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Modeling Runoff and Sediment Yield in Highly Gullied Regions of Kashmir using SWAT Model: A Case Study of Lolab Watershed

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ABSTRACT Soil erosion in highly gullied regions of Kashmir valley is a serious global issue due to its impacts on economic productivity and environmental consequences leading to land disintegration. Further, Lolab is a flood prone area and has witnessed many disastrous floods in the past due to which the assessment of hydrological behavior becomes an utmost priority and identification of most problematic sub-basins contributing to the erosion and excessive runoff needs to be identified so that proper management strategies can be applied. In this study, SWAT (Soil and Water Assessment Tool) was integrated with Arc software to simulate the runoff and sediment yield of Lolab Watershed due to its flexibility in input data requirements and capability of modeling larger catchments and mountainous areas. While carrying out sensitivity analysis four most sensitive parameters were found for runoff estimation of which Initial soil conservation service Curve number II was the most sensitive one and two most sensitive parameters were found for sediment estimation of which channel erodability factor was the most sensitive parameter. After calibrating the values of these sensitive parameters, model provided reliable Nash-Sutcliffe(N_{SE}) and Coefficient of determination(R^2) efficiencies which makes SWAT a good analyzing tool to assess the hydrological behavior of highly gullied region and un-gauged basins of Kashmir. Coefficient of determination (R^2) and Nash-Sutcliffe efficiency (N_{SE}) of above 0.90 was found for both runoff and sediment yield while validating the model. SWAT estimated the sediment yield rates at individual sub-basin levels from which a prioritization map was prepared to find out the most problematic sub-basins in the watershed.

KEYWORDS Runoff, Sediment yield, Un-gauged basins, SWAT, Sensitivity analysis

1 INTRODUCTION

Soil erosion has been a long standing problem throughout the globe which has its adverse effects on the crop productivity and functioning of civil structures. Thus, management of watersheds at gross root level has become a priority so as to limit the disintegration of arable lands and malfunctioning of hydraulic structures (Nikolaidis et al., 2013; Bisantino et al., 2015)). Watershed management refers to optimum utilization of its resources without compromising on the balance of natural resources and environment (Van Andel, 2010).Different conventional methods are available to evaluate the soil loss from a watershed but its reliable prediction becomes tedious and time consuming by using these methods. Watershed models have revolutionized the process of analyzing hydrology of the catchment by giving reliable output and by saving the precious time of decision makers. These watershed models are divided into three different categories and are classified as Empirical models, conceptual models and physical models. Empirical models analyze the hydrological parameters by using the coefficients evaluated from actual observation or measured data (Wheater et al, 1993).Conceptual models incorporate a general depiction of catchment thereby avoiding point by point data necessities and represents a catchment as a progression of internal storages (sorooshian, 1991).Physical models, on the other hand, analyze the entire erosion process by evaluating its individual components from the solution of corresponding equations. However, all these models vary significantly in their analysis of parameters, input and output flexibility, scale accountability, processing ability, computational efficiency and capability of modeling the changes in catchments. Appropriate model should be employed so that runoff and sediment yield from the watershed can be predicted and most problematic sub-basins can be identified for rational utilization of land, soil and water resources (Himanshu et al., 2017). A model can perform well in one range of conditions and lack its performance in other set of conditions; therefore, it becomes necessary to choose the appropriate model for the particular watershed after proper evaluation to get the accurate and desired results. A comprehensive review of models and their application worldwide revealed that SWAT, ANSWERS, AGNPS, WEPP and SHETRAN models are the most capable ones for prediction and assessment of various hydrological parameters like runoff and sediment yield, and hence, these physical watershed models are more reliable for accomplishing sustainable watershed management practices (Gull and Shah, 2020). SWAT has an advantage of working better in large watersheds and mountainous areas and has choice of methods in predicting runoff (Shen et al, 2009). SWAT model performs well in hilly areas and is a better tool for assessment of hydrological parameters in general (Pradhan et al., 2020). Earlier, attempts were made to predict the runoff and sediment yield of Lolab watershed using a combination of manual and auto-calibrated SWAT model for different set of time period and with low resolution input data (Gull et al., 2017).SWAT model is suitable for best management practices of watersheds and performs well within vide range of conditions (Zhang et al., 2014)

2 METHODS

This study employs SWAT (Soil and Water Assessment tool) due to its ability of predicting the impact of land management practices on hydrology of large complex watersheds. The main focus of the study will be to check the efficiency of SWAT model using a high resolution input data by comparing its output with the actual observed runoff and sediment yield data of Pohru watershed and identification of sub-basins which draw the maximum amount of sediment.

