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ORIGINAL ARTICLE

# Assessment of impacts of land use/land cover changes upstream of a dam in a semi-arid watershed using QSWAT

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## Abstract

The study of hydrodynamic responses of the watershed influenced by the changes occurring in the climate and pattern of land use is vital in the management of sustainable water resources. The open-source soil and water assessment tool QSWAT has been adopted in this study to link the meteorological factors with land-surface hydrology and present a complete response of an ungauged watershed in the Krishna basin. The main objective of the present work is to assess the adaptability of the QSWAT model for the selected semi-arid watershed, which has undergone drastic land use/land cover (LULC) changes due to the construction of a dam. The impact of the LULC changes on the hydrodynamic response of the watershed is analysed. For automatic calibration and uncertainty analysis, SUFI-2 algorithm is used. Initially, the model adaptability for the watershed is assessed by simulating for 32 years, of which 27 years (from 1982 to 2008) are used for calibration and 5 years (from 2008 to 2013) for validation. Further, Landsat satellite images along with 14 LULC classifications for the year 1998 and 2009, indicating scenarios of pre- and post-construction of the dam, respectively, are used as input to QSWAT to analyse the influence of LULC changes on the water balance components. The comparison indicates decrease in the agricultural area, barren land and urban built-up area. The annual water yield and surface runoff of the watershed have been reduced by 28.97% and 29.91%, respectively. An increment of 6% evapotranspiration loss with a decreasing trend in rainfall is noted which is alarming. The simulated results indicate that the hydrological responses are influenced by the LULC changes. The basin LULC and hydrological components have been affected by the storage reservoir created due to the dam. The QSWAT seems to be reliable tool as there is a good agreement between the simulated and observed flows. The obtained model performance indices: the NSE and $R^2$ calibration values are 0.89 and 0.96, respectively, and the values for validation are 0.79 and 0.83 respectively, hence indicating a strong and predictive capability of the model to the ungauged watersheds with drastic LULC changes. Apart from establishing sustainable water resources management techniques in the watershed, there is a stressing need for such analysis before any human intervention into the natural system like construction of dams.

**Keywords** QSWAT · Water balance · Evapotranspiration · Groundwater recharge · LULC

## Introduction

Watershed, a basic hydrological unit, is a complex system under the influence of spatial and temporal varying soil characteristics, land use/land cover (LULC) practices and vegetation. A broad detailing of the watershed hydrological processes is the prerequisite for water resource management. In the case of arid and semi-arid regions with extreme climatic conditions and varied intermittent precipitation, the need for understanding the hydrological processes is of utmost priority for the conservation of water resources and sustainable management. The study of the system becomes more entangled due to data scarcity in ungauged watersheds as is the case of most of the minor river basins of India.

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The hydrological responses of a watershed such as evapotranspiration, infiltration, interception, surface and subsurface flow are greatly influenced by the changes occurring in the climate and pattern of land use. Anthropogenic activities have altered the LULC patterns leading to changes in the biogeochemical characteristics of the watershed. From the findings of previous researchers, it is quite evident that, apart from the meteorological aspects, varied LULC changes greatly influence the water balance components (Ghaffari et al. 2010; Wijesekara et al. 2012; Chotpantarat and Boon-Kaewwan 2018). Therefore, a holistic approach which links the meteorological factors with land-surface hydrology is necessary to understand the complete response of the watershed in terms of the spatial and temporal variations. This comprehensive view can be better addressed by using hydrological and water management models linked with spatial analysis tools like GIS.

Models help to incorporate the complexities involved in the interaction of various parameters in the watershed and reduce the uncertainty involved in their estimation. Various hydrological processes like evapotranspiration, runoff, infiltration, recharge and non-hydrological processes such as erosion, cropping patterns, water regulation, etc. must be included in the hydrological modelling of the watershed. These important physical processes are not included in conceptual hydrological models. Dynamic continuous mathematical models which are performing based on a combination of physical and semi-empirical elements along with spatial disaggregation are better adapted to the different hydrological processes (Bieger et al. 2015).

Some of the hydrological models such as Integrated hydrological model (MIKE-SHE), Semi-distributed Land use-based runoff processes (SLURP), Soil Water Assessment Tool (SWAT) (Arnold et al. 1998), Hydrological Modelling System (HEC-HMS; HEC, 2000) and Soil–Water–Atmosphere–Plant (SWAP) are being used by researchers for analysing the hydrological parameters and their responses. Out of these models, SWAT has drawn a lot of attention in modelling the sediment yield and runoff at desired spatial and temporal scales (Arnold et al. 1998; Suryavanshi et al. 2017). Gosain et al. (2006) used SWAT to access the impacts of climate change on twelve different river basins in India, and noted that SWAT does not require much calibration. Kim and Arnold (2008) applied the model to Musimcheon basin in South Korea for simulating the groundwater recharge effectively with and without pumping details. Further, the model was satisfactorily tested for regions with data scarcity (Ndomba et al. 2008). SWAT uses a GIS interface to obtain most of the SWAT parameters (Zhang et al. 2008) and can be easily connected to the database for improved accuracy. Sisay et al. (2017) applied SWAT model to simulate the water balance and status of the hydrological process for the ungauged urban watershed of Vadodara City, Gujarat, India and illustrated the viability and strong predictive ability of SWAT for the ungauged watershed. Boufala et al. (2019) evaluated the hydrological balance and erosion at Upper Sebou watershed (u/s part of Allal El Fassi dam), Morocco using SWAT. Further, the authors assessed the siltation rate at the Allal El Fassi dam and indicated the reliability of SWAT modelling for climate change studies, agricultural practices, and water resources allocation. Welde and Gebremariam (2017) used SWAT integrated with GIS to study the effect of land use/land cover dynamics on the hydrological response of Tekeze dam watershed, Northern Ethiopia and simulated the change in the streamflow and sediment yield. Gyamfi et al. (2017) assessed the feasibility of SWAT in analysing the effect of LULC on groundwater recharge and recommended the model for such studies. SWAT was efficiently adopted in analysing the impact of Groundwater dynamics, water quality, non-point pollution, climate changes, LULC, BMPs in agricultural watersheds and water budget studies. (for example, Gassman et al. 2007, 2014; Krysanova and Arnold 2008; Tuppad et al. 2011; Krysanova and White 2015; Dagnew et al. 2016; Dile et al. 2016; Wu et al. 2015; Abbaspour et al. 2018). These studies have indicated the wide applicability of SWAT to different cases and regions.

The SWAT model was tested for Indian conditions by Tripathi et al. (2003), Suryavanshi et al. (2017), Garg et al. (2012), Narsimlu et al. (2015). SWAT was used efficiently to estimate the daily and monthly runoff and sediment yields in Nagwan watershed of Eastern India by Jadhao et al. (2010) and Tripathi et al. (2003). To calibrate and validate the total flow and low flow, Rouhani et al. (2007) applied the SWAT model successfully, proving the unbiased nature of SWAT in flow estimation. Sensing the substantial impact of LULC on soil and water, Kumar et al. (2018), applied SWAT to analyse the impact of LULC on hydrological processes in Tons River basin, Madhya Pradesh, India. Considerable changes were noted for the mixed crop, residential and forest areas. It was noted that water-intensive crops lead to a greater impact on the hydrological parameters in the watershed.

The hydrological models along with geospatial techniques have made the watershed modelling more reliable. From GRASS to the recent ArcGIS, many versions of GIS interface are linked with the modelling process (Tuppad et al. 2011). As a recent development, open-source software is widely recognised in research owing to its financial benefits, easy collaboration and continuous improvement. Chen et al. (2010) used the open-source Quantum GIS (QGIS) to model water resource management in developing countries and concludes that QGIS outperformed other software and was efficient even under poor computing conditions. The interface of QGIS was developed for SWAT to fulfil the rising demand of SWAT users. Dile et al. (2016) developed QSWAT, the new open-source interface for SWAT and the model was demonstrated successfully with Gumera watershed located in Lake Tana basin, tropical highland region of Ethiopia.

Since last few decades, the brunt of manmade large water storage structures on the environment is being debated over. LULC changes due to dam can alter local to global hydrometeorology resulting in the modification of extreme precipitation (Woldemichael et al. 2012). Several studies explore and justify the impact of LULC on hydrological components of several watersheds, but not many have explored the effect of LULC changes induced due to large water storage structures on water balance components and its influence on the hydrological regime. Moreover, the open-source interface QSWAT is not explored for its applicability for such conditions of LULC changes.

The model is associated with integrated SUFI-2 algorithm for automatic calibration and uncertainty analysis. QSWAT, being the improved version of SWAT, has enhanced processing capabilities, consumes lesser processing time and has better statistical and dynamical representation of outputs, and hence has been chosen in this study. The study area has undergone drastic changes due to construction of a dam, resulting in submergence of a vast stretch of land. The drastic topographic changes induced by the dam and the drift in agriculture towards water-intensive crops has altered the hydrological parameters in the area. In the last three decades, the gross irrigated area has doubled [Agricultural Statistics of Karnataka-Annual season crop report of Defence equipment and support (ASCR of DE&S)], resulting in increased demand for water. Therefore, the particular watershed located upstream of the dam was selected to explore the overall impacts. So far, this particular watershed (study area) has not been subjected to such studies and in general, the overall consequences on the hydrological parameters and water balance due to dam construction have not been addressed by any researcher; which makes this study unique and significant.

In this paper, we assess the changes in the LULC patterns induced by the water storage reservoir in its upstream watershed of North Karnataka region of India. The specific objective is to check the feasibility of the new open-source interface QSWAT in analysing the effect of LULC changes on the hydrodynamics of the watershed. The model is simulated linking the meteorological factors with land-surface hydrology for better representation of the watershed characteristics. Detailed spatial scale in the form of catchments, sub-catchments and HRUs is used to improve the accuracy and processed for a detailed temporal, daily time step.

