



# Investigating the influence of future landuse and climate change on hydrological regime of a humid tropical river basin

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## Abstract

Landuse landcover (LULC) and climate change have significant hydrological impacts, especially in humid tropical regions. Cautious planning and development based on early preparedness can result in LULC patterns that may improve the well-being of human beings and ecosystem. This demands significant knowledge related to the climatic and hydrological variables. In this study, the impact of future climate and LULC change of a humid tropical catchment Periyar river basin (PRB) in the Western Ghats, India, is investigated using the Soil and Water Assessment Tool (SWAT). The study critically evaluates the individual and combined impacts of LULC and climate change on water balance components including precipitation, surface runoff, evapotranspiration, soil water storage, percolation, base flow, and lateral flow. The future LULC maps are projected to 2030, 2050, 2075, and 2100 using the past data with the help of the Cellular Automata-Markov transition matrix. LULC change indicated an increased urbanization and cropland, whereas a decreased forests and plantations in future. For future climate change impact assessment, ensemble of five global circulation models with RCP 4.5 and RCP 8.5 scenarios is considered. The results suggest climate change impact is dominant over LULC change in the near (2011–2040) and mid (2041–2070) future, whereas vice-versa in the far (2071–2100) future. The quantitative assessment of spatial and temporal variation in hydrological components append insights to the hydrological processes. The results can further add value to studies related to irrigation requirement, groundwater recharge, crop water demand, soil permeability and integrated water resource management. Furthermore, the current modeling framework can be implemented in other humid tropical river basins to understand the hydrological regime changes aiming effective water resources and environmental management.

**Keywords** Climate change · Hydrological regime · Humid tropical river basin · Landuse landcover (LULC) change · SWAT model

## Introduction

The humid tropics cover around 20% of the Earth's land and produce the highest volume of runoff compared to any other biome on a global scale (Fekete et al. 2002; Wohl et al. 2012). Due to the unique ecohydrology of humid tropical regions, it has been a point of attraction for human settlements (Wohl et al. 2012; Hamel et al. 2018). Over three billion people worldwide depend on the water supplies of tropical watersheds for survival (State of the Tropics 2014). This makes these regions susceptible to both population and natural resource vulnerabilities. Tropical humid regions are heavily affected by climate change dynamics due to their proximity to the Intertropical Convergence Zone (ICTZ). Past (IPCC AR5, 2012) and recent studies by IPCC (IPCC AR6, 2022) acknowledge a significant impact of climate change on the natural water systems. To comprehend, variation in

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precipitation patterns have a direct consequence on runoff and water availability, whereas temperature, humidity, and radiation have an impact on evapotranspiration. Climate change impact leads to various hydrologic extreme events including floods (Tabari 2020) and droughts (Zhao et al. 2020). Both of these studies have shown that these extreme events show variation in frequency varying across the globe as well as across regions. Furthermore, it was also noted that these changes vary in different climate zones and seasons based on the water availability.

Such changes cause a severe damage to river basins, livestock, and alters the hydrological balance. This may include altering aquifers recharge system (Pardo-Igúzquiza et al. 2019) that serve as a local water source especially for remote regions. However, the impact of climate change is not always negative, for instance, a reduction in desertification in North China was observed between 1975 and 1990 (Zhang et al. 2020) which suggest that climate change sometimes has a positive impact on vegetation cover and soil quality.

Furthermore, changes in land use land cover (LULC) can also impact the hydrology of a river basin by altering the infiltration capacity of the soil, evapotranspiration, as well as the surface and subsurface flow patterns within the ecosystem. The LULC changes reflect separate response in the semi-arid (Garg et al. 2017), sub-tropical (Kundu et al. 2017), tropical (Marhaento et al. 2018), semi arid and humid subtropical (Saddique et al. 2020) regions.

Research conducted in the past has indicated that LULC and climate change have substantial impact on water resources at the river basin scale. Various studies have identified links between LULC and climate change impact on flood (Chang and Franczyk 2008), water quality and quantity (Praskievicz and Chang 2011), sediment yield (Khoi and Suetsugi 2014), runoff (Shahid et al. 2021), water yield (Yang et al. 2021) and other hydrological variables in tropical catchments (Zhang et al. 2016; Marhaento et al. 2018) as well as in agricultural watersheds (Schilling et al. 2008). These studies have also addressed issues related to environmental degradation in transboundary water services (Mendoza-Ponce et al. 2021). Further research has been conducted to segregate the effect of human intervention and climate change on stream discharge (Wang 2014) and to propose suitable adaptive measures. Thus, it is crucial to understand the potential effects of climate and LULC change on streamflow, runoff, and other water balance components for long-term water resource planning and management on river basin scale (Dixon and Earls 2012).

Other than LULC and climate change, certain anthropogenic entities like reservoirs operations also have some effects on the streamflow (Adam et al. 2007; Zajac et al. 2017; Yun et al. 2020). These structures provide benefits like provision of water supply for domestic use, irrigation purpose, power generation, and flood risk

reduction. However, their drawbacks include habitat fragmentation and loss of biodiversity. Alteration of the natural river dynamics of water nutrients and sedimentation are other negative effects (Graf 1999, 2006; Rosenberg et al. 2000; Magilligan and Nislow 2005). Watersheds having reservoirs are subjected to these complexities due to the obstructed water flow along with various operation policies. Un-coordinated reservoir operation, flow constraints, transboundary water flow, data unavailability, etc., further exacerbate the problems (Ammar et al. 2017; Gunawardana et al. 2021). Therefore, an extensive regional study is required for long-term development and adaptation in the Anthropocene.

The present study focuses on a humid tropical river basin in the Western Ghats region of India. The Western Ghats is an interesting region for study as it is subjected to various climatic irregularities and has a unique topographic. Western Ghats runs parallel to the west coast of India and receives very high annual rainfall up to 6000 mm (Das et al. 2017) during the Indian Summer Monsoon (ISM), and its topography plays a major role in the hydrology. The windward side (West) is subjected to high precipitation due to orographic and topographic variations making it flood-prone during the monsoon. Whereas the leeward end (East) often faces water scarcity and leads to drought-like situation. In Western Ghats, extreme precipitation events have become more frequent (Vijaykumar et al. 2021). Sometimes, it lasts for hours, days, and sometimes weeks with intermittent breaks (Das et al. 2017). These complexities make it a challenging area for study when subjected to climate change.

Western Ghats has more than 45 rivers and Periyar river is one among the major rivers in South India. It is an essential source for water, irrigation, and power generation. It has been experiencing heavy precipitation frequently and has been subjected to various natural and anthropogenic changes. Thus, this river basin is suitable to investigate the impacts of LULC and climate change on water balance components. The Periyar river basin (PRB) has been considered for various past studies like assessment of rainfall pattern and hydrological characteristics; role of reservoirs in event-based studies; and water quality (Gosain et al. 2006; Sreelash et al. 2018; Sudheer et al. 2019) but no study has been done so far on the future climate and LULC change impacts. Thus, any information related to future possibilities related to climate and LULC change will be of immense importance and help in planning water and environmental management.

To assess the effects of climate and land use changes on water balance, it is often required to use physically based hydrologic models. With the progress in computational resources, computer models can now discretize the spatial heterogeneity of watershed parameters and accurately simulate the hydrologic cycle. The Soil and Water

Assessment Tool (SWAT) is one such hydrological model that has been widely used to study the landuse and climate change impact on watersheds globally (Luo et al. 2016; Paul et al. 2017; Chen et al. 2020) as well as in India (Anand et al. 2018; Sinha and Eldho 2018). Furthermore, this model is also tested to analyse the water yield (Yang et al. 2021), water quality (Abbaspour et al. 2015), and future scenario generations to test hypothesis (Chanapathi and Thatikonda 2020; Dau et al. 2021). Thus, SWAT is considered as a suitable model for the analysis in this study.

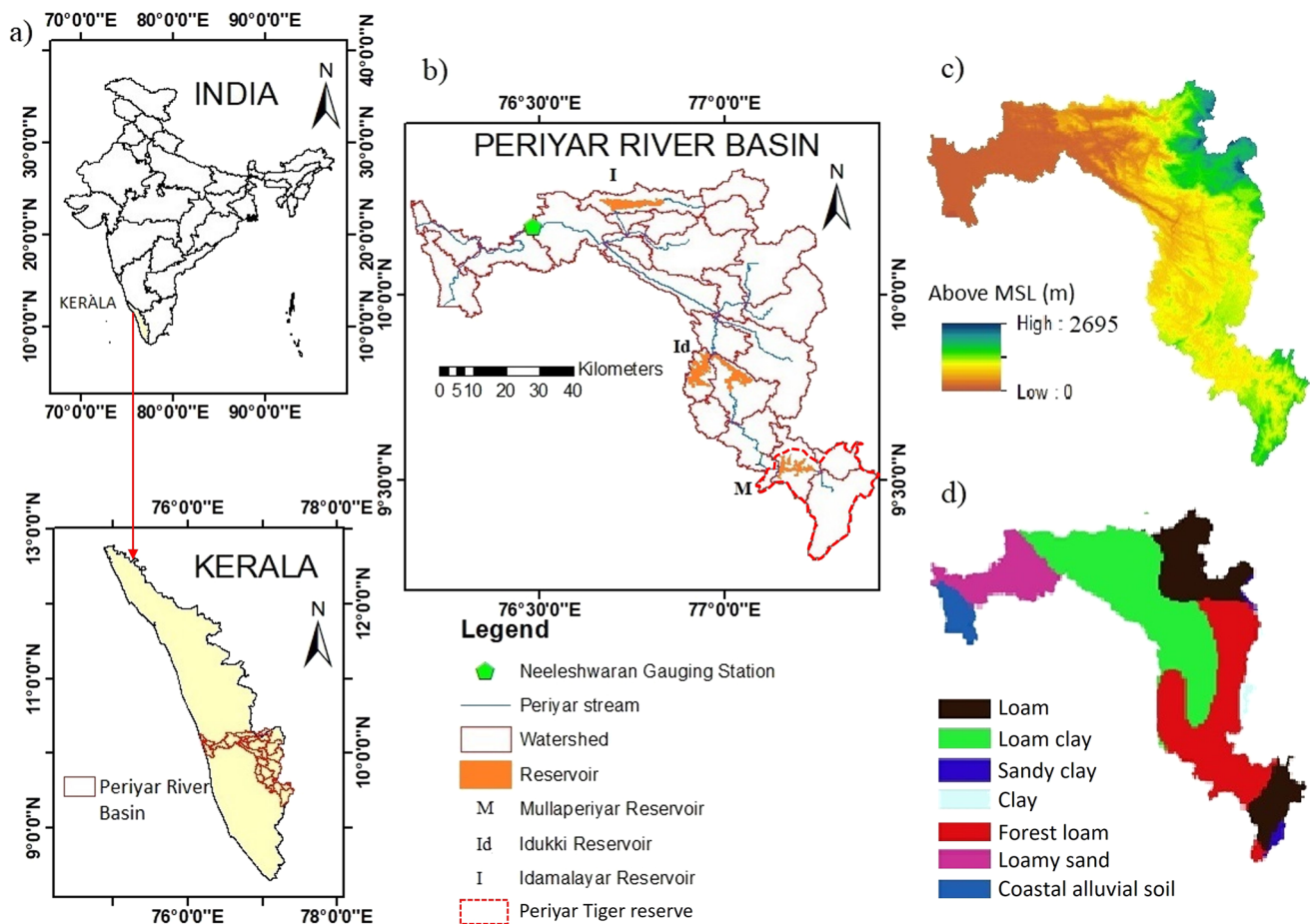
The objectives of the present study include the projection of future landcover changes at river basin scale; calibration of the SWAT model; and the assessment of hydrological responses to climate and landuse changes, both individual and combined influences. The paper is organized into six sections. A brief discussion about the study area is given in “Study area and datasets”. The methodology of the study and data collection details are described in “Methodology”. The results are presented in “Results”. A detailed discussion of the learning from the outcomes

