Attribution of Hydrologic Changes in a Tropical River Basin to Rainfall Variability and Land-Use Change: Case Study from India

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Abstract: In recent decades, several parts of the world have been facing severe droughts and frequent floods against a background of anthropogenic influences and changes in climatic variables. For efficient management and adaptation measures, it is important to understand the relative effect of climate variability and anthropogenic influences. The Nagavalli River Basin (NRB), located in India, has experienced significant changes in hydroclimatic variables and land use in the last decade and therefore serves an ideal basin for investigating the attribution of rainfall variability and land-use changes. In this study, the characteristics of precipitation, temperature, and streamflow were analyzed for the period 1970–2012. It was observed that there is a significant increasing trend in precipitation and streamflow. Further, there have been substantial land-use change in terms of scrubland conversion. Investigations on rainfall-runoff coherency using wavelet coherence showed that there were noteworthy changes during the periods of 1991–2001 and 2002–2012. The contributions of land-use and rainfall variability to the changes in the streamflow were quantified using a semidistributed hydrological model (Soil Water Assessment Tool). The results showed that for the whole NRB, the variations of mean annual streamflow in 2002–2012 were primarily affected by rainfall variability with reference to 1990s, whereas human activities played a complementary role. The quantitative assessment revealed that rainfall variability resulted in an increase in runoff by 103 mm in 2002–2012 for the whole catchment, accounting for 41.52% of runoff changes relative to the 1990s. However, land-use changes are responsible for a decrease in runoff by 59 mm during the period of 2002–2012, which accounts for −23.54% of runoff changes. Overall, it was observed that the agricultural intensification in terms of scrubland conversion counteracted the effect of rainfall variability, resulting in the reduction in the margin of increase in streamflow. **DOI: 10.1061/(ASCE)HE.1943-5584.0001937.**

Author keywords: Attribution of land-use and rainfall variability; Agricultural intensification; Increased streamflow; Nagavalli River Basin.

Introduction

Several parts of the globe have been experiencing alterations in streamflow patterns in the last few decades, and these changes stem from different causes, such as changes in land use, climate, agricultural practices, and population growth. These changes affect the hydrological regime by changing the rainfall partitioning into actual evapotranspiration and runoff (Booij et al. 2019). Several studies have shown that there is an increasing number of flood events (Rogger et al. 2017; Hirabayashi et al. 2013) and drought events (Samaniego et al. 2018; Dai et al. 2013) across the globe, attributed either to land-use change or climate variability. Many studies have shown that land-use change in a catchment in terms of deforestation/afforestation and agricultural intensification can significantly affect the hydrological processes such as interception, infiltration, and evapotranspiration (ET), resulting in alterations of surface and subsurface flows (Gashaw et al. 2018; Jaksa and Sridhar 2015; Ahiablame et al. 2017; Kidane and Bogale 2017; Wang et al. 2014a; Niraula et al. 2015; Seong and Sridhar 2017; Sridhar and Wedin 2009; Sridhar and Anderson 2017).

Similarly, climate variability induces distinct changes to hydrological regimes and influences the spatial and temporal patterns of water resources in a region (Paul et al. 2018; Ghosh et al. 2012; Sridhar et al. 2013; Jin and Sridhar 2012). In the context of global climate, most of India has experienced a significant increase in the maximum intensity of rainfall, and spatial heterogeneity has been observed over the last half-century (Vinnarasi and Dhanya 2016; Bisht et al. 2017a, b). The changes in both temperature and precipitation exhibit remarkable regional variability; the tropical region of India is projected to experience a warmer and wetter climate in the future. The altered precipitation patterns in terms of timing and intensity might have substantial implications on the hydrology of the regions, including droughts, particularly in the tropical semiarid regions of peninsular India where water availability plays a major role in agricultural and economic development (Kumar et al. 2018; Shrestha et al. 2017; Pervez and Henebry 2015; Bisht et al. 2019).

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In recent years, several studies have estimated the attribution of changes in streamflow due to land-use changes and/or climate variability (Anand et al. 2018; Marhaento et al. 2017; Zhang et al. 2016; Aich et al. 2015; Nie et al. 2011; Wang et al. 2014b; Wang et al. 2013; Pokhrel et al. 2018; Sridhar et al. 2019). The findings of these studies are helpful for understanding the causes of hydrological variations as well as developing adaptation measures. However, the results from these studies are quite different because the effects of climate variability and land-use change may vary from place to place due to their geographical variations, necessitating further investigation at regional scales.

This study is focused primarily on investigating the causes and attribution of the recent increase in floods in the Nagavalli River Basin (NRB), which is situated in the eastern peninsula of the Indian subcontinent. NRB forms the lifeline for more than 5 million farmers in Srikakulam and Vizianagaram districts (Andhra Pradesh) and supplies drinking water for Srikakulam. Being close toward the east coastline, NRB has typical characteristics of this region, such as most of the river basin (64%) is under forest cover (Setti et al. 2018). In recent decades, there has been an increasing number of floods that last for several days, resulting in severe damages to crops, life, and property (Deccan Chronicle 2017). Further, compared with the last 2 decades, the annual average rainfall has increased by 100 mm in recent years (2002–2012) (Setti et al. 2018). On the other hand, significant land-use changes (increased area under cultivation) have resulted owing to the developmental projects of the government through the construction of storage reservoirs such as Modduvalasa, Thotapally, Narayanapuram, and Jhanjavati. These simultaneous changes in the rainfall and land-use patterns have led to complicated streamflow dynamics at the basin level. In order to plan for sustainable development of the water resources of the Nagavalli River Basin, it is necessary to understand the implications and individual contributions of climate variability and land-use changes to the alterations in the streamflow.

Several studies have been carried out to explore impacts of land-use and climate variability on river basins based on two distinct approaches: empirical data analysis and hydrologic modeling. Empirical data analysis has been widely used to measure the relative effects of land-use and climate change on hydrology; for example, Wei and Zhang (2010) and Zhang et al. (2012) used the modified double mass curve to exclude the effect of climate change on runoff generation in a deforested area. Tomer and Schilling (2009) used a coupled water-energy budget approach for estimating the relative impacts of land-use change and climate variability. However, the reliability of these methods greatly depends upon the quality and length of the observed data, and these methods are influenced by changes in land surface condition and other factors (Guo et al. 2018; Dey and Mishra 2017; Leon et al. 2014).

On the other hand, the modeling-based approach provides a better alternative way to understand the impact of the changes on the hydrology of the system. In the past, several studies used different modeling methods such as Soil Water Assessment Tool (SWAT), variable infiltration capacity (VIC), and Xiangiang models (Ehtiat et al. 2018; Guo et al. 2016; Wang et al. 2014a; Wang et al. 2013; Fiseha et al. 2012; Mengistu and Sorteberg 2012; Nathan et al. 2011; Asres and Awulachew 2010; Srinivasan et al. 2010; Bosch et al. 2011).

The objective of this work is, therefore, to quantify the hydrological impacts of land-use change and climate variability separately in the NRB in the recent past (1990–2012). By taking advantage of an integrated modeling approach using the SWAT model, this study specifically aims to address the following questions:

- How has land-use and rainfall variability changed in the recent past from 1990 to 2012?
- What are their relative roles in affecting the water yield of the NRB?
- What will the response of the catchment be to future climate change scenarios?

Materials and Methods

Study Area

The Nagavali River Basin (Fig. 1) is a tropical river basin lying in between the Mahanadi and Godavari River Basins of south India. The geographical area is about 9,510 km^2 within the geographical coordinates 18°17′–19° 44′N and 82°53′–83° 54′ E. It originates in the Eastern Ghats at 1,663 m elevation of Kalahandi district in Odisha state. It travels around 256 km through the Eastern Ghats, enters Andhra Pradesh at an elevation of 150 m, and then joins the Bay of Bengal. The study area had 1,138 mm of average annual rainfall and around 34.5°C premonsoon (March–May) and 28.3°C postmonsoon (October–December) average temperature for the period 1970–2012. It is bounded in the north by the Vamsadhara River and in the south by the Champavathi River. NRB is the lifeline of 5 million farmers and is the source of water for industrial and domestic purposes. In the last 25 years, there has been an increase in water resources development projects, which have led to the intensification of agricultural activity in the river basin. The major crops include paddy, sugarcane, wheat, potatoes, and cotton during the different cropping seasons.