The work is presented in the following order:

1. Collection of data
2. Processing the inputs for the SWAT model
3. Simulation for the baseline scenario
4. Sensitivity analysis, calibration and validation
5. Incorporation of changes in LULC, for pre (1998)- and post (2009)-dam construction periods simulation
6. Simulation of the watershed response
7. Analysis of LULC changes and hydrologic components of pre and post dam construction periods

## Materials and methods

### Study area

Geographically, the Krishna basin forms the south-central part of the Indian Peninsula. The study area is a watershed of Ghataprabha basin, which is one of the southern major tributaries of the Krishna River. Ghataprabha originates at an altitude of 884 m in the Western Ghats and travels for a distance of 283 km in the eastward direction before its union with the Krishna River at Almatti. At Almatti, a gravity dam is constructed, designed to store water with a gross storage of 123.08 TMC (to an RL of 519.6 m) and is a part of upper Krishna project. Construction of the dam was completed in 2002 and the water is being stored up to the level of 519.6 m, which has led to the submergence of a vast area including rural, urban and agricultural lands. Construction of multiple dams in Krishna basin has affected the hydrological regime of the basin. The Ghataprabha basin, with a catchment area of 8829 km$^2$, spreads through the states of Maharashtra and Karnataka, covering more than three-fourths of Karnataka. The study area is confined between 16° 32′ and 16° 08′ North Latitude and 75° 59′ and 75° 85′ East Longitude. It forms a watershed in Ghataprabha basin, located within the Bagalkot district, Northern part of Karnataka, India, with a geographical area of 637.11 km$^2$. The geographical location of the study area is depicted in Fig. 1. Geological information indicates that Archaean crystalline formations which include granites, gneisses, and metasediments of Dharwar supergroup, sandstones, shales, limestones and quartzite of Kaladgi series, of both older and younger generation are present in the study area. These hard rocks range from weathered to semi-weathered fractured formations and tend to hold the groundwater within confined and semi-confined aquifers. The weathered zone thickness varies widely in the study area. The unconfined aquifer stretches to a 30 m depth below the topsoil, forming the shallow aquifer and further exists in the deep aquifer with fractured strata stretching to 80 m and beyond (CGWB district report, 2011). Soil data of the catchment indicate loamy, silty and sandy clay, a major part being clayey soil.

The study area consists of rural area, with 71% of the total population depending on agriculture as main occupation. The terrain is gently undulating with isolated hills with elevations ranging from 480 to 729 m above mean sea level (msl), sloping from west to east. The district with the

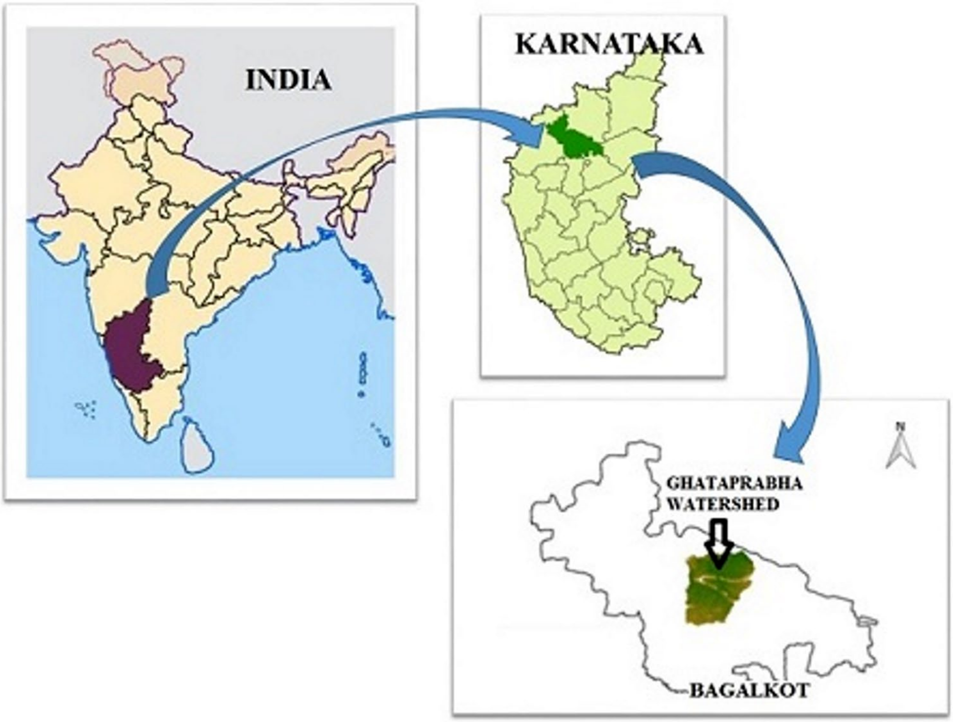


**Fig. 1** Location map of the study area

semi-arid climate in the Northern dry agro-climatic zone is identified as one of the drought-prone areas. The rainfall in the district increases gradually from west to east with a mean of 559.9 mm.

The seasonal distribution indicates that south-west monsoon between the months June and September approximately contributes to 66% of the annual rainfall. About 21% is contributed during the post-monsoon period of October to December and the remaining in the other seasons. Jowar, corn, wheat, bajra, sugarcane, sunflower, pulses and groundnut are the major crops grown in the area.

## Soil water assessment tool (SWAT)

The soil and water assessment tool (SWAT) is a physically based watershed model which operates on a daily time scale (Arnold et al. 1998; Arnold and Fohrer 2005). SWAT is a product of the USDA Agricultural Research Service, USDA-Natural Resources Conservation Services and Texas A&M. The main components considered in the model are hydrology, climatic variations, LULC variations, plant growth, nutrients and pesticides (Arnold et al. 1998; Gassman et al. 2007). The model uses the water balance Eq. (1) given below (Neitsch et al. 2009).

$$\mathrm{SW_t} = \mathrm{SW_o} + \sum_{i=1}^{l} (R_{\mathrm{day}} - Q_{\mathrm{surf}} - E_{\mathrm{a}} - W_{\mathrm{seep}} - Q_{\mathrm{gw}}). \quad (1)$$

In this equation, $\mathrm{SW_o}$ indicates the initial soil water content (mm) on a particular time step, $R_{\mathrm{day}}$ is the amount of precipitation at the same time step (mm), $E_{\mathrm{a}}$ is the amount of evaporation, and the amount of surface runoff (mm) is indicated by $Q_{\mathrm{surf}}$, whereas $W_{\mathrm{seep}}$ is the amount of water entering the vadose zone from the soil profile (mm) and the return flow (mm) is indicated by $Q_{\mathrm{gw}}$. $\mathrm{SW_t}$ indicates the final soil water content (mm). The entire watershed is divided into several smaller areas known as hydrological response units (HRUs) based on similar patterns of soil and land use. In the simulation process, some of the critical parameters considered for the analysis of variation in the hydrological parameters are water yield, runoff, evapotranspiration and groundwater recharge. Model estimates the watershed's water yield $W_{\mathrm{yld}}$ based on the Eq. (2)

$$W_{\mathrm{yld}} = Q_{\mathrm{surf}} + Q_{\mathrm{gw}} + Q_{\mathrm{lat}} - T_{\mathrm{loss}}, \quad (2)$$

where $Q_{\mathrm{surf}}$ is the surface runoff (mm), $Q_{\mathrm{gw}}$ is the groundwater contribution to the streamflow (mm), $Q_{\mathrm{lat}}$ is the lateral flow contribution to the stream (mm) and $T_{\mathrm{loss}}$ is the transmission loss.

The surface runoff (mm) is estimated based on the Eq. (3)

$$Q_{\mathrm{surf}} = \frac{(R_{\mathrm{day}} - 0.02S)^2}{(R_{\mathrm{day}} + 0.8S)}, \quad (3)$$

where the rainfall depth (mm) for the day is indicated by $R_{\mathrm{day}}$ and $S$ is the retention parameter, which is based on the SCS curve number. Evapotranspiration potential can be assessed through the Penman–Monteith method and Priestly–Taylor methods. In this process, the Penman–Monteith method has been used as it gives more accurate result in comparison to the Priestley–Taylor method (Tyagi et al. 2019). Lateral flow is simulated using kinematic flow equation considering the slope, saturated hydraulic conductivity and porosity of the soil layer as major factors. The drainable water quantity is bifurcated into shallow and deep level storages. For an efficient simulation of irrigational requirement, each HRU can be incorporated with the particular crop variety, irrigational requirements, sowing and harvesting times. The amount of water entering aquifers during the time step (mm) is termed as groundwater recharge (GW_RCHG).

### QSWAT: an open-source interface of SWAT

QSWAT, an open-source software set up with Python, linked to QGIS has improved the processing capabilities of the SWAT model. QSWAT processes the activities through two sections, namely QSWAT control and QSWAT functions. The geoprocessing activities are based on Digital Elevation Models (TauDEM), which form the base for further interactions with different QGIS functions. The standard Message Passing Interface (MPI) is used in multiprocessing mode, reducing the DEM processing time. The QSWAT has an advantage of the classified storing project directory and the files are processed without affecting the original ones.

In hydrological models, homogeneous HRUs represent the results better whereas, smaller and insignificant HRUs lead to the variation of the output. QSWAT allows the merging of smaller sub-basins and elimination of insignificant HRUs without affecting the output. The outputs generated through QSWAT can be viewed statically, dynamically or in the form of graphs, which leads to a comparison of simulated and observed outputs easily.

## Input data

The basic input files required for delineating the watershed into basins, sub-basins and HRUs are Digital elevation model (DEM), LULC map and soil map. The NASA Shuttle Radar Topographic Mission (SRTM) DEM was used to delineate the watershed boundary at a 30-m spatial resolution and to obtain topographical parameters such as slope, drainage network, etc., and is shown in Fig. 2a. The LULC map was obtained from images of LISS-III from the National Remote Sensing Centre (NRSC) with a spatial resolution of 23.5 m which is shown in Fig. 2b. Based on the data collected from KSDA's Raita-Mitra and field surveys, the entire LULC in the selected watershed was bifurcated into 14 categories and these categories along with their areas and coverage percentage throughout the watershed are depicted in Fig. 2c.

