Climate change impact assessment on hydrology of Indian river basins

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As part of the National Communication (NATCOM) project undertaken by the Ministry of Environment and Forests, Government of India, the present study has been taken up to quantify the impact of the climate change on the water resources of Indian river systems. The study uses the HadRM2 daily weather data to determine the spatio-temporal water availability in the river systems. A distributed hydrological model namely SWAT (Soil and Water Assessment Tool) has been used. Simulation over 12 river basins of the country has been made using 40 years (20 years belonging to control or present and 20 years for GHG (Green House Gas) or future climate scenario) of simulated weather data. The initial analysis has revealed that under the GHG scenario, severity of droughts and intensity of floods in various parts of the country may get deteriorated. Moreover, a general reduction in the quantity of the available runoff has been predicted under the GHG scenario. This paper presents the detailed analyses of two river basins predicted to be worst affected (one with respect to floods and the other with respect to droughts).

Keywords: Climate change, water resources, NATCOM, HadRM2, SWAT model.

THE per capita annual water resource (AWR) has been used to classify countries with respect to the water scarcity[1]. Countries with an AWR per capita of 1700 cu m and above have been termed as countries where shortage will be rare; those with an AWR per capita of less than 1000 cu m as water-stressed countries; and those with an AWR per capita of 500 cu m and below as countries where availability of water is a primary constraint to life. In 1955, only seven countries were found to be with water stressed conditions. In 1990 this number rose to 20 and it is expected that by the year 2025 another 10 to 15 countries shall be added to this list. It is further predicted that by 2050, 2/3rds of the world population may face water-stressed conditions. It is worth noting that this assessment has been made without taking into account the possible impact due to predicted changes in global climate. Such consideration may aggravate the situation of AWR further.

The general impacts of climate change on water resources have been brought out by the Third Assessment report of the Intergovernmental Panel on Climate Change[2]. It indicates an intensification of the global hydrological cycle affecting both ground and surface water supply. Changes in the total amount of precipitation, its frequency and intensity have also been predicted. Such changes when on the surplus side may affect the magnitude and timing of runoff but shall create drought-like situations when these are on the deficit side. The impacts of climate change are also predicted to be dependent on the baseline condition of the water supply system and the ability of water resource managers to respond to climate change in addition to pressures due to increase in demand due to population growth, technology, and economic, social and legislative conditions. The coping capacity of the societies shall vary with respect to their preparedness.

Thus, climate change impacts are going to be most severe in the developing world, because of their poor capacity to adapt to climate variability. India also comes under this category. The NATCOM study[3] was the first attempt to quantify the impact of the climate change on the water resources of the country. The present paper first presents the summary results of the twelve river basins (leaving only two major systems on account of data availability) modelled. This is followed with detailed analyses on two river basins selected with respect to the extreme drought and flood conditions predicted on account of the climate change.

Methodology

The climate change impact assessment on water resources can be best handled through simulation of the hydrological conditions that shall prevail under the projected weather conditions in an area. Such a treatment is essential because of the fact that the hydrological response is a highly complex process governed by a large number of variables such as terrain, landuse, soil characteristics and the state of the moisture in the soil. The last element warrants a continuous time simulation so as to keep track of the changing moisture conditions. The SWAT (Soil and Water Assessment Tool) water balance model is one such model and has been used in the present study to carry out the hydrologic modelling of the river basins of the country.

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The SWAT model[4] simulates the hydrologic cycle at daily time steps. SWAT is a distributed, continuous, hydrological model with an ArcView GIS interface (AVSWAT). The interface is used for pre- and post-processing of the data and outputs.

The spatio-temporal water availability is determined in the present study without incorporating any man-made changes like dams, diversions, etc. The same framework is then used to predict the impact of climate change on the availability of water resources (under GHG) with the assumption that the land use shall not change over time.

Data

The SWAT model requires the data on terrain, land use, soil and weather for assessment of water yield at desired locations of a drainage basin. These data (at 1 : 250,000 scale) for all the river basins of the country (barring Brahmaputra and Indus rivers) have been used to generate the hydrological time series for the present/control (representing the period 1981–2000) and the future/GHG (representing the period 2041–2060) simulated weather data.

