

# Identifying the Potential Impacts of Climate Change on Streamflow in a Humid Tropical Basin



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**Abstract** The preservation of ecosystems in a river is based upon the replication of its original pristine conditions in the river regime. One of the main variables influencing a region's hydrology is climate change. The research investigated the impact of climate change on the streamflow within the Meenachil River basin located in Kerala, India. The present study employed the Soil and Water Assessment Tool (SWAT) model to simulate the hydrological processes of the basin. The calibration and validation of the model are done, and the model performance is determined considering the Nash Sutcliffe Efficiency (NSE), coefficient of determination ( $R^2$ ), and percentage bias (PBIAS), and it is observed to be good. The data for the future climate are taken from National Aeronautics and Space Administration (NASA) Earth Exchange Global Daily Downscaled Projections (NEX-GDDP) data for Representative Concentration Pathway (RCP) 4.5. The response of streamflow to the climate in the future time period (2025–2099) is evaluated by considering three scenarios, S1, S2, and S3, with reference to a baseline scenario. In order to analyze the impact of climate change in the basin, the high and low flow indices (Q5 and Q95) of the scenarios under consideration are established using the flow duration curve of annual streamflow. Q5 showed a reduction of 20, 8.3, and 1.6% for the considered scenarios compared to the baseline period. The low flow index, Q95, showed an increase of 9.8, 15.3, and 15.1% in the scenarios concerning the baseline period. The findings of the present study will aid in developing adaption techniques for improved basin-wide management of water resources.

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## 1 Introduction

Water is a valuable natural resource and the basis of all other natural resources [10]. The environmental protection and sustainable growth of an area are highly dependent on its water resources [5]. At global, regional, and local levels, climate change is seen as a key factor impacting the availability and quality of water [8]. Increasing temperatures since the middle of the twentieth century may be directly attributed to the warming effects of increased quantities of greenhouse gases, which have been documented across the climate system. The intricate interdependence of the worldwide climate system is underscored by the fact that forthcoming climatic conditions and their impacts on ecological systems are contingent upon not only greenhouses gas emissions but also economic status and developmental strategies [14]. The extent of these alterations will be contingent upon forthcoming human activities alongside technological and economic advancements [15]. It is expected that climate change and the subsequent increase in atmospheric CO<sub>2</sub> concentration will have an impact on hydrological systems across the globe [14].

The phenomenon of climate change can disrupt the typical hydrological processes, potentially resulting in significant consequences for the water resources of a region [6]. Any changes in the distribution of climate variables affect surface water and water vapor circulation [17]. This indicates that the implications of climate change give rise to various adverse impacts on society [11]. Climate change directly affects the hydrology cycle, triggering a cascade of effects that affect, among other things, agriculture, energy, and ecology. Assessing how climate change may affect local and regional water supplies comes first before designing mitigating efforts. The topic of climate change has been the subject of extensive research in numerous large-scale watersheds worldwide. Further investigation is necessary to evaluate the influence of climate change on watersheds at a more localized level. Implementing improved water management strategies can be facilitated through this approach [11].

Studies on the effect of climate change on water resources, especially at the catchment scale, are important as the developmental activities of the region depend on these resources [6, 12]. The most advanced tools for predicting climate variability and changes are General Circulation Models (GCM) [7]. To examine the consequences of climate change, GCM models are most often used to analyze the manner in which various scenarios will affect hydrological systems. To perform an effect assessment at the basin size, we downscale the GCM's global-scale simulation to the basin scale [17]. The Coupled Model Intercomparison Project (CMIP) of the World Climate Research Programme (WCRP) has produced GCMs that serve as valuable instruments for comprehending the mechanisms of historical climate and predicting potential future climate alterations based on hypothetical emission scenarios [14]. The coarser scale GCM simulations are scaled down to a finer scale, and simulations

under different emission scenarios are incorporated in impact assessments [17]. The need for hydrologic models to understand the effects of the changing climate on the water balance is growing. Climate, Soil, and Land use land cover (LULC) are just a few examples of the critical inputs required to run hydrologic models. The incorporation of climate data is a crucial factor in determining the output of computer models' simulations. The climate projections necessary for conducting climate research are obtainable at a less detailed resolution from various GCMs. However, to utilize these data in hydrologic simulations, it must be refined at the Regional Climate Model (RCM) level. The conversion of data from GCMs to RCMs necessitates the implementation of bias correction and downscaling techniques. Future climate data resolution and simulation accuracy are critical for the success of climate change research evaluation [11]. The most common method for impact assessment is to drive a hydrological model with GCM outputs [12, 14].

