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Modeling of a River Basin Using SWAT Model and SUFI-2

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Abstract

This paper presents the hydrologic modeling for the development of management scenario and the simulation of the effect of management practices on water and sediment yielding in Gharasu watershed (5793 km^2) using the Soil and Water Assessment Tool (SWAT2000) model. The SWAT2000 interfaced with Arc View GIS data layers including Digital Elevation Model (DEM), land cover and soil map by AVSWAT2000 software. The model was calibrated from 1991 to 1996 and validated from 1997 to 2000. Then the model was calibrated again using SUFI-2. The results showed there is no considerable difference between the value of parameters that were obtained by SWAT and SUFI-2, but the duration of calibration was reduced from four months to one week. The calibrated model for hydrological conditions was used to assess suspended sediment load. Eventually, the model was used to predict the effect of changing land use and conservation practices on sediment yield within the basin.

KEYWORDS: Karkheh River Basin, sediment yield, simulation, SWAT, SUFI-2

Introduction

Because of geographical and climatic characteristics of Karkheh River Basin, the soil erosion is one of the main severe problems of this basin. The severity of this problem is more pronounced in arid and semi-arid land, where high rain fall intensities of short duration on grazing lands and rain-fed farms and human mismanagement of land has accelerated soil losses by erosion. 19% of the upper watershed’s rangelands and 70% of its forests have been significantly degraded [5]. Unless erosion is controlled, sedimentation will significantly reduce the storage capacity of the Karkheh dam reservoir. The Karkheh River Basin has an average yearly sediment yield of 920 tones per km^2 each which is one of the country’s highest [5]. In this paper, one of the sub-basins of Karkheh River Basin, Gharasu River Basin, was chosen to determine soil erosion and sedimentation transport loading pattern. The main problem of Gharasu basin is conversion of rangelands to rain fed crop in hilly lands without any conservation practices.

SWAT2000 Description

SWAT2000 has been chosen for this study because it can be used in large agricultural river basin scales and it is easy to use for simulating crop growth and agricultural management. SWAT[1] incorporates features of several ARS[2] models and is a direct outgrowth of the SWRRB[3] model. SWAT can be used to simulate a single watershed or system of multiple hydrologically connected watersheds. Each watershed is first divided into sub-basins and then into hydrologic response units (HRUs) based on the land use and soil distribution. By using a DEM and stream network, the study area is divided into 66 sub-basins. Each sub-basin is further divided into 437 HRUs, which are determined by unique intersections of the land use-soils within each sub-basin. Each HRU within a given sub-basin can be characterized with a unique set of management practices such as crop growth and irrigation.

The water storage components are soil profile, shallow aquifer, deep aquifer and snow cover. A daily water budget is established for each HRU based on precipitation, surface runoff, evapotranspiration, base flow (groundwater and lateral flow), percolation and soil moisture change. A detailed theoretical description of SWAT and its major components can be found in Neitsch et al. (2002) [9].

SWAT is widely used in the United States and in other regions of the world; exploring the potential impact of reforestation on the hydrology of the upper Tana river catchments and the Masinga dam in Kenya (9753 km^2) [7], hydrologic modeling of the Iroquois River watershed, simulation of hydrologic and sediment loading in connonsville River Basin (1200 km^2) [3], water quality modeling for the Raccoon River watershed (9397 km^2) in west central Iowa [8], sediment, nitrogen and phosphorus loading simulation of Bosque River TMDL in Earth county, Texas [11]. In this study, simulation of hydrologic and sediment loading by SWAT has been performed in approximately large basin (5793 km^2). The model calibration by SWAT is time consuming, so in this study SUFI-2 (Sequential Uncertainly Fitting Ver. 2) [1] was used to evaluate SWAT by performing calibration and uncertainly analysis. SUFI-2 is a semi-automated inverse modeling procedure for combined calibration-uncertainly analysis [2].