SWAT Model and Inputs

The SWAT model is a comprehensive semidistributed hydrological model (Arnold et al 2012a, b, 1998) developed by Agriculture Research Service (ARS) of the United States Department of Agriculture (USDA). The model is capable of simulating the rainfall-runoff process and water quality in streams (Neitsch et al. 2011; Young et al. 1989; Taylor et al. 2016; Thilakarathne et al. 2018; Sehgal et al. 2018).

SWAT simulates different hydrological components of watersheds by using a water balance equation at daily time steps (Neitsch et al. 2009; Neitsch et al. 2002). The runoff is estimated using the Soil Conservation Service (SCS) curve number (SCS-CN) method, and potential evapotranspiration (PET) is estimated using any of the three methods: Penman-Monteith, Priestley-Taylor, or Hargreaves methods. Percolation is estimated by using a storage-routing technique combined with a crack flow model. In this study, the Penman-Monteith method is used for ET estimation because it is more reliable than the other alternative methods (Nazeer 2010; Monteith 1965).

Spatial and temporal input data are required by the SWAT model. Spatial data include a digital elevation model (DEM) and land-use and soil maps. The temporal data include hydrological data (observed stream flow) and climatic data (precipitation, solar radiation, relative humidity, wind speed, and temperature).

Temporal Data Sets

The high-resolution (0.250×0.250) gridded daily rainfall data from the Indian Meteorological Department (IMD 2014) for the period 1953–2013 were used as the rainfall forcing for the SWAT model. The IMD gridded temperature data were considered, and the forcing variables including solar radiation, wind speed, and relative humidity were downloaded from CFSR (2014) for 19 grid points within and along the boundary of the study area. The daily streamflow discharge data, which were used for calibration, were obtained from the Water Resources Information System of India (Central

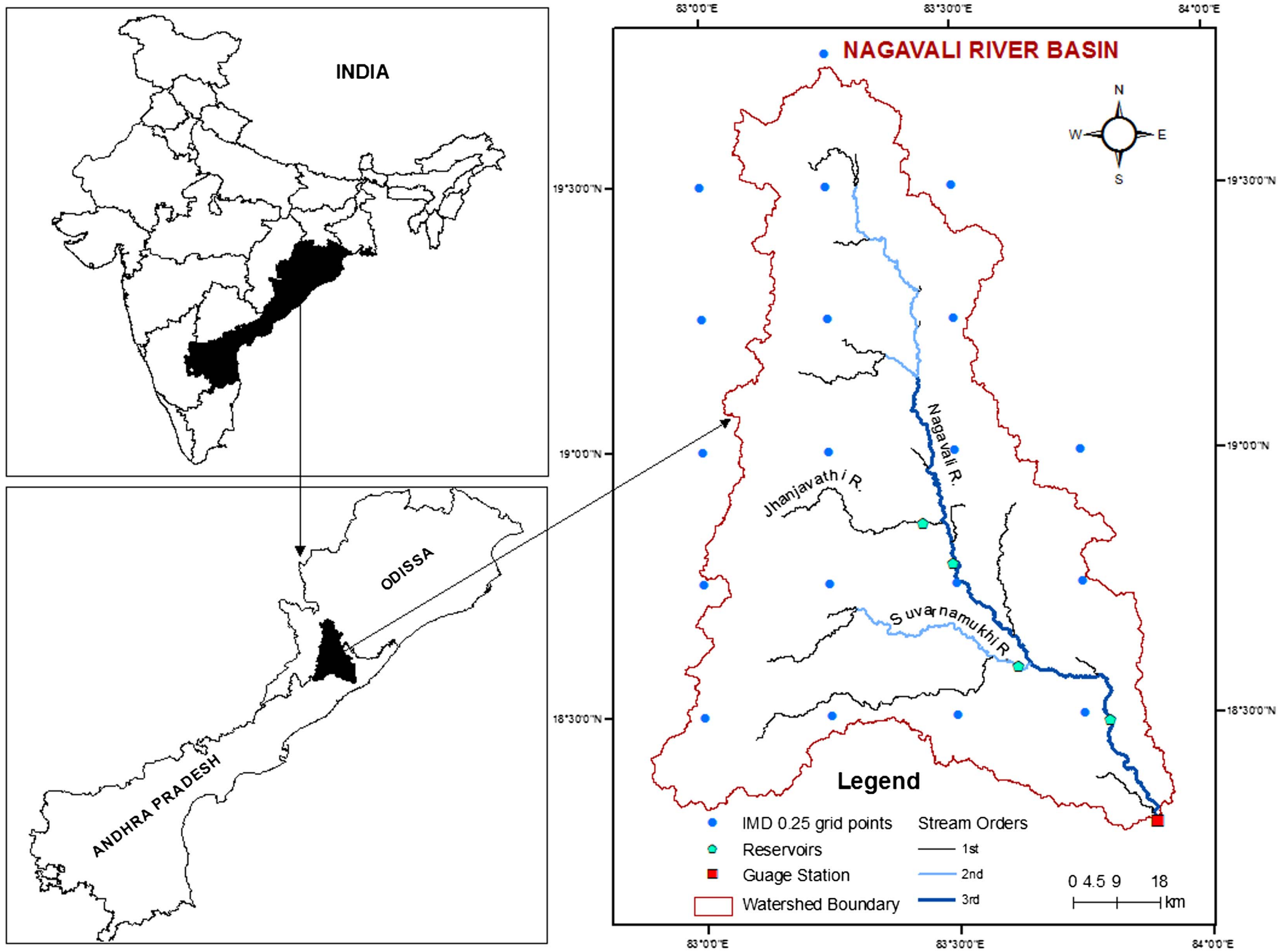


Fig. 1. Stream network of the Nagavalli River Basin with gauge discharge at Srikakulam and meteorological observation locations.

Table 1. Source of input data and description

Data type	Scale	References
DEM	30 × 30 m	SRTM (2006)
LULC	30 m	Landsat 5 (1990, 2005)
Soil	1:1,500,000	LSMSD (2012)
Weather data	0.25° (~32 km)	IMD (2014) and CFSR (2014)
Discharge data	Daily	Central Weather Commission (CWC 2012)

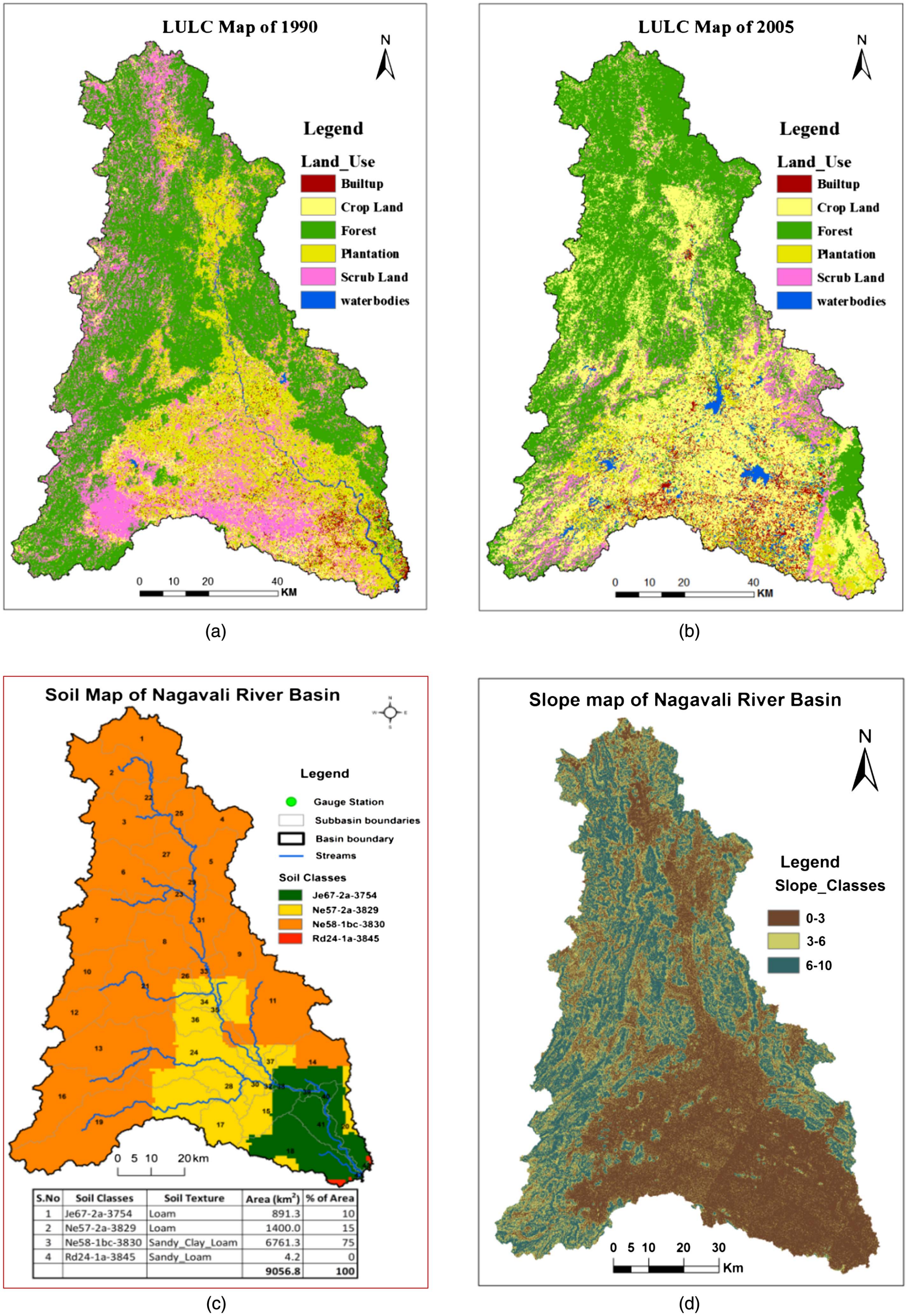
Water Commission 2012) for the period 1985–2012 at Srikakulam gauging station as presented in Table 1. The reservoir inflow and outflow data were obtained from the State Water Resources Department (Srikakulam Division) and have been incorporated in the SWAT model for implementing flow regulations.

