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RESEARCH ARTICLE

Impact of Climate Change on the Hydrology of Bharathappuzha River in Kerala, India

Anu Varughese[1]* • M.S. Hajilal[2]

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Abstract In this context, climate change has become a major threat for food security. This is especially true in a developing country like India, which is highly dependent on the monsoons for its agricultural production. Climate change also has a profound impact on the water cycle and water availability at the global, regional, basin, and local levels. The past climate data of the Bharathappuzha catchment area was analysed, and it was seen that the mean, maximum and minimum temperatures are having an increasing trend and that the average precipitation in the region is declining at the rate of 15 mm per year. Statistical comparison of historical climate model data with the observed data showed that the best model for the region is GFDL-CM3 regional climate model (RCM). Future data of RCP4.5 and RCP8.5 scenarios for the areas were extracted and bias corrected for use. The analysis of predicted rainfall indicates that there is a possibility for the shift in the rainfall pattern with maximum monthly rainfall to be shifted July–August rather than the previous trend of June–July. A decrease in south-west monsoon (June–September) and an increase in north-east (October–November) monsoon is also predicted. The physically based distributed hydrologic model Soil and Water Assessment Tool (SWAT) was used for modelling. The projections of the climate variables, rainfall and temperature were used and the potential effects of climate change on the hydrology of the river basin were assessed.

Keywords: Bharathappuzha, Climate change, CORDEX, Hydrologic modelling

1. Introduction

Land and water are the two primary natural resources which are indispensable for life and are becoming scarce. The availability of fresh water for food production and other major uses depends on effective water management (Cosgrove and Loucks, 2015). Climate change is a multifaceted problem which involves complex interactions between the natural resources, environment and human beings (Devendra, 2012). It is likely that the freshwater resources are affected by the changes in climate (Bates *et al.,* 2008) and the worldwide demand for water is projected to increase by about 55% by 2050 (WWDR, 2015). The changing climate is imposing a major threat on water resources availability and distribution (Beran *et al.,* 2016).

The research work was carried out in the Bharathappuzha river basin in the state of Kerala in India. The river flow is highly affected by increased water use and reduced recharge caused due to increasing population, urbanisation and unscientific management practices. The river faces severe drought and dearth of water flow during the recent times and hence, the research was undertaken to analyse the reasons for the reduced river flow during the non-monsoon periods with the help of hydrologic models. Climate change also has a profound impact on the

[1]Department of IDE, Kelappaji College of Agricultural Engineering and Technology, Kerala Agricultural University, Tavanur, Kerala, India
[2]Department of Agricultural Engineering, College of Agriculture, Kerala Agricultural University, Thiruvanthapuran, Kerala, India
*Corresponding author email id: anuvarughese31@gmail.com

water cycle and water availability at the global, regional, basin, and local levels. In order to study the changes in hydrology due to change in climate, land use, watershed interventions, etc. the rainfall-runoff process need to be understood. Understanding the hydrologic processes in a watershed is of prime importance for which we need to make use of the different hydrologic models. Among the various hydrologic models available- Soil and Water Assessment Tool (SWAT) was selected for this study because of its higher level of accuracy in prediction and capability to be used to study impact of climate change on the hydrology of rivers (Gosain *et al.,* 2006). In this context, an attempt was made to analyse how future climate change can influence the hydrology of the Bharathappuzha river catchment.

2. Methodology and Description of the Area

2.1 Study Area

Bharathappuzha river with a length of about 209 km (Bijukumar *et al.,* 2013) is situated between 10°252 –11°252 N and 75°502 –76°552 E. It encompasses a drainage area of 5,988 km^2 (Magesh *et al.,* 2013) and is the major source of water for three districts in Kerala and two districts in Tamil Nadu. Figure 1 shows the river basin with locations of rain gauge and stream flow stations.