2.1 Model Description

SWAT is a river basin scale, continuous spatially distributed physical watershed model designed to simulate different hydrological parameters in large complex watersheds and capable of integration with GIS interface (Arnold et al, 1998).SWAT creates Hydrologic Response Units to analyze the diversity of a catchment in terms of land use/ land cover, soil characteristics and slope. The movement of water in the channel and the overland flow is simulated in the routing phase and land phase of the model respectively. The movement of water on the surface is analyzed by the water balance equation given by Setegn et al (2008) defined in equation 1 given as:

$$\mathrm{SWt} = \mathrm{SW0} + \sum_{i=1}^{t}(Rday - Qsurf - Ea - Wseep - Qgw)x \text{.........................} \text{ (1)}$$

Where, SWt= Final soil water content in millimeters, SW0= Initial soil water content in millimeters, t= Time in days, Rday = Precipitation of day x in millimeters, Qsurf = Surface runoff on day x in millimeters, Ea = Evapotranspiration on day x in millimeters, Wseep = Water entering the vadose zone on day x in millimeters, Qgw = Return flow on day x in millimeters.

SWAT calculates surface runoff by two methods (Neitsch et al., 2011) giving an option to the user to choose the method suitable according to the availability of data and output requirement.

The SCS curve number method (SCS, 1985) analyses runoff by the equation 2 given as:

$$\mathrm{Qsurf} = \frac{(Rday - Ia)^2}{(Rday - Ia + S)} \text{...} \text{ (2)}$$

Where, Rday = Precipitation of day x in millimeters, Ia = initial abstractions which includes surface storage, interception and infiltration prior to runoff in millimeters, S= Surface retention in millimeters which depends on the soil water content and is given by equation 3 as:

$$\mathrm{S}=25.4\left(\frac{1000}{CN}-10\right) \text{.......................................} \text{ (3)}$$

Where, CN = Curve number for the day.

SWAT utilizes modified version of Universal Soil Loss Equation (Wischmeier and Smith, 1978) to calculate the sediment drawn from a particular response unit which is given in equation 4 as:

$$\mathrm{Tsediment} = (\boldsymbol{Q}surf \times \boldsymbol{q}peak \times \boldsymbol{A}hru)^{0.56}\ \mathrm{Kusle}\times\mathrm{Cusle}\times\mathrm{Pusle}\times\mathrm{LSusle}\times\mathrm{Cfrg} \text{ ....} \text{ (4)}$$

Where, Tsediment=Sediment yield in metric tons, Qsurf= Surface runoff volume in millimeters per hectare, qpeak= peak runoff rate in m3/s, Ahru= Area of hydrologic response unit in hectares,Kusle = Soil erodibility factor ,Cusle =Cover and management factor, Pusle = Support practice factor, LSusle = Topographic factor,Cfrg =Coarse fragment factor.

Description of SWAT model and its different components is explained in SWAT documentation given by Neitsch et al, (2011).

2.2 Study Area

Lolab watershed (Figure 1) is one of the watersheds of Pohru catchment with an area of about 45Km2 and classified in three different physiographic units viz flood plains, karewas and mountains(Ahmed and Mir.,2014). It lies between 34˚41’ to 34˚24’ N Latitude and 74˚09’ to 74˚23’ E Longitude. Elevation of Lolab watershed starts from 1500 meters and goes upto 3900 meters. The study area is mostly dominated by cambrio-slurian formations and panjal traps, followed by Agglomeratic slates, granites and recent alluvium(Thakur and Rawat, 1992). Agriculture is the dominant land use category in the Lolab watershed with 34.14 percent followed by the sparse forest cover with 26.18 percent of total watershed area. The major class of soil in Lolab is Fine Loamy soil which accounts for 79.58 percent of the total watershed area. Being a mountainous area, the major area of the watershed varies from steep to very steep with a slope of more than 9 degrees.