Spatial Data Sets

This study uses the Shuttle Radar Topography Mission (SRTM)–based digital elevation model (DEM) for representing the topography. The 30 × 30 m resolution data were obtained from the USGS website (SRTM 2006). The raster soil map of the study area was obtained from the Food and Agriculture Organization (FAO) website (LSMSD 2012). Soil properties such as depth of soil layer, soil texture, bulk density, hydraulic conductivity, and organic carbon content were obtained from major soils of the world (FAO) (Fig. 2). The land-use data were prepared from Landsat 5 thematic mapper (TM) satellite images, and these are obtained from the USGS website with 30-m spatial resolution (Landsat 5 1990).

The supervised classification method along with maximum likelihood algorithm in ArcGIS version 10.2 for generation of land use land cover (LULC) maps (Bekele et al. 2019). The LULC of NRB is categorized into six LULC classes for 1990 and 2005, respectively (Fig. 2). The slope map for this study has been generated from SRTM DEM (30-m spatial resolution) using the ArcGIS tool, and the entire area was classified into three slope classes as shown in Fig. 2.

The dominant parameters for the SWAT model were identified using a sensitivity analysis, which provides insights as to which parameters contribute most to the output variance due to input variability (Holvoet et al. 2005). This study adopted the Latin hypercube one-factor-at-a-time (LH-OAT) method (Van Griensven et al. 2006) for identification of the most important influencing parameters in the model. Eighteen parameters from various published literature were considered for the sensitivity analysis. The sensitivity analysis and calibration of the model were performed using the SWAT calibration and uncertainty procedures (SWAT-CUP). The model results were evaluated by comparing the simulated



S.No	Soil Classes	Soil Texture	Area (km^2)	% of Area
1	Je67-2a-3754	Loam	891.3	10
2	Ne57-2a-3829	Loam	1400.0	15
3	Ne58-1bc-3830	Sandy_Clay_Loam	6761.3	75
4	Rd24-1a-3845	Sandy_Loam	4.2	0
			9056.8	**100**

Fig. 2. Thematic maps used as inputs: (a) land-use land cover map during 1990; (b) land-use land cover map during 2005; (c) soil map; and (d) slope map.

discharges with the observed discharges using the following performance criteria:

- Nash-Sutcliffe effciency (NSE) coeffcient, proposed by Nash and Sutcliffe (1970), is defined by Eq. (1). If the NSE value is close to 1, then the model is optimal and it is able to simulate the hydrological processes accurately, and if NSE is negative, the model simulation performance is worse in comparison with the mean or peasant's model (i.e., mean of the process is used as model). Thus, if NSE is negative, it indicates poor performance of the model.
- Percent bias (PBIAS) [Eq. (2)] measures the average tendency of the simulated data (Gupta et al. 1999; Legates and McCabe 1999), and the optimal value of PBIAS is zero. If PBIAS is a positive value, the model underestimates the streamflow, and if PBIAS is negative, the model overestimates the streamflow.

The model is unsatisfactory if NSE ≤ 0.5, satisfactory if $0.5 <$ NS ≤ 0.65, good if $0.65 <$ NS ≤ 0.75, and very good if $0.75 <$ NS ≤ 1.00) and PBIAS $> \pm 25\%$ for streamflow (Moriasi et al. 2007)

$$\mathrm{NSE} = 1 - \left[\frac{\sum_{i=1}^{n}(Y_i^{\mathrm{obs}} - Y_i^{\mathrm{sim}})^2}{\sum_{i=1}^{n}(Y_i^{\mathrm{obs}} - \bar{Y})^2}\right] \quad (1)$$

$$\mathrm{PBIAS} = \left[\frac{\sum_{i=1}^{n}(Y_i^{\mathrm{obs}} - Y_i^{\mathrm{sim}}) \times 100}{\sum_{i=1}^{n}(Y_i^{\mathrm{obs}})}\right] \quad (2)$$

where Y_i^{sim} and Y_i^{obs} = ith time step simulated and observed values, respectively; and $\bar{Y}$ = mean of n observed values.

Separation Methodology

This study adopts a strategy for separating the influence of land-use and rainfall variability on changes in the streamflow. In this strategy, one factor was changed at a time and the rest of the factors were held unchanged. Here, a total of four scenarios were generated to estimate the contributions of LULC and changes in the climate.

Firstly, baseline models were calibrated and validated with different land-use information (1990 LULC and 2005 LULC) and the corresponding climate data. The exact reason for choosing these years was based on the analysis and will be discussed in the subsequent section. Model 1 was calibrated and validated using the data from 1990–2001, and it characterized the hydrologic system for the period 1990–2001. Similarly, Model 2 was calibrated and validated using the measured data for 2002–2012 and therefore represents the catchment behavior for the period 2002–2012. Using these model formulations, four different scenarios were generated with different time slice data of land-use land cover and weather conditions. The details of these four scenarios are detailed in Table 2 and shown in Fig. 3.

The differences in the streamflow generated using Scenarios 4 and 1 are caused by the changes in the land use defined as ΔQ_{LULC}. Similarly, the differences in discharges obtained in Scenarios 2 and 1 are caused by different weather conditions (rainfall, temperature, and humidity), defined as ΔQ_W.

Subsequently, the impact of rainfall variability on streamflow ζ_w and that of land-use change ζ_L can be separately calculated by

$$\zeta_L = \left(\frac{\Delta Q_{\mathrm{LULC}}}{\Delta Q_{\mathrm{COM}}}\right) \times 100\% = \left(\frac{Q_{\mathrm{SimIV}} - Q_{\mathrm{SimI}}}{Q_{\mathrm{SimI}}}\right) \quad (3)$$

$$\zeta_W = \left(\frac{\Delta Q_W}{\Delta Q_{\mathrm{COM}}}\right) \times 100\% = \left(\frac{Q_{\mathrm{SimII}} - Q_{\mathrm{SimI}}}{Q_{\mathrm{SimI}}}\right) \quad (4)$$

where Q_{sim} = annual average streamflow generated in the corresponding scenarios.

Result and Discussion

Changes in Land Use and Trends in Precipitation, Temperature, and Streamflow

The Nagavalli River Basin underwent tremendous changes in terms of land use in 2000–2001 owing to the increased storage capacity of Narayanapuram Reservoir, which facilitated irrigation and thereby increasing area under agriculture. It is assumed that the 1990 land-use data represent the period from 1991–2001 and the 2005 land-use scene characterizes the land use during the period from 2002–2012. The analysis of the land-use percentage (Table 3) shows that there is a significant change in LULC, where the percentage of area under agriculture expanded from 7.14% to 34.34% from 1990 LULC to 2005 LULC, respectively. On the other hand, the percentage area under plantation and scrubland decreased from 22.48% to 5.98% and 22.68% to 7.65% for periods of 1990 and 2005, respectively. Therefore, in this study, it is assumed that the change point is 2001 and two periods, 1991–2001 and 2002–2012, are considered for further analysis.