For real-time monitoring, the different types of crops grown in the study area were correlated by ground control points established with the geospatial techniques. From the data collected, it was noted that over 50% of the watershed was under cultivation. The soil map was obtained with a spatial resolution of 1:50,000 from the National Bureau of Soil Science and Land Use Planning (NBSS and LUP) and is shown in Fig. 2d. Along with the soil map, collected soil samples from the study area were analysed and seven different soil types were identified.

As per the data collected, the type of crop, its irrigational requirement, sowing and harvest periods were incorporated in the model's irrigational management aspect. Weather input data such as solar radiation, relative humidity, wind speed, maximum and minimum temperature and rainfall for a period of 32 years (1982–2013) were extracted from the rain gauge stations located at North Latitude 16° 4′ 47.28″; 16° 23′ 31.2″ and 75° 37′ 30″; 75° 56′ 15″ East Longitude and Global weather data.

### Land-cover/land-change scenarios

Perceiving the drastic changes in LULC occurring in the watershed due to construction of the dam, LULC maps of 1998 and 2009 (before and after the dam construction respectively) were obtained from images of LISS-III from the National Remote Sensing Centre (NRSC) with a spatial resolution of 23.5 m to comprehend the LULC scenarios in the watershed. It has been noted that the hydrological processes are also influenced by LULC changes in the basin. It alters the surface runoff leading to the variation of water supply and demand which, in turn, affects the groundwater recharge and soil infiltration capacity (Ghaffari et al. 2010; Wijesekara et al. 2012). The LULC changes identified in this study were based on the emphasis given to the change in agricultural land and its effect on the hydrological components such as surface runoff and recharge. The changes in the watershed before (1998) and after (2009) the completion of dam construction were analysed and the maps of the same are demonstrated in Fig. 3a, b, respectively.

## Model setup

As stated earlier, all the input data (digital elevation model (DEM), land use/land cover (LULC) data, soil data and weather details) were collected from various authenticated sources such as NASA, LISS-III Satellite Imagery and NBSS for the period 1979–2013. The weather data in a daily time scale were obtained from rain gauge stations situated near the study area and cross verified with the Global weather data. The pre-processing of input data is

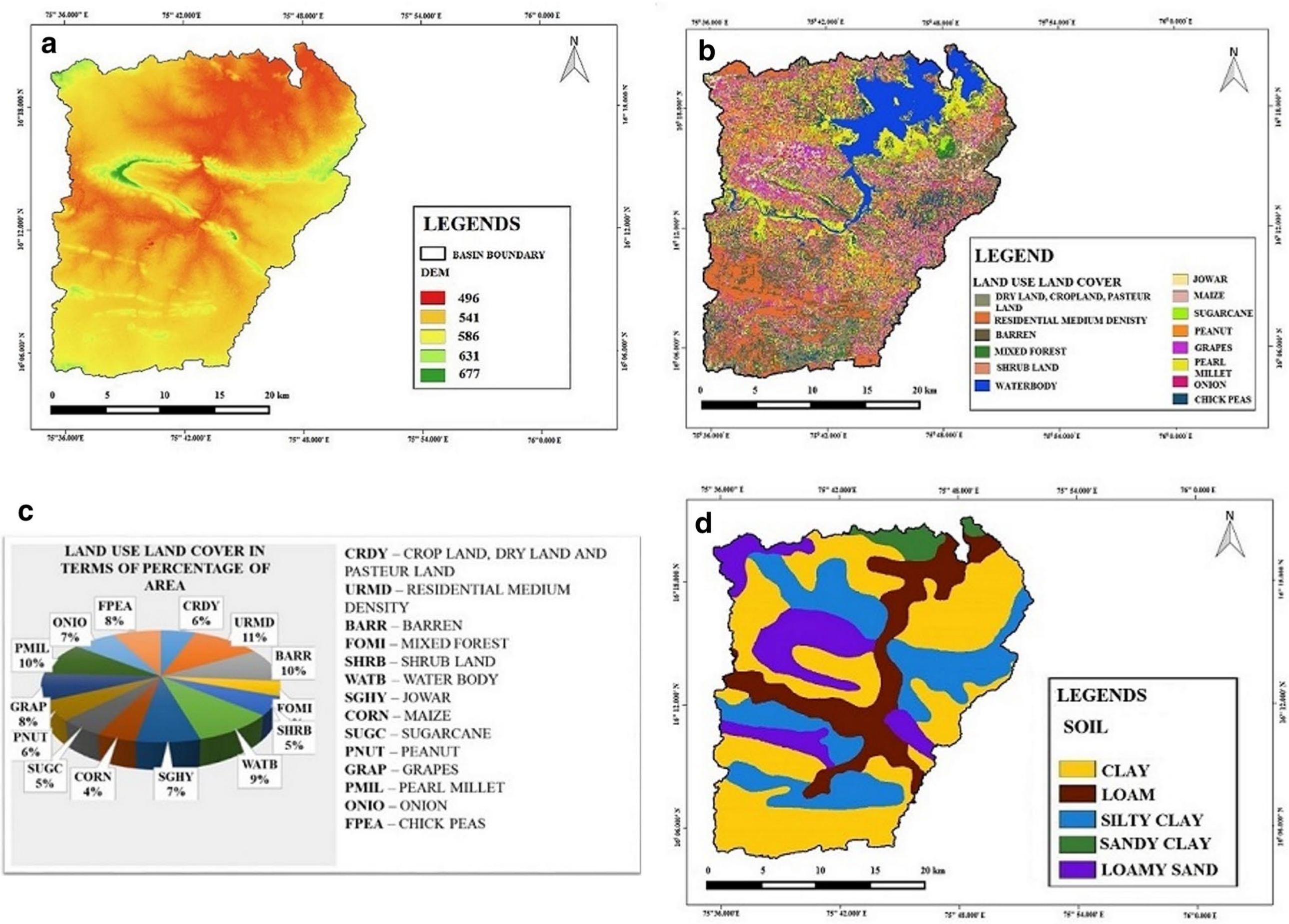


**Fig. 2** **a** DEM of the study area. **b** LULC map of the study area with its Classification. **c** LULC classifications in terms of percentage of area. **d** Soil map with its classification coverage percentage

done using QGIS. These processed DEM, LULC, soil data and weather data were used as input to QSWAT. Based on the inputs, the drainage network was prepared, it indicated two outlet points in the entire watershed and the threshold of the stream network in the watershed was delineated. The watershed was bifurcated into 37 sub-basins. Each sub-basin reach point was identified. These sub-basins were divided into hydrological response units (HRUs). The crop management practices such as sowing and harvesting times, irrigation requirements, etc. were input into the model. The QSWAT model was input with various watershed parameters and weather conditions discussed in the above sections as input and the simulation was performed for a period of 32 years (1982–2013) as the baseline scenario. QSWAT model is initially simulated and aggregated at HRU level and, further, it is transferred to sub-basin level, and finally as the output of the entire watershed. During the simulation initial three years were used up as a warm-up period. Further based on standard split mechanism, the period was bifurcated into two parts, one for calibration (27 years) and the other for validation (5 years). The model calibration, validation and sensitivity analysis were performed using SWAT-CUP, SUFI-2 algorithm. The model outputs such as water yield and surface runoff for the simulation period were obtained. This validated model was rerun to study the impact of different LULC patterns for the prior and post water storage conditions, and the hydrologic outputs were evaluated. The overall procedure followed is as per the steps depicted in the flow chart in Fig. 4.

### Model performance indices

The SWAT model performance is assessed by various indices. In this study, the performance of the model was evaluated using Nash–Sutcliffe Efficiency (NSE) (modelling efficiency index) and Coefficient of Determination ($R^2$) (the goodness of fit) (Arnold et al. 2012). The Nash–Sutcliffe efficiency is defined as a normalised statistics which determines the relative magnitude of the residual variance in comparison with the measured data variance (Gashaw et al.

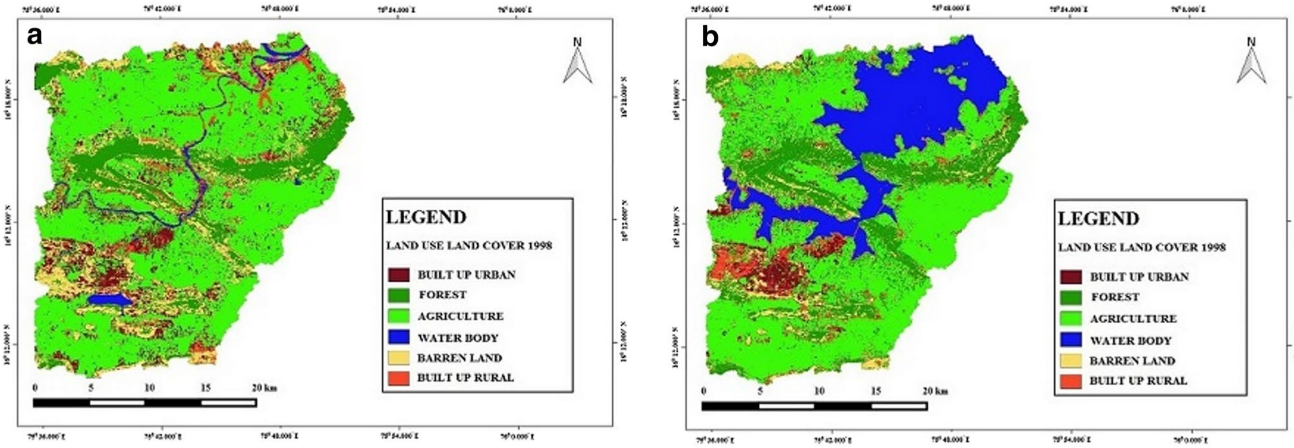


**Fig. 3** **a** LULC map of the study area in 1998; before the dam. **b** LULC map of the study area in 2009; after the dam

2018). The NSE values range from $-\infty$ to 1, usually better performance is indicated with higher values. According to Efthimiou (2016), it does not have a lower limit. The consistency between the simulated and observed data is measured with Coefficient of Determination ($R^2$). It ranges from 0 to 1, a higher value indicates less error variance (Moriasi et al. 2007).

