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# Assessing impacts of potential climate change on watershed hydrologic response using flow duration curves (FDCs)

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**Abstract:** Local hydroclimatic variables such as temperature and rainfall, influence the streamflow response of watersheds by modulating the different processes of hydrological cycle. In this regard, the ramifications of projected climate change on water resources management at local and regional scales are diverse and need to be evaluated. The purpose of the study is to investigate the potential impacts of projected future climate change on streamflow regimes of a tropical agricultural watershed in India using the popular Soil and Water Assessment Tool (SWAT) hydrological model and high-resolution Indian Monsoon Data Assimilation and Analysis (IMDAA) climatic inputs for more accurate flow simulations. For flow simulations in future periods, downscaled and bias corrected climate model projections from three general circulation models (GCMs) are input to the hydrological model. With high resolution inputs, it is found that the SWAT model performed quite well during the baseline period. Finally, the flow duration curve (FDC) analysis is performed to quantify the likely impacts of climate change on flow regime in this watershed, specifically the annual maxima (AM) and inter-quartile range (IQR) values. The results suggest that the far-future will experience higher AM values with percentage increase of 44% and 61%, projected by BCC-CSM2-MR and MPI-ESM1-2-HR GCMs respectively, when compared with their baseline estimates. The results from the third GCM used in the study - EC-Earth3-Veg model suggest a general over-estimation of the high flows as compared to the BCC-CSM2-MR and MPI-ESM1-2-HR GCMs.

**Key words:** Soil and Water Assessment Tool (SWAT); Climate change; Flow Duration Curve (FDC); Indian Monsoon Data Assimilation and Analysis (IMDAA); General Circulation Model (GCM)

## 1. INTRODUCTION

Hydroclimatic variables such as rainfall and temperature, and their variability modulate and impact the different processes of the hydrological cycle (infiltration, evapotranspiration, groundwater recharge, surface runoff, baseflow) that finally affect the streamflow response at the outlet of the watersheds (Singh & Kumar, 2018). Farming, water supply and water resources management at local and regional scale are affected by the erratic patterns in these processes. Further, the projected anthropogenic future climate change with its inherent uncertainty, can have numerous implications on watershed hydrology as well as on hydroclimatic extreme events (Loukas et al., 2007; Maestro et al., 2014). These, in turn, pose challenges to water resources management, food security, and ecosystem resilience. Changes in precipitation patterns, including changing frequency, intensity, and distribution of rainfall and snowfall, have been known to influence runoff dynamics and water availability at watershed-scale (Trenberth, 2011; Tarmizi et al., 2019). Similarly, the increases in frequency and intensity of extreme events, such as heavy rainfall, have been found to exacerbate flooding, erosion, sediment transport, water quality deterioration and watershed degradation. These changes not only affect reliability of water resources systems but also pose dangers to aquatic ecosystems and human health due to increased transport of point and non-point source contaminants from these ecosystems that lead to pollution and hazardous algal blooms in water bodies. To address these challenges, integrated watershed management for promoting resilience to climate change impacts and to maintain the health and sustainability of watersheds is the need of the hour (Nilawar & Waikar, 2019). This process is inevitably dependent on our knowledge of the impacts of potential climate change on water balance and streamflow.

Simulation of hydrologic parameters using hydrological models under climate change scenarios is the first step in investigations undertaken for evaluating the possible implications of climate change on water resources at local scale. Hydrological models, ranging from simple conceptual models to complicated numerical models (WATFLOOD, VIC, MIKE-SHE, TOPMODEL, HEC, IHDM, and SWAT), are capable of simulating the local hydrological cycle, including processes such as evapotranspiration, surface runoff, and groundwater flow (Kavetski et al., 2003; Parajka et al., 2005; Meenu et al., 2013; Golmohammadi et al., 2014; Devi et al., 2015). Incorporating potential climate change scenarios with these models enables us to assess how projected changes in temperature, precipitation patterns, and other climatic factors are about to impact hydrological processes in short-term as well as long-term future. Furthermore, hydrological modeling under climate change can aid in watershed development by mitigating future risks of water stress, flooding, and/or water quality degradation (Chu et al., 2013; Campbell et al., 2018; Kwakye and Bardossy, 2022). Thus, by integrating climate projections with hydrological models, researchers and decision-makers can better understand future hydrological dynamics and develop effective measures to enhance water resource sustainability in a changing climate (Loukas et al., 2015).

The hydrological impacts of natural and anthropogenic climate change can be determined by combining simulations of hydrological models with future climate change projections. Global reanalysis datasets typically applied for investigating significant climatic patterns, trends, oscillations, and teleconnections (Kalnay et al., 1996) are less precise for regional/local water balance research because of their coarse resolution. Therefore, researchers have advised the use of high-resolution regional reanalysis data by various studies (e.g., Dahlgren et al., 2016; Aggarwal et al., 2022). High resolution datasets from general circulation models (GCMs) after downscaling and bias correction (Mohan and Bhaskaran, 2019) are important inputs to hydrological models in order to quantify the possible changes in future water balance at local scales. Regional models with high resolution allow more precise and broad investigation of climatic variables in reanalysis projects as compared to global models with lower resolution (Mesinger et al., 2006; Dahlgren et al., 2016; Yang & Kim, 2017; Bromwich et al., 2018). The Indian Monsoon Data Assimilation and Analysis (IMDAA), a regional atmospheric reanalysis product for the Indian subcontinent, has been beneficial in this regard. Due to its high resolution (12 km), the IMDAA rainfall data have the capacity to accurately reflect the dynamics of Indian summer monsoon rainfall and extreme rainfall events (Mahmood et al. 2018; Ashrit et al., 2020). Nevertheless, the potential of this reanalysis dataset for extended studies encompassing hydrological modelling, integrated watershed management, and climate change impact assessment is yet to be explored. We utilize this study as an opportunity for integrating high resolution regional reanalysis datasets with climate model data, that can then be used for simulating water balance under future climate.

