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# A conceptual framework to disentangle land use and climate change impacts on water balance components and sediment yield

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## Abstract

Individual and combined impacts of land use and climate change on water resources in a river basin cannot be easily categorized due to feedback effects. These impacts should be assessed separately to determine the dominant role of land use and/or climate change affecting planning and management of natural resources. In this study, a conceptual framework is proposed to disentangle individual as well as combined impacts of land use and climate changes on hydrology of the Betwa River basin in central India. Land use maps of the years 2013 (classified) and 2040 (simulated) were used as inputs in the Soil and Water Assessment Tool (SWAT) model for the land use change impact study. Downscaled and bias-corrected CMIP5 GCM data was firstly evaluated using observed station data, and then used in the SWAT model for simulation of basin hydrology over five periods of time, i.e., baseline (1986–2005), horizon 2039 (2020–2039), horizon 2059 (2040–2059), horizon 2079 (2060–2079), and horizon 2099 (2080–2099). The study reveals that the impact of climate change dominates effects on water resources in the future, especially due to increased precipitation. Changes in dense forest, agriculture and waterbody induce positive responses; nevertheless, changes in degraded forest and barren land induce negative responses to the changes in hydrology of the Betwa basin. The proposed conceptual framework can disentangle individual and combined impacts of land use change and climate change on basin hydrology. Thus, it can be utilized as an important tool for sustainable river basin management.

**Keywords** Land use change · Climate change · SWAT model · Conceptual framework · River basin hydrology

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## 1 Introduction

Land use and climate are the intrinsic drivers of hydrological processes (Blöschl et al., 2007; Juckem et al., 2008; Li et al., 2009). Human activities (such as reservoir construction, urbanization, and industrialization), population growth (resulting in increased water demand), and climate change (mainly changes in temperature and precipitation variables) are widely acknowledged to be the primary catalysts for changes in hydrological response of a river basin (Gao et al., 2010; Grum et al., 2017; Hovenga et al., 2016; Mahmoodi et al., 2021a). Recent studies have demonstrated that land use and climate change have significant impacts on water balance (Cornelissen et al., 2013; Mango et al., 2011; Morán-Tejeda et al., 2010; Tigabu et al., 2019; Wagner et al., 2016) and sediment (Gebremicael et al., 2013; Julian & Ward, 2014; Khoi & Suetsugi, 2014). These studies demonstrate that both surface water and sediment loads have been significantly affected by rapid land use and climate changes in recent decades (Gao et al., 2010; Miao et al., 2010; Pandey & Palmate, 2018; Zhao et al., 2014).

Land use change is induced progressively and abruptly by human–environment interaction and the result of socio-economic and biophysical drivers (Lambin et al., 2001). Changes in agriculture, deforestation, and urbanization have pronounced impacts on soil erosion, flooding, drought, and agricultural productivity, which may also cause land degradation (Lørup et al., 1998; Palmate et al., 2022). In addition to land use change, climate change affects the hydrologic cycle (Mahmoodi et al., 2021b; Tigabu et al., 2021). Temperature change affects evapotranspiration losses and may alter regional weather circulation patterns. This can lead to changes in the frequency and intensity of precipitation, which in turn can increase flash flooding and droughts. Soil erosion, a process of detachment, transportation, and deposition of soil particles, is primarily caused by extreme precipitation events (Burt et al., 2016; Feng et al., 2015; Nearing et al., 2005; Palmate & Pandey, 2021). Climate change has an influence on soil erosion processes in terms of the amount, concentration, and distribution of fluvial sediments in a river basin (Lal & Pimentel, 2008; Routschek et al., 2014; Zuo et al., 2016). Thus, it is important to investigate the extent of climate change impact that would impair current conditions and future management of water resources. Previous studies have analyzed the individual impact of land use change (Bieger et al., 2015; Huang et al., 2009; McGinn et al., 2021; Niehoff et al., 2002; Wagner et al., 2013) and climate change (Li et al., 2011; Setegn et al., 2011; Wagner et al., 2015) on water balance components, sediment or nutrients loads in various river basins under considerably different conditions. Combined land use and climate change impact has also been investigated (Juckem et al., 2008; Li et al., 2009; Santos et al., 2014; Tu, 2009; Wagner et al., 2016). Simple statistical methods or process-based models have been used to study changes in runoff and sediment fluxes (including soil erosion and sediment transport). Process-based models are reliable for simulations under changing land use/climate conditions. Statistical methods lack a physical mechanism, so process-based models are preferred. Among presently available hydrologic models, the Soil and Water Assessment Tool (SWAT; Arnold et al. 1998, 2012) has been widely used to assess land use and climate change impact on water resources (Benaman et al., 2005; Conradt et al., 2012; Hyandye et al., 2018; Khoi & Suetsugi, 2014; Kim et al., 2013; Pandey et al., 2016). The SWAT model can incorporate climate projections from downscaled global climate models (GCMs) and regional climate models (RCMs) (Jha & Gassman, 2014; Nar-simlu et al., 2013; Phan et al., 2011; Shrestha et al., 2013; Wagner et al., 2015). Some hydrological modeling studies have investigated both land use and climate change using

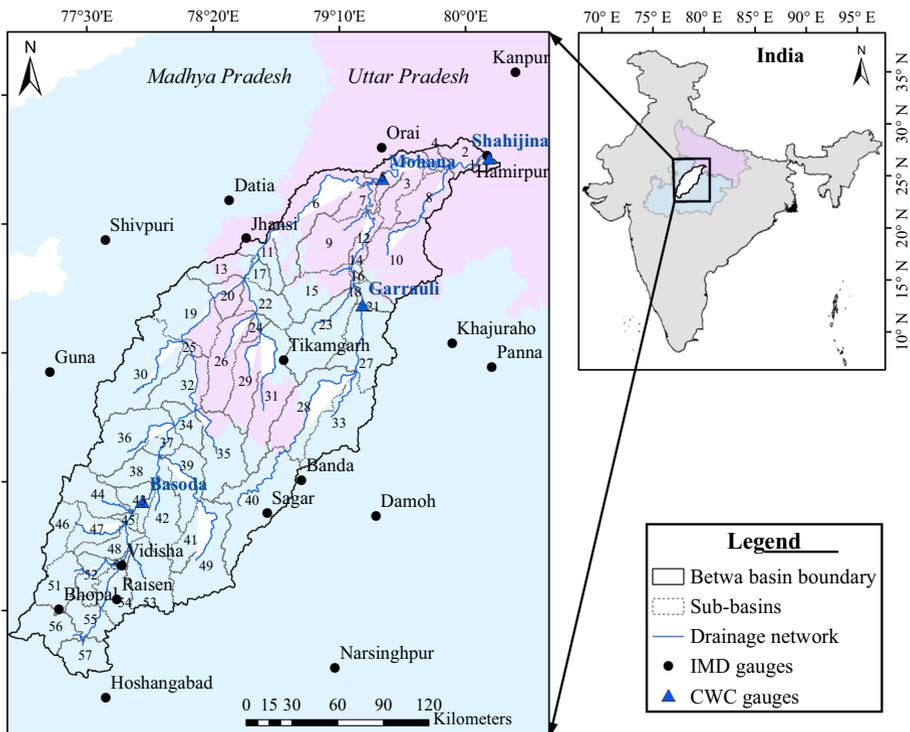
SWAT (Bronstert et al., 2002; Chen et al., 2005; Feng et al., 2016; Park et al., 2011; Pervez & Henebry, 2015; Schilling et al., 2008; Semadeni-Davies et al., 2008; Wagner et al., 2016; Yan et al., 2013). Effects of land use and climate change are complex, but they can be disentangled using modeling framework. Scenario-based simulations can demonstrate the potential effects of future changes, which can then be used as a basis for sustainable management practices of natural water resources. Climate change information can be used to mitigate and adapt future management strategies based on the hydrological response of a river basin. Therefore, the assessment of land use and climate change impacts on hydrological processes and sediment loads is imperative for water resource and land use planning.

Consequently, this study aims to investigate isolated and combined land use and climate change impacts on water balance and associated sediment loads using a modeling framework for the Betwa River basin, located in central India.

## 2 Materials and methods

### 2.1 Study area

The Betwa River basin covers approximately 43,937 km<sup>2</sup> between 77° 05' 38" E and 80° 13' 48" E longitude and between 22° 51' 51" N and 26° 3' 5" N latitude. It is an interstate river basin in the States of Madhya Pradesh and Uttar Pradesh (Fig. 1). Elevation of the



**Fig. 1** The Betwa River basin study area

Betwa river basin varies from 76 to 715 m above mean sea level. The climate of the basin is humid-subtropical. The study area receives a mean annual rainfall ranging from 700 to 1200 mm and more than 80% of that rain occurs during monsoon season, from June to September. The average minimum and maximum temperature varies from 6.7 to 44.2 °C. Hence, the study basin experiences a mild winter (October to February) and a hot summer (March to May). The land use of the catchment is dominated by agriculture (about 68%), with wheat, millet and gram as the main crops. Forest area has the second largest percentage (about 26%), out of which dense forest (about 14%) is in the South-East, while degraded forest (about 12%) is in the Northern part of the basin. The settlement area only accounts for about 0.3%, even though Bhopal city, which is located in the upstream basin, has been rapidly growing due to industrialization and urbanization (around 1.8 Million inhabitants; Chandramouli & Sinha, 2014). Barren land (about 3.7%) and water bodies (about 2%) cover smaller percentages of the Betwa basin. Changes in the water body area mainly depend on the variation of monsoonal rainfall.

