



Assessing climate change impacts on river hydrology – A case study in the Western Ghats of India

T M SHARANNYA*, AMOGH MUDBHATKAL and A MAHESHA

*Department of Applied Mechanics and Hydraulics, National Institute of Technology, Karnataka,
Surathkal, Mangalore 575 025, India.*

**Corresponding author. e-mail: sharannyatm@gmail.com*

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The objective of this study is to evaluate the hydrological impacts of climate change on rainfall, temperature and streamflow in a west flowing river originating in the Western Ghats of India. The long-term trend analysis for 110 yr of meteorological variables (rainfall and temperature) was carried out using the modified Mann–Kendall trend test and the magnitude of the trend was quantified using the Sen’s slope estimator. The Regional Climate Model (RCM), COordinated Regional climate Downscaling EXperiment (CORDEX) simulated daily weather data of baseline (1951–2005) and future RCP 4.5 scenarios (2006–2060) were used to run the hydrological model, Soil and Water Assessment Tool (SWAT), in order to evaluate the effect of climate change on rainfall, temperature and streamflow. Significant changes were observed with regard to rainfall, which have shown decreasing trend at the rate of 2.63 mm per year for the historical and 8.85 mm per year for RCP 4.5 future scenarios. The average temperature was found to be increasing at 0.10 °C per decade for both historical and future scenarios. The impact of climate change on the annual streamflow yielded a decreasing trend at the rate of 1.2 Mm³ per year and 2.56 Mm³, respectively for the past and future scenarios. The present work also investigates the capability of SWAT to simulate the groundwater flow. The simulated results are compared with the recession limb of the hydrograph and were found to be reasonably accurate.

Keywords. Base flow; climate change; Gurupura catchment; Mann–Kendall; RCM; SWAT.

1. Introduction

Hydrologists and water management planners are in a quandary over the availability of water. The impacts of climate change contribute to this uncertainty to a great extent. The quality and quantity of water is affected by activities such as land-mining, agriculture, urban development and other anthropogenic activities within a watershed. Since the various watershed processes are interdependent and are highly variable with respect to time and space, prediction of watershed processes is not

an easy task (Wagener *et al.* 2003). It is very important to understand the possible impacts of climate change on water resources for ensuring their appropriate management and utilization.

The General Circulation Models (GCMs) and Regional Climate Models (RCMs) are used to project future climate data based on the CO₂ emission scenarios. The RCMs are of finer spatial resolution and are better tools for dynamic downscaling of climate features for a particular region (Jones *et al.* 2004). Statistical downscaling using pre-defined statistical relationship or

dynamical downscaling using an RCM nested in a GCM is essential to assess hydrological impacts of climate change (Marengo *et al.* 2009).

The COordinated Regional climate Downscaling EXperiment (CORDEX) provides regionally down-scaled climate for GCM projections as per the fifth Coupled Model Intercomparison Project (CMIP5) (Evans 2011). The present paper is an attempt to investigate the impact of climate change on the hydrology of the west coast basin of India, i.e., Gurupura River catchment of Karnataka.

The physically-based semi-distributed model, Soil and Water Assessment Tool (SWAT) (Arnold *et al.* 1998) is widely used in assessing the impact of climate change on hydrology (Liew and Garbrecht 2003; Zhang 2007; Raneesh and Santhosh 2011; Ajeeth and Thomas 2013).

The western coast of Indian peninsula is covered with the mountain range known as the Western Ghats, which is located entirely along and parallel to the west coast of India. Considerable transitions have been taking place over the decades causing changes in the area. The hydrological regime in the humid tropics of the Western Ghats has been least explored by the scientific community and considerable impacts of climate change are anticipated in the rivers of the Western Ghats. SWAT is efficient for predicting climate change impact on streamflow. In view of this, the Government of India is implementing the research scheme involving the climate change impact assessment of all the major river basins of India. Given the importance of west coast region in India, in terms of population, growth and industrialization, studies on the impact of climate change in this region are crucial for sustainable water resource development and utilization under the ongoing climate change scenario. The river Gurupura is one of the major rivers in Dakshina Kannada district on the west coast of India and provides water to the city of Mangalore and its suburbs. The present study on climatic trend and impact is carried out using data over a period of 110 yr (55 yr of historic/baseline data and 55 yr of RCP 4.5 data). The Rossby Centre Regional Atmospheric Model (RCA4) simulations of CORDEX experiment were specifically selected for the simulation using SWAT owing to its good performance (close proximity to observed data) in the complex mountainous topography of India (Ghimire *et al.* 2015). An effort is also made in the present work to simulate the subsurface flow component using SWAT hydrological model in addition to the streamflow.

2. Study area

2.1 Characteristics of the study area

The river Gurupura is one of the major rivers in the Dakshina Kannada district of Karnataka. The river originates at an elevation of 1880 m above the mean sea level (msl) in the steep slopes of the Western Ghats and flows westward to join the Arabian Sea. The Gurupura River takes a right-angled turn prior to joining the sea and flows southward parallel to the coast for a length of 6 km and joins the Arabian Sea after its confluence with the Nethravathi River. The catchment area up to gauging site at Polali is 712 km², which extends from 12°50' to 13°10'N and 74°50' to 75°15'E. Six rain gauge station are located around the basin. They are (1) Bantwal, (2) Belthangadi, (3) Kalasa, (4) Karkala, (5) Bajpe and (6) Mulky (figure 1). The catchment receives an average annual rainfall of 4019.35 mm. The maximum and minimum temperature of catchment varies in between 36 to 25°C, respectively. Towards the east of the catchment, the topography is characterized by the steep hill slopes. The lateritic plateaus dominate in the central portion and the west coast consists of flat lands. The vegetation comprises of dense forest in the hilly regions, natural shrubs in the midlands and agricultural croplands in the coastal plains.