2.2 Software and Database

ArcGIS software was used for the preparation of data base and maps needed for SWAT model. The spatial data sets needed are digital elevation model (DEM), land use map and the soil map. It was also used for setting projection for all the SWAT inputs such as DEM, land use and soil map. Georeferencing of soil map and the toposheets required for the study area have been carried out using this tool. Watershed boundary corresponding to the lowest point of the area was delineated using SWAT model in ArcGIS platform. Delineation was done based on the Shuttle Radar Topographic Mission (SRTM) DEM. Datum and projection used were WGS_1984 and UTM Zone 43, respectively.

2.3 Methodology

Trend analysis was performed for the rainfall and temperature data of the region and its magnitude was assessed using the Mann–Kendall test. Analysis was done for the mean, maximum and minimum temperature and also for the precipitation data. The watershed was divided into sub-catchments (sub-basins) and hydrologic response units (HRUs) based on the DEM) and the drainage network. For determining runoff, SCS curve number method which

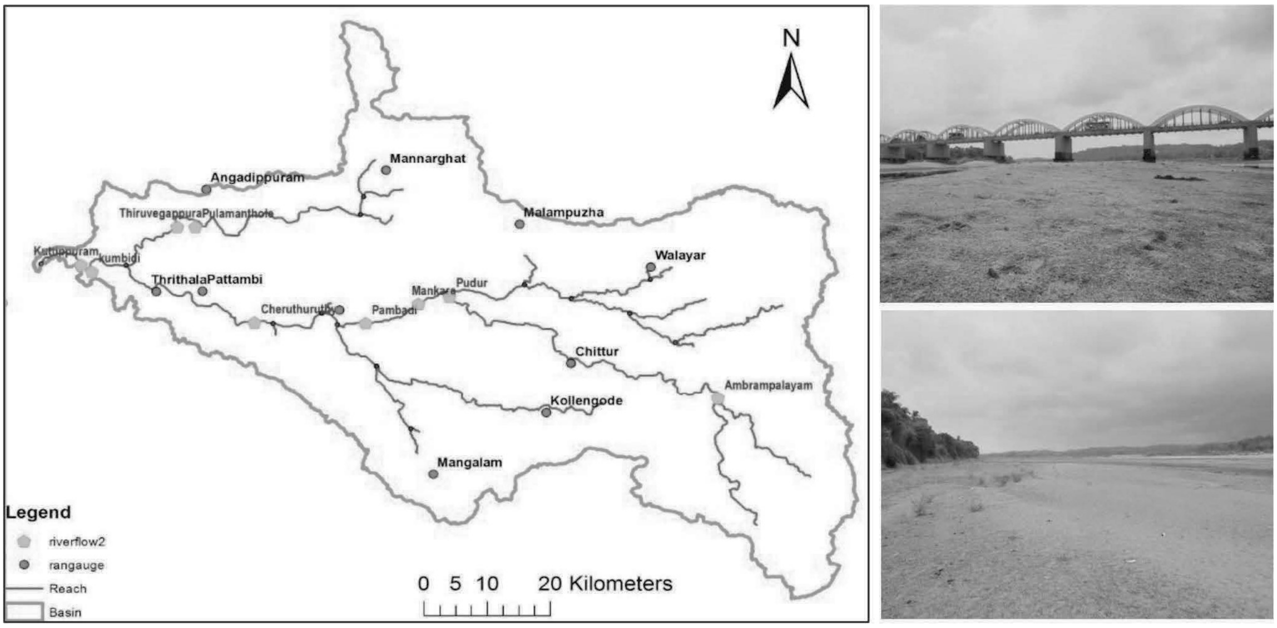


Figure 1. Location of Rain Gauge and Stream Gauge Stations in Bharathappuzha. The Photographs on the Right Shows the Dry Riverbed During the Summer

is a function of land use, antecedent soil moisture conditions and soil permeability was selected.

Climate change data were downloaded from CORDEX-South Asia multi models output site of Centre for Climate Change Research (CCCR). The general circulation models output is in coarse scale and need to be downscaled for use in the river basin scale to study the impact of climate change on the river hydrology. The uncorrected bias in the downscaled data was corrected before use. The power law transformation method (Leander and Buishand, 2007) was used to correct for bias in precipitation data. For bias correcting the temperature data, a method involving changing and adjusting the mean and the variance was adopted.

