

# Application of SWAT in an Indian river basin for modeling runoff, sediment and water balance

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**Abstract** The present study integrated remote sensing derived products, gridded precipitation and temperature data, and the Soil and Water Assessment Tool (SWAT) within a geographic information system modeling environment to evaluate the hydrology, sediment yield and water balance for a medium-sized Ken basin of Central India. The entire basin was divided into 10 sub-basins comprising 143 hydrological response units on the basis of unique land cover, soil and slope classes using the SWAT model. Monthly and daily calibrated (1985–1995) and validated (1996–2005) SWAT model used the observed discharge and sediment data of the Banda site of the Ken basin. The runoff simulation was good on daily basis ( $R^2 = 0.766$  and  $0.780$  for calibration and validation period, respectively) and was further improved (very good) on monthly basis ( $R^2 = 0.946$  and  $0.959$  for calibration and validation period, respectively). The sediment simulation was considerable on daily basis ( $R^2 = 0.429$  and  $0.379$  for calibration and validation period, respectively) and was further improved (good) on monthly basis ( $R^2 = 0.748$  and  $0.721$  for calibration and validation period, respectively). The water balance study of the basin showed that evapotranspiration is more predominant accounting for about 44.6% of the average annual precipitation falling over the area. The average annual sediment yield of the basin was

found to be 15.41 t/ha/year, which falls under high erosion class.

**Keywords** GIS · HRU · Ken basin · Sub-basin · Remote sensing · SWAT

## Introduction

“Scarcity and misuse of fresh water causes a critical and spreading threat to sustainable development, management and protection of the water resources. Unless land resources and water are managed more efficiently in the present decade and beyond than they have been in the past, food security, human health and welfare, industrial development and the ecosystems on which they depend, are all at risk” (ICWE 1992). Korzoun and Sokolov (1978) estimated that total volume of water on earth is about 1386 BCM (million km<sup>3</sup>), out of which only a small fraction, i.e., only 2.53%, is freshwater on the earth. Major part of this freshwater lies frozen in polar regions or is in inaccessible deep aquifers and thus not available for use. It is estimated that the annual renewable freshwater supply in the world is about 44800 BCM (Shiklomanov 1998), evaluated as the difference between the estimated annual precipitation and evaporation on the land surface. This amounts only to about 0.13% of total freshwater on earth. The annual renewable surface water potential of India is estimated as 1869 BCM by Central Water Commission (CWC 2005). At national level, the per capita availability of water was about 3074 cubic meters in 1975 which has been reduced to the 1882 cubic meters in 2001 and is likely to reduce to about 1434 cubic meter in 2025 (CWC 2005). This complicates the challenge of management and development of water resources in a sustainable manner in the light of the

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pressure of population increase, climate change and economic growth.

The past four decades are marked as the development and refinement of hydrological models, and it is required to understand thoroughly their characteristics to effectively use their services (Jajarmizadeh et al. 2012). Hydrological models are categorized on the basis of temporal and spatial scales used, presentation of different processes, and methods of solution to equations used (Singh 1995). The nature of basic algorithms (empirical, conceptual or process based) is the main characteristics for distinguishing the approaches: whether a deterministic or stochastic approach is taken to parameter specification or input and whether the spatial representation is lumped or distributed. With the development of computational capabilities and algorithm supported with newly available distributed database like high-resolution digital elevation models (DEMs), remotely sensed satellite data, radar rainfall and space technology, a variety of models have been developed and these are available for applications in variety of water resource problems (Pandey et al. 2016). Remote sensing and GIS can provide the appropriate platform for convergent of large volume of multi-disciplinary data required for hydrological modeling (Himanshu et al. 2013). Among these models, the Areal Nonpoint Source watershed Environment Response Simulation (ANSWERS) (Beasley et al. 1980), Precipitation Runoff Modeling System (PRMS) (Leavesley et al. 1983), Agricultural Nonpoint Source model (AGNPS) (Young et al. 1989), Water Erosion Prediction Project (WEPP) (Lafren et al. 1991), CASCade of planes in 2-Dimensions (CASCAD) (Julien and Saghafian 1991), Hydrological Simulation Program-Fortran (HSPF) (Bicknell et al. 1993), MIKE 11 (MIKE 1995), Soil and Water Assessment Tool (SWAT) (Arnold et al. 1998), Large-Scale Catchment Model (LASCAM) (Viney and Sivapalan 1999), Dynamic Watershed Simulation Model (DWSM) (Borah et al. 1999), Systeme Hydrologique European-TRANsport (SHETRAN) (Ewen and Parkin 2000) are few being used widely.

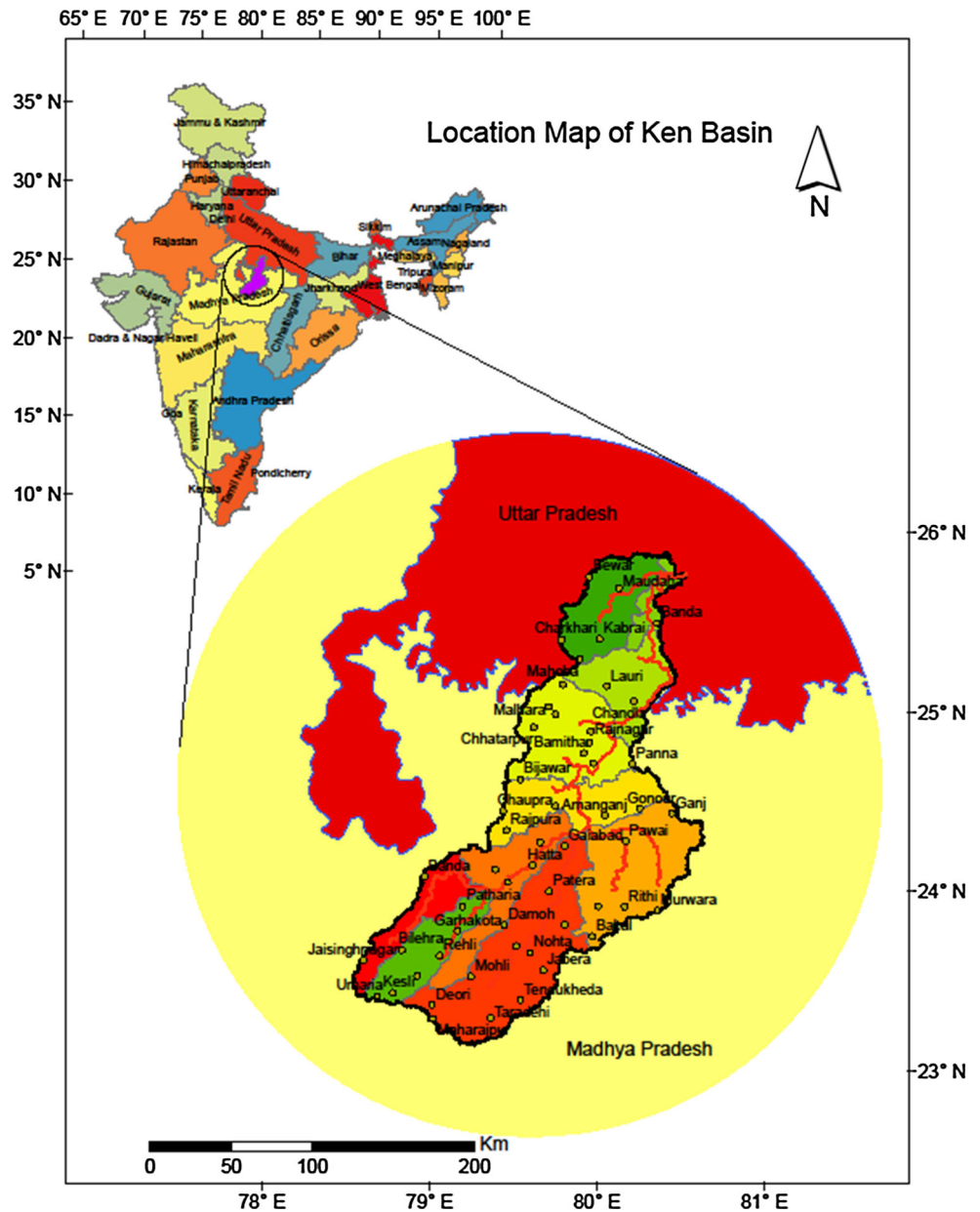
SWAT is process-based, semi-distributed, continuous-time scale river basin model (Arnold et al. 2012). It has been employed widely to estimate the hydrological and water quality impacts of agricultural practices and land management (Arnold and Fohrer 2005; Miller et al. 2007). Hydrological simulation is the primary step for all the SWAT applications whatever may be the focus of study. Different statistical tools have been used for evaluation of the SWAT hydrological simulations. The most extensively tool used for statistics for hydrological evaluation is the Nash–Sutcliffe model efficiency (NSE) (Nash and Sutcliffe 1970) and the regression correlation

coefficient ( $r^2$ ). Moriasi et al. (2007) recommended that, in order for modeling results to be satisfactory, the value of NSE should exceed 0.5. SWAT model has been tested for runoff simulation by several researchers globally (Ndomba et al. 2008; Rouhani et al. 2009; Kusre et al. 2010; Jiang et al. 2011; Akiner and Akkoyunlu 2012), and they reported satisfactory performance. Some of the feeble results may be as a result to insufficient rainfall inputs representation, either due to inadequate rain gauge network in the simulated sub-watershed or watershed configurations that were too coarse to cover the rainfall inputs spatial details (Cao et al. 2006). Inaccuracies in estimated runoff data (Harmel et al. 2006), paucity of model calibration (Bosch et al. 2004; Jayakrishnan et al. 2005) and relatively shorter period of calibration and validation (Chanasyk et al. 2003) are some other factors which may have adverse effects on SWAT hydrological evaluations.