This research investigates the effects of climate change on the hydrology of the Meenachil basin in Kerala, India. To simulate the climate change effects in the research, the SWAT hydrological model is used. Possible applications of these findings include improved water resource management and implementing measures to mitigate the regional impact of climate change.

## 2 Methodology

### 2.1 Study Area

The Meenachil Basin (Fig. 1) in Kerala, India's southernmost state, is selected for study. This is a west-flowing river, which discharges into Vembanad Lake before flowing onto the Arabian Sea. The Western Ghats mountain range defines the basin's eastern border. The Meenachil River originates at Araikunnumudi, which is located at an elevation of 1097 MSL; the basin's drainage area is 1272 km<sup>2</sup>. The study area has a hot and humid climate. The southwest monsoon, which lasts from the month of June to September, contributes to the majority of the region's rainfall and is followed by the northeast monsoon, which continues from October to November. The region receives around 3000 mm of rain on average each year, and the temperature falls between 17 and 37 °C. The region gets sufficient rainfall during the monsoon yet experiences water shortages throughout the summer.

### 2.2 Dataset

The inputs to hydrological modeling include Digital Elevation Model (DEM), climate data, soil map, hydrological data, and LULC maps. The ASTER DEM of 30 m resolution and the Food and Agriculture Organization (FAO) soil map is used in the study.