DEM is an essential prerequisite for a hydrological model like SWAT. SRTM DEM was downloaded from Earthexplorer.usgs.gov. Land use map was prepared through supervised classification in consultation with Kerala State Remote Sensing and Environment Centre using LISS III imagery of IRS P6 of 2008. Visual interpretation and ground truthing were employed to assist supervised classification process and the image processing was done using ERDAS Imagine 2015 developed by Intergraph, USA.

The morphological characteristics of the soil and the soil map needed for the SWAT model were collected from the Directorate of Soil Survey & Soil Conservation of Kerala State. To understand the effect of changes in climate on the hydrologic response of the area SWAT was used. The model works on the water balance equation. The elevation details, land use and soil details are initially used for the identification of the HRUs. Other major inputs of the model are climatological data like precipitation, temperature, solar radiation, wind speed and relative humidity.

2.4 Sensitivity Analysis and Calibration of the Model

SWAT-CUP 2012 version 5.1.6 links SUFI-2, PSO, GLUE, Parasol and MCMC procedures to SWAT and was used for the study for the sensitivity analysis, calibration, validation and uncertainty analysis. The method for calibration in SWAT-CUP is first selected and the repeated process carried out in the programme helps to attain convergence. In the study, SUFI-2 programme was used for calibration. The sensitivity analysis method used was Latin-Hypercube One-Factor-At-a-Time (LH-OAT). The response of various model parameters to different processes in the basin are identified and based on that the number of parameters was reduced and the model was made ready for calibration.

Multi-site calibration was carried out using the average monthly observed flow at 4 river gauging stations Kumbidi, Pulamanthole, Mankara and Thiruvegappura. For doing calibration of the model, the data available with monthly stream flow records were divided into two. For calibration, the first 12-year data of 1989–2000 were used and the later 9-year data of 2001–2009 were taken for validation. Many researchers have divided the available meteorological data sets to two sub data sets (Thampi *et al.,* 2010; Musau *et al.,* 2015; Fukunaga *et al.,* 2015) for doing hydrologic modelling studies. The model performance was evaluated using the efficiency criteria's Nash–Sutcliffe efficiency (NSE), coefficient of determination, per cent bias (PBIAS), etc. based on the recommended statistics (Moraisi *et al.,* 2007).

2.5 Study of Impact of Climate Change on River Basin Hydrology

The bias corrected future climate change data of rainfall and temperature were used as input in the calibrated model to predict the hydrology of the river basin in future. Future climate change data for RCP 4.5 and RCP 8.5 for the two periods 2041–2070 and 2071–2099 under IPCC AR5 were used.

3. Results and Discussion

3.1 Historical Climate of the Region

The hydrologic cycle is usually accelerated due to an increase in temperature and hence the understanding of the temperature variations over the years is very important. The trend analysis of past climate data in the Bharathappuzha river basin during 1951–2013 indicated that the mean, maximum and minimum temperature increased at the rate of 0.07°C per decade, 0.14°C per decade and 0.04°C per decade, respectively. Similar results were published by different researchers across the country (Bhutiyani *et al.,* 2007; Thomas *et al.,* 2015). Mann–Kendall test result also gave the confirmation of the trend. The increasing trend of temperature values are seen to be significant at 99% level of significance.

In the study area, around 60% of the precipitation is received during the period June–August with maximum monthly record in July. Analysis of trend of rainfall in the area showed that the decrease in rainfall is at the rate of 15 mm per year.

Studies were conducted by scientists from all over India to analyse the variations in the rainfall pattern of the past. The regional variations need to be understood for a better understanding of the variations in the hydrologic cycle. Researchers have reported increasing occurrence of extreme rainfall events (Thomas *et al.,* 2015; Rajeevan *et al.,* 2008). Seasonal variations with increasing and decreasing trends are also reported (Krishnakumar *et al.,* 2009; Manikandan and Tamilmani 2012; Thomas *et al.,* 2015).