2.2 Data used

The hydrological data, i.e., streamflow at Polali gauging station was procured for a period of 12 yr (1974–1985) from the Karnataka Public Works Department (Karnataka PWD). The meteorological data such as daily rainfall and temperature for a period of 25 yr (1970–1995) were obtained from the India Meteorological Department (IMD) and Water Resources Development Organization (WRDO) Karnataka, respectively. The Digital Elevation Model (DEM) of 90 m spatial resolution was obtained from the Shuttle Radar Topography Mission (SRTM). The land use and land cover map of the catchment was obtained from the supervised classification of Landsat-7 imagery and soil map was obtained from the WATERBASE global dataset (www.waterbase.org). In order to provide robust hydro climatic variables, the World Climate Research Programme (WCRP) initiated the CORDEX framework (Evans 2011). The CORDEX framework is based on the Coupled Model Intercomparison Project phase 5 (CMIP5) using the

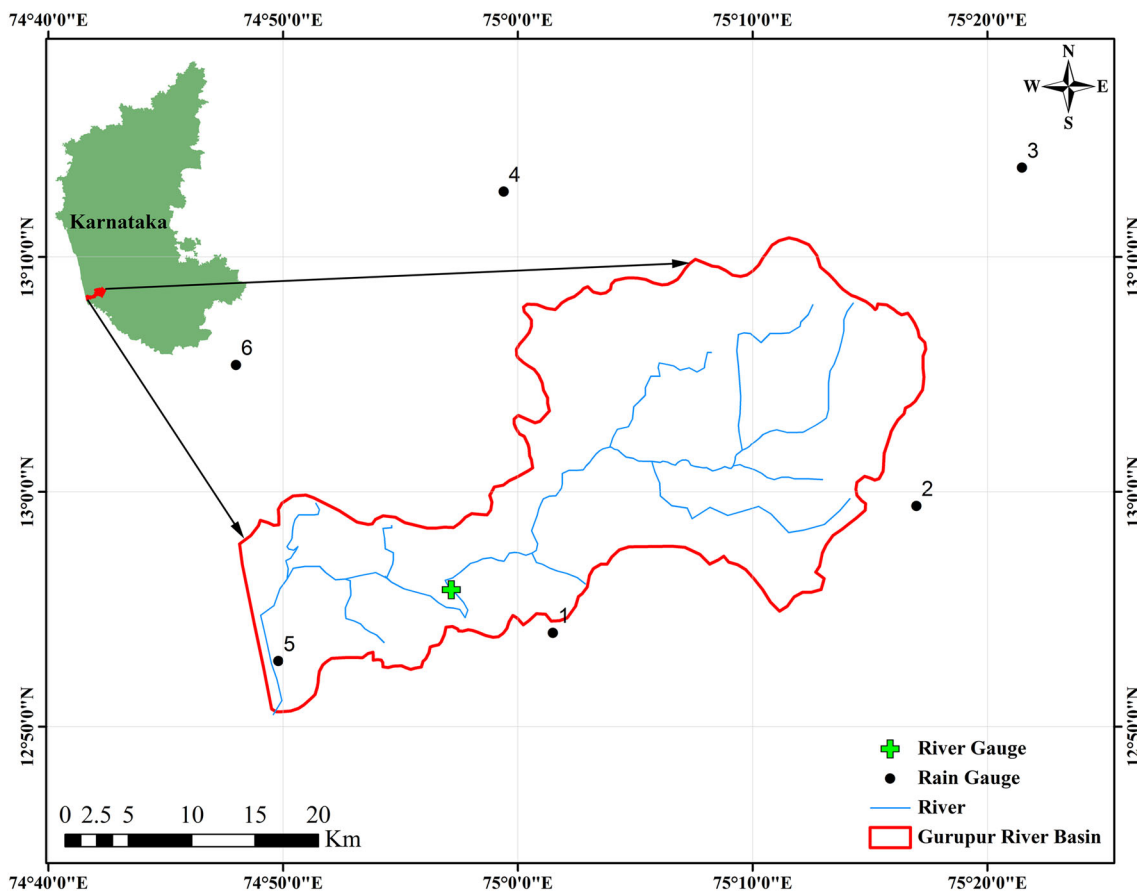


Figure 1. Location map of Gurupura catchment.

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 W/m^2 . Representative Concentration Pathways (RCPs) with use of CORDEX datasets can be used to demonstrate potential impacts on climate change on hydrology (Li *et al.* 2016; Shrestha and Aung 2016; Mudbhatkal *et al.* 2017). The climatic data from CORDEX RCM for RCP 4.5 scenario was corrected for bias using Delta Change correction method and given as an input to the SWAT model. The historical and forecasted data for a period of 55 yr (1951–2005 and 2006–2060) from CORDEX was also used and the analysis for historical and future scenarios were carried out.