The selection of scale for spatial data is based on the tradeoff between the availability of the required terrain data (in the form of contours data on the topographic maps) and the processing effort required for its preprocessing using the GIS interface. The following sections provide brief description of data elements used and preprocessing performed on them.

Digital elevation model

Digital elevation model (DEM) represents a topographic surface in terms of a set of elevation values derived at a finite number of points. DEM has been generated using contours taken from 1 : 250,000 scale topographic maps.

Delineation of the river basins

Automatic delineation of the river basins is done by using the DEM as input and the final outflow point on the drainage of the river basin as the final pour/drainage point. Figure 1 depicts the modelled river basins (automatically delineated using GIS). The river basins have been divided into sub-basins using an arbitrarily selected threshold value. Table 1 presents the threshold values used on the DEM of the respective river basins during the process of automatic delineation. It also provides the number of sub-basins the river basin got sub-divided into as a result of this threshold (which basically controls the drainage density of the artificially constructed drainage system and thereby the number of sub-basins). The total area of the river basin as obtained from the automatic delineation has also been provided.

Weather data

The data generated in transient experiments (HadRM2) by the Hadley Centre for Climate Prediction, UK, at a regional climate model resolution of $0.44° \times 0.44°$ latitude by longitude grid points (Figure 1) has been obtained from IITM (Indian Institute of Tropical Meteorology), Pune, India. The daily weather data on precipitation, temperature (maximum and minimum), solar radiation, wind speed and relative humidity at all the grid locations were used. The HadRM2 grid has been superimposed on the sub-basins for deriving the weighted means of the inputs for each of the sub basins. The centroid of each sub-basin is then taken as the location for the weather station to be used in the SWAT model. This procedure has been used for the present/control (representing series 1981–2000) and the future/GHG (representing series 2041–2060) climate data.

Figure 1. The modelled river basins along with the RCM grid locations.

Table 1. Some of the basic details of the basins analysed

Basin	Threshold value used (Ha)	No. of sub-basins	Total area (Ha)
Brahmani	99,700	19	4,999,399
Cauvery	350,000	11	6,467,199
Ganga	2,000,000	29	87,180,000
Godavari	600,000	27	30,003,299
Krishna	600,000	21	24,647,200
Luni	750,000	9	12,793,400
Mahanadi	400,000	21	14,027,300
Mahi	100,000	13	3,579,000
Narmada	350,000	15	9,765,000
Pennar	200,000	11	5,524,600
Sabarmati	48,900	8	1,668,026
Tapi	200,000	13	6,853,799

Land cover/land use layer

Classified land cover data (13 categories) produced by the University of Maryland Global Landcover Facility, using remote sensing with resolution of 1 km grid cell has been used[5].

Soil layer

Soil map adapted from FAO Digital Soil Map of the World and Derived Soil Properties (ver. 3.5, November 1995) with a resolution of 1:5,000,000 have been used[6].

Hydrologic modelling of the river basins

The AVSWAT (SWAT running on ArcView GIS) distributed hydrologic model has been used on each of the river basins given in Table 1. The basins have been subdivided using the threshold values given in Table 1. These values are obtained iteratively to divide the basin into a reasonable number of sub-basins so as to account for the spatial variability. After mapping the basins for terrain, landuse and soil, each of the basins has been simulated for hydrological response by imposing the weather conditions predicted by Hadley centre (output of regional climate model – HadRM2 version) for control and GHG climate conditions.

Control climate scenario

The control climate scenario represents the simulated baseline weather conditions (1981–2000). Each of the river basins has been simulated using the SWAT model by using this generated daily weather data (HadRM2) of control climate scenario. Although the SWAT model does not require elaborate calibration, yet, in the present case, any calibration was not meaningful since the simulated weather data has been used for the control period whereas the historical recorded runoff with which the model is usually calibrated is the response to the actually observed weather conditions. Therefore, these two series are not comparable at short time intervals. However, the SWAT model has been used on various Indian catchments of varied sizes and it has been experienced that the model performs very well without much calibration[7]. Furthermore, in the present exercise every river basin has been treated as a virgin area without any manmade change incorporated (since very data intensive). This was done because the intent of the study was to quantify the impact of climate change on hydrologic regime of the river systems. The impact of manmade changes on the overall hydrological regime is usually not of a very high order of magnitude and can be ignored for the first level study of making the initial national communication to the UNFCCC (the basic objective of this study).

