Modelling of Streamflow Considering the Effects of Land Use Land Cover Change Over the Sabari River Basin, India

Subbarao Pichuka and Nandikanti Siva Sai Syam

Abstract Land Use Land Cover (LULC) significantly affects hydrological variables like streamflow. This chapter studies the effects of change in LULC over streamflow in the Sabari Basin, India. The LULC change detection analysis has been carried out for three decades (1985–1995, 1995–2005, 2005–2020). The LULC classes (Barren land, Built-up Area, Cropland, Fallow land, Forest, Grassland, Plantations, Shrubland, Wasteland, and Waterbodies) are analyzed. The change for individual classes and converted area analysis from one class to another is also conducted. By the end of 2005, the built-up area, cropland, and shrubland were increasing by 12.1%, 0.43%, and 3.25%, respectively, when compared to 1985, and the remaining classes were decreasing by each decade. Monthly streamflow is modeled for 30 years (1982–2012) using the Soil and Water Assessment Tool (SWAT). Two Sub-basins (Saradaput and Konta) are considered for the analysis. The R^2 between the modeled and the observed data in the Saradaput and Konta Sub-basins is 0.78 and 0.74, respectively. The results indicate that urbanization and agricultural intensification have contributed to increased streamflow. These LULC change detection can be further used in modeling this basin using different hydrological models to compare the performance of the different models in this basin.

Keywords SWAT · Sabari basin · LULC change · Streamflow

1 Introduction

India is one of the most water-stress countries in the world. The impending water supply in India is becoming most uncertain. Anthropogenic activities such as deforestation, overconsuming water resources and releasing aerosols into the atmosphere in their daily life, and many more aspects lead the climate to change rapidly. Climate

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and Land use changes are some of the significant factors in altering the hydrological cycle. In recent years, the implication of these changes has been investigated. They increased the extreme events in magnitude and intensity, creating and intensifying many other water resources-related problems [12]. Rainfall is a crucial resource for worldwide socio-economic activity and is vital in the hydrological cycle. In India, most of the agriculture is rainfed. Rainfall and baseflow influence the high and low streamflow extremes, which are crucial for flood management, hydropower, navigation, and ecological concerns [17]. Hence, understanding the consequences of LULC change on the hydrological cycle is necessary [4]. The hydrology of river basins is significantly affected by LULC changes, mainly through variations in baseflow during floods [6] and average annual discharge [7]. Several investigations demonstrated a connection between land use changes and other mechanisms in the local hydrological cycle [3, 20, 21]. Akbar et al. [1] followed the Markov approach to forecast the future LULC after generating the historical LULC maps to study its effects on urbanization. It resulted in a decrease in the water bodies and vegetation and increased the urban area by 2040.

The effects of climate change and LULC on basin hydrology can be analyzed using hydrologic models. SWAT is a semi-distributed hydrological model that can simulate more precisely by considering several hydrological parameters and their interconnections. Along with them, it considers the topographical features of the watershed and decentralizes the watershed at a continuous time step [23]. Using SWAT, a study on Kenya's Sondu Basin shows the model's ability in African watersheds [13]. Zhang et al. [24] compared SWAT with their developed SWAT-T model regarding the response of a hydrological catchment to LULC change. The Change in LULC affected all hydrological variables, among which streamflow is prominent. Sahana and Timbadiya [19] considered the Upper Godavari Basin to study the climate change and LULC effects for different GCMs in different scenarios using SWAT. A thorough knowledge of the river basin's water balance and parameters is crucial when constructing a reliable hydrologic model [16]. The conventional fixed parameterization is compared with the varied parameterization approach resulting in a better performance of the varied approach. Du et al. [8] used this approach in studying the watershed hydrology in urban regions of China. This chapter has two objectives—(i) to find the LULC changes over Sabari River Basin (SRB) from 1985 to 2015, (ii) using the classified LULC map, model the streamflow in the Sabari basin and to observe the anomalies.