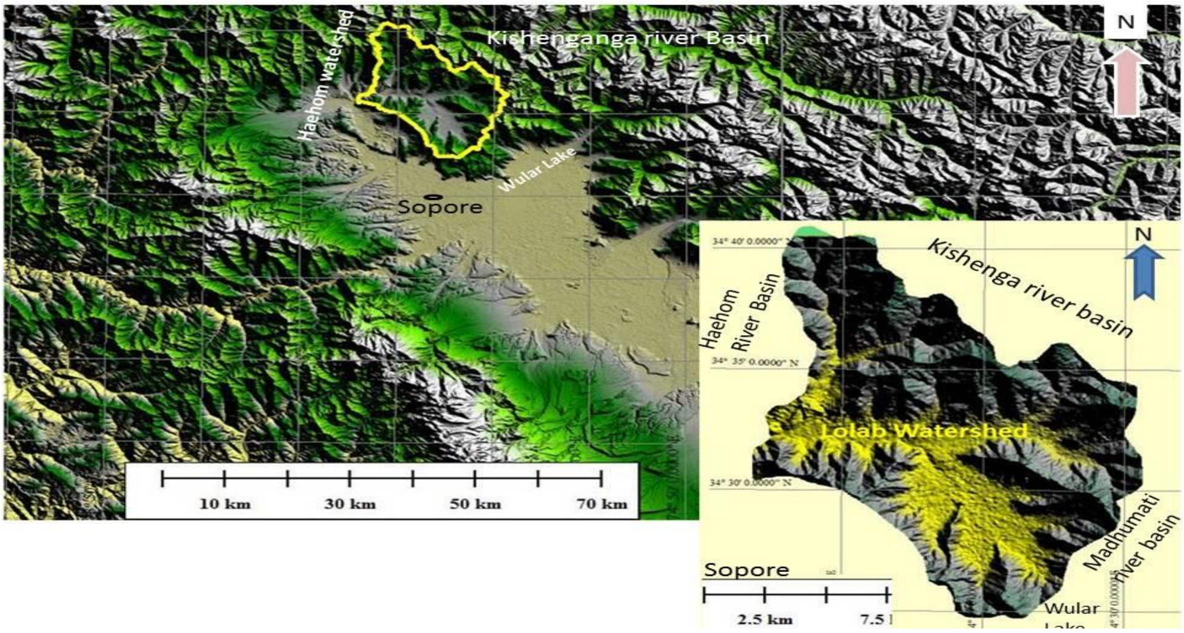

Figure 1. Study Area (Lolab Watershed of Pohru Catchment)

2.3 Data Requirement and Preparation

SWAT uses different inputs at watershed level, sub-basin level as well as HRU (Hydrologic Response Unit) level (Arnold et al., 2012). Watershed level input includes the method to be selected to model evapotranspiration to analyze all the HRU’s in the watershed. Sub-basin level inputs are the inputs which will simulate all the HRU’s in a particular sub-basin. These include precipitation and temperature data for particular sub-basin.HRU level inputs can be set to unique the values for individual HRU’s such as management scenarios. ArcSWAT 2012 needs spatial databases digital elevation model (DEM), land use/ land cover and soil characteristics. Meteorological data includes daily rainfall, temperature, relative humidity, solar radiation and wind speed etc. Further, observed hydrological data is needed to carry out the sensitivity analysis.

Table 1. Source of different inputs used in this study.

S.No	Input	Source	Resolution	Use
1	DEM	Derived from 30-meter STRM Data set	30 m × 30 m	a)Delineation of watershed b)Analysis of drainage pattern c)Derivation of slope

2	Land use / Land cover	Department of Geography, University of Kashmir	100m × 100m	a)Categorization of area b)Affects Runoff, evapotrapiration and other hydrological processes
3	Soil data	Soil conservation Department, Kashmir	250m × 250m 3 soil profiles	a)Categorization for individual HRU's
4	Weather data	Meteorological Department of Kashmir	4 gauging stations	Model inputs for evaluation of hydrological data
5	Measured data of runoff and sediment yield	Irrigation and Flood Control Department Kashmir	Daily data from Jan 2009- Dec 2017	Data used for calibration and validation of estimated data

2.4 Model Setup

SWAT model (2012 version) was integrated with ArcGIS (version 10.1) for effective use of spatial data to enhance model behavior and to provide a user-friendly editing environment. Watershed was automatically delineated into sub-basins and further into Hydrologic Response Units (HRUs) to describe spatial heterogeneity in terms of slope, land cover and soil characteristics within the catchment. The first step was to import a 30 m × 30 m resolution Digital Elevation Map. A polyline stream network data set was burnt into SWAT to improve the hydrological segmentation and reduce the processing time. A threshold critical source area of 300 hectares was used which delineated the whole area into 43 sub-basins. A land use/ land use cover map of resolution 100 m × 100 m in a projected grid format was loaded into the SWAT along with the soil data to determine the spatial heterogeneity within each sub-basin which resulted into delineation of 43 sub-basins into 182 Hydrologic Response Units taking into consideration 5%, 10% and 10% threshold levels for land use, soil and slope classes. The land use classifications were re-classified in a form to match the land use classes recognized by SWAT and are categorized in table 2.

Table 2. Re-classification of Land-use/ Land cover classes

S.No	Land use Class	Re-classification into 4-letter SWAT code	Percentage area
1	Dense forests	FRSD	9.18
2	Moderate forests	FRSD	8.98
3	Sparse forests	FRSD	26.18
4	Agriculture	AGRL	34.14
5	Horticulture	RNGE	10.39
6	Water bodies	WATR	7.52
7	Snow	WATR	3.61

Land use swat description used in reclassifying land use/land cover map was obtained from USDA-NASS (The United States Department Of Agriculture-National Agricultural Statistics Science crop land data layer).

