Climate change impact assessment of water resources of India

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The present study has been taken up to quantify the possible impact of the climate change on the water resources of Indian river systems within the constraints of the uncertainty of climate change predictions. The study uses the PRECIS daily weather data to determine the spatio-temporal water availability in the river systems. A distributed hydrological model, namely SWAT has been used to simulate all the river basins of the country. The analysis has been performed to evaluate the severity of droughts and floods and thus identify the vulnerable hotspots that may require attention in view of the climate change in various parts of the country. The analysis is also performed on the blue and green water so as to identify the climate change impacts on these sub-components of water that are responsible for environmental functions and biomass production. These results have been made available at http://gisserver.civil.iitd.ac.in/natcom for use by a large cross-section of users.

Keywords: Climate change impact assessment, floods and droughts, hydrological model, water resources.

Introduction

The study evaluates the possible impacts of climate change on water resources of the river basins in India. Figure 1 shows the various regions (according to the Central Water Commission nomenclature) that have been simulated (complete basins ignoring the international boundaries have been taken). The drainage systems have been assigned the unique code numbers that have been designed as part of the standardization process (http://gisserver.civil.iitd.ac.in/natcom).

Although full river systems have been modelled, analyses have been made only for the geographical areas of India. Figure 2 provides the relative proportions of these river systems that fall into the geographical area of India. It may be seen that although the Brahmaputra is a much bigger river system, the two largest systems that cover the geographical area of India are the Ganga and Indus rivers.

Impacts of climate change and climate variability on the water resources are likely to affect irrigated agriculture, installed power capacity, environmental flows in the dry season and higher flows during the wet season, thereby causing severe droughts and floods in urban and rural areas. Climate change impacts on water resources which are addressed and analysed in the present study include impacts on annual and inter-annual water availability as well as extreme events of droughts and floods. It is important to understand that there are a large number of assumptions made and there are uncertainties in the predictions used as major inputs for the modelling. Uncertainty in the climate change predictions, especially in the precipitation, the major input for hydrological modelling, is well known. The other assumptions that have been made in the analysis are that land use shall not change in future and there are no man-made changes in the river systems.

Methodology

All the river basins of the Indian region have been modelled using the hydrologic model, soil and water assessment tool (SWAT) and incorporating the total basin area of each river system (including the one outside the Indian boundary). The SWAT model1,2 is a distributed parameter and continuous time simulation model. The model (i) is physically based, (ii) uses readily available inputs, (iii) is computationally efficient to operate and (iv) is capable of simulating the effects of management changes. The major advantage of the SWAT model is that unlike the other conventional conceptual simulation models, it does not require much calibration and therefore can be used on ungauged watersheds (in fact, the usual situation). The model requires information on terrain, soil profile and land use of the basin area as input, which has been obtained from the global sources. These three entities have been assumed to be static for future as well. The other information that is essential for the analysis is the weather conditions of the present and future. The data on weather conditions have been provided by the Indian Institute of Tropical Meteorology (IITM), Pune, as the output of a regional climate model (RCM-PRECIS) at daily interval at a resolution of about 50 km. The PRECIS model is the
Hadley Centre portable RCM, developed to run on a PC with a grid resolution of $0.44^\circ \times 0.44^\circ$.

Simulated climate outputs from PRECIS RCM for the present (1961–1990, BL) near term (2021–2050, MC) and long term (2071–2098, EC) for A1B IPCC SRES socio-economic scenario (characterized by a future world of rapid economic growth, global population that peaks in the mid-century (MC) and declines thereafter, and rapid introduction of new and more efficient technologies, with the development balanced across energy sources) have been used. Q14 quantifying uncertainty in model predictions (QUMP) ensemble has been used for the PRECIS simulation. The potential impacts of climate change on water yield and other hydrologic budget components are quantified by performing SWAT hydrological modelling.
with current and future climates respectively, for the river systems.

The study determines the present water availability in space and time 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 water resources with the assumption that the land use shall not change over time. A total of 90 years of simulation has been conducted; 30 years each belonging to IPCC SRES A1B baseline (BL), near term or MC and long-term or end century (EC) climate scenarios. While modelling, each river basin in the region has been further subdivided into reasonable sized sub-basins so as to account for spatial variability of inputs under the BL and GHG scenarios.

Data used

Spatial data used for the study and their source include:

- Digital elevation model: SRTM, of 90 m resolution (http://srtm.cgiar.org).
- Drainage network – hydroshed (http://hydrosheds.cr.usgs.gov/).
- Soil maps and associated soil characteristics (http://www.lib.berkeley.edu/EART/fao.html).