Most of the literature cited the robustness of the SWAT model in evaluation of the sediment yield (Xu et al. 2009; Oeurng et al. 2011; Moriasi et al. 2011; Qiu et al. 2012; Ayana et al. 2012), yet there are some poor results also. Due to dependence of the SWAT model on different empirical and semiempirical models, such as MUSLE and SCS-CN, model evaluates specific sediment load and peak runoff less accurately (Qiu et al. 2012). Their results showed that SWAT can predict monthly surface runoff reasonably, while the monthly sediment load, especially high values, was frequently underestimated. In most of the river basins, continuous data for discharge and sediment yield are not available. Schmalz et al. (2015) assessed SWAT in a data-scarce Chinese river basin for evaluation of surface runoff and sediment yield. Worldwide application of the SWAT demonstrated the flexibility and robustness of the model for applications in a diversity of watershed simulation problems.

Murty et al. (2014) carried out yearly and monthly simulation of runoff for the Ken River basin. There is huge possibility of water resources planning and development over the Ken River basin considered being underexploited, as there is no major projects existing either on any of the tributaries or on the main river (Murty et al. 2014). Looking to the aforementioned, present study was carried out primarily to evaluate the runoff, sediment yield and water balance of the Ken River basin using satellite data, GIS and SWAT model on monthly and daily basis. Further, sub-basin annual average water balance and monthly breakup of average annual water balance over the entire basin were estimated. A detailed erosion study was also carried out to understand the severity of erosion in the Ken basin which can provide a guideline for recommendations of the best management practices (BMPs).

**Fig. 1** Location map of the Ken River basin



**Study area**

The study area covers the whole Ken River basin. The Ken River originated from Ahirgawan village of the Kaimur hills (northwest slopes) in Jabalpur district of Madhya Pradesh (MP) at an elevation of about 550 meters above mean sea level (msl). The Ken is an interstate river between MP and Uttar Pradesh (UP). From its origin, the total length of the river up to the confluence with the Yamuna River is 427 km, out of which 292 km lies in MP, 84 km in UP and 51 km forms the common boundary between MP and UP. The Ken River joins the river Yamuna near Chilla village in UP at an elevation of about 95 m above msl. Before the Yamuna River joins the Ganga

River, the Ken River is the last tributary of Yamuna. The Ken River basin lies between the latitudes of 23°8'3"N and 25°53'15"N and longitudes 78°30'57"E and 80°37'53"E as shown in Fig. 1. The total catchment area of the Ken River basin is 28,672 km<sup>2</sup>, out of which 24,841 km<sup>2</sup> lies in MP and the remaining 3831 km<sup>2</sup> in UP. The important tributaries of the Ken River are Kali, Alona, Shyamari, Mirhasan, Bearma, Sonar, Urmil, Kutri, Banne and Chandrawal.

The climate of the area is semiarid to dry sub-humid. The average annual rainfall over the study area (1982–2005) is about 1133 mm out of which about 94% is received during five months (June to October) of monsoon period. The average minimum and maximum temperatures

are 2.0 and 47.6 °C, respectively. The minimum and maximum monthly mean relative humidity ranges from 9 to 95%, respectively, during monsoon and summer seasons.

## Materials and methods

In the present study, SWAT model was employed for simulation of runoff, sediment yield and water balance studies of the Ken River basin. To create a SWAT dataset, it required ArcGIS compatible raster (GRIDS) and vector datasets (shape files and feature classes) and database files in the SWAT formats, to provide information about the watershed. The SWAT model requires four type of dataset, viz. hydro-meteorological, soil, topographical and land use (management) data for evaluating the hydrological processes.

The principal datasets within hydro-meteorological datasets are hydrological data such as stream flow data, sediment concentration data, weather data and respective spatial information describing the location of stations. Discharge data and total suspended sediment data for the years 1982–2005 (24 years) of the Banda G & D site on river Ken were collected from Central Water Commission (CWC) which covers more than 88% of the study area. The sediment concentration in the Ken River seems to be high with annual average value of 110.8 mg/lit. The sediment concentration is approximately 276–534 mg/lit during flood season. India Meteorological Department (IMD) has recently published high-resolution gridded daily data of precipitation and temperature at a grid interval of 0.5° and 1.0°, respectively, for the whole country India, prepared using data of 1803 precipitation stations. Twenty-three grid points of precipitation cover the study area and are considered in this study. The gridded precipitation and temperature data of the years 1982–2005 were used in the current study. The SWAT model assigns rainfall data of only one rain gauge station to all the HRUs in one sub-basin. To overcome this, weighted rainfall for each of the 10 sub-basins is computed considering all the 23 precipitation grid points using Thiessen's polygon method.

The DEM is used for watershed and stream network delineation and the computation of several geo-morphological parameters of the catchment including slope for HRU definition. The Shuttle Radar Topography Mission (SRTM) elevation DEM data downloaded from the <http://srtm.csi.cgiar.org> were used in the present study. The processed DEM was supplied to ArcSWAT for watershed delineation. The minimum, mean and maximum elevation of the study area was found to be 86, 344 and 750 m, respectively. A threshold value of 15000 ha was used in this study to delineate streams and outlet points for defining

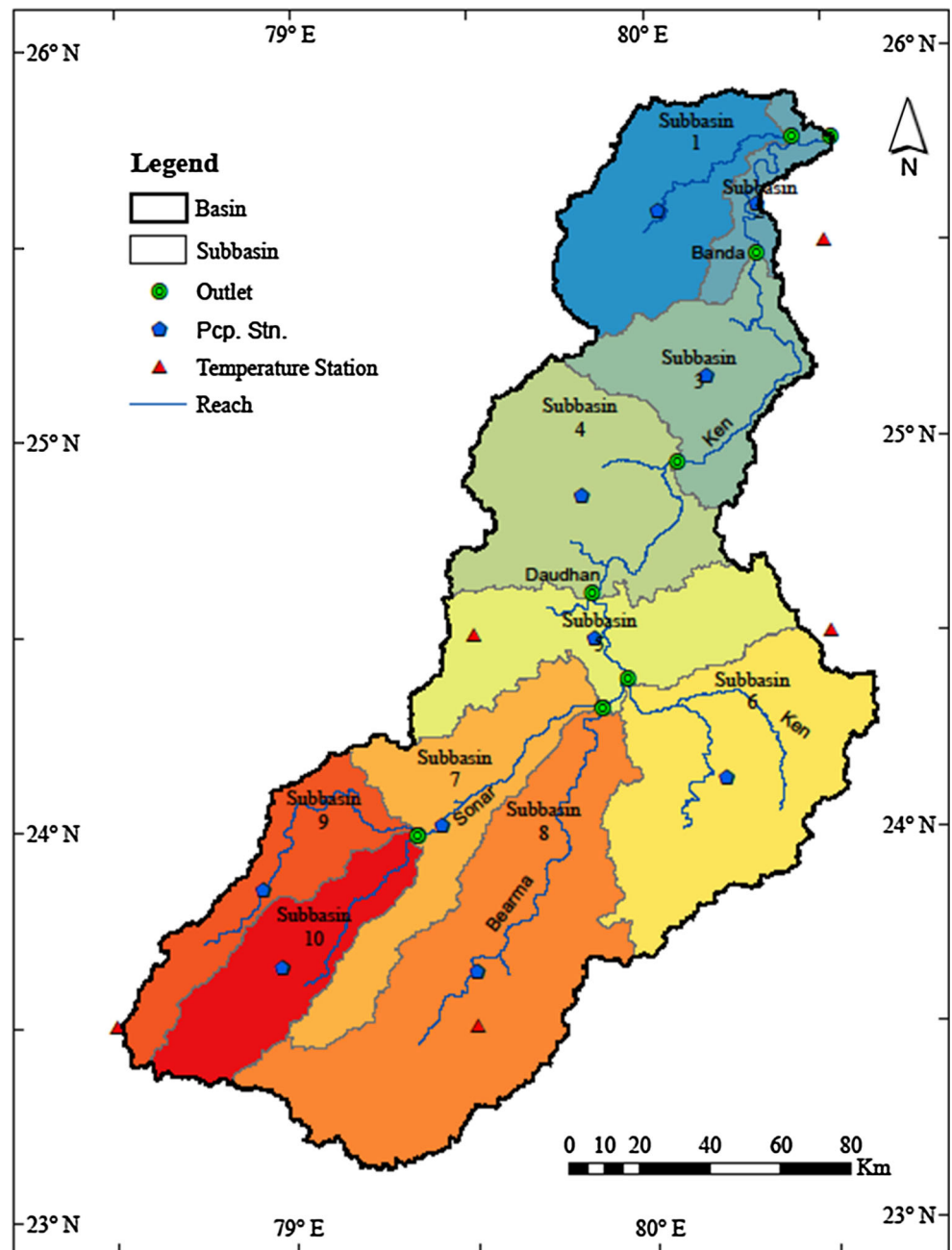
sub-basins. Further, the study area was divided into 10 sub-basins such that the system is kept relatively simple and to enable analysis as required. The sub-basin division map and drainage map of the study area are presented in Figs. 2 and 3, respectively.

