Impacts of Climate Change on Varied River-Flow Regimes of Southern India

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Abstract: This paper assesses the possible impact of climate change on the hydrology of the subhumid and perhumid river regimes originating from the western mountain range (Western Ghats) of India. The modified Mann-Kendall test evaluates the trend of observed data (1975–2004) and RCP 4.5 data (2006–2070) of climatic variables. The results indicate a decreasing trend for annual rainfall over the Malaprabha River catchment (26 mm per year at the 5% significance level), whereas no trend is observed over the Netravathi River catchment at the 10% level. Indian southwestern monsoon rainfall shows a decreasing trend from 84 to 80% of total rainfall in the Malaprabha River catchment and from 80 to 77% in the Netravathi River catchment. Summer rains are found to be increasing in the Malaprabha River catchment (3–4.5% of total rainfall), whereas there is no significant trend for the Netravathi River catchment. Furthermore, the postmonsoon rainfall also shows a significant increase in the Malaprabha catchment (40 mm per decade at the 5% significance level) and the Netravathi catchment (30 mm per decade at the 10% significance level). The Netravathi River shows a decreasing trend for annual flow (0.22 Mm^3 per year at the 10% significance level). However, for both catchments the temperature is found to be increasing by 0.2–0.8°C per decade. The soil and water assessment tool (SWAT) model is used to simulate the river catchments and exhibits a Nash–Sutcliffe efficiency of 0.831 and 0.857 for the Malaprabha and Netravathi River catchments, respectively. In addition, a decreasing trend in the high flow is estimated for Netravathi, whereas the trend is increasing for Malaprabha. Thus the impacts of climate change over the Western Ghats are very evident, but the flow of each river responds differently. **DOI: 10.1061/(ASCE)HE.1943-5584.0001556.** *© 2017 American Society of Civil Engineers.*

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Introduction

In recent years there has been a growing global concern over the impacts of climate change on environmental dynamics and their subsequent implication for societal activities such as drinking water, irrigation, food, energy requirements, and hazard prevention. From shifting weather patterns to rising sea levels, the impacts of climate change are global in scope and are unprecedented in scale. Several investigations report on the potential impact of climate change on the fundamental drivers of the hydrological cycle (Giang et al. 2014; Gosain et al. 2006; Narsimlu et al. 2013; Pervez and Henebry 2015). The hydrological cycle, as the key link between the atmosphere and the biosphere, is inevitably influenced by climate change. As a consequence, changing patterns of precipitation and temperature are affecting the available water resources. Hence it is important to investigate the trends of climatic variables for future water management and life sustenance. The evidence of a clear change of pattern in the annual streamflow is reported by the researchers globally. Regions at higher latitude are experiencing an increase in annual streamflow (Hyvärinen 2003; Tao et al. 2003a, b; Walter et al. 2004). Studies claim that a 1°C rise in temperature in the twentieth century will lead to an increase in global total streamflow of almost 4% (with regional variation) (Labat et al. 2004). Milly et al. (2005) reported that southern Latin America, southern Europe, and West African regions are experiencing decreased streamflow. However, these findings were challenged because nonclimatic factors also influence the streamflow and there could be bias in the data due to lesser data points (Legates et al. 2005). In addition, reports from the Intergovernmental Panel on Climate Change (IPCC 2007, 2014) indicate an increase in global surface temperature of 0.74°C from 1906 to 2005, with a rapid warming over the past 50 years.

Several investigations of catchments/basins of diverse scales have reported the effects of climate change on the streamflow in rivers across India (Gosain et al. 2006; Narsimlu et al. 2013; Giang et al. 2014; Pervez and Henebry 2015). The impact of climate change on India is significant due to its geographical complexity, varied climatic conditions, and growing anthropogenic activities. There are strong indications of change in the trend of climatic parameters at the regional level in line with the effect of global warming (Zhu and Houghton 1996; IMD 2013; IPCC 2014). The climate of India is dominated by the southwest monsoon precipitation (June to September), which is widely distributed in space and time. India receives approximately 80% of its total rainfall during the southwest monsoon season, and studies report changes in the trend of climatic variables at the regional level due to global warming. According to the Central Water Commission (CWC), the average annual precipitation in India has decreased from approximately

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4,000 billion cubic meters (BCM) (CWC 2005) to 3,882 BCM (CWC 2009) over 5 years, signifying a decreasing trend in the precipitation. According to Gleick et al. (2012), China and India use approximately 40% of global freshwater for irrigation.

The Western Ghats mountain range of India is a global hotspot of diversity and many major rivers of peninsular India originate in the Western Ghats. The population in the six southern states of India—Karnataka, Kerala, Tamil Nadu, Andhra Pradesh, Maharashtra, and Goa—is critically dependent on the rivers originating in the Western Ghats. The region faces problems related to extreme weather conditions such as prolonged drought. Ramachandra (2014) and Reshmidevi and Nagesh Kumar (2014) reported the effects of rapid land-use changes on the hydrologic responses of the rivers of the region. A great deal of research has been conducted on the changing climate of the Western Ghats of India, but few studies have been carried out on the prognosis of water availability in the rivers flowing on either side of the Western Ghats.

The hydrological models used to study climate change require temperature and rainfall data at a high resolution. The hydrological models usually are calibrated against observational data, and these are quite sensitive to the climate model bias (Berg et al. 2012). The global climate model (GCM)-derived climate data seldom are used directly for climate change studies in hydrology due to coarse resolution (Forest et al. 2002; Allen and Ingram 2002; Mearns et al. 2001). Several studies have employed RCMs (regional climate models) to study river flow (Gosain et al. 2006; Ma et al. 2010; Im et al. 2010; González-Zeas et al. 2012; Teutschbein and Seibert 2010) due to their high-resolution data.

The present investigation has the following objectives: (1) to establish and understand the uncertainties and alternative futures in the trends of climatic variables and streamflow of Malaprabha and Netravathi Rivers originating in the Western Ghats of India using historical data and RCP 4.5 forecasted data, and (2) to simulate the catchment response under forecasted climate conditions by using the soil and water assessment tool (SWAT) hydrological model and to compare their responses. The outcome of the study will be useful to plan agricultural activities and riverwater utilization.

Study Area

The study area (Fig. 1) is composed of two river catchments: a subhumid catchment (Malaprabha River) and a perhumid catchment (Netravathi River), both originating in the evergreen tropical forests of Western Ghats of India in Karnataka. According to Thornthwaite (1948), regions with moisture indexes greater than 100 and between 0 and 20 are termed perhumid and subhumid climate types, respectively.

The Malaprabha River originates at Kanakumbi village in the Belgaum district of Karnataka at an altitude of 793 m above mean sea level (MSL) and flows eastward through the plains region with a slope of approximately 1.8 m/km as a tributary of the Krishna River. It is a seasonal river with no flow from January to May. The drainage area considered for this investigation is 550 km^2, with a flow length of about 65 km. Geologically, the catchment is dominated by Tertiary basaltic rock (96%) with sandy loams, red loams, and medium black soils of depths varying between 0.5 and 10 m. The catchment receives an annual average precipitation of 2,259 mm. The annual average temperature ranges from 19.2 to 29.5°C. The river supplies the drinking water and irrigation requirements of the people of Belgaum, Dharwad, Gadag, and Bagalkot districts.