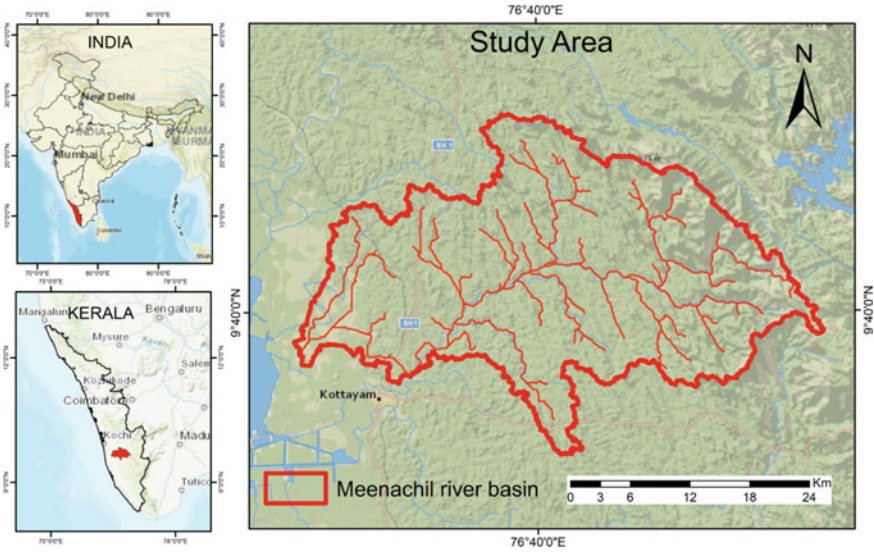


Fig. 1 Location of the study area

The Landsat satellite imagery is extracted from the Google Earth Engine platform and classified with a Random Forest algorithm to prepare the study’s LULC map [3]. India Meteorological Department (IMD) gridded rainfall, maximum and minimal temperatures, as well as NASA power grid data for solar radiation, relative humidity, and wind speed, serve as the climatic data for the historic period. The NEX-GDDP dataset of resolution  $0.25^\circ \times 0.25^\circ$  under the emission scenario RCP 4.5 is considered for the future. The models (Table 1) are considered based on ranking for selecting a suitable subset of GCM [2]. For future precipitation, the ensemble mean of MIROC-ESM-CHEM (Model for Interdisciplinary Research on Climate Earth system models CHASER-coupled version), MIROC-ESM (Model for Interdisciplinary Research on Climate Earth system models), BCC-CSM1-1 (Beijing Climate Center Climate System Model. Version 1) and NorESM1-M (Norwegian Earth System Model, Intermediate Resolution) is taken. The ensemble mean of MIROC-ESM-CHEM, MIROC-ESM, MPI-ESM-MR (Max Planck Institute Earth System Model at the mixed resolution version), and MPI-ESM-LR (Max Planck Institute Earth System Model at the low-resolution version) are employed for maximum temperature, whereas for minimum temperature, the models MIROC-ESM-CHEM, MRI-CGCM3 (Meteorological Research Institute coupled atmosphere–ocean general circulation model 3), BNU-ESM (Beijing Normal University Earth System Model), and MIROC-ESM are applied. The streamflow data collected from the Central Water Commission (CWC), India website are used in model calibration and validation.

**Table 1** GCMs considered in the study [2]

Model	Modeling institution
BNU-ESM	Institute of Global Change and Earth System Sciences, Beijing Normal University, China
MIROC-ESM MIROC-ESM-CHEM	Atmosphere and Ocean Research Institute, Japan
MPI-ESM-LR MPI-ESM-MR MRI-CGCM3	Max Planck Institute for Meteorology, Germany
NorESM1-M	Norway Consumer Council, Norway
BCC-CSM1-1	Beijing Climate Centre, China

### 2.3 Hydrological Modeling with SWAT

Streamflow is a crucial component of the hydrologic cycle, and alterations in precipitation and evapotranspiration brought about by climate change can significantly impact streamflow [18]. The interconnections and associations between flow regimes and ecosystems hold significant value in forecasting the reactions of riverine ecosystems to global transformations. Additionally, they aid watershed managers in identifying efficacious strategies to sustain the equilibrium of riverine and wetland ecosystems. Environmental alterations exert a direct influence on the hydrological mechanisms of a watershed, thereby affecting its flow dynamics. Distributed hydro-ecological models have proven to be efficacious instruments for examining the impacts of alterations in water flow on riverine ecosystems. These models have limits in forecasting riverine ecosystem responses to environmental changes such as climate change, LULC, and water and soil management for conservation methods such as the implementation of vegetation filter strips, agricultural management practices such as alterations in fertilizer application methods, and rules governing water retention structures. Enhancing the predictive capabilities of said models regarding low flow has emerged as a prevalent issue among hydrological and hydro-ecological communities [20].

The hydrological processes in the research basin are simulated using the SWAT model [4]. The division of the watershed into sub-basins is followed by a further subdivision into Hydrologic Response Units (HRUs), which take into consideration the regional variation based on LULC and soil. The land phase and the routing phase make up the majority of the SWAT modeling of the hydrologic cycle. Water, nutrients, sediments, and pesticide loadings for each HRU are first calculated during the land phase. Sub-basin loadings are then calculated by adding the loads from all HRUs located within that sub-basin. The sub-basin major channel is loaded with the resultant sediment [20]. The hydrological processes in the model are determined by the water balance calculation, which serves as the governing equation. The soil conservation service (SCS) curve number (CN) approach is used in the model to determine the surface runoff from a watershed [19] and is determined as

$$Q_{surf} = \frac{(R_{day} - 0.2S)^2}{(R_{day} + 0.8S)} \tag{1}$$

where ‘ $Q_{surf}$ ’ is the surface runoff in mm, ‘ $R_{day}$ ’ is the precipitation in mm, and ‘ $S$ ’ is the potential maximum retention. The methodological framework of the study is shown in Fig. 2.

