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Simulation of Runoff and Sediment Yield for a Kaneri Watershed Using SWAT Model

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Abstract

Watershed as an entry point acts as a beginning to address the issues of sustainable rainwater management for improving livelihoods. Extraction of watershed parameters using Geographical Information System (GIS) and use of simulation models is the current trend for hydrologic evaluation of watersheds. In the present study, the open Source Tool Quantum GIS 2.2.0 was used for preparation of maps to verify the spatial extent of the area. The Soil and Water Assessment Tool (SWAT) having an interface with Arc-View GIS software (ArcGIS 10.1 with Arc SWAT 2012 extension) was selected for the estimation of runoff and sediment yield from Kaneri watershed, located in Western Maharashtra region. The coefficient of determination (R^2) for the monthly and yearly runoff was obtained as 0.849 and 0.951 respectively for the calibration period 1979 to 2000 and 0.801 and 0.950 respectively for the validation period 2001-2013. The R^2 value in estimating the monthly and yearly sediment yield during calibration period was computed as 0.722 and 0.788 respectively. The R^2 for monthly and yearly sediment yield values for validation period was observed to be 0.565 and 0.684 respectively.

Keywords

Arc SWAT, Calibration, Validation, GIS, Runoff, Sediment Yield, Coefficient of Determination R^2

1. Introduction

Watershed as an entry point acts as a beginning to address the issues of sustainable rainwater management for improving livelihoods. To deal with water management issues, one must analyze and quantify the different elements of hydrologic processes taking place within the area of interest. Obviously, this analysis must be carried out on a watershed basis because all these processes are taking place within individual micro watersheds. Only after understanding the spatial and temporal variation and the interaction of these hydrologic components, one

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can scientifically formulate strategies for water and soil conservation. To achieve this goal, the choice and use of an appropriate watershed model is a must as stated by Sathian and Shyamala [1]. The Soil and Water Assessment Tool (SWAT) is a physically-based continuous daily step hydrologic model as mentioned by Arnold *et al.* [2] and Neitsch *et al.* [3] and is developed to assess the impact of land management practices on water, sediment, and agricultural chemical yields in large multifaceted watersheds with varying soils, land use and management conditions over long spans of time. Tripathi *et al.* [4] use it to predict water and soil loss in agriculturally dominant small watersheds. For assessing the impact of land management practices and climate on water flow and sediment yield in ungauged Kaneri watershed, Swami and Kulkarni [5] use SWAT (Soil and Water Assessment Tool) model in the study.

1.1. Study Area

Kaneri village is located in south Maharashtra region and is dominated by undulating plateau. It is located south-east to Kolhapur city on Pune-Bangalore highway in Maharashtra state. It is located at 16.6055 and 16.6412N and 74.2535 and 74.2906E and is 11 kms away from Kolhapur. It is surrounded by small hills. **Figure 1** explains the location of the watershed. Geographical area of the village is 975.94 hectares. Kaneri lies in extreme elevation variation from 589 m to 692 m. The village falls in agro-climatic zone IV and is characterized by rainfall ranging from 800 to 1000 mm. The main occupation of the village is agriculture as 68.84% of the total area of village is under cultivation.

1.2. SWAT Model

The water balance is the driving force for the simulation of hydrology. SWAT uses two steps for the simulation

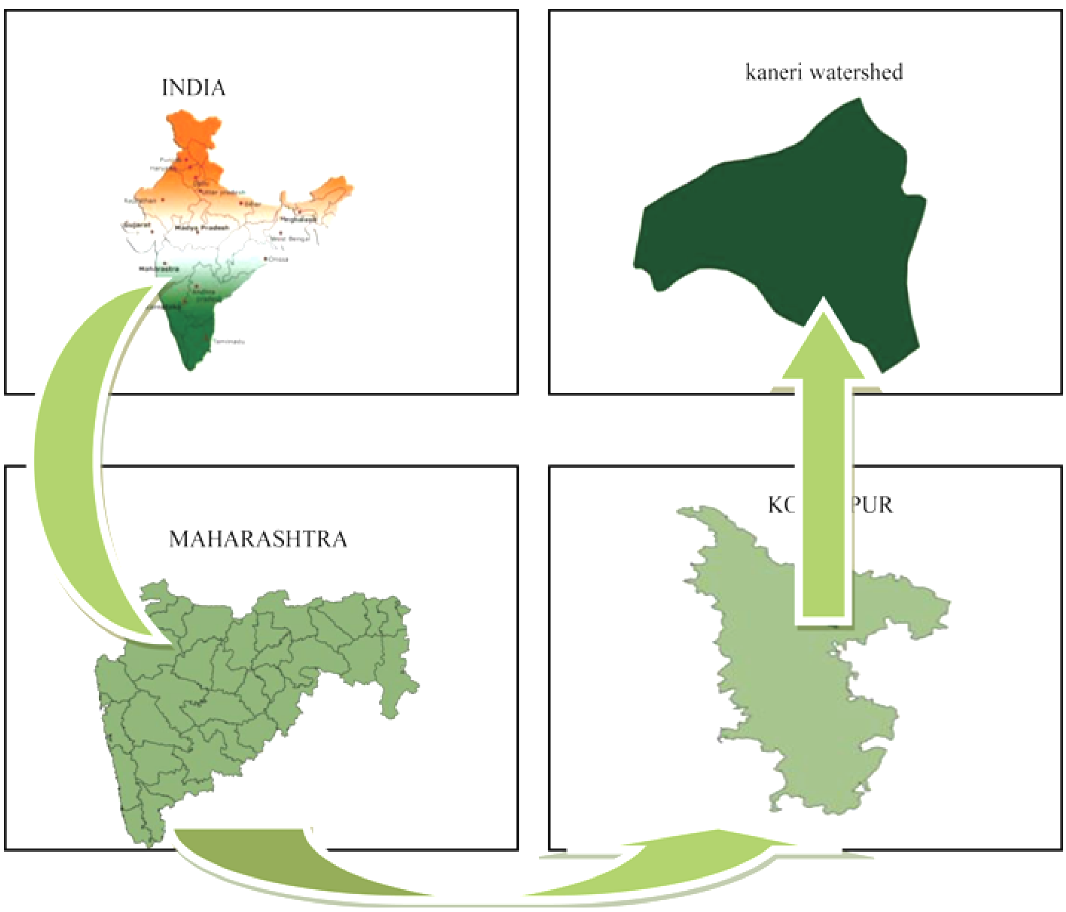


Figure 1. Location of Kaneri.

of hydrology, land phase and routing phase. The land phase is the phase in which the quantity of water, sediment, nutrient and pesticides loadings in the main channel from each subbasin are calculated. Water balance equation for SWAT model is

$$SW_t = SW_o + \sum\left(P_{day}\right) - Q_{surt} - AET - Q_{seep} - Q_{gw}$$

where SW_t is the final water content in millimeters, SW_o is the initial soil water content on day *i* (mm), P_{day} is precipitation on day *i* (mm), Q_{surf} is surface runoff on day *i* (mm), AET is the actual evapo-transpiration on day *i* (mm), Q_{seep} is the water flowing into the unsaturated zone form the soil profile on day *i* (mm) and Q_{gw} is the return flow from the shallow aquifer and lateral flow on day *i* and t is time in days [3]. In the present study, SWAT model is used for prediction of runoff and sediment yield in the micro watershed Kaneri. Santosh Kumbhar [6] estimated soil loss for Kaneri watershed as 17.67 Tonnes/Ha/Year, which is beyond the acceptable limits. Permissible soil loss given by Mannering (1981), is from 4.5 to 11.2 tonnes/ha/year.