Characterization of Study area

Gharasu River Basin is located in the north west of Karkheh River Basin in the far western corner of Iran. The area of the basin is approximately 5793 km^2. The elevation changes from 1237 to 3350 and the mean elevation is 1555 masl. The average land–surface slope from DEM is 14%. Annual mean temperature of the study area is 14.6 °C, varying from 1.1 °C in February to 27.3 °C in August. annual average precipitation is about 447 mm, ranging from 215 mm to 785 mm. The predominate land use is agriculture which covers about 67% of the basin (Landsat 1993). Wheat and barley are the major crops grown in the basin. Some 5370 km^2 of the total area of basin is drained into the outlet, where the main gauge station, Gharabaghestan, is located. Soil is predominately a heterogeneous mix of silt or clay with some local deposits of sand in lowlands. Soil texture in lowland is clay to heavy clay and poor drainage.

Daily weather data for precipitation, maximum and minimum temperature were obtained from the records of the climate stations and rain gauge stations for the period of 1988 – 2000. Twenty years (1980–2000) of monthly rainfall, maximum and minimum temperature, relative humidity, wind speed and solar radiation data of the basin were obtained from two climate stations. Daily stream flow was obtained from three stations and Total

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[1] Soil and Water Assessment Tool

[2] Agricultural Research Service (USDA)

[3] Simulator for Water Resources in Rural Basins

Suspended Solids (TSS) were obtained from two stations for the period from 1991 to 2000 within the basin and the main station located at the outlet of the basin.

In total, 1172 discharge and sediment samples were collected for generating monthly TSS. The monthly TSS was used for model calibration and validation. Figure 1 shows the location of the stream flow, TSS, rain gauges and climate stations used in the model calibration. Data layers include DEM (50×50 m), land use (Landsat 1993), soil map and streams shape file. The soil map includes 8 types of soils. Soil texture, percent of silt, clay and sand and organic carbon content information was available for different layers of soil. Six main classes of land use were: agriculture (rain-fed irrigated), range (poor-fair-good) and mixed-forest. Winter wheat is chosen as a main growing the crop basin. After a tillage operation, winter wheat is planted on the 20th of October, it is harvested on the 15th to 20th and the soil is tilled again. About 400 mm of water is used every 15 days for irrigation during 6 months. Table 1 summarizes the data used to develop, calibrate, and validate the model.

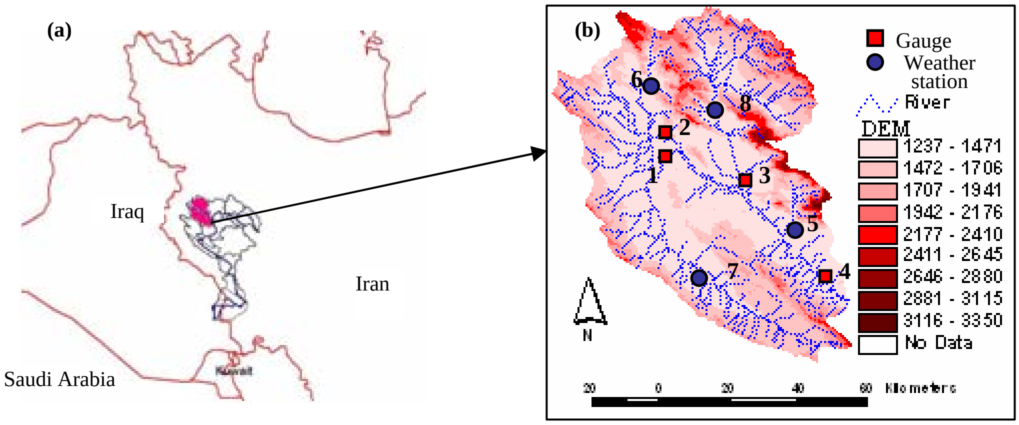


Figure 1 Study area: (a) Location of Karkheh river basin in Iran (b) Location of flow, climate and TSS stations in Gharasu sub-basin.

Table 1. Summary of data used in model development, calibration and validation.