The model generates detailed outputs on flows, actual evapotranspiration and soil moisture status (sub-basin level) at daily interval. Many additional sub-components of the total water balance such as surface runoff, interflow, subsurface runoff, groundwater recharge, etc., are also available as part of the detailed output.

GHG climate scenario

The model has then been run on each of the basins using GHG climate scenario (representing 2041–2060 period) data but without changing the land use. The outputs of these two scenarios have been analysed firstly at the basin level to quantify the possible impacts on the precipitation, runoff, soil moisture and actual evapotranspiration. Subsequently, detailed analyses have been performed on the river basins to quantify the impacts at the sub-basin level. In the latter exercise relatively shorter time interval of month has been used in the analyses (although the detailed outputs at daily time interval are available at the sub-basin level). Due to paucity of space, analysis of only two of the river systems, namely Krishna and Mahanadi is presented to demonstrate the impacts at the sub-basin level. These are the river basins that have been predicted to experience maximum effect with respect to droughts and floods respectively.

Summary results of climate change impact on Indian river basins

Figure 2 shows the plot of the change in selected water balance components from the control to GHG climate scenarios for the 12 river basins modelled. It may be observed that the impacts are variable over the basins. A close examination also reveals that the increase in rainfall is not resulting always in an increase in the surface runoff as may be general perception. For example, in the case of Cauvery River basin an increase of 2.7% of rainfall has

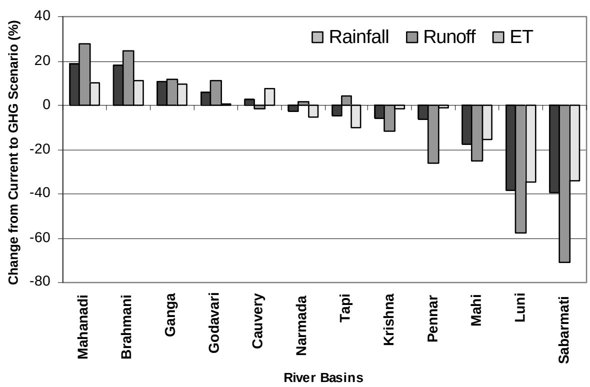

Figure 2. Per cent change in mean annual water balance components for control and GHG climate scenarios.

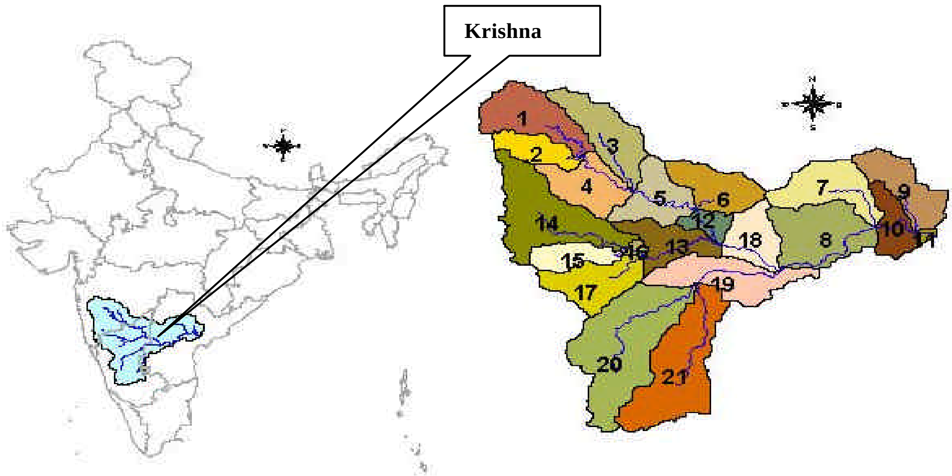

Figure 3. Krishna River Basin showing sub-basins.