3. Methodology

The SWAT is a semi-distributed, continuous watershed model (Arnold *et al.* 1998) has been used

for rainfall-runoff modeling in the present study. The SWAT is capable of providing necessary hydrologic simulations related to the impacts of climate variations on water resources (Liew and Garbrecht 2003). The following inputs were prepared in the required format for the catchment: (1) digital elevation model, (2) land use and land cover map, (3) soil map, and (4) daily climatic data, which includes precipitation, minimum and maximum temperature. It is assumed that physical characteristics such as LULC, topography and soil of the study area have not changed over the time period. The SWAT model was run for the period 1970–1995 and the calibration and validation of the model was carried out during 1974–1981 and 1982–1985, respectively as data for streamflow was consistent only for those period. The performance of the model was evaluated using the Nash–Sutcliffe Efficiency (NSE), coefficient of determination (R^2) and the percentage of deviation from the observed streamflow (PBIAS). The closer the values of NSE and R^2 to unity, the better the model performance. For PBIAS, the optimal value is 0 and positive value indicates underestimation and a negative value indicates an

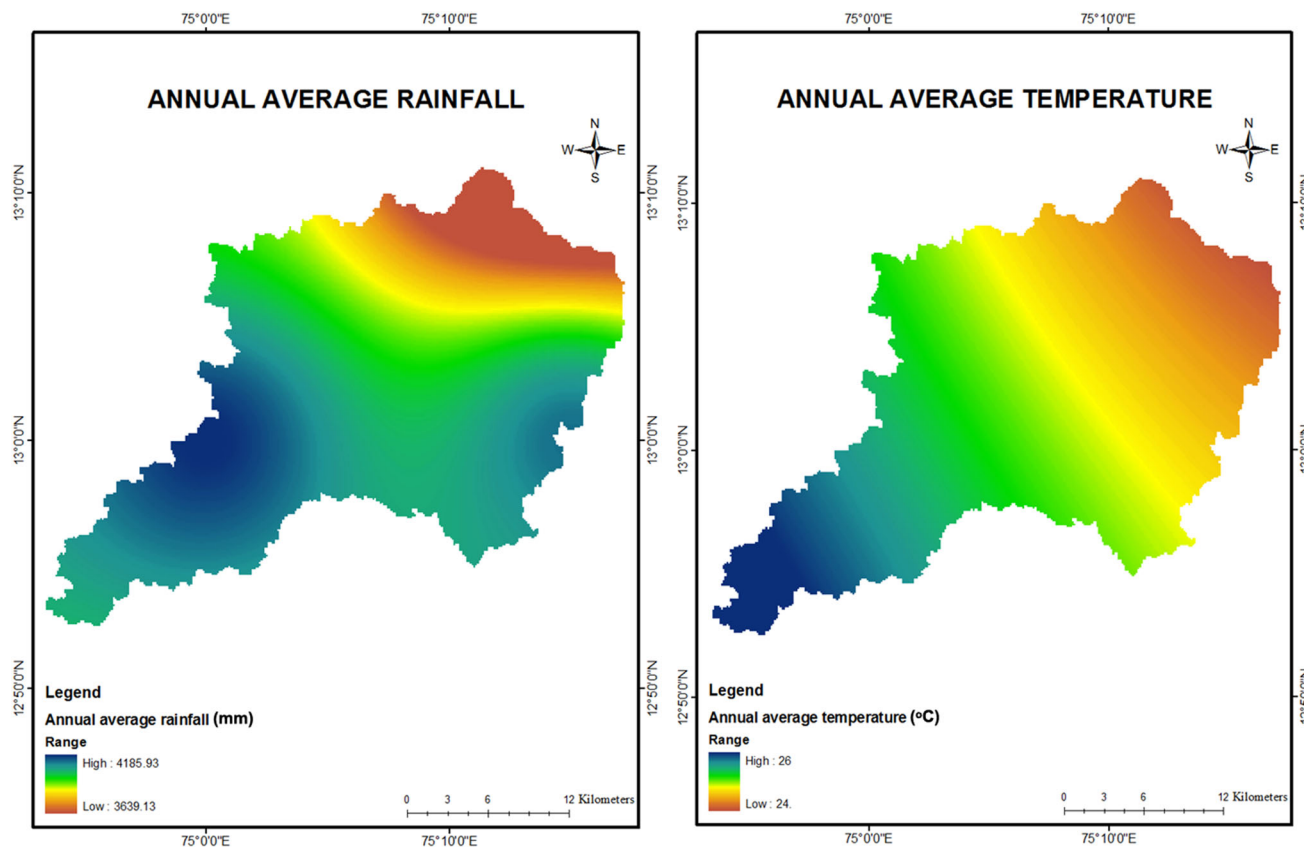


Figure 2. Annual average rainfall and temperature of Gurupura basin.

overestimation of observed discharge values. In this study, the sequential uncertainty fitness (SUFI-2) algorithm was used for calibration, sensitivity analysis, and validation. The global sensitivity analysis was performed in order to identify the most sensitive parameters. The sensitivity analysis plays a critical role in reducing the number of parameters to be changed from a large number of parameters in SWAT. The significance of the rainfall, temperature and streamflow can be estimated by trend analysis (Raju and Nandagiri 2017). The modified Mann–Kendall trend test is used in the present study to evaluate the trend of climatic variables. No trend in the series is given by null hypothesis H_0 . Negative, non-null, or positive trend are the three hypotheses given in the test. The modified Mann–Kendall is used since it eliminates the influence of serial correlation.

4. Results and discussion

4.1 Available water

The river Gurupura along with the other west flowing rivers of Karnataka is a seasonal river. The north-east monsoon rainfall in the region is not as

predominant as the south-west monsoon and the rivers start depleting. The rivers are usually dry or have insignificant flow beyond February. Annual average rainfall and temperature of the catchment is shown in figure 2. It can be analyzed that maximum rainfall is occurring at the middle portion of the catchment and annual average rainfall is less at the Western Ghats and increase as it moves little far from the Ghats. Temperature is less near the hilly regions of the catchment and it increase as it moves towards the coastal area. The maximum discharge recorded in the river Gurupura was 1746.23 cumecs on 3rd August 1982.