The model is calibrated and validated by the use of the SUFI-2 in SWAT CUP [1]. The model’s efficacy in modeling streamflow is evaluated with a coefficient of determination ( $R^2$ ), Nash–Sutcliffe efficiency (NSE), and Percent Bias (PBIAS). The mathematical expression for determining the performance indicators is as follows:

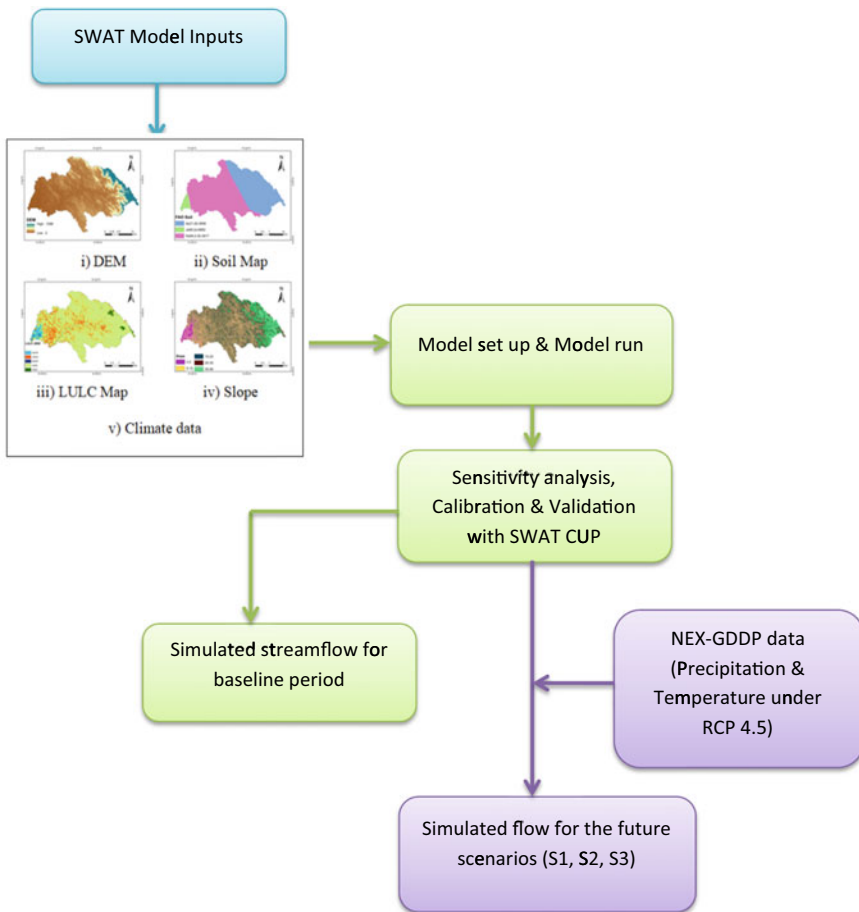


Fig. 2 The methodological framework of the study

$$R^2 = \frac{\sum_{i=1}^n (Q_{\text{obs}} - \overline{Q_{\text{obs}}}) * (Q_{\text{sim}} - \overline{Q_{\text{sim}}})}{\sqrt{\sum_{i=1}^n (Q_{\text{obs}} - \overline{Q_{\text{obs}}})^2} * \sqrt{\sum_{i=1}^n (Q_{\text{sim}} - \overline{Q_{\text{sim}}})^2}} \quad (2)$$

$$\text{NSE} = 1 - \frac{\sum_{i=1}^n (Q_{\text{sim}} - Q_{\text{obs}})^2}{\sum_{i=1}^n (Q_{\text{obs}} - \overline{Q_{\text{obs}}})^2} \quad (3)$$

$$\text{PBIAS} = \frac{\sum_{i=1}^n (Q_{\text{sim}} - Q_{\text{obs}})}{\sum_{i=1}^n Q_{\text{obs}}} \quad (4)$$

where  $Q_{\text{obs}}$  and  $\overline{Q_{\text{obs}}}$  are the observed and the average streamflow;  $Q_{\text{sim}}$  and  $\overline{Q_{\text{sim}}}$  are the simulated flow and the mean simulated flow, respectively. The variable 'n' represents the quantity of data points related to the flow. Several researchers have utilized the model to examine the hydrological events at the river basin scale [5–8, 14, 16].