SWAT model uses the concept that whenever the rate of water application to the ground surface exceeds the rate of infiltration, surface runoff occurs. SWAT uses the Modified Universal Soil Loss Equation (MUSLE) to estimate the soil loss from each HRU. The peak runoff rate is the highest runoff rate that occurs with a given precipitation event. SWAT calculates the peak runoff rate with a modified rational method. The factors K_{USLE}, C_{USLE}, P_{USLE}, LS_{USLE}, and CFRG are taken and used based on previous studies on the watershed and the definition and calculations of the parameters presented in the SWAT documentation. Lateral flow is important in watersheds with soils with high hydraulic conductivities in surface layers and in impermeable or semi-permeable layer at a lesser depth. The water that collects above the impermeable layer is the spring of water for lateral subsurface flow [3].

SWAT calculates percolation for each layer in the profile and this process occurs only when the moisture content of the soil is more than field capacity. Recharge to an unconfined aquifer occurs by percolation to the water table from a major portion of the land surface. Depending on the water table height in the shallow aquifer, there is a base flow contribution to the main channel. This flow occurs only when the water stored in the shallow aquifer is greater than the threshold water level in the shallow aquifer for ground water input to the main channel to occur. This value is defined by the user or in the SWAT interface the variable is presented as GWQMN [3]. Integration of SWAT model with rainfall data available from the WSR 88 D radar network helps us to incorporate the spatial variability of rainfall into the modeling process. Four case studies were presented by Jay Krishnan *et al.* [7]. The study demonstrated the usefulness of radar rainfall data in distributed hydrologic studies and potential of SWAT for application in flood analysis and simulation.

Ashok Mishra *et al.* [8] used SWAT model to assess sediment transport from 17 km^2 Banha watershed located in Northern India. Watershed has mixed land use and check dams are provided for on-stream sediment control. Model is run with and without check dams to test its capability to evaluate their impact on sediment control and proved to be successful. Weruweru catchment of drainage area 101 km^2 with annual precipitation 1500 mm to 3000 mm at the foot slopes of Kilimanjaro in Northern Tanzania is studied for water balance modeling by using SWAT model. Model is performed on annual and monthly basis using spatial and attribute data. The predicted mean daily stream flow is found to be 1.92 m^3/sec. exactly as observed during simulation period. Birhanu *et al.* [9] shows in his study that SWAT model can be a potential monitoring tool for watersheds in hilly terrains. Samira Akhavan *et al.* [10] applied SWAT to simulate the amount and dynamics of nitrate leaching from a crop rotation in Hamadan-Bahar watershed, Iran, presented model and its results showed the potential to provide a strong base for considering different scenarios for reducing nitrate leaching and also for providing Best Management Practices (BMP) in the watersheds. An agricultural watershed of 0.8 Ha area was studied for prediction of runoff flow using SWAT tool with sub daily configuration which assessed flow from the watershed within the range of acceptable accuracy. Ganga Ram Mahajan *et al.* [11] showed that hourly precipitation record for SWAT sub daily with Green Ampt infiltration method was found to be efficient for run off estimation for field sized watershed with better accuracies which could be efficiently used to develop site specific Best Management Practices (BMPs) considering rainfall intensity rather than simply using daily rain fall data.

2. Methodology

2.1. Creation of Database

To delineate the watershed and sub basins and to determine drainage networks SWAT uses the digital representation of the topographic surface. DEM is the digital representation of the topographic surface. A 30 m by 30 m resolution ASTERDEM was derived and re-sampled to 15 m × 15 m for ease in data acquisition. **Figure 2** shows DEM of Kaneri village. Sub basin parameters such as slope gradient, slope length of terrain and the stream network characteristics such as channel length, width and slope were calculated for the base village area and used by the model. **Figure 3** gives drainage map of Kaneri village.

A land use map was created by recording the crop type on each plot in the watershed and by identifying the land cover on areas other than cultivated fields. LULC map was acquired from LISS III (Linear Imaging and Self Scanning Sensors). The digital Google image was geo-referenced by taking control points around and inside the watershed. The shape file representing each plot and other land covers was created using the digitizing tools provided in ArcGIS, ArcMap. The soil map obtained from the NBSS&LUP was geo-metrically registered to the base data to match Landsat & IRS satellite imageries. The geo-referenced soil map was used to assist in visual classification of satellite imagery for obtaining soil categories. The final vector map was stored in a geodatabase which is amenable to spatial analyze.

SWAT requires daily or sub-daily meteorological data. For Kaneri watershed the daily climate data from two rain gauge stations was used. Daily rainfall data was used for SWAT Model Run. Multiple Gauges were used for weather data input. The main inputs used for weather data in the model are gridded rainfall and temperature. The curve number method (USDA-SCS, 1986) was chosen for calculating runoff. Penman-Monteith method (Monteith, 1965) was chosen for calculating potential evapotranspiration. The variable storage method was chosen as the channel routing mechanism with the assumption that channel dimensions remain constant. The model was set to run from 1st January 1979 to 31st July 2014 with a monthly printout interval. By considering the drainage lines the stream network was prepared. The watershed outlet was manually added and selected for finalizing the watershed delineation (**Figure 4**). With this information the model automatically delineated a watershed of 535.48 ha and 28 sub basins were produced. Multiple HRUs were defined within a sub basin by ignoring land uses less than 2% of the subbasin and also ignoring soil types in a subbasin covering less than 5% of the subbasin. **Figure 5** shows land use land cover map of Kaneri watershed.

The watershed of total area 535.48 Ha has been classified in following land uses (**Table 1**).