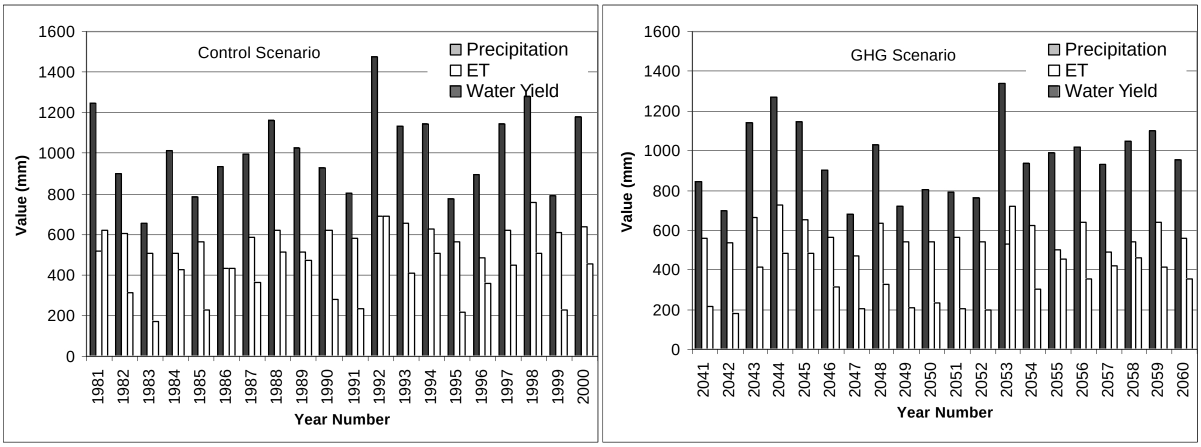

Figure 4. Annual water balance components for control and GHG scenarios.

been observed but the runoff has in fact reduced by about 2% and the actual evapotranspiration has increased by about 7.5%. On the contrary, a reduction in rainfall in Narmada has resulted in increase in the runoff, which is again contrary to the usual expectation. It is important to understand that these outcomes have been the result of a very elaborate computation of continuous water balance with daily time through the distributed hydrological modelling framework. This has enabled the simulation of the natural processes in a realistic manner so as to represent the complex spatio-temporal variabilities inherent in the natural systems. Due to paucity of space, Figure 2 presents only three major components (that too aggregated over time and space) of the water balance. However, sub-basin level results have been available for all the river basins.

Results of two river basins

Detailed results for two river basins, viz. Krishna and Mahanadi, one with predicted severe drought conditions and the other with pronounced flood conditions, respectively have been presented.

Krishna River Basin

The Krishna river basin has been predicted to undergo severe drought conditions under GHG scenario. The basin has been sub-divided into 21 sub-basins as depicted in Figure 3.

The annual average precipitation, actual evapotranspiration and water yield as simulated by the model over the total Krishna basin for control and GHG scenarios are shown in Figure 4. The year numbers used here are only representative of the period and should not be taken as chronological series that are comparable to the actual observed series. A close examination of the results reveals that this river basin is expected to receive reduced level of precipitation in future. Reduction has also been predicted in evapotranspiration and water yield of the basin.

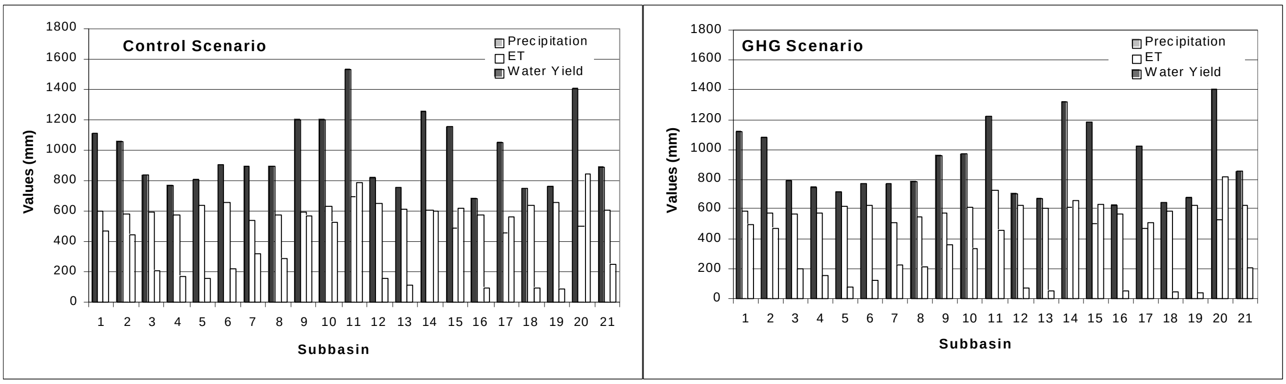

Figure 5. Sub-basin water balance components for control to GHG for Krishna.