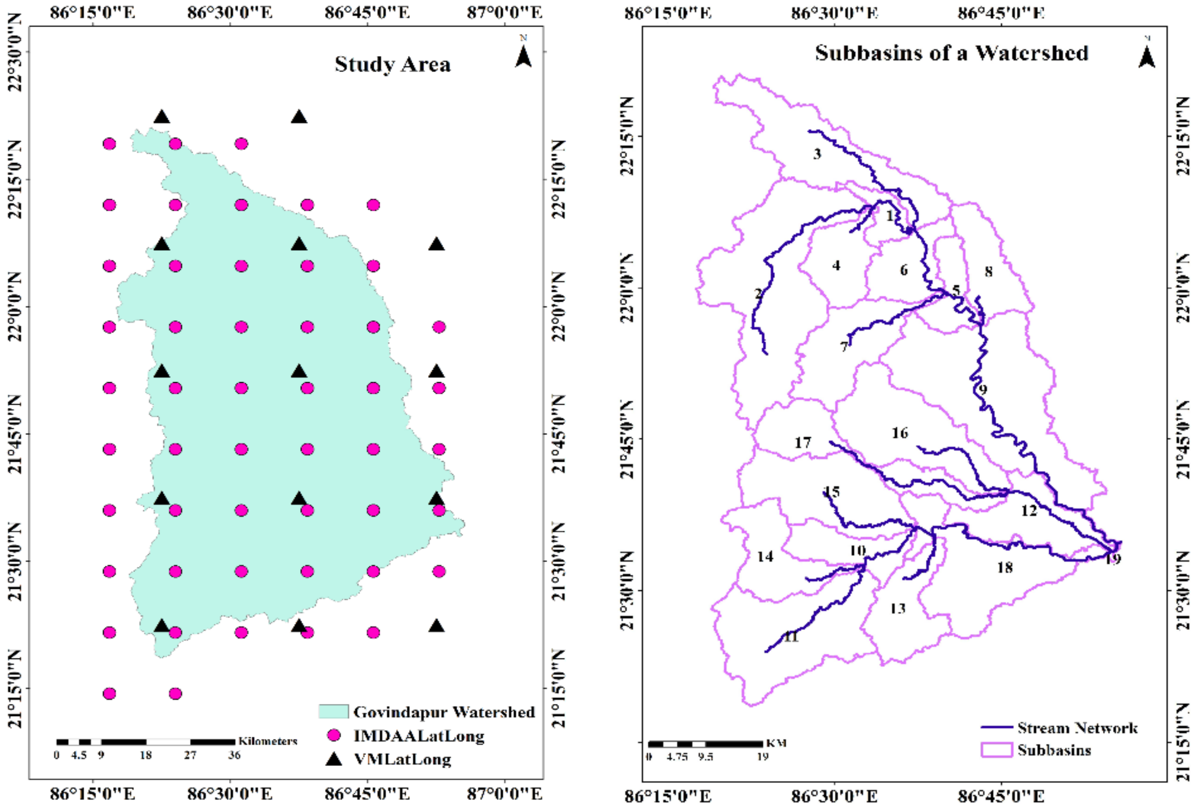
Additionally, hydrological models can aid in detecting changes in hydrological regime of streamflow that need to be studied in the context of climate change. This can be accomplished by using flow duration curve (FDC) analysis that shows the magnitude of low and high range daily streamflows (Cigizoglu and Bayazit 2000), and allows comparison between baseline and future flow regimes. Overall, FDCs are important for guiding sustainable water management practices and guaranteeing the resilience of water systems in the face of dynamic environmental challenges.

The primary objective of this study is to assess the potential impacts of projected future climate change on hydrologic response at watershed-scale, utilizing FDCs. We simulated the future streamflow for a tropical agricultural watershed located in eastern part of India using the popular SWAT hydrological model. The analysis is performed for two time slices in future, that is, near and far future. Future climate projections generated by different GCMs are firstly downscaled and bias corrected, and then input to the calibrated hydrological model for the study watershed. The future projections of climate variables are in fact generated at a high resolution (0.12° or 12-km) to improve the water balance simulations. Thus, the study (i) provides an assessment of future climate change at local scale as projected by three different GCMs, (ii) investigates how use of high resolution hydroclimatic data such as IMDAA reanalysis dataset can result in better performing hydrological models for impact assessment studies, and (iii) analyses the possible changes in future streamflow regime under climate change. During FDC analysis, annual maxima (AM) and inter-quartile range (IQR) parameters that highlight the regime changes in the low and high flows under climate change, are evaluated and compared.

## 2. MATERIALS AND METHODS

### *2.1 Study area and data*

The study area Govindpur watershed lies in the eastern part of India between 21°30' N to 22°38' N latitudes and 86°28' E to 86°94' E longitudes (Figure 1a). The average annual rainfall in the region varies in the range from 1000 to 2500 mm, and the mean minimum and maximum temperatures recorded in the region are 19°C and 30°C respectively. The major land-use in the study watershed is agricultural lands (40% to 50%), followed by forest area (40 % to 45%). The land use/land cover data is obtained at 1:250000 scale from the Bhuvan portal maintained by the National Remote Sensing Centre (NRSC) of Indian Space Research Organization (ISRO).