Land use map is a critical input for SWAT model. Land use/land cover map was prepared using remote sensing data of Landsat ETM+. The classification of satellite data mainly follows two approaches *i.e.* supervised and unsupervised classification. The intent of the classification process is to categorize all pixels in a digital image into one of several land cover classes, or themes [12]. The detailed Sub Basin wise land use distribution is as in

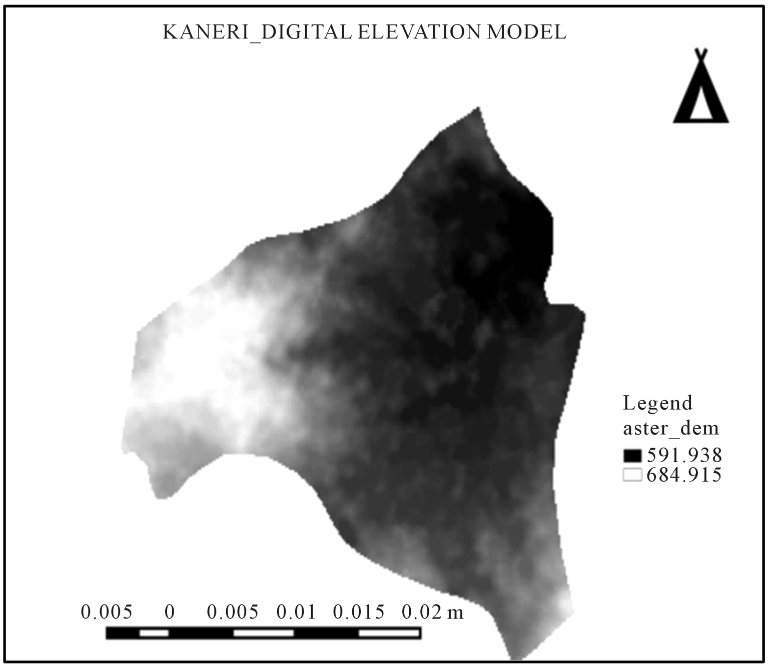


Figure 2. Digital elevation model of Kaneri.

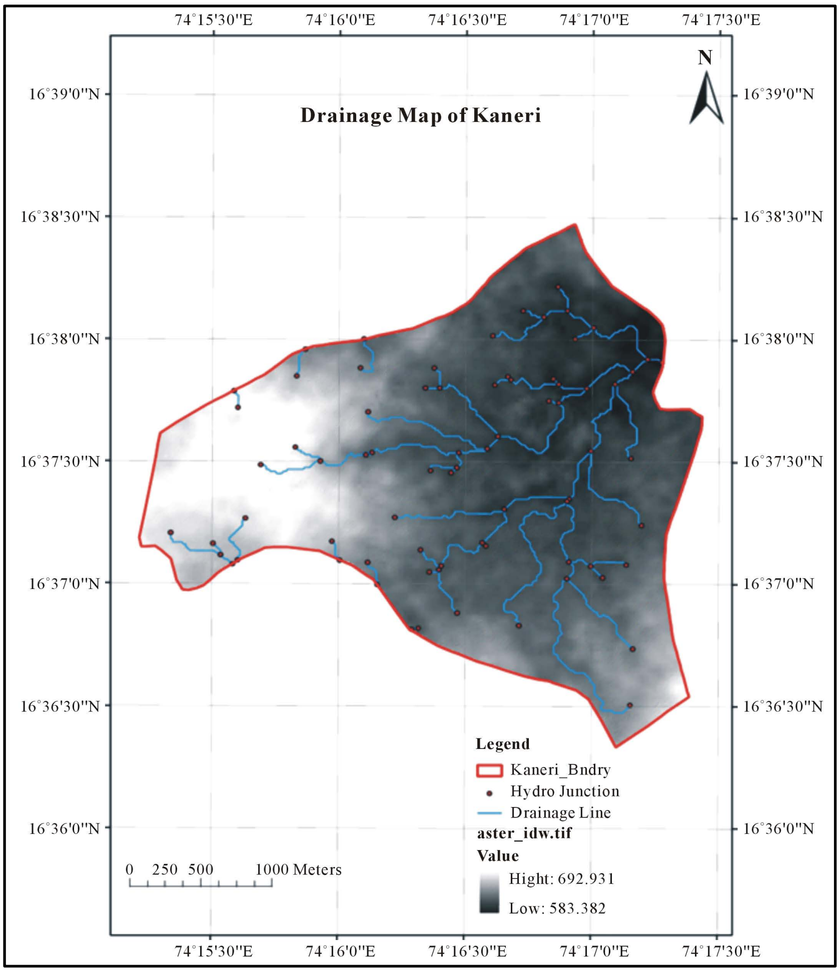


Figure 3. Drainage map of Kaneri Village.

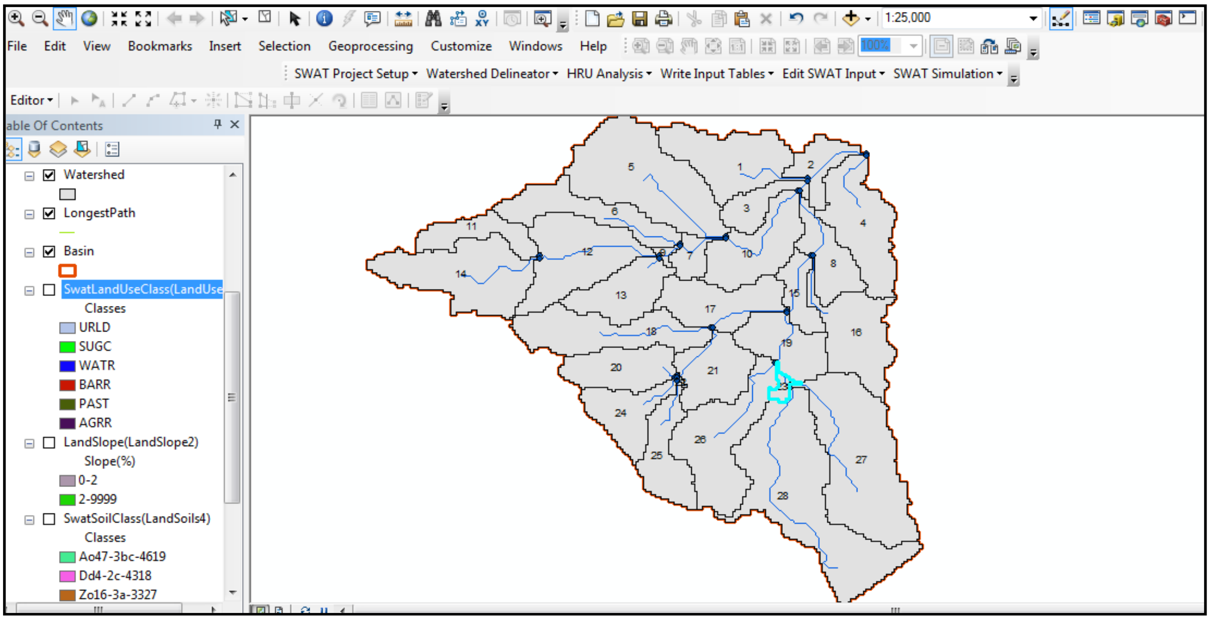


Figure 4. Watershed delineation map.