3.2 Projected Future Climate of the Region

IPCC reports a significant change in the worldwide air temperatures to the mid of the 21st century (IPCC, 2013). Prediction of future climate is essential for doing the climate change impact analysis in the Bharathappuzha basin. So, for getting reliable future climate data of the region based on the latest CMIP5 data set, the observed data of Bharathappuzha river basin on precipitation and temperature were statistically compared with the historical data from the five regional climate models. The comparison was made on the basis of Standard deviation, coefficient of variation, Correlation coefficient, and cantered RMSE. The results are given in Table 1. Jena *et al.* (2016) have reported that GFDL-CM3 is one of the best models in the CMIP5 data set which can capture the pattern of Indian rainfall.

3.3 Prediction and Downscaling of Future Climate Data

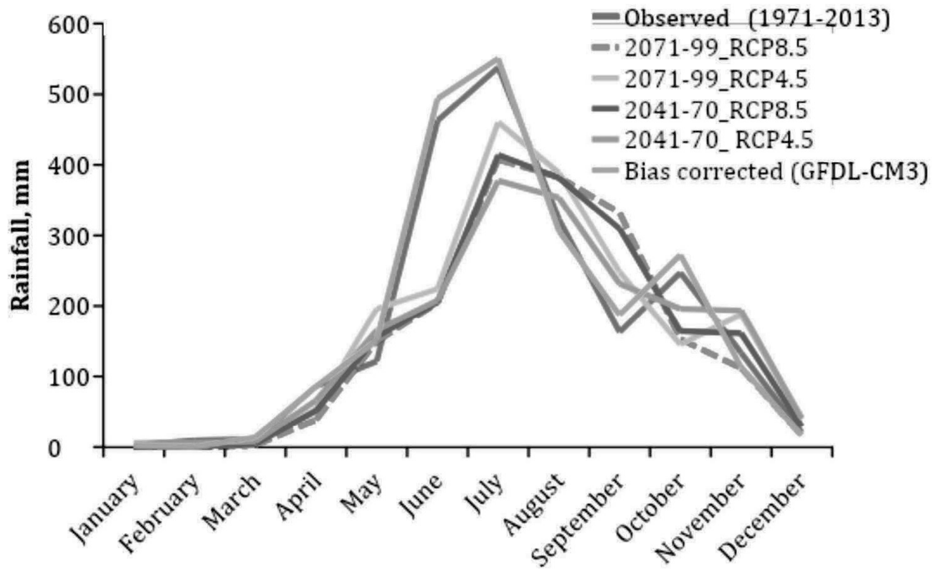
The predicted data of GFDL-CM3 data for the two periods 2041–2070 and 2071–2099 were used for the hydrologic modelling. Two projection scenarios, RCP8.5 having high amount of emissions and RCP4.5 under partially controlled condition were chosen for the impact study. The uncertainties on the future rainfall data were corrected by the method reported by Leander and Buishand (2007). The constants a and b in the equation used were found out on a monthly basis. Correction for temperature was done by shifting and scaling to adjust the mean and the variance.

The monthly variation of the bias corrected data of precipitation for the two scenarios and for two future durations 2041–2070 and 2071–2099 is shown in Figure 2. There is a consistent decrease in rainfall during majority of the months except May, August, September, November

Table 1. Statistical Comparison of Model Estimates with Observed Data

	EC-Earth	CCSM4	CNRM-CM5	GFDL-CM3	MPI	Observed
Precipitation						
Standard deviation	49.69	56.50	58.52	73.43	56.87	181.46
Correlation coefficient	0.24	0.68	0.74	0.76	0.78	
Coeff. of variation	0.44	0.58	0.62	0.66	0.59	1.03
Centred RMSE	3.86	1.75	1.88	1.57	1.71	
Maximum Temperature						
Standard deviation	2.92	2.47	2.62	2.32	2. 50	2.39
Correlation coefficient	-0.14	0.72	0.69	0.76	0.73	
Coeff. of variation	0.10	0.09	0.10	0.09	0.09	0.07
Centred RMSE	3.86	1.75	1.88	1.57	1.71	
Minimum Temperature						
Standard deviation	1.52	1.72	1.82	1.71	1.82	1.09
Correlation coefficient	0.49	0.77	0.78	0.82	0.81	
Coeff. of variation	0.09	0.08	0.09	0.08	0.09	0.05
Centred RMSE	1.31	1.07	1.13	0.99	1.08	