2.5 Model Calibration and Validation

SWAT model was applied to the watershed under study for period of 8 years from 2010-2017.Data from 2010-2013 was used for calibration and the model was validated for the period of 2014-2017.SWAT has manual calibration as well as auto-calibration built-ins. Manual calibration, being a time consuming procedure (Eckhardt & Arnold, 2001), whose successes depends on the experience of the modeler was avoided in this study. Auto-calibration technique was used to carry out the calibration task and to find the optimal parameters using the Shuffled Complex Evolution Method (SCEM) algorithms (Arnold et al., 2012).After finding out the most sensitive parameters, for both stream-flow and sediment yield, the model was validated and the efficiency of model was checked using Coefficient of determination (R2) and Nash-Sutcliffe Coefficient (NSE) given in equation 5 and 6 respectively (Tuppad et al., 2011).

$$\text{ENS}= 1- \frac{\sum_{i=1}^{n}(Observed_i - Predicted_i)^2}{\sum_{i=1}^{n}(Observed_i - Mean_{Observed})^2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots (5)$$

$$\text{R2}= \left\{\frac{\sum_{i=1}^{n}(Observed_i - Observed_{mean})(Predicted_i - Predicted_{mean}]}{[\sum_{i=1}^{n}(Observed_i - Observed_{mean})^2]^{1/2}[\sum_{i=1}^{n}(Predicted_i - Predicted_{mean})^2]^{1/2}}\right\}^2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots (6)$$

Where, ENS is Nash-Sutcliffe coefficient, R2 is coefficient of determination, $Observed_i$ is the actual measured data for the time period i, $Predicted_i$ is the data estimated by model for the time period i, $Mean_{Observed}$ is the mean of the actual measured data, $Predicted_{mean}$ is the mean of data estimated by model, n is the number of values in comparison.

Nash-Sutcliffe gives the efficiency between -∞ to 1 to relate the goodness-of-fit of the model to the variance of observed data. An efficiency of 1 corresponds to the perfect match between the data estimated by model and the actual observed data. A Nash-Sutcliffe efficiency of zero means that the data estimated by the model is as accurate as the mean of the actual observed data. An efficiency of less than zero depicts the inefficiency of model to estimate the data. Efficiency between 0.7 to 1 depicts that the model predicts extremely well (Calder, I.R., 1998). The value of coefficient of determination lies between zero and 1 where the efficiency of zero means there is no correlation at all between the actual measured data and the data predicted by the model. An efficiency of 1 indicates a perfect match between the two set of data.

3 RESULTS AND DISCUSSION

First simulation by SWAT was unable to quantify the desired outcome. The actual peak discharges were underestimated due to which the model calibration was necessary. Four most sensitive parameters were identified and calibrated accordingly to improve the efficiency of SWAT. The parameters were modified according to the procedure and ranges defined in SWAT model documentation (Arnold et al., 2012). The initial soil conservation service Curve Number II was increased by 16% of the original Curve number value to amplify the runoff by decreasing the total infiltration. The available soil water capacity was reduced by 10% of the original value so that the movement of water through soil layers can be increased. The average slope length was also moderated for each sub-basin with the values ranging from 46m-290m throughout 43 sub-basins. The saturated hydraulic conductivity was decreased by 8% of the original value in order to reduce the lateral flows. These sensitive parameters for estimation of runoff are summarized in table 3 along with their ranks.

Table 3. Most sensitive parameters for runoff estimation

Parameter	Rank	Range of calibration	Calibrated value
Initial Soil Conservation Service Curve Number II	1	±25%	16%
Available Soil Water Capacity	2	±25%	10%
Average Slope Length in meters	3	10 to 300	46-290
Saturated Hydraulic Conductivity(mm/h)	4	±15%	8%

Likewise two most sensitive parameters were identified for calibration process of sediment which includes Channel erodability factor and channel cover factor whose values were adjusted to 0.65 and 0.43 respectively. Sensitive parameters for sediment calibration are summarized in table 4.

Table 4. Most sensitive parameters for Sediment yield estimation

Parameter	Rank	Range of calibration	Calibrated value
Channel erodability factor	1	0-1	0.65
Channel cover factor	2	0-1	0.43

The monthly observed values of runoff and values predicted by the model for the calibration period from 2010-2013 were in average relationship with each other with Nash-Sutcliffe efficiency and Coefficient of determination of 0.56 and 0.81 respectively (Figure 2). However, these efficiencies improved while SWAT was run for the validation period from 2013-2017 with Nash-Sutcliffe efficiency and Coefficient of determination as 0.98 and 0.99 respectively (Figure 3). The efficiency of SWAT along with the fitting equation between observed and simulated values of runoff during calibration and validation period is shown in table 5.