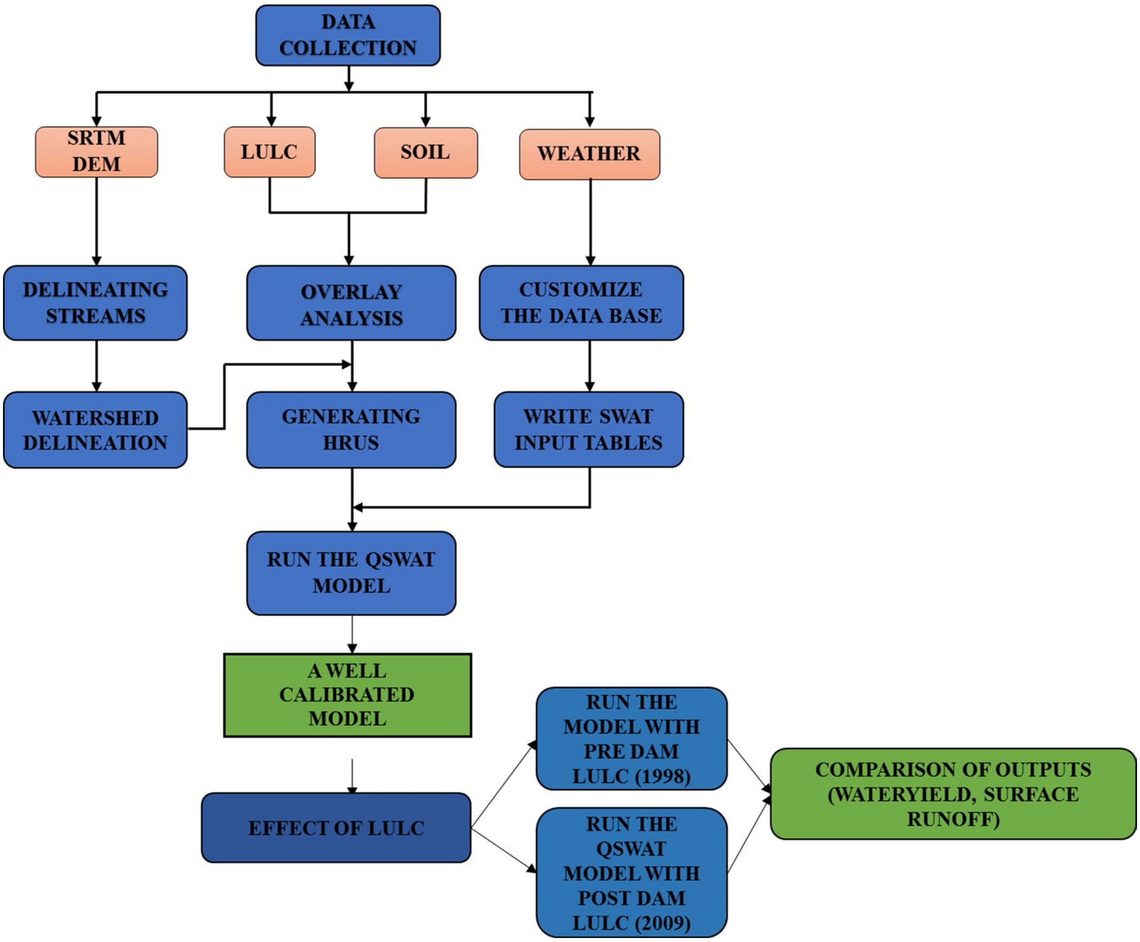


**Fig. 4** Flowchart of the processed QSWAT model

### Model calibration and validation

Auto-calibration of the model was performed by SWAT-CUP. The number of input parameters, iterations and the complexities encountered, govern the model calibration accuracy (Gevaert et al. 2010). Recently, many techniques like Markov Chain Monte Carlo method (MCMC), generalised likelihood uncertainty estimation (GLUE), parameter solution (Parasol) (Yang et al. 2008) and sequential uncertainty fitting (SUFI-2) have been related to SWAT through SWAT-CUP for calibration and uncertainty analysis. Among these, SUFI-2 was effectively adopted for model calibration, sensitivity and uncertainty analysis by Abbaspour et al. (2018) and Tang et al. (2012). The same technique was adopted by Yang et al. (2008) justified that the analysis can be performed with lesser iterations. SUFI-2 considers the parameter uncertainty from various sources of uncertainties, such as rainfall (driving variable), conceptual model, input data, etc.. Chung et al. (2010) considered SUFI-2 algorithm as the best fit for the simulation of flow.

The modelling process requires various parameters to be adjusted and numerous objectives to be satisfied, which has led to higher preference for automatic calibration over the manual calibration. Liew et al. (2005) compared the manual and automated calibration for two watersheds, namely Little Washita and Little River and indicated the better efficiency of automatic calibration. Paul and Negahban-Azar (2018) compared three different optimization algorithms, generalised likelihood uncertainty estimation (GLUE), parameter solution (Parasol) and sequential uncertainty fitting (SUFI-2) with five evaluation parameters [coefficient of determination ($R^2$), Nash–Sutcliffe efficiency (NSE), the percentage of bias (PBIAS), Kling-Gupta efficiency (KGE) and ratio of the standard deviation of observations to root mean square error (RSR)] in simulating the streamflow for a semi-arid region of San Joaquin watershed, California. The study concluded that SUFI-2 algorithm was the best suited one.

The calibration and uncertainty strength is measured by p-factor (the percentage of measured data) and d-factor (the ratio of average 95PPU band thickness and the standard deviation of measured data). The p-factor is held by 95% prediction uncertainty (95PPU) and is used to measure the uncertainties extent. 95PPU is calculated at the 2.5% and 97.5% levels of the cumulative distribution of an output variable obtained through Latin hypercube sampling (Abbaspour et al. 2018). In the initial stages, larger uncertainty is assumed within the physical range and it is gradually reduced to allow the measured data to fall within 95PPU. The process is rated based on p-factor and d-factor. For an ideal situation, p-factor is considered as a hundred percent and d-factor as zero percent (Abbaspour et al. 2007).

Sensitivity analysis is conducted with one-at-a-time sensitivity analysis, it is also known as Latin Hypercube One-Factor-At-Time (LH-OAT). The most sensitive parameter is considered as the most important parameter for the hydrological process. Sensitivity statistics are measured conforming to $t$ value and $p$ value. The $t$ value defines the measurement of sensitivity (larger values indicate greater sensitivity) and the $p$ value defines the influence of significant parameter (smaller values indicate greater sensitivity). The sensitivity parameters are assessed based on the $t$ value and are ranked accordingly (Abbaspour et al. 2007). The process followed for the calibration and sensitivity analysis is depicted in the flow chart shown in Fig. 5.

## Results and discussion

### Model simulation for the baseline scenario

Various input maps obtained from satellites and some generated using QSWAT to represent spatial variation of topographic features along with weather parameters are input to simulate the hydrodynamics of the watershed. The QSWAT and SWAT-CUP integrated with Sufi-2 algorithm for automatic calibration and sensitivity analysis was used to improve the prediction of water balance components of interest. The Model performance indices used were NSE and $R^2$. Initially, baseline scenario was run for 32 years from 1982 to 2013 (27 years were used for calibration and 5 years were used for validation). The years from 1979 to 1982 were considered as warm-up years. The warm-up period is considered to mitigate the impact of certain unknown initial conditions. After the warm-up period, the model was calibrated and validated, which is based on the standard split sample calibration and validation process (Klemeš 1985). Longer calibration period is used for better parameterization and to reduce the uncertainty in model output. The obtained relative sensitivity of the parameters influencing the surface flow and groundwater flow simulation and their details are shown in Table 1 and Fig. 6.

The results of the sensitivity analysis show that the most sensitive parameters are Alpha Bf, Gw_Delay, EPCO and CN2. Alpha Bf: the basic alpha flow factor is the direct groundwater flow response index for recharge changes varying from 0 to 1 based on the recharge response. The obtained value is near 0, which indicates a slow recharge response. Gw_Delay: the Groundwater delay time indicates the time lag between the water reaching the shallow aquifer from the existing soil profile, which cannot be directly measured. It depends on the hydraulic properties of the soil formations and the water table depth. The obtained higher value of Gw_Delay indicates that a major part of groundwater contribution is to the base flow. Hence, a decrease in surface runoff can be noted. The plant uptake compensation factor (EPCO) value varies between 0.01 and 1. As the value approaches 1,