*(a) (b)*

*Figure 1. (a) Map of Govindpur watershed with GCM (VMLatLong) and IMDAA grid points and (b) drainage network*

We extracted daily streamflow data for the 1990-2014 (baseline) period, recorded at the outlet of this tropical watershed (see Figure 1b), from the India-Water Resources Information System (WRIS) web portal. Hydroclimatic data at daily time step and at 0.12° grid resolution for precipitation, maximum and minimum temperature for the baseline period, are obtained from the Indian Monsoon Data Assimilation and Analysis (IMDAA; Ashrit et al. 2020), an international collaboration project of the National Centre for Medium Range Weather Forecasting (NCMRWF), Government of India. The IMDAA project incorporated a range of meteorological datasets, such as surface observations, satellite imaging, and atmospheric soundings for developing the reanalysis data for facilitating high resolution estimates of atmospheric conditions and monsoon fluctuations across the Indian subcontinent. It has been known to generate accurate and timely predictions on the monsoon's commencement, intensity, and spatial distribution. Forty years (1979-2018) of these reanalysis products are available at https://rds.ncmrwf.gov.in (Mahmood et al. 2018). The IMDAA datasets are considered superior to the gridded rainfall (at 0.25° resolution) and gridded temperature (at 0.5° resolution) data available from the Indian Meteorological Department (IMD) owing to their high resolution as well as their ability to capture observed climatic patterns of the country.

For simulating future scenarios, we used the coupled multi-model inter-comparison project phase 6 (CMIP6; Eyring et al. 2016) GCMs' hydroclimatic data, that were downscaled to 0.25° spatial resolution and made freely available by Mishra et al. (2020). In this study, future periods of 2041-2070 (near future) and 2071-2100 (far future) are considered. Specifically, future climate projections from three different GCMs (BCC-CSM2-MR, EC-Earth3-Veg and MPI-ESM1-2-HR) corresponding to an extreme climate change scenario or shared socioeconomic pathway (SSP), known as SSP585 are utilized in this study. Further, in this study, these datasets are regridded to 0.12° resolution (see Figure 1a) using bilinear interpolation method, and then bias corrected using power transformation and CDF matching techniques utilizing IMDAA data (as proxy for observed hydroclimatic data for the study region).

### *2.2 SWAT hydrological model*

The Soil and Water Assessment Tool (SWAT) is a semi-distributed, continuous-time, process-based model (Arnold et al., 1998) that is capable of simulating impact of management on water, sediment, and agricultural yield in watersheds at daily time step. It was developed by the United States Department of Agriculture (USDA), to simulate the complex mechanisms that drive hydrologic processes at a catchment-scale, such as nutrient cycling/transport, streamflow, and soil erosion. SWAT requires diverse data sources including topography, soil properties, land use, and climate, for simulating hydrological response at the outlet of a watershed. The water balance equation on which the SWAT hydrological model is based, is presented in Equation 1.

$$SW_t = SW_0 + \sum_{i=1}^{t}\left(R_{day} - Q_{surf} - ET_i - W_{seep\ i} - Q_{gw}\right) \quad (1)$$

where $t$ is time (days), $SW_t$ is the final content of water in the soil (mm), $SW_0$ is the content of water in the soil at the start of stimulation i.e. day $i$ (mm), $R_{day}$ is precipitation on day $i$ (mm), $Q_{surf}$ is surface runoff on day $i$ (mm) is determined as given in Equation (2), $ET_i$ is evapotranspiration on day $i$ (mm), $W_{seep\ i}$ is soil interflow on day $i$ (mm), $Q_{gw}$ is return flow on day $i$ (mm), $S$ is the retention parameter (mm).

$$Q_{surf} = \frac{(R_{day} - 0.2S)^2}{(R_{day} + 0.8S)} \quad (2)$$

The calibration program in SWAT (SWAT-CUP) can be utilized to improve the precision and dependability of model forecasts by tackling parameter uncertainty. SWAT-CUP utilizes different optimization techniques to adjust model parameters based on observed data such as streamflow, sediment yield, and/or water quality parameters. In this study, the SWAT model is calibrated using the IMDAA baseline hydroclimatic data and observed streamflow, and further used for simulating flows using bias corrected GCMs' data for baseline and future periods for impact assessment study.

### *2.3 Flow duration curve (FDC)*

Flow duration curve (FDC) is a useful tool for watershed studies that provides detailed information about the river streamflow variations for the desired time scale. They represent the percentage of time that streamflow is equalled or exceeded for a given catchment (Boscarello et al., 2016). The cumulative frequency curve (see Figure 2) shows the percentage of time during which a certain magnitude of discharge may be equalled or exceeded (Holmes et al., 2002; Croker et al., 2003). FDCs are popular for hydrologic design and management actions concerning water supply, hydropower generation, irrigation, and hydrologic extreme events (Cigizoglu & Bayazit, 2000; Liucci et al., 2014). Moreover, FDCs facilitate the characterisation of watershed hydrology, allowing hydrologists to determine dominant flow regimes and quantify the implications of human activities and climate change on water resources and ecosystems. In the present study, FDCs are established based on the ranks assigned to the annual daily maxima values followed by estimation of exceedance probabilities. As shown in Figure 2, flow regimes are broadly classified into low, mid, and high regimes based on percentile values. Based on FDCs, popular flow characteristics such as annual maxima (AM, cumecs), inter-quartile range (IQR, cumecs) that is the difference between the 75th and 25th percentile flow magnitudes to measure day-to-day streamflow variability, as well as low flows corresponding to Q90 (cumecs) that is exceeded 90% of the time and high flows corresponding to Q10 (cumecs) that is exceeded only 10% of the time can be examined. In this study, impacts on AM and IQR are investigated under anthropogenic climate change in near and far future periods.