The average annual flow in the river is about 3035.57 Mm^3 . The maximum annual flow observed was 4266.83 Mm^3 (3.13 times the minimum) in 1978 and the minimum annual flow observed was 1360.9 Mm^3 in 1985 (figure 3). The average monthly flow is analyzed for the same period which shows a very high variation due to the uneven distribution of rainfall over the year. The average monthly flow was 176.1 cumecs. The highest monthly flow of 592.67 cumecs was observed in July 1980. It is also observed that 98% of the annual flow takes place during six months (June–November) of the year (figure 4).

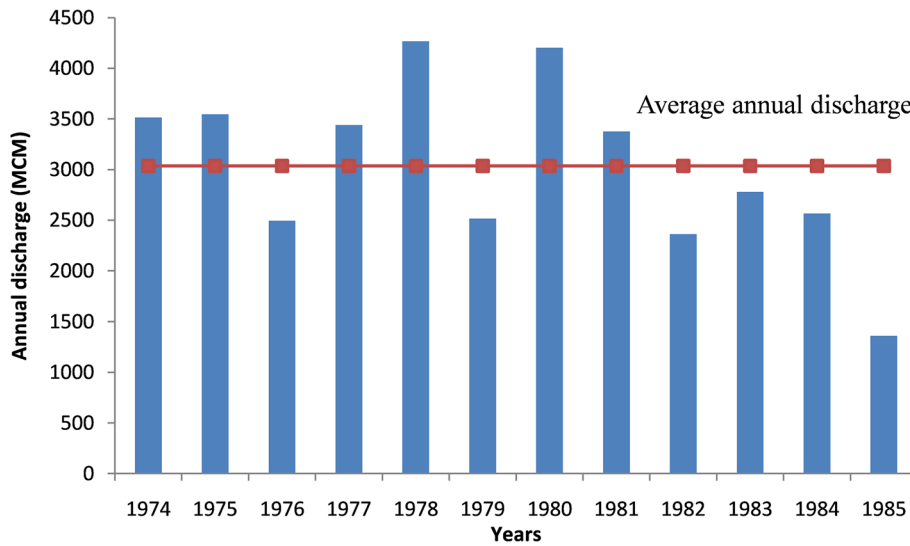


Figure 3. Average annual flow in the Gurupura river.

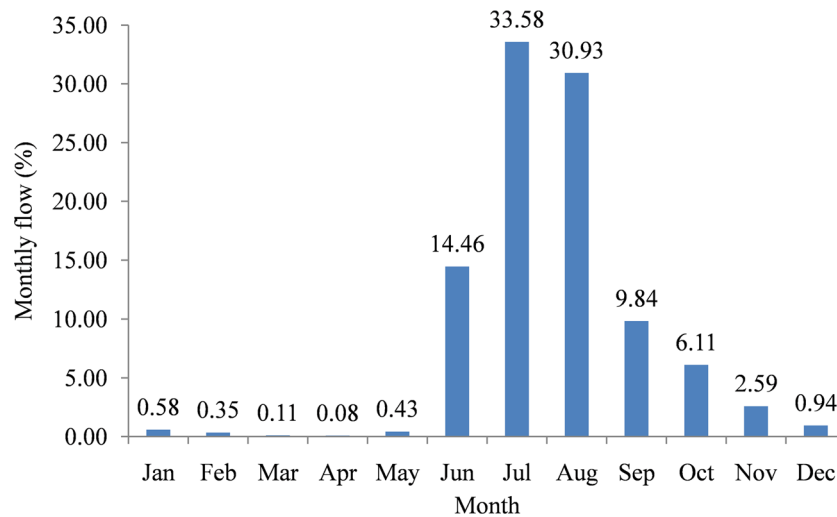


Figure 4. Variation of average monthly flow during a year.

4.2 Flow duration curve

The relationship between discharge and percentage of time that the discharge is equaled or exceeded is related by the Flow Duration Curve (FDC). The flow duration curve of Polali outlet based on 12 yr data is shown in figure 5. The FDC provides a concise description of the temporal variability of run-off and provides estimates of flow quantiles or dependable flows. The flow quantiles represent % of time flow happened in the river (Q10, Q20, Q30, etc.). The flow corresponding to Q90 should be the minimum flow available for drinking water or irrigation projects. The flow quantiles for the FDC is given in table 1. The average flow, i.e., 50% of time flow at Polali outlet is 45.12 cumecs. The low flow, Q90 which represents the base flow is 4.09 cumecs,

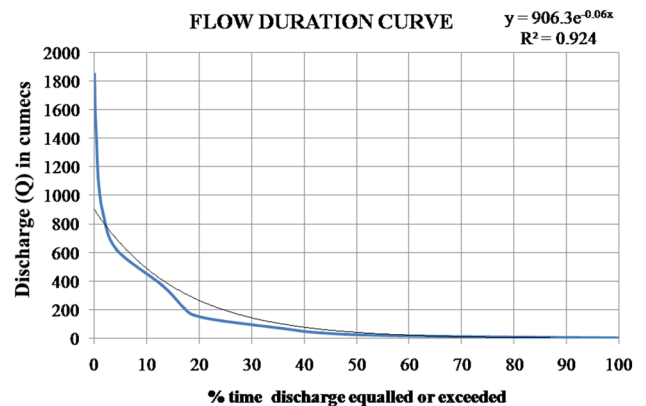


Figure 5. Flow duration curve at Polali outlet.

which is available till third week of February. The maximum discharge observed was 1746.23 cumecs, which is useful to estimate the design flood.

