CHAPTER 7

CLIMATE CHANGE AND RIVERFLOW

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7.0 Introduction

Runoff, a major component of the hydrologic cycle, is composed of surface runoff and interflow/subsurface runoff. Surface runoff is that portion of rainfall, snowmelt, and/or irrigation water that runs over the soil surface towards the stream rather than infiltrating into the soil. Interflow or subsurface flow includes water which moves just below the surface and makes its way relatively quickly to the stream channel. The actual physical processes that convert rainfall to runoff are both complex and highly variable. As such, these processes cannot be replicated mathematically with exact certainty. However, through the use of simplifying assumptions and observed data, there are several mathematical models and equations that can simulate these processes and predict resultant runoff volumes and rates from rainfall occurrence with acceptable accuracy.

The streamflow (or riverflow) refers to the amount of water flowing through a river section in a particular duration. The observed flow at a site may be affected by landuse/land cover changes and the water utilization for different purposes in the contributing basin. Changes in the landuse (say, afforestation/deforestation, urbanization, irrigation development etc.) impacts the timing and quantity of water flow in downstream river sections. Further, the streamflow consists of contributions from melting of snow/ ice and rainfall-induced runoff, all of which are sensitive to changes in climate conditions (Wendel, 2015). In the 21st century, climate change will affect the global hydrological cycle [Figure - 7.1 by Singh and Kumar (2018)] including higher occurrence of extremes (Hisdal et al. 2001; Arnell and Lloyd-Hughes 2014) and magnitude of changes will largely depend on representative concentration pathways (RCPs) (Koirala et al. 2014). Higher precipitation intensities are expected to impact the extreme flow conditions (both, low and high flows). Therefore, assessment of potential impact of climate change on hydrology and water resources of rivers is important for future planning and management of water resources.

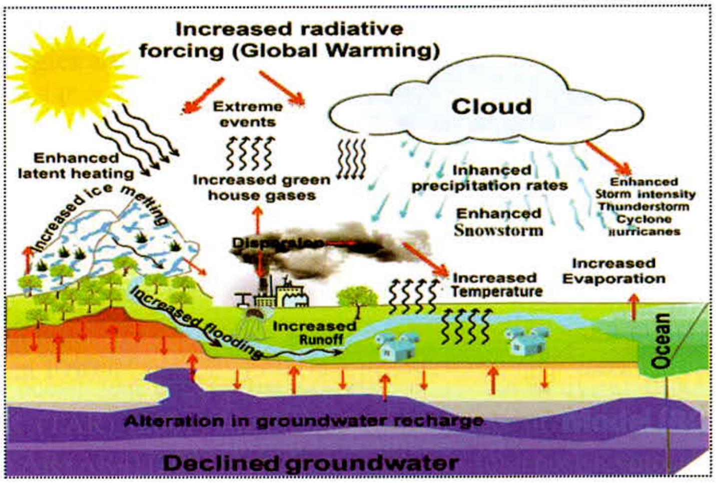

Figure - 7.1: *Influence of global hydrological cycle in context of climate change.*

Climate change is expected to alter the hydrological conditions, posing additional pressure on water resources with different authors having varied opinion. Increase in water stress and alteration of river flows in different parts of the world will be a major consequence of future climate change (Arnell 2004; Musau et al. 2015). With the doubling of CO_2 concentration, global mean runoff may increase by 5% as a result of reduced evapo-transpiration due to CO_2 enrichment (Betts et al. 2007). Stonevicius et al. (2016) opined that simultaneous increase in precipitation and evaporation may produce no overall change in the runoff even with change in both of these parameters. However, it is certain that there will be a significant change in runoff if increase in earth's temperature and change in precipitation take place simultaneously (Mousavi et al. 2018).

Since flow in the river is a result of complex interactions among different hydrological variables, hydrological models are the suitable tools to understand the impact of climate as well as LULC changes on water resources because of their ability to simulate or model such interactions. To establish the impact of climate change on river flows, the outputs of General Circulation Models (GCMs) are coupled with a deterministic hydrological model. By simulating stream flows resulting from precipitation and temperature data derived from GCM outputs corresponding to any specific climate change scenario, it is possible to quantify the impact of corresponding climate change on the hydrology of the basin. However, there is also a need to validate the hydrological model for the baseline time period with the downscaled output of GCMs. Only if the simulation results corresponding to the baseline period have similar streamflow characteristics when compared to the corresponding historical data, the model can be reliably used to simulate possible hydrological impact of future climate change scenarios (Dibike and Coulibaly, 2007). Another approach used in climate change impact studies is based on hypothetical scenarios (Xu, 1999). This approach has four stages:

a) Determine the parameters of a hydrological model in the study basin using current climatic inputs and observed river flows for model validation.

a) Perturb the historical time series of climate data according to some climate change scenario.

b) Simulate the hydrological characteristics of the catchment under the perturbed climate using the calibrated hydrological model.

c) Compare model simulations of the current and possible future hydrological characteristics.