2 Study Area and Data Source

2.1 Sabari River Basin (SRB)

The GRB is the second-longest and third-largest river in India. The Sabari Basin is located between 17°31′33″ N to 19°6′42″ N latitudes and 81°3′36″ E to 83°3′5″ E longitudes. The annual average rainfall is approximately 1250 mm. Saradaput and Konta sub-basins are considered to study streamflow anomalies. The Konta is the largest sub-basin of SRB. The Saradaput and Konta stations are located at 18°36′45”N, 82°08′34”E and 17°47′56″ N, 81°23′34″ E, respectively. The basin map and its position in India are presented in Fig. 1.

2.2 Data Used

The Landsat images for the years 1985, 1995, 2005, and 2015 are collected from the USGS web portal. ASTER Digital Elevation Model (DEM) of 30 m resolution is downloaded from the NASA web portal (https://www.earthdata.nasa.gov/news/new-aster-gdem). The daily rainfall data at 0.25° × 0.25° resolution [18] and temperature

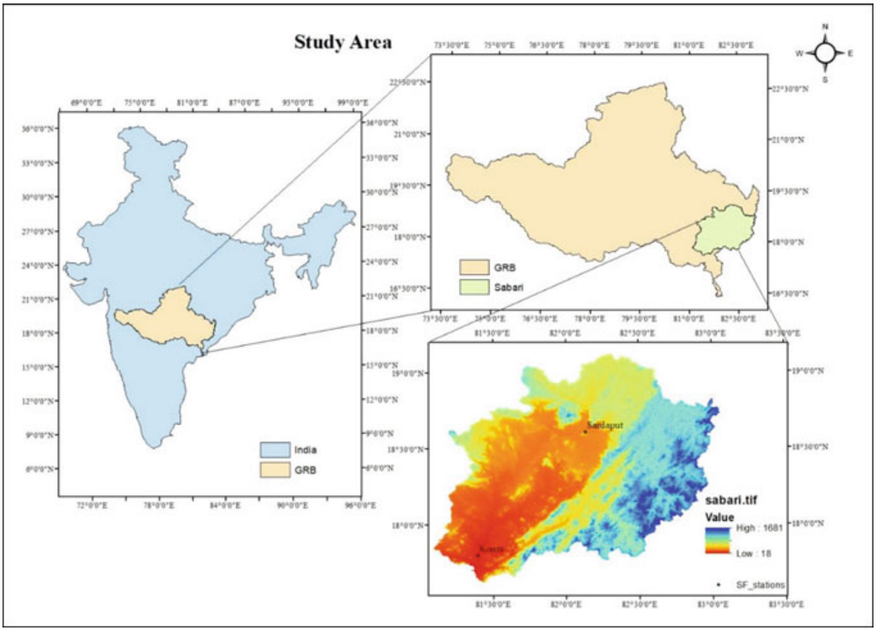

Fig. 1 Study area map

data at 1° × 1° resolution [22] for the GRB are obtained from IMD, Pune. The weather data is collected from the NCEP- NCAR website. FAO (Food and Agriculture Organization) soil map is utilized for this sub-basin.

3 Methodology

See Fig. 2.

3.1 LULC Change Detection

The raw Landsat images for the years 1985, 1995, 2005, and 2015 are classified using the Normalized Difference Vegetation Index (NDVI). Among different normalized difference indices developed for remotely sensed imagery, NDVI is the most widely used index [5]. The image is classified into six classes: cropland, built-up area, dense vegetation, sparse vegetation, range land, and waterbodies, depending on the NDVI