The Netravathi River originates in the Bangrabalige valley in the Chikkamagaluru district at an elevation of 1,000 m above MSL in the Western Ghats and flows westward for a distance of about 125 km before joining the Arabian Sea, and has a catchment area of 3,350 km^2. The river has a very steep slope of approximately 43.5 m/km for the initial 20 km, which gradually reduces to approximately 1.6 m/km. Geologically, the area is dominated by the lateritic soil underlaid by gneiss. The average annual precipitation of the catchment is 4,030 mm, with a temperature range of 16–42°C. The flow volume during the monsoon season (June–September) accounts for approximately 86% of the total annual flow. The Netravathi River is the primary source of drinking water for the Dakshina Kannada district, including Mangalore city. It facilitates irrigation in Hassan, Dakshina Kannada, and Kodagu districts.

This paper assesses the trend of climatic variables and determines the hydrologic response of the two river regimes.

Data Sources and Methodology

Daily rainfall data for the period 1975–2004 were collected for the Malaprabha River catchment from seven rain gauges of the India Meteorological Department (IMD) and for the Netravathi River catchment from 18 rain gauges of the Water Resources Development Organization (WRDO) of the government of Karnataka. Daily flow data were collected for Khanapur and Bantwal stations from the WRDO and Central Water Commission (CWC), respectively. These data were used for trend detection, model calibration, and validation. Fig. 1 shows the drainage map with rain gauge and river gauge stations of the catchments. For the development of the SWAT model, all the spatial data were obtained from a suite of open sources. The digital elevation model (DEM) was obtained from the National Aeronautics and Space Administration's (NASA) Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model Version 2 (ASTER GDEM2) with approximately 30-m resolution [Figs. 2(a and b)]. The land-use/land cover maps were taken from the WaterBase global dataset (2015) (GLU-LC). The major land uses in the study area are evergreen broadleaf forest (FOEB) and savanna (SAVA) [Figs. 2(c and d)]. The study used a digital soil map at a 1:5,000,000 scale from the Food and Agricultural Organization (FAO). Figs. 2(e and f) show the cropped region for the Malaprabha and Netravathi River catchments.

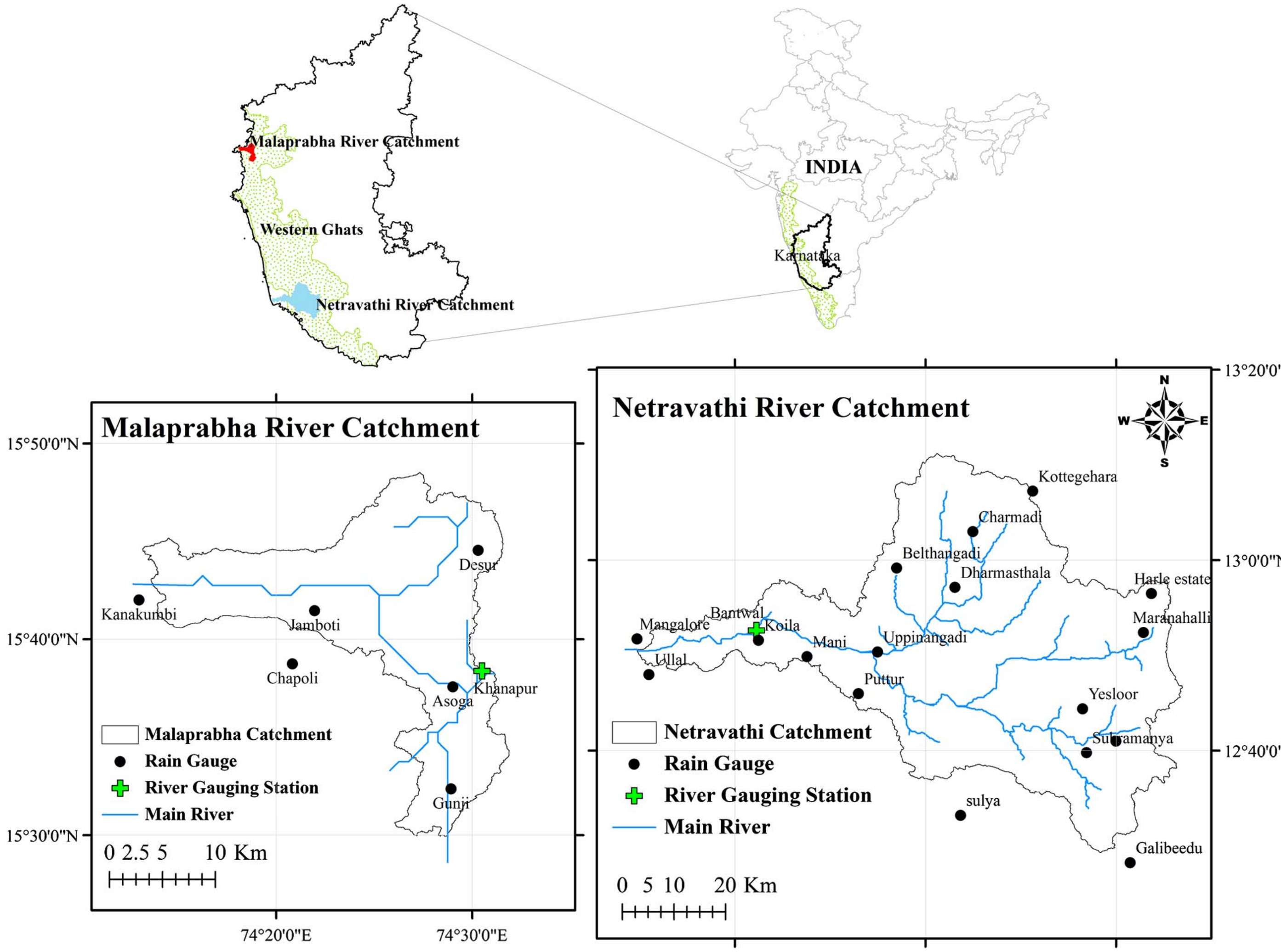
Representative Concentration Pathways

In order to provide robust hydroclimatic variables, the World Climate Research Programme (WCRP) initiated the COordinated Regional climate Downscaling EXperiment (CORDEX) framework (Chaturvedi et al. 2012; Giorgi et al. 2009). The CORDEX framework is based on the Coupled Model Intercomparison Project phase 5 (CMIP 5) using the RCPs recommended by the Fifth Assessment Report of the IPCC (2014).

Radiative forcing represents the net effect of anthropogenic greenhouse gases (GHGs) along with other forcing agents. The RCP 4.5 scenario used in the present study describes medium stabilization after the year 2100 without overshoot pathway to 4.5 $\mathrm{W/m}^2$. The data were obtained from the EC-EARTH global climate model (2017) and downscaled using the Rossby Centre regional atmospheric model version 4 (SMHI-RCA4 2015) for the South Asian domain (WAS-44).

Trend Analysis

This study used the modified Mann–Kendall trend test (Mann–Kendall test with prewhitening of time series) to rectify serially correlated data with a 95% confidence interval. Hydrological time



(a) (b)

Fig. 1. Major drainage and weather stations in (a) Malaprabha; (b) Netravathi

series frequently are encountered with non-normally distributed, censored, and missing data, making them more suitable for nonparametric methods, which are distribution free (Salas 1993; Hirsch et al. 1992). Incorrect results leading to invalid inferences could be obtained with the use of parametric methods when the data are not normally distributed (MathSoft 1999). The best known nonparametric approach for trend detection is the Mann–Kendall test (WMO 1988). Some of the latest methods for nonparametric trend analysis include the Spearman's rank correlation test (Yue and Wang 2002), wavelet based trend analysis (Antoniadis et al. 1994; Craigmile et al. 2004), LOWESS (Champely and Doledec 1997), and seasonal Kendall test (Hirsch et al. 1982).