Therefore, studies related to the climate change impacts on the river flows may be broadly categorized into: (i) studies using GCMs to directly predict the impact of climate change scenarios, and (ii) studies that use hydrological models under assumptions of plausible hypothetical climatic inputs. Many studies have investigated the impact of climate change on water resources, especially streamflow, in many parts of the world. In the following sections, impact of climate change on river flows in global as well as Indian context have been discussed.

7.1 Impact of Climate Change on Riverflows– Global Context

Among the early users of GCM approach, Kite in 1993 used mean monthly climatic variable values from Canadian Climate Centre second generation GCM. He found increase in both, high discharge and extreme rainfall, events. Contradictorily, when Arora and Boer (2001) studied the hydrology of some of the world's major river basins using CGCM1 model, they did not observe any such high discharge events.

Based on A2 and B1 scenarios, Van et al. (2013) revealed that the earth will experience decrease in low and increase in high flows in future. A reduction of freshwater may aggravate the water management problems for regions of mid and low-latitude; while higher amount of surface flow will be experienced in the higher-latitude regions (Nohara et al. 2006; Arnell and Gosling 2013). Arora and Boer (2001) from their study concluded that low-latitude rivers will experience negligible decrease in annual discharge while high- and mid-latitude rivers will face decrease in annual phase and amplitude of streamflow cycle. However, according to Nijssen et al. (2001), the annual streamflow would increase for the high-latitude rivers and would decrease for tropical to mid-latitude rivers.

Wetherald and Manabe (2002) specified that most of the tropical and mid-latitude rivers would experience positive as well as negative changes in runoff, except the Ganges and the Amazon. In these two rivers, the runoff is projected to increase quite substantially. Different researchers concluded that the rivers Mississippi, Brahmaputra, Danube and Lena will experience increased runoff (Jha et al. 2007; Costard et al. 2007; Ye et al. 2009; Bormann 2010; Gain et al. 2011; Ghosh and Dutta 2012). However, for the rivers Nile, Indus and Ganga, the researchers do not have clear consensus about the future runoff (Soliman et al. 2009; Taye et al. 2010). Based on the simulations from different models, the same river basins are projected to have both; high and low runoff states (Bhatt and Mall 2015). Tong et al. (2016) carried out a study in the Las Vegas Wash watershed in the USA and revealed that under B1 climate scenario, discharge in the watershed will decrease during winter and increase during summer. According to a study on future water availability in Bangladesh, Kirby et al. (2016) found that climate change will significantly impact the runoff in the region. He et al. (2013) found annual streamflow variations in the upper San Joaquin basin due to future climate change projections. Tall et al. (2017) witnessed increase in runoff in Senegal by the middle of 21st century due to increase in precipitation, temperature and evaporation.

Senent-Aparicio et al. (2017) reported that in Spain, future climate change will increase temperature by 1.5 to 3.3°C, decrease precipitation by 6 to 32% and decrease runoff by 2 to 54%. Xu and Luo (2015), from their study using GCMs and A1B scenario, found that temperature, precipitation and seasonal discharge will change up to 8.6°C, 139% and 304% respectively in China. Huang et al. (2015) studied the impact of climate variables on runoff in the Minjiang River and showed that variation in precipitation had more impact on simulated runoff than variation in temperature. Boyer et al. (2010) used the hydrological model 'HSAMI', three GCMs, viz. HadCM3, CSIRO-MK2 and ECHAM4, and A2 and B2 emission scenarios to study the impact of projected climate variability on seasonal discharge in the St. Lawrence tributaries, Quebec, Canada. Their results showed that the discharge will increase during wintertime and decrease during springtime. Azari et al. (2016) used climatic projections and hydrologic models to simulate the streamflow in northern Iran and reported that discharge would increase and decrease in the wet and dry seasons respectively and the overall annual discharge will increase. Shahini et al. (2016) also revealed an increase in wintertime runoff and decrease in springtime runoff due to variation in projected future temperature and precipitation.

Based on six different GCMs under three SRES scenarios, a study by Mousavi et al. (2018) on the Dez Dam basin, Iran indicated33% reduction of annual flow in the future. Based on the results of CGCM1 fed into a coupled hydrology-hydraulic model, substantial increase in the runoff volume (with up to 250% in maximum discharge) and water level was predicted in Chateauguay river basin of Quebec, Canada by Roy et al. (2001). To evaluate the impacts of climate change on water resources in the Pungwe river basin, Andersson et al. (2011) linked the Rossby Centre Regional Climate Model (RCA3) and hydrological model HBV. Their experiments indicated a decrease in available water and river flow rate for the entire river basin as a result of combined impact of decrease in precipitation and increase in evaporation and river flow reduces by 50 to 60%during the end of dry season. Stonevicius et al. (2016) used CMIP5 model outputs for RCP 2.6 and RCP 8.5 and applied water balance model WatBalon in the Nemunas River which is one of the largest tributaries of Baltic Sea. The results revealed a decrease in spring runoff and increase in winter runoff with an overall likely decrease in annual runoff.