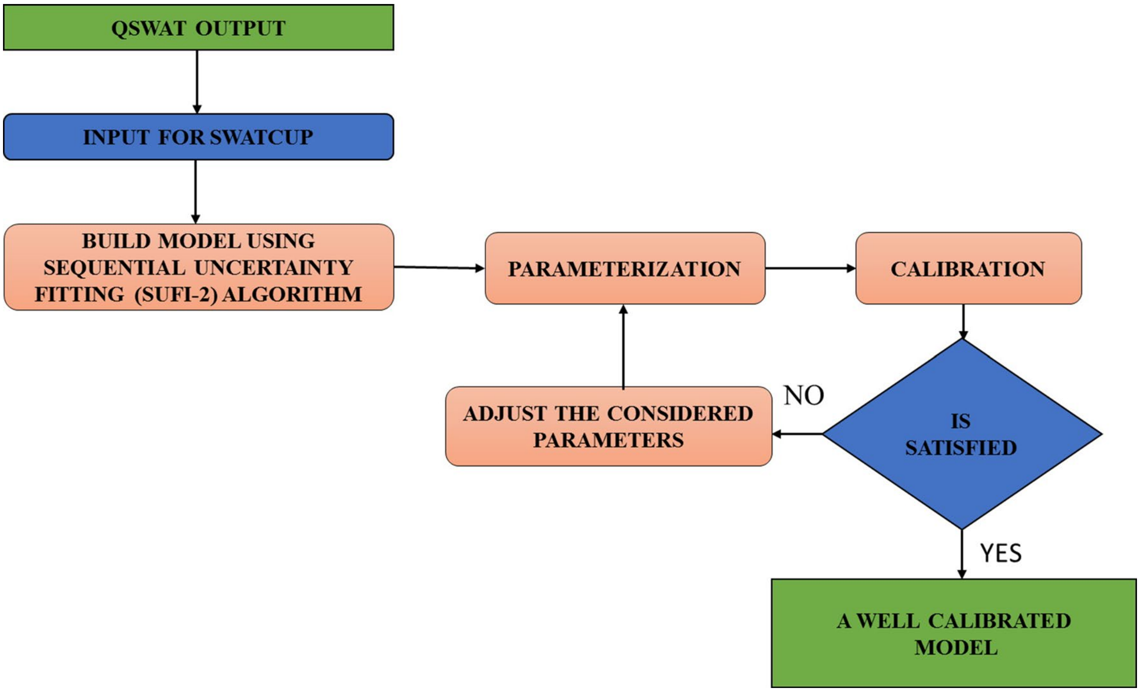


**Fig. 5** Flowchart of calibration and validation

it indicates the lesser potential in the upper layers; hence, the lower soil layers need to satisfy the demand. In this study, EPCO value is approaching 1; hence, the lower layers tend to meet the demand. The SCS curve number (CN2) is the driving factor for land use, permeability and moisture condition of the soil. It is observed that the decrease in CN2 value indicates lesser surface runoff. The obtained lower value of CN2 indicates the same. The range for good simulation obtained for CN2 co-relates the value obtained by Reshmidevi and Nagesh (2012), for Malaprabha watershed, which is another sub-basin of the Krishna river, adjacent to our study area.

The obtained model performance indices (NSE and $R^2$) for calibration and validation are depicted in Table 2. The NSE and $R^2$ calibration values are 0.89 and 0.96 respectively and the values for validation are 0.79 and 0.83 respectively. The values are greater than 0.5, hence reflect lesser error variance between simulated and observed values. Figure 7 shows the observed and simulated calibrated outflows along with 95PPU, whereas Fig. 8 shows the same after validation.

Lesser error variance shows a good correlation between the observed and simulated flow in calibration and validation. The graphical depiction of the same is shown in Figs. 7

**Table 1** The sensitivity of the identified parameters

| Parameter | Parameter description | Rank |
|---|---|---|
| V__ALPHA_BF.gw | Baseflow recession coefficient | 1 |
| A__GW_DELAY.gw | Delay time for aquifer recharge | 2 |
| V__EPCO.hru | Plant uptake compensation factor | 3 |
| R__CN2.mgt | Curve number | 4 |
| R__SOL_AWC(..).sol | Available water capacity of the soil | 5 |
| V__ESCO.hru | Soil evaporation compensation factor | 6 |
| A__GWQMN.gw | The threshold water level in the shallow aquifer for base flow | 7 |
| A__RCHRG_DP.gw | Deep aquifer percolation coefficient | 8 |
| R__SOL_K (..).sol | Saturated hydraulic conductivity of the soil | 9 |
| A__REVAPMN.gw | The threshold depth of water in the shallow aquifer for revap* | 10 |
| V__CH_K2.rte | Channel hydraulic conductivity | 11 |

*Revap is the upward movement of water from the shallow aquifer when the upper unsaturated layers are dried up

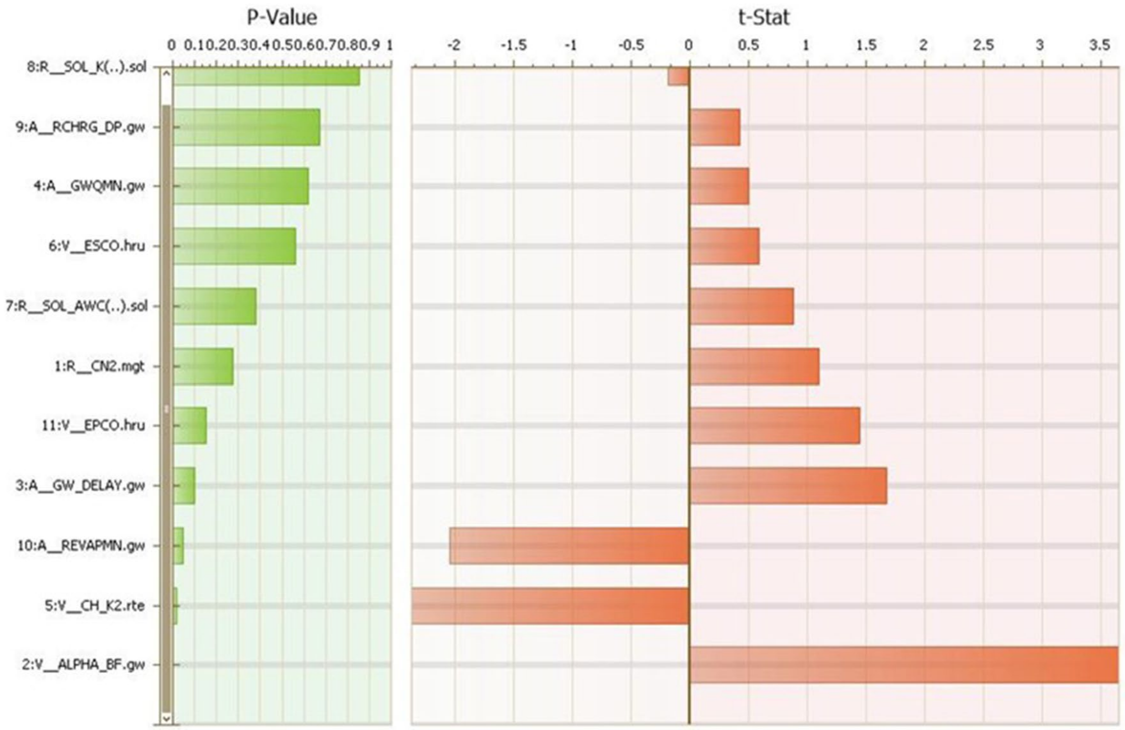


**Fig. 6** *p* value and *t* Stat value of the identified parameters

**Table 2** Model performance statistics for the calibration and validation

| Period | Evaluation of statistics | |
|---|---|---|
| | NSE | $R^2$ |
| Calibration | 0.89 | 0.96 |
| Validation | 0.79 | 0.83 |

and 8. The range for good simulation for the selected parameters is listed in Table 3.

## Analysis of LULC changes

The storage reservoir created due to the construction of the dam was intended to facilitate irrigational requirement to the surrounding agricultural fields. But in the process of water storage creation, a lot of topographic changes were induced in the watershed. To analyse the changes, two scenarios of LULC, one being before the dam construction (the year 1998) and the other being after the dam construction (the year 2009) were evaluated. The percentage-wise bifurcation of the LULC patterns of 1998 and 2009 is shown in Fig. 9.

From the analysis, it is apparent that the construction of the dam has brought about changes in the water body, built-up area and agricultural land of the watershed. Comparing the before (1998)- and after-dam (2009) scenarios, it can be observed that the water body has increased from 1.76 to 20.14%. The agricultural land has reduced from 56.31 to 43.77% and the built-up urban area has reduced from 10.75 to 5.36%. A larger area of Bagalkot district (where study area lies) has been submerged leading to the reduction in the agricultural and built-up area, which can be indicated by the prominent increase in the water body in the watershed. The forest area has also increased from 14 to 19% which is one eco-friendly aspect.

## Watershed response

Annual precipitation during the study period of 32 years is plotted in Fig. 10. It can be observed that the precipitation in the period of 1982–1998 is high, with a value crossing 800 mm, most of the time. After 2002, there is a decrease in the annual precipitation, most of it in the range of less than 800 mm. The evapotranspiration, surface runoff, and recharge of the watershed in terms of percentage of precipitation are compared in Fig. 11. Surface runoff in terms of percentage of precipitation follows a decreasing trend. From 1982 to 1998, a substantial amount of runoff is generated amounting to 25% of the precipitation, but after 2002, it has decreased to less than 20% of the annual precipitation. In the case of evapotranspiration, the effect tends to reverse as it shows an average value of less than 50% of the precipitation from 1982 to 2002. After 2002, an increasing trend in evapotranspiration can be observed with an average value greater