Sen's slope estimator (Sen 1968) can predict the magnitude of the trend in the annual and seasonal series. Sen's slope estimator is a nonparametric approach which gives a robust estimate of the magnitude of a monotonic trend. The change in the mean of the sample over the observation period is determined with an assumption that the trend is linear. The average changes over a region give an estimate of the magnitude of the trend (Hirsch et al. 1982; Hirsch and Slack 1984; Gan 1998; Lettenmaier et al. 1994; Zhang et al. 2000; Yue et al. 2003). Sen's slope estimator is a widely used tool in quantifying trends in hydrometeorological time series (Lettenmaier et al. 1994; Yue and Hashino 2003; Yunling and Yiping 2005; Partal and Kahya 2006; ElNesr et al. 2010; Tabari and Marofi 2011; Tabari et al. 2011).

SWAT Hydrological Model

The soil and water assessment tool is a catchment scale, continuous time model operating on a daily basis (Arnold and Fohrer 2005; Neitsch et al. 2009). For the development of the models, the required spatial database was projected to the Universal Transverse Mercator (UTM) Zone 43 North and WGS84 coordinates using *ArcGIS 9.3*. The ASTER GDEM 2 was used to delineate the watershed and to analyze the drainage patterns of the land surface terrain. This study used the Soil Conservation Service (SCS) curve number procedure to estimate the streamflow in the SWAT model, and it used Hargreaves' method (Hargreaves and Samani 1985) to calculate the potential evapotranspiration. Hargreaves' method is a temperature-based method for computing potential evapotranspiration which gives reasonable results with global validity (Allen et al. 1998). Hargreaves' method was used for computing potential evapotranspiration due to its limited data requirement. Although the Penman–Monteith method is widely used for agriculture studies

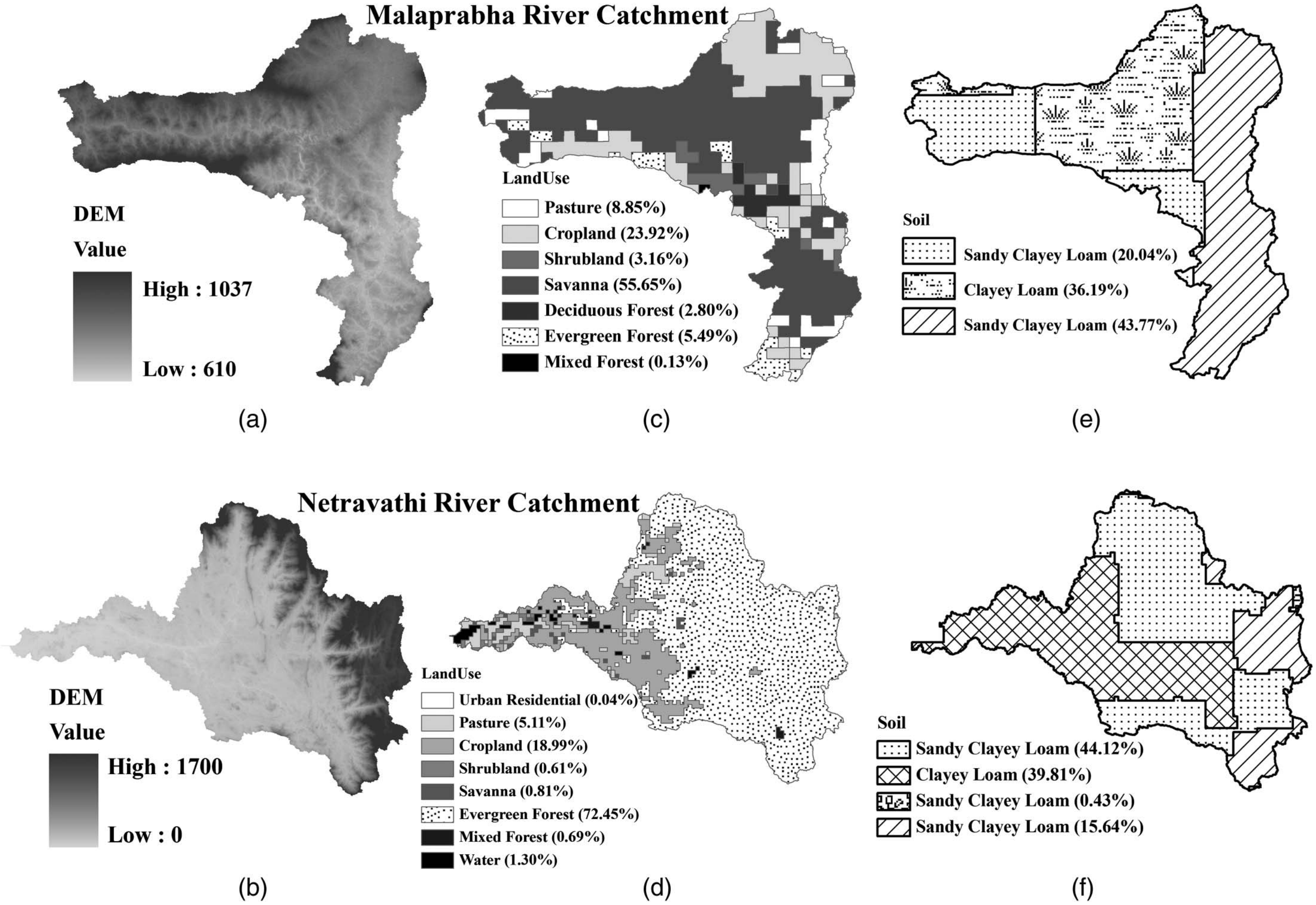


Fig. 2. (a) Malaprabha DEM; (b) Netravathi DEM; (c) Malaprabha land use; (d) Netravathi land use; (e) Malaprabha soil; (f) Netravathi soil

(Shukla et al. 2014), it requires an extensive database, which was not available for this study.

Methodology

The tasks conducted in the present investigation were as follows:

1. Trend analysis of historical daily rainfall, temperature, and streamflow data was conducted (Scenario 1) on a seasonal and annual basis using the modified Mann–Kendall method. The magnitude of the trend was estimated using Sen's slope estimator for the period 1975–2004. The trends were detected at 0.1% (extremely significant), 1% (significant), 5, and 10% significance levels. The principal seasons for India (MoEF 2004) are monsoon (June–September), postmonsoon (October–November), winter (December–February), and summer (March–May). The annual and seasonal variations of rainfall and temperature for each station were computed with respect to the mean and the variations were plotted over time. The trend was examined by fitting the linear regression line, and the slope of the simple least-square regression gave the rate of change of parameters.
2. The SWAT hydrological model for the Malaprabha and Netravathi River catchments was developed using historic data series, and the hydrological model parameters were obtained during calibration.
3. The SWAT hydrological model was calibrated using station data on daily rainfall and temperature for the period 1975–1994 (Scenario 1). The SWAT model was calibrated on the basis of 14 sensitive parameters (Table 1) which govern the model, as specified by the Latin hypercube–one factor at a time (LH-OAT) method (van Griensven et al. 2006). The calibration of the model and the parameterization therefore were manually performed using the heuristic approach. The SWAT-simulated streamflow was verified against 1995–2004 station data from the Khanapur and Bantwal stations, respectively, for Malaprabha and the Netravathi River catchments.