Hamid et al. (2010) assessed the impact of climate change on flood-plain and hydrologic ecotones over the Lower Tualatin basin in the Pacific Northwest US using daily downscaled data of precipitation and temperature. They considered the effect of three different GCM climate change emission scenarios (high from the IPSL GCM's A2 scenario, middle from the ECHAM5 GCM's A2 scenario and low from the GISS GCM's B1 scenario) and used SWAT model to predict daily flows in the basin and HEC-RAS model to delineate the flood-plain extents for various climate scenarios. Their study predicted significant decrease in 50-year recurrence interval (RI) flow (between 18,000 to 19,000 cusec) compared to the observed 50 year RI of approximately 26,000 cusec for the low and middle emission scenarios. However, under the high emission scenarios, the 50-year RI flow increases to nearly 33,000 cusec.

*7.1.*1 Combined Impact of Climate Change and LULC Change on River Flows

Various researchers, from their study in different parts of the globe, found that runoff in a basin is sensitive to both, climate change and LULC change. Urbanization leads to changes in precipitation and temperature in a way that surface air temperature increases and precipitation changes in intensity and spatial pattern (Giannaros et al. 2013). Again, due to deforestation, there may be decrease and increase in surface air temperature in temperate and tropical regions respectively (Costa and Piers 2010).

Based on the results from SWAT model, Liu et al. (2003) found that during 1980-1990, the runoff in a region of the Yellow River decreased by 109% due to climate change and increased by 10% due to LULC change. Li et al. (2009), using SWAT model, found that runoff decreased by 9.6% due to LULC change and by 95.8% due to climate change in the Heihe catchment of Loess plateau. Huang and Zhang (2004) studied the impact of LULC change on mean annual runoff in the Jialuhe River catchment and found that runoff decreased by 32% during 1967-1989 due to conservation practices implemented in the catchment.

Mu (2007) reported that runoff will decrease by 29% and 71% due to precipitation change and LULC change respectively in the He Long region of the Yellow River. For the Langat river basin of Malaysia, Noorazuan (2003) found that due to change in LULC, surface runoff increased by 20.35% and 27-31.4% during 1983-1988 and 1988-1994 respectively. Guo et al. (2016) applied SWAT model in the Xiying river basin in China to evaluate the impact of change in climate and LULC on runoff. Their study indicated that during 1990-2008, mean annual runoff increased by 102.8% which was primarily due to climate change. From the future projection study, while comparing the runoff with that for the period 1961-1990, they found that under A2 and B2 scenarios, there will be a decrease in mean annual streamflow by 5.4% and 4.5% respectively for the period 2010-2039. Again, under these two scenarios, runoff will decrease by 21.2% and 16.9% respectively for the period 2040-69. Tan et al. (2015) applied SWAT model to understand the impact of change in climate and LULC in the Johor River basin, Malaysia. They concluded that impact of climate change on streamflow is more significant than LULC change in the study basin. From the Mann-Kendall and Sen's slope test, they found that in contrast to the significant increasing trends of precipitation and temperature, the increasing trend of streamflow is very insignificant. While considering the combined impact of LULC and climate change, the streamflow increased by 1.2% in the Johor River.

Trang et al. (2017) studied the impact of LULC change and climate change for future three different time periods, viz., 2015-2039, 2045-2069 and 2075-2099 using ensemble of five GCMs for RCP 4.5 and RCP 8.5 for the 3S river basin. Indicating that there will be increase and decrease in discharge in wet and dry seasons respectively for the selected time periods, they concluded that throughout the 21st century, the discharge will increase in the 3S river basin. Using Joint UK Land Environment Simulator (JULES) and Land Surface Model (LSM), Tsarauchi and Buytaert (2018) investigated the impact of future climate and LULC changes on hydrological response in upper Ganga River Basin in northern part of India for the period 2000-2035 using CMIP5 outputs of 21 models for RCP4.5 and 8.5, and 15 land-use pathways. They carried out the experiments for separate as well as combined impact of LULC and climate change and predicted severe increase in high extremes of flows.

7.2 Impact of Climate Change on Flows of Indian Rivers

7.2.1 Current Scenario

There are two major river systems in India. The first system includes all the major rivers and their tributaries that originate in the Himalayas and second system includes the rivers draining the Deccan Peninsula (Rashtriya Barh Ayog, 1980). India has a monsoon type of climate and about 80-90% of the annual river flows occur during four monsoon months (Jain 2017). The aspect related to changes in streamflow due to snow and glacier-melt has been covered in separate chapter in this report and is not elaborated here. Some other studies in the field of hydrologic impacts of climatic change on Indian river basins is presented here.

