRMS model by matching the observed and simulated streamflow on annual, monthly and daily basis at four different gauging stations simultaneously (namely, Tilga, Jaraikela, Gomlai and Jenapur) showed a good agreement between observed and simulated streamflow. Calibration (1980-1982) and validation (1983-1985) results of the model at Jenapur gauging station is shown in Fig. 6. The coefficient of determination and modeling efficiency (Nash-Sutcliffe coefficient) were found to vary from 0.96 to 0.98 and 0.81 to 0.69, respectively during calibration phase, and 0.94 to 0.99 and 0.85 to 0.93, respectively during validation phase.

Sensitivity of streamflow to different hypothetical climate change scenarios indicated 76% increase in annual streamflow with a 30% increase in rainfall and no change in temperature (T0P30). If temperature increases by 4 °C (T4P30), increase in streamflow reduces to 62%. A maximum decrease of 33% in annual streamflow is observed with 4°C increase in temperature and 10% decrease in rainfall (Fig. 7). Correlation between changes in temperature and rainfall, and changes in streamflow indicated that rainfall changes had a large effect on monthly, seasonal and annual streamflow. This could be attributed



(a) Calibration Period (b) Validation Period

Fig. 6 Observed and simulated discharges during calibration and validation periods.

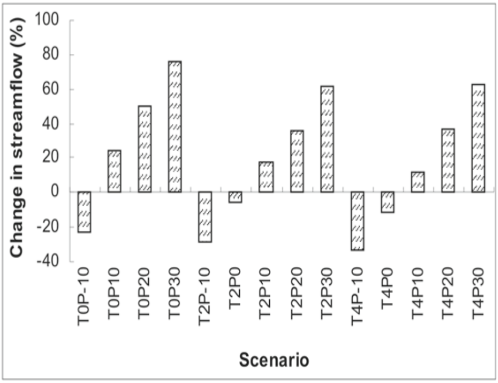


Fig. 7 Changes in the streamflow under hypothetical climate change scenarios.

to sub-humid climatic condition in the basin with lower part of the basin being located in the coastal region.

Simulation using HadCM3 derived climate change scenarios indicated increase in annual as well as seasonal streamflow under both A2a and B2a emission scenarios (Fig. 8). Under A2a emission scenario 15, 9 and 26% increase in annual streamflow was estimated during 2020, 2050, and 2080 respectively. Though, there is increase in streamflow during different periods, the magnitude of increase during 2050 is low as compared to 2020 and 2080. This could be due to changes in monthly rainfall pattern, with no uniform trend during different periods (Fig. 9). There is 6.2, 6.5 and 13.0% increase in annual rainfall during 2020, 2050, and 2080 respectively. Though the annual increase in rainfall during 2020 and 2050 is almost equal, the increase in monsoon rainfall in 2050 (5.41%) is less as compared to 2020 (8.76%) and 2080 (13.09%). Further, increase in rainfall in a particular month not only results in increased streamflow during that month, but also contributes to streamflow as subsurface and groundwater flow

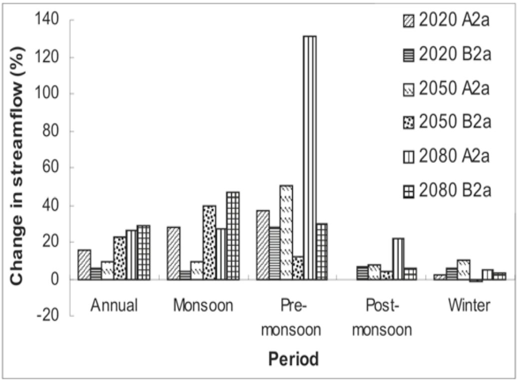


Fig. 8 Changes in the streamflow under HadCM3 generated scenarios.