### 3 Results and Discussion

#### 3.1 Future Climate in the Study Area

The expected changes to the climate variables, maximum and minimum temperature, and precipitation are determined (Fig. 3) by considering the baseline period from 1991 to 2015. Three-time slices are selected from the future, P1 (2025–2049), P2 (2050–2074), and P3 (2075–2099). The three-time slices exhibited a rise in the mean annual, monthly, and seasonal temperatures compared to the baseline period. The mean annual maximum temperature rises by 1.4%, 3%, and 4.4%, respectively. The minimum temperature showed a higher increase with a 6, 9, and 11% rise compared to the baseline. The mean temperature showed the highest value during the Pre-monsoon season (April). At the end of the century, it is anticipated that the percentage change in the maximum and minimum temperature will be significant in the time slice P3. The warming climate expected in the future increases the susceptibility to drought in the region [16]. Also, temperature rise accelerates the hydrological cycle, which leads to changes in the timing and quantity of rainfall and runoff in the area [10]. The average annual precipitation for the future scenarios is found to be less compared to the baseline scenario by 9%, 27%, and 10%, respectively, suggesting a decrease in rainfall in the basin. Monthly analysis reveals that there is a reduction in precipitation during the monsoon months, June and July, whereas there is an increase during August and September. The pattern of seasonal precipitation is likewise similar, with the exception of winter, where the precipitation is found to be increasing compared to baseline scenario.

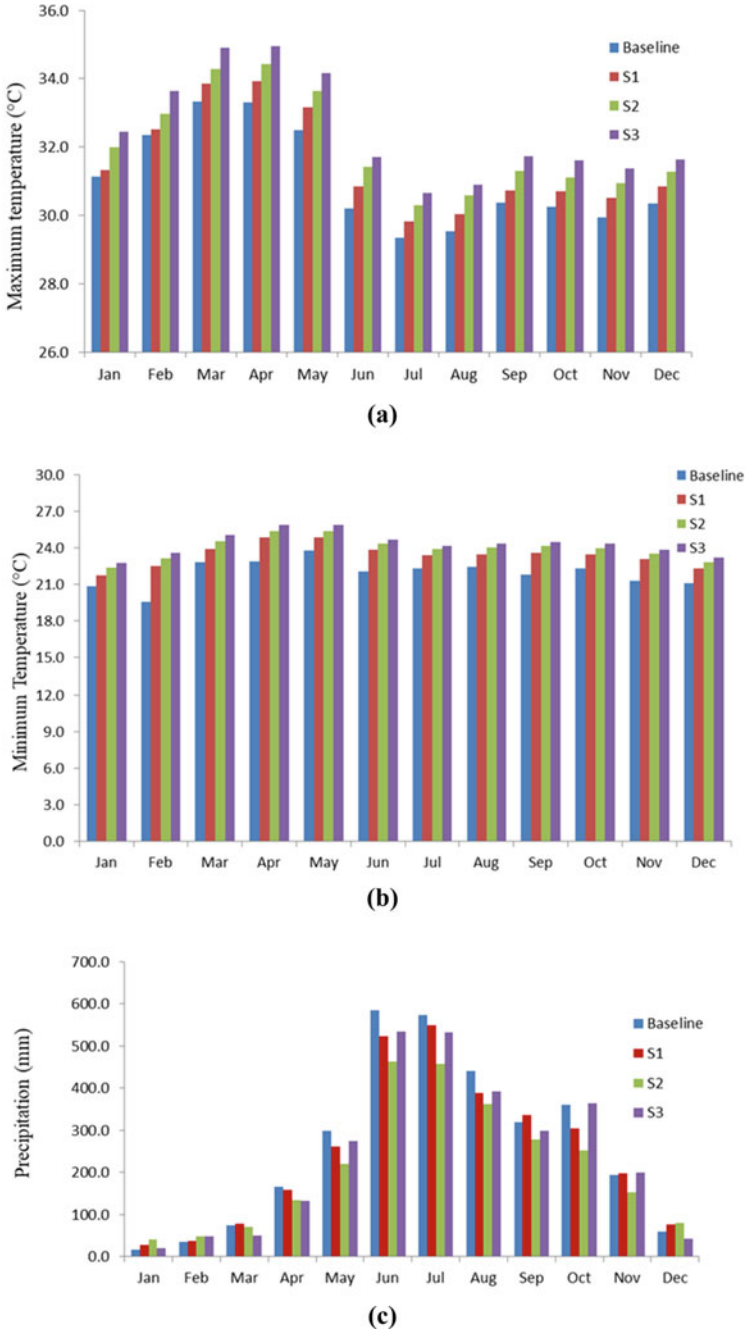


Fig. 3 Monthly variation of climate variables in the study basin: a Maximum temperature (°C), b Minimum temperature (°C), c Precipitation (mm)