The land use/land cover data are required in the SWAT model for HRU definition and subsequently for assigning the curve numbers (CN) to different combinations of land use and soil for runoff computations and hydrological analysis. The land use/land cover of an area is one of the major factors which affect surface runoff, erosion and evapotranspiration in a watershed during evaluation (Neitsch et al. 2011). Land use map of the study area was developed from classification of the Landsat Thematic Mapper (TM) satellite data pertaining to November 09, 2011. The image was classified using ArcGIS 10 into five land use/land cover classes, viz. (1) built-up area, (2) water bodies, (3) cultivable land, (4) barren/waste land and (5) forest. The classified image was further processed with post-classification processes available in GIS. The accuracy assessment of the classified image was carried out with the help of latest available maps, toposheets and images from Google Earth. The overall classification accuracy and Kappa coefficient were found to be 83% and 0.73, respectively. The classified land use/land cover map of the study area is presented in Fig. 4. The sub-basin-wise areas under different classes of land use, applied in the HRU definition are furnished in Table 1. Table 1 shows that cultivable land accounts for more than 61% of the area, whereas forest land accounts for about 28% of the study area.

For HRU definition in the SWAT, the topography of the study area needs to be grouped into various convenient slope intervals, such that the area with unique land use, soil group and topographical features represented by the slope is lumped together to define HRUs. In this study, the slope map was generated from the DEM and reclassified. The study area was divided into 3 slope groups, viz. 0–7%, 7–18% and more than 18%. The soil map of the study area was procured from the “National Atlas and Thematic Mapping Organization, Government of India.” In the study area, eight different soil types were identified. Spatial distribution of soil types in the study area is presented in Fig. 5.

The hydrological analysis in the SWAT model was carried out at HRU level, in daily time steps. HRUs are lumped land areas within each sub-basin with unique slope, land cover, soil and management combinations. The land use/land cover map, soil map and DEM of the study area were overlaid, and threshold values were assigned to each parameter, viz. land use, soil type and slope. Area below the given respective threshold values is ignored while delineating the HRUs. In the present study, threshold

**Fig. 2** Delineated sub-basin and reach map of the study area including weather stations

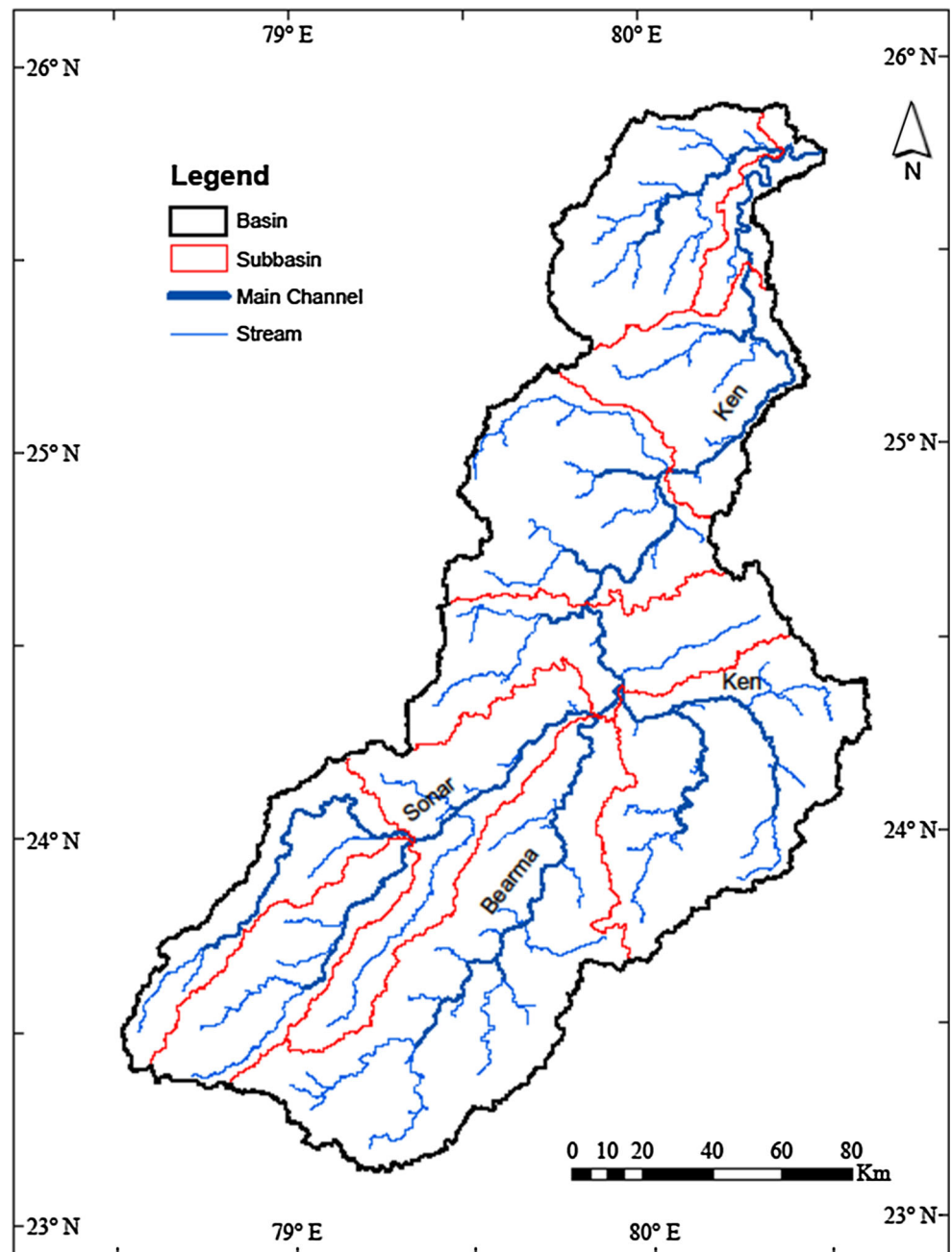


values of 1, 2 and 3% were considered for land use, slope and soil class, respectively, and 143 HRUs (representing homogeneous land use, slope and soil) were formed over 10 sub-basins spread in the study area. It is used to determine the area and the hydrological parameters of each land-soil category simulated within each sub-basin. Once the overlay is completed, a detailed report is added to the current project. This report describes the land use, soil and slope class distribution within the basin and within each sub-basin unit. Average area of HRUs in the study area was found to be 200.50 km<sup>2</sup>, the maximum and minimum areas being 2106.94 and 0.09 km<sup>2</sup>, respectively.

Built-in weather generator module available in the SWAT model was used to fill up missing rainfall data and to simulate weather parameters for which observed data are not available. The weather generator requires monthly parameters of mean rainfall, standard deviation, skewness, details of dry days, wet days, etc., mean values of temperature (maximum, minimum, due point), wind speed and solar radiation. Five weather generator stations were prepared for the study area, and required files for each of the stations were prepared by supplying above-mentioned data to the SWAT weathergen.xls which is available at the SWAT Web site. Finally, the weather generator file