The long-term temperature, precipitation in the period 1900–2012 for the Nagavalli River Basin were investigated using the nonparametric Mann Kendall trend test. Further, the annual streamflows for the period 1970–2012 were also investigated. The total precipitation and streamflow denote the arithmetic sum of precipitation and streamflow in a given year. The annual variability of average daily minimum and average daily maximum temperature, precipitation, and streamflow are shown in Fig. 4. The results in terms of p-values from the Mann Kendall trend test are provided in Table 4 with a significance level of alpha = 0.05. The results indicate that there is an increasing trend in the maximum temperature, precipitation, and streamflow for the period 2002–2012, suggesting that the climate during this period is becoming warmer and wetter than in the period of 1991–2001. Overall, for these two periods considered, there is an overall increase of 140 mm in annual average precipitation. It is entirely plausible that the changes in the climate in these two periods can be due to the natural long-term climatic cycles or due to climatic changes.

For the present study, it is very difficult to assert the exact reason due to limited data. However, studies on long-term changes in climatic parameters by other authors such as Kumar et al. (2010) and Vinnarasi and Dhanya (2016) showed a statistically

Table 2. Different land-use and climate change scenarios

Scenario	Model used	Land use	Climate	Remarks
1	Model 1	1990 LULC	1991–2001	Baseline scenario before land-use change
2	Model 1	1990 LULC	2002–2012	Simulates the scenario under changing climate while keeping the land use unchanged
3	Model 2	2005 LULC	2002–2012	Baseline scenario after land-use change
4	Model 2	2005 LULC	1991–2001	Simulates the scenario under changing land use while keeping climate unchanged

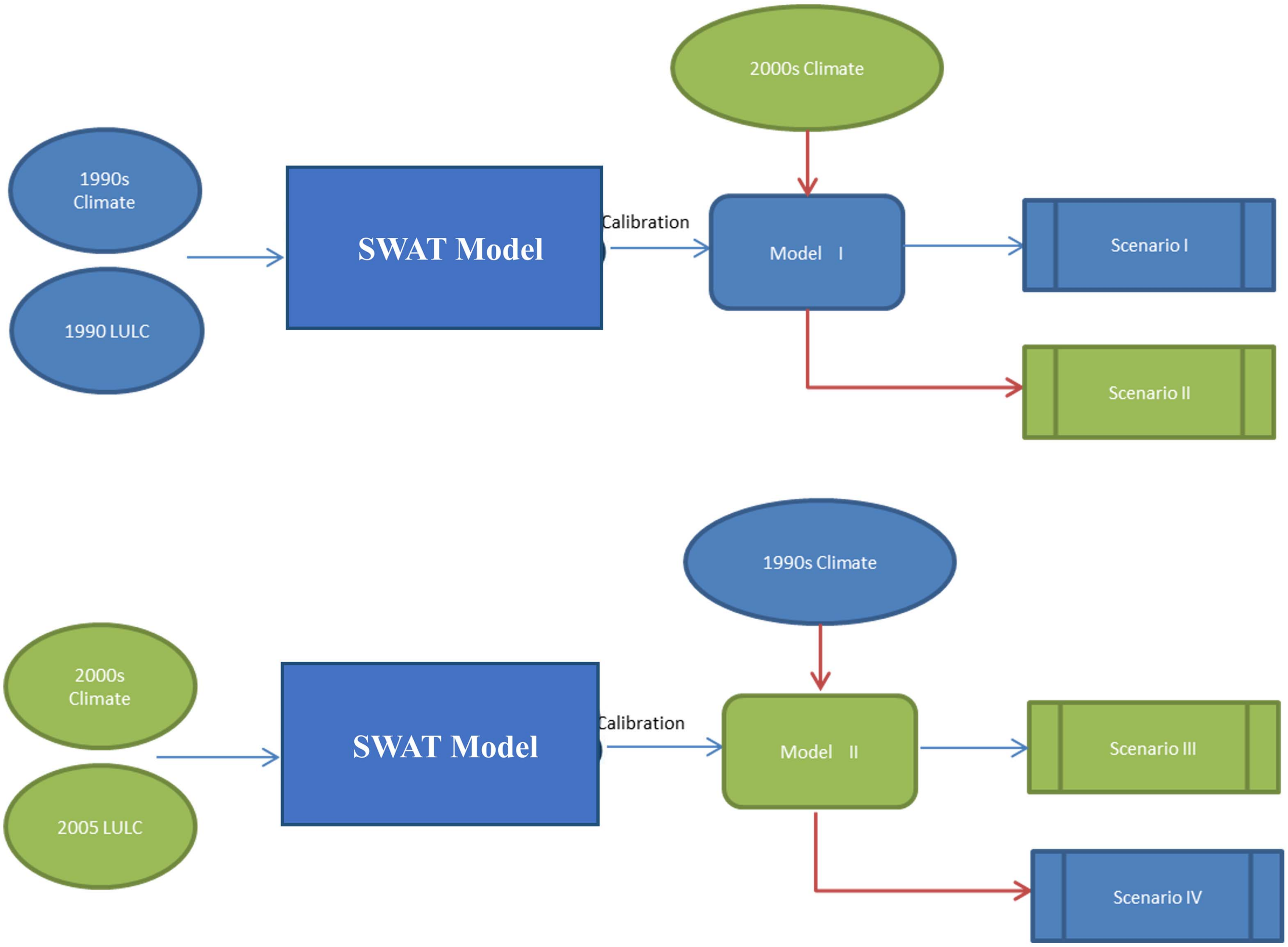


Fig. 3. Schematic of the proposed methodology and scenario generation.

Table 3. Land-use land cover changes (km^2)

		1990 LULC		2005 LULC		
S. No	LULC_Classes	Area	Amount (%)	Area	Amount (%)	Changes (%)
1	Built up	192.43	2.12	378.50	4.18	2.05
2	Crop land	646.56	7.14	3,109.74	34.34	27.20
3	Forest	4,042.12	44.63	4,061.53	44.85	0.21
4	Plantation	2,035.79	22.48	541.84	5.98	−16.50
5	Scrub land	2,053.80	22.68	692.82	7.65	−15.03
6	Waterbodies	85.73	0.95	272.02	3.00	2.06
—	—	9,056.4	100	9,056.4	100	—

significant increasing trend in the annual precipitation in the coastal Andhra Pradesh region. The analysis of the number of precipitation events as provided in Table 5 demonstrates that there is a clear indication of an increase in the number of violent rain events (events > 50 mm) in the later period, thereby increasing the precipitation. It is also important to point out that the percentage of annual rainfall in the form of violent rain has increased in the latest decade.

As discussed by Wagener and Wheater (2006), flow-duration curves provide useful insights into catchment behavior. The shape of the flow-duration curve is linked to the storage characteristics: topography, vegetation, and land use (Kavetski et al. 2011). The changes in the streamflow during the periods 1991–2001 and 2002–2012 can be detected in the flow-duration curves as plotted in Fig. 5. There is a significant increase in the peak discharges during the period 2002–2012 when compared with 1991–2001. On the other hand, there is a decrease in the medium flows in the latter period when compared with 1991–2001 flows.

To understand the change in streamflow dynamics, a wavelet coherence plot between the observed streamflow and the observed rainfall for the two periods under consideration has been made. Grinsted et al.'s (2004) MATLAB version R2014a Toolbox is used to plot the wavelet coherence plot. More details about wavelet coherence have been given by Grinsted et al. (2004) and Maheswaran and Khosa (2012). From the wavelet coherence plot shown in Fig. 6, there seems to be an increase in the coherence between the rainfall and runoff in the latter part of the time period because there is an increased number of patches in the period from 8 days (0.031 years) to 1 month (0.125 years).

In the period 1991–2001, coherency between precipitation (P) and discharge (Q) was weak, as evidenced by the large areas that do not show significant coherence between P and Q, even though strong coupling occurs at the annual time scale owing to the large synchronous annual cycles of P and Q. On the other hand, couplings at the shorter time scale have increased in the period 2002–2012 as evident from the increased patches. It can also be seen that the coupling between P and Q extends to a period of 1 month in the latter plot when compared with the former.