Table 1. Flow quantiles estimated for the Gurupura River.

Time (%)	Discharge (cumec)
10	497.39
20	272.97
30	149.81
40	82.22
50	45.12
60	24.76
70	13.59
80	7.46
90	4.09

4.3 Sensitivity analysis

The sensitivity analysis, calibration and validation are used to assess the simulation ability of the model. With sensitivity analysis, the key parameters required for model calibration are identified and the number of parameters for calibration is reduced to 13. In this study, global sensitivity analysis was performed. Table 2 shows the sensitiveness rank of parameters.

4.4 Model calibration and validation

The SWAT model was executed using the default parameters and then considered for calibration using the SUFI-2 algorithm. The number of sub-basins and Hydrological Response Units (HRU) formed was 27 and 301, respectively. The output file basin.rch contains simulated streamflow.

Table 3. Initial and final ranges of the parameters used for the calibration.

Parameters	Initial range		Final range	
	Min	Max	Min	Max
CN2	-0.2	0.2	-0.437	-0.436
ALPHA_BF	0	1	0.565	0.661
GW_DELAY	0	500	22.6	30.99
GWQMN	0	2	1.77	1.948
ESCO	0	1	0.0818	0.742
CH_N2	0	0.3	-0.1467	0.0622
CH_K2	5	130	76.3	128.69
SOL_AWC	0	1	0.55	0.93
SOL_K	-0.8	0.8	0.39	0.68
EPCO	0	1	0.11	0.12
SOL_BD	-0.5	0.6	0.24	0.53
REVAPMN	0	10	0	10
HRU_SLP	0	2	0.0359	0.48

A number of iterations were made in order to match the simulated results with the observed data. SWAT-CUP provides a set of several objective functions. Table 3 shows the initial and final range of the calibration parameters, the final range was consequently used in the validation step without change.

The outlet of the study area, i.e., Polali gauging station has been used for calibration for streamflow. In the 12 yr record, 1974–1981 was taken as calibration period and 1982–1985 was considered for validation on the daily basis. The trend line for the plot between observed and simulated monthly streamflows shows good correlation value. The hydrograph and statistical indicators during

Table 2. Sensitiveness rank of the flow parameters for the calibration period (1974–1981).

Parameter	Sensitiveness rank
Manning's 'n' value for the main channel (CH_N2)	1
Bulk density of moist soil (mg/m^3) (SOL_BD)	2
Saturated hydraulic conductivity (mm/h) (SOL_K)	3
Soil evaporation compensation factor (ESCO)	4
SCS runoff curve number for moisture condition II (CN2)	5
Threshold depth of water in the shallow aquifer required for return flow to occur (mm) (GWQMN)	6
Threshold depth of water in the shallow aquifer for 'revap' or percolation to the deep aquifer to occur (mm) (REVAPMN)	7
Available water capacity of the soil layer (SOL_AWC)	8
Base flow alpha factor (days) (ALPHA_BF)	9
Average slope steepness m/m (HRU_SLP)	10
Effective hydraulic conductivity in main channel alluvium (mm/h) (CH_K2)	11
Groundwater delay time (days) (GW_DELAY)	12
Plant uptake compensation factor (EPCO)	13

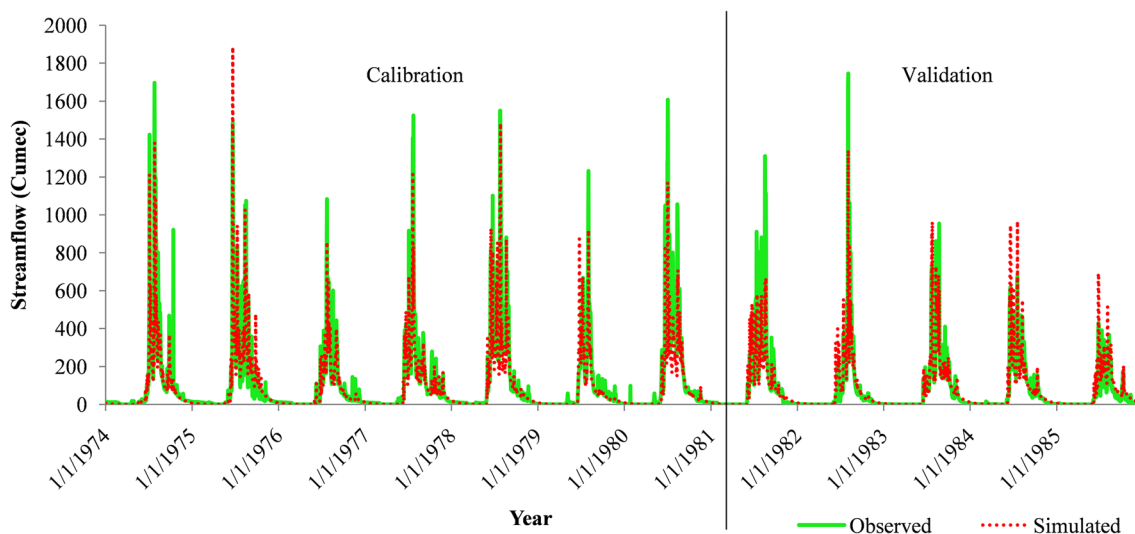


Figure 6. Time series hydrograph during calibration and validation.