is provided in “Discussion” and the conclusions from the study are summarized in “Conclusions”.

## Study area and data sets

### Study area

The entire modeling effort has been demonstrated over the Periyar river basin (PRB) in the Western Ghats region of South India (Fig. 1a). The Periyar river is the second-longest river of Kerala, with a length of approximately 244 km (CWC 2018). The river originates at Sivagiri peak (80 km towards South from Devikulam district) in the Western Ghats, India, at an elevation of 2438 m above mean sea level and joins the Arabian Sea towards the west. The highest elevation in the basin is 2695 m above mean sea level at Anamudi Peak (Fig. 1c). The watershed area ranges from longitude 76° E to 77° 30' E and latitude 9° 16' N to 10° 20' N (Fig. 1b). The average annual rainfall of the basin is 3200 mm (CWC 2018). It is majorly covered with forests (1581 km<sup>2</sup>, 33.32% of watershed area) and plantations



**Fig. 1** Periyar river basin details: **a** location map; **b** river basin with sub-basins; **c** DEM-elevation profile; **d** soil texture

(2492 km<sup>2</sup>, 52.02% of watershed area) with little built-up area (240 km<sup>2</sup>, 5.31% of watershed area) as per the landcover map of 2016. The details of landcover types is discussed in “Data collection and preparation of data-inventory”. The soil texture mainly consists of combinations of sandy, clayey and loamy soil (Fig. 1d). The Periyar river, being a perennial river, is a vital source of water in the central parts of Kerala. The maximum temperature of the basin ranges between 25 °C and 32 °C, whereas the minimum temperature of the basin lies between 14 °C and 19 °C (Sudheer et al. 2019). There is one active hydrological observation station, Neeshwaram gauging station (10° 12' N 76° 5' E), and three major reservoirs: Mullaperiyar, Idukki, and Idamalayar reservoir located in the basin. The details of the reservoirs are mentioned in Table 1.

For reservoir operation, target storage and release method has been adopted as it has been identified as the most promising method at daily and monthly scale (Zhao et al. 2016; Zajac et al. 2017; Yassin et al. 2019). For Idamalayar reservoir, the maximum flow rate from the spillway is 3012.8 cumecs (Mohanakrishnan and Verma 1997), and the same has been assumed to be the monthly average outflow. It is observed that from the Idukki reservoir, there is no regular water release in the Periyar river. It was released only thrice, i.e., in 1981, 1992, and 2018, in the last 50 years. The water stored in the reservoir is directed towards Thodupuzha river in Thriveni sangamam at Moolamattom Power Station for power generation outside the watershed area (source: <http://www.kseb.in>). To replicate this condition in the SWAT model, a 500 MCM of water consumption was assumed to compensate the outflow from the Idukki reservoir into the Periyar river.

Similarly, for the Mullaperiyar reservoir, the water stored is mainly used for irrigation purposes. Since it is located on the boundary of two states, Kerala and Tamil Nadu, water stored is used by the population on both sides. A major portion of water is released into the Vaigai river in Tamil Nadu, and the rest is used by nearby districts in Kerala. There is an Inter-State Water dispute between the two states, and the exact consumption of water is still not clear (Ram Mohan and Chavaly 2015; Sreejith 2022). As most of the water stored in the dam is utilized for irrigation purposes, it is assumed that there will be very low or no flow of water from

the Mullaperiyar reservoir into the Periyar river. Based on these assumptions, a SWAT model setup was done for the Periyar River basin. The catchment area after delineation was 4792.83 km<sup>2</sup>. Other than this, the Periyar Tiger Reserve, a UNESCO World Heritage site (<https://www.periyartigerreserve.org/>), is situated upstream of the Mullaperiyar reservoir (Fig. 1b) within the basin. This forest reserve spans approximately 777 km<sup>2</sup> of the basin area and is predominantly composed of forests and plantations (Figs. 1b and S1).

## Data collection and preparation of data-inventory

The topography data used in the study include elevation, slope, flow direction, and accumulation. These were generated from CartoDEM digital elevation model (DEM) with a 30 m grid resolution provided by National Remote Sensing Centre (NRSC) (Fig. 1c). The soil texture data is obtained from the National Bureau of Soil Survey and Land Use Planning (NBSS and LUP), having a 1:500,000 scale. The soil type is primary in loamy and clayey texture (Fig. 1d).

For LULC analysis, Landsat LIS-III satellite images for 1988, 1992, 2002, and 2016 were used for creating landcover maps to capture decadal change. Level 2 LandSat images were used for classification, which was free of cloud and atmospheric interference. Furthermore, these images were collected in the post-monsoon season (October to January) to capture the wetlands and vegetation adequately. Supervised maximum likelihood technique is used for classification due to its advantages over other methods (Lu and Weng 2007). The major landuse classes were identified as water (3.67%), built-up (5.31%), plantation (52.02%), cropland (3.06%), barren land (2.62%), and forests (33.31%) as per the LULC of the year 2016 (Fig. S1). The overall classification accuracy ranges between 84% and 93%, and the kappa coefficient ( $\kappa$ ) ranges between 0.81 and 0.87, respectively.

The meteorological data includes precipitation, solar radiation, temperature (minimum and maximum), and wind speed. Historical precipitation and temperature were obtained from IMD (India Meteorological Department) and other meteorological data from CFSR (Climate Forecast System Reanalysis). The future meteorological data is extracted from five GCMs (Global Circulation models)

**Table 1** Details of reservoirs (Source: Kerala State Electricity Board, Mohanakrishnan and Verma 1997)

Name of reservoir	Built in years	Full reservoir level (m)	Full reservoir capacity (MCM)	Effective volume (MCM)	Surface area at FRL (sq. km)
Idamalayar	1985	169.00	1089.00	1017.80	28.30
Idukki	1973	168.91	5550.00	1460.00	60.03
Mullaperiyar	1895	46.33	443.23	443.23	20.55

MCM is million cubic meters (i.e., 10<sup>6</sup> m<sup>3</sup>)

of CMIP-5 which were statistically downscaled and bias corrected as downscaled data may show considerable bias (Salvi et al. 2013). The GCMs used are BNU-ESM, CCCma-CanESM2, CNRM-CM5, MPI-ESM-LR and MPI-ESM-MR. These GCMs were selected on the basis of their performance in representing the Indian climatic conditions as identified in the past literature (Shashikanth et al. 2014; Madhusoodhanan et al. 2018; Singh et al. 2019).

All the data is in gridded format at various resolutions. Further details of the data used are mentioned in Table 2. Gauge discharge and reservoir level data were obtained from CWC, India. This data is used for calibrating the SWAT model output.

## Methodology

### LULC change model

For determining the effects of change in land cover on runoff, the future land cover maps of PRB were projected for 2030, 2050, 2075, and 2100. For this TerrSET Land Change Modeler (LCM) is used (Adhikari and Southworth 2012; Anand et al. 2018; Liping et al. 2018; Marhaento et al. 2018; Chanapathi and Thatikonda 2020). LCM compares two maps to identify the transition trend from one class to another and then uses a multi-layer perceptron (MLP) neural system to develop an empirical relation between the transition and influencing elements (driver variables) responsible

for landcover change. The results create a series of transition potential maps, and these are used with the Markov chain transition matrix technique (Muller and Middleton 1994) combined with cellular automata technique (Clarke and Gaydos 1998) to generate future maps. Markov model for prediction of future landcover can be mathematically represented as follows:

$$M_{t+1} = P_{pq} * M_t \tag{1}$$

where  $M_t$  and  $M_{t+1}$  are landcover maps at time  $t$  and  $t + 1$ , respectively.  $P_{pq}$  is the matrix to show transition probability from state  $p$  to  $q$ .  $P_{pq}$  is represented as

$$P_{pq} = \begin{bmatrix} P_{11} & P_{12} & \dots & P_{1j} \\ P_{21} & P_{22} & \dots & P_{2j} \\ P_{31} & P_{32} & \dots & P_{3j} \\ \dots & \dots & \dots & \dots \\ P_{i1} & P_{i2} & \dots & P_{ij} \end{bmatrix} \tag{2}$$

Here  $P_{pq}$  must satisfy the two conditions  $\sum_{m=1}^m P_{pq} = 1$  and  $0 \leq P_{pq} \leq 1$ . It should be noted that Markov chain only considers the state of a cell at time  $t$  to predict state at  $t + 1$  and is independent of the influence of state of neighbouring cells. Thus, here cellular automata comes into action and improve the analysis based on considering the transition in state of neighbouring cells. The combined information of Markov chain and cellular automata is then used in projecting the probable future. The details of Markov chain and cellular automata and its applications is discussed in detail