Table 5. Efficiency of SWAT model for prediction of runoff during calibration and validation period

Observed and Predicted Runoff(mm)	Nash-Sutcliffe Efficiency	Coefficient of determination	Linear fit equation (Y= predicted flow; x=observed flow)
Calibration Period(2010-2013)	0.56	0.81	Y= 0.66x+5.89
Validation Period (2013-2017)	0.98	0.99	Y=0.93x-0.21

SWAT showed satisfactory results while modeling sediment yield with Nash-Sutcliffe efficiency and Coefficient of determination values of 0.75 and 0.76 respectively during the calibration period (Figure 4) and these efficiencies increased during the validation period with Nash-Sutcliffe efficiency of 0.91 and coefficient of determination as 0.94 (Figure 5). The efficiency of SWAT along with the fitting equation between observed and simulated values of sediment yield during calibration and validation period is shown in table 6. Although the statistical evaluation showed the satisfactory runoff simulation for both calibration and validation periods, SWAT tended to underestimate the runoff during high-flow periods. This could be partly because the present curve number technique is unable to generate accurate runoff prediction for a day that experience several storms. When several storms occur during a single day, the soil moisture level and the corresponding runoff curve number vary from storm to storm (Kim et al., 2018). However, SCS-CN methods define a rainfall event as the sum of all rainfall that occurs during one day, and this might lead to underestimation of runoff (Chow et al., 1988)

Table 6. Effeciency of SWAT model for prediction of sediment yield during calibration and validation period.

Observed and Predicted Sediment yield(t/ha)	Nash-Sutcliffe Efficiency	Coefficient of determination	Linear fit equation (Y= predicted yield; x=observed yield)
Calibration Period(2010-2013)	0.75	0.76	Y= 0.88x+2.58
Validation Period (2013-2017)	0.91	0.94	Y=0.85x+2.42

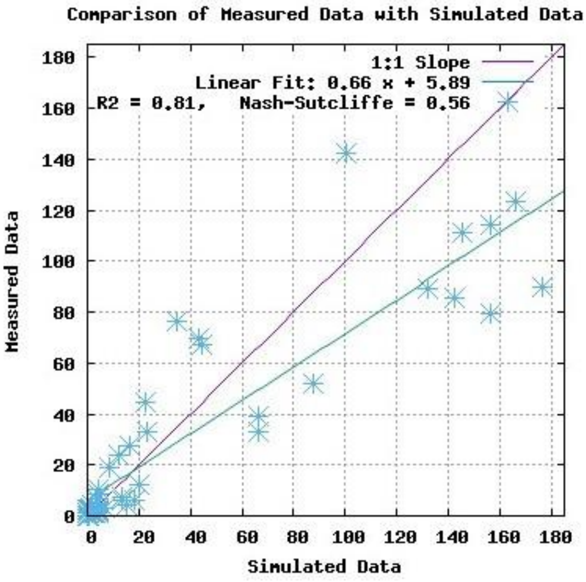

Figure 2. Scatter plot showing relation between observed and predicted runoff during Calibration period.

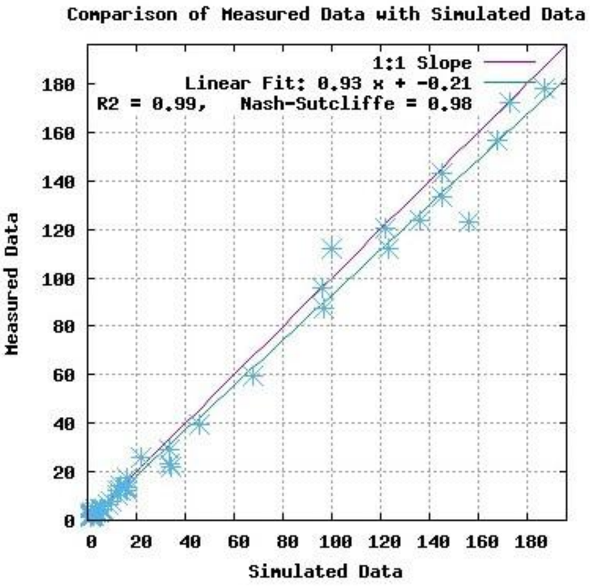

Figure 3. Scatter plot showing relation between observed and predicted runoff during validation period.