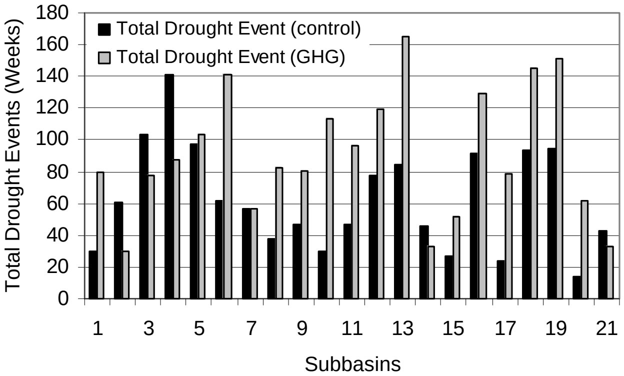

Figure 6. Number of drought weeks in sub-basins of Krishna for control to GHG scenarios.

Annual average precipitation, actual evapotranspiration and water yield as simulated by the model over the sub-basins of the Krishna basin for control and GHG scenarios are given in Figure 5. The variation in mean annual water balance components from control to GHG scenario, both in terms of change in individual values of these components as well as percentage of change over control, show that reduction in precipitation by about 20% of the current value has been predicted in the sub-basins of Krishna. The corresponding decrease in water yield over the sub-basins is predicted to vary from 30% to 50%. The actual evapotranspiration is also predicted to reduce by about 5% over most of the sub-basins.

Drought analysis

Drought indices are widely used for the assessment of drought severity by indicating relative dryness or wetness effecting water sensitive economies. The Palmer Drought Severity Index (PDSI) is one such widely used index that incorporates information on rainfall, land use, and soil properties in a lumped manner[8]. The Palmer index categorizes drought into different classes. PDSI value below 0.0 indicates the beginning of drought situation and PDSI value below –3.0 indicates severe drought condition.

Recently, a soil moisture index has been developed[9] to monitor drought severity using SWAT output. This formulation has been employed in the present study to focus on the agricultural drought where severity implies cumulative water deficiency. Weekly information has been derived using daily SWAT outputs which in turn have been used for analysis of drought severity. The soil moisture index has been computed for all the sub-basins of the River Krishna.

Number of drought weeks in the sub-basins of Krishna (consisting of the weeks with SMI of less than or equal to –3.0), for both control and GHG scenarios are shown in Figure 6. The SMI for GHG scenario has been computed using the soil moisture deficit ratio parameters of control scenario.

It may be observed from Figure 6 that the numbers of drought weeks have considerably increased during GHG scenario barring about five sub-basins of the Krishna basin. Analyses have also been performed with respect to drought conditions over monsoon and non-monsoon periods separately but could not be presented here due to lack of space.

Mahanadi River Basin

The Mahanadi river has been selected as the one which has been predicted to have maximum impact on account of the flood conditions. The basin has been sub-divided into 21 sub-basins for modelling (Figure 7).

The annual average precipitation, actual evapotranspiration and water yield as simulated by the model over the total Mahanadi basin for control and GHG scenarios are given in Figure 8. A close examination reveals that this river basin is expected to receive comparatively higher level of precipitation in future and a corresponding increase in evapotranspiration and water yield is also predicted.