Table 1. Description of SWAT Parameters and Sensitivity Ranks

Parameter	Description	Rank
CN2	Initial SCS curve number for AMC II	1
SOL_K	Saturated hydraulic conductivity of soil	2
SLOPE	Average slope steepness	3
SOL_AWC	Soil available water capacity	4
ESCO	Soil evaporation compensation factor	5
SOL_Z	Soil depth from bottom of layer	6
CANMX	Maximum canopy storage	7
CH_K2	Channel effective hydraulic conductivity	8
SURLAG	Surface run-off lag time	9
ALPHA_BF	Base flow alpha factor	10
EPCO	Plant evaporation compensation factor	11
CH_N	Manning's coefficient for channel	12
GW_DELAY	Groundwater delay time	13
GW_REVAP	Groundwater *revap* coefficient	14

4. The annual and seasonal trend analysis of RCP 4.5 forecasted daily rainfall and temperature data for the period 2006–2070 (Scenario 2). From the historical and forecasted temperature data, the potential evapotranspiration was estimated using Hargreaves' method.
5. River flow for Scenario 2 was simulated with SWAT. The results were split into two periods (2006–2040 and 2041–2070). Frequency analysis was conducted on the river flow to obtain flow quantiles at 10% duration intervals in the range 10–90%. The high flow index (HFI) (Q10/Q50) and the low flow index (LFI) (Q90/Q50) were derived from the flow quantiles (Sahoo et al. 2016; Durbude et al. 2014). The HFI was used to characterize the relative magnitudes of peak flow (Q10) with reference to the median flow (Q50), and the LFI was used to characterize relative magnitudes of low flow (Q90) with reference to the median flow. The Q10 and Q90 classes of quantiles are adopted for designing large irrigation structures and drinking water schemes, respectively, whereas the Q50 quantile indicates the general water availability in the river.

The evaluation metrics for streamflow simulation were the coefficient of determination (R^2) and the Nash–Sutcliffe efficiency (NSE).

Results and Discussion

Trend Analysis

Rainfall

Table 2 provides the Mann–Kendall statistics for historical (station data) and forecasted (RCP 4.5) average annual and seasonal rainfall time series of Malaprabha and Netravathi River catchments. The average annual rainfall in the Malaprabha River catchment was found to be decreasing at 26 mm per year (5% significance level) during the historical period, and there was no statistically significant improvement in the forecasted time series. Average annual rainfall in the Netravathi River catchment showed an increase of 19 mm per year, with no statistical significance.

The average monsoon rainfall over the Malaprabha catchment showed a significant decreasing trend of 31 mm per year (0.1% significance level) during the monsoon season. However, the trend was not as pronounced for the Netravathi catchment, which showed a decrease of 5 mm per year (no statistical significance). The output of RCP 4.5 also showed a decreasing trend of average monsoon rainfall up to the year 2070 in the Netravathi catchment, without statistical significance. During the postmonsoon season, the average rainfall over the Malaprabha and Netravathi River catchments showed a 10 mm per decade increase and 5 mm per decade decrease, respectively. The winter season showed scanty rainfall in the Malaprabha River catchment, with very few rainy days. The Netravathi River catchment showed a decreasing trend (at 5% significance level) during winter which was insignificant for the outputs of RCP 4.5. The summer rainfall was found to be decreasing at a rate of 5 mm per decade, with no statistical significance, over the Malaprabha River catchment. The Netravathi River catchment also showed a decrease in summer rains (10% statistical significance). Hence it may be concluded that the temporal trend analysis of rainfall over the two river catchments showed an increased trend of rainy days for the RCP 4.5 outputs (2006–2070), indicating prolonged monsoon rains from May to October. The study carried out by Dash et al. (2007) for India showed similar observations of increasing trend of premonsoon and postmonsoon rainfall and a decreasing monsoon rainfall for the period 1871–2002.

Table 2. Rainfall Classification for Malaprabha and Netravathi Rivers (1975–2004)

Rainfall class (mm)	Malaprabha River	Netravathi River
	Number of rainy days	Number of rainy days
>100	61 (10.06)	179 (20.30)
>80	55 (6.37)	116 (8.92)
>60	105 (10.16)	221 (13.87)
>40	249 (17.10)	451 (19.59)
>20	628 (24.70)	851 (22.15)
<20	3,321 (31.60)	1965 (15.14)

Note: Values in parentheses represent the percentage.

The west coast of India experiences approximately 140 rainy days (>2.5 mm/day) per year (Jain et al. 2007). Table 3 presents the rainfall intensity and the number of rainy days for the two catchments. The intensity and frequency of heavy rainfall events (rainfall > 100 mm/day) were significantly less over the Malaprabha River catchment, contributing to only approximately 10% (61 days over the span of 30 years) of the total rainfall. Rainfall intensities of less than 20 mm/day (31.60% of total rainfall and 3,321 days) and of 20–40 mm/day (24.70% of total rainfall and 628 days) were the predominant rainfall patterns for the Malaprabha catchment. The Netravathi River catchment, on the other hand, was characterized by heavy rainfall events, and the maximum contribution was by rainfall intensities higher than 100 mm/day (20.30% of total rainfall with 179 days) and of 20–40 mm/day (22.15% of total rainfall with 851 days). Decreases in the amount of precipitation and the number of rainy days and increases in higher intensity rainfall also have been reported across several parts of Asia (Goswami et al. 2006; Shrestha et al. 2000; Khan et al. 2000; Mirza 2002; Lal 2003; Min et al. 2003). However, these observations are not specific to the Western Ghats of India.

Temperature

The annual and seasonal average temperature for the Malaprabha River catchment showed no statistically significant increase in temperature during the historical period (1975–2004), with an exception during the monsoon season. The average temperature during the monsoon season showed an increase of 0.4°C per decade (5% significance level). The temperature forecasted by the RCP 4.5 scenario indicated warmer years, with a highly significant postmonsoon temperature increase of 0.10°C per decade and temperature increases of 0.08°C per decade for annual average, monsoon season, and summer season (0.1% significance level). Table 4 shows the result of trend analysis for the Malaprabha and Netravathi River catchments.

The average annual temperature over the Netravathi River catchment increased at 0.12°C per decade (5% significance level). The seasonal temperatures also showed a statistically significant rise in temperature, of 0.9°C per decade during the winter season and 0.8°C per decade during the summer season. The forecasted temperatures from the RCP 4.5 scenario showed an increase of 0.1°C per decade (0.1% significance level) annually and during monsoon, postmonsoon and winter seasons. Dash et al. (2007) also showed that the increase in maximum temperature was highest along the west coast of India (approximately 1.2°C) during the last century.

Changes in temperature directly affect the rate of evapotranspiration in the river catchments. In order to evaluate these effects, Hargreaves' method was used to calculate the potential evapotranspiration over the two river catchments. Fig. 3 presents the combined plot of temperature and potential evapotranspiration for the Malaprabha and Netravathi River catchments. The bar charts

Table 3. Trend Analysis of Rainfall for Malaprabha and Netravathi Rivers

Scenario	Time series	Years	Statistic value	Sen's slope estimator (mm/year)	Trend
Malaprabha River					
Scenario 1 1975–2004	Annual rainfall	30	−**2.34**[a]	**26.45**	Decreasing
	Monsoon rainfall	30	−**2.75**[b]	**31.10**	Decreasing
	Postmonsoon rainfall	30	**2.39**[a]	**3.75**	Increasing
	Winter rainfall	30	−0.24	0.00	No trend
	Summer rainfall	30	**2.04**[a]	**1.75**	Increasing
Scenario 2 2006–2070	Annual rainfall	63	**3.46**[c]	**31.44**	Increasing
	Monsoon rainfall	63	**3.44**[c]	**31.01**	Increasing
	Postmonsoon rainfall	63	1.44	0.95	No trend
	Winter rainfall	63	—	—	No trend
	Summer rainfall	63	−0.75	−0.55	No trend
Netravathi River					
Scenario 1 1975–2004	Annual rainfall	30	−1.57	18.93	No trend
	Monsoon rainfall	30	−**1.77**[d]	**24.08**	Decreasing
	Postmonsoon rainfall	30	**1.73**[d]	**3.23**	Increasing
	Winter rainfall	30	−**2.41**[d]	**0.02**	Decreasing
	Summer rainfall	30	0.25	0.60	No trend
Scenario 2 2006–2070	Annual rainfall	63	−1.13	7.29	No trend
	Monsoon rainfall	63	−1.10	5.36	No trend
	Postmonsoon rainfall	63	−0.81	0.44	No trend
	Winter rainfall	63	0.07	0.00	No trend
	Summer rainfall	63	−**1.78**[d]	**2.13**	Decreasing

Note: Bold indicates statistically significant values.