Figure 2. Monthly Variation of Present and Future Precipitation



and December for the two emission scenarios and for both future periods. The study revealed that June and July rainfall showed a decrease, while that of August and September showed an increase over the present rainfall. It also indicates a possibility for a seasonal change in the rainfall occurrence. The rainfall during June–July is likely to decrease whereas the rainfall during August–October is likely to increase.

Based on the predictions, there will be a decrease of 4% and 11% in average annual rainfall in the basin during 2041–2070 under RCP4.5 and RCP8.5, respectively. A decrease of up to 8% and 15% in annual rainfall during 2071–2099 is also predicted for RCP4.5 and RCP8.5, respectively, along with the seasonal shift.

This declining trend in rainfall during the period June–July in southern region of India have been reported by others (Guhathakurta and Rajeevan, 2007; Raneesh and Thampi, 2013; Patwardhan *et al.,* 2014).

3.4 SWAT Model Setup

The river basin area or watershed was delineated from the DEM. Outlets were added at points in the drainage network where gauging stations were available. This was done so that comparing the simulated flow with the measured data could be done. Sub-basin outlets were added at Mankara, Pudur, Thiruvegappura, Pulamanthole and Kumbidi where river gauging stations are available. The inlet of draining watershed option was used so that the inflow from an area to the modelled area can be given as input and the inlet point was selected such that it coincides with Ambarampalayam gauging station. is shown in Figure 3.

3.5.1 HRU Definition

HRUs are defined so that each HRU represents unique soil/land use characteristics. With the details of elevation, soil and land use, HRUs were created for the entire river basin. A total of 401 HRUs were defined within the basin.

3.5.2 SWAT Model Run

For calibration, simulation was done from 1 January 1989 to 31 December 2000, and for validation, simulation was done from 1 January 2001 to 31 December 2009. A warm-up period of 3 years were given in each case and is indicated as number of years to skip (NYSKIP) during the simulation.

3.5.3 Sensitivity Analysis

SWAT calibration and uncertainty program (SWAT-CUP) was used for carrying out the sensitivity analysis. Selection of parameters depends on the basin and review of literatures (Heuvelmans *et al.,* 2004; Gosain *et al.,* 2006). After doing a one at a time analysis, thirteen parameters were selected initially for the global sensitivity analysis.