The meteorological data pertaining to the river basins are required for modelling the basins. These include daily rainfall, maximum and minimum temperature, solar radiation, relative humidity and wind speed. The weather data from PRECIS RCM outputs for BL (1961–1990), near term (2021–2050, MC) and long-term (2071–2098, EC) for A1B IPCC SRES scenario (http://www.tropmet.res.in/static_page.php?page_id=51), Q14 QUMP ensemble were used.

Results and analysis

Detailed outputs of SWAT modelling have been analysed with respect to the major water balance components of water yield and actual evapotranspiration (ET) that are highly influenced by the weather conditions dictated by temperature and allied parameters. Furthermore, the analysis has also been extended to the detection of extreme events of droughts and floods that may be triggered on account of the climate change and are of major concern to the local societies.

All the analyses have been performed by aggregating the inputs/outputs at the sub-basin level that are the natural boundaries controlling the hydrological processes and have also been used to depict the spatial variability of these entities using GIS. Since it is not possible to put all the spatial and temporal results in a physical report, a GIS framework has been created and all the results have been loaded in this framework, which is accessible to every user (http://gisserver.civil.iitd.ac.in/natcom). Subsequently, this framework can also be effective in the integration of various sectors for implementing integrated water resources management strategy.

Hydrologic simulation of the BL scenario

The SWAT model has been used on each of the river basins separately using daily weather generated by the PRECIS RCM A1B BL scenario (1961–1990). Although there has been recent literature where validation of SWAT has been performed for PRECIS simulation of historic climate using ET and crop yields as the check points for the ungauged basins, in the present case any calibration was not meaningful since first, the elaborate basin-wide data on ET are not available and secondly, the BL to which the observed flows correspond has huge man-made interventions in the river basins, whereas the simulation assumes virgin conditions. All the same it is also true that the SWAT model does not require elaborate calibration if the basic characteristics of the basin are incorporated properly.

The model generates detailed outputs at daily interval at the sub-basin level; outflow, actual ET and soil moisture status are some of the useful outputs. Sub-components of the total flow such as surface and subsurface run-off are also available. It also provides natural recharge to the groundwater on a daily basis.

Hydrologic simulation of the climate change scenario

The model was then run using PRECIS GHG climate scenarios for near term (2021–2050, MC) and long-term (2071–2098, EC) without changing the land use. The outputs of these two scenarios have been analysed with respect to the possible impacts on the run-off, sediment yield and actual evapotranspiration.

Analysis of climate change impacts

Effect of climate change on the water balance components has been analysed for each basin. The spatial distribution of water yield, ET and sediment yield along with precipitation has been analysed for the BL, MC and EC scenarios.

The long-term variation in percentage in these basic water balance elements for various regions is shown in Figures 3–7. Figure 3 presents the percentage change in major components of water balance (precipitation, water yield and ET) from BL to MC and EC respectively. Positive
change indicates decrease from BL and negative change indicates increase from BL.

Majority of the river systems show increase in precipitation at the basin level. Only Brahmaputra, Cauvery and Pennar show marginal decrease in precipitation under MC scenario. The basins with reduction in precipitation show associated decrease in water yield. The decrease in water yield in Pennar basin is more pronounced, which may be on account of changes in the distribution of precipitation under MC. The situation under EC improves wherein all the river systems exhibit increase in precipitation. There is also an associated increase in water yield for all the river systems under EC. The change in ET under the MC scenario exhibits appreciable increase (close to 10%) for Brahmaputra, Indus and Luni river basins. All other systems show marginal increase or decrease. Maximum decrease is for Mahi River (4.1%). This situation changes drastically under EC for which the magnitude of change increases drastically. For majority of the river systems, ET has increased by more than 40%.
The only two river basins which show some decrease in ET under the EC scenario are the Cauvery and Krishna. The major reason for such an increase in ET is on two accounts one is the increase in temperature and the second is the increase in precipitation which enhances ET.

In Figure 3, changes in core entities of precipitation, water yield and ET have been provided, which give the average value of these changes over the whole river basin. Many of these basins are big and have considerable spatial variability. While doing SWAT modelling, each of the river systems was divided into a large number of sub-basins and all the detailed outputs were obtained. Figures 4–7 provide a composite picture of the spatial variability of precipitation, water yield, ET and sediment yield respectively, under MC and EC scenarios. The extent of variation under each entity has also been depicted in the lower part of each figure by quantifying the maximum and minimum percentage change exhibited by any of the sub-basins of the respective basin (two ends of the blue bar) and also depicting the average condition of the basin (red cross bar) under MC and EC scenarios.