## 2.2 Model input data

In this study, daily observed rainfall data and minimum and maximum temperature data for the years 2001–2013 were obtained from the India Meteorological Department (IMD) Pune. For the same years, discharge and sediment data of the gauging sites Basoda (HO 676), Garrauli (HO 693), Mohana (HO 714), and Shahijina (HO 737) (CWC and NRSC, ) were procured from the Yamuna Basin Organization (YBO), Central Water Commission (CWC), New Delhi. A digital elevation model (DEM) based on the Shuttle Radar Topography Mission (SRTM) data of 30 m spatial resolution was used (Farr et al., 2007; Jarvis et al., 2008). This DEM data informed the extraction of elevation and slope information, as well as river basin delineation of the study area. Soil data was obtained from the National Bureau of Soil Survey & Land Use Planning (NBSS&LUP), Nagpur.

Land use data for 2013 and 2040 years was used in the study for land use change impact assessment. Data from 2013 has an overall classification accuracy of 82% and a Kappa coefficient of 0.775 (Palmate et al., 2017). An integrated Cellular Automata–Markov Chain (CA-MC) model was used to simulate a future land use map for the year 2040 (Palmate et al., 2017). Land use data was classified into six major classes, i.e., dense forest, degraded forest, agriculture area, barren land, waterbody and settlement.

Downscaled and bias-corrected Coupled Model Inter-comparison Project Phase 5 (CMIP5) data of the Max-Planck-Institute-Earth System Model-Medium Resolution (MPI-ESM-MR) model datasets were used to study the climate change impact on the river basin hydrology. MPI-ESM-MR model data at  $0.25^{\circ} \times 0.25^{\circ}$  spatial resolution was obtained from the Centre for Climate Change Research, Indian Institute of Tropical Meteorology, Pune. We used the climate data for the RCP 8.5 scenario, as it represents severe conditions and could be considered a worst-case scenario. This scenario would be the upper limit for potential climate change impact analysis. The MPI-ESM-MR model was selected based on the model performance evaluation and climate change impact studies conducted in other Indian regions (Das et al., 2018; Guo et al., 2016; Roxy et al., 2016; Sharmila et al., 2015). Station-wise future climate variables were initially extracted and then bias-corrected using the quantile mapping method (Thrasher et al., 2012). Quantile mapping bias correction algorithms are commonly used to correct systematic distributional biases in climate model outputs (Cannon et al., 2015, Cannon 2018). They adjust the distribution of variables originating from climate model outputs, so that they are able to preserve changes

in quantiles and extremes of GCM variables (Cannon et al., 2015). In this study, the SWAT model was calibrated and validated using observed climate data. The selected GCM model includes climate data for both baseline and future periods. Therefore, we have validated the bias-corrected GCM data by statistical comparison with the observed climate data and then utilized it as input to the calibrated and validated SWAT model for simulating water balance components and sediment yields.

## 2.3 Hydrological modeling using SWAT

The Soil and Water Assessment Tool (SWAT) is a semi-distributed hydrologic model developed by USDA's Agricultural Research Service (ARS) that operates at daily or sub-daily time-steps (Arnold & Fohrer, 2005; Arnold et al., 1998, 2012). The SWAT model is a useful tool for modeling hydrologic processes in a river basin, it uses water balance as the basis of river basin simulation (Neitsch et al., 2005, 2011). In this study, ArcSWAT, an extension and interface for SWAT in ArcGIS, has been employed for setting up the SWAT model, i.e., to derive model parameters from the input data. The model itself is run outside of ArcGIS and ArcSWAT.

### 2.3.1 SWAT model set-up and run

ArcSWAT interface has been used to set-up and run the model for the period 2001–2013. Given that we were focusing on long-term changes in water balance components and sediment yields, only monthly model outputs were used in this study. The Betwa basin was divided into 57 sub-basins (SB) based on a critical source area of 50,000 ha. The threshold value was selected based on desired stream network density, and the connectivity of drainage networks to reservoirs and weirs that mainly affect river channel flow and outflow at CWC gauging sites. Gauging sites and outlet points provided for nine reservoirs and weirs were implemented. Further, the study area was divided into 3,874 Hydrological Response Units (HRUs) representing homogenous areas with unique land use (threshold value=0%), soil type (threshold value=1%) and slope (threshold value=0%). With this set-up, the SWAT model was run using the curve number approach and the MUSLE (Modified Universal Soil Loss Equation) method for runoff and erosion processes.

### 2.3.2 Reservoir management in SWAT model

The reservoir module of ArcSWAT was used to implement, manage, and simulate different reservoirs and weirs of the Betwa basin. Limited information for 7 reservoirs and 2 weirs was obtained from India-WRIS (Water Resources Information System) and WRIS publications (CWC and NRSC, 2012, 2014). Available information on reservoirs and weirs is limited to the year of completion, maximum target storage, and storage volume. Nevertheless, remotely sensed surface area and outflow regulations were obtained for successful reservoir management in the SWAT model (McFeeters, 1996). Wagner et al. (2011) derived parameters for six reservoirs located in the Western Ghats of India. Also, Zhang et al. (2012) estimated parameters for small to large reservoirs in China. The same methodology has been adopted in this study for the estimation of surface area and outflow regulations. In addition, the average daily principle spillway release rate (RES\_RR) for all the reservoirs and weirs has been incorporated, as shown in Table 1.

**Table 1** Characteristics of reservoirs estimated by general management rules using measured river discharge at the downstream gauges

Reservoir name	Surface area (ha)	Maximum target storage (MCM)	Number of days to reach target storage	Average daily principle spill-way outflow ( $\text{m}^3 \text{s}^{-1}$ )	Monsoon minimum outflow ( $\text{m}^3 \text{s}^{-1}$ )	Non-monsoon maximum outflow ( $\text{m}^3 \text{s}^{-1}$ )
Bah Dam	195.6	76.5	2	41	12.2	24.3
Devri Dam	266.7	21.0	3	40	4.6	26.6
Dhukwan Weir	1396.9	95.0	1	118	30.8	118.4
Halali Dam	6240.0	226.1	3	41	12.2	24.3
Lachura Dam	116.0	20.6	2	40	4.6	26.6
Matatila Dam	13,885.0	1019.4	2	118	30.8	118.4
Maudaha Dam	5939.0	179.0	3	75	48.6	220.0
Pariccha Weir	802.0	77.2	2	118	30.8	118.4
Rajghat Dam	24,210.0	1975.0	3	118	30.8	118.4

### 2.3.3 Model calibration and validation

The SWAT-Calibration and Uncertainty Programs (CUP) Sequential Uncertainty Fitting version 2 (SUFI-2) algorithm (Abbaspour et al., 2007, 2015) has been used for calibration and validation of the model on a monthly time-scale using data from 2001 to 2013. The first 2 years (2001 and 2002) of the simulation period were reserved as 'warm-up period' to realistically set up internal hydrological components, e.g., groundwater storage and soil moisture content. Measured hydrologic data of the initial seven years (2003–2009) and the last 4 years (2010–2013) were used for calibration and validation, respectively.

For calibration, parameters and their value range were considered based on the available literature and previous studies carried out for the Betwa river basin, the regions located near the study area, as well as in India (Anand et al., 2018; Kumar et al., 2017; Murty et al., 2014; Narsimlu et al., 2013; Suryavanshi et al., 2017). Identified parameters were initially tested for sensitivity and uncertainty analysis using the SUFI-2 algorithm in SWAT-CUP. After a One-At-a-Time (OAT) sensitivity analysis, the selected parameters were used for calibration and validation of the SWAT model on a monthly time-scale. A total of 23 sensitive parameters were considered for streamflow (9 parameters) and sediment (14 parameters) based on the sensitivity order obtained in SWAT-CUP (Table 2). Model performance criteria suggested by Moriasi et al. (2007) was used to evaluate monthly hydrologic simulation of the SWAT model by statistical measures of Nash–Sutcliffe efficiency (NSE), percent bias (PBIAS), and ratio of the root mean square error to the standard deviation of measured data (RSR), as well as the coefficient of determination ( $R^2$ ).

### 2.3.4 Land use and climate change impact assessment

After calibration and validation of the SWAT model, classified and simulated land use data of the years 2013 and 2040 was used to study land use change impacts, and the downscaled and bias-corrected CMIP5 GCM climate data of MPI-ESM-MR model was used for climate change impact study. Station-wise GCM-derived climate data was initially compared with the observed climate data, and evaluated using statistical measures (maximum, minimum, average, standard deviation, and root-mean-square error values). A detailed flow-chart depicting the methodology used in this study is provided in Fig. 2.

We considered four scenarios based on the input(s) used for model simulation (S1–S4, Table 3). S1 is the baseline simulation in which the land use map of the year 2013 and climate data of the historical years 1986–2005 were used as inputs to the SWAT model. S2 was used to study individual land use change impact based on the 2040 predicted future land use map and climate data of the baseline period (1986–2005). S3 shows individual climate change impact by using climate change input data from 2020 to 2099 and the land use map of the baseline period (2013). In the combined impact assessment study (S4), the 2040 land use map and climate change data from 2020 to 2099 were employed. The analysis of S2 vs. S1 represents individual land use change impacts, and the analysis of S3 vs. S1 represents individual climate change impacts. Combined land use and climate change impact were assessed by comparing S4–S1.