Table – 1: Basin-wise average flow of major Indian rivers:

S. No.	River	Average annual flow (km^3/yr)
1	Indus	73.31
2	Ganga-Brahmaputra-Meghna Basin 2 (a) Ganga 2 (b) Brahmaputra sub-basin 2 (c) Meghna sub-basin	 525.02 629.05 48.36
3	Brahmni-Baitarani	28.48
4	Mahanadi	66.88
5	Godavari	110.54
6	Krishna	69.81
7	Pennar	6.32
8	Cauvery	21.36
9	Tapti	14.88
10	Narmada	45.64
11	Mahi	11.02
12	Sabarmati	3.81

Source: Kumar et al. 2005

Out of many rivers in India, 12 are classified as the major rivers. Most of the rivers are perennial and few are seasonal. For the Himalayan rivers, the average water yield per unit area is more than that of the south peninsular rivers due to snow and glacier melt contribution from the mountains to the Himalayan rivers (Mall et al. 2006).

Ghosh and Majumdar (2008) carried out a study for Mahanadi River basin and used the vector machine with fuzzy clustering to project the future monsoon streamflow considering the CCSR/NIES GCM with B2 scenario. Their study revealed a decreasing trend in monthly peak flows which may be attributed to high surface warming that leads to significant reduction in occurrence of high flows. Additionally, they used conditional random field (CRF) downscaling model with AR4 projections and found that for most of the future scenarios, there will be a decrease in the mid-level flows. However, for the period 2040-65, for most of the scenarios, significant increase in high flows and slight increase in low flows was predicted.

As recorded by Climate Change Cell of Ministry of Environment, Bangladesh (2009), there was an increase in streamflow at Bahadurabad in the Brahmaputra River during 1956-2007 due to some particular flood occurrences. At the Mundali outlet in the Mahanadi basin, Dadhwal et al. (2010) reported an increase in annual streamflow by 4.53% during the period 1972-2003 due to reduction in forest cover by 5.71%. Panda et al. (2013) reported decreasing streamflow at the rate of 3388 million cubic meter (MCM) per decade for the period 1972-2007 at Tikerpara gauging site of Mahanadi river in Peninsular India, which was attributed to increased upstream usage in the river.

For the Brahmani River basin, Islam et al. (2012a) used the USGS's Precipitation-Runoff Modeling system (PRMS) to study the impact of climate change on streamflow. They found that impact of change in rainfall on annual and seasonal streamflow is more significant than change in temperature in the basin. Abeysingha et al. (2016) observed decreasing trend in annual streamflow of Gomti River for the period of 1982-2012. Anandet al. (2018) used SWAT model along with statistical methods to detect trend and critical changes in streamflow of Ganga river. They found increase in streamflow from the snow-fed areas but significant decline in streamflow in lower reaches which may be attributed to anthropogenic changes.

Saharia et al. (2018) evaluated future climate change impact on hydrologic processes in Bharalu (urban) and Basistha (rural) basins using SWAT model for two different climatic scenarios - RCP 2.6 and RCP 8.5. Various hydrological processes such as precipitation, discharge, water yield, surface runoff, actual and potential evapo-transpiration were examined. In the mid-century and late century, the stream flow, water yield, surface runoff and actual evaporation were found to decrease in urban basin as compared to rural basin. Under RCP 2.6 and RCP 8.5 scenarios, the average annual discharge was found to increase by 1.43 cumec and 2.20 cumec respectively as compared to base line scenario.

Reshmidevi et al. (2017) estimated the impact of climate change on water balance in an Indian catchment using an ensemble of 5 GCMs (MPI-ECHAM5, BCCR-BCM2.0, CSIRO-mk3.5, IPSL-CM4, and MRI-CGCM2). Modified Markov Model-Kernel Density Estimation (MMMKDE) and k-nearest neighbor downscaling models were used. Present and future hydrological simulation was done using SWAT model. They found decreasing trends in runoff ratio, annual stream flow and groundwater recharge by the end of the century. An increasing trend of temperature as well as evapo-transpiration was predicted which in turn, will increase the irrigation demands. Also, there will be an increase in average precipitation towards the end of the century under future climatic projection. The authors conclude that due to reduction in streamflow and ground water recharge along with increase in irrigation demands, the water stress in the region will be aggravated.