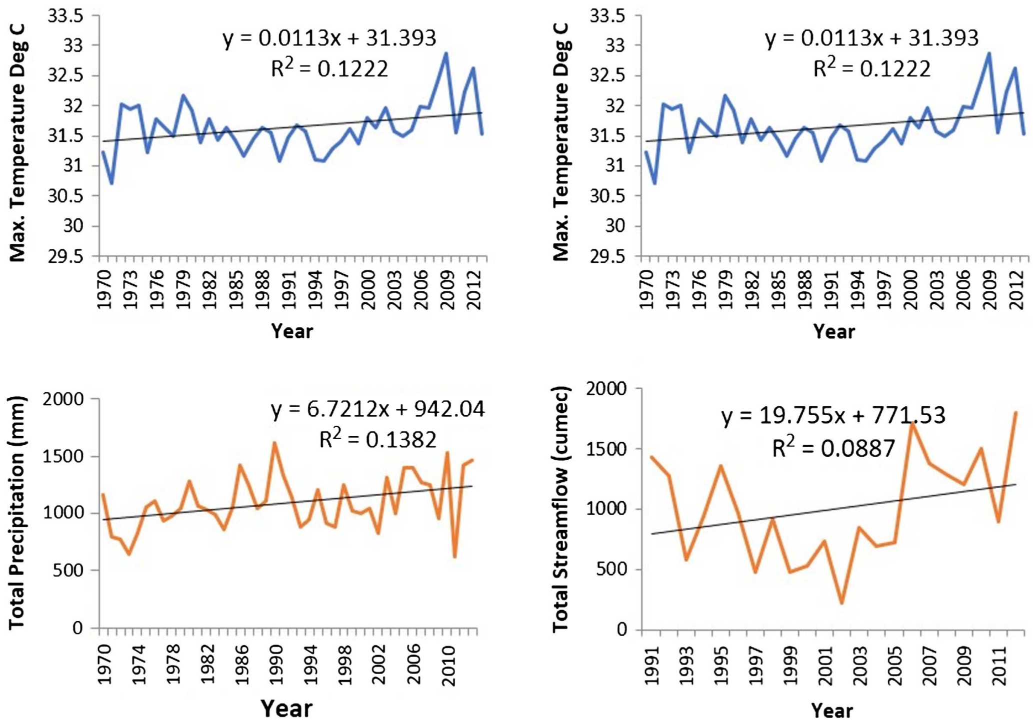


Fig. 4. Mann-Kendall trend test for maximum and minimum temperature, precipitation, and streamflow for NRB during the period 1970–2012.

Table 4. Trends in maximum and minimum temperature, precipitation, and streamflow

S. No	Variable	Time	Mean	*p*-value	Nature of trend
1	Minimum temperature (°C)	1970–2001	21.31	0.16	No trend
		2002–2012	21.27	0.54	No trend
2	Maximum temperature (°C)	1970–2001	31.42	0.5124	No trend
		2002–2012	33.93	0.045	Increasing
3	Precipitation (mm)	1970–2001	1,220	0.47	No trend
		2002–2012	1,360	0.035	Increasing
4	Streamflow (mm)	1970–2001	241	0.16	No trend
		2002–2012	288	0.0124	Increasing

These clearly indicate the increased *P*-*Q* coupling with reference to the period 1991–2001, which is strong evidence of change in the rainfall-runoff dynamics. The change in the *P*-*Q* coupling might be resulting from the change in precipitation and infiltration characteristics due to the change in the land-use pattern. Due to increase in more violent storms in the recent years and also increases in agriculture area (majorly, rice), there is an increased in discharge and, in turn, the *P*-*Q* coupling.

Sensitivity Analysis Calibration and Validation

Sensitivity Analysis for Streamflow

For the two periods of 1991–2001 and 2002–2012, the SWAT model was developed using the corresponding land-use maps and denoted as Model 1 and Model 2, respectively. From the results of the sensitivity analysis for these two periods (Table 6), it is seen that the dominant parameters affecting the hydrology of the system have changed significantly, indicating the changes in the dynamics of the catchments.

Among the parameters, a significant shift in ranking can be observed in CN2 (SCS curve number for moisture condition II), LAT_TIME (have an important controlling effect on the amount of lateral flow entering the stream reach during quick flow), HRU_SLP, and SOL_AWC (affects base flow simulation). It can also be seen that the ranking of RCHRG_DP (deep aquifer percolation) has shifted significantly. The aforementioned shift in the LAT_TIME can be explained by the increase in agricultural area in the 2000s due to which there is increased quick flow. Similarly, the shift in the ranking of RCHR_DP can be explained due to the conversion of flat scrublands to paddy fields with bunds, which allows deep percolation of water. The changes in SOL_AWC can also be attributed to the increased soil water availability due to ponding in the paddy cultivation. Furthermore, these changes in the ranking of the parameters indicate that the underlying model is sensitive to changes in the land use as well as changes in climatic conditions.

Calibration and Validation for Streamflow

In order to effectively account for the changes caused by rainfall patterns and land use separately, it is important to accurately calibrate the underlying baseline model. The calibration and validation of the baseline models performed using the streamflow records at Srikakulam. During the calibration process, the changes in terms of reservoir operation and land use were incorporated in the baseline models. Table 7 provides the calibrated parameters for both the baseline models for each of the major land uses. Investigation of the values of the calibrated parameters shows a clear difference between the two scenarios. For example, there is a significant difference in LAT_TIME (which has an important controlling effect on the amount of lateral flow entering the stream reach during quick flow), ESCO, and CN2 parameters.

Table 8 provides the model performance during the calibration and validation in terms of NSE and PBIAS. The model results are

Table 5. Comparison of rainfall events during 1991–2001 and 2002–2012

Rainfall classification		2002–2012		1991–2001	
Rainfall amount	Class	No. of events	Rainfall amount (mm)	No. of events	Rainfall amount (mm)
Dry days	0	2,688	0	2,658	0
No rain/tiny rain	0–1	352	148.58	345	144.97
Light rain	1–2	157	238.02	143	219.10
Low moderate rain	2–5	233	788.23	264	683.57
High moderate rain	5–10	225	1,598.75	222	1,601.66
Low heavy rain	10–20	172	2,467.56	198	2,393.51
High heavy rain	20–50	152	4,346.65	162	4,310.99
Violent rain	>50	39	3,204.16	26	1,971.67
Total	—	—	12,791	—	11,325

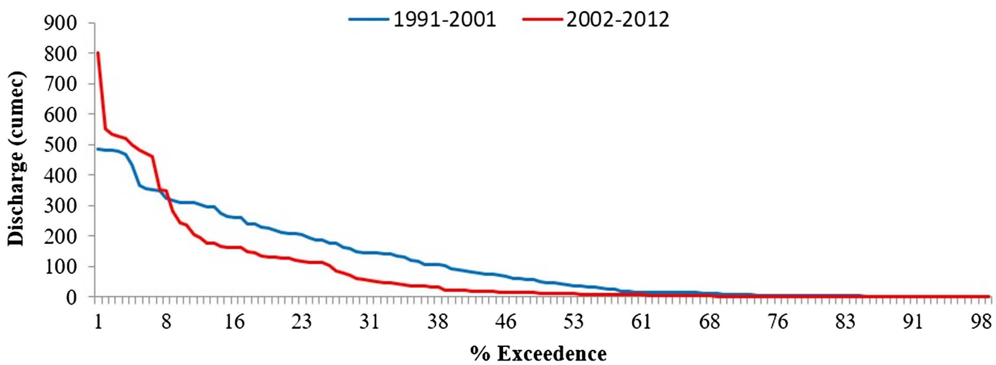


Fig. 5. Flow-duration curves for the observed daily streamflow at Srikakulam gauging point for the two periods.