Table 4. Values of statistical indicators.

Indicators	Calibration	Validation	Remarks
NSE	0.83	0.85	Good
R^2	0.86	0.85	Good
PBIAS	17.5	-3.9	Good

the calibration and validation are presented in figure 6 and table 4, respectively. It can be noticed that, the SWAT model underestimated the peak flow during calibration and overestimated the peak flow during validation. The overestimation may be attributed to the fact that water which percolates deep into the aquifer might not have been included in the simulation process. However, the underprediction and overprediction during a few days may be attributed to the uncertainty stemming from the observed data, climate data and non-physical parameters used in SWAT, which are immeasurable. In order to assess the changing climate, long-term trend analysis (110yr) of meteorological variables (rainfall and temperature) was carried out using the modified Mann–Kendall trend test and the magnitude of the trend was quantified using the Sen’s slope estimator. The trend analysis was also carried out for the available historical data (1951–2005) on streamflow and future scenarios (2006–2060).

4.5 Climate change assessment

The CORDEX regional climatic model data were analyzed to study the variation induced in the climatic parameters through the RCP 4.5 scenario.

The long term variation in average temperature and rainfall for baseline and future scenarios for RCP 4.5 have been shown in the figure 7(a and b), respectively. The average temperature is rising at 0.10 °C per decade for both baseline and future scenarios. Significant changes were observed with rainfall decreasing at the rate of 2.63 mm per year for baseline period and a declining trend for rainfall with 8.85 mm per year for future RCP 4.5 scenario.

4.6 Assessment of model output

The CORDEX simulated daily weather data of baseline (1951–2005) and future RCP 4.5 scenarios (2006–2060) were used to run the model. The results of simulated streamflow from the model have been analyzed on annual basis. The impact of climate change on the annual streamflow yielded a decreasing trend at the rate of 1.2 Mm³/year for the baseline period (1951–2005) and in the future RCP 4.5 scenario it is found that, there is a decrease in streamflow at the rate of 2.56 Mm³/year. The trend of streamflow for both baseline and future RCP 4.5 scenarios is shown in figure 7(c).

4.7 Model performance for subsurface component

The SWAT model for the basin gave reasonably good result for the surface component streamflow. To analyze the performance for subsurface component, base flow simulations have been carried out for the period 1974–1985. The GW_Q of