7.2.2 Future Projections

As per IPCC 5th Assessment Report, India in 2080 as compared to 1961-1990, will experience warming of the order of 1.5, 2.4, 2.8 and 4.3°Cunder RCPs 2.6, 4.5, 6.0 and 8.5 respectively (Chaturvedi et al. 2012). There will be a general trend of increase in mean average annual temperature and enhanced precipitation in the Indian subcontinent (Cruz et al. 2007). Mall et al. (2006) reported that the pre-monsoon and monsoon rainfall over the central plains of Indian sub-continent would increase by the end of the century which would result in an increase in the monsoonal and annual runoff. However, due to no substantial change in winter rainfall, the winter runoff over the central plain will not change significantly.

Sharma et al. (2000) and Sharma (2000) studied the impact of potential climate change scenarios on hydrology of the Kosi Basin. Their study revealed that, compared to precipitation, increase in runoff was higher in the basin for all the scenarios. However, the scenario created by considering contemporary precipitation and a rise in temperature by 4°C, caused decrease in runoff by 2 – 8% depending upon the areas considered and the model used.

Gosain and Rao (2003) studied the impact of future climate change on runoff of different river basins and sub-basins in India. For Mahanadi, Brahmani, Ganga, Godavari and Cauvery River basins, the authors predicted that corresponding to increase in precipitation; there will be no increase in the annual runoff because of increase in evapo-transpiration due to increased temperature and variation in precipitation distribution. For the Sabarmati River basin, appreciable decrease in projected precipitation and correspondingly total runoff was predicted which may cause severe drought conditions in the basin in future. Singh and Kumar (1997) used various climate change scenarios to study the impact on runoff in Spiti River, a high altitude Himalayan River in Satluj basin. They found linear increase in snowmelt runoff, glacier-melt runoff and total streamflow due to changes in temperature.

Das and Umamahesh (2018) projected the monthly monsoon streamflow in the Wainganga basin, India using 40 GCM outputs and four RCPs. Relevance vector machine (RVM) was used to simulate future monsoon flows. Their results indicated that upper extremes of monsoon flow will continuously decrease in future while medium and low flows will increase under the different RCPs. Towards the end of the 21st century, the decrease in mean annual monsoon flow was found to be more significant.

Mishra and Lihare (2016) considered 18 Indian major sub-continental basins viz., Indus, Brahmaputra, Ganga, Brahmani, Cauvery, Godavari, North Coast, South Coast,East Coast, West Coast, Mahanadi, Krishna, Narmada, Tapti, Sabarmati, Mahi, Pennar and Subarnarekha to assess the impact of climate change on hydrological processes under RCP 4.5 and RCP 8.5 scenarios using SWAT model. The analysis was performed for three different future time frames, 2010-39, 2040-69 and 2070-99. They reported that under RCP 4.5, there will be significant increase in streamflow for Ganga, Brahmaputra, Narmada and South Coast Rivers, while, there will be decrease in streamflow for Mahi and Tapti Rivers during monsoon season. Under RCP 8.5, Brahmani, Ganges, Godavari, Mahanadi, Narmada, Pennar and Subarnarekha Rivers will experience significant increase in streamflow. The projected change in streamflow during monsoon season for different basins as given by authors are represented in Figure- 7.2. In the mid and end of 21st century, majority of the sub-continental river basins will experience increase in streamflow by 20-40%. The authors attributed it to increase in precipitation with relatively lesser increase in evapo-transpiration during monsoon season.

For the Barmanghat gauging site in Narmada basin, Sudheer (2016) used six RCMs and two RCPs (4.5 and 8.5) to run the SWAT model and identified dependable flows at 5%, 10%, 20%, 50%, 75%, 90% and 95% dependability. He reported that the 5% dependable flow during 2006-40 varies between 405.6 cumec for ACCESS to 452.2 cumec for MPIESM. During 2041-70, the 5% dependable flow varies between 382 cumec for CNRM to 520.4 cumec for GFDL. However, the 5% dependable flow may increase during 2071-99 varying between 507.9 cumec for MPI-ESM to 607.3 cumec for CNRM indicating possibilities of occurrence of floods towards the end century.