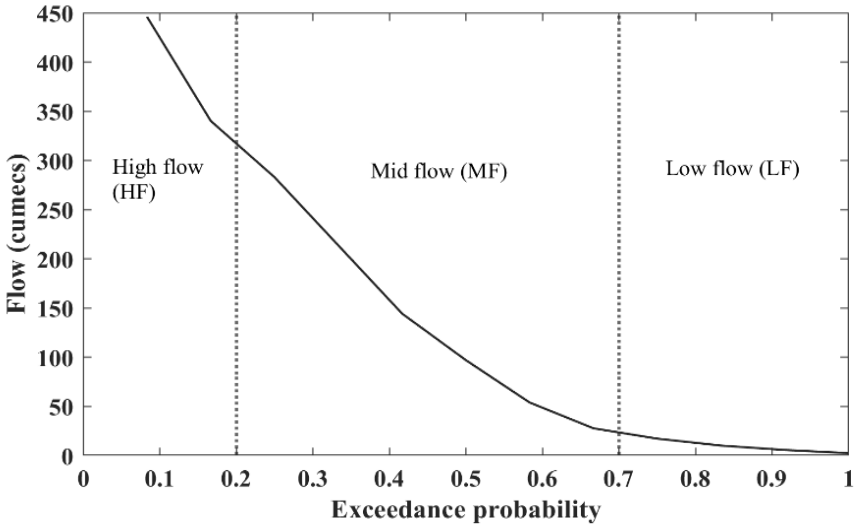



*Figure 2. Partitioning of flow based on flow duration curve (FDC) into four zones: peak flow (0%-1%), high flow (1%-20%), midflow (20%-70%), and low flow (70%-100%)*

## 3. RESULTS AND DISCUSSION

### 3.1 SWAT simulations using high resolution hydroclimatic inputs

Using IMD gridded rainfall and temperature data as inputs, SWAT hydrological model for the Govindpur watershed had been developed as part of a previous research study. The calibration and validation performance of the model (at monthly time step) measured using coefficient of determination ($R^2$) was observed in the range of 0.63-0.70 (Manekar and Ramadas, 2024). In this study, the performance of the same SWAT model input with the IMDAA datasets shows promising results: $R^2$ is obtained as 0.76. Figure 3 shows the comparison between observed flows and the SWAT simulated flows for the baseline period. In the next step, bias corrected inputs from the three GCMs are input to the calibrated SWAT model, for simulating baseline period streamflows. The baseline streamflows obtained for each GCM are then compared with the respective future simulated flows for assessing impacts of climate change on hydrologic response of the watershed as well as the FDC-derived flow characteristics (AM, IQR).

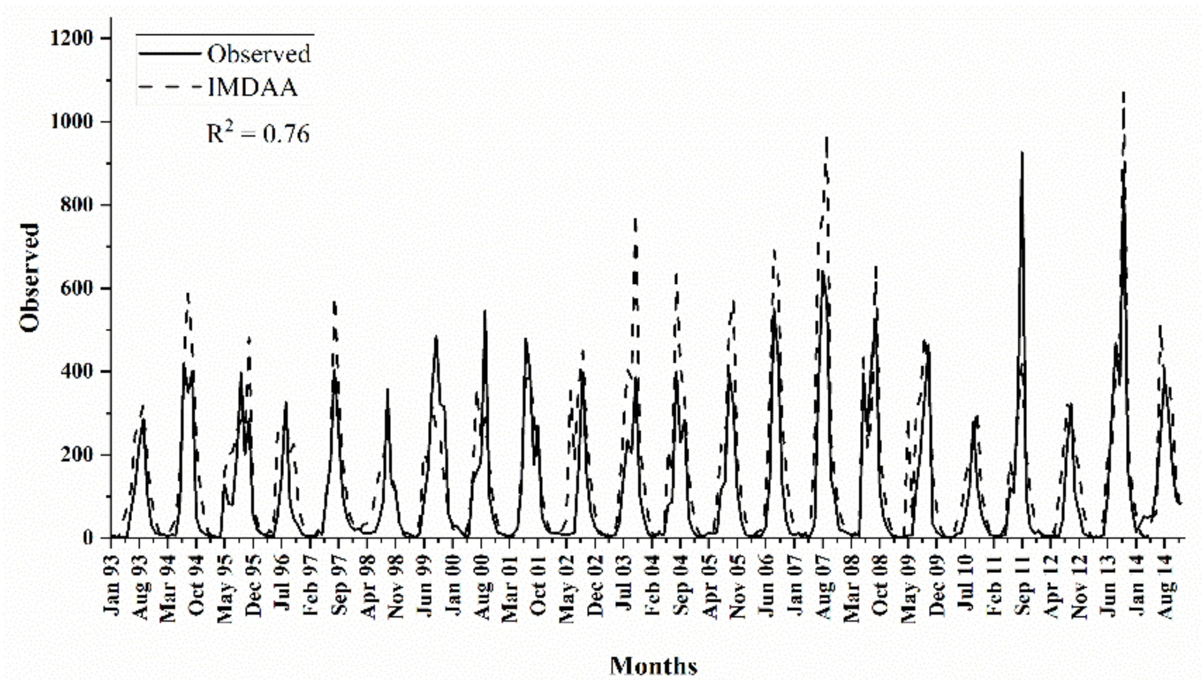



*Figure 3. Performance of SWAT simulated streamflow from the IMDAA data inputs with the observed flow data for the baseline period*

### *3.2 Future climate change assessment for Govindpur*

Figure 4 presents the changes in average monthly temperatures in the watershed. Increases in maximum and minimum temperature are projected by all the GCMs in the near future. For instance, for minimum temperature, increase is projected in the range 2-13% by the MPI-ESM1-2-HR GCM model, while in the case of maximum temperature, temperature increases are likely to vary in a smaller range 0.5-3.5% across the year. The projected increase is between 3-5.8% for maximum temperature and 4-22% for minimum temperature under BCC-CSM2-MR and EC-Earth3-Veg models under the considered SSP585 climate change scenario. Overall, the magnitude of change in temperatures are observed to be highest during the months of December to February.