[a] 5% significance level.

[b] 1% significance level.

[c] 0.1% significance level.

[d] 10% significance level.

Table 4. Trend Analysis of Temperature for Malaprabha and Netravathi Rivers

Scenario	Time series	Years	Statistic value	Sen's slope estimator (°C/year)	Trend
Malaprabha River					
Scenario 1 1975–2004	Annual temperature	30	0.75	0.011	No trend
	Monsoon temperature	30	2.53[a]	0.041	Increasing
	Postmonsoon temperature	30	1.62	0.066	No trend
	Winter temperature	30	1.31	0.024	No trend
	Summer temperature	30	0.79	0.013	No trend
Scenario 2 2006–2070	Annual temperature	63	3.95[b]	0.008	Increasing
	Monsoon temperature	63	3.61[c]	0.008	Increasing
	Postmonsoon temperature	63	2.51[a]	0.010	Increasing
	Winter temperature	63	2.87[c]	0.007	Increasing
	Summer temperature	63	2.78[c]	0.008	Increasing
Netravathi River					
Scenario 1 1975–2004	Annual temperature	30	2.03[a]	0.012	Increasing
	Monsoon temperature	30	4.75[b]	0.041	Increasing
	Postmonsoon temperature	30	−0.86	−0.007	No trend
	Winter temperature	30	5.67[b]	0.088	Increasing
	Summer temperature	30	−4.75[b]	−0.080	Decreasing
Scenario 2 2006–2070	Annual temperature	63	5.15[b]	0.010	Increasing
	Monsoon temperature	63	4.34[b]	0.011	Increasing
	Postmonsoon temperature	63	3.91[b]	0.011	Increasing
	Winter temperature	63	4.00[b]	0.010	Increasing
	Summer temperature	63	3.44[b]	0.009	Increasing

Note: Bold indicates statistically significant values.

[a] 5% significance level.

[b] 0.1% significance level.

[c] 1% significance level.

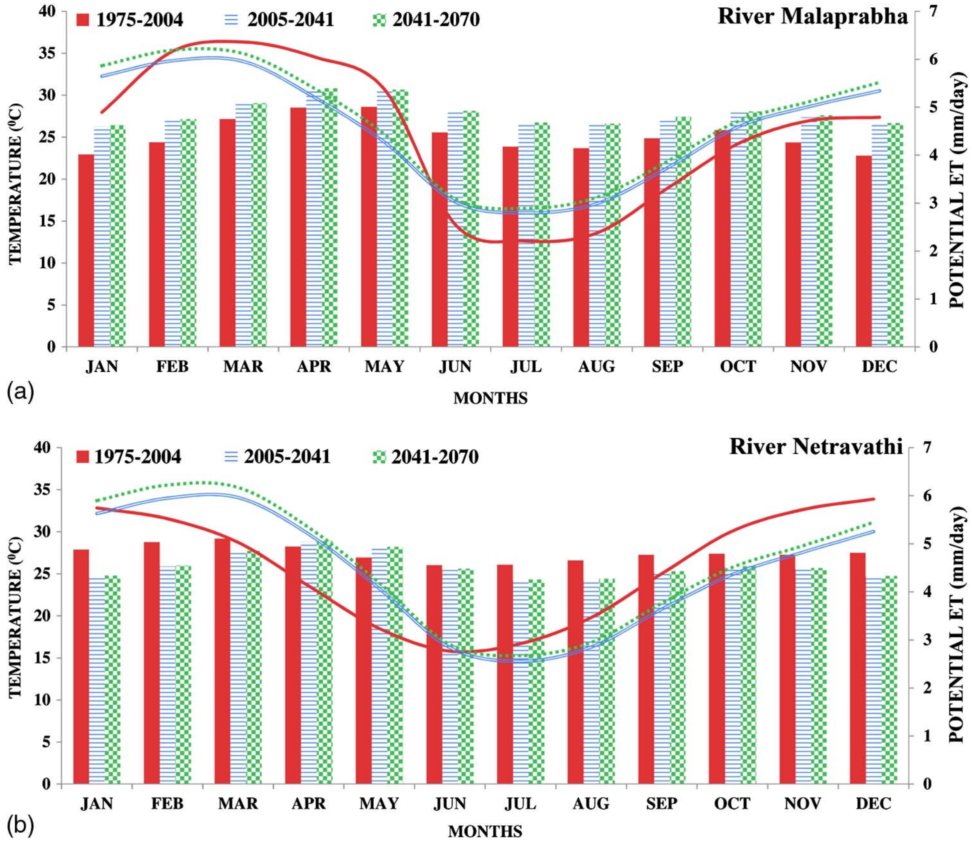


Fig. 3. Monthly temperature and potential evapotranspiration for (a) River Malaprabha; (b) River Netravathi

represent the temperature and the curve represents the potential evapotranspiration. In the forecasted scenario, the Malaprabha River catchment showed a significant increase in the potential evapotranspiration from June to January. The Netravathi River catchment showed an increase in temperature from January to June.

Calibration and Validation of SWAT

The daily time-scale calibration at the Khanapur station (Malaprabha River catchment) and Bantwal station (Netravathi River catchment) for the 20-year period from 1975 to 1994 showed fairly good values of NSE and R^2 (0.831 and 0.829, respectively, for the Malaprabha catchment and 0.857 and 0.859, respectively, for the Netravathi catchment. Because the calibration was carried out on a daily scale, these values may be taken as an indicator of fairly good performance. The validation over the period 1995–2004 agrees well with the streamflows of the Malaprabha and Netravathi River catchments, with R^2 of 0.831 and 0.857 and NSE of 0.81 and 0.83, respectively.

Hydrologic Response to Climate Change

Streamflow

Table 5 furnishes the results of Sen's slope estimator for the streamflow forecasted from RCP 4.5 scenario data for the period 2006–2070 along with the results of historical trend analysis for the Malaprabha and Netravathi River catchments. The annual and postmonsoon streamflows were found to increase at a rate of 0.03 Mm^3 per year and 0.01 Mm^3 per decade (0.1% significance level), respectively. The results also indicated increasing streamflow of 0.09 Mm^3 per decade (1% significance level) during monsoon season. The annual, monsoon, and summer streamflows in the Netravathi River catchment were found to decrease at 0.11, 0.29, and 0.03 Mm^3 per year (5% significance level), respectively. The historical period (1975–2004) also witnessed a decreasing trend in the monsoon streamflow, at a rate of 0.65 Mm^3 per year (5% significance level). The decreasing rate of the monsoon streamflow of 0.65 Mm^3 per decade and 0.29 Mm^3 per year at the 5% significance level is a clear indication of weakening monsoon, which is the lifeline of the country.