### 3.2 Model Calibration and Validation

Before beginning the calibration process, the sensitivity analysis is taken into consideration. The SUFI 2 technique included in SWAT CUP is used for calibration and validation of the SWAT model. The parameters for sensitivity analysis are selected based on previous literature. The rank obtained for the selected parameters after sensitivity analysis is shown in Table 2. The most critical parameter is found to be SCS-CN (SCS curve number for moisture condition II), followed by SOL\_BD (Moist bulk density), ESCO (Evaporation compensation factor), and other parameters. The SWAT model is calibrated for streamflow using historical climate data and LULC for the year 2000. The observed monthly flow at the gauging station, Kidangoor, during (1988–2001) is used for calibration, and (2009–2015) is used for validation. The  $R^2$  and NSE values obtained are greater than 0.8, and PBIAS within  $\pm 10\%$  for calibration as well as validation (Table 3). From the validation, it is found that satisfactory results are obtained in the simulation of the streamflow in the Meenachil basin (Fig. 4).

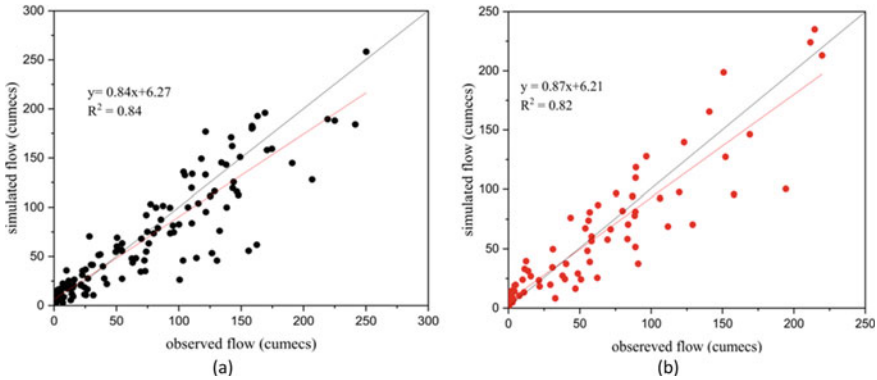
The climate change impact is further studied with the calibrated validated model. The simulated streamflow from 1991 to 2015 is considered a baseline scenario. The future time period from 2025 to 2099 is considered in three-time slices to generate three scenarios, S1, S2, and S3. Scenario S1 indicates simulated streamflow from

**Table 2** Parameters considered and ranks obtained in hydrological modeling

Parameters	Lower limit	Upper limit	Fitted value	t-stat	Rank
r__CN2.mgt	-0.2	0.2	-0.18	6.75	1
r__SOL_BD().sol	0	1	0.65	4.989	2
v__ESCO.hru	30	450	166.69	2.217	3
v__CANMX.hru	0	2	1.78	1.055	4
v__GWQMN.gw	0	500	147	0.828	5
v__REVAPMN.gw	-0.25	0.25	0.036	0.719	6
v__GW_REVAP.gw	-0.25	0.25	0.306	0.151	7
r__SOL_Z().sol	-0.25	0.25	-0.0167	0.1172	8
v__EPCO.hru	-0.25	0.25	-0.13	0.1088	9
r__SOL_K().sol	0	1	0.235	0.1013	10
v__GW_DELAY.gw	0	1	0.61	0.0746	11
r__SOL_AWC().sol	0	50	4.1	0.0646	12
v__ALPHA_BF.gw	0	0.2	0.18	0.0374	13

**Table 3** Performance of the hydrological model during calibration and validation

Evaluation criteria	$R^2$	NSE	PBIAS
Calibration	0.84	0.84	5.5
Validation	0.82	0.82	3.0



**Fig. 4** Scatter plot of simulated versus observed monthly streamflow during **a** calibration and **b** validation

2025 to 2049, S2 for 2050 to 2074, and the simulated streamflow in the period 2075 to 2099 is considered as scenario S3. For all the scenarios, the LULC for the year 2000 is taken.