**Table 2** Data sources, resolutions and time period

S. no.	Data type	Resolution	Time period	Source
1	Meteorological data			
	Historical			
	Precipitation	0.25° × 0.25°	1980–2014	IMD
	Temperature	1.0° × 1.0°	1980–2014	IMD
	Wind speed	0.5° × 0.5°	1980–2014	CFSR
	Solar radiation	0.5° × 0.5°	1980–2014	CFSR
	Future			
	Precipitation	0.25° × 0.25°	2011–2100	GCM
	Temperature	1.90474° × 1.875°	2011–2100	GCM
	Wind speed	2.5° × 2.5°	2011–2100	GCM
2	Digital elevation model	30 m × 30 m	2005	CartoDEM (bhuvan.nrsc.gov.in)
3	Soil texture	30 arc second	2012	NBSS and LUP
4	LULC	30 m × 30 m	1988, 1992, 2002 and 2016	LandSAT (Earthexplorer.usgs)
5	Gauge discharge	Daily	1980–2015	Central Water Commission (CWC)
6	Reservoir water level	Daily	1980–2015	

CFSR Climate Forecast System Reanalysis (CFSR) data <https://rda.ucar.edu/>; GCM statistically downscaled (bias-corrected w.r.t. IMD) data from 5 GCM (BNU-ESM, CCCma-CanESM2, CNRM, MPI-ESM-LR, MPI-ESM-MR); IMD India Meteorological Department; NBSS and LUP National Bureau of Soil Survey and Land Use Planning

by Ghosh et al. (2017). This mechanism is applied to project future land cover maps.

In this study, initially classified land cover maps of 1988 and 2002 are used to project landcover of 2016 which is compared with the classified landcover map of 2016. This is done to calibrate the MLP neural network in the LCM and identify the driver variables (Adhikari and Southworth 2012; Anand et al. 2018; Sinha and Eldho 2018; Chanapathi and Thatikonda 2020). In this study, elevation, slope, distance from: road, barren land, cropland, water, built-up area, forest, and water cover are identified as the driver variables. The modeled LULC showed a good spatial correlation (accuracy > 81%) with the LULC data of the year 2016. The detailed comparison has been added in Supplementary Table ST1. The same neural network was retrained and then used to project 2030 landcover with 2002 and 2016 as input. Since PRB contains Periyar Tiger Reserve and other restricted regions (Fig. 1b), a constraint was applied using the Planning feature in TerrSet Land Change Modeler to prevent change in the forest cover in selected areas. The same process is repeated to prepare 2050, 2075, and 2100 land cover maps.

### Hydrological modeling using SWAT

Soil and Water Assessment Tool (SWAT) is a physical semi-distributed hydrological model which requires information about the weather data, elevation details, soil composition, and landcover to simulate the hydrological processes. The model employs the water balance equation to simulate the hydrological components in a region. The runoff generation is based on Soil Conservation Service-Curve Number (SCS-CN) method and channel routing by variable storage method. Whereas the evapotranspiration calculations are based on the Penman–Monteith equation (Arnold et al. 1998). The weather inputs are wind speed, precipitation, solar radiation, and temperature (maximum and minimum). The model separates the watershed into sub-basins based on the details from the digital elevation model and creates hydrologic response units (HRUs) with different combinations of slope, LULC, soil type. These HRUs are useful for determining the properties of un-gauged basins.

### SWAT model calibration and validation

After preparing the SWAT model with all the inputs, the model is calibrated by adjusting the sensitive parameters using the sequential uncertainty fitting (SUFI-2) algorithm in SWAT-CUP (Abbaspour et al. 2007). SUFI-2 considers a large range of uncertainty band initially and then aims at reducing the uncertainty. This is done by reducing the range of sensitive parameters. For identification of the sensitive parameters, Latin hypercube (McKay et al. 1979) sampling

is used. The sampling is based on considering  $p$  parameter combinations, where  $p$  is the number of simulations. These sampled parameter sets are used as input in SWAT, and the simulation results are compared with gauged data. To check the goodness of fit of results is tested using the coefficient of determination ( $R^2$ ) and Nash-Sutcliffe efficiency (NSE) (Legates and McCabe 1999).

### Scenarios and experiments

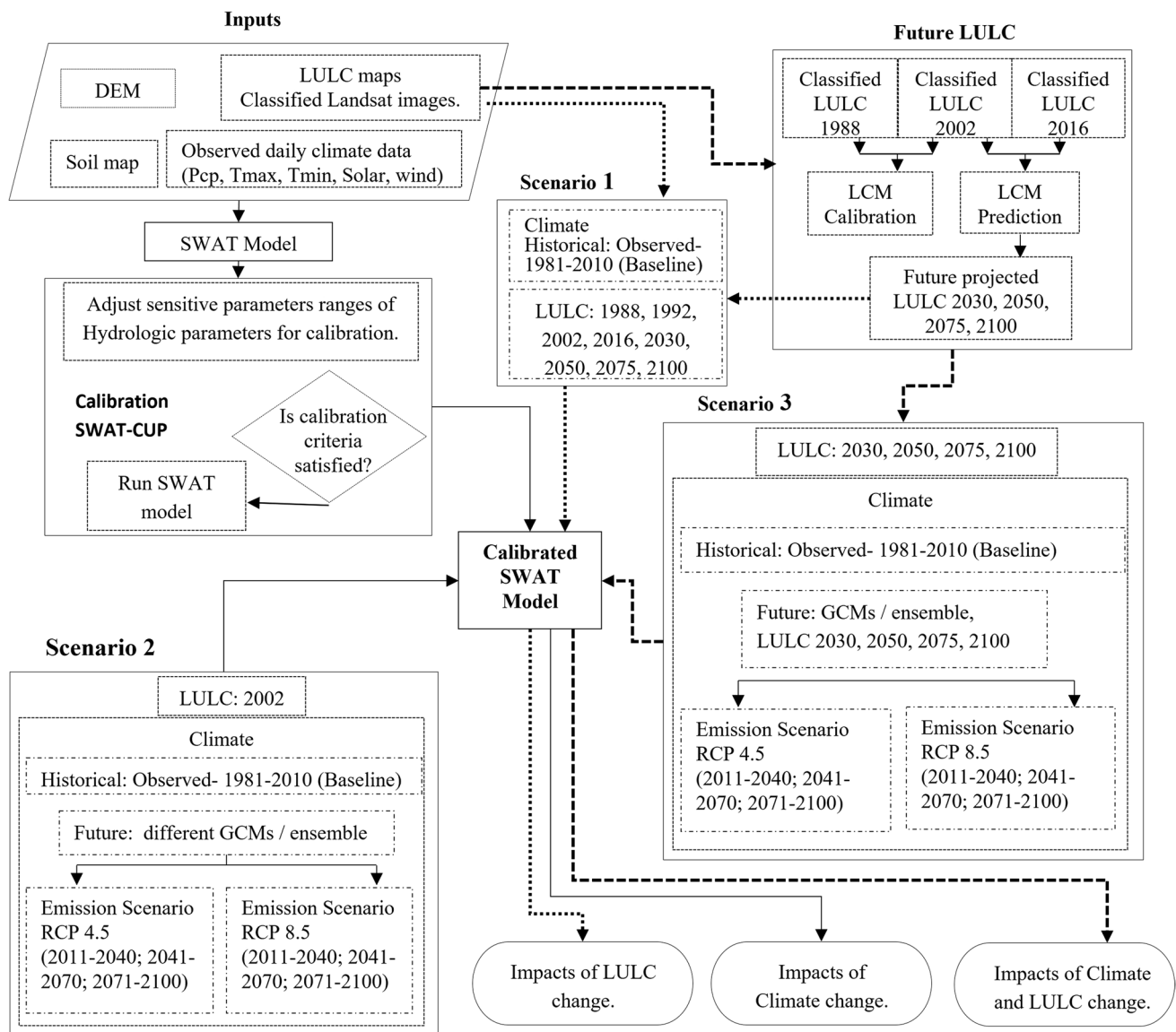
Three scenarios are designed to investigate the impacts of LULC and/or climate change (under the RCP 4.5 and 8.5 scenarios) on hydrological components of the river basin. Scenario 1 is for assessment of impact of LULC change alone, scenario 2 for climate change alone, and Scenario 3 for combined impact. SWAT model is simulated on monthly scale from 1981 to 2100 to analyse the change in hydrological components for each scenario. These hydrological components include precipitation ( $P$ ), surface runoff ( $Q$ ), evapotranspiration (ET), soil water storage (SW), percolation (Per), base flow ( $Q_b$ ) and lateral flow ( $Q_l$ ).

To analyze the changes, simulated outputs for each future period under both scenarios are compared to the corresponding values for the baseline period. For LULC change impact assessment, scenario 1 is designed by assuming the climatic parameters to be constant as in the baseline period (1981–2010) and changing LULC with 1988, 1992, 2002, 2016, 2030, 2050, 2075, and 2100. For climate change impact assessment, in scenario 2, the LULC is fixed with 2002, and climate variables are changed for the corresponding near (2011–2040), mid (2041–2070), and far (2071–2100) future time periods. For combined climate and LULC change impact assessment, scenario 3 is designed by considering the specific LULC for the ongoing time period, i.e., LULC 2030, 2050, and 2075 for near, mid and far future, respectively. The results are then compared to analyze the change among the hydrological components. Figure 2 shows the proposed methodological framework implemented in this study.

## Results

### Future GCM data

To check the suitability of GCM data, historical GCM data is compared with IMD precipitation and temperature for 1981–2005. The statistics of the observed and GCM-simulated climate variables were compared and presented in the Taylor diagram in supplementary data (Fig. S2.1). For precipitation (Fig. S2.1a), the model cluster showed a good correlation (> 0.7) between observed and GCM precipitation. A similar relation is observed with



**Fig. 2** Flowchart showing the proposed methodology for assessing the impact of climate or/and LULC change on the hydrological regime at a river basin scale

minimum temperature ( $T_{min}$ ) and maximum temperature ( $T_{max}$ ) (Fig. S2.1b and S2.1c). After the necessary bias correction, the GCMs demonstrated their ability to accurately represent the climatic patterns of precipitation and temperature (Fig. S2.2). As a result, the downscaled variables proved to be a reliable representation of the climate in the PRB, and were subsequently utilized in the SWAT model.