In order to evaluate the hydrologic response of climate change on intra-annual flow, the average monthly discharge of the Malaprabha and Netravathi River catchments were plotted (Fig. 4) for historical and forecasted scenarios. The bar charts (with primary axis) represent the rainfall and the curves (secondary axis) represent the streamflow. Fig. 4(a) displays the annual cycle of discharge in the Malaprabha river catchment. The rainfall during the monsoon months of June to September increased in the RCP 4.5 forecasted data. Subsequently, greater streamflow was observed during the postmonsoon season from October to November due to the contribution of delayed storage and base flow. The winter flow is crucial considering the storage requirement for the subsequent summer season. Summer rains usually are scanty in the region; however, the results forecast an increase in the rainfall during the month of May, which is a favorable effect of climate change. Fig. 4(b) shows the annual discharge cycle of the Netravathi River catchment. The rainfall was found to decrease in all months except May and June. Subsequently, the streamflow was found to peak in July and then decline during the second half of monsoon season (August and September) and during postmonsoon season.

Fig. 5 presents the box-whisker plots of the monthly streamflow for Scenario 1 and Scenario 2 for the Malaprabha and Netravathi

Table 5. Trend Analysis of Streamflow for Malaprabha and Netravathi Rivers

Scenario	Time series	Years	Statistic value	Sen's slope estimator (Mm^3/year)	Trend
			Malaprabha River		
Scenario 1 1975–2004	Annual streamflow	30	0.82	0.01	No trend
	Monsoon streamflow	30	0.54	0.01	No trend
	Postmonsoon streamflow	30	2.68[a]	0.04	Increasing
	Winter streamflow	30	—	—	—
	Summer streamflow	30	—	—	—
Scenario 2 2011–2070	Annual streamflow	63	3.43[b]	0.03	Increasing
	Monsoon streamflow	63	3.14[a]	0.09	Increasing
	Postmonsoon streamflow	63	3.32[b]	0.01	Increasing
	Winter streamflow	63	3.18[a]	0.00	Increasing
	Summer streamflow	63	0.89	0.00	No trend
			Netravathi River		
Scenario 1 1975–2004	Annual streamflow	30	1.70[c]	0.22	Decreasing
	Monsoon streamflow	30	1.98[d]	0.65	Decreasing
	Postmonsoon streamflow	30	0.70	0.09	No trend
	Winter streamflow	30	1.95[c]	0.03	Decreasing
	Summer streamflow	30	1.84[c]	0.01	Decreasing
Scenario 2 2011–2070	Annual streamflow	63	−2.37[d]	0.11	Decreasing
	Monsoon streamflow	63	−2.10[d]	0.29	Decreasing
	Postmonsoon streamflow	63	−1.21	0.05	No trend
	Winter stream streamflow	63	−0.96	0.00	No trend
	Summer streamflow	63	−2.43[d]	0.03	Decreasing

Note: Bold indicates statistically significant values.
[a] 1% significance level.
[b] 0.1% significance level.
[c] 10% significance level.
[d] 5% significance level.

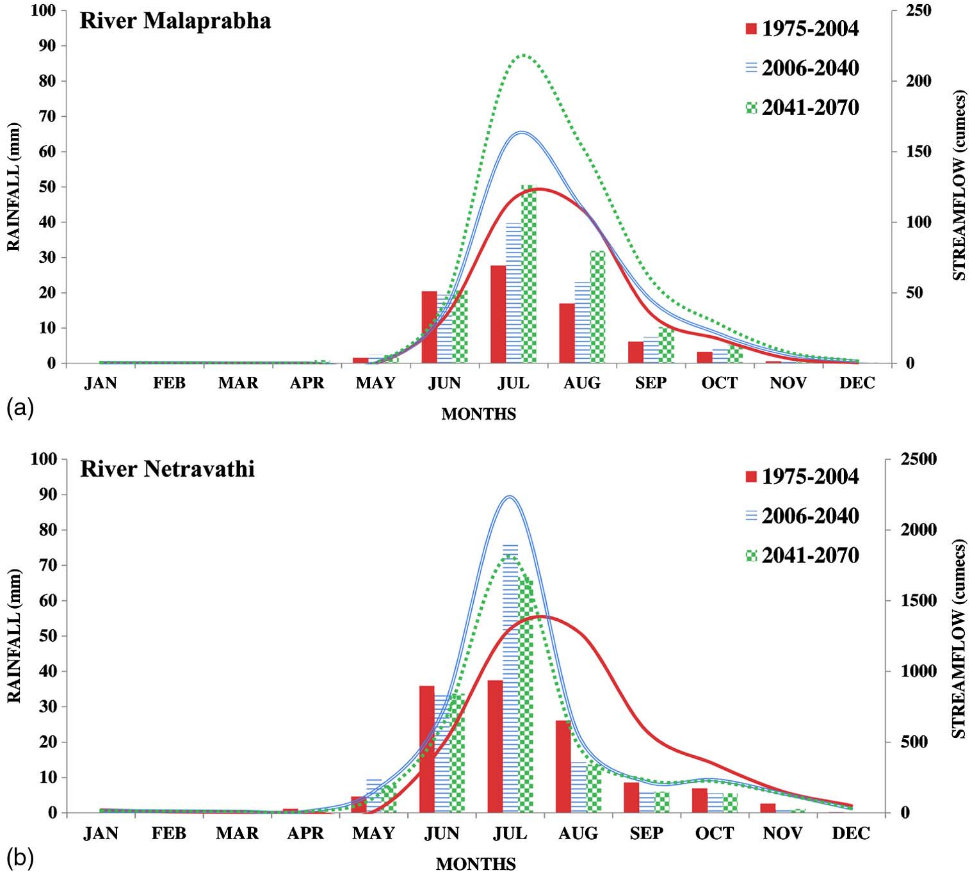


Fig. 4. Monthly precipitation and streamflow for (a) River Malaprabha; (b) River Netravathi