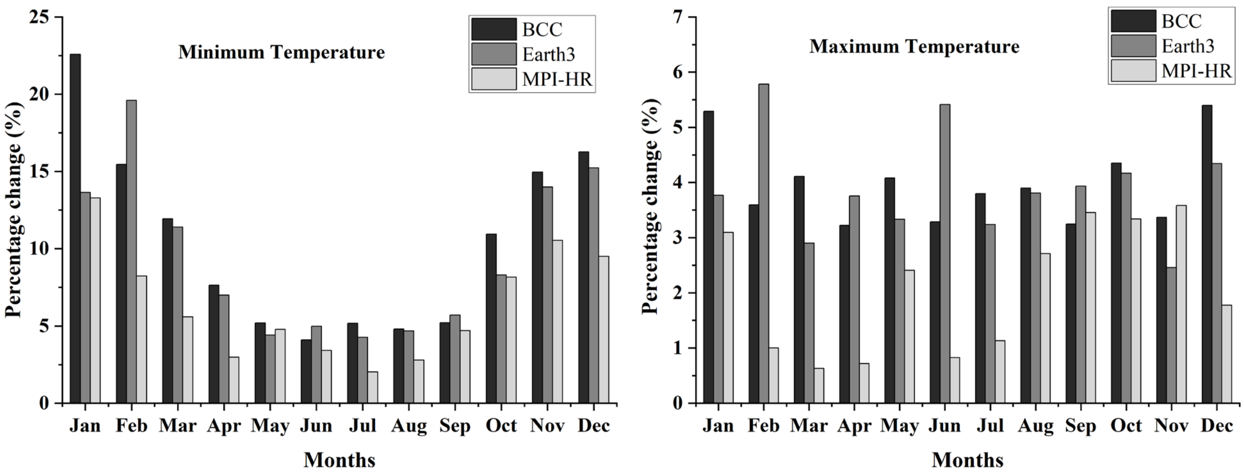



*Figure 4. Changes in minimum and maximum temperature under SSP585 scenario in near future (2041-2070) projected by the GCMs*

Projected changes in precipitation and streamflows in the near and far future periods obtained from the three different GCMs are tabulated in Table 1. While average rainfall in the study watershed is likely to increase during the future periods according to BCC-CSM2-MR (by 0.5-7%) and EC-Earth3-Veg (by 50-80%) models, the MPIESM1-2-HR model projected decrease (13-15%) in the average rainfall with maximum decrease in the near future. The streamflow variability is captured satisfactorily by the model-based SWAT simulations, however, in some cases, near and far future flows may be overpredicted, as is suspected in the case of the EC-Earth3-Veg model (Table 1). According to BCC-CSM2-MR model, an increase in the streamflow in the near future (7.2%) is likely whereas the decrease is projected in far future despite chances of increased precipitation. The decrease in streamflow (8-15%) as indicated by the MPIESM1-2-HR model projections in fact agree with the projected decrease in precipitation resulting in both the time periods.

*Table 1. Percentage change in the precipitation and streamflow for the near and far future time period under SSP585 scenario*

| | Rainfall | | Streamflow | |
|---|---|---|---|---|
| | Near future (2041-2070) | Far future (2071-2100) | Near future (2041-2070) | Far future (2071-2100) |
| BCC-CSM2-MR | 0.66 | 7.26 | 7.20 | -5.42 |
| EC-Earth3-Veg | 53.69 | 73.76 | 11.08 | 36.34 |
| MPI-ESM1-2-HR | -14.55 | -13.23 | -15.57 | -8.29 |

### *3.3 Future flow characteristics using FDC analysis*

Changes observed when future streamflows simulated using different GCMs are compared with baseline flows also reflect the changing flow regime characteristics at local and regional scales. Comparison of FDCs of baseline and future periods as shown in Figure 5 suggest that high flows (Q10) are likely to increase slightly (by 2%) in the far future as per BCC-CSM2-MR, while MPI-ESM1-2-HR projects a large increase (67%). But, a reduction of the low flows (Q90) is projected in the future ranging between 6% to 47%, implying possible depletion of water resources in this region and water supply shortages for meeting different demands during the non-rainy periods.