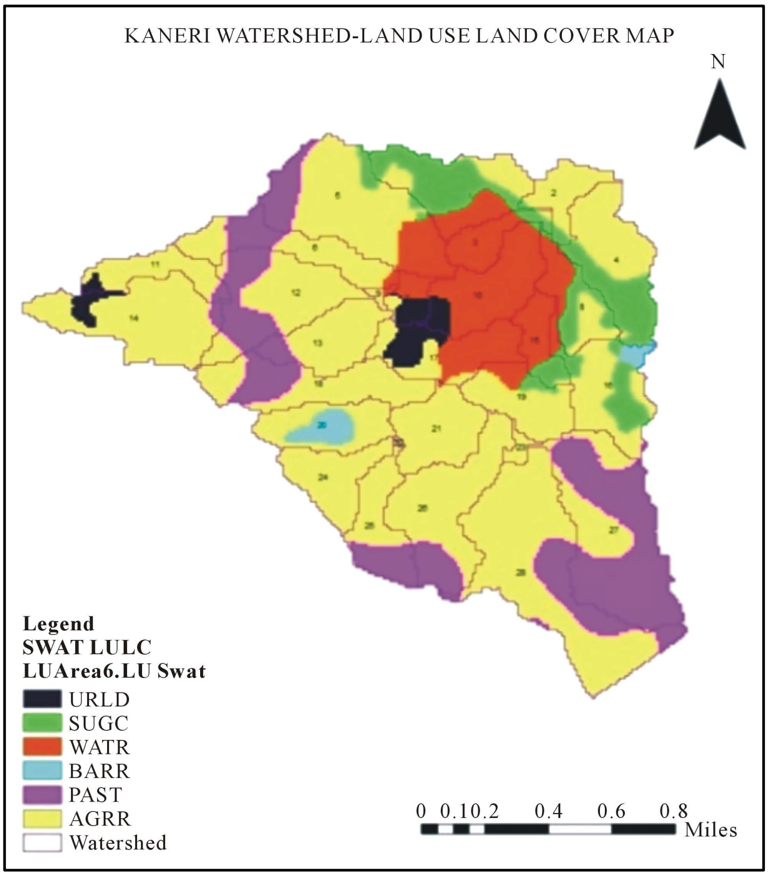


Figure 5. LULC of Kaneri Watershed.

Table 1. Land use classification with total area distribution.

Sr. No.	Land Use Category	Code	Area (Ha)	% of Watershed Area
1	Urban Residential Low density	URLD	11.93	2.228
2	Sugarcane	SUGC	37.84	7.069
3	Water bodies	WATR	64.20	11.99
4	Barren	BARR	85.25	15.919
5	Pasture	PAST	5.72	1.069
6	Agriculture Land	AGRR	330.54	61.724

Table 2. This categorized data may then be used to produce thematic maps of the land cover present in an image.

2.2. Model Setup

SWAT allows the user to delineate the watershed and sub basins using the Digital Elevation Model (DEM). Drainage network is also prepared which can be useful for delineation. **Figure 3** shows the drainage map of Kaneri Watershed. **Figure 4** gives delineated watershed through Arc-SWAT. The delineated watershed by Arc SWAT and the prepared land use map overlapped 100%. **Figure 6** shows Land Use Land Cover map overlay. For runoff to produce, the basic necessity of the model is to have the total rainfall more than field capacity of the soil. If it is less, then the subsurface flow is modeled. SWAT runs for both the possibilities and computes peak rate, transmission losses and sediment yield in first case and computes soil water routing, evapo-transpiration, crop growth, pond, wetland balances, ground water flow in the second case. While running the model land use

Table 2. Detailed sub basin wise land use distribution of Kaneri Watershed.

OID	SUBBASIN	URLD	SUGC	WATR	PAST	BARR	AGRR
1	1		12.27188	5.145494			6.739872
2	2		0.724717				8.261779
3	3		0.917975	7.053916			0.338201
4	4		9.711213	0.096629	0.096629		14.97749
5	5		1.594378	7.005602		6.329199	26.25893
6	6			0.507302		4.56572	12.92413
7	7	2.19831		2.391567			0.70056
8	8		4.082575	4.855607			4.29999
9	9			0.26573			0.748875
10	10	2.149995	0.144943	18.45614			
11	11	0.773032				0.628088	9.590427
12	12					9.759528	18.72187
13	13					2.174152	13.72132
14	14	2.294939				0.869661	27.75668
15	15		1.956737	5.870211			0.26573
16	16		5.580324	1.256177	1.521907	0.144943	13.45559
17	17	4.517405		8.817395			5.459538
18	18					6.280884	18.38367
19	19		0.869661	2.439882			12.19941
20	20				4.106732		11.76458
21	21			0.048314			16.30614
22	22						0.169101
23	23						1.811794
24	24						14.32525
25	25					5.483695	9.276383
26	26					5.169651	24.49545
27	27					33.02296	12.75503
28	28					10.82245	44.83585

land cover map, soil map, slope map and weather data is provided as an input on which the processing is done through SWAT model.

Modeling process once over, gives the output in the form of surface runoff, PET (Potential Evapo Transpiration), Evapo Transpiration, Percolation, Ground water flow, Soil Moisture, Water Yield and Sediment Yield. In this study by Ashok Mishra *et al.* [8], the estimated runoff and sediment yield from each sub-watershed were compared with measured values and the effect of LU/LC, soil and topographic characteristics was then evaluated. **Figure 7** shows soil map overlay for SWAT model setup.

Multiple HRUs were defined within a sub basin by ignoring land uses less than 2% of the subbasin and also ignoring soil types in a subbasin covering less than 5% of the subbasin. A total of 76 HRUs for 28 sub basins were created. **Figure 8** shows slope map overlay of Kaneri Watershed.

SWAT tool having an interface with Arc View GIS software (AVSWAT 2000) was used by Jain S. K. *et al.* [12] for runoff and sediment yield from area of Suni to Kasol, watersheds of satluj river, western Himalaya, performed well for runoff prediction. Coefficient of determination (R^2) for daily and monthly runoff was 0.53 and 0.90 respectively for calibration period (1993-1994) and 0.33 and 0.62 respectively for validation period (1995 to 1997) R^2 values in estimating daily and monthly sediment yield during calibration period was found as 0.33 and 0.38 respectively, and for validation period it was observed 0.26 and 0.47 respectively showing a little low performance for sediment yield estimation.

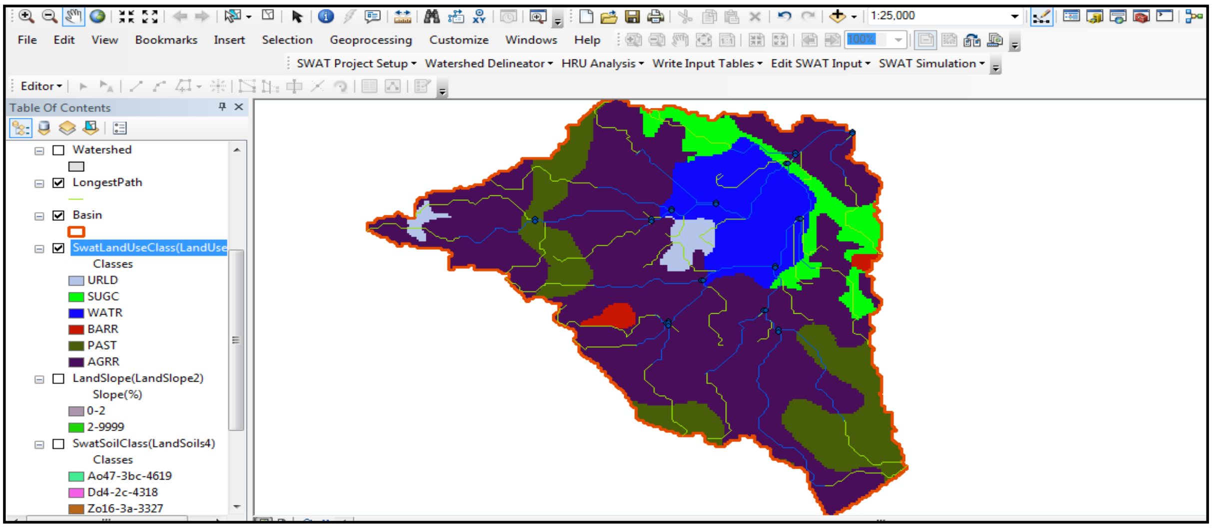


Figure 6. Land use land cover map overlay for SWAT model setup.