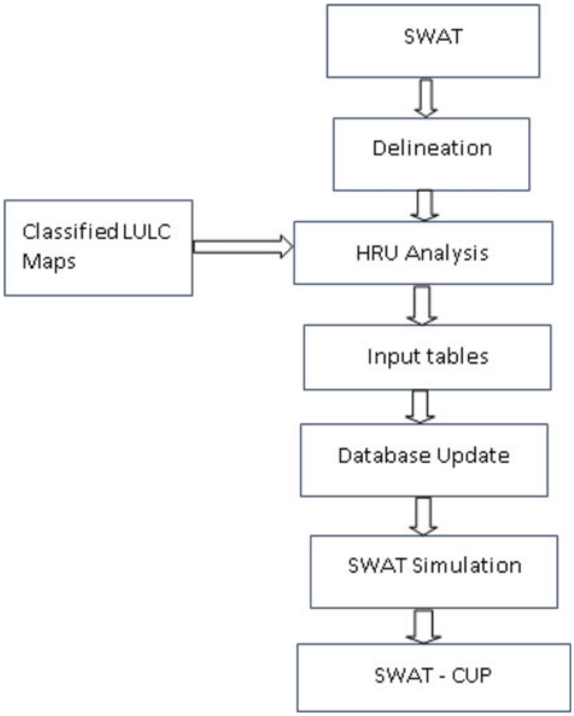

Fig. 2 Methodological flowchart

ranges. The NDVI classification is used due to the vegetative occupancy in the Sabari basin. The two LULC maps are overlaid to detect the change in each class.

3.2 SWAT Model

SWAT is developed by (USDA-ARS) [2] and is used to find the anomalies in the streamflow concerning the change in the LULC for different decades. The model works based on the water balance equation represented by Eq. 1 and SWAT distributes the basin into sub-basins that will eventually connect with the system. Hydrologic Response Units are also generated with the sole allocation of gradient, soil type, and land cover [14]. The weather data is defined using the observed data. To estimate the surface runoff for the selected catchments, the model utilizes the SCS-CN method represented by Eqs. 2 and 3. The model is simulated monthly from 1979 to 2014, skipping three years by considering the lag effect.

$$SW_f = SW_0 + \sum_{j=1}^{n} (P_d - Q_s - ET_j - W_{\text{seep}} - Q_g) \tag{1}$$

$$\begin{aligned} Q &= \tfrac{(P-0.2\,\mathrm{s})^2}{P+0.8s} && \text{if } R > 0.2\,\mathrm{s} \\ Q &= 0 && \text{if } R \le 0.2\,\mathrm{s} \end{aligned} \tag{2}$$

$$s = 254\left(\frac{100}{CN} - 1\right) \tag{3}$$

where SW_f = Final Soil water content; SW_0 = Initial Soil Water content; P_d = daily Precipitation; Q_s = Surface flow; Q_g = Return flow; ET_j = Evapotranspiration on jth day; W_{seep} = Soil interflow; n = time. All units are in mm. CN is the curve number; s is the retention parameter depending on the topographical features and soil water content. The equation for the retention parameter is represented by Eq. 3.

3.3 Model Calibration and Validation

SWAT is calibrated using SWAT-CUP by optimizing the parameters and determining the parameters' sensitivity toward hydrological processes such as streamflow [11]. Therefore, in many significant applications, the calibration process might become challenging. Because of SWAT, CUP's intelligence, model parameters can be set, optimized, and manually modified after every iteration of calibration. Multi-objective optimization has been carried out by considering NSE, R^2, and PBias as the objective functions. For this study, 11 parameters were priorly selected, corresponding to their sensitivity and impact on the water balance [9].

$$R^2 = 1 - \frac{\text{Sum of Squares of Residuals}}{\text{Total sum of the squares}} \quad (4)$$

$$SE = 1 - \frac{\sum_{t=1}^{T} X_m^t - X_0^t}{\sum_{t=1}^{T} X_0^t - \underline{X_0}} \quad (5)$$

$$\text{PBIAS} = \frac{\sum_{t=1}^{T} (X_0^t - X_m^t)}{\sum_{t=1}^{T} X_0^t} \times 100 \quad (6)$$

where X_m^t = Modeled data at time t; X_0^t = Observed data at time t; $\underline{X_0}$ = Observed mean.