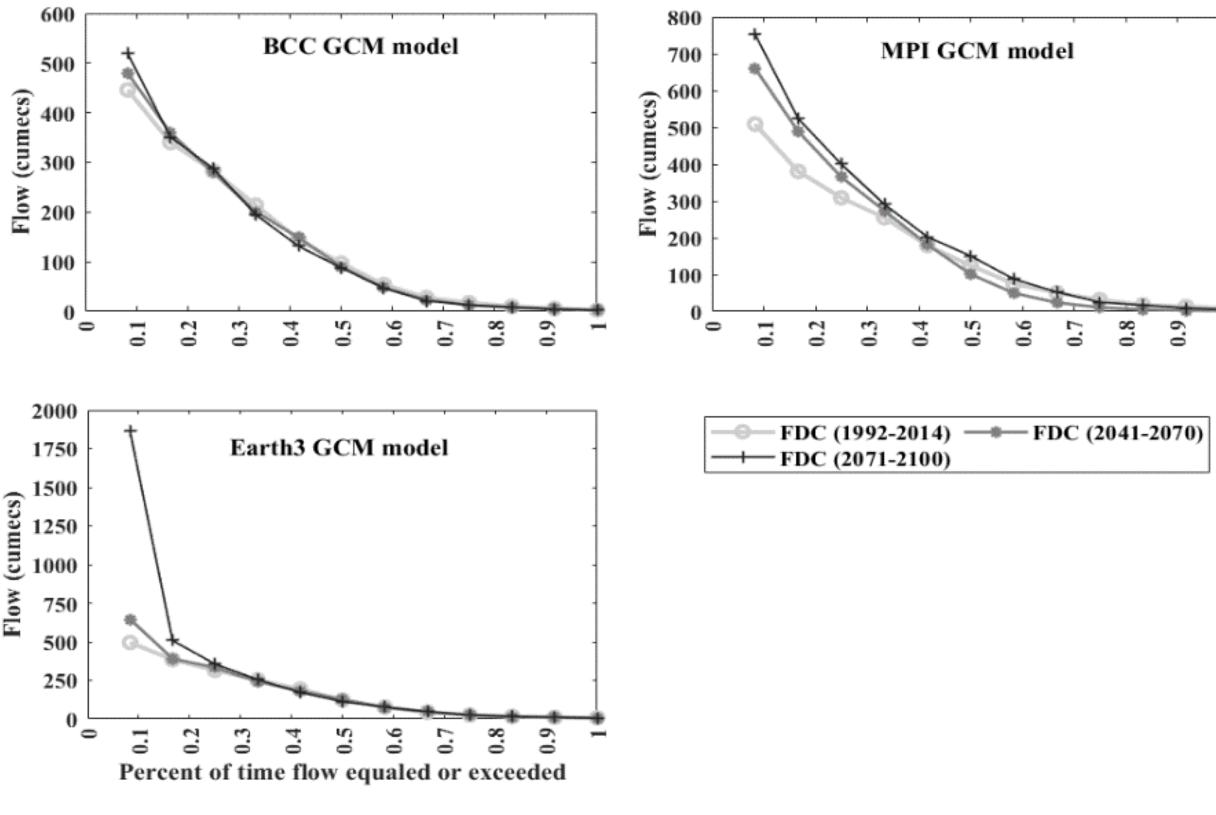



*Figure 5. Comparison of FDCs of the baseline period with future projections from GCMs*

Without considering the temporal variations in land use or water usage in the watershed, the patterns observed in the streamflow trends in this study watershed is assumed to be due to effect of temporal variation in the climatic conditions. In this study, annual maxima (AM) and inter-quartile range (IQR) factors are computed for different GCMs for baseline (1992-2014), near future (2041-2070), and far future (2071-2100) climate scenarios. It can clearly be seen from the Figure 6 that BCC-CSM2-MR model is showing great variability under different time period with respect to both AM and IQR. The maximum values of flow are observed to be increasing in the far-future with the average flow value of 3340 cumecs. Whereas, the average flow values for the baseline and near future are found to be 2327 and 2695 cumecs respectively. The IQR plot suggests that the trend is negative in nature for baseline and near future, but resulting in positive trend in far future (Figure 6) indicating presence of moderate flow in the stream for the designated period. The variability within the 75$^{th}$ and 25$^{th}$ percentile flow is higher (275 cumecs) in the far-future period, whereas baseline (266 cumecs) and near-future (268 cumecs) values are lower, suggesting temporal variability in flows under climate change.

Similar analysis performed using the MPI-ESM1-2-HR GCM flows (Figure 7) suggests that there is positive trend for annual maxima under all the three time periods (baseline, near, and far future). With the baseline flow values ranging from 1700-7500 cumecs, near future flow values varied from 1300-10000 cumecs, whereas the values ranging from 1700-13000 cumecs are observed in far future under MPI-ESM1-2-HR climate change. In fact, a greater variability can be seen in IQR values under this model, with a difference between 75$^{th}$ and 25$^{th}$ percentile flow values of 277 cumecs under baseline, 354 cumecs under near-future, and 417 cumecs under far-future climate scenarios. This suggests that a large uncertainty is present in the flow results obtained for MPI-ESM1-2-HR model with far-future period projected to be highly vulnerable to climate change impacts.