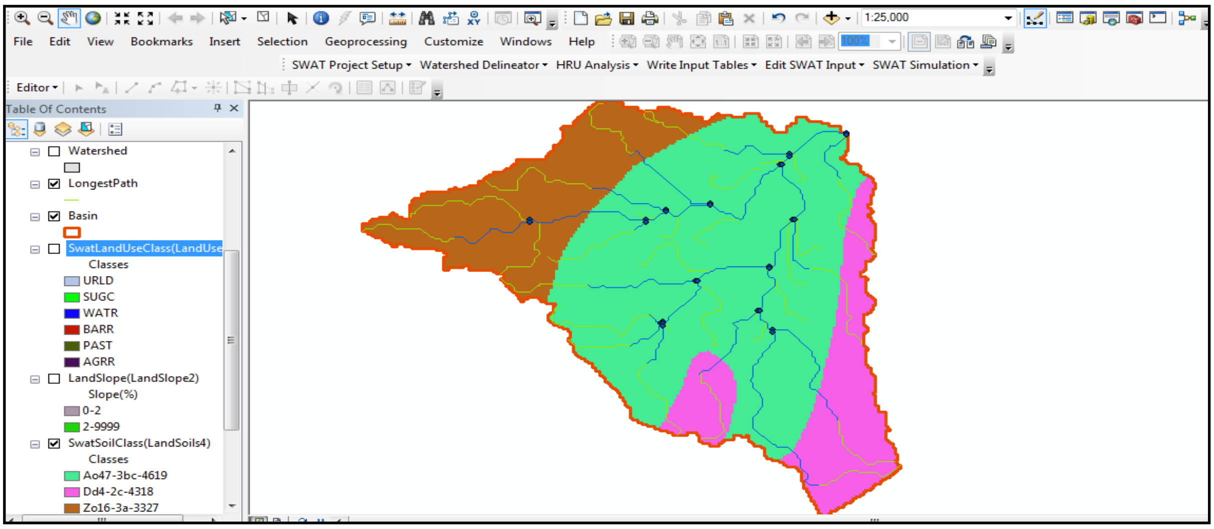


Figure 7. Soil map overlay for SWAT model setup.

Narayan K. Shreshtha *et al.* [13] examined SWAT model performance of Kilene Nete Watershed Belgium with area 581 sq. km. Seven SWAT model parameters were calibrated (1994-1998) and validated (1999-2002). The Parameter Ch_K_2 (Channel effective hydraulic conductivity) was found to be the most sensitive. R^2 and NSE values for calibration and validation were found to be 74 and 67 percent respectively, showing satisfactory goodness of fit statistics. Puwadon Phomcha *et al.* [14], while simulating monthly stream flow in Lam Sonthi watershed in Thailand found R^2 and NSE values greater than 0.7 and deviation of runoff volumes with acceptably accurate values. Some months of simulated flows showed over estimated values but most simulated flows were close to observed flows by both visual and statistical approaches.

Calibration and validation of a SWAT model applied by Arun Babu *et al.* [15] for Krishnagiri Reservoir Watershed, TamilNadu were carried for testing model performance. Model Calibration (2000-2005) and validation (2006-2010) were carried by using the measured discharge and sediment load from a gauge station. It showed a satisfactory agreement between the measured monthly flow with simulated flow values with R^2 value 0.9 and NSE value 0.8. For a small agricultural watershed in Tamilnadu, India, SWAT model was applied by Kaviya K. *et al.* [16] for prediction of water balance parameters. The investigation was carried out using a 10 year rainfall record from Jan. 88-Jan. 98 for calibration and validation. Model performed well with R^2 value greater than 0.98 and correlation coefficient value greater than 0.9.

2.3. Performance Evaluation of the Model

For calibration and validation, different techniques are being used. In the present study, conventional method along Arc SWAT tool was used. The main function of an interface is to provide a link between the input/output of a calibration program and the model. The simplest way of handling the file exchange is through text file formats. The model was run for thirty six years 1979 to 2014. Surface runoff and sediment calibration for the Kaneri watershed was conducted for the years 1979 to 2000. Similarly, surface runoff and sediment validation for the Kaneri watershed was carried out for the years 2001 to 2013. The most widely used criteria, for testing performance of a model is coefficient of determination R^2

$$R^2 = \frac{\left[\sum \left(Q_{\text{sim i}} - Q_{\text{asim i}}\right)\left(Q_{\text{obs i}} - Q_{\text{aobs i}}\right)\right]^2}{\sum \left(Q_{\text{sim i}} - Q_{\text{asim i}}\right)^2 \sum \left(Q_{\text{obs i}} - Q_{\text{aobs i}}\right)^2}$$

where,

R^2 = coefficient of determination;

$Q_{\text{obs i}}$ = Observed value at time step *i*;

$Q_{\text{sim i}}$ = Simulated value at time step *i*;

Q_{aobsi} = Average of observed value at time step *i*;

$Q_{\text{asim i}}$ = Average of simulated value at time step *i*.

R^2 describes the percentage of the variance in calculated data experienced by the model. According to the criteria developed by Sameh *et al.* [17] R^2 ranges from 0 to 1, with greater values indicating low error variance, and typically values greater than 0.5 are considered acceptable. Krause *et al.* [18] stated that R^2 statistic provided an estimate of how well the variance of measured values are replicated by model predictions. The general performance rating criteria developed by Sameh *et al.* [17] for calibration and validation of SWAT model are given in **Table 3**.