SWAT model outputs from 2020 to 2099 were grouped into four future climate horizons, i.e., horizons 2039 (2020–2039), 2059 (2040–2059), 2079 (2060–2079) and 2099 (2080–2099) for climate change analysis. We used 20 years for analysis, as the historical

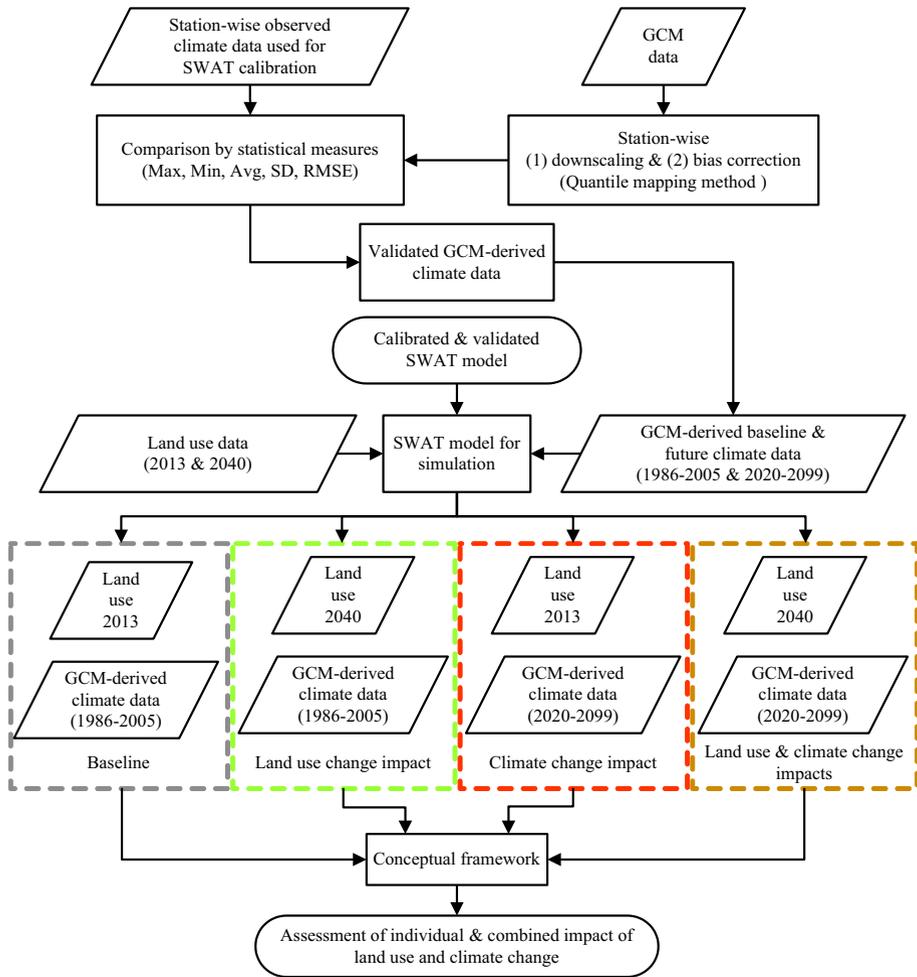
**Table 2** Calibrated parameters with their fitted values and sensitivity order for streamflow and sediment

Sensitivity order	Parameters	Calibration range	Fitted value
<i>Streamflow</i>			
1	CN2.mgt	-0.2 to 0.2	-0.17
2	SURLAG.bsn	0.05 to 10	1.64
3	ALPHA_BF.gw	0.3 to 0.9	0.41
4	GDRAIN.mgt	0 to 1	0.63
5	RCHRG_DP.gw	0 to 0.8	0.36
6	ESCO.hru	0.01 to 1	0.58
7	GWQMN.gw	0 to 30	0.07
8	GW_DELAY.gw	0 to 150	31.70
9	SOL_AWC().sol	0 to 0.5	0.08
<i>Sediment load</i>			
1	CH_ERODMO().rte	0 to 0.5	0.03
2	USLE_K().sol	0 to 0.5	0.13
3	RES_STLR_CO.bsn	0.2 to 0.9	0.76
4	PRF.bsn	0.5 to 2	1.90
5	CH_COV1.rte	0.01 to 0.3	0.08
6	ADJ_PKR.bsn	0.8 to 1.5	0.85
7	RES_SED.res	400 to 1600	1133.79
8	CH_COV2.rte	0.1 to 0.8	0.50
9	USLE_P.mgt	0.3 to 0.8	0.65
10	LAT_SED.hru	0 to 100	7.54
11	USLE_C{1}.plant.dat_____AGRL	0.05 to 0.2	0.15
12	RES_NSED.res	10 to 200	19.48
13	SPEXP.bsn	0.5 to 1.5	0.76
14	USLE_C{7,8}.plant.dat_____FRSD,FRSE	0.1 to 0.4	0.23

Streamflow parameter description: CN2.mgt=Initial SCS runoff curve number for moisture condition II; GDRAIN.mgt=Drain tile lag time (hr); ALPHA\_BF.gw=Baseflow alpha factor (1/days); GW\_DELAY.gw=Groundwater delay time (days); GWQMN.gw=Threshold depth of water in the shallow aquifer required for return flow to occur (mm H<sub>2</sub>O); RCHRG\_DP.gw=Deep aquifer percolation fraction; SOL\_AWC().sol=Available water capacity of the soil layer (mm H<sub>2</sub>O/mm soil); SURLAG.bsn=Surface runoff lag coefficient; ESCO.hru=Soil evaporation compensation factor

Sediment parameter description: USLE\_P.mgt=USLE equation support practice factor; USLE\_K().sol=USLE equation soil erodibility (K) factor; USLE\_C{1}.plant.dat\_\_\_\_\_AGRL=Minimum value of USLE C factor applicable to the agriculture land; USLE\_C{7,8}.plant.dat\_\_\_\_\_FRSD,FRSE=Minimum value of USLE C factor applicable to the forest area; PRF.bsn=Peak rate adjustment factor for sediment routing in the main channel; SPEXP.bsn=Exponent parameter for calculating sediment re-entrained in channel sediment routing; ADJ\_PKR.bsn=Peak rate adjustment factor for sediment routing in the sub-basin (tributary channels); RES\_STLR\_CO.bsn=Reservoir sediment settling coefficient; CH\_ERODMO().rte=Jan. channel erodability factor; CH\_COV1.rte=Channel erodibility factor; CH\_COV2.rte=Channel cover factor; LAT\_SED.hru=Sediment concentration in lateral flow and groundwater flow (mg l<sup>-1</sup>); RES\_SED.res=Initial sediment concentration in the reservoir (mg l<sup>-1</sup>); RES\_NSED.res=Equilibrium sediment concentration in the reservoir (mg l<sup>-1</sup>)

climate data was also available for 20 years (1986–2005). However, only horizon 2039 climate data was analyzed for climate change and land use change impact assessment using the corresponding 2040 future land use map.



**Fig. 2** Methodology flowchart used for assessment of individual and combined impacts of land use and climate change on river basin hydrology

**Table 3** Model simulation scenarios considered in the present study

Scenario	Land use data year	Climate data period	Remark
Scenario-1 (S1)	2013	1986–2005	Baseline
Scenario-2 (S2)	2040	1986–2005	Change in land use data
Scenario-3 (S3)	2013	2020–2099	Change in climate data
Scenario-4 (S4)	2040	2020–2099	Change in both land use and climate data

The conceptual framework of this study disentangles individual and combined impacts of climate and land use change on water balance components and sediment yield. It is structured into four quadrants showing all combinations of constant and changed land

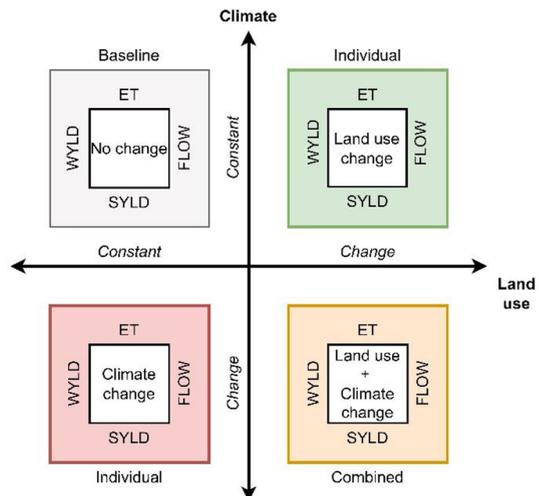
use and climate impacts based on the SWAT model outputs obtained from scenarios S1, S2–S1, S3–S1 and S4–S1 (Fig. 3). The first quadrant consists of constant land use and climate, i.e., no change, and hence represents the baseline. The second quadrant shows results for constant climate and changed land use, representing individual land use change impact. The third quadrant depicts constant land use and changed climate, representing individual climate change impacts. And the fourth quadrant represents changes in both, land use and climate, hence showing their combined impacts. This framework is limited to using one set of climate change and land use data for the same future period, which in our case is the horizon 2039 climate data and the 2040 land use map.