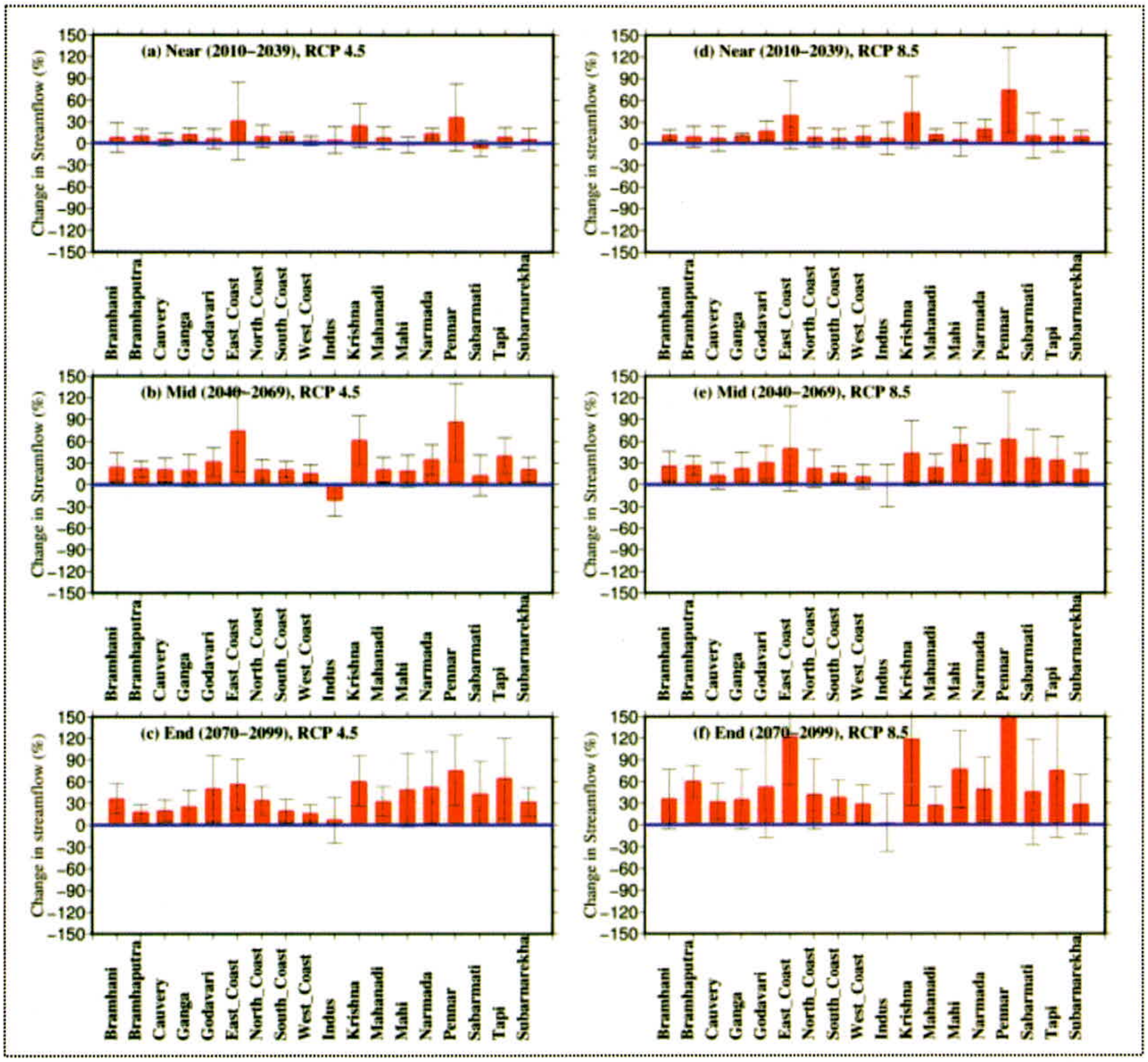

***Figure- 7.2**: Multi-model ensemble mean projected changes (%) in mean monsoon season streamflow under RCP 4.5 and 8.5 scenarios for the Near (2010-2039), Mid (2040-2069), and End (2070-2099) term climate with respect to the historic (1971-2000). Bars show multi model ensemble mean change, while error bars show intermodal variation using one standard deviation (Source: Mishra &Lihare 2016).*

Pervez and Henebry (2015) applied SWAT model using downscaled CGCM3.1 precipitation from CMIP3 and Image-derived LULC to assess impact of climate and LULC change on the hydrology of the Brahmaputra River basin. The impact was analyzed for A1B and A2 scenarios taking 1988-2004 as the base period. The results predicted strong increasing trend of streamflow during August-October (indicating possibility of floods) and strong decreasing trend of streamflow during May-July of 21stcentury (indicating possibility of drought) in the basin.Kamal et al. (2013) studied the seasonal variability of monsoon and dry periods through projected data of the period of 2020s, 2050s and 2080s and found that peak flow of GBM (Ganges, Brahmaputra, Meghna) rivers may enhance by about 4.5 to 39.1% in the monsoon period while in the dry season, the low flows may decline by about 4.1to 26.9%.

Masood et al. (2015) assessed the impacts of climate change (considering high-emission path) on runoff, evapo-transpiration, and soil moisture using five CMIP5 GCMs. Results showed that by the end of 21st Century, these basins will be warmed by ~4.3 °C and changes in mean precipitation (runoff) are projected to be +16.3% (+16.2%), +19.8% (+33.1%), and +29.6% (+39.7%) in the Brahmaputra, Ganges, and Meghna basins respectively. A study by Mahanta et al. (2014), based on 22 GCMs and A1B, B1 and A2 scenarios, revealed that the flow of Brahmaputra River at Chilmari will increase by 5to20% by the end of 21st century. Lutz et al. (2014) used a distributed cryosphere-hydrological model on the upstream basins of the Ganges, Indus and Brahmaputra and predicted a consistent increase in the runoff at least until 2050.