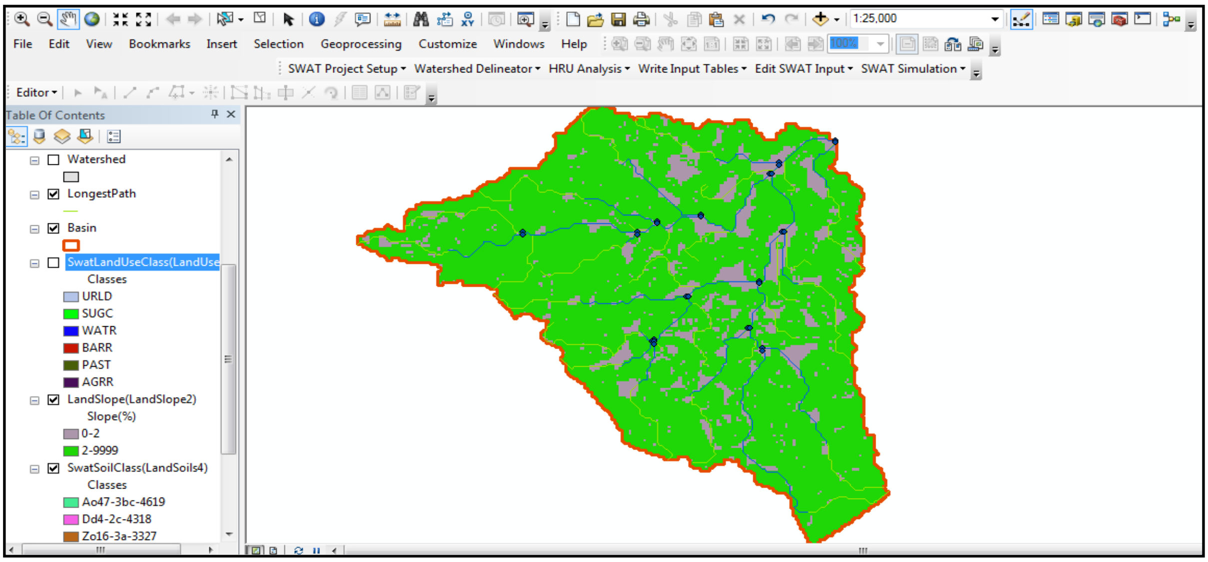


Figure 8. Slope map overlay for SWAT model setup.

Table 3. Performance rating for calibration and validation of SWAT model.

Performance rating	R^2
Very Good	$R^2 > 0.70$
Good	$0.60 < R^2 \leq 0.70$
Satisfactory	$0.50 < R^2 \leq 0.60$
Unsatisfactory	$R^2 < 0.50$

The model goodness-of-fit was evaluated on a yearly and monthly basis. The linear graphs for the measured and simulated values both for flow and sediment on yearly basis for calibration and validation are presented. The linear graphs for the measured and simulated values both for flow and sediment on monthly basis for calibration and validation are also produced.

3. Results and Discussion

3.1. Model Calibration

The SWAT model was calibrated using the yearly data of runoff and sediment yield recorded at the outlet of the study watershed for the years 1979 to 2000. Several simulation runs were applied to achieve the model calibration. The time series of the observed and simulated monthly sediment yield for the calibration period were plotted for visual comparison (**Figure 9** and **Figure 10**). The total monthly runoff computed by the model was, found to be 6792.11 mm against the observed runoff of 6992.77 mm during 1979 to 2000. The sediment yield computed by the model during respective months was obtained as 124.61 t/ha against the observed sediment yield of 118.26 t/ha.

The observed and predicted values were plotted against each other in order to determine the goodness-of fit criterion of coefficient of determination (R^2) both for runoff and sediment yield. The R^2 for yearly and monthly values was obtained as 0.951 and 0.849 respectively for runoff (**Figure 11(a)**, **Figure 11(b)**) and 0.788 and 0.722 respectively for sediment yield (**Figure 11(c)** and **Figure 11(d)**). It was reported that SWAT's yearly flow predictions, in general, were not as good as monthly flow predictions.

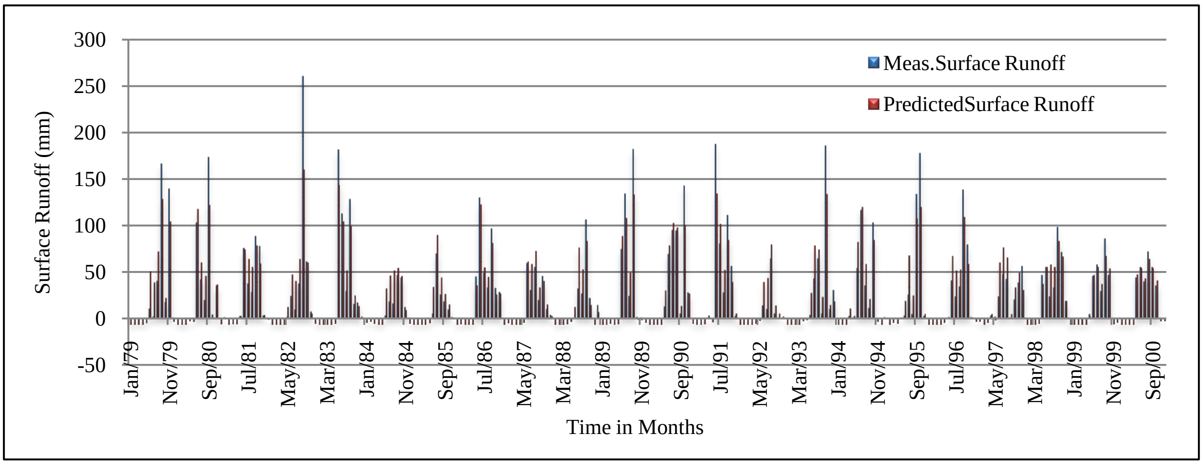


Figure 9. Measured and predicted surface runoff for calibration period 1979-2000.

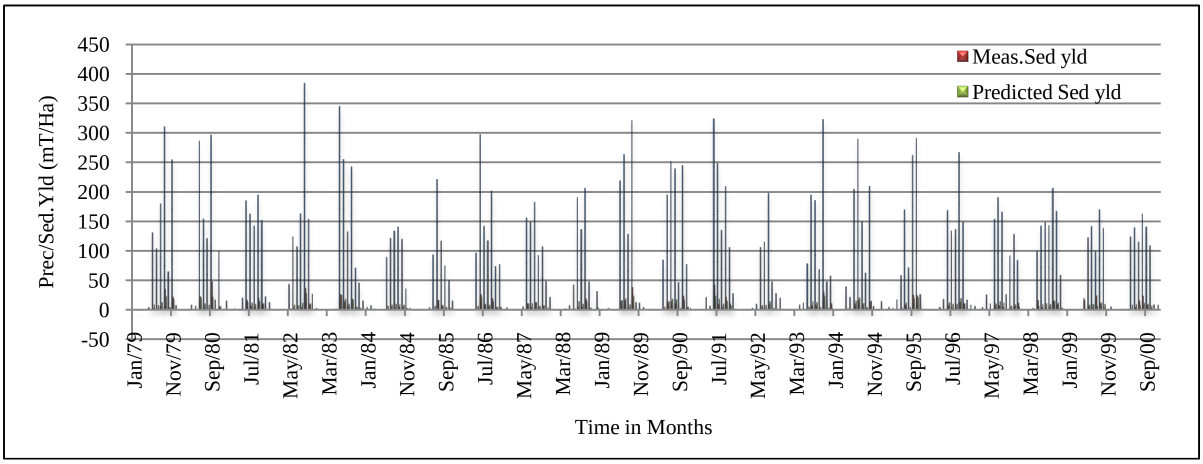
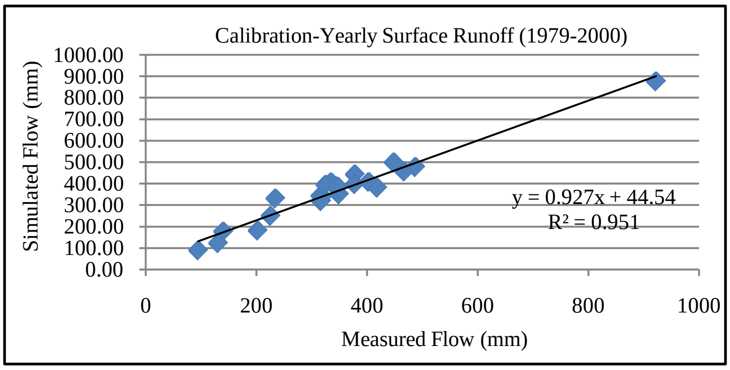
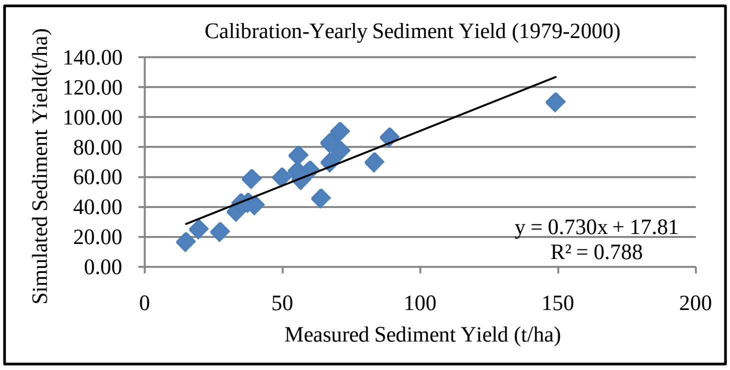