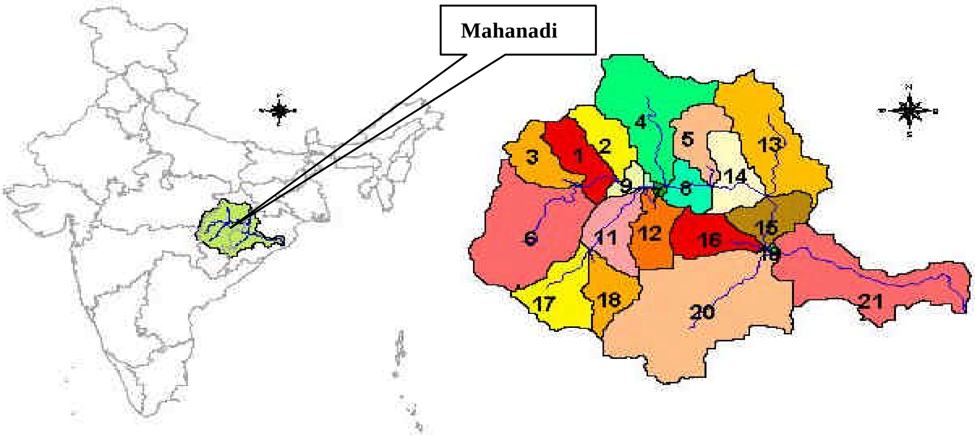

Figure 7. Mahanadi River Basin showing sub-basins.

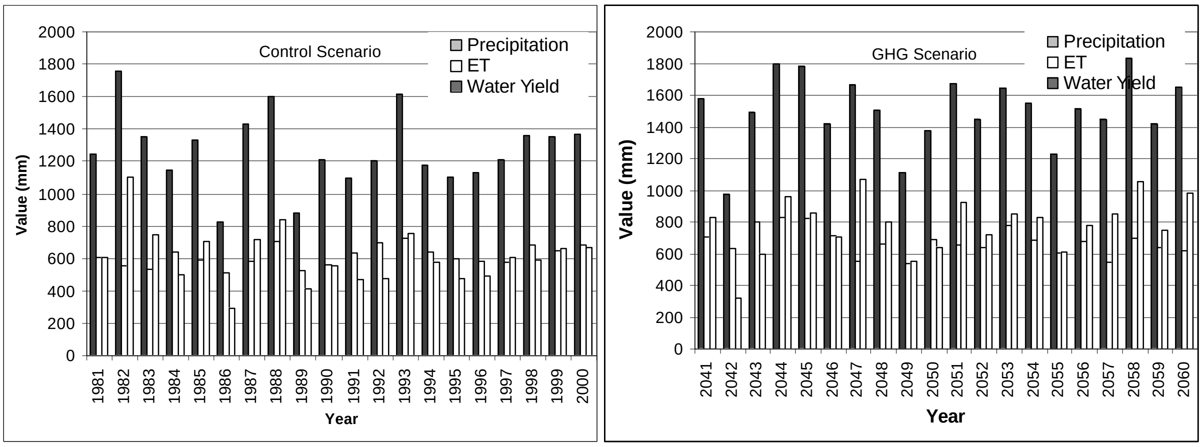

Figure 8. Annual water balance components for control and GHG scenarios.

Annual average precipitation, actual evapotranspiration and water yield as simulated by the model over the sub-basins of the Mahanadi basin for control and GHG scenarios are given in Figure 9. The variation in mean annual water balance components from control to GHG scenario, both in terms of change in individual values of these components as well as percentage of change over control show that there has been an increase in precipitation, water yield and evapotranspiration components predicted in all the sub-basins of Mahanadi.

The impact of the climate change on the dependability of the water yield of the river basin has been analysed with respect to four arbitrarily selected levels of 25, 50, 75 and 90%. Figure 10 depicts the flow duration curves for the control and GHG scenario. Table 2 shows the values corresponding to the levels of 25, 50, 75 and 90% dependability.

It may be noted that the flow for all the dependable levels has increased for the GHG scenario over the corresponding control flow magnitude but for the 50% level of dependability, at which the flow has marginally reduced.

Flood analysis

Although the flow duration curve is indicative of severity of flood conditions, detailed analysis for one of the sub-basins experiencing the severest flooding under the GHG scenario has been carried out (Figure 11).

The worst affected sub-basin in Mahanadi (sub-basins 15) has been analysed for flood severity (Figure 11). The annual maximum peak in the sub-basin has exceeded from the present level of about 20000 cumecs under control scenario to a maximum level of about 37000 cumecs under GHG scenario. In the GHG scenario, there have been three years when the peak level of 30000 cumecs has been predicted to surpass. Such an increase in flood peak may be detrimental to a large number of existing structures on these drainage systems.