**Fig. 3** Drainage map of the Ken River basin



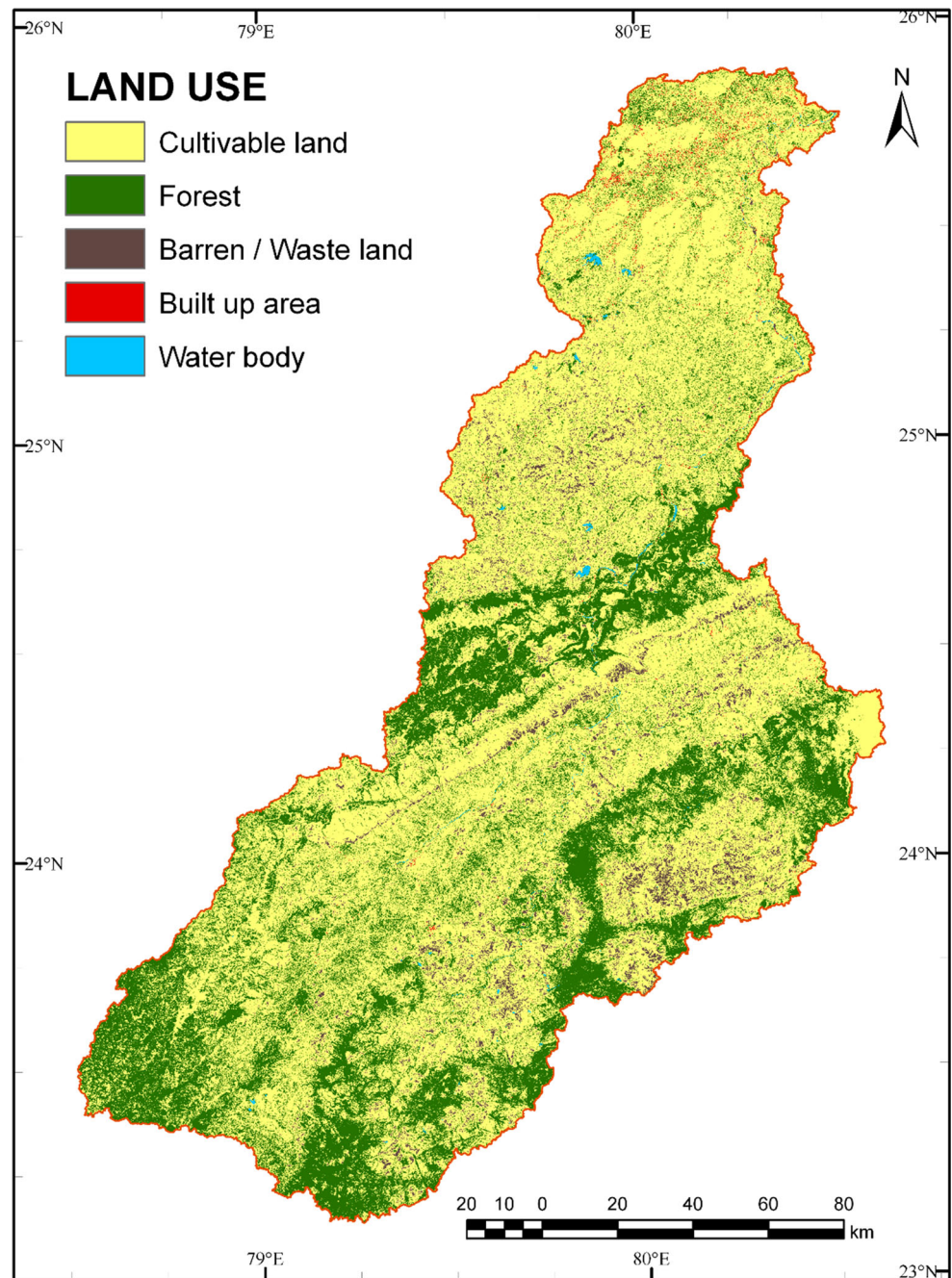
(.WGN) was created and supplied to the SWAT model through the weather generator input file. Similarly, station-wise daily values of rainfall and maximum and minimum temperature were supplied through input database files.

As there are no major existing storage projects on the Ken River, reservoirs or ponds are not included in the present study. Further, though the SWAT can simulate pesticide/nutrient loadings also, the same were kept out of scope of the present study. In this study, the total simulation period of January 1, 1982, to December 31, 2005, was divided into 4 years of warm-up period (January 1, 1982 to December 31, 1985), 10 years of

calibration period (January 1, 1986 to December 31, 1995) and 10 years of validation period (January 1, 1996 to December 31, 2005).

In this study, calibration of both stream runoff and sediment was carried out. Objective function was first defined which is sum of squared residuals (SSQ). Parameter solution method (Parasol) method was selected as method of calibration in this study. Twenty-seven sensitive parameters for runoff and sediment were considered for calibration, and the model was run for validation period with 3000 runs. Using the model's built-in sensitivity analysis methods, sensitivity analysis was performed to

**Fig. 4** Land use/land cover map of the study area



rank the model parameters that provide the highest variation in model output. The most sensitive model parameters are those which produce the maximum average percentage change in the objective function (Veith and Ghebremichael 2009).

In the present study, monthly as well as daily time steps were used for evaluation of the SWAT model. Different evaluation parameters were employed to assess the model performance as recommended by Moriasi et al. (2007), viz. (1) Nash–Sutcliff efficiency (NSE), (2) graphical technique using hydrograph, (3) RMSE-observations standard

deviation ratio (RSR) and (4) percent bias (Pbias). In addition, index of agreement (D) and coefficient of determination ( $R^2$ ) were also computed and compared.

The land portion of the hydrological cycle is based on a water mass balance. The hydrological processes in the SWAT application are simulated over each HRU in daily time steps using the following soil water balance equation (Neitsch et al. 2011)

$$SW_t = SW_o + \sum_{i=1}^n (R_{day} - Q_{surf} - E_a - w_{seep} - Q_{gw})$$

**Table 1** Sub-basin-wise land use/land cover of the study area

Sub-basin no. SWAT LU designation	Built-up area (ha) URBN	Water body (ha) WATB	Cultivable land (ha) AGRL	Barren/waste land (ha) BSVG	Forest (ha) FRST	Total (ha)
1	1719.79	822.93	248903.60	801.81	2173.10	254421.30
2	567.04	2268.96	62815.89	687.27	375.32	66714.48
3	912.29	4246.27	203198.70	5174.81	13870.45	227402.60
4	487.42	10854.92	186670.20	46133.01	114804.50	358950.00
5	183.60	2783.19	96041.92	36252.12	141524.20	276785.10
6	142.17	4305.57	158446.80	36813.47	227612.20	427320.10
7	394.81	1815.65	182338.60	41357.88	44801.53	270708.50
8	258.33	6754.88	318540.20	41123.11	229436.70	596113.30
9	215.28	1687.30	144941.10	15162.93	21893.44	183900.00
10	240.46	627.96	161359.90	21694.41	20928.34	204851.10
Total	5121.19	36167.63	1763257.00	245200.80	817419.80	2867166.00
Percent (%)	0.18	1.26	61.50	8.55	28.51	100

where  $SW_t$  = final soil water content (mm  $H_2O$ );  $SW_o$  = initial soil water content (mm  $H_2O$ );  $t$  = time (days);  $R_{day}$  = amount of precipitation on day  $i$  (mm  $H_2O$ );  $Q_{surf}$  = amount of surface runoff on day  $i$  (mm  $H_2O$ );  $E_a$  = amount of evapotranspiration on day  $i$  (mm  $H_2O$ );  $w_{seep}$  = amount of percolation and bypass exiting the soil profile bottom on day  $i$  (mm  $H_2O$ );  $Q_{gw}$  = amount of return flow on day  $i$  (mm  $H_2O$ ).

The Penman–Monteith method is used to compute the actual evapotranspiration as well as potential transpiration. Modified soil conservation service curve number (SCS-CN) method (USDA 1972) and modified rational method are used for computation of surface runoff and peak runoff rate, respectively.

## Results and discussion

In this study, the SWAT model was evaluated for its practical usage to perform runoff, sediment yield and a water balance study. The evaluation of the SWAT model encompasses sensitivity analysis to identify SWAT model parameters, calibration of discharge and sediment concentration on both daily and monthly basis. Further, sub-basin annual average water balance and monthly average annual water balance over entire Ken basin were also evaluated. A detailed erosion study was also carried out to understand the severity of erosion in the Ken River basin.

### Sensitivity analysis of the SWAT model parameters

The SWAT model is a comprehensive conceptual, semi-distributed model and depends on different parameters varying widely on spatial and temporal scale. Sensitivity