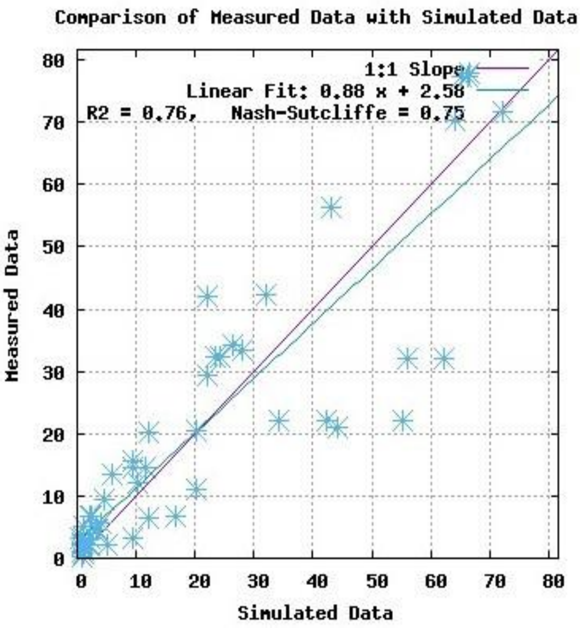

Figure 4. Scatter plot showing relation between observed and predicted sediment during Calibration period

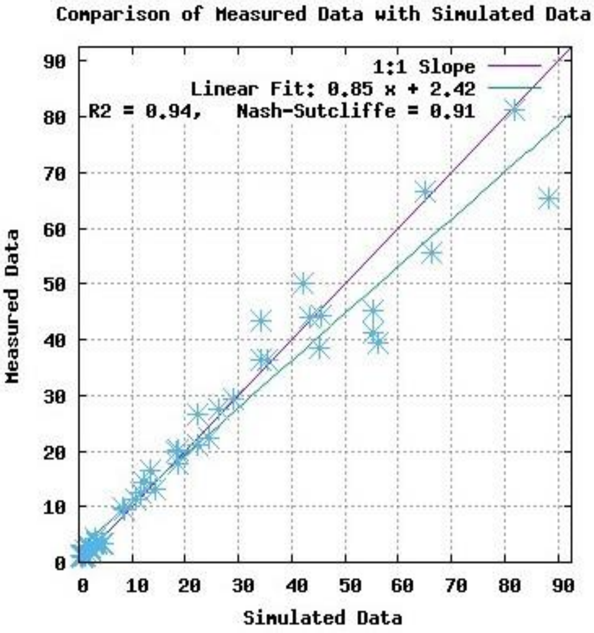

Figure 5. Scatter plot showing relation between observed and predicted sediment during validation period.

Bar-charts showing the variation between the observed and predicted values of runoff during the calibration and validation periods are shown in figure 6 and 7 respectively.

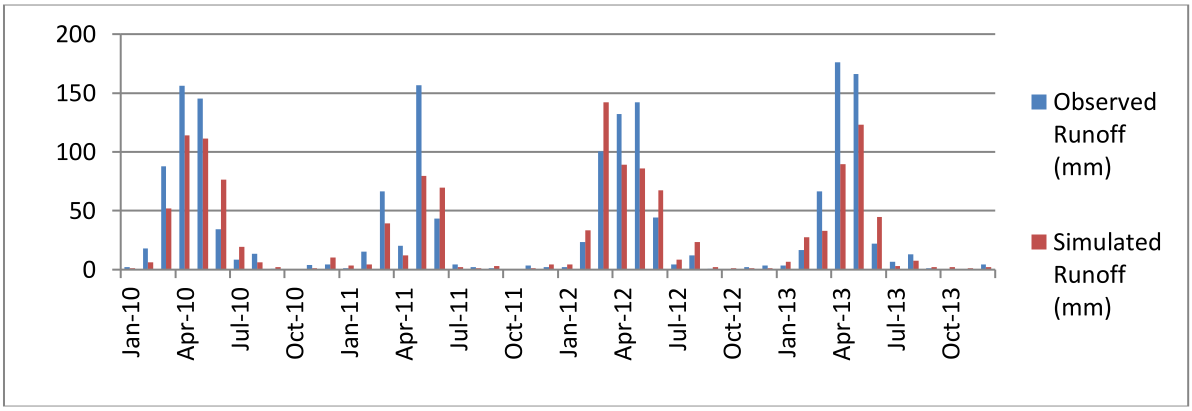

Figure 6. Bar-chart showing monthly values of observed and predicted runoff during calibration period.