4 Results and Discussions

4.1 LULC Analysis

The classified decadal LULC maps are shown in Fig. 3. The magnitude of each class in each decade, along with the proportionate change in the LULC from 1985 to 2015, is represented in Table 1. The analysis shows that the SRB is a dominant vegetative basin with overall vegetation (cropland, dense vegetation, and sparse vegetation) area of 19,974 km^2 in a total basin area of 20,840 km^2. The remaining area is covered by a built-up area of 125 km^2 and water bodies of 740 km^2. It is observed that from 1985 to 2015, the built-up area almost doubled (94.95%), whereas the dense and sparse vegetation was reduced by 5% and 4%, respectively. The cropland in the Sabari basin increased by 8.8%, and waterbodies decreased by 32% during 1985–2015. The reduced area of the water bodies, dense and sparse vegetation, is converted into cropland and built-up area. Most of the reduced dense and sparse vegetated area is converted into cropland.

4.2 Performance of the SWAT Model

The model is developed using the topographical and meteorological data for 1979–2014, considering three years (1979–1982) as a lag time. The performance, sensitivity analysis, calibration, and validation of the model using SWAT-CUP are performed. The slope of the SRB varies between 0 and 70%. There are four different soil classes as per the FAO soil map in the study area. The SWAT generates a total of 180 HRUs in the SRB.

The hydrographs of the Sardaput and Konta basins are presented in Figs. 4 and 5. The hydrographs are plotted for three decades 1985–1995, 1995–2005, and 2005–2015. The observed average decadal streamflow during pre-monsoon, monsoon, and

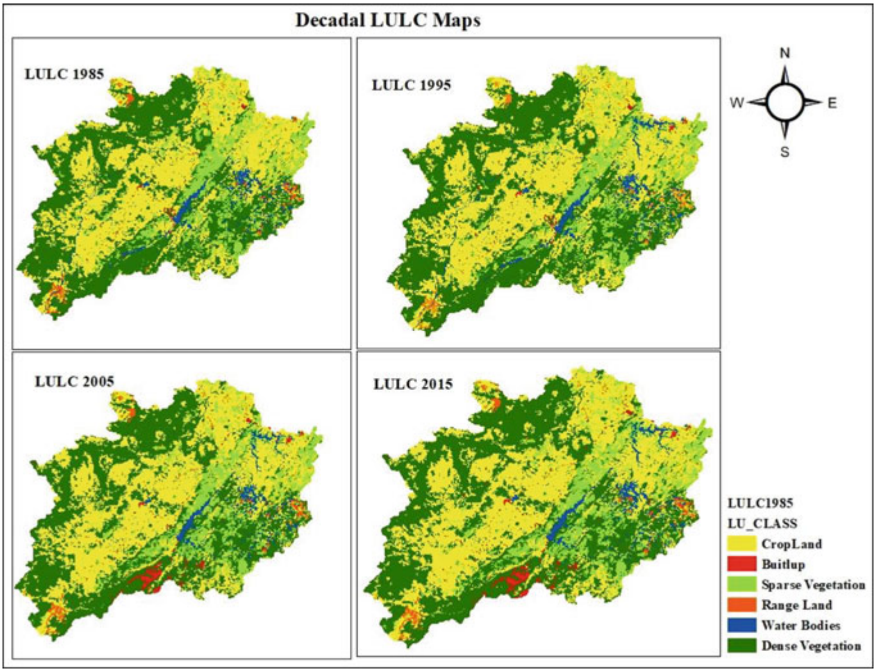

Fig. 3 Decadal LULC maps of Sabari basin

Table 1 Magnitude and % change in the LULC

Class	Decade				% Change between 1985 and 2015
	1985	1995	2005	2015	
Built-up area	125.8	138.1	126.8	245.3	94.96
Cropland	8274	8288	8293	9007	8.86
Dense vegetation	8944	8926	8908	8490	−5.08
Sparse vegetation	2755	2623	2815	2635	−4.35
Water bodies	740.3	864	697.9	502.5	−32.12