The future GCM data showed an increasing trend in minimum and maximum temperature, whereas a decreasing trend in precipitation for PRB (Fig. S2.3a, S2.3b, and S2.3c). The projected average annual precipitation for the future ranges between 2400 and

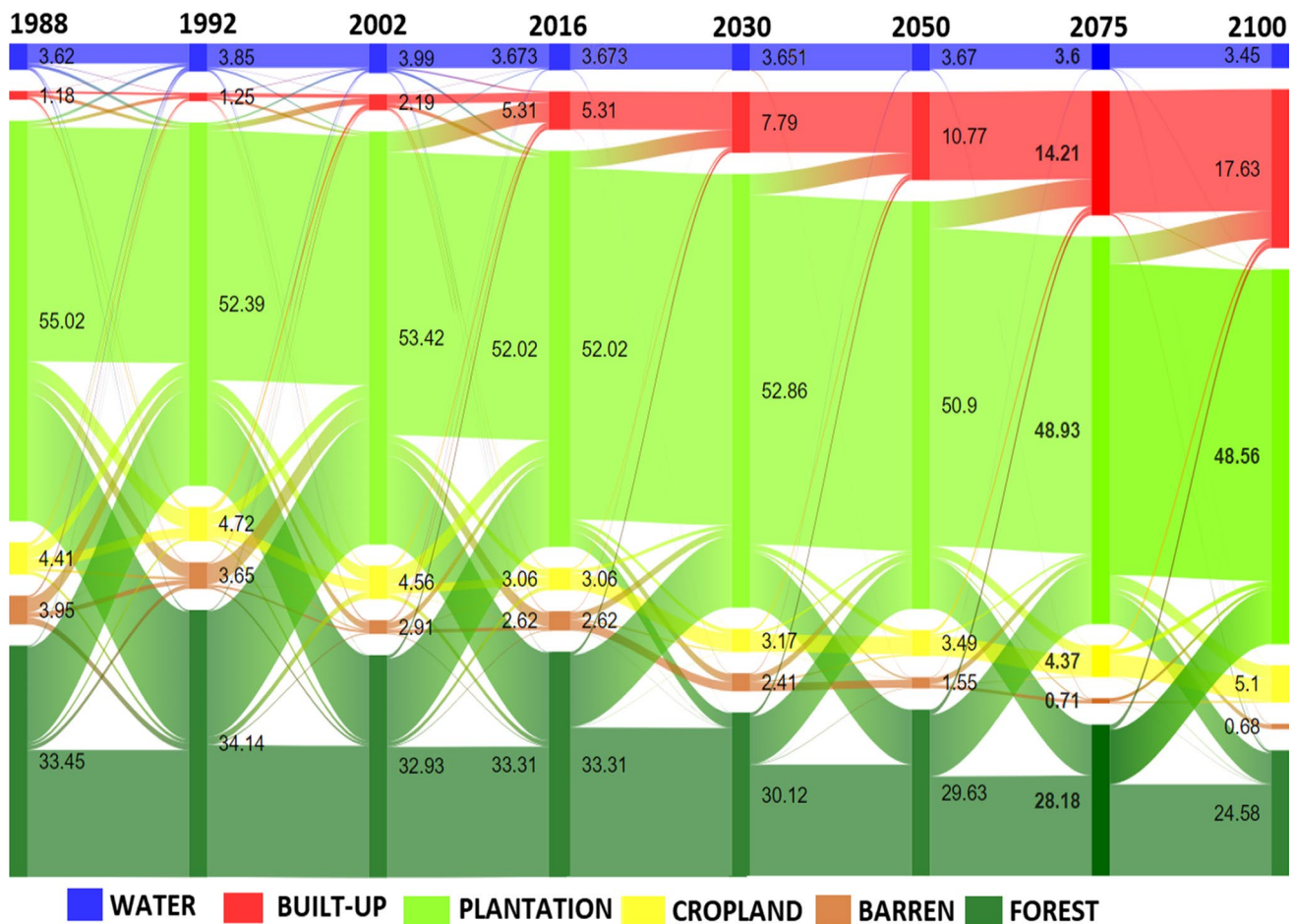
3800 mm for both RCP 4.5 and 8.5 scenarios (Fig. S2.3a).  $T_{max}$  and  $T_{min}$  are expected to rise by approximately 2 °C and 4 °C for RCP 4.5 and 8.5 scenarios, respectively (Fig. S2.3b and S2.3c).

### Future LULC change

The LULC maps for 1988, 1992, 2002, 2016, 2030, 2050, 2075, and 2100 are represented in Fig. S1 in Supplementary. Water, built-up, plantation, cropland, barren land and forests are the major LULC classes, and spatial coverage of each LULC class is tabulated in Table 3. Cropland and urbanization are expected to increase in future up to 5.1%

**Table 3** LULC transition from 1988 to 2100 with percent change with respect to LULC 1988

Years	Class (%)					
	Water (%)	Built-up	Plantation (%)	Cropland (%)	Barrenland (%)	Forest (%)
1988	3.62	1.18%	55.02	4.41	3.95	33.45
1992	3.85 (+0.23%)	1.25% (+0.07%)	52.39 (- 2.63%)	4.72 (+0.31%)	3.65 (- 0.3%)	34.14 (+0.69%)
2002	3.99 (+0.37%)	2.19 (+1.01%)	53.42 (- 1.60%)	4.56 (+0.15%)	2.91 (- 1.04%)	32.93 (- 0.52%)
2016	3.67 (+0.05%)	5.31% (+4.13%)	52.02 (- 3.00%)	3.06 (- 1.35%)	2.62 (- 1.33%)	33.32 (- 0.13%)
2016 (predicted)	3.73 (+0.11)	5.54% (+4.36%)	50.97 (- 4.05%)	3.6 (- 0.81%)	2.53 (- 1.42%)	33.63 (+0.18%)
2030	3.65 (+0.03%)	7.79% (+6.61%)	52.86 (- 2.16%)	3.17 (- 1.24%)	2.41 (- 1.54%)	30.12 (- 3.33%)
2050	3.67 (+0.05%)	10.77% (+9.59%)	50.9 (- 4.12%)	3.49 (- 0.92%)	1.54 (- 2.41%)	29.63 (- 3.82%)
2075	3.6 (- 0.02%)	14.21% (+13.03%)	48.93 (- 6.09%)	4.37 (- 0.04%)	0.71 (- 3.24%)	28.18 (- 5.27%)
2100	3.45 (- 0.17%)	17.63% (+16.45%)	48.56 (- 6.46%)	5.10 (+0.69%)	0.68 (- 3.27%)	24.58 (- 8.87%)



**Fig. 3** Sankey diagram to show transition among different LULC classes for PRB

and 17.63%, respectively, till 2100. Forest cover will reduce to 24.58% till 2100. Such changes are alarming as these factors affect the streamflow and can result in floods and other environmental impacts.

The transition among different LULC classes is represented with the help of Sankey diagram (Fig. 3). The

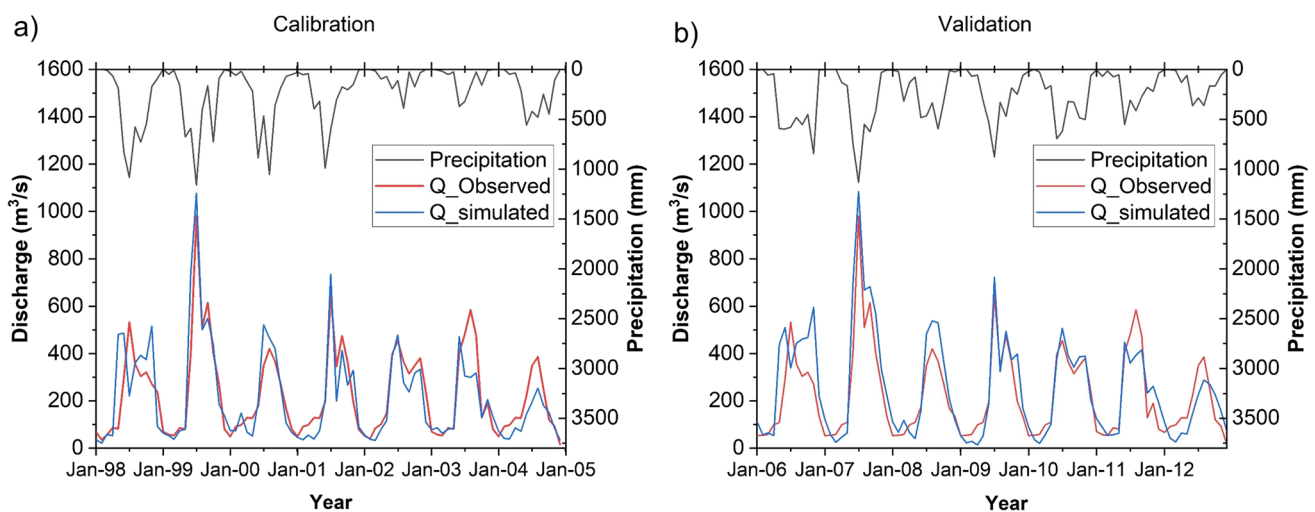
thickness of each node represents the percentage covered by each class, and the thickness of the link represents the transition weight. The major transitions identified are from plantations to built-up and forests to plantation. Some inter-conversion between forests and plantations is also observed. In PRB, barren land is continuously decreasing and mostly



converted to plantation. A little transition of plantation to cropland is also observed. These results can help to understand the changes occurring in the river basin and thus be helpful in its strategic planning and management. The results suggest that deforestation and urbanization in the future will lead to land degradation. These factors significantly affect the water balance of the watershed. Thus, approaches like soil stabilization, preventing wind and water erosion, and maintaining the soil nutrients cycle are necessary to protect land degradation and desertification in the PRB.