One may observe that the change in precipitation is highly variable with most of the river basins (Figure 4). This is not so only in big basins such as the Ganga, but also for smaller basins such as the Cauvery and Pennar. It may also be observed from Figure 4 (lower left hand box) that the average change in precipitation shown through the red cross bar is reflecting increase in precipitation for majority of the river basins although there are few sub-basins within specific river basins that may be showing
decrease in precipitation under MC scenario. The situation is further improved when we see the EC scenario for which there is increase in the average basin precipitation compared to the BL scenario. However, even in this scenario many river systems such as the Ganga, Indus, Luni, Godavari, Krishna, etc. have sub-basins which show decrease in precipitation.

The implications of changes in precipitation have been quantified in the form of resulting water yields through SWAT modelling. The response of water yield is dependent upon a combination of factors such as terrain, land use, soil type and weather conditions. This is reflected in Figure 5 for all the river systems of India. It may be observed that despite the increase in precipitation from the MC to EC scenario, the Krishna river system shows a reduction in the water yield. This can be on account of higher ET (because of increased temperatures). It may also be observed that in the case of the Cauvery river system, although there is an improvement in the average water yield from the MC to EC scenario, there are some sub-basins that show reduction in water yield (also reflected in the bar chart – maximum reduction increasing from about 30% (MC) to more than 50% (EC).

The ET is an important component of water balance with respect to the biomass and agricultural activities. The potential evapotranspiration is driven by the weather conditions, but the actual ET besides other factors is also dependent on the prevalent moisture conditions. The soil moisture accumulation and depletion is a complex process and is closely related to not only the amount of

Figure 5. Change in water yield (water availability) towards 2030s (MC) and 2080s (EC) with respect to 1970s (BL).
precipitation, but the intensity and frequency of precipitation as well. The outcome of the actual ET has been obtained after continuous simulation on daily basis for all the sub-basins of various river systems, and the changes in ET values (%) are shown in Figure 6 for all the sub-basins of the river basins under the MC and EC scenarios. In general, majority of the northern river systems show increase in ET under MC scenario, whereas majority of the southern river systems show marginal reduction in ET despite increase in precipitation. One possible reason can be higher intensities of rainfall under MC scenario, which has not allowed sufficient time for water to be stored in the soil through infiltration. The EC conditions show considerable improvement in ET which has increased for majority of the river basins (guaranteeing better crop production and less of agricultural droughts) but for the Indus and Luni rivers which show reduction in ET under the EC scenario.

The SWAT model also provides assessment of sediment erosion which is driven by the intensity of precipitation, terrain, soil and land use characteristics. This information is important with respect to water resources projects that are designed for accommodating a specific extent of sediment load. In the event of any increase in the sediment load, it becomes essential to undertake steps such as catchment area treatment to arrest sediment erosion. Figure 7 provides the percentage of change in sediment erosion under MC and EC scenarios. It may be

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**Figure 6.** Change in evapotranspiration towards 2030s (MC) and 2080s (EC) with respect to 1970s (BL).
noticed that majority of the river systems show overall increase in sediment load at the basin level, with some basins such as the Ganga, Brahmaputra, Krishna, Pennar and Cauvery having sub-basins that show reduction in sediment load under the MC scenario. Under the EC scenario there is further deterioration. The magnitude of erosion is much higher; however, the trends are quite similar to the MC scenario. The Ganga system shows significant increase in sediment load in majority of its sub-basins. Some areas of Krishna, Pennar and Brahmaputra show reduction in sediment load under EC scenario. However, the overall situation is bad and needs attention to deliberate on the viable options to cope with such a situation.

**Impact assessment – droughts**

The outputs from the hydrological model have also been used to assess the impact of climate change on the river basins in the regions in terms of occurrence of droughts. Drought indices are widely used for the assessment of drought severity by indicating relative dryness or wetness.

The Palmer drought severity index (PDSI) is one such widely used index that incorporates information on rainfall, land use and soil properties. PDSI categorizes drought into different classes. PDSI value below 0.0 indicates the beginning of drought situation and a value below –3.0 as severe drought condition.
Narasimhan and Srinivasan developed a soil moisture index to monitor drought severity using SWAT output to incorporate the spatial variability, and the same has been used in the present study to focus on the agricultural drought. Weekly information has been derived using daily SWAT outputs, which in turn have been used for subsequent weekly analysis of drought severity.