**Fig. 7** Observed and simulated values of outflow of calibration

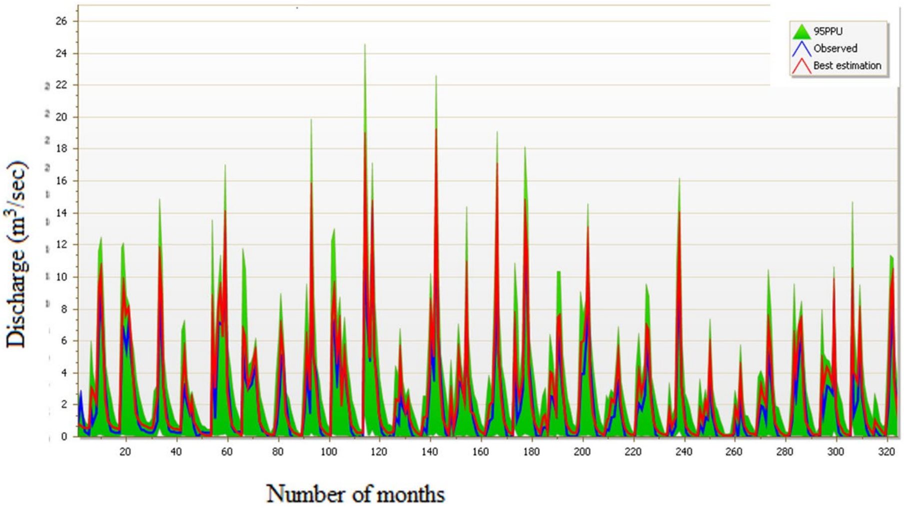


**Fig. 8** Observed and simulated values of outflow of validation

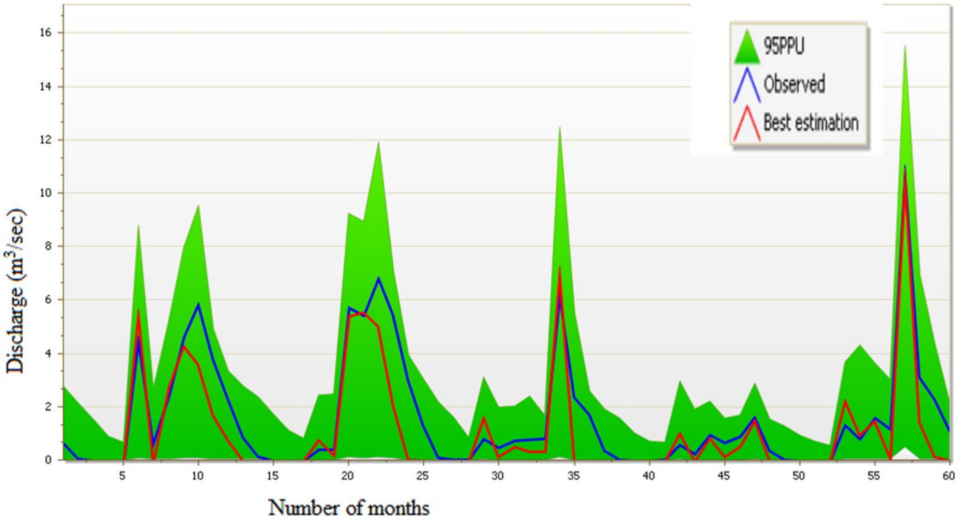


**Table 3** Selected parameter ranges for good simulation

| Sl. no. | Parameters | Range for good simulation |
|---|---|---|
| 1 | r__CN2.mgt | 9.34 to 70.11 |
| 2 | v__ALPHA_BF.gw | − 0.34 to 0.59 |
| 3 | a__GW_DELAY.gw | 186.01 to 588.99 |
| 4 | a__GWQMN.gw | 1732.57 to 5517.42 |
| 5 | v__CH_K2.rte | − 164.5 to 289.49 |
| 6 | v__ESCO.hru | 0.19 to 0.75 |
| 7 | r__SOL_AWC().sol | 0.31 to 1.03 |
| 8 | r__SOL_K().sol | − 510.33 to 1210.33 |
| 9 | a__RCHRG_DP.gw | 0.34 to 1.1 |
| 10 | a__REVAPMN.gw | 222.57 to 702.42 |
| 11 | v__EPCO.hru | 0.47 to 1.48 |

than 50% of the precipitation. The recharge rate (percentage of precipitation) values noted in the study area from the period 1982–2013, follow a uniform trend. From the period 1982–1998, the recharge rate has been observed to be above 20 mm, but after 2002 there is a reduction in groundwater recharge with its values around 15 mm. The decrement in the recharge can be attributed to a combined effect of reduced precipitation, increased evaporation and evapotranspiration, which are major influential factors. The hydrogeological factors of the study area, with major clayey upper soil layers (54.5% of the area) and deeper hard rock formations have added to lower permeability resulting in decreased recharge.

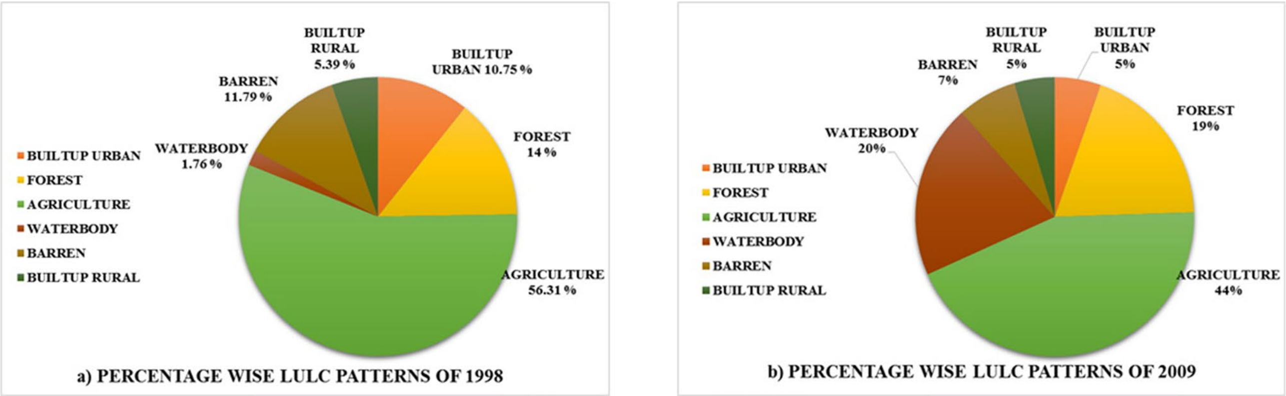


**Fig. 9** LULC changes in % **a** Pre (1998) and **b** Post dam construction period (2009)

**Fig. 10** Precipitation of the study area during the study period (1982–2013)

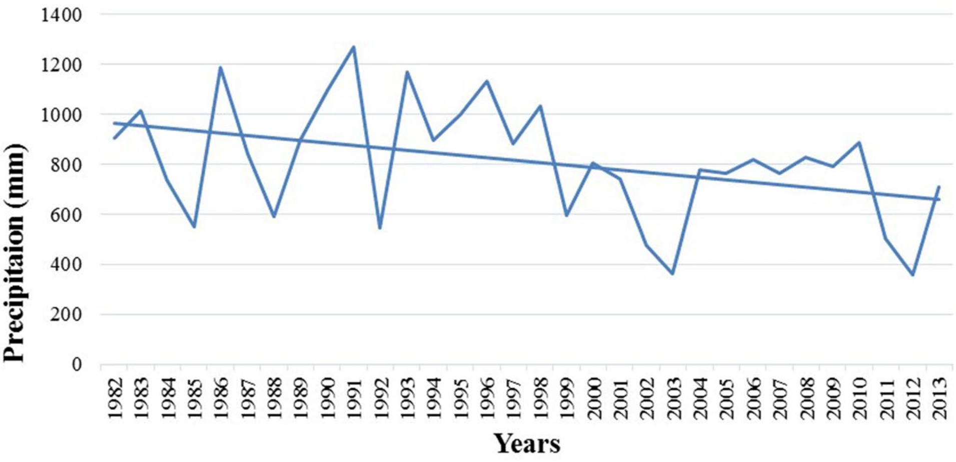
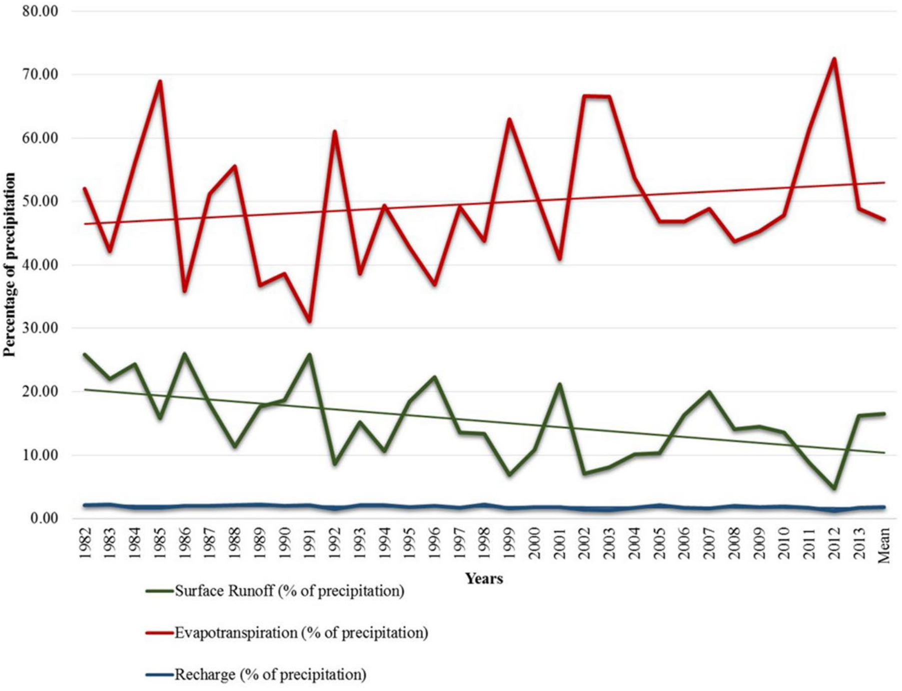


**Fig. 11** Comparison of surface runoff, evapotranspiration and recharge in terms of percentage of precipitation in the study area during the study period (1982–2013)



## Effect of LULC changes on hydrological components

The LULC changes due to the construction of the dam are very much evident. To compare the changes the validated SWAT model was simulated with LULC prior (1998) and post (2009) dam construction. The simulated outputs of the model using LULC of 1998 and 2009 such as water yield, runoff, evapotranspiration and groundwater recharge were compared and the same is depicted in Fig. 12.

From the comparative analysis of the water balance components before and after the dam construction, it can be seen that: evapotranspiration has increased from 43 to 49%, groundwater recharge has reduced from 42 to 39% and surface runoff has reduced from 15 to 12%. The modelling results for the pre and post dam construction scenario indicate that there is a decrement in the annual runoff and water yield. The results indicate 29.91% of reduction in the watershed runoff and 28.97% reduction in water yield of the watershed which is stated in Table 4.