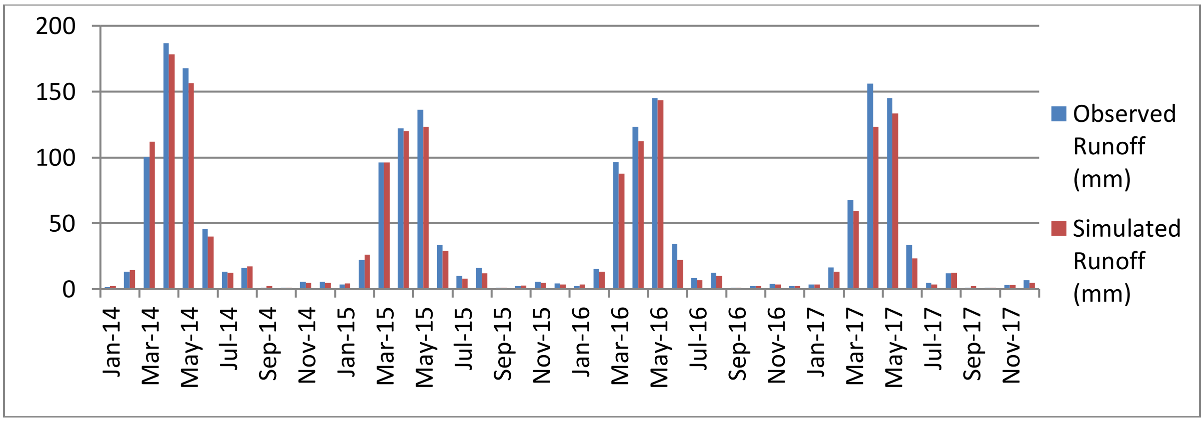

Figure 7. Bar-chart showing monthly values of observed and predicted runoff during validation period.

A plot of monthly observed and predicted sediment yield during the calibration and validation periods is shown in the form of bar-charts in figure 8 and figure 9 respectively.

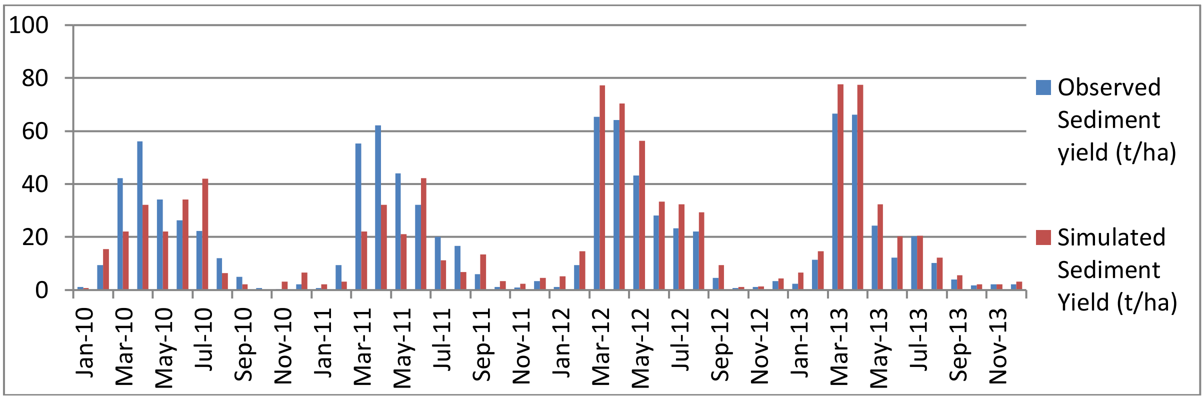

Figure 8. Bar-chart showing monthly values of observed and predicted sediment yield during calibration period.

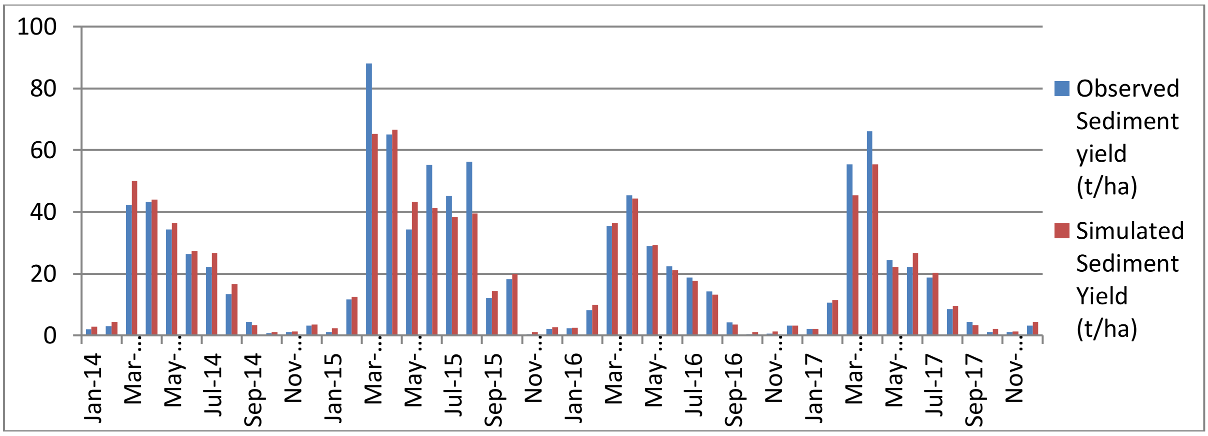

Figure 9. Bar-chart showing monthly values of observed and predicted sediment yield during validation period.

The annual average sediment drawn from each sub-basin was calculated to find the most problematic sub-basins and on the basis of that a prioritization map was prepared as shown in figure 10.