The severity of drought is proportional to the relative change in climate. For example, an area with nominal climatic deviations from the normal shall exhibit quite dramatic effects on experiencing even a moderate dry period. On the other hand, another area with large climatic variations shall require a dry period to produce equally dramatic effects. In the current context, scale 1 (index between 0 and –1) represents the drought developing stage and scale 2 (index between –1 and –4) represents mild to moderate and extreme drought conditions.

Weekly soil moisture deficit index (SMDI) was calculated using simulated soil moisture data of 30 years each under BL (1961–1990), MC (2021–2050) and EC (2071–2098) climate change scenarios. The spatial distribution of percentage change in drought weeks from BL to MC and EC respectively was worked out using the SWAT output for drainage basins and is shown here in the GIS format (Figure 8). Areas where the soil moisture deficit may start drought development (drought index value between 0 and –1) as well as those which may fall under moderate to extreme drought conditions (drought index value between –1 and –4) have been assessed (Figure 8).

It may be seen that there is an increase in the moderate drought development (scale 1) for Krishna, Narmada, Pennar, Cauvery and Brahmini river systems which have either predicted decrease in precipitation or have enhanced level of ET for the MC scenario. It is also evident from the depiction that the moderate to extreme drought severity (scale 2) has been pronounced for the Baitarni, Sabarmati, Mahi and Ganga river systems, where the increase ranges between 5% and 20% for many areas despite the overall increase in precipitation.

The situation of moderate drought (scale 1) is expected to improve under the EC scenario for almost all the river systems, except for the Tapi basin which shows about 5% increase in drought weeks. However, the situation for moderate to extreme droughts (scale 2) does not appreciably improve under the EC scenario despite the increase in precipitation. However, there is some improvement in the Ganga, Godavari and Cauvery basins.

Impact assessment – floods and low flows

The vulnerability assessment with respect to the possible future floods has been carried out using the daily outflow discharge taken for each sub-basin from the SWAT output. These discharges have been analysed with respect to the maximum annual peaks. Maximum daily peak discharge has been identified for each year and for each sub-basin. Analysis has been performed to earmark the basins where flooding conditions may deteriorate under the GHG scenario. The analysis has been performed to ascertain the change in magnitude of flood peaks above 99th percentile flow under BL (1961–1990), MC (2021–2050) and EC (2071–2098) climate change scenarios (Figure 9).

Figure 9 shows percentage of change from BL to MC and EC scenarios in peak discharge equalling or exceeding 1% frequency for sub-basins of various rivers. It may be observed that a majority of the river basins show an increase in flooding varying between 10% and over 50% of the existing magnitudes. There are few sub-basins of the Ganga, Brahmaputra, Krishna, Cauvery and Pennar that show some decrease in the peak flow magnitudes. This has a severe implication for the existing infrastructure such as dams, bridges, roads, etc. for the areas and shall require appropriate adaptation measures to be taken up.

Besides the floods which are important from the structural stability point of view, the dependability of other levels of flow, such as high (90%) or medium (75%) flows, is equally important for the design, operation and management of water resources projects. The lower part of Figure 9 provides the percentage of change in the 90% dependable (10th percentile) flow under the MC and EC scenarios. It may be observed that there is general increase in the 10th percentile for many of the river systems such as Indus, Ganga, Brahmaputra, Tapi, Godavari, Narmada, Mahanadi, etc. Parts of Krishna, Cauvery, Brahmaputra and Ganga show decrease in the 10th percentile flow. Although the trends under EC are similar to those under MC, there is general improvement in the magnitude of 90% dependable flow.

Analysis for blue and green water

There is a high spatial and temporal variability in the availability of water resources within each of the river basins as well as between the river basins. Freshwater availability is a prerequisite for food security, public health, ecosystem protection, etc. A large number of studies on freshwater availability have mainly focused on the quantification of ‘blue water’, while ignoring ‘green water’ as part of the water resource and its importance, especially for rainfed agriculture (highly prevalent in India). Therefore, a comprehensive analysis has been performed to create understanding on the impact of climate change with respect to the blue and green water.

Blue water flow or the internal renewable water resource (IRWR) is traditionally quantified as the sum of the water yield and the deep aquifer recharge. Green water, on the other hand, originates from the naturally infiltrated water which is considered as manageable water
CLIMATE CHANGE; PROJECTIONS AND IMPACT FOR INDIA

PERCENTAGE CHANGE IN DROUGHT WEEKS (JJAS) ACROSS INDIA
Based on Agriculture Drought Index ranging from -2 to -4 (moderate to extreme soil moisture stress during critical growth stages of crops)

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Figure 8. Change in monsoon drought weeks for 2030s (MC) and 2070s (EC) with respect to 1970s (BL).

resource. Falkenmark and Rockström\(^7\) differentiate between two components of green water: green water resource (or storage), which equals the moisture in the soil, and green water flow, which equals the sum of the actual ET (the non-productive part) and the actual transpiration (the productive part).