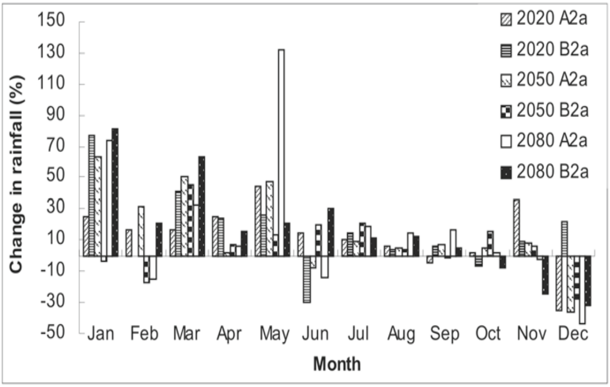


Fig. 9 HadCM3 generated rainfall change in the basin.

during the subsequent months. There is substantial subsurface and groundwater storage during monsoon months and contributes as streamflow during post-monsoon period. For example, increase of 131% rainfall in May 2080 resulted in a substantial amount of subsurface flow during June 2080, and hence higher streamflow (even though there is a decrease in rainfall) as compared to June 2050. Under B2a emission scenario, 23 and 28% increase in annual streamflow is estimated during 2050 and 2080, respectively, which is higher than the estimated streamflow under A2a emission scenario during the same period. This could be attributed to higher monsoon rainfall during 2050 (12.89%) and 2080 (13.87%). Though there is increase in streamflow during all the seasons, the increase is maximum during pre-monsoon season (March-May) under A2a emission scenario, whereas under B2a emission scenario maximum increase in streamflow is estimated in the monsoon season during 2050 and 2080, and pre-monsoon season during 2020.

Analysis of monthly results revealed that the percentage increase in monthly streamflow is maximum in May during all the periods (2020, 2050, and 2080) under A2a emission scenario. During post-monsoon (September-November) and winter (December-February) seasons, increase in streamflow is less than 10%, except for the post-monsoon period of 2080 under A2a emission scenario. Under A2a emission scenario, decrease in monthly streamflow is estimated during October and December in 2020, June in 2050, and June and February in 2080. In case of B2a emission scenario, decrease in monthly streamflow is observed during June and February in 2020, February in 2050, and October to December in 2080.

The results of simulation under PRECIS scenario also indicated an increase in annual as well as seasonal streamflows. An increase of 53% is estimated in the annual streamflow during 2080 (2071-2100) under PRECIS RCM scenario. As there is a variation in the results under different emission scenarios (i.e., A2a and B2a), the estimation of water resources availability using other GCM generated scenarios will help to ascertain these changes. The temporal variability in the availability of water resources in the basin under the influence of climate change indicated the need for developing different adaptation strategies, particularly for winter crops.

6. ADAPTATION TO CLIMATE CHANGE AND MITIGATION MEASURES

Climate change is just one of a number of factors influencing hydrologic systems and water resources. Population growth, changes in land use, restructuring of industrial sectors, and the demands for ecosystem protection and restoration are all occurring simultaneously. Adaptation to climate change takes place through adjustments to reduce vulnerability or enhance resilience in response to observed and expected changes in climate and associated extreme weather events. Individuals, organizations, and society as a whole will inevitably adapt to the changing conditions across a number of scales, sometimes successfully and sometimes unsuccessfully (Dessai et al., 2005). As awareness about the potential impacts of human-induced climate change has grown, so has the desire to plan for the impacts of climate change so that negative hazards can be mitigated and benefits enhanced (Scheraga and Grambsch, 1998). To address the impacts of climate change from long- and medium-term perspectives, urgent mitigation measures are needed such as reducing greenhouse gas (GHG) emissions and enhancing GHG removals as well as adaptation measures. Water is primary medium through which climate change will have an impact on people, ecosystems and economy. Therefore, water resources management should be an early focus for adaptation to climate change (Sadoff and Muller, 2007). Water managers typically rely on well established planning methods and hydrologic estimation tools which assume that the future climate will have same statistical properties of precipitation and temperature that has been experienced in the past. Climate change is likely to result in hydrologic conditions and extremes that will be different from those for which the existing projects were designed.

In the absence of explicit efforts to address the issues of climate variability and climate change, the societal impacts of water scarcity will rise as the competition for water use grows and supply and demand conditions change. As such it may not be safe enough to mention that there are specific adaptation strategies meant to tackle the impact of climate change in India. However, a number of programs and measures are available, which may be capable to alleviate such impacts to a limited extent in water and food sectors. These include supply and demand management measures either meant at conserving or enhancing or improving the water supply. The greatest potential for short-term adaptation is in demand control and more efficient and integrated management of surface and groundwater supplies.