### 3 Results and discussion

#### 3.1 Performance evaluation of the SWAT model

Performance of the SWAT model was evaluated with monthly streamflow and sediment yield. Results show satisfactory performance during calibration and validation on monthly time-scale at all gauging sites (Table 4). High values of  $R^2$  (0.88–0.94), NSE (0.84–0.92), and low values of PBIAS (–4 to –17) and RSR (0.29–0.41) indicate good model performance at Basoda and Garrauli, very good model performance at Mohana, and satisfactory model performance at Shahijina gauges for streamflow simulation (Table 4; Moriasi et al., 2007). Flow duration curves of simulated streamflow also show good agreement with observed streamflow data at different flow segments, providing additional confidence in the model representation (Fig. 5). Monthly streamflow dynamics are well represented by the SWAT model (Fig. 4a). However, peak values are sometimes underestimated during the monsoon season, e.g., in 2013 at the upstream gauge Basoda (Fig. 4a). Also, the flow duration curve indicates an underestimation of high flows at the Basoda gauge. This may be attributed to the fact that these strong peak flows were not present in the calibration period. Nevertheless, a better representation of the peak flows in 2013 was achieved at the outlet Shahijina. In addition, low

**Fig. 3** A conceptual framework to compare individual as well as combined impacts of land use and climate changes on river basin hydrology, i.e., streamflow (FLOW), sediment yield (SYLD), evapotranspiration (ET) and water yield (WYLD)



**Table 4** Performance evaluation of the SWAT model on monthly time-scale

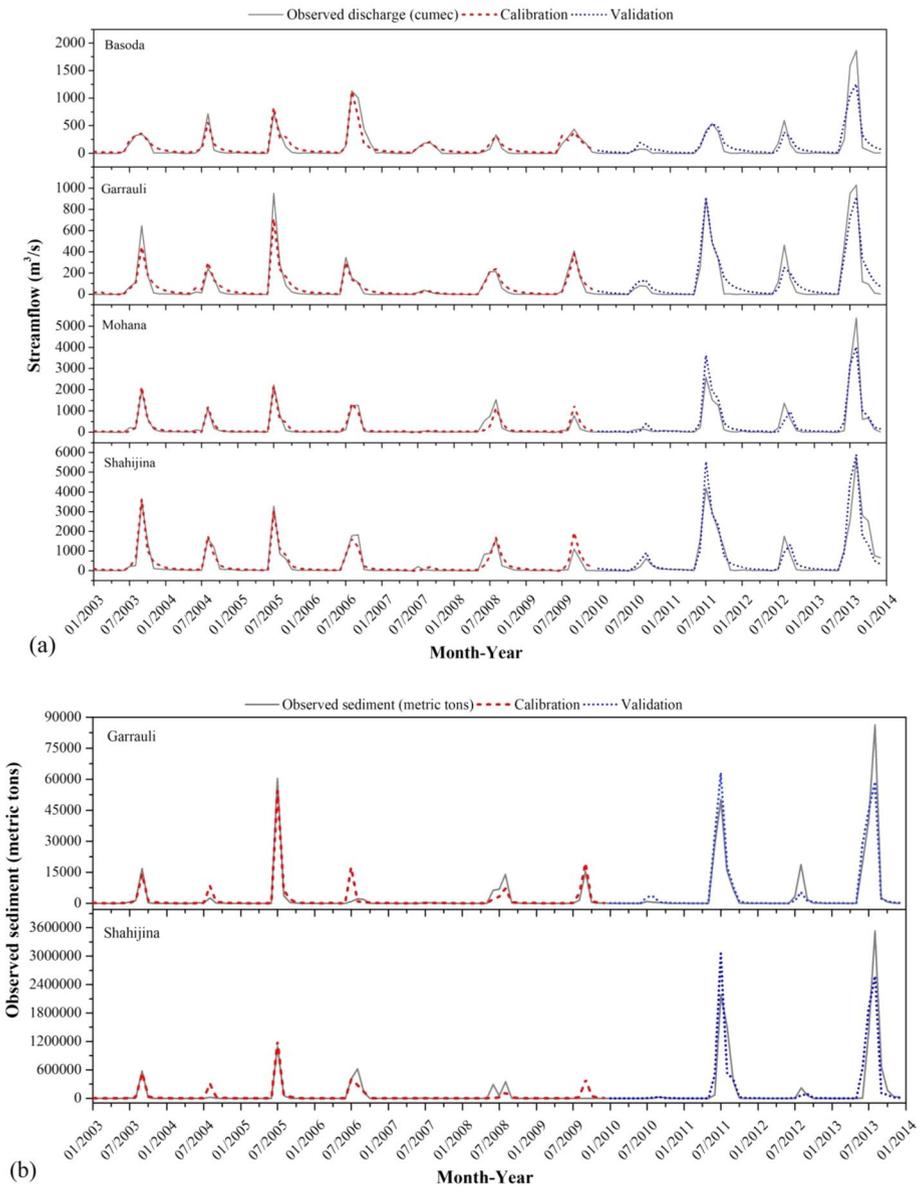
Gauging site	Calibration				Validation			
	$R^2$	NSE	PBIAS	RSR	$R^2$	NSE	PBIAS	RSR
<i>Streamflow</i> ( $\text{m}^3 \text{s}^{-1}$ )								
Basoda	0.90	0.88	-14.20	0.34	0.90	0.84	-13.60	0.41
Garrauli	0.94	0.91	-11.10	0.30	0.92	0.91	-16.50	0.30
Mohana	0.91	0.91	-7.70	0.31	0.90	0.89	-3.90	0.33
Shahijina	0.92	0.92	-16.30	0.29	0.88	0.86	-7.50	0.38
<i>Sediment yield</i> ( $\text{t ha}^{-1}$ )								
Garrauli	0.89	0.89	-9.30	0.33	0.90	0.90	0.70	0.32
Shahijina	0.78	0.77	-4.10	0.48	0.81	0.81	1.60	0.44

PBIAS values (about 2–8% to -4%) for the Mohana, a downstream gauging site of reservoirs and weirs, indicate that implementation and management of upstream reservoirs or weirs in the SWAT model is feasible.

Furthermore, the SWAT model shows a lower performance for sediment as compared to the streamflow simulation (Table 4), which is a common effect (Bieger et al., 2015; Gebremicael et al., 2013; Hovenga et al., 2016; Khoi & Suetsugi, 2014; Yan et al., 2013). Nevertheless, the analysis shows that high values of  $R^2$  and NSE, and low values of PBIAS and RSR in Table 4 indicate satisfactory to good model performance for sediment simulation (Moriassi et al., 2007). Low performance can be attributed to underestimated peak sediment loads (Fig. 4b). These may be associated with the MUSLE method that is used in SWAT for soil erosion, which generates lower peak sediment loads (Qiu et al., 2012). We observed better performance at the Garrauli site (without upstream reservoirs or weirs) when compared to the Shahijina site (with management of 7 reservoirs and 2 weirs upstream), which could be expected as a general reservoir management scheme was applied.

### 3.2 Evaluation of GCM-derived climate data

In this study, GCM-derived climate variables were evaluated prior to use in the analysis. Statistical measures, such as maximum, minimum, average, standard deviation and root-mean-square-error values, were used to compare the observed and the GCM-derived precipitation and temperature variables on daily, monthly and annual time-scales (Table 5). Analysis results show that statistical measures of minimum and maximum temperature variables have an acceptable range (Table 5). Daily precipitation values mostly differ more pronounced (e.g., maximum value, standard deviation, RMSE), but the differences are smaller on the annual scale. The differences regarding temperature values are much smaller when compared to the precipitation differences, which are commonly known (e.g., Deng et al., 2018; Li et al., 2010; Piani et al., 2010; Wagner et al., 2015; Yang et al., 2018). Overall, the analysis shows that GCM-derived climate variables have a reasonable agreement with the observed climate data and are suitable for impact analysis on the monthly time scale.



**Fig. 4** Comparison of measured and simulated **a** streamflow and **b** sediment data during calibration (2003–2009) and validation (2010–2013) period at a monthly time scale

### 3.3 Individual land use change impact assessment

#### 3.3.1 Land use changes between 2013 and 2040

Initially, land use changes between 2013 and 2040 were derived for six land use classes