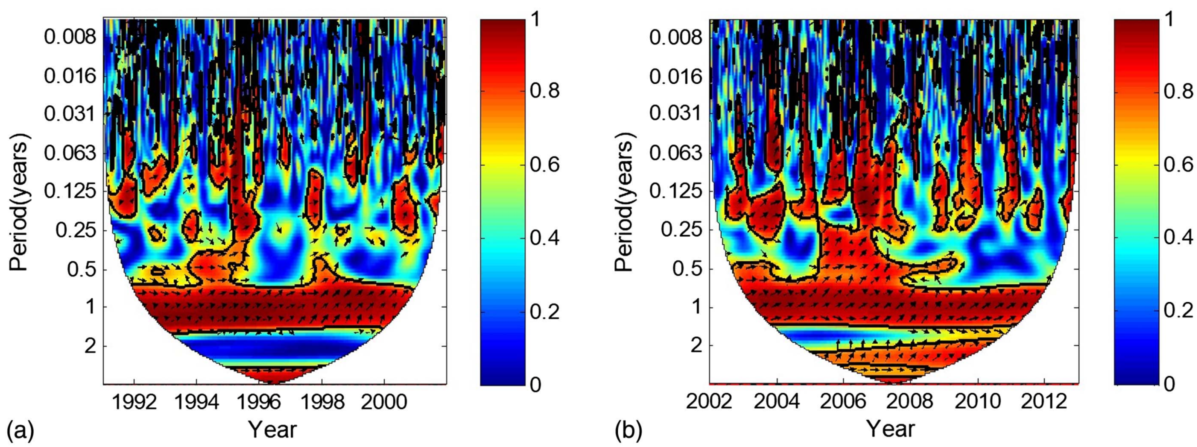


Fig. 6. Wavelet coherence between precipitation and discharge for (a) 1991–2001; and (b) 2002–2012. Arrows indicate the phase difference between precipitation and streamflow discharge (left arrow indicates both the time series are completely out of phase, whereas the right arrow shows that the time series are in phase). Thick lines inside the plot bounding the shaded areas show the significant coherence at the 95% level against noise.

satisfactory in comparison with the values provided by Moriasi et al. (2007). Visual inspection of the flow hydrographs as shown in Figs. 7 and 8 clearly indicates the overall ability of the model in capturing the underlying system dynamics of the catchment. There is a slight underestimation of the streamflow during the periods of 1995–1996 and 2010–2011 and overestimation in 2001, which indicate the absence of systematic bias in the model.

The model performance analysis indicated values of NSE equal to 0.86 and 0.85 during the calibration and validation periods for Model 1, respectively. Similarly, the values of NSE were found to be 0.86 and 0.73 during the calibration and validation for Model 2, respectively. These high values of NSE show that these models have the ability to simulate the underlying hydrologic system and can be used reliably for generating other scenarios.

Attribution of Changes in Streamflow to Rainfall Variability and Land-Use Changes

To attribute the changes in the observed streamflow and catchment rainfall-runoff relationship, the four scenarios with different

Table 6. Sensitivity parameters ranking with different LULC's with 1,000 simulations for streamflow

S. No	Parameter	Minimum	Maximum	Model 1	Model 2	Description
1	HRU_SLP	0	1	5	3	Average slope steepness (m/m)
2	LAT_TTIME	0	180	7	1	Lateral flow travel time (days)
3	ALPHA_BNK	0	1	16	8	Bank flow recession constant
4	CH_K2	−0.01	500	11	18	Hydraulic conductivity of channel (mm/h)
5	SLSUBBSN	10	150	8	7	Average slope length (m)
6	ESCO	0	1	2	2	Soil evaporation compensation factor
7	CN2	−0.1	0.1	1	4	Curve number
8	SOL_AWC	0	1	4	6	Available water capacity of the soil layer (mm)
9	EPCO	0	1	3	10	Plant evaporation compensation factor
10	OV_N	0.01	30	10	12	Manning's n value for overland flow
11	RCHRG_DP	0	1	12	5	Deep aquifer percolation fraction
12	SOL_K	0	2,000	13	9	Soil hydraulic conductivity (mm/h)
13	GW_REVAP	0.02	0.2	18	16	Groundwater revap coefficient
14	GW_DELAY	30	450	14	13	Groundwater delay (days)
15	ALPHA_BF	0	1	15	17	Base flow alpha factor (days)
16	REVAPMN	0	500	9	15	Threshold depth of water in the shallow aquifer for revap to occur (mm)
17	GWQMN	0	5,000	17	14	Threshold depth of water in the shallow aquifer (mm)
18	SURLAG	0.05	24	6	11	Surface runoff lag time (days)

Table 7. Best-fitted parameter values for each land use for Scenario 1 (Model 1) and Scenario 3 (Model 2) during the model calibration period

S. No	Parameter name	Land uses					Minimum	Maximum
		AGRR	FRST	ORCD	URMD	SHRB		
				Scenario 1 (Model 1)				
1	1:R__CN2.mgt	−0.05	−0.10	−0.09	−0.09	0.00	−0.1	0.1
2	2:V__REVAPMN.gw	223.15	408.23	180.31	136.30	383.44	0	500
3	3:V__SLSUBBSN.hru	14.76	24.98	51.77	118.66	61.23	10	150
4	4:V__HRU_SLP.hru	0.45	0.79	0.09	0.23	0.88	0	1
5	5:V__OV_N.hru	13.53	11.94	15.43	16.91	5.84	0.01	30
6	6:V__LAT_TTIME.hru	65.75	36.88	138.43	58.63	75.71	0	180
7	7:V__ESCO.hru	0.40	0.83	0.07	0.16	0.37	0	1
8	8:V__EPCO.hru	0.08	0.65	0.31	0.24	0.52	0	1
9	9:V__SURLAG.bsn	17.98	18.89	8.07	18.53	23.60	0.05	24
10	10:R__SOL_AWC(.)	0.00	0.04	−0.02	−0.03	−0.02	−0.1	0.1
11	11:V__CH_K2.rte	326.08	156.03	438.73	171.75	226.92	−0.01	500
				Scenario 3 (Model 2)				
1	r__CN2.mgt	−0.14	0.02	−0.01	0.03	−0.01	−0.1	0.1
2	v__GWQMN.gw	1,825.14	1,430.93	276.58	2,216.36	1,590.95	0	5,000
3	v__RCHRG_DP.gw	0.43	0.19	0.26	0.18	0.49	0	1
4	v__SLSUBBSN.hru	94.18	14.64	16.22	22.34	53.45	10	150
5	v__HRU_SLP.hru	0.49	0.70	0.76	0.75	0.42	0	1
6	v__LAT_TTIME.hru	76.08	101.55	60.32	117.11	167.38	0	180
7	v__ESCO.hru	0.07	0.64	0.30	0.60	0.84	0	1
8	r__SOL_AWC().sol	0.64	0.99	0.14	0.63	0.85	0	1
9	r__SOL_K().sol	−0.01	0.04	0.06	0.13	−0.07	−0.1	0.1
10	v__ALPHA_BNK.rte	0.44	0.19	0.41	0.35	0.88	0	1

Table 8. Model performance statistics of the baseline models

S. No	Parameters	Model 1		Model 2	
		Calibration (1994–2001)	Validation (1991–1993)	Calibration (2002–2007)	Validation (2008–2012)
1	NSE	0.86	0.85	0.86	0.73
2	PBIAS	−5.8	1.5	17.9	5.7

land-use land cover and climate data sets are used. Scenarios 1 and 3 (Table 2) are the baseline scenarios representing the periods of 1991–2001 and 2002–2012 in terms of the climate as well as land use. Scenario 2 represents the effects of rainfall variability while keeping the land use unchanged, whereas Scenario 4 represents the effects of changing land use without changing rainfall and temperature variability. These scenarios were simulated, and the corresponding annual average streamflow is tabulated in Table 9.

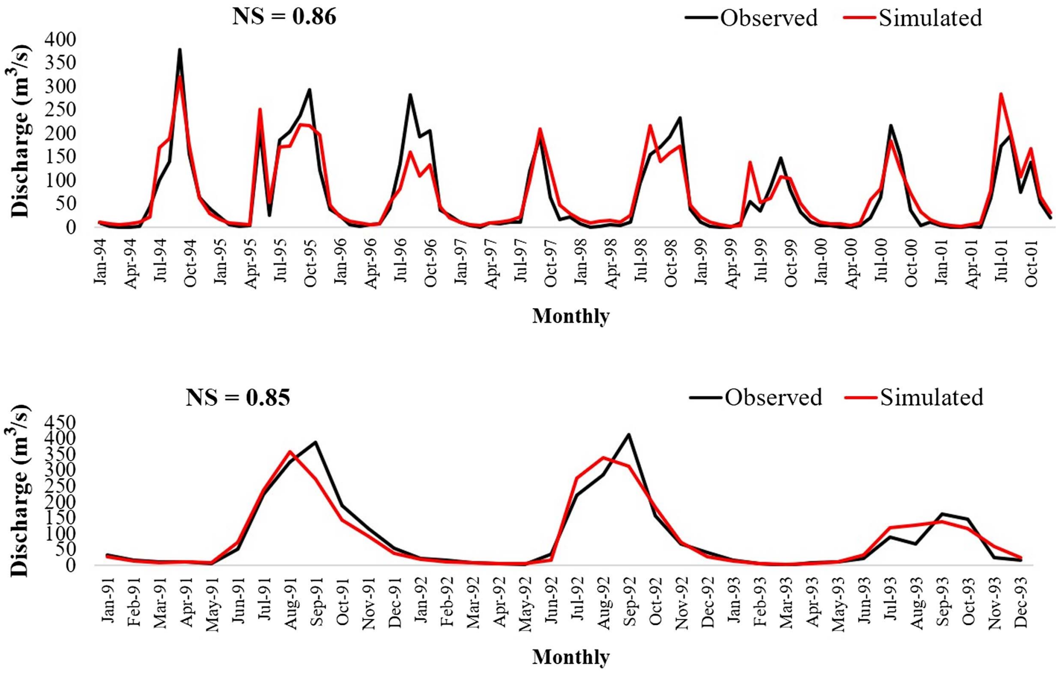


Fig. 7. Observed and simulated monthly discharge hydrograph during calibration (1994–2001) and validation (1991–1993) for Model 1.