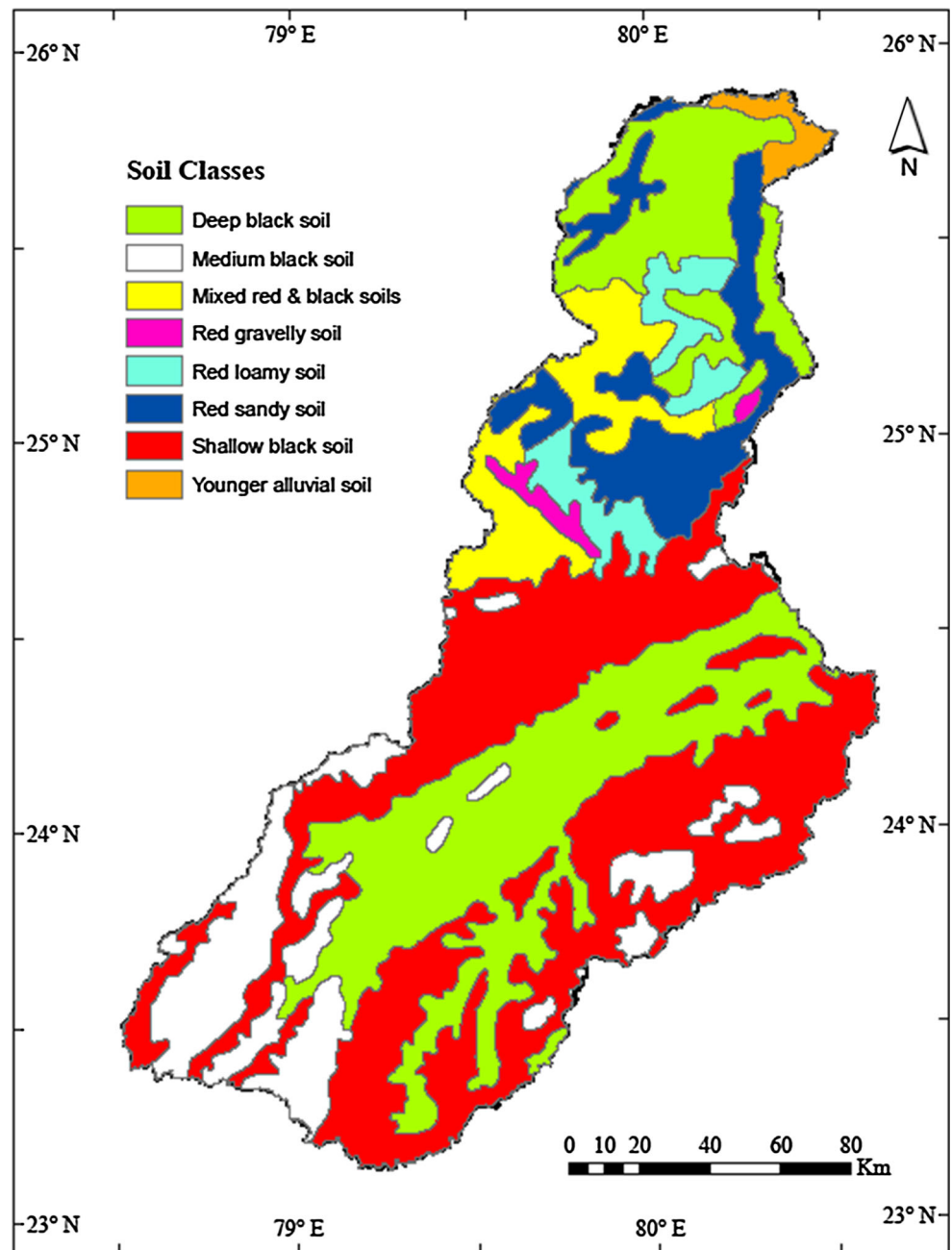
analysis is helpful to identify the model parameters which have crucial influence on the model output. This in turn is helpful in calibrating the model by considering only the sensitive parameters for calibration, which can significantly reduce the model run time for achieving good results. The sensitivity analysis was carried out on the pre-calibrated simulation, without observed data, and the results are presented in Table 2. A total of 27 sensitive parameters were considered collectively for runoff and sediment, and their rank was determined according to sensitivity to the output. Sensitivity analysis shows that curve number (CN2) and effective hydraulic conductivity (Ch\_K2) are most sensitive model parameters for both runoff and sediment yield computations. Soil evaporation compensation factor (Esco), available water capacity of soil layer (Sol\_Awc), depth from soil surface to bottom of layer (Sol\_Z) are relatively more sensitive to runoff but less to sediment. Similarly, Manning's roughness coefficient (Ch\_N2), surface runoff lag coefficient (Surlag), USLE P factor (Usle\_P) are more sensitive to sediment than runoff. Some of the SWAT parameters used were found less sensitive to both runoff and sediment, viz. channel cover factor (Ch\_Cov), deep aquifer percolation fraction (Rchrg\_Dp), channel erodibility factor (Ch\_Erod), etc. The relative sensitivity of the SWAT parameters was kept in view while calibrating the model for the study area.

### Evaluation of the SWAT model for runoff and sediment yield

In the present study, SWAT model was evaluated using observed stream runoff as well as sediment concentration on daily and monthly basis for the Ken River at Banda G & D site. Auto calibration procedure was followed using built-in Parasol method in SWAT 2009. A total of 27



**Fig. 5** Soil map of the study area



sensitive parameters were considered collectively for runoff and sediment for calibration (Table 2). Simultaneous calibration of runoff and sediment concentration was performed using the 3000 iterations. The calibrated model was run to examine the model predictive capability on data, which is not used for calibrating model parameters. The performance of the SWAT model for stream runoff and suspended sediment concentration at daily and monthly time step was evaluated.

The goodness of fit of the calibrated model during calibration and validation period was evaluated using visual interpretation and statistical parameters described previously

between observed and model estimated outputs. The overall visual matches such as trends of recession, matching of peaks and general agreement in hydrograph characteristics were provided by the visual comparison. In this study, both stream runoff and suspended sediment concentration were calibrated and validated at daily and monthly time step. The graphical representation of daily as well as monthly observed versus simulated total runoff and observed versus simulated sediment yield is illustrated in Figs. 6, 7, 8, 9, 10, 11, 12 and 13. The values of  $R^2$  for different goodness of fit drawn between observed versus simulated runoffs and sediment concentration are summarized in Table 3.

**Table 2** SWAT parameters with rank according to sensitivity to the output

Parameter	Lower bound	Upper bound	Model sensitivity rank	Flow sensitivity rank	Sediment sensitivity rank	Remarks
Alpha_Bf	0	1	1	12	11	Base flow alpha factor
Ch_N2	0	1	2	15	3	Manning's 'n' for main channel
Ch_K2	0	150	3	6	2	Main channel's effective hydraulic conductivity
CN2	-25	25	4	2	4	Initial SCS runoff curve no for moisture condition II
Surlag	0	10	5	13	5	Surface runoff lag coefficient
Esco	0	1	6	1	10	Soil evaporation compensation factor
Sol_Z	-25	25	7	4	13	Depth from soil surface to bottom layer
Gw_Delay	-10	10	8	14	17	Groundwater delay time
Canmx	0	10	9	8	16	Maximum canopy storage
Sol_Awc	-25	25	10	3	12	Available water capacity of soil layer
Gw_Revap	-0.036	0.036	11	5	18	Groundwater revap coefficient
Sol_K	-25	25	12	16	19	Saturated hydraulic conductivity
Revapmn	-100	100	13	7	21	Shallow aquifer's threshold water depth for percolation to deep aquifer to occur
Blai	0	1	14	9	14	Maximum potential leaf area index
Gwqmn	-1000	1000	15	11	23	Shallow aquifer's threshold water depth to return flow to occur
Slsubbsn	-25	25	16	20	15	Average slope length
Epc	0	1	17	10	9	Plant uptake compensation factor
Slope	-25	25	18	17	8	Tributary channel's average slope
Sol_Alb	-25	25	19	18	22	Moist soil albedo
Biomix	0	1	20	19	24	Biological mixing efficiency
Ch_Erod	0	1	33	33	33	Channel erodibility factor
Spexp	1	2	33	33	7	Exponent parameter for calculating sediment re-entrained in channel sediment routing
Rchrg_Dp	0	1	33	33	33	Deep aquifer percolation fraction
Spcon	0.0001	0.01	33	33	1	Linear parameter for calculating sediment re-entrained in channel sediment routing
Ch_Cov	0	1	33	33	33	Channel cover factor
Usle_C	-25	25	33	22	20	USLE cover factor
Usle_P	0	1	33	21	6	Support practice factor

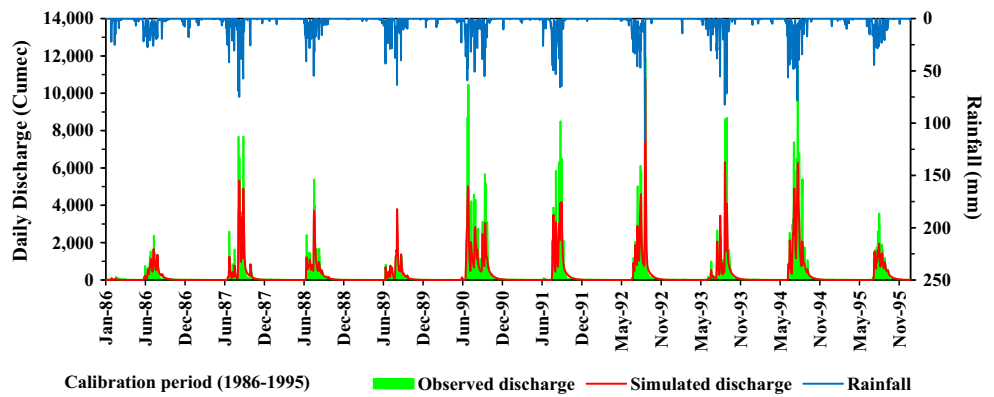
From the hydrograph (Fig. 6), it can be found that the daily peak runoffs are seldom simulated. Runoff is over-estimated by 9.68% during the calibration period. However, Fig. 8 reveals that daily sediment yield is consistently lower than the observed. The model underestimated the sediment yield by 25.56% during the calibration period. Similar is the case for validation period.

Monthly evaluation shows relatively good response of the model for both stream runoff and sediment concentration. Simulated hydrograph is more or less following the observed hydrograph pattern. Base runoffs as well as most of the peaks are well simulated. In the years 1990 and 1994, peaks are under-predicted while in the years 1987, 1989 and 1992, it overpredicted the peak runoffs while maintaining the general pattern. For validation period, all the hydrographs are nearly in line with observed data

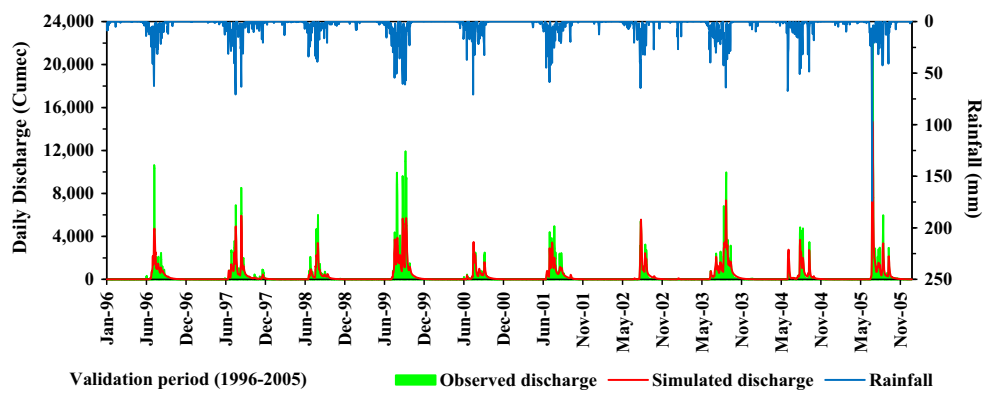
except for the year 1999 where it under-predicts to some extent. However, the sediment simulation is again consistently under-predicted by approximately 25%.