Adaptation issues

Strategy for coping with the climate change impacts on water resources can be no different from the present day

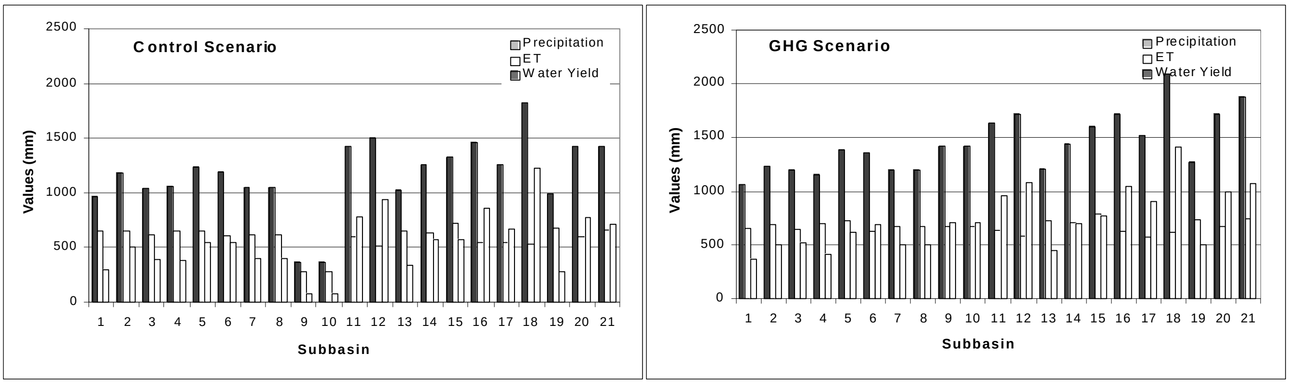

Figure 9. Sub-basin water balance components for control to GHG for Mahanadi.

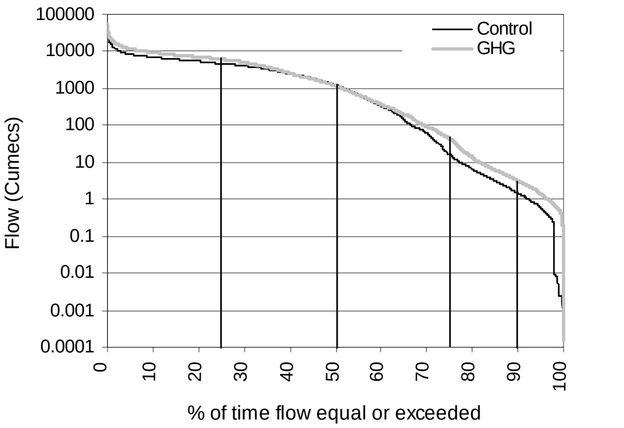

Figure 10. Flow duration curve for Mahanadi river for control and GHG scenarios.

Table 2. Dependable flow at 25, 50, 75, 90% level for control and GHG scenario

Dependable flow (cumecs)	25%	50%	75%	90%
Control	4716	1206	15.9	1.468
GHG	6103	1168	43.39	3.182

strategy of coping with the ever increasing demands and other environmental impacts on this precious resource. Prerequisite to adaptation and coping is the application of Integrated Water Resources Management strategy at different levels of usage starting from individual households to local communities, and watersheds to catchments. The Governmental view on the integrated water resources development has been presented in the recent report of the Nation Commission for Integrated Water Resources Development[1]. Some of the programmes undertaken by the Government of India to cope with the present variability, include, command area development, water-logging and drainage, crop diversification, irrigation water management, water distribution systems, conjunctive use of surface and ground water, reuse of waste water and flood control and flood management. However, these initiatives can only be termed as isolated interventions. The best way forward is to incorporate such interventions through a unified framework which can be conducive to integrated approach. Local level planning and management strategies need to be evolved and validated through the common framework so as to generate and evaluate various coping options suitable for the local conditions. Some of the possible coping activities may include:

- Study of the operation strategies of existing systems to enhance the water use efficiency
- Identification of options to enhance the availability by combining new infrastructure with other supply-oriented measures such as desalinisation, re-use, water marketing, etc.
- Demand management, conservation and efficiency enhancement
- Early flood and drought warning system
- Integrated information system.