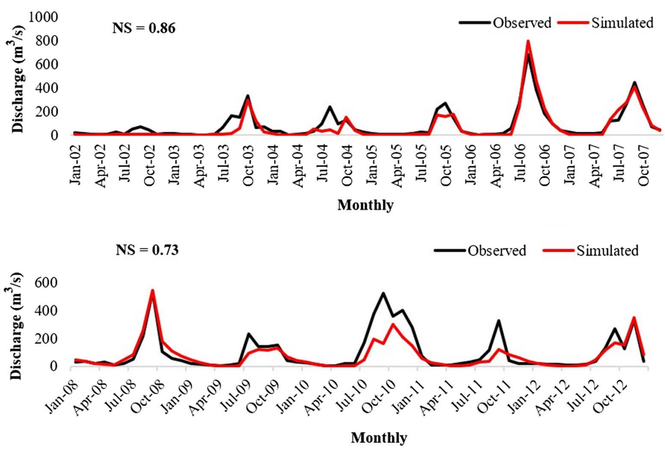


Fig. 8. Observed and simulated monthly discharge hydrograph during calibration (2002–2007) and validation (2008–2012) for Model 2.

It was observed that during the period 2002–2012 (Scenario 3), there is an increase in the flow when compared with the period 1991–2001(Scenario 1), which is similar to the trend in the observed streamflow. Comparisons of Scenarios 1 and 2 show that there is an increase in the annual average streamflow from 243.2 to 352.93 mm due to the change in rainfall variability alone. However, there is a significant decrease in the streamflow (from 249.38 to 190.67 mm) due to stand-alone changes in the land-use conditions as depicted by Scenarios 4 and 1. It can be noticed that the rainfall variability (increase by 140 mm) led to an increase in the streamflow, whereas the change in land-use conditions reduced the streamflow. However, the quantitative effects of these individual factors were significantly different. The overall increase in the observed streamflow (comparing Scenarios 1 and 3) of the order of 47.99 mm can be attributed to both rainfall variability and land-use changes accounting for 41.52% and −23.54%, respectively.

Table 9. Effect of land-use dynamics on streamflow (m^3/s) of NRB at Srikakulam gauge point during 1991–2001 and 2002–2012

LULC scenarios	Mean annual average streamflow (mm)
Scenario 1	249.38
Scenario 2	352.93
Scenario 3	297.37
Scenario 4	190.67
ζ_W (%)	41.52
ζ_L (%)	−23.54

Results indicate that both rainfall variability and LUCC have contributed significantly to the changes in the streamflow dynamics of the NRB. The changes in temperature and precipitation have surpassed that of the LULC changes (increased area under cultivation) and became the main factor in influencing the hydrological change in NRB. Annual average precipitation in the NRB has increased in the period 2002–2012 compared with the period 1991–2001 by 11% (around 140 mm). Further, it was observed that the total rainfall in the form of violent storms has increased significantly in the latter period by 50% from 1,971 to 3,204 mm (Table 5). The increase in precipitation and increased soil moisture due flood irrigation for paddy fields resulted in an overall increase in the streamflow in NRB. The results are supported by several previous studies done elsewhere in the world, which include those by Naz et al. (2018), Guo et al. (2016), Su et al. (2017), Gupta et al. (2015), and Ye et al. (2003), wherein changing climate patterns have larger impacts compared with human activity.

However, contradicting results were reported by studies such as those by Hayhoe et al. (2011), Wohl et al. (2012), and Sahin and Hall (1996), wherein the anthropogenic (land-use changes) influence was much higher when compared with climate impacts. The individual contribution of land use and climate on a given catchment is a function of several factors such as type of climate, nature of the land-use changes, and also its intensity. Therefore, generalization of the results obtained in this study may not possible to other climatic zones.

Like many regions in India, NRB has undergone severe land-use changes in terms of conversion of scrubland to agricultural land owing to the water resources development projects and improved canal irrigation facilities. In the last decade, three irrigation projects, Jhanjavati, Narayanapuram Anicut, and Thotapally barrage, were commissioned by the government of Andhra Pradesh. These projects have significantly increased agricultural intensification. Agriculture intensification increases the water retention capacity and thereby decreases the surface runoff because there is a higher resistance offered by the plants and longer flow paths. Fig. 9 shows the comparison of the water balance components as derived from the baseline models. It shows that there is an increase in ET as well as in the ground water (GW) recharge. In the last 20 years, with the expansion of the agriculture land from 646.56 to 3,109.74 km^2 in NRB, and the groundwater recharge (due to enhanced infiltration) and ET has increased (due to flood irrigation for paddy fields). These findings were supported by studies by Thanapakpawin et al. (2007) and Wang et al. (2007), who observed that with irrigation, annual streamflow decreases due to water abstraction for irrigation and enhanced evapotranspiration.

From the results, it was observed that the contribution of recent LULC changes to the hydrologic changes in NRB was −23.54% when compared with the LULC in the 1990s. However, this decrease in the streamflow was compensated for by the increased rainfall on the order of 140 mm. Comparing the results from Scenario 2 (without land-use change) with the present conditions, it can be said that the changes in land use have marginally reduced the impact of rainfall variability. Changes in land use in terms of increased agricultural areas have offset the impact of increased precipitation to a greater extent.

Effect of Future Climatic Condition on the NRB

It is important to investigate the effect of the future climate projections on the streamflow conditions in NRB because it provides pertinent information for future water resources management and planning. For this purpose, a case with the present land use and the future climate projections up to 2050 was analyzed, and its impact on the streamflow was evaluated. The Canadian Earth System Model-Second Generation (CanESM2) global climate model data with representative concentration pathways (RCPs) 4.5 and 8.5 scenarios (Moss et al. 2010) were used for evaluation of future climate scenarios. For this purpose, three different ensemble runs were used for each of the RCPs (Canadian Centre for Climate Modelling and Analysis Data 2019). For running the future scenarios, precipitation, wind speed, solar radiation, relative humidity, and minimum and maximum temperatures from the different ensemble general circulation model (GCM) simulations were used. The data were downscaled using the bias-correction approach (Lenderink et al. 2007; Fang et al. 2015). In this method, the temperature is corrected with an additive term, and rainfall is corrected with a multiplier on monthly basis. The same procedure is adopted for downscaling other climatic variables

$$P_{dws,\mathrm{mon,day}} = P_{\mathrm{GCM,mon,day}} \times \frac{\mu(P_{\mathrm{obs,mon}})}{\mu(P_{\mathrm{GCM,mon}})} \tag{5}$$

$$\mathrm{Temp}_{\mathrm{dws,mon,day}} = \mathrm{Temp}_{\mathrm{GCM,mon,day}} + \mu(\mathrm{Temp}_{\mathrm{obs,mon}}) - \mu(\mathrm{Temp}_{\mathrm{GCM,mon}}) \tag{6}$$

where $P_{\mathrm{dws,mon,day}}$ and $\mathrm{Temp}_{\mathrm{dws,mon,day}}$ = downscaled precipitation and temperature on a given day of the month; $P_{\mathrm{GCM,mon,day}}$ and $\mathrm{Temp}_{\mathrm{GCM,mon}}$ = GCM outputs on the given day and month; and $\mu(P_{\mathrm{GCM,mon}})$ and $\mu(\mathrm{Temp}_{\mathrm{obs,mon}})$ = monthly mean of precipitation and temperature from the IMD data set.