Different statistical coefficients were employed to check the model performance, viz. Nash–Sutcliffe simulation efficiency (NSE) (Nash and Sutcliffe 1970), RMSE-observations standard deviation ratio (RSR), coefficient of determination ( $R^2$ ), percent bias (Pbias) and index of agreement (D index). Based on the recommendations by Moriasi et al. (2007), the performance of SWAT model for the study area on daily and monthly basis is very good during calibration and validation period in respect of runoffs (NSE > 0.75; Pbias <  $\pm 10\%$ ; and RSR < 0.5). In case of sediment simulation on daily basis, the performance is reasonable during calibration and validation period. Similarly, on monthly basis, sediment simulation is

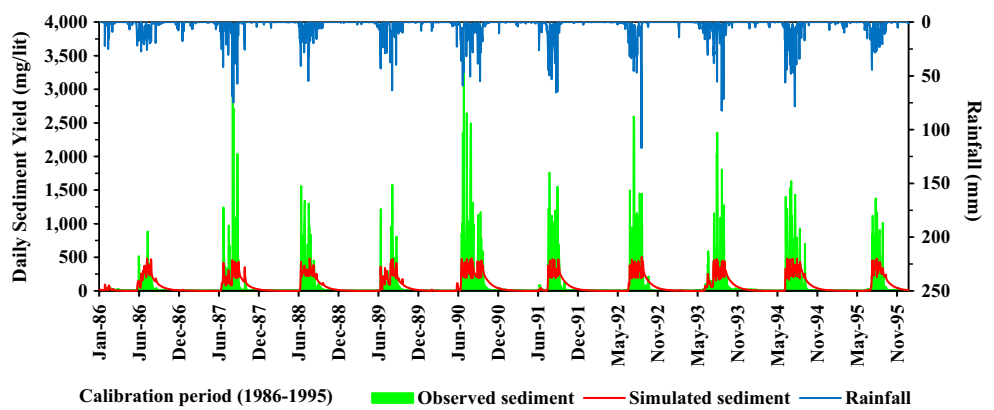
**Fig. 6** Daily observed versus simulated runoffs during calibration period (1986–1995)



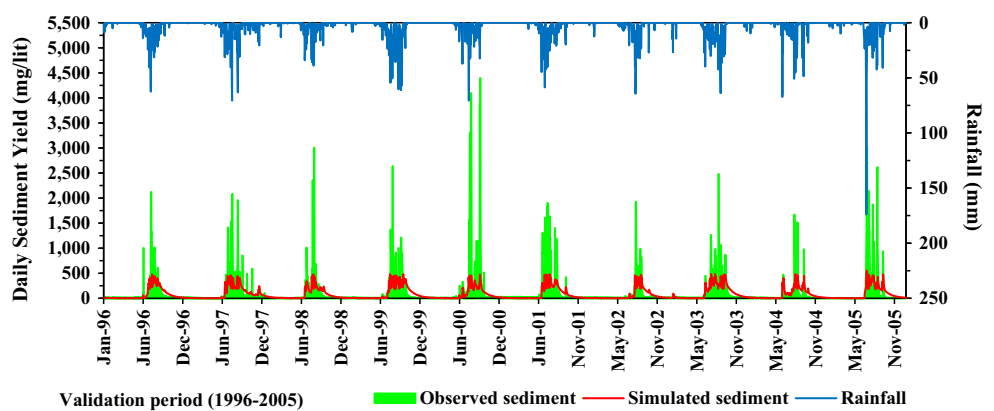
**Fig. 7** Daily observed versus simulated runoffs during validation period (1996–2005)



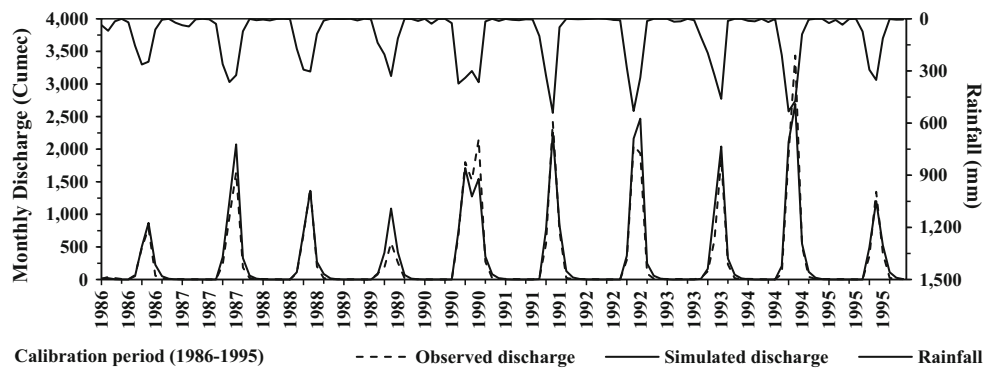
**Fig. 8** Daily observed versus simulated sediment concentration during calibration period (1986–1995)



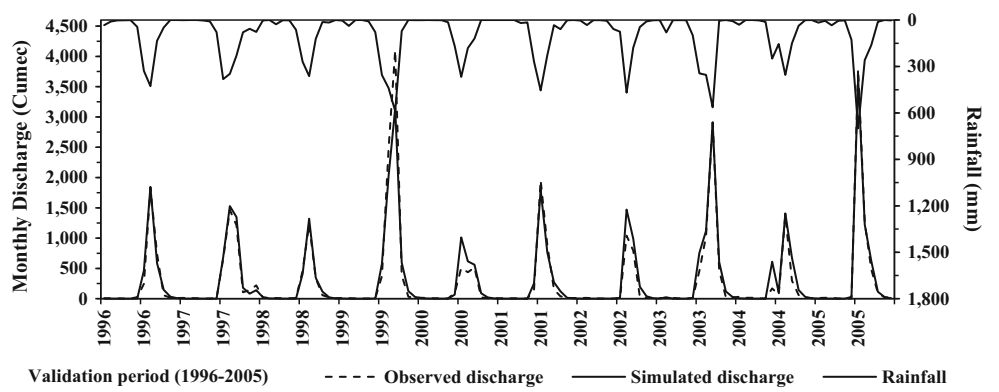
**Fig. 9** Daily observed versus simulated sediment concentration during validation period (1996–2005)



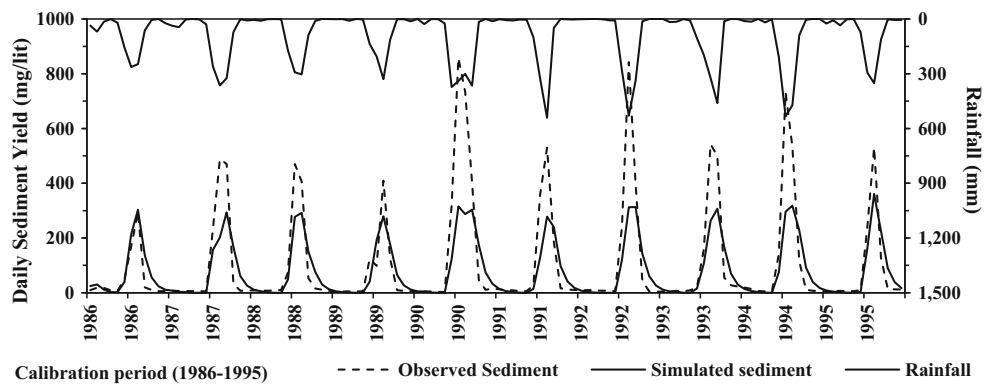
**Fig. 10** Monthly observed versus simulated runoffs during calibration period (1986–1995)



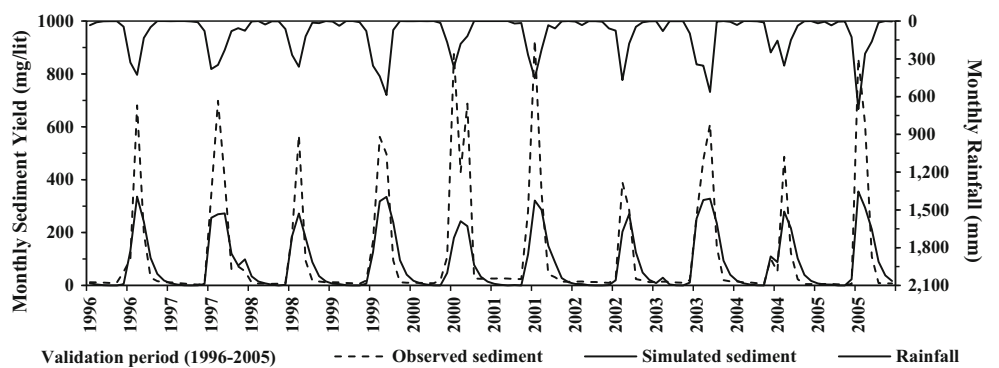
**Fig. 11** Monthly observed versus simulated runoffs during validation period (1996–2005)