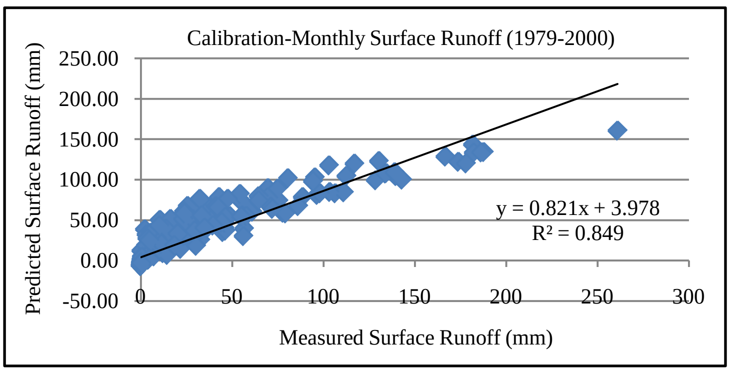
Figure 10. Measured and predicted sediment yield for calibration period 1979-2000.



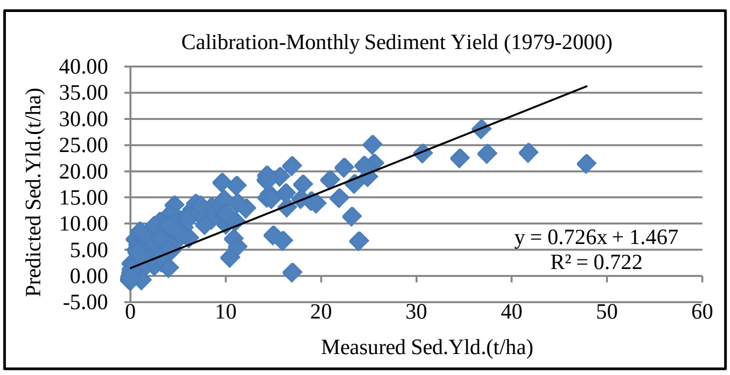
(a)



(b)



(c)



(d)

Figure 11. (a) Determination of coefficient of determination for yearly surface runoff; (b) Determination of coefficient of determination for yearly sediment yield; (c) Determination of coefficient of determination for monthly surface runoff; (d) Determination of coefficient of determination for yearly sediment yield.

3.2. Model Validation

The model validation was carried out for yearly and monthly surface runoff and sediment yield for the years 2001 to 2013. A graphical comparison of the observed and simulated yearly and monthly flows and sediment yield are shown in **Figure 12** and **Figure 13**.

The total monthly surface runoff computed by the model was, found to be 3228.04 mm against the observed runoff of 3027.38 mm during 2001 to 2013. The sediment yield computed by the model during respective months was obtained as 60.06 t/ha against the observed sediment yield of 66.40 t/ha. The observed and predicted values were plotted against each other in order to determine the goodness-of fit criterion of coefficient of determination (R^2) both for runoff and sediment yield. The R^2 value for monthly and yearly surface runoff was obtained as 0.801 and 0.950 respectively (**Figure 14(a)**, **Figure 14(b)**) and 0.565 and 0.684 respectively for sediment yield (**Figure 14(c)** and **Figure 14(d)**). It was reported that SWAT's yearly flow predictions, in general, were better than monthly flow predictions.

4. Conclusions

In the present study, The Soil and Water Assessment Tool (SWAT) having an interface with Arc-View GIS software (ArcGIS 10.1 with Arc SWAT 2012 extension), was applied to the hilly watershed for modeling runoff and sediment yield. After preparing all the thematic maps and database as per the format of AVSWAT model,

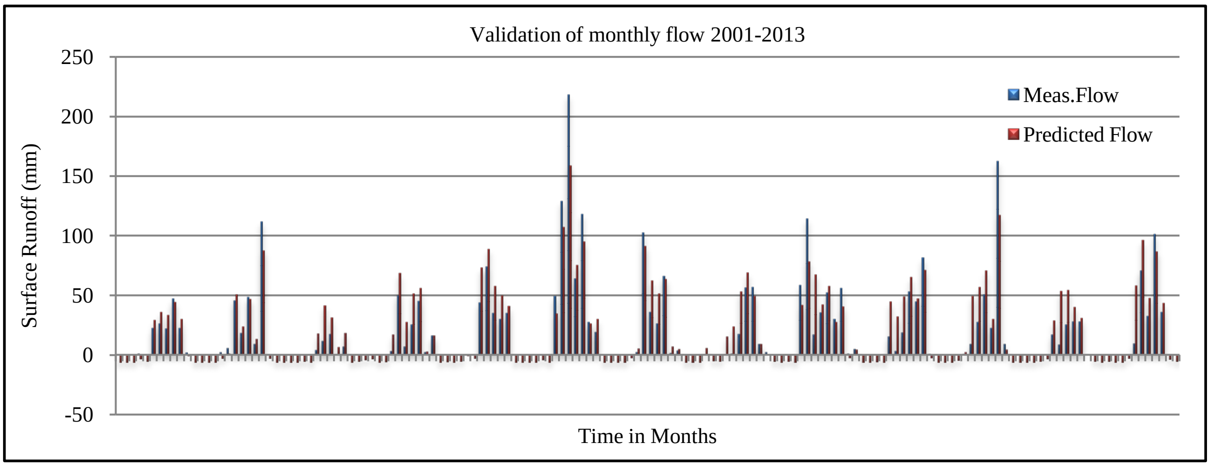


Figure 12. Measured and predicted surface runoff for validation period 2001-2013.