### Calibration and validation

The SWAT model setup is done for the basin, and the watershed is delineated into 27 sub-catchments with a total area of 4792.83 km<sup>2</sup> (Fig. 1b). The model is calibrated for monthly streamflow with respect to the Neeleshwaram gauging station managed by CWC (Fig. 1b). The calibration is done for the period 1994–2002 (refer to Fig. 4a). The coefficient of determination ( $R^2$ ), Nash-Sutcliffe efficiency (NSE), and Percent Bias (PBIAS) are used for calibration criteria. In calibration,  $R^2$ , NSE, and PBIAS are obtained as 0.92%, 0.84%, and 6.5%, respectively (Fig. 4a). For validation, the model is tested for 2006–2012 and resulted in  $R^2$ , NSE, and PBIAS values as 0.85%, 0.67%, and 11.8%, respectively (Fig. 4b).



**Fig. 4** Observed and simulated discharge for **a** calibration (1998–2004) and **b** validation (2006–2012) period at Neeleshwaram gauging station for PRB

**Table 4** Sensitive parameters for streamflow calibration

Rank	Parameter	Description	Process	Min value	Max value	Fitted value
1	WURCH.hru	Water use in reach ( $\times 10^4$ m <sup>3</sup> )	Channel	0	5005.677	2.5028 ( <i>v</i> )
2	GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur (mm)	Groundwater	1124.862	3375.138	2390.6420 ( <i>v</i> )
3	CN2.mgt	SCS-Curve Number value	Surface runoff	- 0.01945	0.00685	- 0.0104 ( <i>r</i> )
4	ALPHA_BNK.rte	Baseflow alpha factor for bank storage	Channel	0	0.304392	0.0662 ( <i>v</i> )
5	SOL_AWC.sol	Available water capacity of the soil layer	Soil–water	0.043715	0.681285	0.2748 ( <i>v</i> )
6	ESCO.hru	Soil evaporation compensation factors	Evapo-transpiration	- 0.13739	0.020885	- 0.0626 ( <i>r</i> )
7	ALPHA_BF.gw	Base flow alpha factor (day)	Groundwater	0	0.054575	0.0050 ( <i>v</i> )
8	GW_DELAY.gw	Groundwater delay (days)	Groundwater	20.88599	280.314	125.0463 ( <i>v</i> )
9	SURLAG.bsn	Surface runoff lag time (days)	Surface runoff	8.138288	24.31816	19.0678 ( <i>v</i> )
10	USLE_K().sol	USLE soil erodibility factor	Soil–water	- 0.65783	0.047428	- 0.5742 ( <i>r</i> )
11	GW_REVAP.gw	Groundwater revap coefficient	Groundwater	0.02	0.118601	0.0294 ( <i>v</i> )

*v* absolute value, *r* relative change

During streamflow calibration, the most sensitive parameters identified are baseflow factor (Alpha\_bf), bank storage factor (Alpha\_bnk), groundwater delay constant (gw\_delay), depth of shallow aquifer (Gwqmn), erodibility factor (USLE\_K), water consumption factor (wurch), groundwater revap coefficient (gw\_revap), soil evaporation compensation factor (ESCO), lag in surface runoff (surlag), and available water capacity of soil (Sol\_awc). The sensitivity range and rank of each parameter is mentioned in Table 4. Alpha\_bf is a direct measure of the reaction of groundwater flow to variations in recharge. Alpha\_bnk determines the bank storage within a sub-basin, which influences the river flow. Gwqmn controls the accessibility of groundwater and USLE\_K controls sedimentation process. The parameter wurch contributes to the water consumption in the sub-basin and gw\_revap regulates the transfer of water into unsaturated layers in response to evaporation water demand. Surlag manages the lag in surface runoff and ESCO contributes to the evaporation process. Sol\_awc changes with soil type, more in case of clay and loam, and has a significant effect on percolation, evaporation, and lateral flow (Neitsch et al. 2011).

The calibration results suggest that the model is well-calibrated and can be used to study the future hydrological responses of PRB. Although some assumptions were made to replicate the natural conditions of the basin (including reservoir and water flow restrictions), such calibration results can suggest the reliability of better results for the future.

## Impact of climate change and LULC change

### Scenario 1: Impact of LULC change only

As discussed in “[Scenarios and experiments](#)”, the simulated water balance components for each LULC is compared with baseline (LULC 1988) and results are plotted in Fig. 5A. Since the weather input data is same for all the cases, there is no change in  $P$ . However, other hydrological components, including  $Q$ , SW, Per,  $Q_b$ , and  $Q_1$  show significant change. These results suggest that changes in LULC affect these parameters and thus the hydrology of the region. Per shows reduction up to 12.89% with the changed LULC of 2100. Urbanization and deforestation are the primary reason for such change. Not much difference is observed in ET due to LULC change suggesting its major dependency on  $P$ .  $Q$  is showing an increasing trend with a nominal change of 1.94% till 2100. One major factor responsible for such change is increased urbanization. However, the maximum change in  $Q$  is + 2.12% observed with the LULC of 2030, suggesting that the effect of the combination of different LULC classes is dominant over an individual class. The change in other components, including  $Q_b$  and  $Q_1$ , varied from – 11.64% to + 5.15% and – 1.2% to + 2.18%, respectively.

Furthermore, to better understand the impact of LULC change throughout the basin, a spatial variation for change in  $Q$  is analyzed for PRB (Fig. 5B). An increasing trend is observed in  $Q$  due to LULC change. It increases by 0.18% from 1988 to 2002 and 1.73% from 2002 to 2016. For the future, it rises to 1.94% till 2100 compared to baseline. Furthermore, the seasonal and annual variation in  $Q$  is also analysed and included in the Supplementary File (Fig. S3.1 and S3.2). Comparing the monthly, seasonally, and annual change, it appears that there is an increasing trend in surface streamflow for all seasons except a little decrease in summer for all future landcover changes (Fig. S3.1). In particular,  $Q$  is predicted to increase significantly in monsoon months, such as July, August, September, and October for future LULC. The same increasing trend has been observed in annual change, indicating the monsoon season dominance over others.

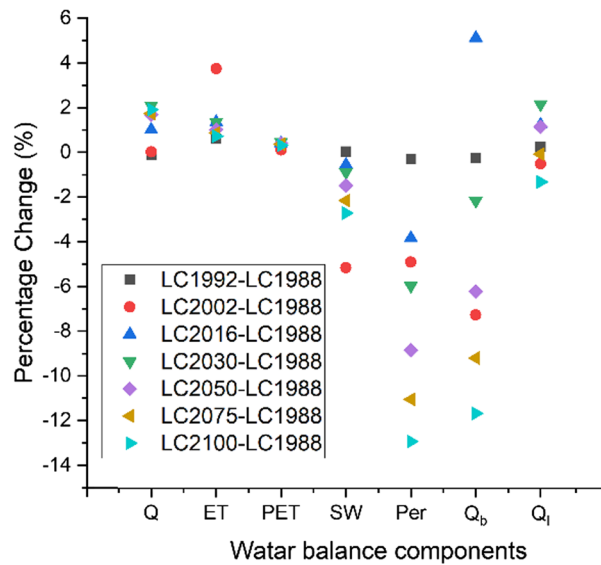
### Scenario 2: Impact of climate change only

As discussed in “[Scenarios and experiments](#)”, the impact of climate change on hydrological components is analyzed by considering meteorological data of five CMIP-5 GCMs, namely, BNU-ESM, Can-ESM, CNMR-CM5, MPI-ESM-LR, and MPI-ESM-MR for RCP 4.5, and RCP 8.5 scenarios of CMIP5 model (Fig. S4.1 in Supplementary Information). The ensemble average of simulated output for the future period under both scenarios (RCP 4.5 and 8.5) is compared to the base period (1981–2010), and the result is plotted in Fig. 6A. To show the uncertainty involved in the results, the output from each GCM is included in supplementary data (Fig. S4.1–S4.6). Similarly, the results of each sub-basin are also tabulated in supplementary data (Table ST1–ST2).

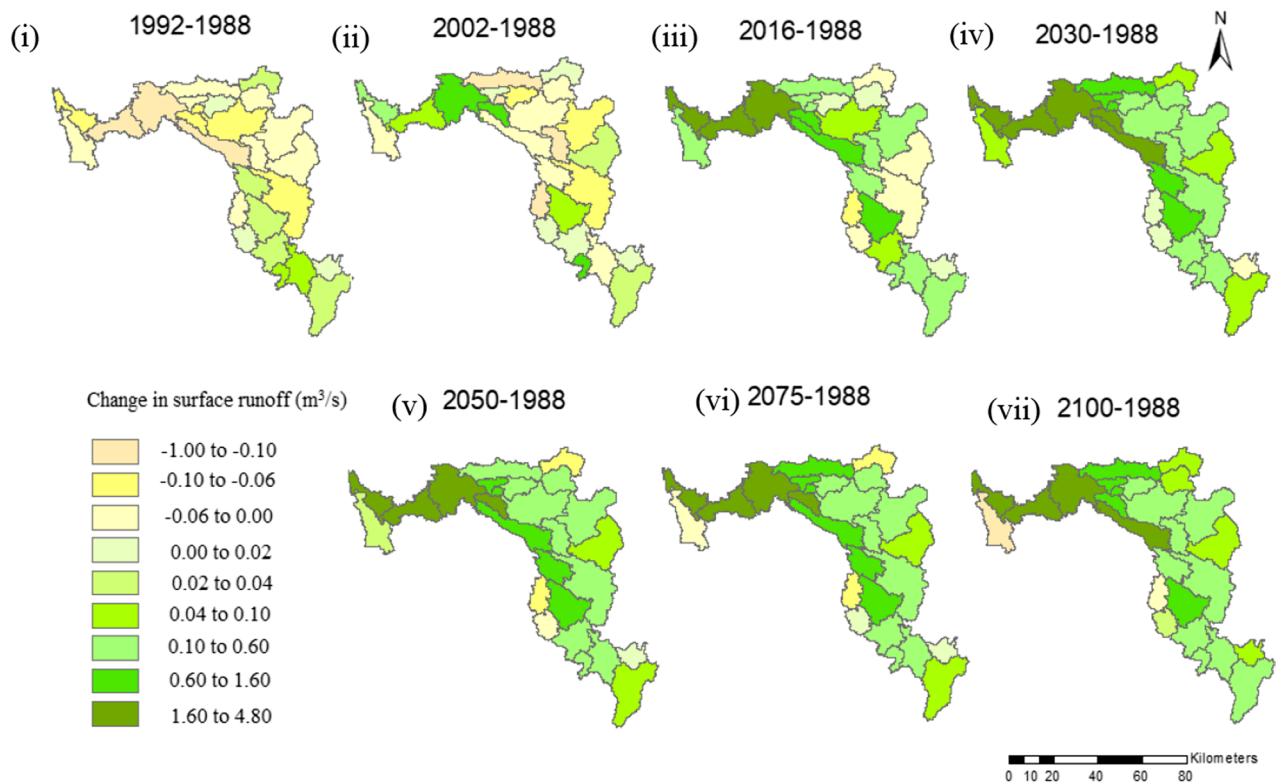
The results show that ET reduces in all three cases of near, mid, and far future by – 27.51%, – 26.55%, and – 25.5% in RCP 4.5 scenario, whereas by – 26.62%, – 25.3%, and – 21.82% in RCP 8.5 scenarios, respectively.  $Q$  showed similar results throughout the three-time segments under both the RCP scenarios. In the RCP 4.5 scenario,  $Q$  decreased by – 3.83%, – 4.53%, and – 4.83% for near, mid, and far future, respectively. For the RCP 8.5 scenario,  $Q$  decreased by – 3.67%, – 5.25%, and – 6.38% for near, mid, and far future, respectively. SW and Per showed an increase ranging between + 26.4% to + 27.22% and + 34.96% to + 40.93%, respectively, considering RCP4.5. In RCP 8.5 scenarios, the change varies between + 23.98% to +26.93% and 38.74% to + 54.35% for SW and Per, respectively, among the future time segments. Reduced ET losses can be a primary reason for this rise.