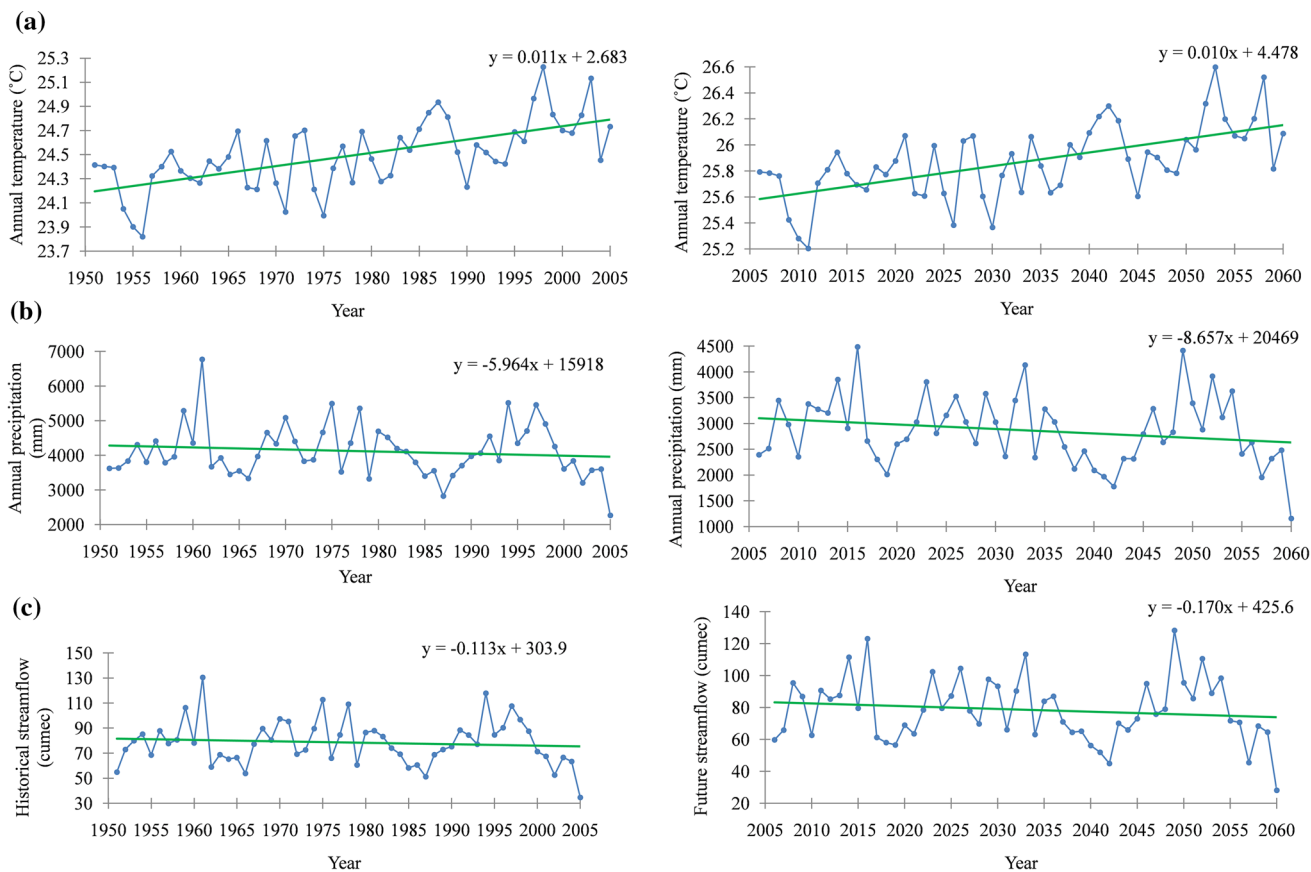


Figure 7. (a) Trend of temperature for baseline scenario and RCP 4.5 scenarios. (b) Trend of rainfall for baseline scenario and RCP 4.5 scenario. (c) Trend of streamflow for baseline scenario and future RCP 4.5 scenario.

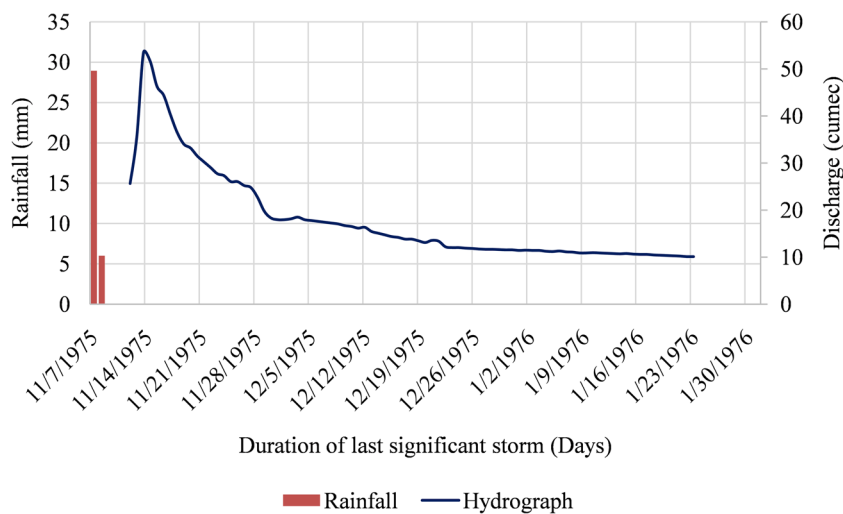


Figure 8. The hydrograph for the last significant storm of the year 1975–1976.

SWAT output file is the groundwater contribution to streamflow (mm), which is the water from the shallow aquifer that enters the main channel during the dry period is considered as simulated base flow. This component is compared with

the low flow, i.e., non-monsoon flow after the last significant storm identified during October–November and beyond till the flow exists. The non-monsoon observed streamflow is compared with the SWAT Bflow, which is a base flow

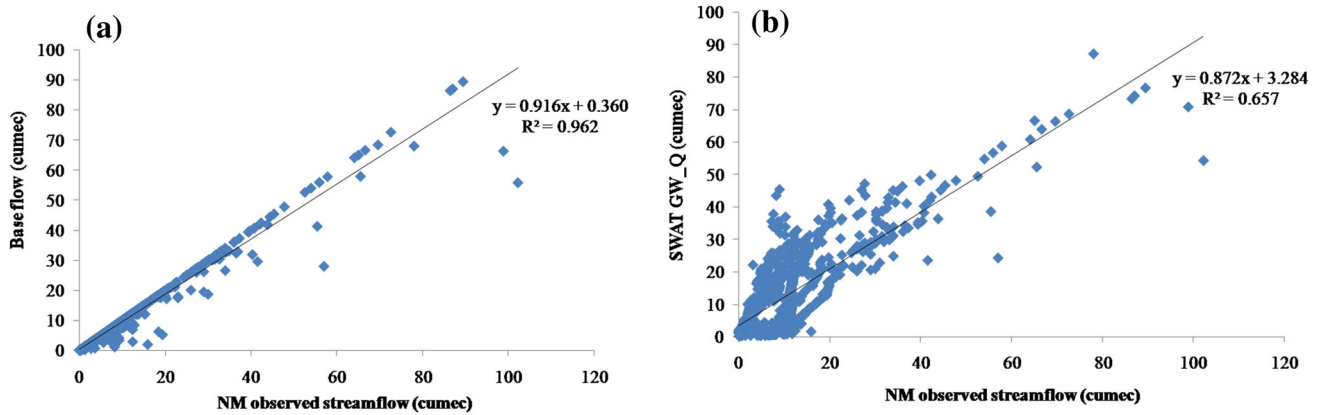


Figure 9. Comparison between observed non-monsoon (NM) streamflow and (a) base flow and (b) SWAT GW_Q.