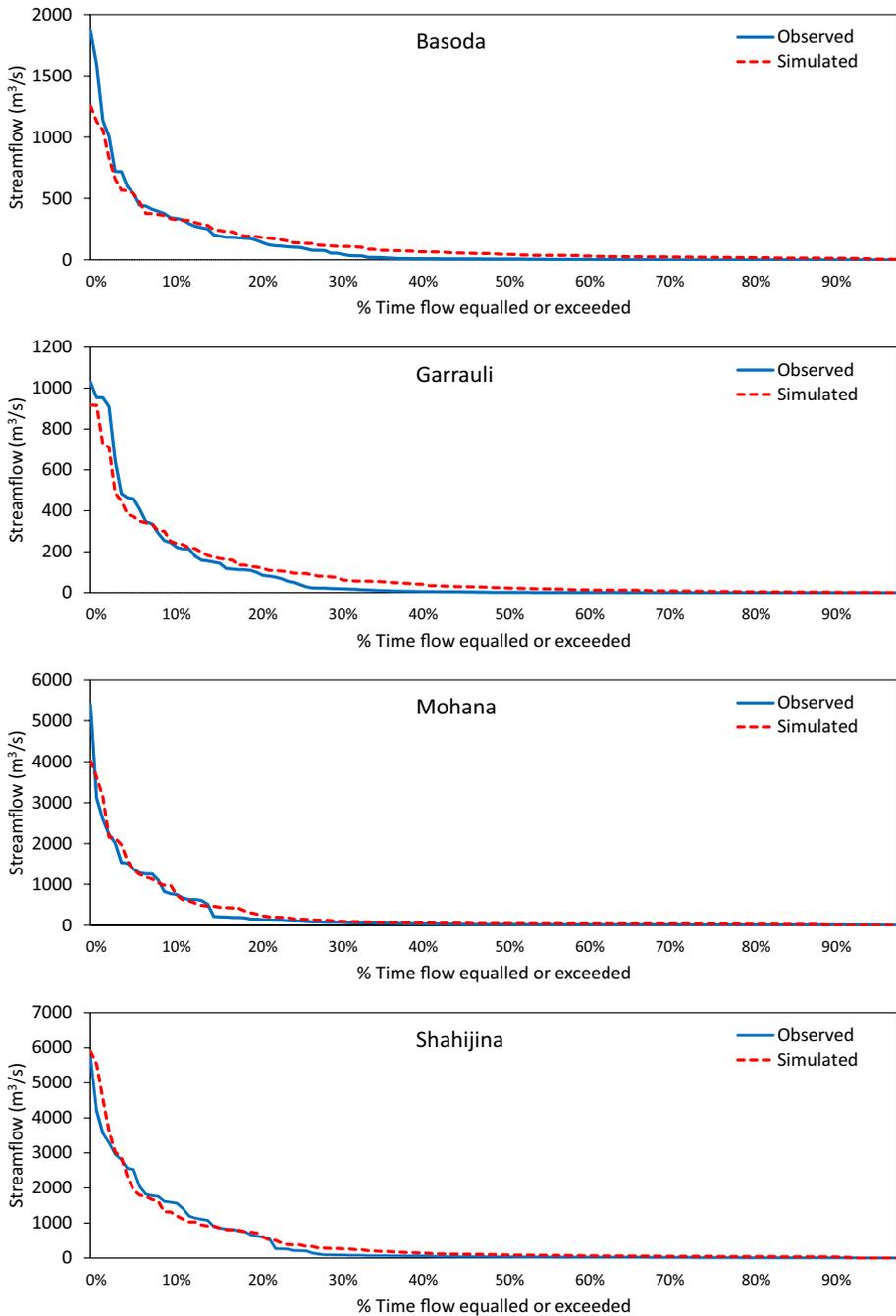


Fig. 5 Flow duration curves of the observed and simulated streamflow values for the whole simulation period

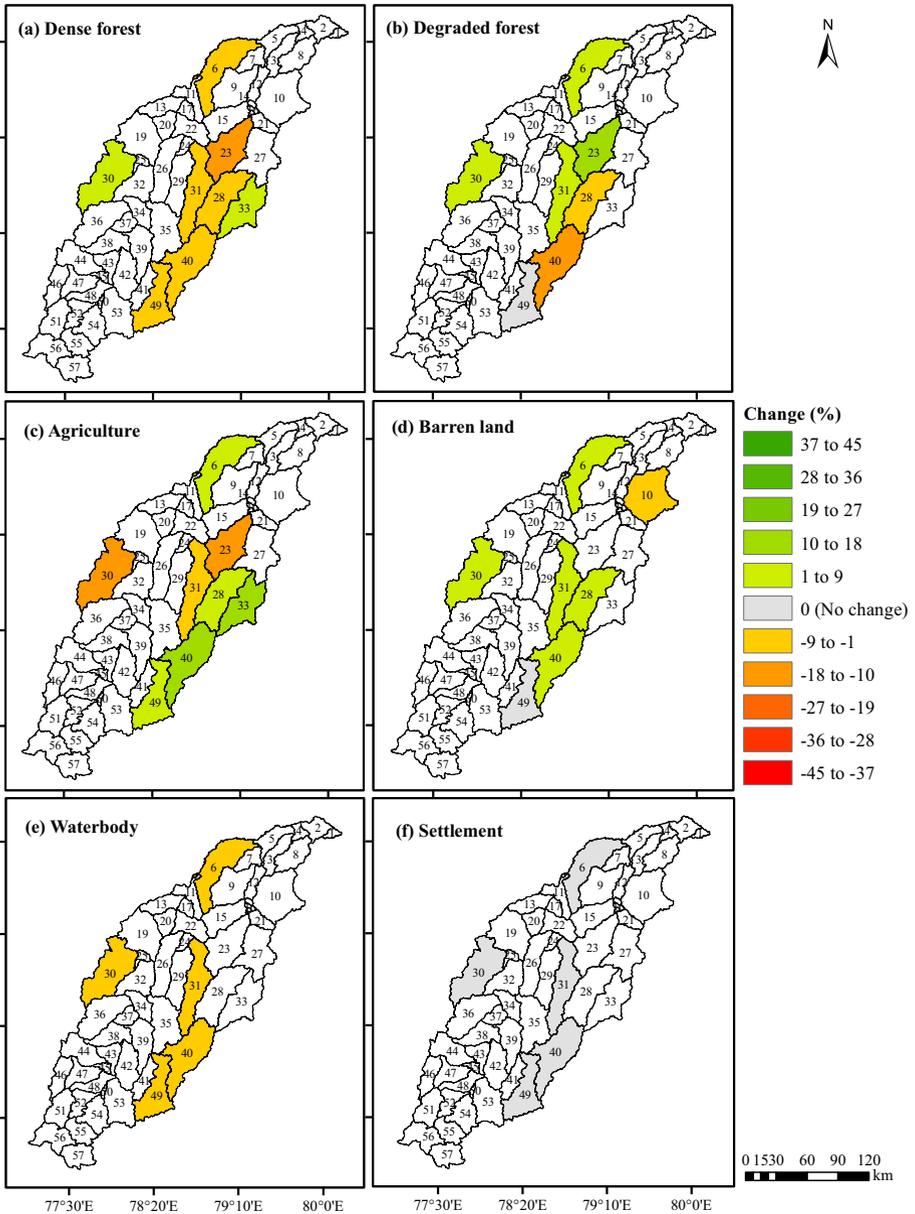
**Table 5** Statistical evaluation of observed and GCM-derived climate data

Statistic	Daily		Monthly		Annual	
	Observed	Downscaled	Observed	Downscaled	Observed	Downscaled
<i>Precipitation (mm)</i>						
Max	103.47	158.95	560.32	707.14	1718.19	1757.31
Min	0.00	0.00	0.00	0.00	657.88	688.50
Avg	2.63	2.98	80.20	90.85	962.37	980.20
SD	7.14	10.16	125.29	151.39	266.82	285.99
RMSE	0.432		0.315		0.295	
<i>Maximum temperature (°C)</i>						
Max	46.27	45.86	43.39	43.15	33.54	33.52
Min	13.48	17.44	21.33	22.96	31.44	31.52
Avg	32.71	32.40	32.70	32.39	32.71	32.40
SD	5.85	5.69	5.38	5.34	0.58	0.52
RMSE	0.091		0.088		0.087	
<i>Minimum temperature (°C)</i>						
Max	31.07	32.42	28.62	29.24	20.18	20.30
Min	3.33	2.78	7.41	7.34	18.31	19.03
Avg	19.36	19.44	19.33	19.41	19.36	19.44
SD	6.32	6.56	6.07	6.30	0.52	0.39
RMSE	0.027		0.023		0.022	

*Max* maximum value; *Min* minimum value; *Avg* average value; *SD* standard deviation; and *RMSE* root-mean-square-error

and all sub-basins (SB) using the two land use maps (Fig. 6). Major drivers of land use changes included anthropogenic impacts in the upper basin part, new sources of water availability in terms of large reservoirs, constructed in the middle part of the basin, and an interstate governments conflicts for land resources utilization and management (Palmate et al., 2017). Results show that the area of dense forest increases in the range of 10–18% in SB-11, SB-13, SB-14, SB-19, SB-20, SB-23 and SB-27 (Fig. 6a). Most of the other sub-basins have 1–9% or no significant change in the dense forest area. Further, degraded forest mostly increases in several sub-basins of the Betwa river basin. In a few sub-basins, degraded forest decreases, especially in SB-25, SB-33 and SB-40 (about 10–18%), and in SB-28, SB-28, SB-32, SB-34, SB-35, SB-41, SB-44 and SB-52 (about 1–9%) (Fig. 6b). Several sub-basins have undergone transitions between degraded forest and agriculture. Among them, the SB-25, SB-32, SB-33 and SB-40 have an increase of 10–18% in agriculture, and SB-28, SB-35 and SB-41 have 1–9% increase in agriculture area (Fig. 6c). SB-1, SB-2, SB-4, SB-22 and SB-24 show a strong 29% to 44% decrease in agriculture between the years 2013 and 2040.

Furthermore, barren land decreases in SB-10, SB-21, SB-56 and SB-57 by 1–9%; and in other sub-basins the barren land increases by 1–29% (Fig. 6d). In most of the sub-basins, waterbodies decrease by 1–9%; except for the SB-18 and SB-32 that show a stronger decrease (Fig. 6d). The settlement area increases by 1–9% in some sub-basins during 2013–2040 (Fig. 6f). Overall, this analysis revealed that dense forest and



**Fig. 6** Spatial variation of percentage change in six land use classes between 2013 and 2040: **a** dense forest, **b** degraded forest, **c** agriculture, **d** barren land, **e** waterbody, and **f** settlement

agriculture are the most rapidly decreasing vegetative areas; and settlement and waterbody are the rapidly changing non-vegetative areas of the Betwa basin.