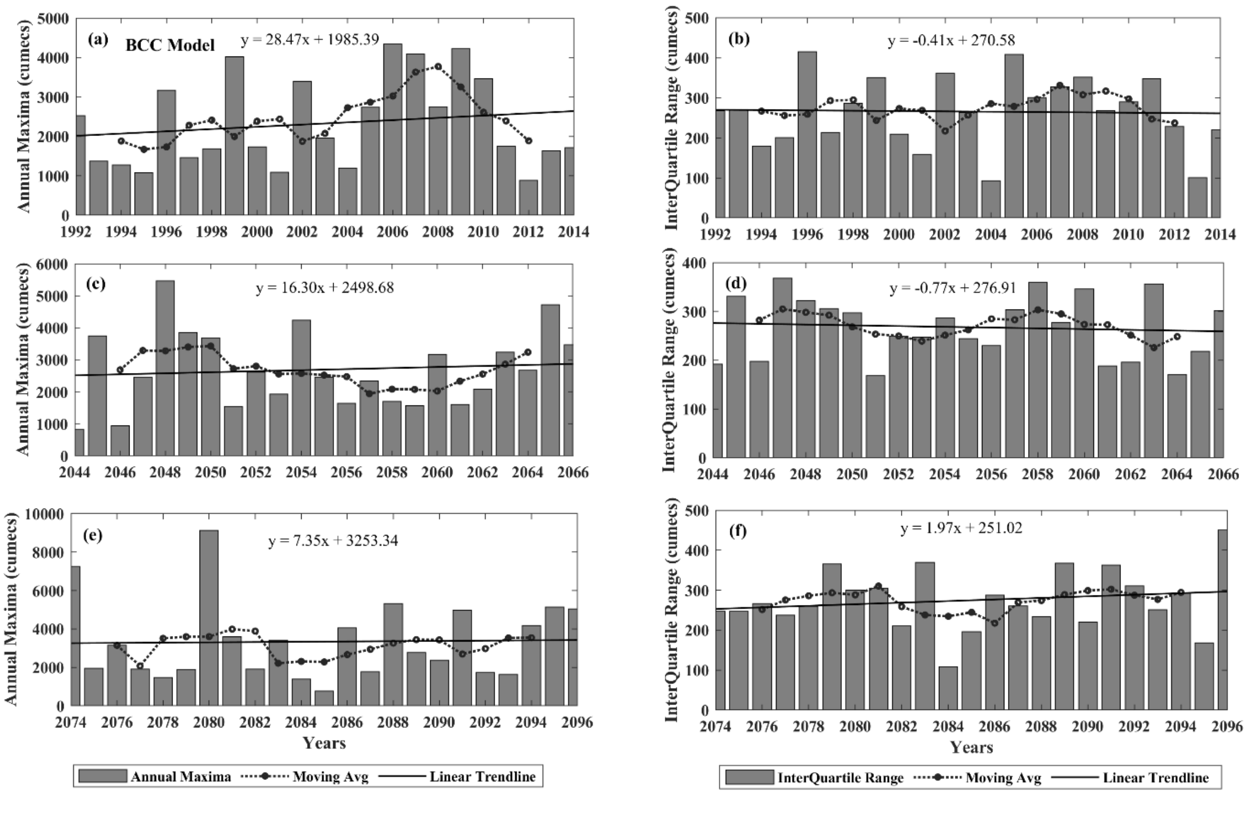



*Figure 6. Comparison of (a) annual maxima (b) inter-quartile range of the baseline period with future projections from BCC-CSM2-MR GCM*

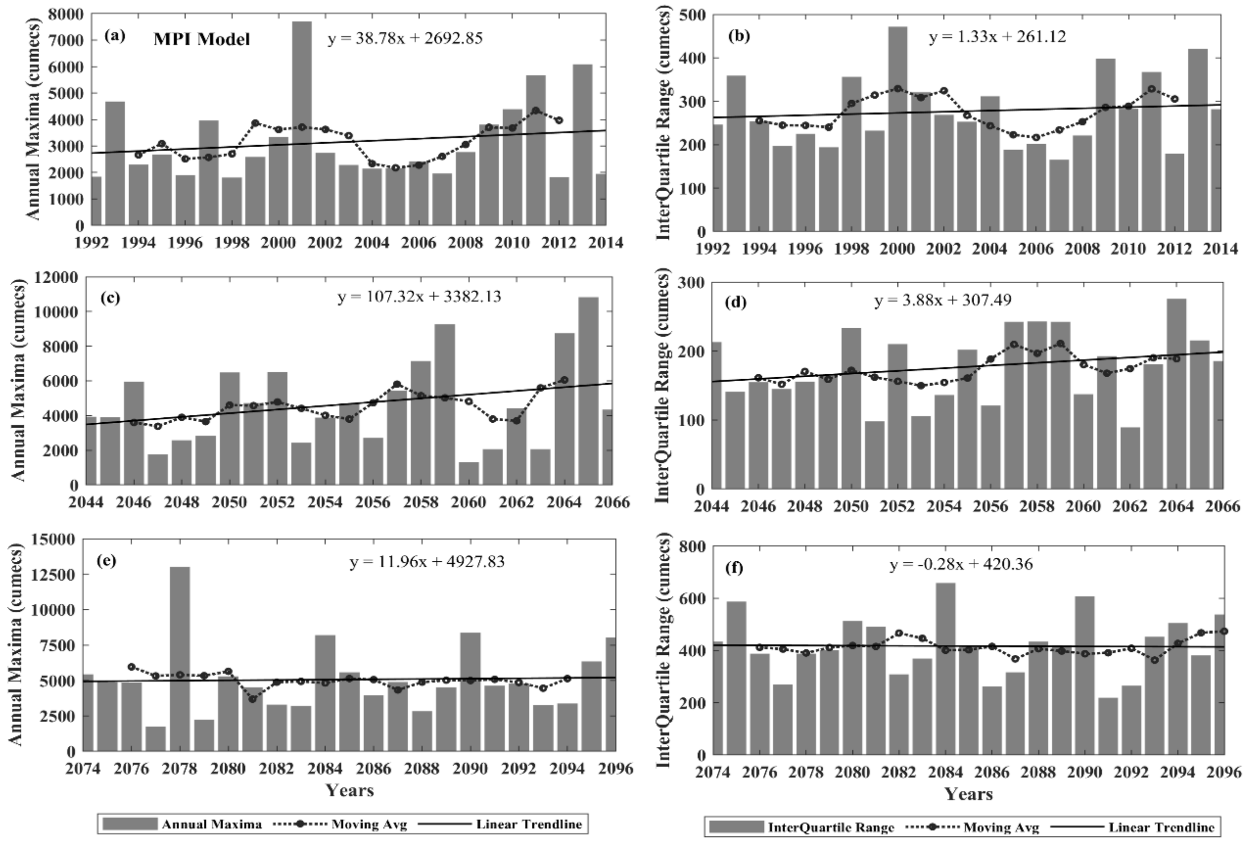



*Figure 7. Comparison of (a) annual maxima (b) inter-quartile range of the baseline period with future projections from MPI-ESM1-2-HR GCM*