### 3.3 Impacts of Climate Change Impact Streamflow

The climate change impact is predicted and analyzed by comparing the streamflow during the three future scenarios with the baseline. The meteorological variables considered for the model are precipitation and temperature. The future scenarios are explored using the calibrated model, and the annual flow duration curve is plotted for the baseline, S1, S2, and S3 cases (Fig. 5). This helps to understand the flow variability between the baseline and the future scenarios.

For scenarios S1, S2, and S3, the annual average streamflow is predicted to decline by 6.8%, 5.5%, and 1%, respectively, relative to the baseline. Also, the percentage changes in the low flow (Q95) and high flow (Q5) indices are evaluated in the study. Q95 is among the most common low-flow indices [9]. Watershed modeling studies need to pay greater attention to low flows since they are crucial for the biotic diversity of aquatic and riparian environments. All of the scenarios for the future predict an increase in the basin's low flows over the baseline. The percentage increase in Q95 for the considered scenarios is expected as 9.8%, 15.3%, and 15.1%, respectively, with respect to baseline. This indicates more water availability during the dry season in the area. The increase in low flow results in lowering the total discharge deficits due to the changes in climate [13]. The high flow indicators (Q5), on the other hand, indicated a significant reduction in the future. The Q5 is found with a decrease of 20, 8.3, and 1.6% compared to the baseline scenario. The patterns of stream flow in the three scenarios are similar but with differences in magnitude.

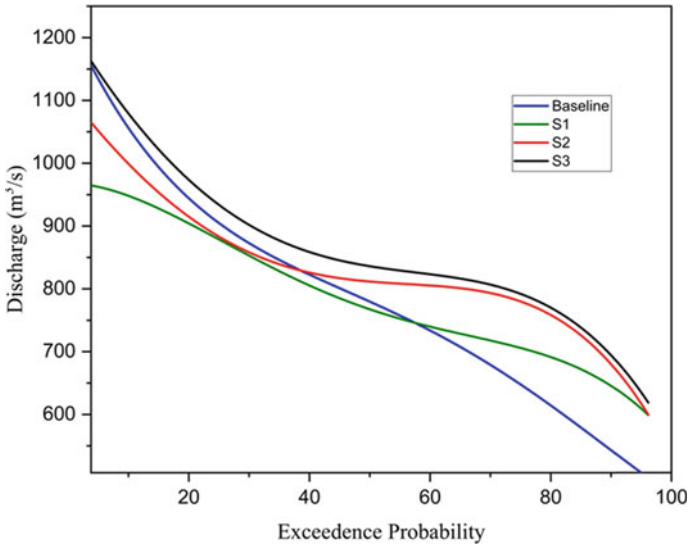


Fig. 5 Annual flow duration curve

## 4 Conclusion

The research findings suggest that Meenachil may experience a reduction in precipitation and an upsurge in temperature under the RCP 4.5 scenario in comparison to the baseline period that was analyzed. The study employs the SWAT model to examine the possible impacts and alterations on streamflow due to the changing climates. The annual average discharge in Meenachil is predicted to decline in all the considered future scenarios. The reduction in flow is expected to be less for the S3 scenario. The low flow indices (Q95) are found to have a rise, and high flow indices (Q5) showed a decline in the predicted scenarios compared to the baseline. The percentage reduction in the two indices is anticipated to be more in the upcoming future. The study may be useful for comprehending the effects of a changing climate in the Meenachil basin and could be taken into account when developing adaptation measures. In this research, an effort was made to determine how streamflow might respond to climate change by taking into consideration basically the moderate emission scenario. In addition, research is needed to estimate the LULC changes and the impacts of LULC changes and other emission scenarios on the hydrology of the study basin, which is the future scope of the study.

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