### 3.3.2 Impact of land use change

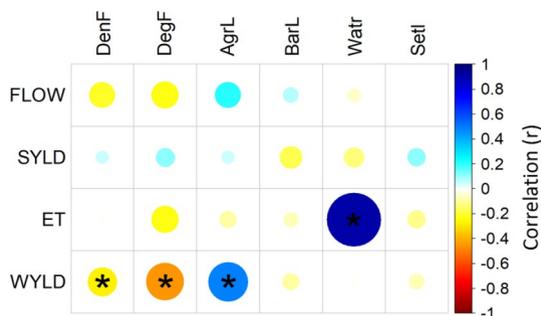
The SWAT model outputs for the baseline simulation (S1) and land use change simulation (S2) were analyzed to study the land use change impact on streamflow, sediment yield, ET, and water yield. In this study, the static delta change approach was used to compare the simulation based on two land use maps of the years 2013 and 2040. Pearson's correlation method at the significance level of 0.05 was used to investigate the impact of percent change in each land use class on the percent change in model simulation at sub-basin level.

This analysis shows that the change in ET is positively related ( $r=0.92$ ,  $p<0.05$ ) to the change in waterbody class (decreased up to 9% at sub-basin level, Fig. 7). This demonstrates the strong impact of surface water evaporation on ET. Furthermore, results show that water yield exhibited significant relationships with the changes in dense forest ( $r=-0.27$ ,  $p<0.05$ ), degraded forest ( $r=-0.45$ ,  $p<0.05$ ), and agriculture ( $r=0.49$ ,  $p<0.05$ ) as shown in Fig. 7. Overall, this analysis reveals that ET and water yield are substantially influenced by land use change. Three vegetation classes, namely dense forest, degraded forest, agriculture, and the waterbody have a significant impact on these water balance components. Thus, vegetation planting and water conservation practices are essential to minimize land use change impact on the hydrology of the Betwa river.

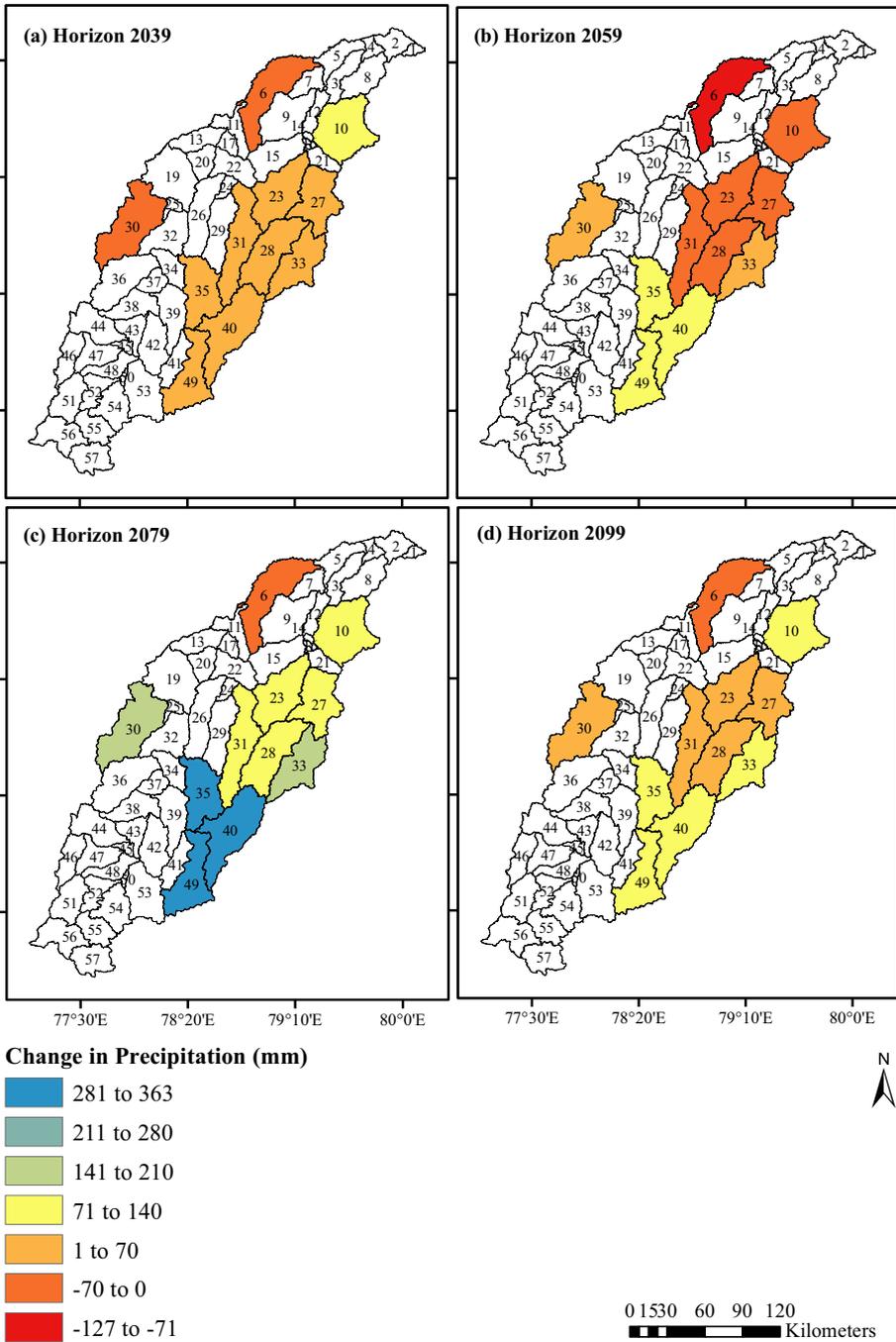
## 3.4 Individual climate change impact assessment

### 3.4.1 Changes in future precipitation at sub-basin level

The climate change simulations (S3) were analyzed with regard to the impact of precipitation change at the sub-basin level. This analysis was performed to investigate the impact of percent precipitation change on the hydrology of the Betwa basin for four future horizons (2039, 2059, 2079 and 2099). When compared to the baseline period, the upper part of the Betwa basin receives increased precipitation amounts, i.e., 71–140 mm during horizons 2039, 141–280 mm during horizon 2059, 281–363 mm



**Fig. 7** Individual land use change impact on streamflow (FLOW), sediment yield (SYLD), evapotranspiration (ET) and water yield (WYLD) of the Betwa basin as indicated by correlation. The star symbol (\*) indicates correlations at the 0.05 significance level. This analysis uses six land use classes, namely dense forest (DenF), degraded forest (DegF), agriculture land (AgrL), barren land (BarL), waterbody (Watr) and settlement (Setl)



**Fig. 8** Spatial variation of change in average annual precipitation (mm) in horizon 2039, horizon 2059, horizon 2079, and horizon 2099 at sub-basin level

during horizon 2079, and 71–210 mm during horizon 2099 (Fig. 8). Nevertheless, in the middle and lower parts of study basin precipitation amounts decrease in future. During horizon 2059, a few sub-basins have precipitation decrease (127 mm) and increase (280 mm) in the lower and upper basin areas, respectively (Fig. 8). The mean annual precipitation is quite different in the future horizons: horizon 2039 and 2059 are relatively dry with mean annual precipitation difference 821 mm and 957 mm, respectively. However, horizon 2099 experiences more (1540 mm), and horizon 2079 has even more (1621 mm) difference in annual precipitation as compared to the baseline (1109 mm). Hence, these dry and wet spells, in combination with different initial moisture conditions at the onset of the rainfall event, have a pronounced effect on the hydrologic response of the Betwa river basin.

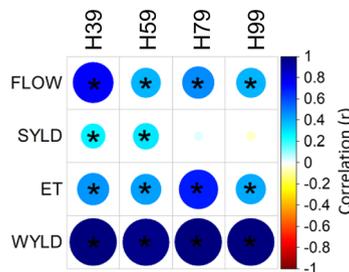
### 3.4.2 Impact of precipitation change

During horizon 2039, the percent precipitation change has a significant impact on streamflow ( $r=0.74$ ,  $p<0.05$ ), sediment yield ( $r=0.27$ ,  $p<0.05$ ), ET ( $r=0.45$ ,  $p<0.05$ ), and water yield ( $r=0.99$ ,  $p<0.05$ ) as shown in Fig. 9. Similarly, in horizon 2059, the precipitation change indicates a significant increase in the values of streamflow ( $r=0.39$ ,  $p<0.05$ ), sediment yield ( $r=0.30$ ,  $p<0.05$ ), ET ( $r=0.42$ ,  $p<0.05$ ), and water yield ( $r=0.97$ ,  $p<0.05$ , Fig. 9).