Detailed assessment of the different components of freshwater availability both in space and time is critical for identifying the vulnerable regions/hotspots. This would enable a proper implementation of the adaptation and mitigation strategy in addressing climate change coping mechanisms.

Freshwater components, i.e. blue water flow (water yield plus deep aquifer recharge), green water flow (actual ET) and green water storage (soil water) are estimated at a sub-basin level with daily weather data for all the river basins of India for all BL as well as GHG scenarios (Figure 10). This depiction is important in understanding the general availability of blue and green water across the various regions of the country. The western and southern parts are deficient in blue water under the present (BL) as well as future (MC and EC) conditions. The green water flow shows similar patterns but for the northern part of the country that has limited green water because of the snow and glacier cover. The Godavari and Mahanadi river systems show some improvement in the blue water under MC and EC scenarios, whereas the Ganga river system shows improvement in the green water flow availability under the MC and EC scenarios. The green water storage has deteriorated in the Luni and Mahi systems under MC and EC scenarios, but has improved for the Ganga system under EC scenario.

In addition to the spatial distribution, the intra- and inter-annual variability of the freshwater availability is also of great importance. Figure 11 shows the coefficient of variation (CV) of the annual values in each sub-basin for the blue water flow, green water flow and green water storage under BL, MC and EC scenarios. In general the CV, which is an indicator of the reliability of a freshwater source, varies considerably across the rivers of the country and was the lowest for the green water flow, whereas it was the largest for the blue water flow under various scenarios. The reason for this is that the supply of water for ET is limited by the capacity of the soil to deliver water to the roots. This capacity is within a narrow range between field capacity and wilting point of the soil. The inter-annual variability of the blue water flow is especially large in the Brahmaputra, Indus, Mahanadi and
Godavari river basins. The coefficient of variation of the green water storage is also large for majority of the southern and western river systems (Figure 11). There is appreciable improvement in CV for the Ganga system under the EC scenario.

The reliability of the water resources decreases as the uncertainties increase. The green water storage can potentially benefit the agriculture in months with little or without precipitation. This information is helpful in planning cropping seasons and patterns, and thereby their
impact on green and blue water flow and storage. Figure 12 shows the average green water storage for monsoon and non-monsoon periods under BL, MC and EC scenarios. The situation with respect to the green water storage is deteriorating in the western and southern river systems of the country.

It is also important to look at the water scarcity of blue water in absolute terms as well as with respect to the per capita availability. This shall bring into focus the water stress on account of changing water availability and population. Figure 13 presents the status of blue water under BL, MC and EC scenarios as well as annual average

Figure 10. Annual average blue water flow, green water flow and green water storage in all 1025 modelled sub-basins in India for IPCC SRES A1B BL, MC and EC scenarios.
blue water flow availability in per capita terms. It may be observed that majority of our country is below the recommended level of 1700 m$^3$ per capita. The enhanced level of precipitation has also not shown much improvement since the advantage is lost on account of the increasing population. The river systems of the Godavari, Mahanadi and Ganga show marginal improvement in the availability of blue water flow under MC and EC scenarios.

**Conclusion**

The present study establishes a comprehensive evaluation of the possible climate change impacts on the water resources of the Indian river systems within the constraints of the uncertainty of climate change predictions using A1B scenario of PRECIS for the MC and EC. The SWAT hydrological model has been utilized...
to perform the simulation using daily data. A comprehensive output on various sub-components of the water balance has been produced and analysed to draw conclusions. The study has been conducted on behalf of the Ministry of Environment and Forests, Government of India, as part of the NATCOM II study (Second National Communication of India to UNFCCC). The present study can be useful for the formulation of the National and State Action Plans on Climate Change undertaken by the country. Specific conclusions are not being made here because of the vastness of the conclusions and also due to the fact that all these inferences are

Figure 12. Annual average green water storage in the monsoon and non-monsoon periods in all 1025 modelled sub-basins in India for IPCC SRES A1B BL, MC and EC scenarios.
Figure 13. Annual average blue water flow availability per capita* for IPCC SRES A1B BL, MC and EC scenarios.

Using 2001 population for baseline and projected population (@ 0.93 %/yr) for future


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