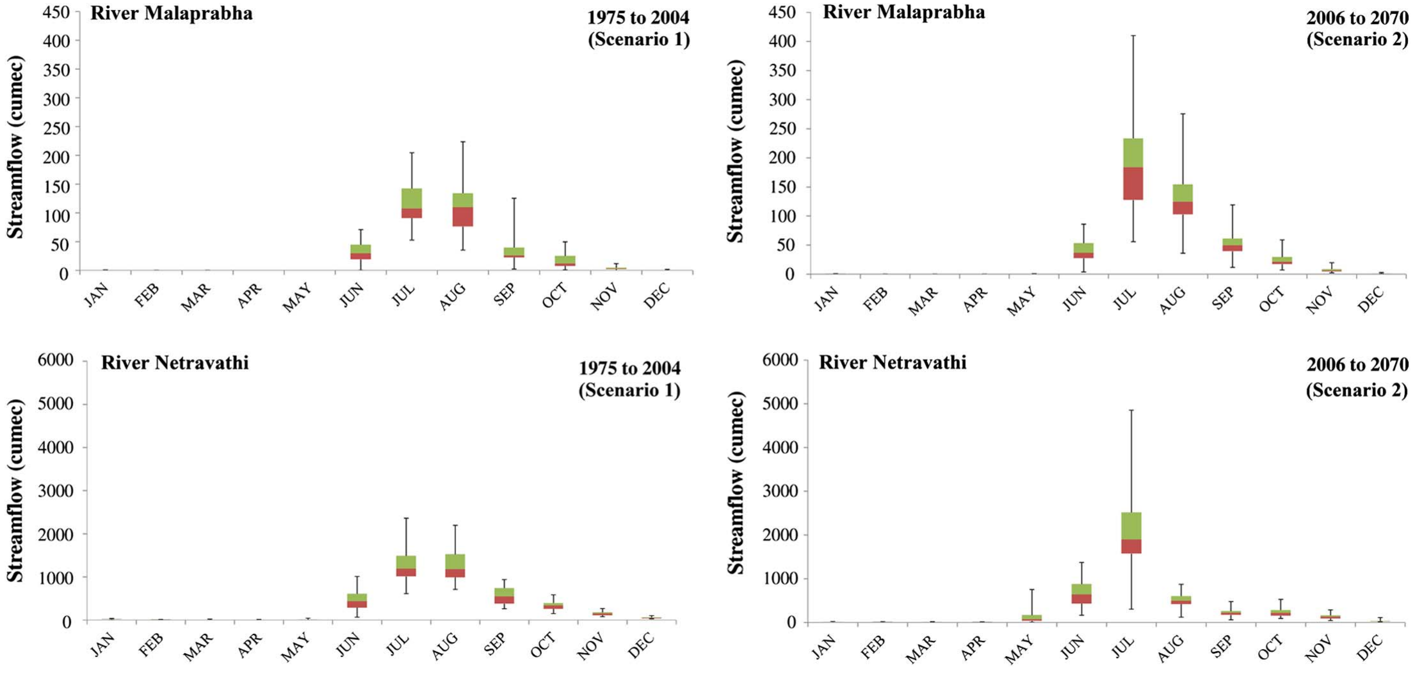


Fig. 5. Monthly percentiles of streamflow

Rivers. The peak forecasted flow in the Malaprabha River shifted from July–August to July. This could indicate a diffused Indian monsoon over the long run. In the Netravathi River (Fig. 5), the major contributing months for streamflow were found to increase from June–October to May–December. A significant decrease of forecasted streamflow was observed during the monsoon season except for July. May and December showed an increase in streamflow (Fig. 5). These observations confirm the weakening of the monsoon by the year 2070.

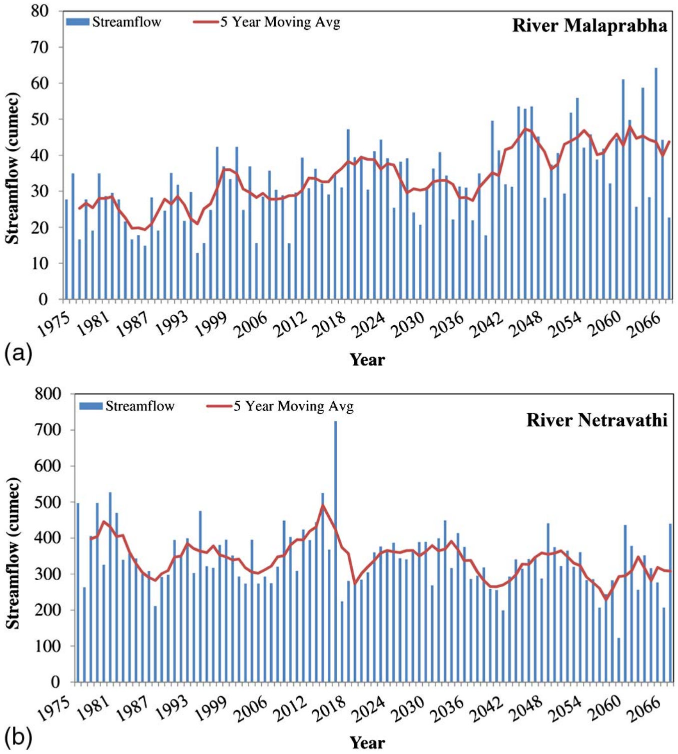


Fig. 6. Annual variation in the observed and simulated streamflow for (a) River Malaprabha; (b) River Netravathi

To evaluate the annual variation of streamflow due to changing climate, Fig. 6 plots the total annual streamflow along with 5-year moving average. The moving average line indicates the increased availability of water in the Malaprabha River catchment toward the end of Scenario 2 [Fig. 6(a)]. On the other hand, the flow in the Netravathi catchment was forecast to decrease [Fig. 6(b)]. In order to evaluate interannual variations of streamflow, Fig. 7 plots the departure values along with the 5-year moving average. Departure above zero indicates a cumulative streamflow greater than the 30-year normal and is considered as a wet year; departure below zero indicates a cumulative streamflow less than the 30-year normal and is considered as a dry year. Alternative wet and dry years were observed for the Malaprabha River catchment [Fig. 7(a)] in Scenario 1 (1975–2004) and frequent wet years were seen for Scenario 2 (2011–2070). The Netravathi catchment [Fig. 7(b)] showed a contrasting result, with wet years in Scenario 1 and prolonged dry years in Scenario 2. This is an alarming situation wherein the declining river water may have to be managed judiciously. The interdecadal streamflow was compared to ascertain the water availability in the catchments (Table 6). An increase in the total streamflow (from 0.20 to 3.14 Mm^3) was observed for the Malaprabha River catchment, whereas total streamflow gradually decreased (from 34.80 to 25.30 Mm^3) in the Netravathi River catchment.

Frequency and Flow Quantiles

In order to assess the impact of climate change on extreme flow conditions, the streamflow was subjected to frequency analysis at a 10-year time interval by calculating the flow quantiles. Prior to the calculation of flow quantiles, bias correction of the RCP data was carried out using the delta-change correction method followed by basic frequency analysis hypothesis verification. The statistical properties of discharge time series of the RCP 4.5 scenario were

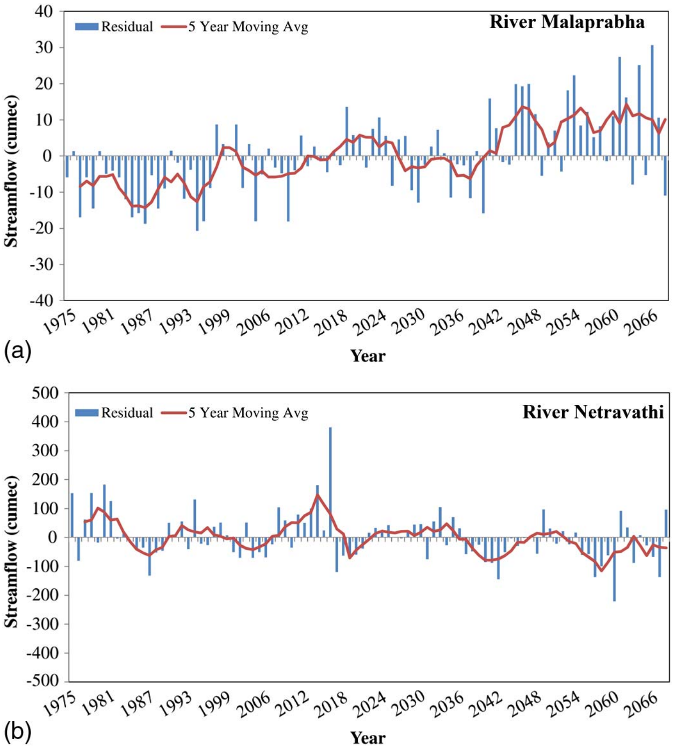


Fig. 7. Interannual variation in observed and simulated streamflow for (a) River Malaprabha; (b) River Netravathi

Table 6. Decadal Variation of Streamflow for Malaprabha and Netravathi Rivers (Mm^3)

	Malaprabha River			Netravathi River		
Period	Total flow	Change	(%)	Total flow	Change	(%)
1975–1984	0.20	—	—	34.80	—	—
1985–1994	0.18	−0.02	−10.75	28.82	−5.97	−17.16
1995–2004	0.23	0.05	26.35	28.48	−0.34	−1.19
2006–2015	1.09	0.86	79.19	33.79	5.31	18.64
2016–2025	1.73	0.64	59.13	30.90	−2.89	−8.56
2026–2035	1.18	−0.55	−31.82	31.77	0.87	2.83
2036–2045	1.75	0.57	48.69	25.39	−6.38	−20.07
2046–2055	2.84	1.09	62.15	29.78	4.38	17.26
2056–2070	3.14	0.30	10.55	25.30	−4.48	−15.05

fairly reproduced in the observed period. Table 7 shows the decadal flow quantiles calculated for the Malaprabha and Netravathi River catchments. The Q10 flow in both catchments decreased, which could be due to weakening of the monsoon, with fewer rainy days having rainfall intensity >100 mm and 80–100 mm. The Q90 flow showed an increase across different decades for Netravathi River. The median flow (Q50) indicated an alternate increasing and decreasing trend throughout Scenarios 1 and 2 for both the catchments. In the Malaprabha river catchment, the relative magnitude of peak flow with respect to the median decreased by a maximum of 40% for the forecasted scenario. The median flow and its relative change showed a decreasing trend in the Netravathi River catchment, similar to that of the Malaprabha catchment, with a maximum change during the decade 2021–2030. This could be due to more rainy days with intensity <20 mm, which may lead to losses including percolation with minimal/no streamflow. Table 8 shows the HFI and LFI. The HFI was found to be increasing (from 7 to 56) for Malaprabha, whereas it was decreasing for Netravathi (from 19 to 11).