Sharannya et al. (2018) studied impact of climate change on hydrology of river Gurupura, one of the major rivers of Dakshina Kannda district of Karnataka. This is a west flowing river that originates in the Western Ghats of India. CORDEX data was used along with SWAT model. The analysis was performed for both, past and future, scenario. The time period of historical analysis was 1951-2005 and for future they used RCP 4.5 scenario for the period 2006-2060. Their result indicated that the annual streamflow in the river showed decreasing trend at the rate of 1.2 MCM/yr for the past and 2.56 MCM/yr for future scenario. Talib et al. (2017) applied the SWAT model at Bhakra, the major reservoir in the Satluj river basin in India to simulate the streamflow for three different time-frames viz., 1961-1990, 2021-2050 and 2071-2098. Climatic change projections generated under PRECIS for IPCC A1B scenarios were considered. The authors found 12.8% and 19.4% increase in annual streamflow at Bhakra for 2021-2050 and 2071-2098 respectively. The monsoonal streamflow would increase by 10% for both the periods as compared to the base period. However, for January-February, the streamflow were projected to increase by 49% and 21% respectively for 2021-2050 and 2071-2098 periods as compared to the base period.

Kumar et al. (2017) studied the impact of climate change on streamflow of the Upper Kharun Catchment, a part of Seonath sub-basin which is a tributary of Mahanadi river in the Chhattisgarh State of India. They used PRECIS regional climate projections for the period 1961-2098 and simulated the streamflow using SWAT model. The authors found an average decrease of annual discharge by 2.9% for 2020s; average increase of 12.4% for 2050s, and average increase of 39.5% for 2080s. Nilawar and Waikar (2019) used SWAT model, three RCMs, and RCPs 4.5 and 8.5 for future four different time periods viz., 2009-31, 2032-53, 2054-75 and 2076-99 to study climate change impact on streamflow and sediment concentration in the Purna river basin of India compared to the base period 1980-2005. The results showed increase in average monthly streamflow by 24.47 to 115.94 cumec under RCP 4.5 and 8.5 and significant increase in future streamflow from June to September at the outlet of the basin was predicted.

Vandana et al. (2018) used Precipitation Runoff Modelling System (PRMS) to study the impact of climate change in the Brahmani river basin. They generated multi-model ensemble climate change scenarios using Hybrid –Delta ensemble method forA2, A1B, and B1 scenarios. Their results indicated that annual streamflow would increase in the range of 2.2 to 2.5%, 2.4 to 4.7% and 7.3 to 12.6% during 2020s, 2050s and 2080s respectively. Increase in high flows and decrease in low flows in the future periods was also predicted by the authors. Gosain et al. (2006) conducted a simulation on 12 river basins of India with size ranging from 1,668 to 87,180 sq. km for the period 2041-2060 using SWAT model and HadRM2 regional climate model. The results predicted a general decrease in future runoff. However, Gosain et al.(2011) used PRECI Sregional climate modelinA1b emission scenario along with SWAT model and found that for most of the Indian Rivers, the water yield will increase during 2030s and 2050s. According to their study, Godavari, Brahamani and Mahanadi River basins were not found to have water shortage and predicted rather severe flood conditions. However, decrease in peak flow magnitudes was observed for a few sub-basins of Ganga, Brahmaputra, Krishna, Cauvery and Pennar River basins.

Pechlivenidis et al. (2016) used climate projections from CORDEX- South Asia framework which were used to run the HYPE hydrological model to predict the runoff in the Ganga basin of Indian subcontinent. Their study revealed that variations in discharge due to climate change vary from season to season and region's hydro-climatic gradient is responsible for the magnitude of this variation. For Mahanadi River basin, Asokan and Dutta 2008 projected the highest increase in peak runoff (38%) for the period of 2075-2100 and the maximum decrease in average runoff (32.5%) in the month of April during 2050-2075.

Mudhatkal et al. (2017) assessed the climate change impact on the hydrology of the Sub-humid and Per-humid river systems that are originating in the Indian western mountain range (Western Ghats). The authors used modified Mann-Kendall test to evaluate the trend of data observed between 1975 to 2004 and RCP 4.5 data (2006-2070) of climatic variables. The Netravati River showed a decreasing trend of annual flow. In addition, a decreasing trend of high flow was estimated for Netravati, whereas the trend was found to be increasing for Malaprabha River. Thus, the climate change impacts on Western Ghats were very evident, but the flow of each river was found to respond differently.