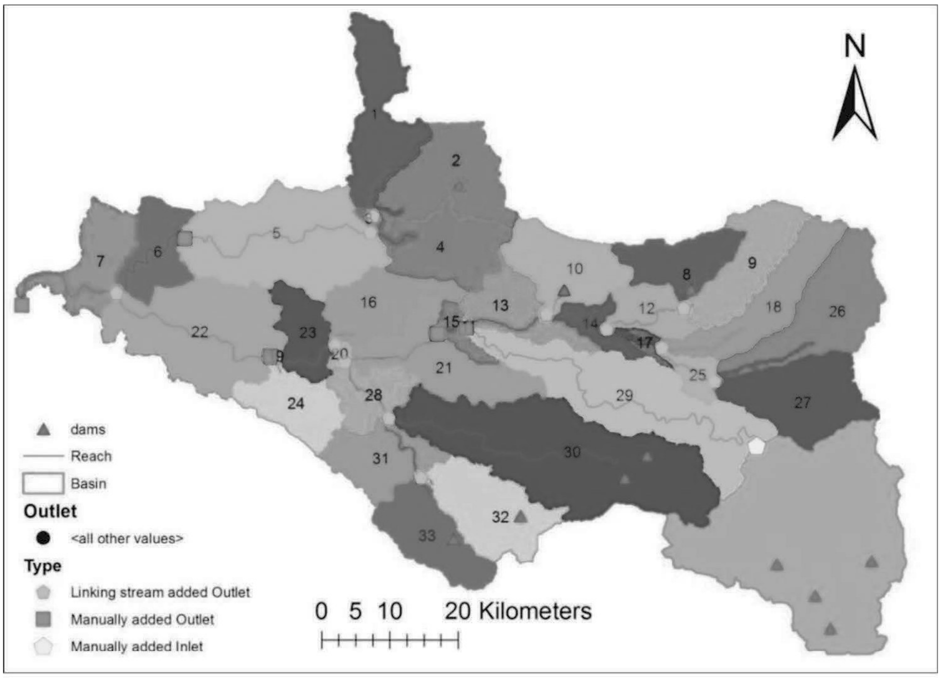


Figure 3. Sub-Basin Delineation and Selection of Outlet and Inlet Points

The SUFI-2 method in SWAT-CUP was selected for the analysis.

The two statistics t-stat and p-value are indicators of sensitivity; t-stat quantifies the sensitivity, whereas p-value gives its significance. With the help of these measures the top ranked and most sensitive seven parameters were used for calibrating the model Table 2.

From the similar studies reviewed, it is seen that the selected parameters were sensitive to streamflow (Schuol *et al.,* 2008; Raneesh and Thampi, 2011; Faramarzi *et al.,* 2009). The model parameters were adjusted manually based on statistical indicators as well as on the characteristics of the study area. Changes were made to the parameters so that they have physical meanings with respect to the characteristics of soil, topography, climate, etc. The SWAT-CUP default range and the calibrated range of values for the sensitive parameters are given in Table 3.

3.5.4 Calibration and Validation of the Model

During calibration, the model input parameters were adjusted based on sensitivity analysis, to match the observed and simulated streamflow. Reiterations were continued until satisfactory results in terms of graphical comparison and statistical evaluation were met, for the simulated discharge against the measurements.

Table 2. Ranking of Sensitive Parameters for Bharathappuzha Watershed

Sensitivity rank	Parameter	Description	t-value	p-value
1	CN2.mgt	SCS runoff curve number	32.48	0.00
2	GW_DELAY.gw	Groundwater delay time (days)	21.79	0.00
3	ALPHA_BNK.rte	Baseflow alpha factor for bank storage (days)	3.69	0.00
4	ESCO.hru	Soil evaporation compensation factor	3.02	0.003
5	CH_K2.rte	Effective hydraulic conductivity of main channel	1.24	0.22
6	GW_QMN.gw	Threshold depth of water in the shallow aquifer	1.06	0.29
7	SOL_AWC.sol	Available water holding capacity of soil	-0.65	0.53

** t-value (large absolute value) and p-value (close to zero) show measure and significance of sensitivity for each parameter, respectively*

Table 3. Sensitive Parameters and Fitted Range of Values

Parameter	SWAT-CUP default range	Range after calibration
r__CN2.mgt	-0.2 to 0.2	-0.14 to 0.04
v__ALPHA_BNK.rte	0 to 1	0.3 to 0.75
v__GW_DELAY.gw	30 to 450	5 to 190
v__GWQMN.gw	0 to 2	0.004 to 0.6
v__ESCO.hru	0.8 to 1.0	0.95 to 1.0
r__SOL_AWC.sol	-0.2 to 0.4	0.3 to 0.69
v__CH_K2.rte	5 to 130	15 to 67

** r- represents that the existing value is multiplied by a value (got by adding one to the given value) and v indicates that the default value is replaced by the parameter*

3.5.5 Model Performance Evaluation

The evaluation of the model and model simulations was done by statistical comparisons. NSE and the Coefficient of determination (R^2) and PBIAS were used to compare the observed and simulated data sets. The model evaluation statistics for the calibration and validation period are shown in Table 4. The NSE, R^2 and PBIAS values showed good performance according to the performance rating by Moriasi *et al.,* (2007).