From the calibration and validation process, we can note that the model performs well for the ungauged semi-arid watershed. The results of the statistical analysis as indicated in Table 2 depicts high values of performance indices, NSE and $R^2$ ($>0.5$). The value of indices are quite satisfactory and denotes the successful simulation of the model. At monthly time scale, the observed and simulated flow values indicate lesser discrepancies, as indicated in Figs. 7 and 8. Comparing the changes in the LULC before and after the dam construction, it can be noted that there is substantial change. Simulation of the model with varied LULC and the comparison of the obtained hydrological parameters validate the influence of these changes on the hydrological parameters of the watershed.

## Conclusions

The present study focuses on the impact of LULC changes brought about by the construction of a Dam on hydrological components of a small watershed in Krishna basin, India using QSWAT (SWAT integrated with QGIS). Automatic calibration and sensitivity analysis were performed using SWAT-CUP integrated with SUFI-2 algorithm. The required input data for the hydrological modelling were obtained from QGIS. The satellite maps obtained were used to generate the required input maps and overlayed to obtain the spatial distribution of the various topographical parameters of the watershed. Such several sets at different times indicating temporal distribution of the same helped to give precise spatial and temporal distribution of input parameters in to the QSWAT. The relative sensitivity of the parameters influencing the surface flow and groundwater flow was simulated. The results of the sensitivity analysis show that the most sensitive parameters are baseflow recession factor (Alpha Bf), groundwater delay time for aquifer recharge (Gw_Delay), Plant root water uptake compensation factor (EPCO) and curve number (CN2). The model was initially simulated for the baseline scenario for 32 years (with calibration for 27 years and validation for 5 years). SWAT is basically a model which simulates water budget of the

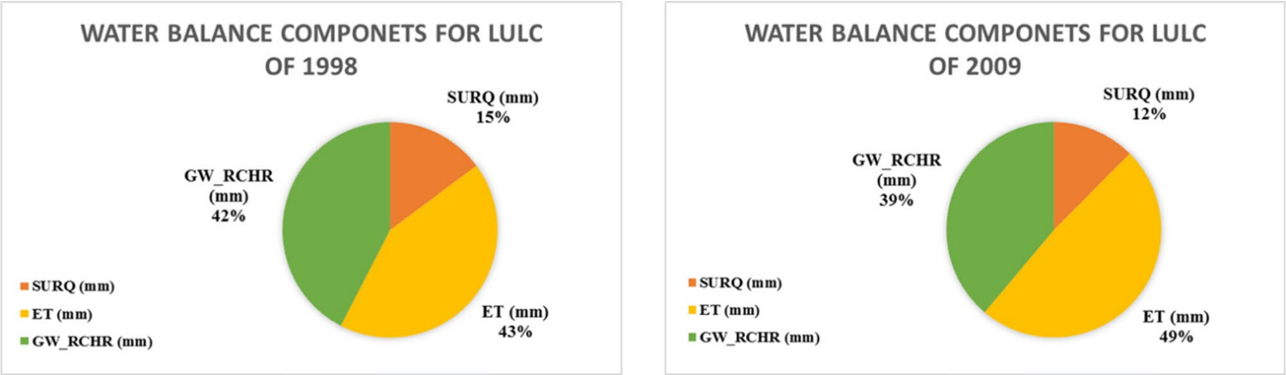


**Fig. 12** Water balance components of **a** pre (1998) and **b** post (2009) dam construction

**Table 4** Pre to post dam construction change (%) in surface runoff and water yield

| Parameters | Pre dam construction period (1998) | Post dam construction period (2009) | Pre to post dam construction change (%) |
|---|---|---|---|
| Surface runoff (mm) | 134.51 | 94.27 | − 29.91 |
| Water yield (mm) | 483.53 | 343.45 | − 28.97 |

watershed, and any missing data can be generated based on the water balance. This has helped us to generate observed flows in the study area which has no gauged flow data. The values of model performance indices (NSE and $R^2$) obtained were greater than 0.75 which indicates higher accuracy in the model performance.

Further, the calibrated model was used to analyse the impact of LULC changes on the hydrological parameters of the watershed. Two scenarios of LULC, one being before the dam (1998) and the other after the dam (2009) were used as inputs for the QSWAT to simulate the hydrological components. The comparative analysis of LULC shows an increase in the water body and forest area, along with a reduction in the agricultural land and urban built-up area. As expected, the increase in the water body and forest has resulted in an increased evapotranspiration, which is also indicated by the results. The comparative study of the effect of LULC changes before and after the dam indicates that, in the watershed, the amount of annual runoff and recharge in terms of percentage of precipitation has decreased; whereas, the evapotranspiration has increased amounting to a value greater than 50% of the precipitation. The deep aquifer recharge amounts to 1.8% of the annual precipitation, which falls within a low recharge range (Ali Rahmani et al. 2018).

The past to current change in percentage for the scenarios considered indicates 29.91% of reduction in annual runoff and 28.97% reduction in annual water yield. The evidence of the effect of LULC changes on the watershed can be indicated by the decreasing trend in the rainfall, higher percentage loss in the evapotranspiration and reduced water yield. The results obtained are alarming since 50% of the watershed is under cultivation and dependent on groundwater resources. The change in the precipitation can be correlated with the findings of Mohammad and Goswami (2019). In the study, the authors have analysed the trend and magnitude of temperature and precipitation over 139 major Indian cities. Different zones were created based on climatic factors. One of the zones, comprising the present study area, was hot steppe area. This area indicated a significant relationship between the temperature and precipitation. A decreasing trend in the precipitation was observed.

It can be concluded that the outcome of the model indicates a good agreement between the simulated and observed flow. The obtained model performance indices indicate the strong and applicable predictive capability of the model to the ungauged watershed. This study might be a small part towards the contribution of required much detailed study of the watershed and no such work has been conducted earlier in this aspect, in this basin. The lesser availability of the monitored data is a major hindrance in this study. Sustainable water resources management techniques are to be adapted in the watershed to increase the overall water yield and groundwater recharge. The local agriculturists need to be made aware of the situation and conjunctive use of surface water, as well as groundwater, needs to be adapted.

**Funding** Not applicable.

**Data availability** LULC: Obtained from images of LISS-III from the National Remote Sensing Centre (NRSC) with a spatial resolution of 23.5 m. (https://bhuvan-app3.nrsc.gov.in/data/download/index.php). Weather data: Obtained from Global Weather data (https://globalweather.tamu.edu/) and rain gauge stations located at North Latitude 16° 4′ 47.28″; 16° 23′ 31.2″ and 75° 37′ 30″; 75° 56′ 15″ East Longitude. DEM: Obtained from NASA Shuttle Radar Topographic Mission (SRTM) DEM at a 30-m spatial resolution. (https://earthexplorer.usgs.gov/). Soil map: Obtained from National Bureau of Soil Science and Land Use Planning (NBSS & LUP) with a spatial resolution of 1:50,000 (https://www.nbsslup.in/).

**Code availability** SWAT: Version 2012—the product of the USDA Agricultural Research Service, USDA- Natural Resources Conservation Services and Texas A & M. (https://swat.tamu.edu/). QSWAT: Version 1.4—an open-source software set up with Python, linked to QGIS (https://swat.tamu.edu/software/qswat/). SWAT-CUP: Version 5.1.6.2—SWAT-CUP is a calibration/uncertainty or sensitivity program interface for SWAT. (https://swat.tamu.edu/software/swat-cup/).

## Compliance with ethical standards

**Conflict of interest** We have no conflict of interest to declare.

## References

Abbaspour KC, Yang J, Maximov I, Siber R, Bogner K, Mieleitner J, Zobrist J, Srinivasan R (2007) Modelling hydrology and water quality in the pre-alpine/alpine Thur watershed using SWAT. J Hydrol 333(2–4):413–430. https://doi.org/10.1016/j.jhydrol.2006.09.014

Abbaspour KC, Vaghefi SA, Srinivasan R (2018) A guideline for successful calibration and uncertainty analysis for soil and water assessment : a review of papers from the 2016 International SWAT conference. Water. https://doi.org/10.3390/w10010006

Ali Rahmani SE, Chibane B (2017) Boucefiène A (2018) Groundwater recharge estimation in semi-arid zone: a study case from the region of Djelfa (Algeria). Appl Water Sci 7:2255–2265. https://doi.org/10.1007/s13201-016-0399-y

Arnold JG, Fohrer N (2005) SWAT2000: current capabilities and research opportunities in applied watershed modelling. Hydrol Process 19(3):563–572. https://doi.org/10.1002/hyp.5611

Arnold JG, Srinivasan R, Muttiah RS, Williams JR (1998) Large area hydrologic modeling and assessment part I: model development. J Am Water Resour Assoc 34(1):73–89. https://doi.org/10.1111/j.1752-1688.1998.tb05961.x

Arnold JG, Moriasi DN, Gassman PW, White MJ et al (2012) SWAT: model use, calibration and validation. Trans Am Soc Agric Biol Eng 55(4):1491–1508. https://doi.org/10.13031/2013.42256

Bieger K, Hörmann G, Fohrer N, Bieger K, Hörmann G, Fohrer N (2015) Detailed spatial analysis of SWAT-simulated surface runoff and sediment yield in a mountainous watershed in China. Hydrol Sci J 60(5):784–800. https://doi.org/10.1080/02626667.2014.965172

Boufala M, El A, Khalid H, Ali C, Abdelhadi E, Ouali E, Taia S (2019) Hydrological modeling of water and soil resources in the basin upstream of the Allal El Fassi dam (Upper Sebou watershed, Morocco). Model Earth Syst Environ 5:1163–1177. https://doi.org/10.1007/s40808-019-00621-y

Chen D, Shams S, Carmona-Moreno C, Leone A (2010) Assessment of open source GIS software for water resources management in developing countries. J Hydro-Environ Res 4(3):253–264. https://doi.org/10.1016/j.jher.2010.04.017