Meenu et al. (2013), based on their study using HadCM3 GCM and the A2 and B2 scenarios, predicted that the average streamflow of river Tungabhadra will increase by 5.4 to 17.1% in 2050 and by 46% in 2080s. They used the downscaled precipitation and temperature data obtained from SDSM as input to HEC-HMS 3.4 model. Shah and Mishra (2018), evaluated changes in total runoff and streamflow in 18 Indian River basins using Variable Infiltration Capacity (VIC) model for RCPs 2.6 and 8.5. They found that streamflow is expected to rise in majority of the river basins except for the Indus basin under projected future climate (Figure - 7.3). The increase in total runoff and streamflow could be due to extreme precipitation during monsoon season.

7.3 Concluding Remarks

It is now well-established that the global climate change is causing and will continue to have a significant impact on the amount and the timing of river flows. In the present scenario, at the global scale and particularly in the context of the diverse Indian sub-continent, climate change has significant impact on annual flows of rivers, though to a different extent in different regions and in different times of the year.

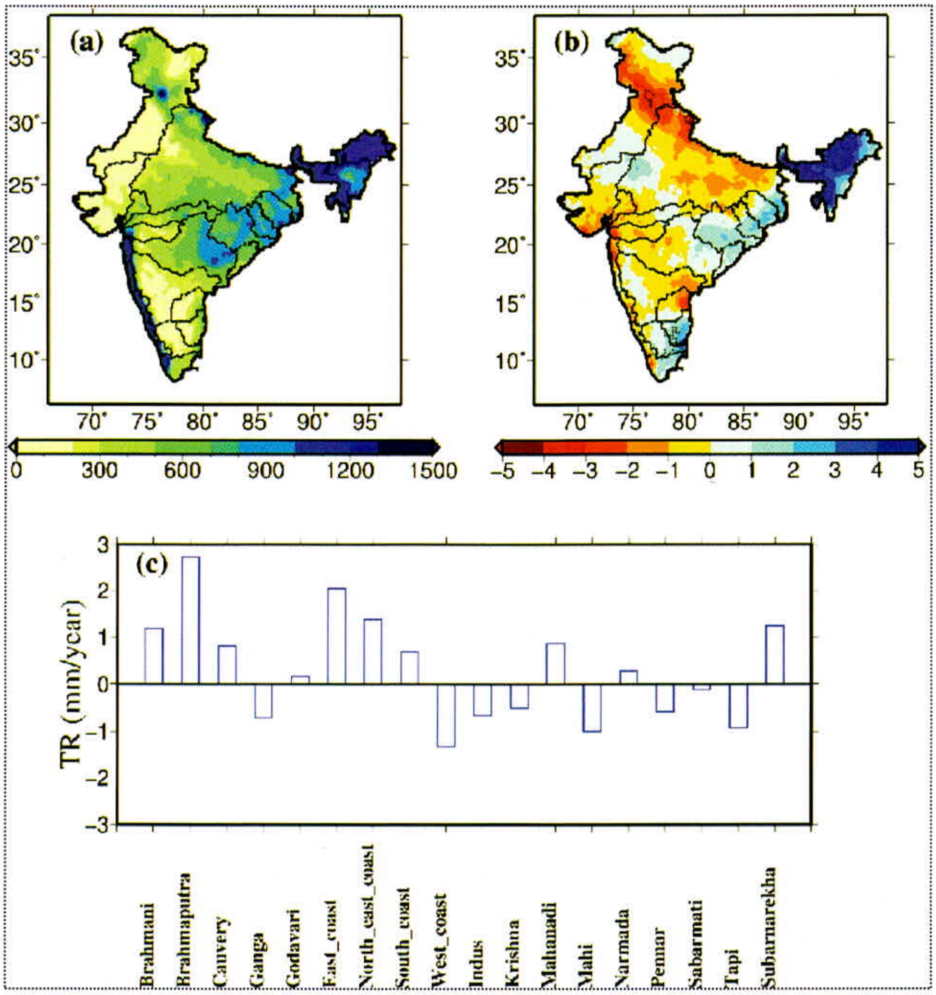

Figure - 7.3: *Ensemble historical mean of five GCMs (a) mean annual runoff (mm), (b) trend in total runoff (mm/year) estimated using Mann-Kendall test; and (c) basin averaged change in total runoff (mm/year) from 1970-99(Source: Shah & Mishra 2018).*

Regional climate dynamics is influenced by both, global climate and LULC changes. However, changes in LULC are often ignored in long-term regional climate projections. In a developing country like India, climate change, LULC change, and fast-pace changes in demography, urbanization, industrialization, and development of surface and groundwater resources have triggered major impact on water resources availability in the country. It is necessary to separate the relative contributions of climate change, LULC change, and impact of anthropogenic effects on runoff generation mechanism. Detailed modeling studies, that consider all such factors, should be carried out for different regions to establish the role and extent of impact of various influencing climate variables on the flow characteristics. These inputs can be useful in finalizing the adaptive strategies for mitigating the climate change impact.

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