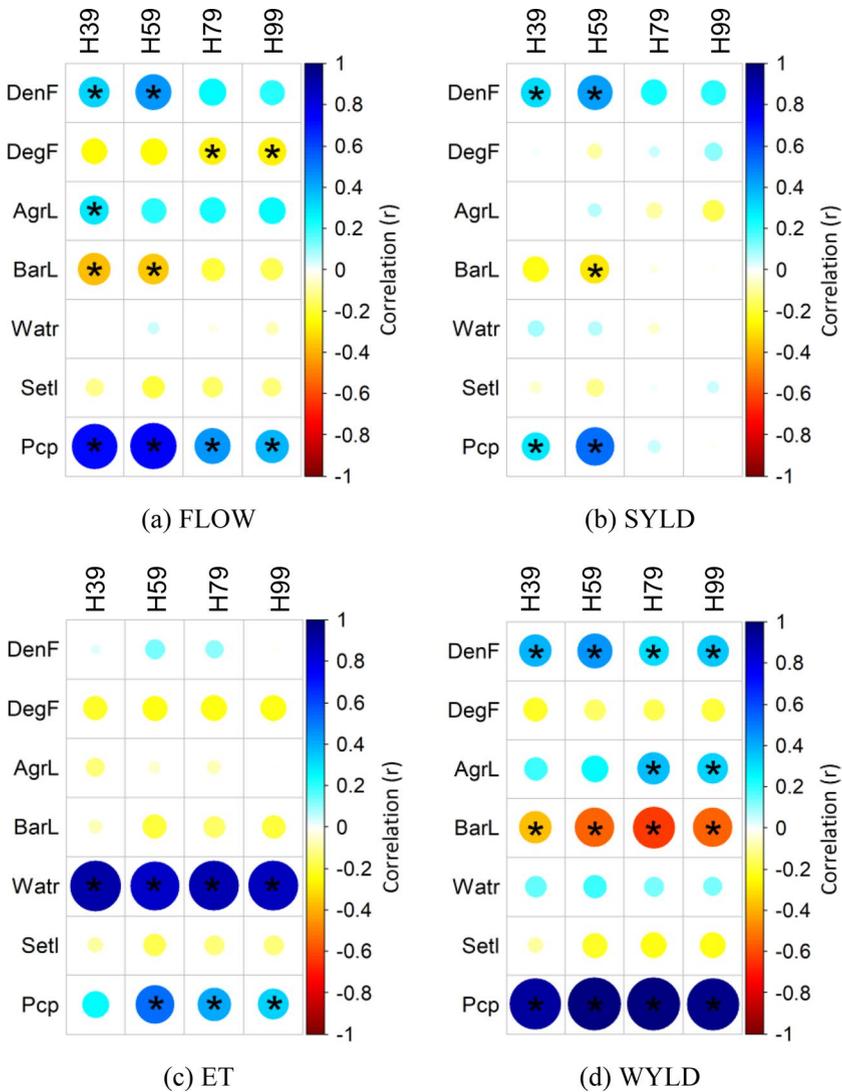
During horizon 2079 and 2099, the precipitation change has a significant impact on streamflow, ET, and water yield, but the relationship with sediment yield is not significant (Fig. 9). The effects on water balance components are reasonable as a change in precipitation results in a change of the available water for streamflow, ET, and water yield. Sediment yield is only indirectly affected by the amounts of precipitation, whereas the intensity of precipitation is much more important, so the correlation is either weak (2039, 2059) or not significant (2079, 2099).

### 3.5 Combined land use and climate change impact assessment

The combined impact of land use and climate changes on streamflow, sediment yield, ET and water yield of the Betwa river basin has been assessed as follows.



**Fig. 9** Individual climate (precipitation) change impact on streamflow (FLOW), sediment yield (SYLD), evapotranspiration (ET) and water yield (WYLD) of the Betwa basin for future climate horizons. The star symbol (\*) indicates correlations at the 0.05 significance level. This analysis uses only one climate parameter, precipitation (Pcp), to study its impact on the basin hydrology



**Fig. 10** Combined impact of land use and climate changes on **a** streamflow (FLOW), **b** sediment yield (SYLD), **c** evapotranspiration (ET), and **d** water yield (WYLD) of the Betwa basin. Star symbol (\*) indicates correlations at the 0.05 significance level. This analysis uses six land use classes, namely dense forest (DenF), degraded forest (DegF), agriculture land (AgrL), barren land (BarL), waterbody (Watr) and settlement (Setl), and one climate parameter, precipitation (Pcp)

### 3.5.1 Combined impact on streamflow

Results of the combined land use and climate change analysis show that a decrease in the area of dense forest significantly decreases the value of streamflow during the first two horizons 2039 ( $r=0.33, p<0.05$ ) and 2059 ( $r=0.46, p<0.05$ ). However, an increase in the degraded forest area significantly decreases streamflow in the last two

future horizons 2079 ( $r = -0.27$ ,  $p < 0.05$ ) and 2099 ( $r = -0.28$ ,  $p < 0.05$ ), as shown in Fig. 10a. Dense forest is primarily changed into degraded forest (Palmate et al., 2017). The effect of barren land on streamflow also exhibited a negative correlation in horizon 2039 ( $r = -0.37$ ,  $p < 0.05$ ) and horizon 2059 ( $r = -0.34$ ,  $p < 0.05$ ). Decrease in the dominant agriculture area causes decreases in the value of streamflow ( $r = 0.299$ ,  $p < 0.05$ ), which are, however, only significant during horizon 2039. Furthermore, an increase in the value of future precipitation shows a significant increase in the value of streamflow in all future periods (Fig. 10a).

### 3.5.2 Combined impact on sediment yield

Results of the combined impact analysis at the sub-basin level show that a decrease in the area of dense forest significantly decreases sediment yield during horizon 2039 ( $r = 0.31$ ,  $p < 0.05$ ) and horizon 2059 ( $r = 0.44$ ,  $p < 0.05$ ). However, the explanatory variables change in precipitation and change in dense forest are correlated ( $r = 0.47$ ,  $p < 0.05$ ). This indicates that these impacts cannot be singularly attributed to land use change, but might result from changes in precipitation. Precipitation changes were correlated to changes in sediment yield in the individual assessment (Fig. 9), whereas changes in dense forest were not correlated to changes in sediment yield (Fig. 7), it is likely that the changes in sediment yield in the combined assessment can be attributed to climate change. Increase in the area of barren land caused a significant decrease in the sediment yield ( $r = -0.30$ ,  $p < 0.05$ ) only in horizon 2059. A weak negative correlation between barren land and sediment yield has already been observed for the individual assessment ( $r = -0.16$ , Fig. 7), which may be attributed to no management measures in these areas. This relationship becomes significant in combined impact analysis ( $r = -0.30$ ,  $p < 0.05$ ), may be due to less rainfall in horizon 2059, which reduces soil losses from barren land. Furthermore, increase in the precipitation amount also shows a significant increase in the sediment yield in horizon 2039 ( $r = 0.29$ ,  $p < 0.05$ ), and horizon 2059 ( $r = 0.53$ ,  $p < 0.05$ ), as shown in Fig. 10b. The non-significant relationships in horizon 2079 and horizon 2099 may be due to wetter weather conditions in which prolonged soil moisture availability results in less soil erodibility (Fitzjohn et al., 1998; Ziadat & Taimeh, 2013). Overall, the present combined impact analysis revealed that sediment yield is only significantly affected in the horizons 2039 and 2059.

### 3.5.3 Combined impact on evapotranspiration

The result of the combined impact analysis shows that changes in land use (waterbody) and climate (precipitation) have a significant impact on ET. The waterbody class exhibited slightly lower correlations ( $r < 0.92$ ,  $p < 0.05$ ) with ET in future climate horizons (Fig. 10c), when compared with the baseline correlation value ( $r = 0.92$ ,  $p < 0.05$ ). Precipitation also exhibited significant positive correlations to ET due to increased water availability, in horizon 2059 ( $r = 0.53$ ,  $p < 0.05$ ), horizon 2079 ( $r = 0.40$ ,  $p < 0.05$ ), and horizon 2099 ( $r = 0.34$ ,  $p < 0.05$ ), which are lower than during the single climate change impact assessment. Thus, the analysis reveals that change in ET considerably depends on changes in water vaporization from surface waterbodies (Fig. 6) in the Betwa river basin. Kundu et al. (2017) reported that the individual impact of land use change is responsible for ET losses in the Narmada river basin of central India.

### 3.5.4 Combined impact on water yield

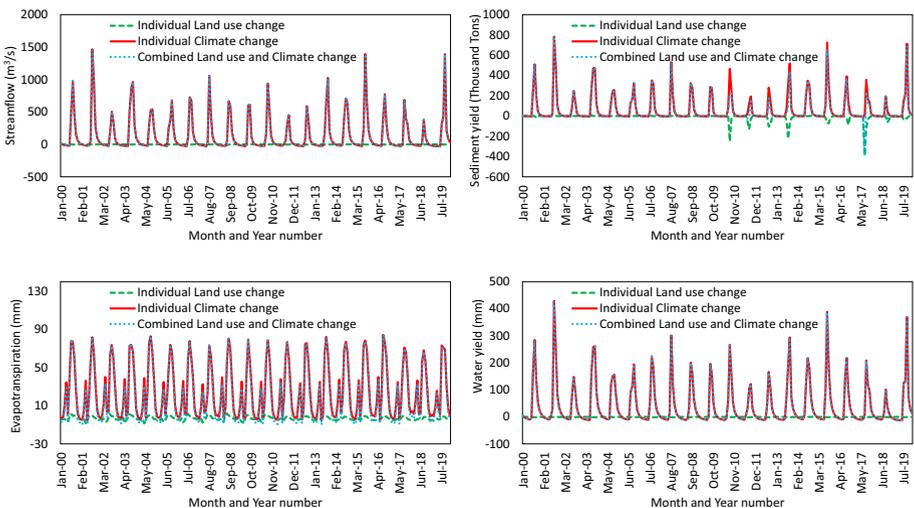
Combined impact analysis shows that changes in dense forest, agriculture, barren land and precipitation have a significant impact on water yield (Fig. 10d). Dense forest, agriculture and precipitation changes with the water yield exhibited positive correlations; however, barren land has a negative correlation with water yield as shown in Fig. 10d. Changes in dense forest and precipitation are correlated, but both variables also showed an impact on water yield in the individual assessment, so that it is likely that both variables affect water yield in the combined assessment as well. Results show that agricultural change has a more substantial impact on water yield during high precipitation periods, i.e., horizon 2079 (1153 mm) and horizon 2099 (1082 mm). Barren land of the Betwa basin contributes to ET losses, but becomes a grassland area during periods of rain that also contributes to groundwater recharge.