3.6 Impact of Climate Change on River Basin Hydrology

The calibrated SWAT model was applied to Bharathappuzha river basin for analysing the impact of climate change on water balance components. The influence of climate change on the hydrology of different basins across the globe was assessed using the SWAT model (Devkota and Gyawali, 2015; Gurung *et al.,* 2013; Lubini and Damowski, 2013; Raneesh and Thampi, 2011).

Hydrologic simulations for the climate change periods (2041–2070 and 2071–2099) were performed with SWAT model using the bias corrected data. Thus, the effect of the changes in climate on the hydrology was assessed by running the calibrated and validated model corresponding to the current scenario and two RCP's, viz., RCP4.5 and RCP8.5. Streamflow simulation for the current scenario was then compared with the predicted flow of future for the two periods and two scenarios.

In Table 5, it is seen that the water balance components in the catchment is also affected by the decrease in precipitation and increase in temperature predicted for future on account of climate change. The decrease in precipitation and increase in temperature may affect the future streamflow in the catchment and it is predicted that there may be up to 15 to 20% decrease in streamflow by 2099, if no mitigation measures are adopted. In this situation, evapotranspiration ranges from 15% to 22% of the annual precipitation, whereas there is chance that it gets increased from 29% to 32% in the RCP4.5 scenario and 32–35% in RCP8.5 scenario due to the increase in temperature during the period. RCP8.5 scenario refers to the worst condition in which the emissions are very high and has a rising tendency over the entire 21st century. No significant change is seen for the lateral flow component over the years and under different scenarios. It ranges from 8% to 10% of the total precipitation.

Monthly streamflow predicted for the two selected periods when correlated with the this flow, it was found

Table 4. Model Evaluation Statistics for Monthly Discharge

Gauging station	Calibration period				
	NSE	R^2	PBIAS (%)	*p*-factor	*r*-factor
Cheruthuruthi	0.84	0.85	1.4	0.48	0.43
Mankara	0.57	0.62	-11.7	0.44	0.47
Pulamanthole	0.74	0.66	14.6	0.51	0.38
Kumbidi	0.79	0.83	12.7	0.53	0.35
Validation period					
Cheruthuruthi	0.71	0.87	11.4	0.44	0.39
Mankara	0.74	0.81	18.1	0.52	0.53
Pulamanthole	0.65	0.74	9.0	0.36	0.32
Kumbidi	0.83	0.88	14.4	0.42	0.32

Table 5. Water Balance Components under Changing Climate Scenario

Scenario/Period	Precipitation (mm)	ET (mm)	Surface flow (mm)	Ground water (mm)	Lateral flow (mm)
1992–2000	2680.55	511.57	946.58	929.53	241.08
2001–2007	2567.46	463.26	980.67	876.96	230.78
RCP4.5_2046–2058	1939.27	553.56	563.14	591.37	170.69
RCP4.5_2059–2070	2074.88	581.67	544.48	619.65	193.92
RCP4.5_2076–2087	2187.29	693.75	649.15	662.08	166.52
RCP4.5_2088–2099	1920.06	595.47	536.62	541.23	190.04
RCP8.5_2046–2058	2187.29	693.75	588.54	662.08	227.12
RCP8.5_2059–2070	1850.06	595.47	496.32	561.54	190.04
RCP8.5_2076–2087	2024.71	681.63	590.28	546.61	192.37
RCP8.5_2088–2099	1819.74	626.20	528.31	498.31	158.10