The best strategy may be to go in for artificial restoration of the hydrological system by enhancement of water storage and infiltration of rainfall in urban areas and in river basins so as to maintain the original water balance. This will be useful for ecological and water resources restoration and implementation of nature-oriented river improvement works.

Gaps and future directions of studies

In the present study, the ‘hot spots’ have been identified only with respect to the natural boundaries in the form of sub-basins of the river systems. Before the adaptation issues are addressed, it will be imperative to qualify these hot spots by geographic areas with respect to population and ecosystems they inhabit[10]. Another gap which shall be required to be addressed is the institutional capacity building at various levels. The creation of unified framework and its maintenance shall be a gigantic task which can be achieved only through major policy restructuring of the institutions at different levels of management.

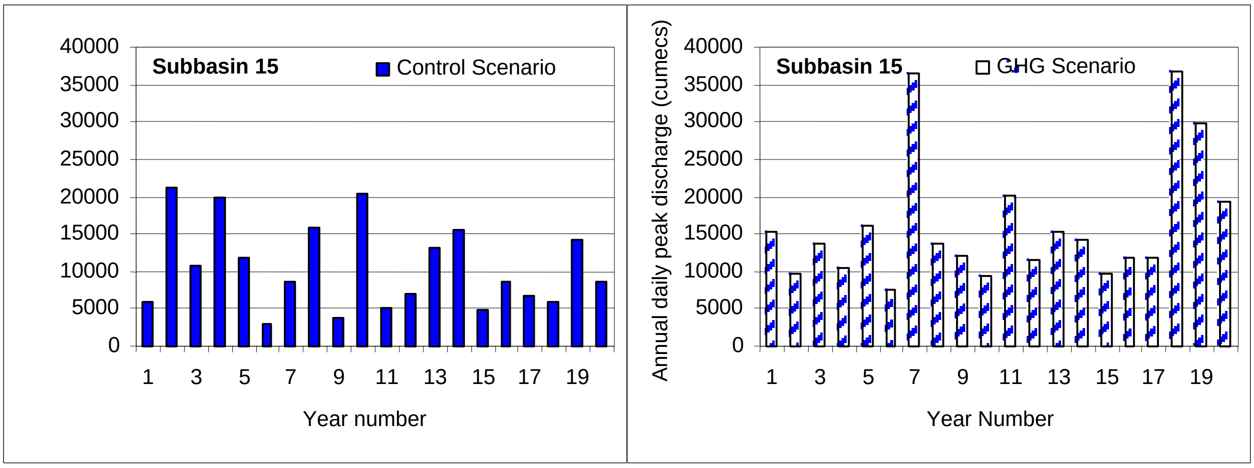

Figure 11. Annual maximum daily peak discharges for Mahanadi sub-basin 15 for control and GHG scenarios.

Conclusions

It has been one of the challenging studies for quantifying the climate change impact wherein the water balance simulation modelling approach has been used to maintain the dynamics of hydrology and thereby make assessments of vulnerability which are more authentic and reliable. Usefulness of such handling has been proved by the fact that the results of the GHG scenarios have been dictated by temporal variability at daily level as well as the spatial state of the land mass in terms of its moisture conditions and land use.

The study has revealed that under the GHG scenario the conditions may deteriorate in terms of severity of droughts in some parts of the country and enhanced intensity of floods in other parts of the country. However, there is a general overall reduction in the quantity of the available runoff under the GHG scenario. Luni with the west-flowing rivers Kutch and Saurastra which occupies about one fourth of the area of Gujarat and 60 per cent of the area of Rajasthan shall face acute water scarce conditions. River basins of Mahi, Pennar, Sabarmati and Tapi shall also face water shortage conditions. River basins belonging to Cauvery, Ganga, Narmada and Krishna shall experience seasonal or regular water-stressed conditions. River basins belonging to Godavari, Brahmani and Mahanadi shall not have water shortages but are predicted to face severe flood conditions[11].

These predicted climate change impacts may induce additional stresses and shall need various adaptation strategies to be taken up. The strategies may range from change in land use, cropping pattern to water conservation, flood warning systems, etc. and need rigorous integrated analysis before paving way into policy decisions.

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