In the agriculture sector, the adaptive measures to counter detrimental impacts of climate variations include changing planting/sowing dates, changing crops and crop varieties that are more tolerant to climatic variations. For irrigated agriculture, increased irrigation efficiency and adoption of drip/sprinkler irrigation systems could reduce water needs. For dryland farming, the implementation of water conservation practices may increase soil moisture, and changes in tillage operation may reduce water losses, and decrease soil erosion. Thus, improving the traditional and community-based irrigation systems, equitable water distribution, rainwater harvesting, groundwater recharge and the development and adoption of efficient irrigation methods such as pressurized irrigation systems could form some of the adaptation strategies. Watershed management could be another example of adaptation strategy especially in the rainfed and dryland areas. Use of seasonal climate forecast in planning and management could possibly reduce the losses due to weather variability and provide opportunities for diversification. Forecasting systems for floods and droughts for people's preparedness may be another example to alleviate the effects of these extreme events. Adaptation measures such as integrated water resources management (IWRM)—"an approach to water management that explicitly recognizes the need to structure and manage the trade-offs required, recognizing that one use affects others and that all depend upon the integrity of the resource base" (Sadoff and Muller, 2007)—will help to achieve water security and sustainability.

The following broad adaptive mechanisms/measures should be planned to reduce the impact of climate change on hydrology and water resources of a basin (Ragab and Prudhomme, 2002; Kumar et al., 2005):

- A strong national climate and water monitoring and research program should be developed, decisions about future water planning and management be flexible, and expensive and irreversible actions be avoided in climate-sensitive areas.
- Improved methods of accounting of climate-related uncertainty should be developed and made part of the decision making process.
- Decision makers at all levels should re-evaluate technical and economic approaches for managing water resources in view of climate variability and climate change.
- Improvements in the efficiency of end uses and the management of water demands must be considered major tools for meeting future water needs, particularly in water scarce regions.
- Water managers should begin a systematic re-examination of engineering design assumptions, operating rules, contingency plans, and water allocation policies under a wider range of climate conditions and extremes than are traditionally used.
- There should be proper coordination and cooperation between water agencies and leading scientific organizations so as to facilitate the exchange of information on the state-of-the-art knowledge about climate change and impacts on water resources.
- There should be timely flow of information among the climate change scientists and the water management community.
- Traditional and alternative forms of water supply can play a significant role in addressing changes in both demands and supplies caused by possible climate change and variability.

7. CONCLUDING REMARKS

It is widely accepted that increasing concentration of greenhouse gases (GHGs) in the atmosphere are causing climate change, but there still exists uncertainty in magnitude, timing and spatial distribution of these changes. With the increasing concern of global climate change, possible impacts of climate change have been widely investigated throughout the world. This chapter focused on the climate change and climate variability in India based on past studies, the role of simulation modeling in assessing climatic change impacts on hydrology and water resources, and a case study on climate change impact assessment in the Brahmani river basin of eastern India.

Continuous increasing trend in mean surface air temperature and changes in rainfall pattern in most parts of the Indian subcontinent has been reported in several studies. An increase in severity of drought and intensity of floods in different river basins of the country has also been reported. Hydrologic simulation models together with the output from GCMs/RCMs are the primary tool for assessing the impacts of climate change on hydrology and water resources. The results of hydrological modeling for assessing water resources availability in the Brahmani river basin using HadCM3 and PRECIS RCM generated scenarios indicated an increase in annual streamflow during different periods.

The majority of the climate change impact assessment studies concentrated on determining the effects of changes in average climate; however emphasis is needed on climate variability and particularly frequency and magnitude of extreme events. Although advances have been made in downscaling approaches, sensitivity analysis using hypothetical scenarios and the simple perturbation approach of altering historical time series with mean monthly changes produced by GCMs are still the most common approach adopted in most impact assessment studies on hydrology and water resources. Impact assessment using the outputs of one or more GCMs provides an estimate of plausible changes, but contains no information about their likelihood. Therefore, tools/techniques are needed to analyze and manage the uncertainty in climate change impact assessment, which is a major concern for climate change studies. Further improvements in spatial and temporal resolution of climate models and development of regional scale climate models with improved hydrologic parameterization at a basin level will enhance the ability of policy makers to use this information in real-world decision making. Integrated modeling frameworks coupling hydrologic, irrigation and crop models is needed to effectively investigate the effects of climate change on water availability, water distribution over space and time, and crop production as well as to prepare adaptation and mitigation strategies.

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