**Fig. 12** Monthly observed versus simulated sediment concentration during calibration period (1986–1995)



**Fig. 13** Monthly observed versus simulated sediment concentration during validation period (1996–2005)





**Table 3**  $R^2$  values for different goodness of fit drawn between observed versus simulated flows and sediment concentration

Goodness of fit	$R^2$ value
Daily observed flows versus simulated flows during calibration period (1986–1995)	0.766
Daily observed flows versus simulated flows during validation period (1996–2005)	0.780
Daily observed sediment concentration versus simulated sediment concentration during calibration period (1986–1995)	0.429
Daily observed sediment concentration versus simulated sediment concentration during validation period (1996–2005)	0.379
Monthly observed flows versus simulated flows during calibration period (1986–1995)	0.946
Monthly observed flows versus simulated flow during validation period (1996–2005)	0.959
Monthly observed sediment concentration versus simulated sediment concentration during calibration period (1986–1995)	0.748
Monthly observed sediment concentration versus simulated sediment concentration during validation period (1996–2005)	0.721

satisfactory ( $0.5 < NSE < 0.65$ ;  $0.60 < RSR < 0.70$ ; and  $\pm 30 < Pbias \pm 55$ ).

Due to dependence of the SWAT model on different empirical and semiempirical models, such as MUSLE and SCS-CN, model evaluates specific sediment load and peak runoff less accurately (Qiu et al. 2012). Some of the peak runoffs are not well simulated by the SWAT model. Borah et al. (1999) in a study of upper Little Wabash River (Effingham), III, observed that “Visual comparisons of the hydrographs demonstrated SWAT’s limitation in evaluating peak monthly runoffs (mostly under-predictions), therefore, SWAT needs improvements in storm event simulations for enhancing its peak and high runoff predictions”. They also observed that the model considerably under-predicted most of the peak monthly runoffs, although the overall statistics on comparisons of the observed and simulated runoffs were admissible. Among many other reasons, the disagreement may be due to spatial rainfall variations and insufficient rain gauge network to precisely capture the variations. In addition to NSE, RSR and Pbias, other evaluating parameters include index of degree of agreement ( $D$ ) and coefficient of determination ( $R^2$ ). Statistical evaluation of model performance is shown in Table 4.

Model results of calibration and validation process for stream runoff showed a good agreement between observed and simulated runoffs. Daily calibration results for runoff were good ( $R^2 = 0.766$ ,  $NSE = 0.77$  for calibration period and  $R^2 = 0.780$ ,  $NSE = 0.77$  for validation period). The results were further improved (very good) on monthly basis ( $R^2 = 0.946$ ,  $NSE = 0.94$  for calibration period and  $R^2 = 0.959$ ,  $NSE = 0.96$  for validation period). The total suspended sediment concentration during calibration and validation was satisfactory on daily basis ( $R^2 = 0.429$ ,  $NSE = 0.36$  for calibration period and  $R^2 = 0.379$ ,  $NSE = 0.30$  for validation period). On monthly basis, the values of  $R^2$  and  $NSE$  were 0.748 and 0.62, respectively, for calibration period, 0.721 and 0.57, respectively, for validation period.

### Water balance of the Ken basin

For the 10 sub-basins in the study area, the annual average water balance, along with balance at Daudhan and Banda, over the entire period of simulation (1986–2005) was carried out from the validated SWAT model and is presented in Table 5 and Fig. 14. It was found that evapotranspiration is more predominant and accounts for about 44.6% of the average annual precipitation falling over the area. Similarly, stream runoff (surface runoff + lateral runoff + shallow aquifer – losses) and deep aquifer recharge are 34.7 and 19.5%, respectively. Table 5 shows that out of average annual precipitation of 1132.83 mm, about 26.8% flows out from the study area as surface runoff. It was found from the sub-basin-wise breakup of annual average water balance (Table 5) that almost all the sub-basins, except sub-basin 4, flow out more than 20% of annual precipitation as surface runoff. This implies that there is need to implement suitable management practices to reduce the volume of runoff by increasing in basin utilization of water.

The monthly breakup of annual average water balance (in mm) over the entire Ken basin study area is furnished in Table 6 and Fig. 15. Table 6 shows that the monthly evapotranspiration in dry months is higher than total precipitation during that month. This is due to the fact that evapotranspiration is a continuous process occurring throughout day and night whether there is rainfall or not. The water for evapotranspiration comes from soil moisture. At the same time, the SWAT model is a continuous model and accounts for change in soil moisture content, which facilitates the consideration of previous day soil moisture content as well. Therefore, during no precipitation day, evapotranspiration is taking place and soil moisture content is being depleted. Therefore, it is possible that in a particular month precipitation is less than evapotranspiration. However, the annual evapotranspiration is less than total precipitation.

**Table 4** Statistical evaluation of model performance

Sr. no.	Parameter	Total stream flow							
		Observed				Simulated			
		Daily		Monthly		Daily		Monthly	
		Cali	Vali	Cali	Vali	Cali	Vali	Cali	Vali
1	Average (mm)	286.02	301.97	283.83	299.95	313.72	322.52	311.39	320.23
2	SD	945.81	1099.21	613.03	692.99	808.80	883.32	604.80	650.66
3	Pbias					9.68	6.81	9.71	6.76
4	D index					0.88	0.89	0.08	0.07
5	NSE					0.77	0.77	0.94	0.96
6	$R^2$					0.766	0.780	0.946	0.959
7	RSR					0.48	0.48	0.24	0.21

Sr. no.	Parameter	Suspended sediment concentration							
		Observed				Simulated			
		Daily		Monthly		Daily		Monthly	
		Cali	Vali	Cali	Vali	Cali	Vali	Cali	Vali
1	Average (mg/l)	108.30	118.62	107.28	117.64	80.62	82.43	80.06	81.89
2	SD	287.56	326.87	194.85	212.68	116.96	118.49	105.35	106.88
4	Pbias					-25.56	-30.51	-25.37	-30.39
6	D index					0.80	0.79	0.85	0.84
5	NSE					0.36	0.30	0.62	0.57
3	$R^2$					0.429	0.379	0.748	0.721
7	RSR					0.80	0.83	0.61	0.65

Cali is calibration (1986–1995) and vali is validation (1996–2005) period

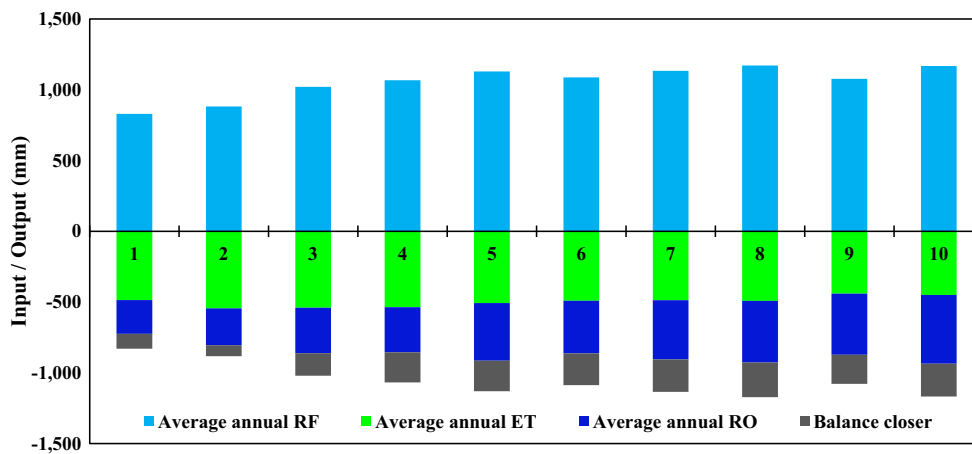
*Pbias* percent bias, *D index* index of agreement, *NSE*, Nash–Sutcliffe efficiency,  $R^2$  coefficient of determination, *RSR* root-mean-squared error-observations standard deviation ratio