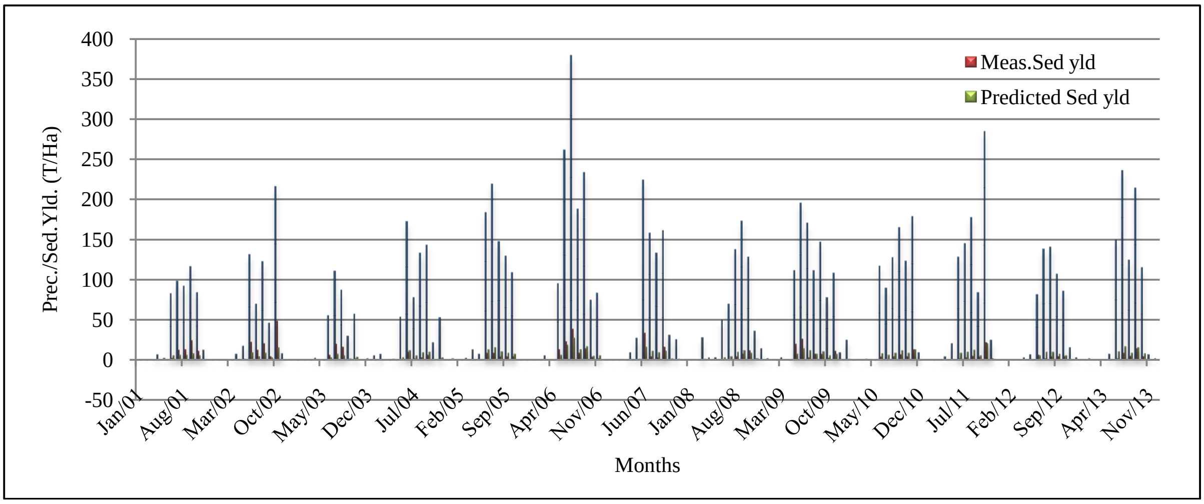
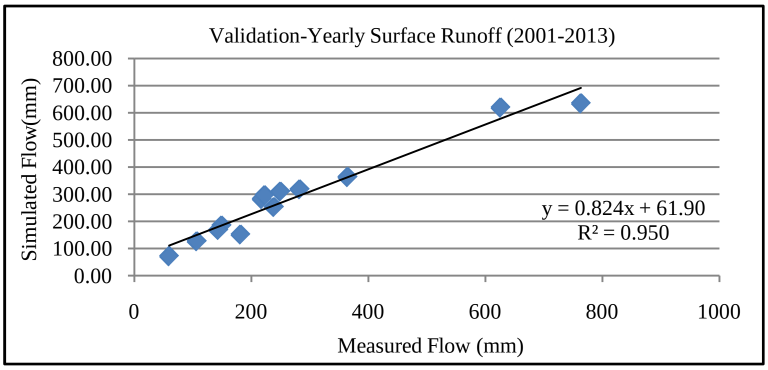
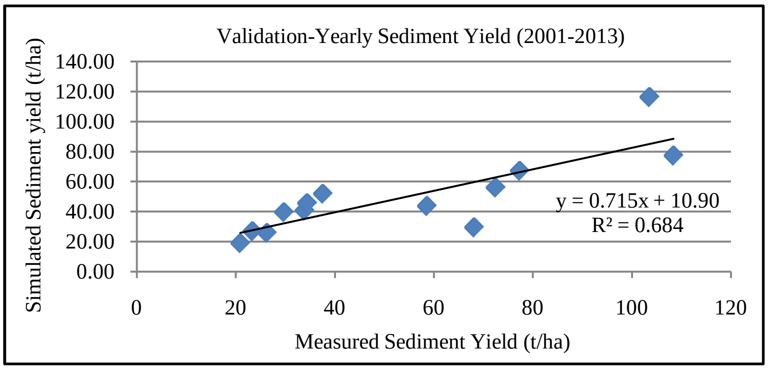


Figure 13. Measured and predicted sediment yield for validation period 2001-2013.



(a)



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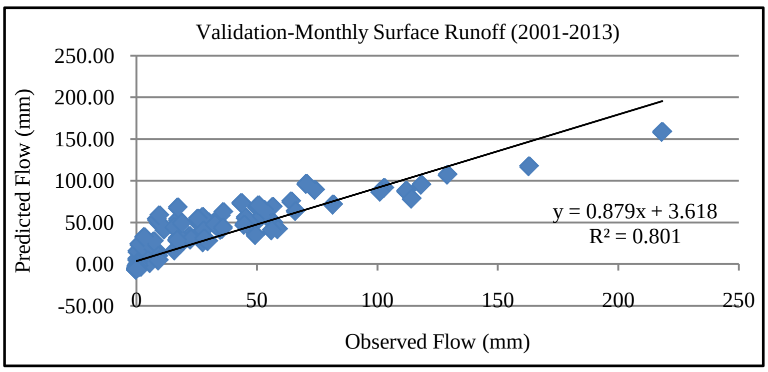
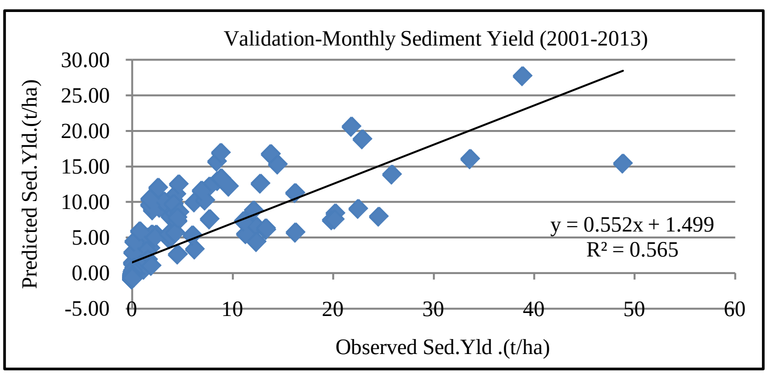


(c)



(d)

Figure 14. (a) Determination of coefficient of determination for yearly surface runoff; (b) Determination of coefficient of determination for yearly sediment yield; (c) Determination of coefficient of determination for monthly surface runoff; (d) Determination of coefficient of determination for monthly sediment yield.

the model was calibrated for the yearly and monthly surface runoff and sediment yield using the observed data of 1979 to 2000. The model validation was carried out for a data set of thirteen years of 2001 to 2013. The simulation performance of the model for calibration and validation was evaluated using graphical and statistical methods.

The coefficient of determination (R^2) for the yearly and monthly runoff was obtained as 0.849 and 0.951 respectively for the calibration period and 0.801 and 0.950 respectively for the validation period. The R^2 value in estimating the yearly and monthly sediment yield during calibration was computed as 0.722 and 0.788 respectively. The R^2 for yearly and monthly sediment yield values during validation period was observed to be 0.565 and 0.684. Thus, the values of R^2 can be considered satisfactory for estimating runoff and sediment yield from a hilly watershed with available data.

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