To analyse the impact of climate change across the watershed, the ensemble average of all five GCMs is plotted in Fig. 6B. The spatial variation of change in  $Q$  for each GCM is included in supplementary data (Fig. S4.2–S4.6).

A.



B.



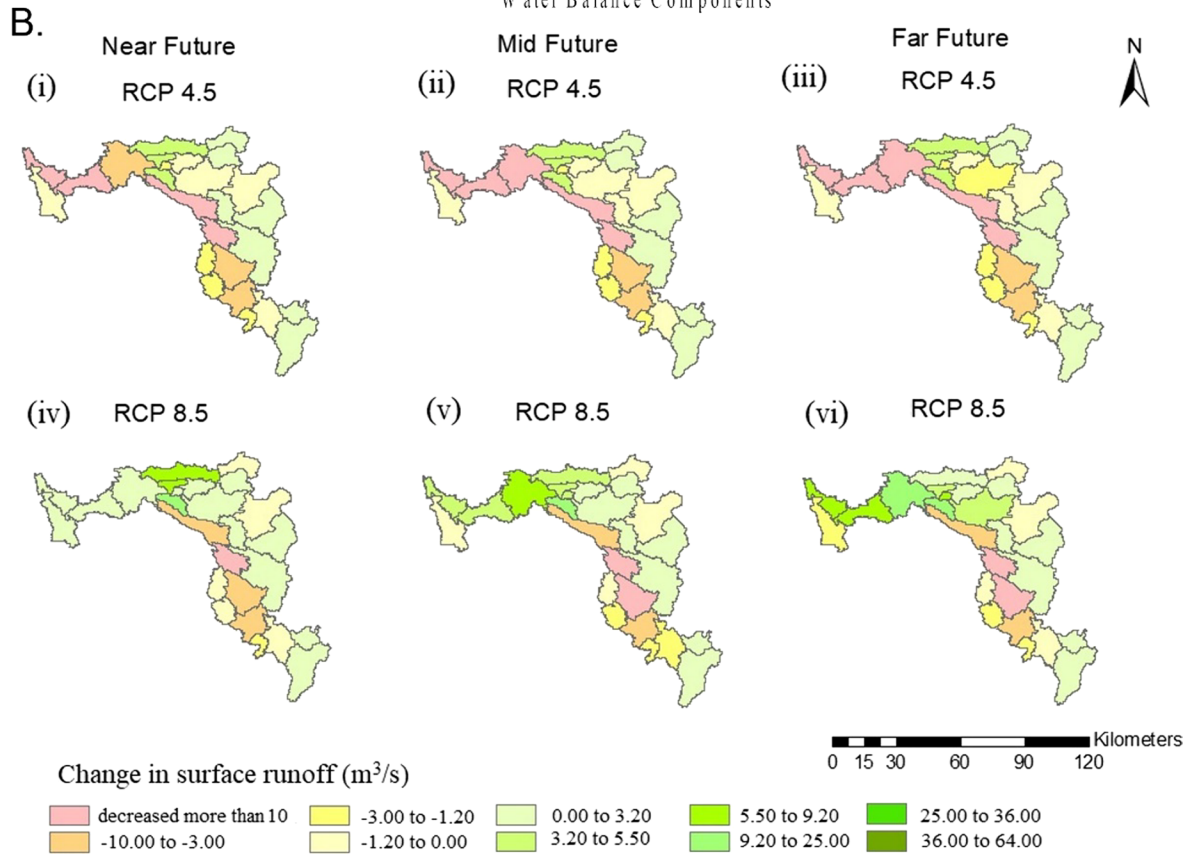
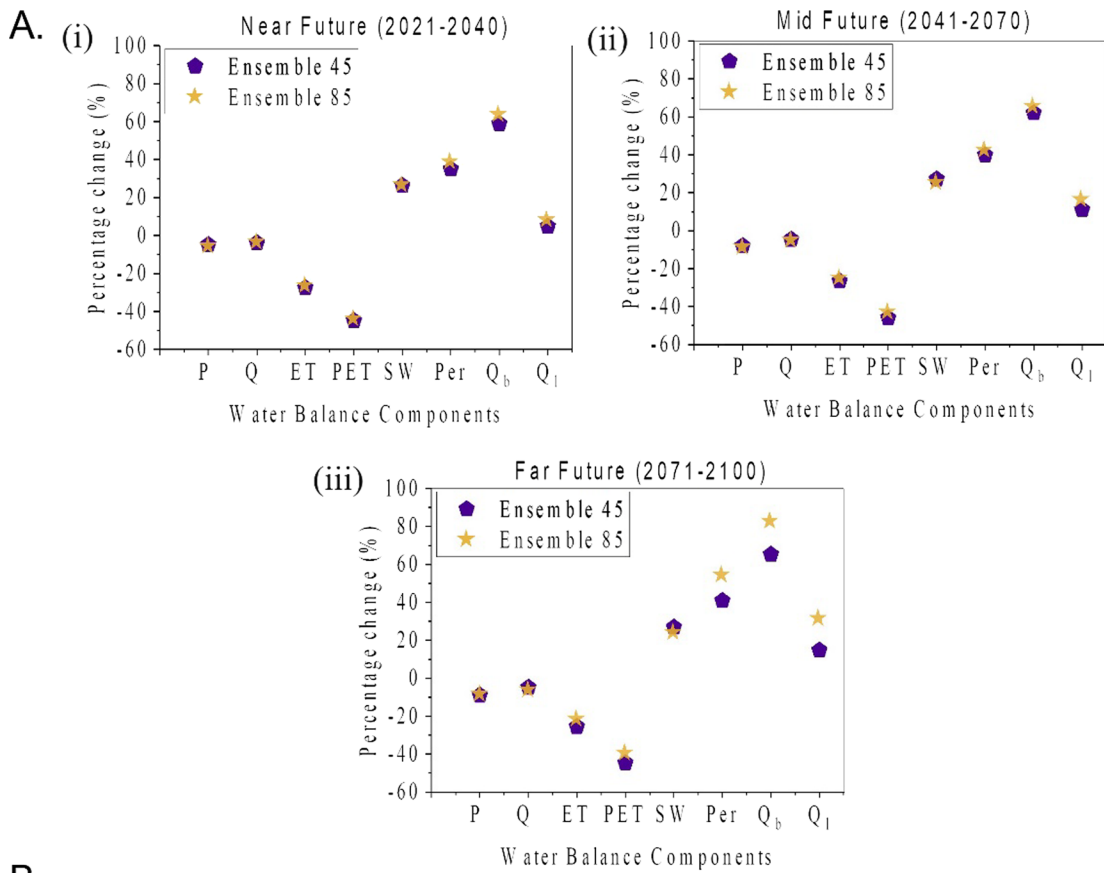
**Fig. 5** A Future changes in hydrological components including surface runoff ( $Q$ ), evapotranspiration (ET), soil water storage (SW), percolation (Per), base flow ( $Q_b$ ), and lateral flow ( $Q_l$ ) due to LULC change (w.r.t. base map 1988) in PRB; B spatial distribution of

change in surface runoff, (B-i) 1992–1988; (B-ii) 2002–1988; (B-iii) 2016–1988; (B-iv) 2030–1988; (B-v) 2050–1988; (B-vi) 2075–1988 and (B-vii) 2100–1988 due to change in LULC with respect to the LULC 1988 in PRB

The spatial distribution of change in  $Q$  shows that runoff increases throughout the basin in the RCP 8.5 scenario. In contrast, a decrease in sub-basins near the river channel is observed in the RCP 4.5 scenario (Fig. 6B). In the RCP 4.5 scenario, most of the sub-basins show negative change

or little positive change. Thus, results suggest that  $Q$  is expected to decrease in the future under both RCP 4.5 and RCP 8.5 scenarios.

Furthermore, the monthly, seasonal, and annual change in  $Q$  due to climate variations for the future period is presented



**Fig. 6** **A** (i) Near (2011–2040); (ii) mid (2041–2070); and (iii) far (2071–2100) future changes in hydrological components including precipitation ( $P$ ), surface runoff ( $Q$ ), evapotranspiration (ET), soil water storage (SW), percolation (Per), base flow ( $Q_b$ ), and lateral flow ( $Q_l$ ) due to climate change (w.r.t. base period 1981–2010, LULC 2002) in PRB; **B** spatial variation of surface runoff due to climate change w.r.t. baseperiod (1981–2010) for near (i and iv), mid (ii and v), and far (iii and vi) future under RCP 4.5 and 8.5 scenarios, respectively

in Fig. S3.2. There appeared to be an increase in the winter and summer seasons, whereas a decrease in monsoon in all scenarios. The decrease in monsoon season for near, mid and far future considering RCP 4.5 is  $-14.06\%$ ,  $-14.59\%$ , and  $-14.78\%$ , respectively, and  $-17.76\%$ ,  $-18.88\%$ , and  $-20.05\%$  while considering RCP 8.5 scenarios. The major reason for such a result is the reduction in annual average  $P$ . The other complementary factors are an increase in SW, Per,  $Q_b$ , and  $Q_l$ . Reduction in ET leads to excess infiltration is another reason for the increase in  $Q_b$  and  $Q_l$  (Price 2011).