### 3.6 Application of conceptual framework

In this study, the developed conceptual framework was employed to assess the individual and combined impacts of land use and climate changes on the hydrology of the Betwa river basin.

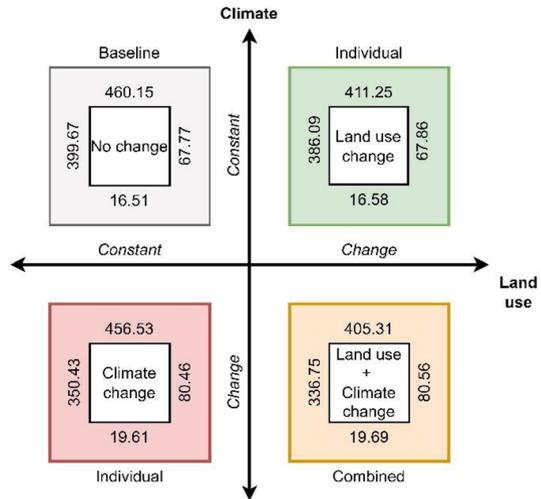
#### 3.6.1 Assessment of individual and combined impacts of land use and climate changes

The conceptual framework representing hydrologic components of the Betwa basin is shown in Figs. 11 and 12. Results show that FLOW increases from 67.77 to 67.86  $\text{m}^3 \text{s}^{-1}$  due to land use change, from 67.77 to 80.46  $\text{m}^3 \text{s}^{-1}$  due to climate change, and from 67.77



**Fig. 11** Temporal changes of water balance components and sediment yield at individual land use change and climate change scenarios, and combined land use and climate change scenarios. Here, month-year number indicates month-wise year from 0 to 19, i.e., in a total of 20 years of analysis

**Fig. 12** Comparison of individual and combined impacts of land use and climate change using a conceptual framework. The value at right side represents streamflow ( $\text{m}^3 \text{s}^{-1}$ ), value at bottom side represents sediment yield ( $\text{t ha}^{-1}$ ), value at top side represents ET (mm), and value at left side represents water yield (mm)



to  $80.56 \text{ m}^3 \text{ s}^{-1}$  due to combined impact of land use and climate changes (Fig. 12). Similarly, the SYLD increases from  $16.51$  to  $16.58 \text{ t ha}^{-1}$  due to land use change, from  $16.51$  to  $19.61 \text{ t ha}^{-1}$  due to climate change, and from  $16.51$  to  $19.69 \text{ t ha}^{-1}$  due to combined impact of land use and climate changes. Both FLOW and SYLD increase due to individual climate and land use change and the combined assessment shows that the impacts of climate and land use change add up. Furthermore, result shows a decrease in ET under land use change (reduced from  $460.15$  to  $411.25 \text{ mm}$ ,  $-48.9 \text{ mm}$ ), climate change (reduced from  $460.15$  to  $456.53 \text{ mm}$ ,  $-3.62 \text{ mm}$ ), and combined land use and climate changes (reduced from  $460.15$  to  $405.31 \text{ mm}$ ,  $-54.84 \text{ mm}$ ) with respect to the baseline ET (Fig. 12). Similarly, the WYLD also decreases under land use change (reduced  $399.67$ – $386.09 \text{ mm}$ ,  $-13.58 \text{ mm}$ ), climate change (reduced from  $399.67$  to  $350.43 \text{ mm}$ ,  $-49.24 \text{ mm}$ ), and combined land use and climate changes (reduced from  $399.67$  to  $336.75 \text{ mm}$ ,  $-62.92 \text{ mm}$ ) with respect to the baseline (Figs. 11 and 12). Thus, both ET and WYLD are decreased by land use and climate change. The combined assessment shows that the sum of the impacts of the individual assessments mostly corresponds to the impact of the combined assessment. Only the value of the combined impacts on ET is  $2.32 \text{ mm}$  greater than the sum of the individual impacts.

Hence, climate change impacts dominate for FLOW, SYLD, and WYLD and the combined change assessment ( $12.69 \text{ m}^3 \text{ s}^{-1}$ ,  $3.18 \text{ t ha}^{-1}$ ,  $-62.92 \text{ mm}$ ) is almost equal (differs only by  $0.01 \text{ m}^3 \text{ s}^{-1}$ ,  $0.01 \text{ t ha}^{-1}$ , and  $0.1 \text{ mm}$ , respectively) to the sum of the individual assessments ( $0.09 \text{ m}^3 \text{ s}^{-1} + 12.59 \text{ m}^3 \text{ s}^{-1}$ ;  $0.07 \text{ t ha}^{-1} + 3.1 \text{ t ha}^{-1}$ ;  $-13.58 \text{ mm} - 49.24 \text{ mm}$ ). Only in the case of ET, the land use change impacts dominate when compared to the climate change impacts and also, the sum of the individual change assessments differs a bit more from the combined change assessment ( $2.32 \text{ mm}$ ). This seems reasonable as ET is more affected by land use than the other variables. A changed land use in combination with a different climate has stronger impacts on ET, so the combined assessment shows a higher value than the sum of the individual assessments and underlines the importance of a combined assessment in this case. However, the relatively small differences between the combined and the sum of the individual assessments for the other variables indicate that the model shows a linear behavior for the prediction of these variables. This might be different if a dynamic and nonlinear land use change was implemented instead of a static

one-time change (Wagner et al., 2016, 2019). Also, land use and climate change data were not related to each other in this study, so no feedback effects were considered that may influence the impacts.

Overall, the climate change impact is greater than the land use change impact on the hydrology of the Betwa River basin. Only ET is more affected by land use change. Kundu et al. (2017) underline these findings as they report that the individual impact of climate change is prominent for water yield, and land use change impact is prominent for ET losses. Due to the impacts of land use and climate change, the FLOW and SYLD components increase while the ET and WYLD components decrease in future scenarios. In this analysis, current management practices related to agricultural land and reservoir water flow regulations were implemented. In the future, sustainable management practices such as soil and water conservation, vegetation planting, changes in the cropping system, and river channel protection are essential to reduce their impacts on changes in the hydrologic components of the Betwa basin. This study can also be a basis for policymakers and Government agencies associated with efficient natural resources management. In general, the proposed conceptual framework helps to interpret the results of model simulation under changing land use and climate conditions. Therefore, it can be used in future research studies focused on the assessment of individual as well as combined impacts of land use and climate change for sustainable river basin management.

## 4 Conclusions

A hydrologic model for the Betwa River basin has been set up to study the individual and combined impacts of land use and climate change. The multi-gauge calibration and validation indicated a satisfactory to very good model performance on the monthly time scale for streamflow and a satisfactory to good performance for sediment yield. Comparison of measured and modeled flow duration curves provides additional confidence in the model. The derivation of suitable reservoir management was crucial when setting up the SWAT model, as observed data from the reservoirs was not available. Implementing the derived general management rules and the characteristics of the seven reservoirs and two weirs has significantly improved hydrological simulations. GCM data has been downscaled to the study area for climate change impact analysis, and classified land use maps of the past and modeled land use maps for the future were employed for land use change impact analysis.

With regard to the impacts of land use and climate change, the following general conclusions are drawn:

1. The spatial analysis showed that land use (from 2013 to 2040) and climate (from 2020 to 2099) of the Betwa basin significantly change in the applied future scenarios, i.e., horizon 2039, horizon 2059, horizon 2079, and horizon 2099.
2. Individual land use change impact analysis at the sub-basin level showed a significant impact on the water balance components, i.e., the change in the land use class waterbody has a significant ( $p < 0.05$ ) impact on ET losses, and the changes in dense forest, degraded forest, and agriculture have a significant impact on water yield in the Betwa basin.
3. Individual climate change impact analysis shows that precipitation significantly ( $p < 0.05$ ) impacts streamflow, sediment yield, ET, and water yield during all future climate horizons. This can be explained by increased precipitation by up to 363 mm

- in the upper Betwa basin and decreases in the middle and lower basin areas by up to  $-127$  mm.
4. The developed conceptual framework can effectively separate the individual as well as the combined impacts of land use change and climate change on four components, i.e., FLOW, SYLD, ET, and WYLD, of the study area.
  5. This study reveals that the impact of climate change dominates the land use change impact on streamflow, water yield, and sediment yield. Only for evapotranspiration, the impacts of land use change dominate those of climate change.

Therefore, we strongly recommend assessing the combined impacts of land use and climate change, as individual impacts might be exaggerated or compensated for. The results show that this is the case for the assessment of changes in evapotranspiration, as the combined impact differs from the sum of the individual impacts. The developed framework provides a useful structure for the differentiation and presentation of the combined and individual hydrologic impacts of land use and climate change in any future study on this topic.

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**Data availability** The datasets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

## Declarations

**Conflict of interest** No potential conflict of interest was reported by the authors.

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