Conclusions

This paper provides an insight into the possible climate change impacts on two different river flow regimes—the Malaprabha and Netravathi Rivers—originating from the Western Ghats of India using the RCP 4.5 scenario. From the historical data for 30 years, the annual rainfall was found to be decreasing for Malaprabha, with no trend for Netravathi catchment. The average rainfall over the Malaprabha and Netravathi catchments during the monsoon season (Jun–Sep) was found to be decreasing at 31 mm per year (1% significance level) and 24 mm per year (10% significance level), respectively, indicating a weakening of the Indian monsoon by the year 2070. Hence filling of storage reservoirs in the catchments may be difficult, indicating water shortage for the lean season. This paper, therefore, discourages the installation of infrastructure which would lead to excessive withdrawal of water from the two rivers. Alternatively, smaller storages may be encouraged along the river course, which will cause minimal environmental damage.

The decrease was estimated to be from 84 to 80% of total rainfall in the Malaprabha catchment and from 80 to 77% in the Netravathi River catchment. Average rainfall during the postmonsoon season (Oct–Nov) increased marginally, by 40 and 30 mm per decade for the Malaprabha and Netravathi catchments, respectively. This may favor water availability for rabi crops in the catchments. The comparison of rainfall during the observed period (1975–2004) and the forecasted period (2006–2070) showed that the rainfall

Table 7. Decadal Variation of Flow Quantiles for Malaprabha and Netravathi Rivers (m^3/s)

	Malaprabha River			Netravathi River		
Decade	Q_{10}	Q_{50}	Q_{90}	Q_{10}	Q_{50}	Q_{90}
1975–1984	161.20	23.63	2.10	1293.3	66.70	3.70
1985–1994	146.39 (−9.19)	25.49 (+7.87)	3.43 (+63.33)	1056.1 (−18.34)	57.80 (−13.34)	2.31 (−37.57)
1995–2004	156.04 (+6.59)	25.36 (−0.51)	0.96 (−72.01)	1048.0 (−0.77)	87.21 (+50.88)	2.30 (−0.43)
2006–2015	102.9 (−34.06)	1.80 (−92.89)	0.15 (−83.65)	852.70 (−18.64)	87.68 (0.54)	8.60 (273.91)
2016–2025	124.60 (21.09)	1.66 (−7.98)	0.18 (14.65)	752.20 (−11.79)	70.50 (−19.59)	9.38 (9.07)
2026–2035	99.78 (−19.92)	1.69 (1.81)	0.18 (0.00)	920.80 (22.41)	77.76 (10.30)	11.78 (25.59)
2036–2045	105.40 (5.63)	2.07 (22.49)	0.18 (0.00)	752.80 (−18.25)	57.55 (−25.99)	9.46 (−19.69)
2046–2055	161.50 (53.23)	1.83 (−11.59)	0.18 (0.00)	798.50 (6.07)	71.92 (24.97)	11.00 (16.28)
2056–2070	132.20 (−18.14)	2.36 (28.96)	0.21 (0.00)	656.40 (−17.80)	59.61 (−17.12)	9.21 (−16.27)

Note: Values in parentheses represent the relative change from preceding decade.

Table 8. Decadal Variation of High and Low Flow Indices for Malaprabha and Netravathi Rivers

	Malaprabha River		Netravathi River	
Decade	High flow index	Low flow index	High flow index	Low flow index
1975–1984	6.82	0.09	19.39	0.06
1985–1994	5.74	0.13	18.27	0.04
1995–2004	6.15	0.04	12.02	0.03
2006–2015	57.04	0.09	9.73	0.10
2016–2025	75.06	0.11	10.67	0.13
2026–2035	59.04	0.11	11.84	0.15
2036–2045	50.92	0.09	13.08	0.16
2046–2055	88.25	0.10	11.10	0.15
2056–2070	56.02	0.09	11.01	0.15

events during the summer month of May increase during the forecasted period for the Netravathi catchment. It is evident from the rainfall analysis that the present Indian monsoon from June to September is likely to be weakened, but with increased duration, i.e., from May to October. The historical trend found that the number of rainy days with higher-intensity rainfall events (>100 mm/day) was less in the Malaprabha catchment (61 days) than in the Netravathi catchment (179 days). However, the trend of heavy rainfall events was found to have been replaced by more less-intense rainy days for both catchments. This will result in reduced streamflow in the catchments, leading to smaller storages. Hence storage at regular intervals may be used to reduce the loss of water in infiltration and evaporation.

From the historical data, the temperature increased at a rate of 0.1°C per decade (1% significance level) for both catchments. The increase in average annual temperature during the forecasted scenario was expected to further increase by 0.08°C per decade and 0.1°C per decade (both at 0.1% significance level) by 2070 in the Malaprabha and Netravathi catchments, respectively. Consequently, the evapotranspiration in the river catchments is also expected to increase, with increased crop water requirement and reduced yield. Hence crops less sensitive to water stress or better adaptable to changes in the climate should be selected for sustainable crop production. Techniques such as drip irrigation, subsurface drip, and mulching (by crop residue and/or polyethylene sheets) should be evaluated based on the knowledge of root zone depth, soil types, and irrigation systems to maximize irrigation water utility. Regular small storages along the river may enhance the soil moisture in the surrounding area, supplementing the water requirements. Annual streamflow for the historical period in the Malaprabha catchment showed no significant trend, whereas in the Netravathi catchment it was found to be decreasing significantly at 0.22 Mm^3 per year (1% significance level). In the case of the Netravathi catchment, the monsoon flow also was found to be decreasing, at a rate of 0.65 Mm^3 per year. This may trigger early tidal (saline water) flow into the fresh river water. This study recommends rainwater harvesting methods to maintain steady baseflow even during nonmonsoon months.

The performance of the SWAT model for the two catchments was found to be good. It forecasted predominantly wet years for Malaprabha, which may result in an increase in streamflow, leading to more water availability to the downstream Malaprabha dam. In contrast, dry years were forecasted for Netravathi catchment, which may require conservation measures for available water. Low flows (90% dependable) were found to be decreasing in the Malaprabha River catchment in future decades, whereas they were found to be increasing in the Netravathi River catchment. Thus the investigation confirms spatiotemporal variation of rainfall and increasing temperatures in the region due to climate change, to which the catchments respond differently. This will result in decreasing monsoon flows in the catchments, leading to reduced storages and tidal aggression from the sea. It was also evident that the climate change impact becomes more pronounced as the catchment area increases. The study thus highlights the need to modify the catchment level infrastructure and conservation of water resources in light of climate change. The outcome of the investigation may be useful for the sustainable regional planning of water storage and utilization.

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