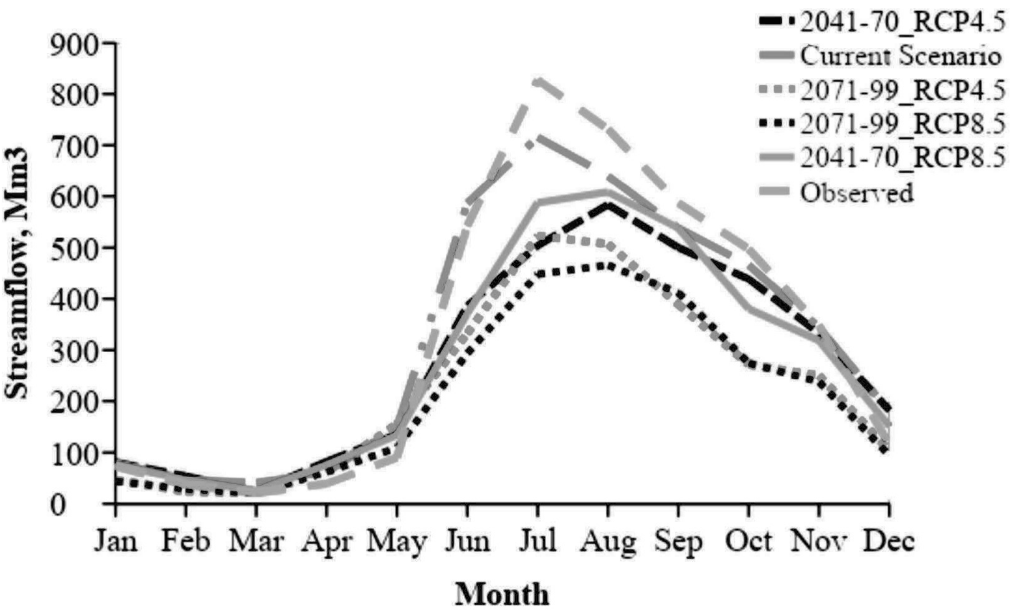


Figure 4. Predicted Monthly Streamflow under Different Scenarios in Comparison with Observed and Current Scenario Stream Flow

that in all months of prediction, irrespective of the scenarios, the flow is predicted to decrease, except during 2041–2070 in the month of August. During 2041–2070, the streamflow in RCP4.5 and RCP8.5 showed almost same variation from the current scenario flow shown in Figure 4. While comparing the monthly future streamflow predicted during 2071–2099 with the current scenario, the streamflow in RCP8.5 is less than that under RCP4.5. It is also predicted that the climate will become drier and warmer in both scenarios in the future.

4. Conclusions

Bharathappuzha river spanning over the three districts of Kerala is the main drinking water source for most of the villagers of the area. The increasing trend in temperature and decreasing trend in rainfall in the region may be due to urbanisation, deforestation and changes in land use. The trend analysis of past climate data of the region (1951–2013) indicated that the mean, maximum and minimum temperature increased at the rate of 0.07°C per decade, 0.14°C per decade and 0.04°C per decade, respectively.

Analysis of trend of rainfall in the area revealed that the decrease in rainfall is at the rate of 15 mm per year.

Monthly streamflow predictions done for the years 2041–2070 and 2071–2099 show that the monthly flow will decrease during both the periods. An exception is seen only during 2041–2070 in the month of August. During 2041–2070, the streamflow in RCP4.5 and RCP8.5 showed almost same variation from the current scenario flow. While comparing the monthly future streamflow predicted during 2071–2099 with the current scenario, the streamflow in RCP8.5 is less than that under RCP4.5. It is also predicted that the climate will become drier and warmer in both scenarios in the future. RCP8.5 scenario refers to the worst condition in which the emissions are very high and has a rising tendency over the entire 21st century.

The results of the research will give an insight to the experts in the field for planning of future development projects to reduce the harmful effects that can occur due to climate change in the area. The engineers, administrators and scientists working in this line must be updated with the latest technologies and the predictions should be incorporated into the framework of developmental policy. This will help to plan and execute intense action towards water conservation and provision of water resources and to mitigate the ill effects of climate change.

The predictions of climate change in the study was done on the basis of only one RCM, and more detailed research based on multiple RCM's is needed to make better conclusions. It has also been reported by researchers that multi-model ensembles predicting climate change reduces the uncertainty in impact studies (Cane *et al.,* 2013; Tebaldi and Knutti, 2007).

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