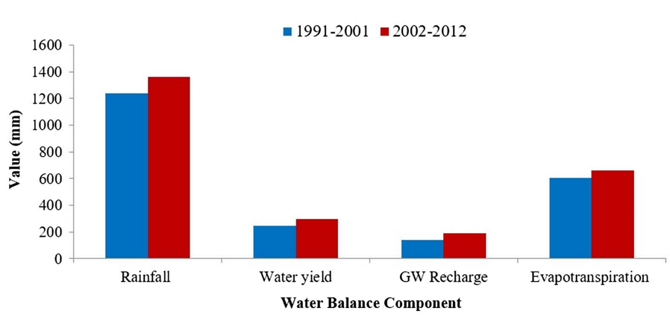


Fig. 9. Comparison of the water balance components derived from the baseline models for 1991–2001 and 2002–2012.

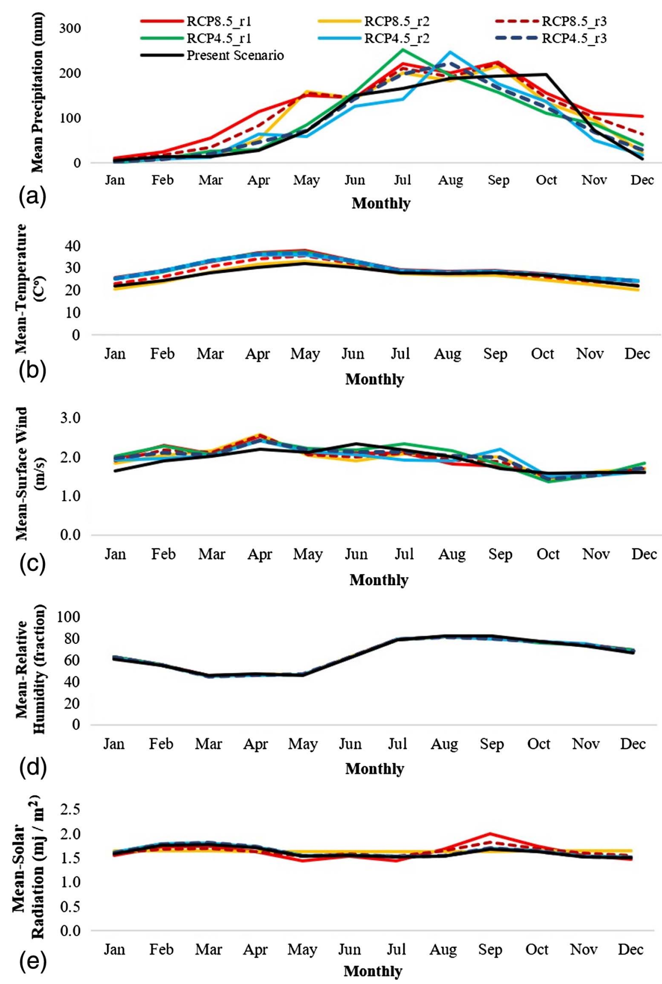


Fig. 10. Future simulated values of (a) average monthly precipitation; (b) average monthly mean temperature; (c) average monthly surface wind; (d) average monthly relative humidity; and (e) average monthly solar radiation for three ensembles of GCM models RCP8.5 and RCP4.5 scenarios for 2020–2050. The present scenario represents present climate and catchment characteristics, respectively, for 2000–2012.

Figs. 10(a–e) show mean monthly downscaled precipitation, temperature, wind speed, solar radiation, and relative humidity for the study region using RCP 4.5 and 8.5 of the coupled model inter-comparison project phase 5 (CMIP5) ensemble runs. There is a clear increase in mean precipitation when compared with the present scenario [Fig. 10(a)] as well as mean monthly temperature [Fig. 10(b)]. Particularly, all the ensemble runs show significant increases of temperature during the summer months for the period from 2020 to 2050 when compared with the present scenario. Similarly, there is an evident increase in the solar radiation and wind speed with respect to the present scenario. The stomata resistance term in the Penman-Monteith equation has been adjusted for the future simulations because the stomata resistance is dependent on the CO_2 levels in the atmosphere. The SWAT model incorporates the effect of changes CO_2 levels on plant stomatal conductance (Butcher et al. 2014) through the equation developed by Easterling et al. (1992). In order to capture the effects of CO_2 levels in the ET estimation, the corresponding average value of atmospheric concentration of CO_2 for each of the RCP scenarios has been incorporated.

The future streamflow was generated using the SWAT model for all the ensembles runs by using the downscaled climate data. Fig. 11(a) shows the streamflow hydrograph obtained from the different ensembles, whereas Fig. 11(b) provides monthly average values for all the ensembles and a comparison with the present scenario. It can be observed that the future streamflows for all months are close to the present scenario. The annual average simulated streamflow was about 290 mm at the Srikakulam gauge station of the Nagavalli River Basin. The future streamflow has not changed increased when compared with the current scenario even though there is significant increase in the precipitation. This might be possible due to the increase in ET (resulting from increased wind speed and temperature), which is evident in Fig. 11(c), where ET values for the future simulation were considerably higher when compared with the present scenario.

The analysis of the attribution of streamflow changes to LUCC and/or climate change is key to basin water resources management and planning. The extent of future conversion of scrubland to agriculture should be investigated when considering future climate scenarios. Further, the forest region of the headwater regions of the NRB should be maintained for its role in protecting the hydrologic and ecological functions. In addition, the findings from this work can be used to differentiate the effects of land-use changes and rainfall variability on streamflow in other tropical areas with similar hydrophysiographic characteristics.

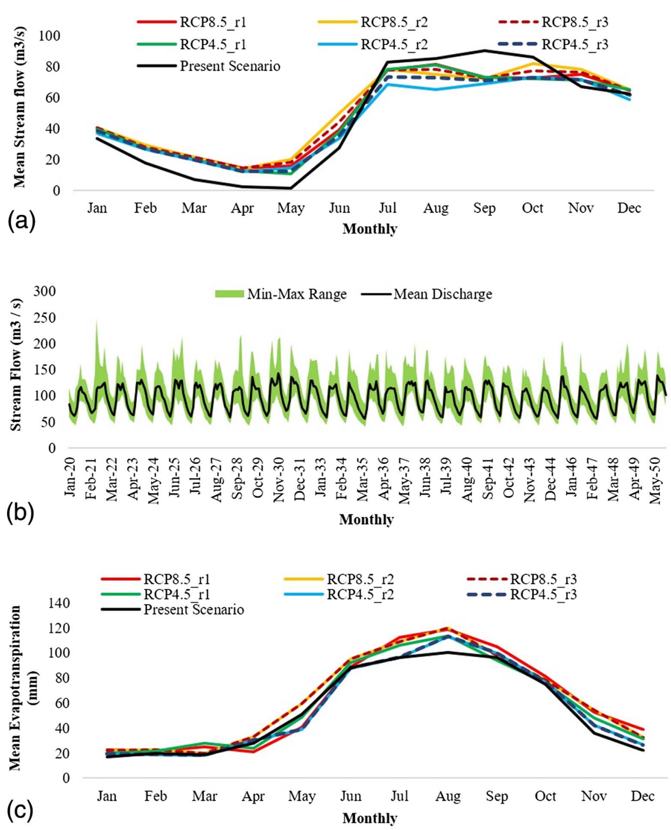


Fig. 11. Future simulated values of (a) average monthly streamflow for 2011–2050; (b) ensemble predictions from the different GCM ensembles shown in the form of minimum–maximum range and mean discharge; and (c) average monthly evapotranspiration for the future (2011–2050) and present scenario.

Conclusions

This study investigated the relative effects of land-use and climate changes on the changes of streamflow in the catchment during the last 5 decades. The trend analysis using the Mann Kendall test estimated a weak but significant increasing trend of precipitation and maximum temperature. Further, there is an increasing trend in annual streamflow over the last decade. The results using the SWAT model suggest that the increase of streamflow 47.99 mm over the period 2002–2012 has been affected primarily by increased precipitation for the whole catchment compared with the reference period of the 1990s, whereas the land use played an opposite role.

The quantitative assessment revealed that variability in rainfall resulted in an increase in runoff by 103 mm in 2002–2012 for the whole catchment, accounting for 41.52% of runoff changes relative to 1990s. However, land-use changes are responsible for the decrease in runoff by 59 mm during the period 2002–2012, which accounts for −23.54% of runoff changes. Overall, it was observed that the agricultural intensification in terms of scrubland conversion counteracted the effect of rainfall variability, thereby reducing the margin of increase in streamflow. It is apparent that the developmental projects in terms of improved network and an increase in the area under agriculture have offset the effects of the increased precipitation on mean annual flows.

Data Availability Statement

Some or all data, models, or code generated or used during the study are available from the corresponding author by request.

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