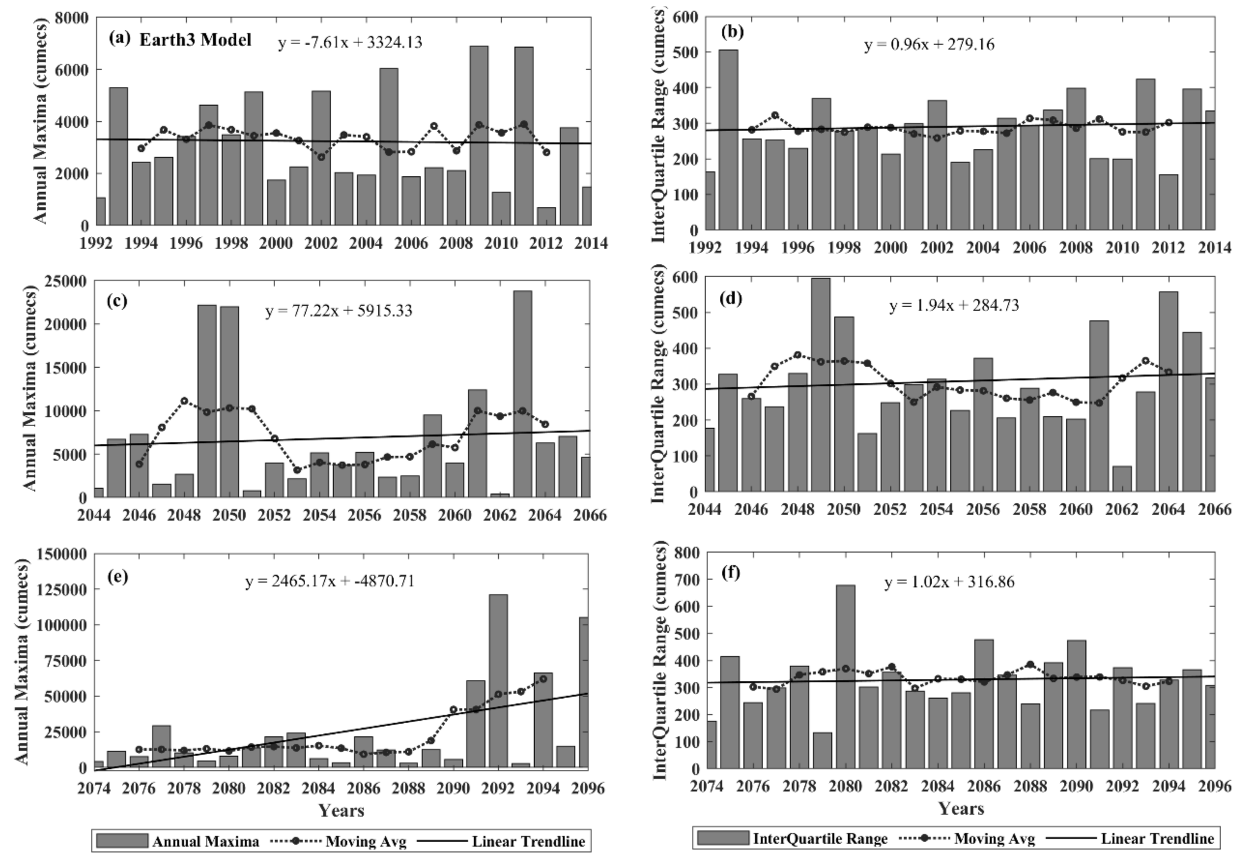



*Figure 8. Comparison of (a) annual maxima (b) inter-quartile range of the baseline period with future projections from EC-Earth3-Veg GCM*

The results obtained from the EC-Earth3-Veg GCM illustrates that annual maxima values are showing negative trend under baseline climate but having positive trend in the near-future and in the far-future periods, that also shows the uncertainty associated with this GCM model (Figure 8). The captured average annual maxima values in the different time periods are 3200 cumecs under baseline, 6800 cumecs under near-future, and 25000 cumecs under the far-future periods respectively. The decade 2090-2100 in the far-future is likely to be experiencing high flow conditions according to this GCM. Overall, IQR results shows there is a positive trend under all the climate scenarios. But there lies a great volatileness within the minimum and maximum values of the IQR over different climate scenarios, where the baseline is resulting IQR values in the range 156-506 cumecs, it varies between 71-600 cumecs in near-future and 133-680 cumecs in the far future.

## 4. SUMMARY AND CONCLUSIONS

In general, the study area is projected to experience higher maximum and minimum temperatures and overall increase in rainfall in future periods under SSP585 climate change scenario. The variability among GCM projections is noteworthy, suggesting uncertainty inherent in climate change impact assessment studies at local and regional scales. The study then utilized the high resolution hydroclimatic inputs in conjunction with calibrated hydrological model of the Govindpur watershed to predict future streamflows as well as to assess the future flow characteristics in the face of climate change. The FDC analysis suggest that both AM and IQR trends vary with the GCM used as well as vary temporally between near (2041-2070) and far future (2071-2100) periods under SSP585 climate change scenario.

The results of the study have demonstrated how tropical watersheds having distinct wet and dry climatic conditions and distinct land use patterns are impacted by climate change, by highlighting the changes in flow characteristics in near and far future. As projected by the GCMs used in this study, a reduction in the low flows in the future can lead to severe water stress, and scarcity of water resources for agricultural and domestic use in this region. Similarly, annual daily maxima increases can be correlated with increased flood peaks and consequent watershed degradation through erosion and disastrous flooding events. The study thus caters to the need for planning and conservation of water resources in the region during dry season and adaption to floods and extreme rainfall events to improve the resilience at a watershed-scale.

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