Chotpantarat S, Boonkaewwan S (2018) Impacts of land-use changes on watershed discharge and water quality in a large intensive agricultural area in Thailand. Hydrol Sci J 63(9):1386–1407. https://doi.org/10.1080/02626667.2018.1506128

Chung I, Kim N, Lee J et al (2010) Assessing distributed groundwater recharge rate using integrated surface water-groundwater modelling: application to Mihocheon watershed. South Korea Hydrogeol J 18:1253–1264. https://doi.org/10.1007/s10040-010-0593-1

Dagnew A, Philip T, Gassman Silvia W (2016) Modeling agricultural watersheds with the soil and water assessment tool (SWAT): calibration and validation with a novel procedure for spatially explicit HRUs. Environ Manage 57:894–911. https://doi.org/10.1007/s00267-015-0636-4

Dile YT, Daggupati P, George C, Srinivasan R, Arnold J (2016) Introducing a new open source GIS user interface for the SWAT model. Environ Model Softw 85(November):129–138. https://doi.org/10.1016/j.envsoft.2016.08.004

Efthimiou N (2016) Hydrological simulation using the SWAT model: the case of Kalamas river catchment. J Appl Water Eng Res 6(3):210–227. https://doi.org/10.1080/23249676.2016.1265471

Garg KK, Bharati L, Gaur A, George B, Acharya S, Jella K, Narasimhan B (2012) Spatial mapping of agricultural water productivity using the SWAT model in upper Bhima catchment. India Irrig Drain 61(1):60–79. https://doi.org/10.1002/ird.618

Gashaw T, Tulu T, Argaw M, Worqlul AW (2018) Modeling the hydrological impacts of land use/land cover changes in the Andassa watershed, Blue Nile Basin. Ethiopia Sci Total Environ 619–620(November):1394–1408. https://doi.org/10.1016/j.scitotenv.2017.11.191

Gassman PW, Reyes MR, Green CH, Arnold JG (2007) The soil and water assessment tool: historical development, applications and future research directions. Trans Am Soc Agric Biol Eng 50(4):1211–1250

Gassman PW, Sadeghi AM, Srinivasan R, Rock W (2014) Applications of the SWAT model special section: overview and insights. J Environ Quality 43(1):1–8. https://doi.org/10.2134/jeq2013.11.0466

Gevaert V, Van Griensven A, Holvoet K, Vanrolleghem PA (2010) SWAT developments and recommendations for modelling agricultural pesticide mitigation measures in River basins. Hydrol Sci J. 53(5):1075–1089. https://doi.org/10.1623/hysj.53.5.1075

Ghaffari G, Keesstra S, Ghodousi J, Ahmadi H (2010) SWAT-simulated hydrological impact of land-use change in the Zanjanrood basin, Northwest Iran. Hydrol Process 24(7):892–903. https://doi.org/10.1002/hyp.7530

Gosain AK, Rao S, Basuray D (2006) Change Impact assessment on hydrology of Indian river basins. Curr Sci 90(3): 346–353. https://www.pik-potsdam.de/~luedeke/yws0910/gosain06_CC_Indian_river_basin.pdf

Gyamfi C, Musyoka J, Geophrey N, Anornu K, Kifanyi GE (2017) Groundwater recharge modeling in a large scale basin : an example using the SWAT hydrologic model. Model Earth Syst Environ 3:1361–1369. https://doi.org/10.1007/s40808-017-0383-z

Jadhao VG, Jadhao AK, Tripathi MP (2010) Estimation of monthly surface runoff and sediment yield from a small watershed by using simulation technique. Int J Agric Eng 2(2):278–284

Kim NW, Arnold JG (2008) Development and application of the integrated SWAT—MODFLOW model. J Hydrol 356(1–2):1–16. https://doi.org/10.1016/j.jhydrol.2008.02.024

Klemeš V (1985) Operational testing of hydrological simulation models. Hydrol Sci J 31(1):13–24. https://doi.org/10.1080/02626668609491024

Krysanova V, Arnold JG (2008) Advances in ecohydrological modelling with SWAT—a review. Hydrol Sci J 53(5):939–947. https://doi.org/10.1623/hysj.53.5.939

Krysanova V, White M (2015) Advances in water resources assessment with SWAT—an overview. Hydrol Sci J 60(5):771–783. https://doi.org/10.1080/02626667.2015.1029482

Kumar N, Singh SK, Singh VG et al (2018) Investigation of impacts of land use/land cover change on water availability of Tons River Basin, Madhya Pradesh, India. Model Earth Syst Environ 4:295–310. https://doi.org/10.1007/s40808-018-0425-1

Mohammad P, Goswami A (2019) Temperature and precipitation trend over 139 major Indian cities: an assessment over a century. Model Earth Syst Environ 5:1481–1493. https://doi.org/10.1007/s40808-019-00642-7

Moriasi DN, Arnold JG, Van Liew MW, Bingner RL, Harmel RD, Veith TL (2007) Model evaluation guidelines for systematic quantification of accuracy in watershed. Trans ASABE 50(3):885–900. https://doi.org/10.13031/2013.23153

Narsimlu B, Gosain AK, Chahar BR et al (2015) SWAT model calibration and uncertainty analysis for streamflow prediction in the Kunwari River Basin, India. Using Sequential Uncertain Fitting Environ Process 2:79–95. https://doi.org/10.1007/s40710-015-0064-8

Ndomba P, Mtalo F, Killingtveit A (2008) SWAT model application in a data scarce tropical complex catchment in Tanzania. Phys Chem Earth Parts A/B/C 33(8):626–632

Neitsch SL, Arnold JG et al (2009) Soil & Water Assessment Tool Theoretical Documentation Version 2009.Texas Water Resources Institute Technical report no. 406 https://swat.tamu.edu/media/99192/swat2009-theory.pdf

Paul M, Negahban-Azar M (2018) Sensitivity and uncertainty analysis for streamflow prediction using multiple optimization algorithms and objective functions: San Joaquin Watershed. California Model Earth Syst Environ 4:1509–1525. https://doi.org/10.1007/s40808-018-0483-4

Reshmidevi TV, Nagesh KD (2012) Modelling the impact of extensive irrigation on the groundwater resources. Hydrol Process 28(3):628–639. https://doi.org/10.1002/hyp9615

Rouhani H, Willems P, Wyseure G, Feyen J (2007) Parameter estimation in semi-distributed hydrological catchment modelling using a multi-criteria objective function. Hydrol Process 21(22):2998–3008. https://doi.org/10.1002/hyp.6527

Sisay E, Halefom A, Khare D, Singh L, Worku T (2017) Hydrological modeling of an ungauged urban watershed using SWAT model. Model Earth Syst Environ 3:693–702. https://doi.org/10.1007/s40808-017-0328-6

Suryavanshi S, Pandey A, Chaube UC (2017) Hydrological simulation of the Betwa River Basin (India) using the SWAT model. Hydrol Sci J 62(6):960–978. https://doi.org/10.1080/02626667.2016.1271420

Tang FF, Xu HS, Xu ZX (2012) Model calibration and uncertainty analysis for runoff in the Chao river basin using sequential uncertainty fitting. Proc Environ Sci 13:1760–1770. https://doi.org/10.1016/j.proenv.2012.01.170

Tripathi MP, Panda RK, Raghuwanshi NS (2003) Identification and prioritisation of critical sub-watersheds for soil conservation management using the SWAT model. Biosys Eng 85(3):365–379. https://doi.org/10.1016/S1537-5110(03)00066-7

Tuppad P, Douglas Mankin KR, Lee T, Srinivasan R, Arnold JG (2011) Soil and water assessment tool (SWAT) hyrologic/water quality model: extended capability and wider adoption. Trans Am Soc Agric Biol Eng 54(5):1677–1684. https://doi.org/10.13031/2013.39856

Tyagi S, Singh N, Sonkar G et al (2019) The sensitivity of evapotranspiration to climate change using the DSSAT model in sub-humid climate region of Eastern Uttar Pradesh. Model Earth Syst Environ 5:1–11. https://doi.org/10.1007/s40808-018-0513-2

Van Liew MW, Arnold JG, Bosch DD (2005) Problems and potential of autocalibrating a hydrological model. Trans Am Soc Agric Eng 48(3):1025–1040

Welde K, Gebremariam B (2017) Effect of land use land cover dynamics on hydrological response of watershed: case study of Tekeze Dam Watershed, Northern Ethiopia. Int Soil Water Conserv Res 5(1):1–16. https://doi.org/10.1016/j.iswcr.2017.03.002

Wijesekara GN, Gupta A, Valeo C, Hasbani JG, Qiao Y, Delaney P, Marceau DJ (2012) Assessing the impact of future land-use changes on hydrological processes in the elbow river watershed in Southern Alberta, Canada. J Hydrol 412–413:220–232. https://doi.org/10.1016/j.jhydrol.2011.04.018

Woldemichael AT, Hossain F, Pielke R Sr, Beltrán-przekurat A (2012) Understanding the impact of dam-triggered land use/land cover change on the modification of extreme precipitation. Water Resour Res. https://doi.org/10.1029/2011WR011684

Wu F, Zhan J, Hongbo Su, Yan H, Ma E (2015) Scenario-based impact assessment of land use/cover and climate changes on watershed hydrology in Heihe River basin of Northwest China. Advances in Meterology. https://doi.org/10.1155/2015/410198

Yang J, Peter Reichert KC, Abbaspour JX, Yang H (2008) Comparing uncertainty analysis techniques for a SWAT application to the Chaohe Basin in China. J Hydrol 358(1–2):1–23. https://doi.org/10.1016/j.jhydrol.2008.05.012

Zhang X, Srinivasan R, Van Liew M (2008) Multi-site calibration of the SWAT model for hydrological modeling. Trans Am Soc Agric Biol Eng 51(6):2039–2049