### Scenario 3: Combined impact of LULC change and climate change

The combined effect of LULC and climate change gives a better idea about the actual possibilities in the future. As discussed in “[Scenarios and experiments](#)”, the analysis is done, and results for average ensemble are plotted in Fig. 7A. The output for each GCM and LULC combination is discussed in supplementary data (Section S4.2). The results show that ET reduces in all three cases of near, mid, and far future by  $-27.6\%$ ,  $-27.8\%$ , and  $-26.63\%$  in RCP 4.5 scenario, whereas by  $-26.93\%$ ,  $-26.34\%$ , and  $-23.35\%$  in RCP 8.5 scenarios, respectively. Reduced  $P$  could be the primary reason for this change.  $P$  decreases by  $-4.78\%$ ,  $-7.93\%$ , and  $-8.94\%$  in RCP 4.5 scenario, whereas by  $-5.82\%$ ,  $-8.92\%$ , and  $-8.62\%$  in RCP 8.5 scenarios for near, mid, and far future, respectively.  $Q$  showed a variation in results throughout the three time segments under both the RCP scenarios. In the RCP 4.5 scenario,  $Q$  decreased by  $-12.63\%$  and  $-6.54\%$  for the near and mid future, whereas it increased by  $+9.08\%$  for the far future. For the RCP 8.5 scenario,  $Q$  increased by  $+3.86\%$ ,  $+5.90\%$ , and  $+12.64\%$  for near, mid, and far future, respectively. The results show a significant impact of LULC and climate change on  $Q$ .

Likewise, other water balance components, including SW and Per, showed an increase ranging between  $+20.13\%$  to  $+29.84\%$  and  $+1.69\%$  to  $+40.51\%$ , respectively, for both RCP4.5 and 8.5 scenarios. This increase can be related to the amplification of cropland and plantation cover, which improves soil porosity and water holding capacity. The same resulted in an increase in  $Q_b$  and  $Q_l$  varying from  $+22.13$  to  $+79.35\%$  and  $-11.53$  to  $+13.74\%$ , respectively, considering all three segments of RCP 4.5. Whereas for the

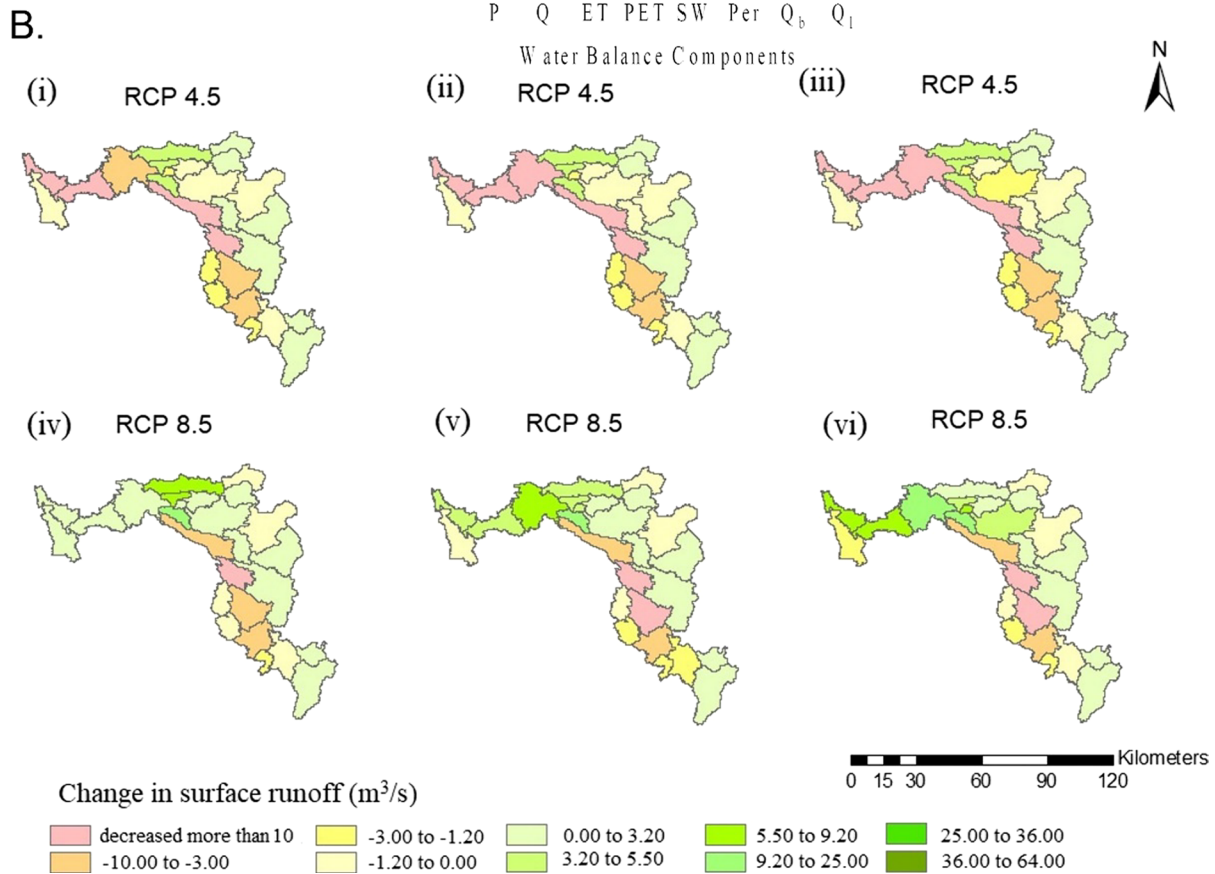
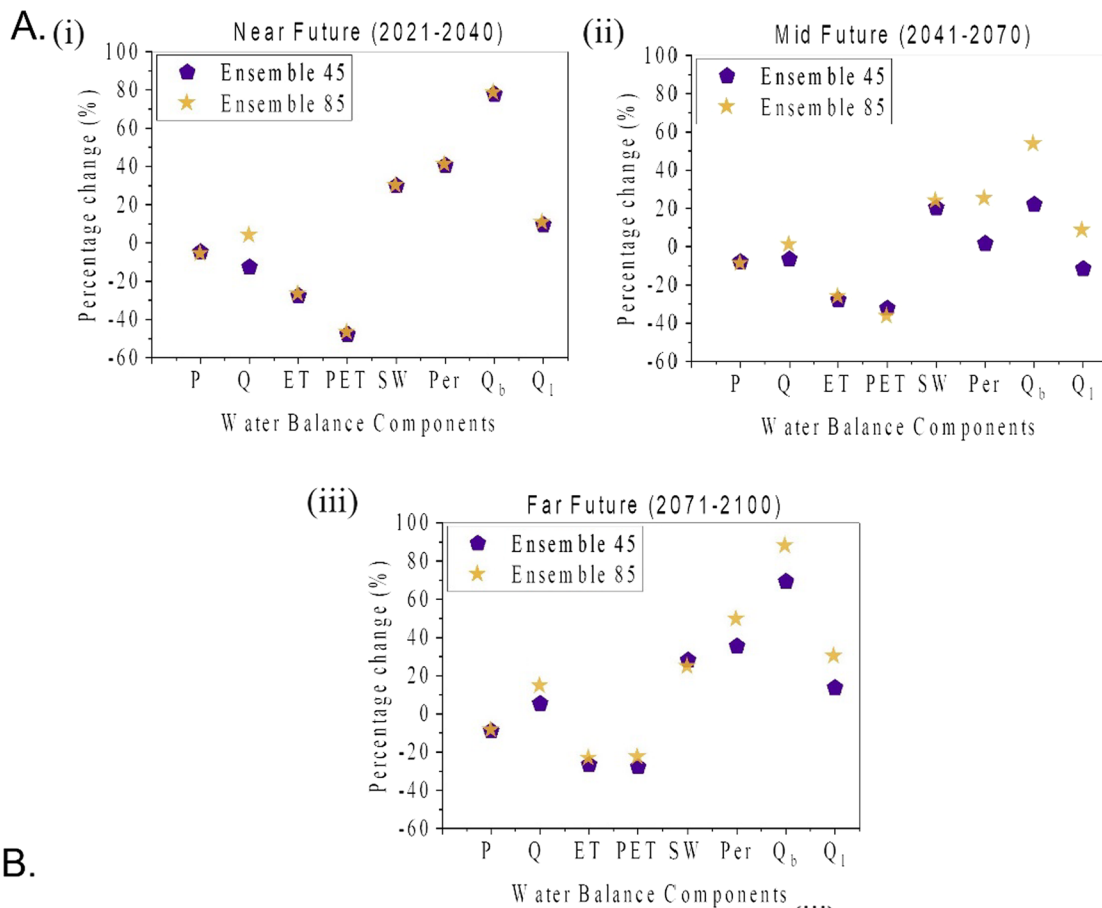
RCP 8.5 scenario, the range is between  $+53.6\%$  to  $+88.01\%$ , and  $+8.4\%$  to  $+30.11\%$  for  $Q_b$  and  $Q_l$ , respectively.

The spatial distributions of change in runoff from baseline condition to future, for RCP 4.5 and 8.5 at sub-basin scale are shown in Fig. 7B. There is a decrease observed in  $Q$  along most of the basin parts in the RCP 4.5 scenario. The average annual change in  $Q$  under RCP 4.5 scenario is  $-10.67\%$ ,  $-6.41\%$ , and  $-4.18\%$  for the near, mid, and far future, respectively, whereas for the RCP 8.5 scenario, it is  $+3.3\%$ ,  $5.77\%$ , and  $+2.99\%$ , respectively. Thus, results suggest that  $Q$  is expected to decrease in the future under RCP 4.5 and increase under RCP 8.5 scenarios. Furthermore, the monthly, seasonal, and annual change in  $Q$  due to varying climate for the future period is presented in Fig. S3.3. The results suggest that the monthly  $Q$  will decrease from June to October under RCP 4.5 and 8.5 scenarios except for August and November in RCP 8.5, scenario (Fig. S3.3) due to higher rainfall in these months. These results of seasonal and annual variation in  $Q$  give a better understanding related to the occurring of hydrological changes.