post-monsoon seasons in the Saradaput is increased by 4 m^3/s (3.7%), decreased by 25 m^3/s (8.15%) and increased by 3.75 m^3/s (5.09%), respectively, by 2015. In comparison with the first decade 1985–95. For the Konta basin, it has increased by 8 m^3/s (3.1%), decreased by 195 m^3/s (34%), and decreased by 35 m^3/s (5%) in pre-monsoon, monsoon, and post-monsoon seasons, respectively. However, the simulated values are quite converse to the observed data. The simulated decadal streamflow data for pre-monsoon, monsoon, and post-monsoon seasons in Saradaput are decreasing by 9 m^3/s (4%), 9 m^3/s (5.8%), and 1.8 m^3/s (15.27%), respectively. In the Konta basin, it has decreased by 35 m^3/s (5%), increased by 355 m^3/s (5%) and 22 m^3/s (10%) in pre-monsoon, monsoon and post-monsoon seasons, respectively. The plots of Saradaput and Konta for the decadal analysis of the observed and modeled streamflow are presented in Figs. 4 and 5, respectively.

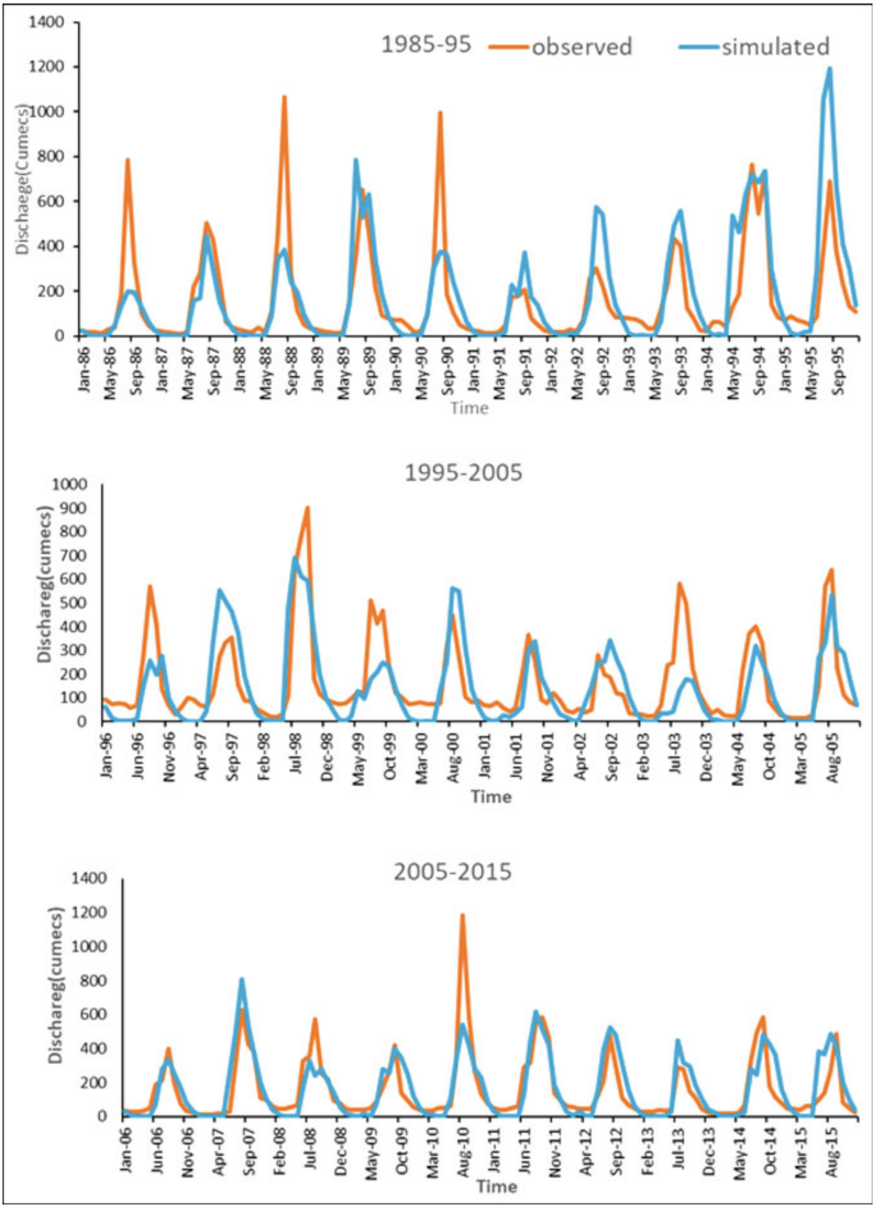

Fig. 4 Observed versus simulated discharge for saradaput sub-basin

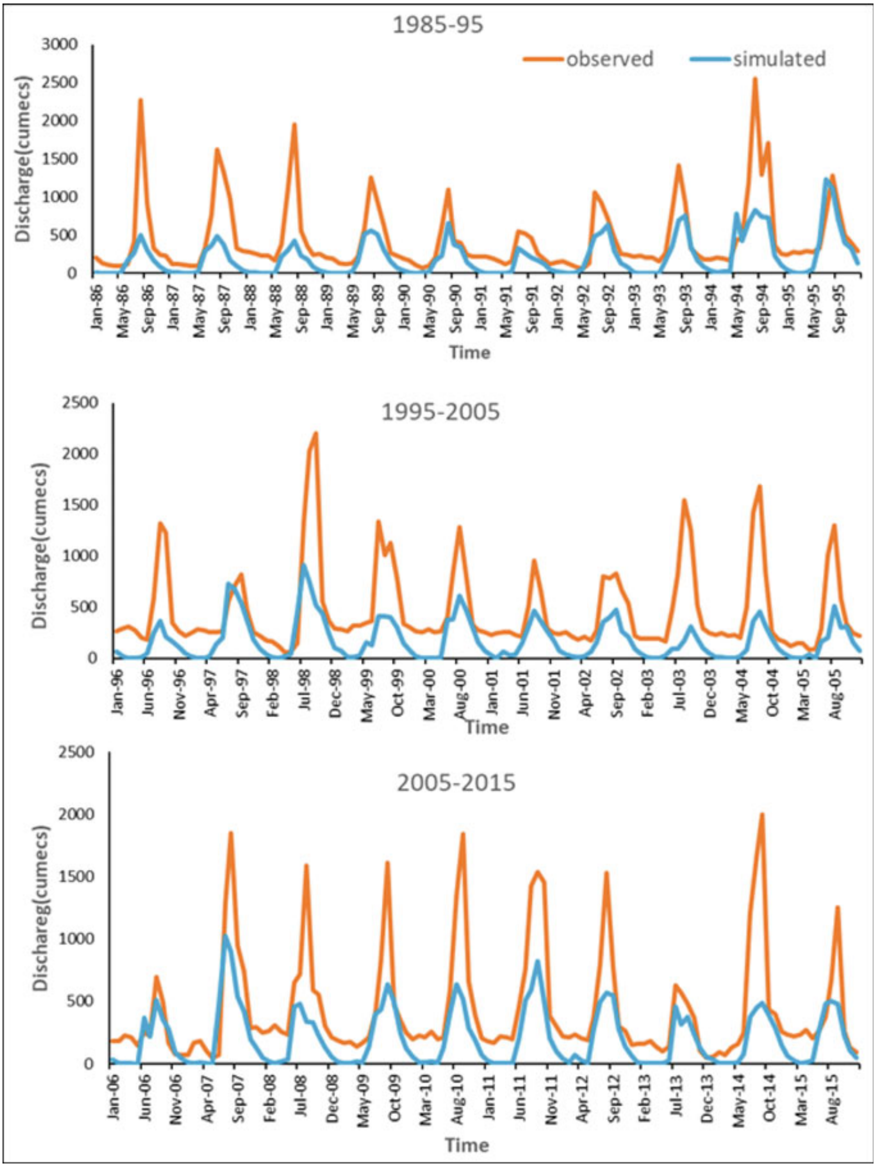

Fig. 5 Observed versus simulated discharge for Konta sub-basin

NSE, PBias, and R^2 are used to check the SWAT performance regarding the sensitivity of parameters. The model is calibrated (1979–2003) and validated (2004–2013) monthly using SWAT-CUP. 11 parameters are selected for sensitivity analysis and after nine iterations of each 400 simulations, a specific value is fitted within the described range. The parameters, description, and fitted value for the best simulation