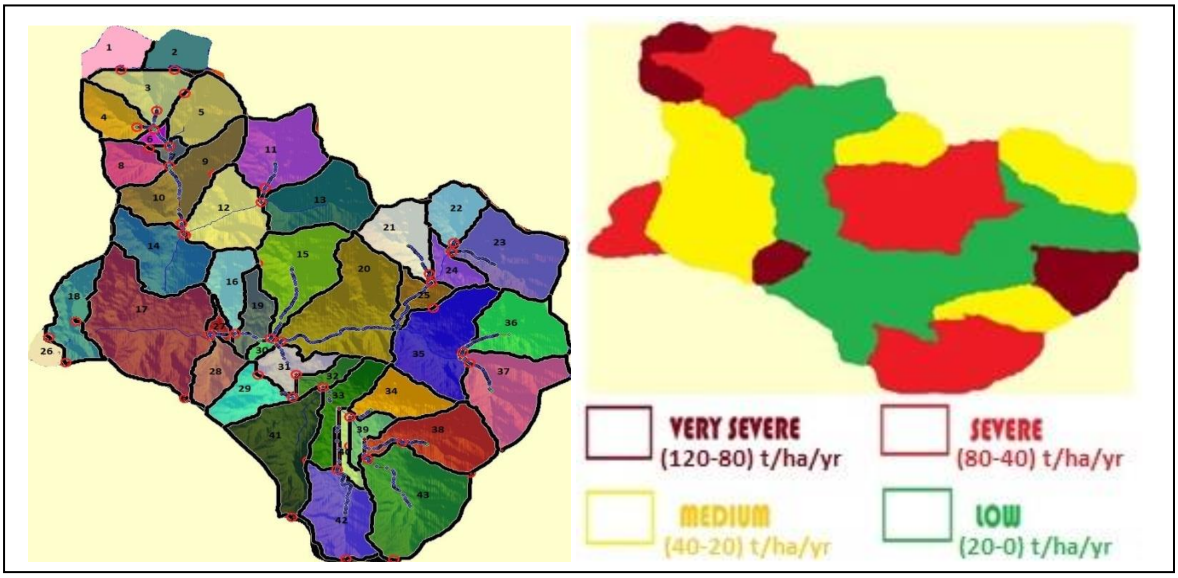

Figure 10. Watershed prioritization map shoving the severity level of erosion in different sub-basins

The sub-basins were categorized in very severe, severe, medium and low severity areas as shown in table 7. The status shows that about 40% of the total area of watershed come under very severe to severe erosion zone. Sub-basin no's 1,4,6,7,28,37 of Lolab watershed at the existing condition generates a maximum annual average sediment yield, this can be reduced by using sediment yield intervention strategies such as land slope stabilization, construction bench terraces, changing the land use of steep area and afforestation.

Table 7. Severity level of sub-basins of Lolab watershed

S.No	Severity level	Sub-basin numbers	Percentage area	Annual average sediment yield (t/ha/yr)
1	Very severe	1,4,6,7,28,37	10.47	80-120
2	severe	2,3,5,15,18,20,21,25,26,42,43	29.17	40-80
3	medium	8,10,13,14,17,22,23,38,39	24.22	20-40
4	low	9,11,12,16,19,24,27,29,30,31,32,33,34,35,36,39,40,41	36.14	0-20

4 CONCLUSION

Even though various efforts are been made to address the soil erosion problem at gross root level and various conventional methods are being used to know the hydrological behavior at watershed level, it is necessary to know about the hydrological parameters at sub-basin or even smaller levels to find out the most problematic areas and factors responsible for degradation of whole watershed. In this study, a semi-distributed physical model SWAT (Soil and Water Assessment Tool) was used to assess the hydrological behavior of a small watershed of Pohru catchment of Kashmir valley. The aim of the present study was to check the efficiency of SWAT model in predicting the runoff and sediment yield of Lolab watershed and to identify the most problematic sub-basins which draw the maximum amount of sediment.

The values estimated by the model were compared with the actual observed data and a good agreement between the observed and simulated values was found with Nash-Sutcliffe efficiencies as 0.56 and 0.75 for runoff and sediment respectively yield and coefficient of determination as 0.81 and 0.76 for runoff and sediment yield respectively during the calibration period.
The efficiencies increased during the validation of model with Nash-Sutcliffe efficiencies of 0.98 and 0.91 for runoff and sediment yield respectively and coefficient of determination as 0.99 and 0.94 for runoff and sediment yield respectively.

Further, a prioritization map was prepared to find the areas which draw maximum amount of sediment so that proper intervention strategies can be applied for management of watershed. In general, SWAT was found to be a good analyzing tool for assessment of hydrological behavior of highly gullied regions and other un-gauged basins of Kashmir valley.

DISCLAIMER

The authors declare no conflict of interest.

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