**Table 5** Sub-basin-wise annual average water balance in the study area

Sub-basin	Area (km <sup>2</sup> )	Rain (mm)	SURQ (mm)	GWQ (mm)	Deep aq. (mm)	Total WY (mm)	ET (mm)	SED (t/h)
1	2632.46	829.82	191.83	56.59		237.93	486.11	9.60
2	713.81	882.36	199.29	62.87		260.21	544.08	11.14
3	2287.32	1020.58	223.45	100.22		321.83	539.50	18.77
4	3549.37	1067.45	177.00	137.72		318.78	536.33	14.30
5	2754.81	1129.41	283.09	125.10		407.04	507.43	15.71
6	4267.52	1087.12	248.58	126.64		371.94	490.60	13.67
7	2665.20	1134.00	319.55	120.84		417.94	487.30	12.58
8	5949.05	1171.74	309.21	136.89		435.23	491.44	15.50
9	1828.19	1077.73	340.81	109.11		431.96	440.10	19.11
10	2023.94	1167.73	376.66	123.47		485.57	449.82	25.56
Ken basin	28671.66	1081.73	268.69	117.98	217.17	378.91	496.47	15.38
Ken (Banda)	25325.40	1113.53	278.64	125.92	224.49	396.90	496.20	16.10
Ken (Daudhan)	19488.71	1132.83	303.63	126.78	228.5	419.94	483.81	16.11

The monthly rainfall pattern was highly concentrated on monsoon months with 94% rainfall occurring during the five monsoon months of June to October. Similar was the

case with stream runoff, about 98% of stream runoff happens during the corresponding months. During the same period, evapotranspiration was at a higher rate with a



**Fig. 14** Sub-basin-wise annual average water balance in study area

**Table 6** Monthly breakup of average annual water balance in the study area

Month	Precipitation (mm)	SURQ (mm)	GWQ (mm)	Deep aq. (mm)	Water yield (mm)	ET (mm)	Sediment (t/ha)
January	10.67	0.07	0.06		0.44	17.14	0.01
February	17.62	0.22	0.06		0.31	23.76	0.01
March	7.34	0.02	0.04		0.08	24.08	0
April	2.91	0	0.02		0.03	11.8	0
May	6.96	0	0.02		0.02	8.6	0
June	125.33	13.96	0.19		13.96	42.1	0.34
July	310.53	76.17	0.92		87.79	92.21	3.23
August	350.96	106.77	1.41		143.54	98.5	6.76
September	213.96	68.95	1.09		105.67	83.34	4.89
October	25.52	2.46	0.29		18.36	55.81	0.14
November	4.24	0.1	0.1		3.99	24.29	0
December	7.45	0.43	0.08		1.63	15.38	0.03
Annual	1083.49	269.15	4.28	217.23	375.82	497.01	15.41

maximum of 98.5 mm per month in the month of August. The sediment yield seems to follow proportionally with the surface runoff. Typically, the months with higher surface runoff, viz. July (76.17 mm) and August (106.77 mm), also accounted for higher rate of sediment load with around 3.23 and 6.76 t/ha, respectively.

HRU-wise water balance analysis reveals that, out of 143 HRUs of the study area, 83 HRUs comprise the cultivable area (agriculture land) and 60 HRUs are covered by forest. From the HRUs with the agricultural area, the average evapotranspiration and surface runoff are found to be about 29 and 43% of precipitation, respectively, and the corresponding values for the HRUs with forest cover are 18 and 46%, respectively. This indicates that there is urgent need to implement suitable management practices (such as vegetative filter strips, grassed waterways and strip cropping) to reduce volume of surface runoff from cultivable areas and to reduce the sediment, nutrient and pesticide loads in surface runoff.

**Soil erosion status in the Ken River basin**

Monthly sediment yield from the sub-basins and the whole basin is furnished in Tables 5 and 6. As per the guidelines suggested by Singh (1995) for Indian conditions, average annual sediment yields in t/ha/year were regrouped into the following scales of priority: slight (0–5), moderate (5–10), high (10–20), very high (20–40), severe (40–80) and very severe (>80) erosion classes as presented in Table 7.

It was observed that sub-basins 9 and 10, comprising the Sonar sub-basin (a tributary of Ken), yield more sediment, about 19.11 and 25.56 t/ha, respectively (Table 5). Majority of sub-basins have high erosion rate, which may be due to lack of management and conservation practices in the basin. Table 7 shows that severe and very severe erosion prone area is about 2% and the HRUs correspond to agricultural and barren land use type; soil is vertisol with steep slope. The higher rate of erosion may be attributed to the higher slope of the area and faulty method of

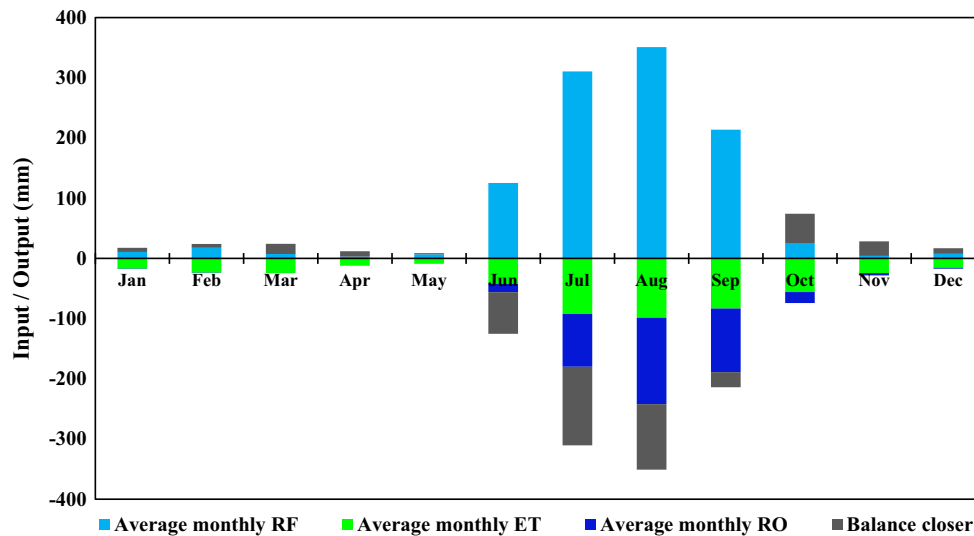


Fig. 15 Monthly average values of water balance components

Table 7 Area under different classes of soil erosion in Ken basin

Sr. no.	Sediment yield (t/ha/year)	Percent area	Soil erosion class
1	0–5	29.56	Slight
2	5–10	11.55	Moderate
3	10–20	27.48	High
4	20–40	29.32	Very high
5	40–80	0.44	Severe
6	>80	1.65	Very severe

cultivation practices in agricultural land, and also the barren land contributes much of the sediment yield. Therefore, immediate attention is required in those areas with a view of soil conservation. About 57% area falls under high to very high soil erosion classes, and the HRUs correspond to agricultural and barren land use type, Mollic Gleysol (loam) as soil type and slope class is moderate. In this area, the soil type and land use/land cover type are playing major role in higher sediment yield. Management practices such as vegetative filter strips and better cultivation practices may be considered from soil conservation point of view in the study area. Similarly, slight and moderate erosion classes cover about 41% of basin area. Under this category, majority of HRUs belong to water body or forest as land cover type with various combinations of soil and slope classes. It is obvious that water body and forestland will generate very less sediment. The average annual sediment yield from the basin as a whole is 15.41 t/ha/yr, which is high and it tends to increase in future due to ongoing deforestation in the area to cope up with the rising population.

The analysis provides the priority of sub-basins for soil conservation measures. This study can be used to provide a framework to develop soil and water conservation

programs to control further reduction in field productivity and soil quality. The result can be implemented further for application of best management practices and agro-environmental policies. Effectiveness of different land management and crop cultivation activities can be assessed in order to conserve soil and water resources.

### Conclusions

Based on the SWAT modeling results, the following conclusions are drawn from this study:

- Sensitivity analysis reveals that effective hydraulic conductivity in main channel (Ch\_k2), initial SCS runoff curve number for moisture condition II (CN2), soil evaporation compensation factor (Esco), Manning’s n for main channel (Ch\_N2), surface runoff lag coefficient (Surlag) and depth from soil surface to bottom of layer (Sol\_Z) are the sensitive parameters for the SWAT model employed in the Ken River basin.
- For daily simulation, results for runoff were good ( $R^2 = 0.766$ , NSE = 0.77 for calibration period and  $R^2 = 0.780$ , NSE = 0.77 for validation period) and



satisfactory for total suspended sediment concentration ( $R^2 = 0.429$ ,  $NSE = 0.36$  for calibration period and  $R^2 = 0.379$ ,  $NSE = 0.30$  for validation period).

- For monthly simulation, results were further improved (very good) for runoff ( $R^2 = 0.946$ ,  $NSE = 0.94$  for calibration period and  $R^2 = 0.959$ ,  $NSE = 0.96$  for validation period) and good for total suspended sediment concentration ( $R^2 = 0.748$ ,  $NSE = 0.62$  for calibration period and  $R^2 = 0.721$ ,  $NSE = 0.57$  for validation period).
- The water balance study of the basin showed that evapotranspiration is more predominant and accounting for about 44.6% of the average annual precipitation falling over the area. Similarly, stream runoff comes out to be 34.7% and deep aquifer recharge is 19.5%.
- Sediment yield study from the basin showed average annual yield of 15.41 t/ha/year which falls under high erosion class.
- From the calibration and validation results, it is concluded that the SWAT model is capable of simulating hydrology and sediment concentration of the study area accurately.
- The use of IMD gridded precipitation and temperature data, available at 0.5° and 1.0° grid interval, respectively, was validated for the Ken River basin of India.

The result can be implemented for application of best management practices and agro-environmental policies.

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