## Discussion

### Effect due to LULC change

The LULC impact study suggests that due to future LULC change, there will be a decrease in SW, Per, and  $Q_b$  but an increase in  $Q$  and  $Q_l$ , whereas no significant difference in ET as they are more dependent on precipitation which was the same in all scenarios. These all changes can also be related to increased urbanization and deforestation. Increased runoff leads to a reduction in percolation and baseflow which finally reduces the soil water content, which damages the soil properties and reduces its fertility. Thus, special consideration should be given to these factors while planning the development of an area. The major change was observed in streamflow throughout the watershed, with maximum changes along the river channel (Figs. 1b and 5B). Past studies in India have also shown a similar trend in their respective areas (Adhikari and Southworth 2012; Kim et al. 2013; Anand et al. 2018; Sinha and Eldho 2018; Chanapathi and Thatikonda 2020; Chen et al. 2020; Sinha et al. 2020), which is alarming as in the case of high precipitation that leads to flash floods. Thus, land use planning is necessary to control further possible damages. Planning shall include preventive measures from deforestation and planned expansion of settlements. Vegetative cover improves infiltration rate, which helps in groundwater recharge further, which improves vegetation growth. These methods can help maintain the green cover over the region and improve the soil moisture holding capacity. In addition, this helps to maintain



◀**Fig. 7** **A** (i) Near (2011–2040); (ii) mid (2041–2070); and (iii) far (2071–2100) future changes in hydrological components including precipitation ( $P$ ), surface runoff ( $Q$ ), evapotranspiration (ET), soil water storage (SW), percolation (Per), base flow ( $Q_b$ ), and lateral flow ( $Q_l$ ) due to climate and LULC change (w.r.t. base period 1981–2010, LULC 2002); **B** spatial variation of surface runoff due to climate and LULC change w.r.t. base period (1981–2010) for near (i and iv), mid (ii and v), and far (iii and vi) future under RCP 4.5 and 8.5 scenarios, respectively

water levels during dry seasons and can solve the problem of seasonal variation in water availability. Other than this, it is noticed that rapid urban expansion is possible in the future. PRB has a protected forest reserve (Fig. 1b), and the same constraint is considered during projections of future LULC. However, it is necessary to strictly follow the regulations, else the damages can be severe in the future. The same has been highlighted in similar studies (Aichele 2005; Anand et al. 2018).

### Effect due to climate change

Future climate projections suggest a reduction in precipitation in the future ( $\approx 10\%$ ) in the near, mid, and far future. This effect is clearly visible on other hydrological components, including ET, which decrease drastically low to 24%. However, this reduction in ET leads to fewer water losses, and thus an increase in baseflow is observed. This further leads to a rise in water percolation and soil water content. These changes will help to improve soil properties for a short period, but reduced precipitation and scarcity of water will be a major setback in the future.

The climate change impact on streamflow suggests that it is directly proportional to precipitation. Since temperature is increasing in the future for all GCMs, the role of precipitation in streamflow change is clear. Adhikari and Southworth (2012) and Sinha et al. (2020) have also reported that streamflow is generally more sensitive to precipitation and temperature changes. The results are in unison with their study. The results suggest that streamflow will decrease near the downstream end and in areas near the river channel. All other locations near the upstream side show very little change in streamflow in the RCP 4.5 scenario and an increase in the RCP 8.5 climate change scenario. Since the coastal side receives more rainfall than the upstream side of PRB, it is more prone to excess rain. However, results suggest that there is a decrement in the flow near the downstream end. Thus, it is important to note that precipitation is expected to reduce in the future, which can affect the seasonal water balance. Furthermore, the requirement for fresh water during the dry season may increase.

Seasonal change adds more information in understanding change in the streamflow. The results indicates an increasing trend in summer and winter, whereas a decreasing trend in

monsoon season in all the time slices for both RCP scenarios compared to the baseline period. The study area has a modified marine climate characteristic, and the southwest monsoon is declining (Krishnakumar et al. 2009); thus, it experiences a wet monsoon and a dry, warm summer. These changes were attributable to a decrease in both the summer monsoon circulation and water vapour. A significant decreasing trend over Kerala was reported by Soman et al. (1988). Thus,  $Q$  is expected to decrease in the future for both RCP 4.5 and 8.5 scenarios. However, some GCMs showed an increasing trend in the RCP 8.5 scenario, but again it is an extreme case scenario, and possibilities are less. The results from all three time slices will help to design better watershed management practices and incorporate future adaptation measures.

### Effect due to combined LULC and climate change

In this study, the combined effect of climate and LULC change in a humid tropical river basin is analysed. The Paris agreement (COP21) shared a vision, where importance to the Land use Land Use Change and Forestry (LULUCF) sector with changing climate was given that aimed at reducing carbon and greenhouse gas emissions (<https://forest.jrc.ec.europa.eu/en/activities/lulucf/>). The LULUCF is a subset of LULC management and mitigation plan that focuses specifically on the impact of land use, land-use change, and forestry activities on greenhouse gas emissions and carbon sequestration. Thus, considering the global interest, this study will contribute to better understand the role of climate and LULC change on the water balance components. The results from the combined analysis give insights into the behaviour of hydrological components in response to climate and LULC change. It is observed that climate change is dominant over LULC change as ET, SW, Per,  $Q_b$ , and  $Q_l$  follow the trend of climate change results (Fig. 7A). However, LULC shows some impact as there is a variation observed in the magnitude of the percentage change. However, the above case is not completely true in the case of  $Q$ . The analysis shows a decrease in  $Q$  for the near and mid future in RCP 4.5 scenarios. This result is the same as that of climate change. However, for the far future, there is an increase observed in  $Q$  for the RCP 4.5 scenario, contrary to the individual effect of climate change. Thus, it can be suggested that LULC will show its dominance in the far future for PRB. The increase in  $Q$  in the RCP 8.5 scenario is up to 25% which is significant as it may lead to a flooding situation in the region. The results suggest that proper landuse planning is necessary in such cases as they highly alter the natural balance of the water resource system. High urban growth is predicted in the late future, along with a reduction in plantation and forest cover (Table 3 and Fig. S1). These are the major reasons for such high change

in streamflow. The seasonal change assessment also adds insights to understand the trend of change in  $Q$ . The results suggest an increase in  $Q$  in the summer and winter seasons but a decrease in the monsoon season. But still, there is an increase observed in annual  $Q$  in the RCP 8.5 scenario. The availability of water in the dry season will provide some relief, but proper planning is needed to balance the water requirement in the monsoon season. In addition, despite less precipitation, an increase in  $Q$  may lead to flash floods and cause damage to property and livestock. The future regarding climate change is uncertain, but preparedness is what is required. Therefore, proper planning of land management practices and restrictions related to deforestation is the most suitable solution to future challenges.

The study of LULC and climate change impact assessment has increasingly become an important issue across the globe. The results of these studies contribute towards better planning in water resource management (Bouwer 2002; Janssen and Lennartz 2009; Garg and Dadhich 2014; Schmitter et al. 2015; Sreeja et al. 2015). Past studies have discussed about the necessity of detailed research in humid tropical regions (Wohl et al. 2012; Hamel et al. 2018). The present study contributes by adding the details of changes in hydrological components in a humid tropical region. It is recommended that the proposed methodology in the study can be adopted into similar complex impaired catchments across the globe. This may include the other river basins in Western Ghats; Bago RB, Myanmar (Shrestha and Htut 2016); Biliu RB China (Zhang et al. 2020); Nam Ngum RB, Laos (Yun et al. 2020); Nan RB, Thailand (Wannasin et al. 2021); Huong RB, Vietnam (Dau et al. 2021); Muda RB, Malaysia (Tan et al. 2019); and Paraibuna RB, Brazil (Lucas-Borja et al. 2020).

## Conclusions

Water resources management in the humid tropics are on the cusp of rapid change. The humid tropical regions are susceptible to population and natural resource vulnerabilities. Thus, it will be seriously influenced by the future climate and LULC changes. Changes in climatic and land management activities are expected to accelerate in future. Therefore, it is essential to have a prior knowledge regarding the response of hydrologic components to these changes.

In this study, the impact of future LULC and climate change on hydrological components of a humid tropical river basin of PRB is investigated. The SWAT model is used to simulate future hydrological components in this complex impaired catchment and LCM is used to project future LULC maps for 2030, 2050, 2075, and 2100. Sankey diagram is used to understand the transition among

different landcover classes. The results suggest increased urbanization and decreased forest cover in the future. LULC change shows a significant effect on the overall change in the hydrological characteristics in humid tropical regions. Dominance of climate change impact over LULC change in the near and mid future is observed. However, interestingly, it was the opposite in the far future. The climatic projections suggest a reduction in average annual precipitation leading to more possibilities of a decrease in streamflow. The spatial analysis adds insights about the variation in hydrology across the river basin. It is helpful in identifying the hotspots sensitive to floods and droughts. The seasonal and annual variation of streamflow results gives a better idea of the river basin changes. In PRB, it indicated that streamflow increased in winter and summer, whereas decreased during the monsoon season for all the future periods under RCP 4.5 and 8.5 scenarios. The results to variation in hydrological components due to climate and LULC change can provide insights in studies related to irrigation purposes, groundwater recharge, crop water demand, soil permeability and integrated water resource management.

The results can be further used as an input to improve understanding of the complex ways in which human landscape alterations (for example, deforestation and land management) affect evapotranspiration and the subsequent runoff ratio. In addition, how the response differs as a function of environment (for example, soil type, climate, topography or land cover) can be explored. Furthermore, the methodological framework can be adopted in other humid tropical watersheds to understand the hydrological impacts of LULC and climate change.

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**Author contributions** All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by KS, TIE, and SK. The first draft of the manuscript was written by KS. TIE and SK commented on previous versions of the manuscript and edited. All authors read and approved the final manuscript.

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**Data availability** The datasets analyzed in the study are available from the corresponding author on request.



## Declarations

**Conflict of interest** The authors have no relevant financial or non-financial interests to disclose.

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