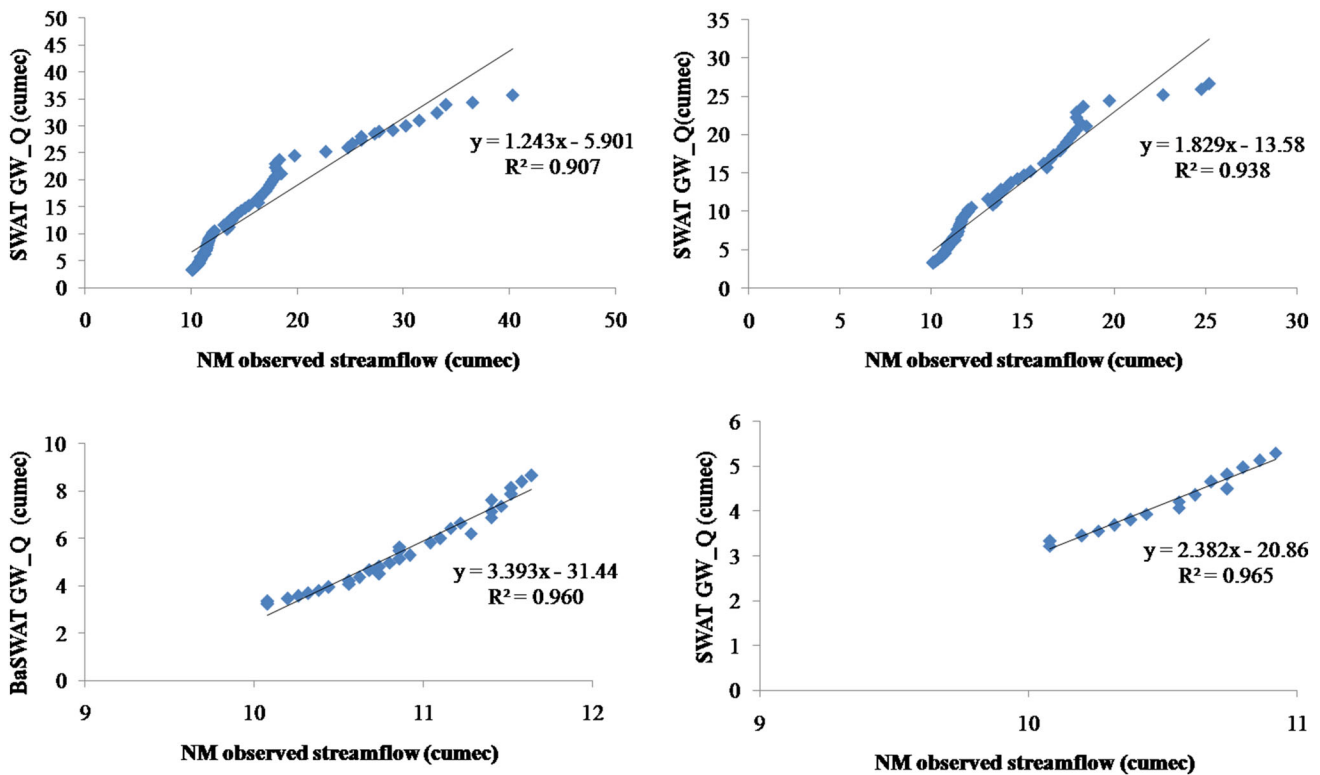


Figure 10. Base flow comparison with the observed NM stream flow.

filter program that determine run-off/base flow fraction in streamflow. The hydrograph for the last significant storm of the year 1975–1976 is presented in figure 8. The storm duration was 2 days. The maximum rainfall occurred during this period was 28.95 mm. The values for statistical indicator R^2 was found to be 0.941 and is in good agreement.

The comparison between the observed streamflow and base flow filter and the correlation between non-monsoon observed streamflow and SWAT GW_Q is shown in figure 9(a and b), respectively.

The values for R^2 , NSE and PBIAS are 0.66, 0.55 and -22.66 , respectively indicating satisfactory performance of the model for the base flow simulation.

As the flow approaches dry season, the value of R^2 is found to be increasing which shows that, the base flow is almost equal to the observed streamflow. The increase in value of R^2 as it approaches to the end of recession is shown in figure 10. The comparison is made by successively excluding a time period of 15 days from the starting point of the recession limb of the hydrograph.

The results show increasing value of R^2 with the progress towards low flow.

5. Conclusions

In this study, the potential impact of climate change on the hydrology of west flowing river basin, i.e., Gurupura basin was analyzed using SWAT. The river could be the sole source of fresh water in future for the fast developing urban establishment around Mangalore city. To have comprehensive view on the changing climate, the historical trend analysis of climatic parameters is also carried out using the modified Mann–Kendall Test. The following inferences may be drawn from the investigation:

- The model was calibrated and validated with the observed data and the performance was found to be good with R^2 , NSE and PBIAS values of 0.86, 0.83 and 17.5, respectively during calibration and 0.85, 0.85 and -3.9 , respectively during validation.
- There was a decreasing trend of rainfall by 2.63 mm per year from the historical trend and a decreasing trend of 8.85 mm per year for the future RCP 4.5 scenario over the catchment.
- The temperature was found to be increasing at the rate of 0.10 °C per decade from both the scenarios.
- The impact on the annual streamflow was evident with a decreasing trend at the rate of 1.2 and 2.56 Mm³/year for the baseline and future scenarios, respectively.
- The low flow in the river (Q90) was 4.09 cumecs, which is available up to the end of February. The high flow for the river (Q10) was 497.39 cumecs, which may be considered as the design flood for water storage/flood protection structures.
- For the first of its kind, the model performance was compared with the base flow component which showed encouraging results with R^2 , NSE and PBIAS values of 0.66, 0.55 and -22.66 , respectively.
- As the dry season approaches, the base flow simulation was more efficient with the improvement in R^2 values up to 0.965. Hence, it may be concluded that, the groundwater (base flow) simulation using SWAT is reasonable for preliminary assessment.
- These predicted decrease in rainfall and river flow may induce additional stresses on water resources of the basin and may require various

adaptation strategies to sustain with the climate change. The results would serve as preliminary guideline for sustainable water resources management of the basin.

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