Table 2 Selected parameters and their fitted values

Sl. No.	Parameter_ Name	Description	Fitted_Value
1	CN2	Curve number for moisture condition II	67.270103
2	ALPHA_BF	Baseflow alpha factor	0.536313
3	GW_DELAY	Groundwater delay	226.575745
4	GWQMN	Threshold depth of water for return flow	753.507507
5	GW_REVAP	Groundwater re-evaporation coefficient	0.020185
6	REVAPMN	Threshold depth of water in the shallow aquifer for "revap" to occur	656.408997
7	CH_N2	Manning's 'n' value in the main channel	0.083838
8	CH_K2	Effective hydraulic conductivity	28.366709
9	SOL_AWC	Soil available water capacity	1.002764
10	ESCO	Soil evaporation compensation facto	0.583095
11	EPCO	Plant uptake compensation Factor	0.612328

Table 3 Performance stats for Saradaput and Konta sub-basins

Period	Performance metric	Saradaput	Konta
Calibration	R^2	0.78	0.58
	NSE	0.51	0.35
	PBIAS (%)	−5.8	−4.2
Validation	R^2	0.74	0.62
	NSE	0.53	0.42
	PBIAS (%)	−3.8	−4.6

are shown in Table 3. Further, the values of the selected objective functions for the best simulation in both the Saradaput and Konta locations are shown in Table 2. Irrespective of the catchment area, the correlation between the extreme events is 0.42. In the case of ordinary events, if the catchment area is small such as Saradaput, the correlation is 0.81, and for a larger sub-basin area, the correlation is 0.75. In Sadaraput, the model performs well with R^2 coefficients of 0.78 and 0.74 with an efficiency of 0.52 and 0.53 in calibration and validation, respectively. For Konta, the R^2 is reduced to 0.58 and 0.62 with an efficiency of 0.35 and 0.42 in calibration and validation, respectively. Therefore in both cases, the model is overestimated.

4.3 Water Balance Components

In SRB, evapotranspiration is the prominent water balance component that consumes about 74% of the rainfall, as it is a vegetation-dominant sub-basin. The surface flow is 8% due to more infiltration in the basin. The remaining rainfall is percolated into the soil depending on the soil condition. From the percolated soil, 4% returns to the surface flow (return flow). The aquifer recharge is 1% for the deep and the remaining precipitation is stored in the shallow aquifer which is readily available. A similar study on a high vegetation basin is conducted by Koneti et al. [15] and Guug et al. [10] also showed that evapotranspiration is the highest component of these types of basins.

5 Conclusion

The increased built-up area might decrease the infiltration capacity, leading to increased surface runoff in the Saradaput sub-basin. The LULC maps represent that most of the decreased cropland is converted into a built-up area. The modeled streamflow contains bias, due to a considerable difference between the observed and the modeled data for the Konta sub-basin in terms of the catchment area. In this study, the SWAT model showed relatively low accuracy in capturing the hydrograph peaks in Konta sub-basin than in the Saradaput sub-basin. It is due to the larger area of the Konta sub-basin consisting of vegetation which leads to the more evapotranspiration when compared to Saradaput sub-basin. While in both the sub-basins, the recession limbs are almost all properly captured due to the range of the groundwater delay and base flow parameters. Overall, the streamflow variations are associated with the change in LULC and it is evident from this study that the built-up area doubled in 2015 when compared with the land cover data of 1985. It is due to the drastic increase in population over the SRB. The growing population demands more land resources for their basic needs, i.e., food and shelter. Therefore, the vegetated land is turned into agriculture and built-up land. The present study is very helpful in understanding the effects of LULC changes on streamflow in other similar basins.

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