Data	Location (Number on fig 1-b)	Period of record	Organization	Primary use
Stream flow Monitoring	Khers abad (1)	1974-present	IWRM	Calibration and validation
	Doab merek (2)	1954-present		
	Hojat abad (3)	1964-1998		
	Gharabaghestan (4)	1954-present		
TSS Monitoring	Khers abad (1)	1974-present	IWRM	Calibration and validation
	Doab merek (2)	1964-present		
	Gharabaghestan (4)	1962-present		
Climate	Kermanshah (5)	1951-present	IRIMO	Model input
	Ravansar (6)	1988-present		
Rain gauge	Mahidasht (7)	1975-present	IRIMO	Model input
	Jelogireh (8)	1976-present		
Land use	Basinwide	1993	RIAEP	Model input
Stream network	Basinwide	Unknown	SCWMRC	Model input
Soils	Basinwide	Unknown	SWRI	Model input
Digital elevation model	Basinwide	Unknown	SCWMRC	Model input

Note: IWRM=Iran Water Resources Management; IRIMO=I. R. of Iran Meteorological Organization; RIAEP=Research Institute for Agricultural Economics and Planning; SCWMRC=Soil Conservation and Watershed Management Research Institute; SWRI= Soil and Water Research Institute.

Initial setting of parameters

After preparing required data files and information layers, the model was run. Then independent of numerical calibration, a number of model inputs and parameters adjusted to better represent known conditions in the basin. These parameters are presented in table 2. All data–driven input parameters in table 2 are constant in the calibration and validation periods. More details about the determination of these parameters can be found in [10].

Table 2. Summary of initial setting of the SWAT model parameters.

Parameter	SWAT variable name	Range	Default value	Final value
Snowfall temperature (ºC)	SFTMP	±5	+1	+2
Surface runoff lag coefficient	SURLAG	1-40	4	1
Manning's "n" value for overland flow	OV-N	0.01-0.8	0.15	Engman, 1983 [6]
Manning's "n" value for the main channel	CH-N2	0.01-0.3	0.014	Chow, 1959 [4]
Lateral flow travel time (days)	LAT-TTIME	0-180	0	Calculated and Varied by HRU [9]
Temperature lapse rate (ºC/km)	TLAPS	0-50	6	5
Elevation at the center of the elevation band (m)	ELEVB	0-8000	0	Determined from AVSWAT elevation report
Fraction of sub-basin area within the elevation band	ELEVB-FR	0-1	0	
USLE equation support practice factor.	USLE-P	0.1-1	0	1
Soil erodibility (K) factor (units: 0.013 (metric ton m^2 hr)/(m3-metric ton cm)).	USLE-K	0-0.65	0	Mountain (0.3) Hill (0.4) Other areas (0.27)
Minimum value of USLE C factor for water erosionapplicable to the land cover/plant	USLE-C	0.001-0.5	Agricultural land (0.03)	0.03
			Range (0.003)	Good (0.002) Fair (0.003) Poor (0.004)
			Forest(0.001)	0.001
Rock fragment content (% total weight).	ROCK	0-100	0	Varied by soil type

Model calibration and validation

Continuous discharge data and a large number of TSS samples over 10 years from multiple locations within the basin were used for model calibration and validation. The model was calibrated over 6 years, from January 1991 to December 1996. Four years (1987 to 1990) were chosen as a warm-up period in which the model was allowed to initialize and then approach reasonable starting values for model state variables. Model predictions are not evaluated in accordance with the 4-year warm-up period until another 4 full years have been simulated. Some parameters used to simulate TSS were driven from available data or known conditions in the watershed. In this study, the calibration process begun by 25 Parameters in the SUFI-2 algorithm, but in the last iteration only 16 were found to be sensitive to discharge and sediment, because high correlated parameters with the smallest sensitivities were not changed any longer in the iteration process. In each iteration, 500 model calls were performed, for a total of 3000 simulations. The calibration parameters are presented in table 3. As shown in table 3, there is not considerable difference between the value of parameters that were calculated by SWAT and SUFI-2, but the duration of calibration was reduced 113 days and more numbers of parameter were determined, such as groundwater delay time (GW_DELAY), Manning's "n" value for overland flow (OV_N) and channel erosion parameters. In previous studies the channel erosion was ignored but by using SUFI-2 we could determine the stream channel erosion parameters. The parameters are ranked according to their sensitivities in table 3. Five parameters were found to be sensitive to sediment only. These included channel re-entrained exponent parameter (SPEXP), channel re-entrained linear parameter (SPCON), peak rate adjustment factor for sediment routing in the main channel (PRF), channel erodability factor (CH_EROD) and channel cover factor (CH_COV). Other parameters were found to be sensitive to both discharge and sediment; but the influence of two parameters (ALPHA_BF and GW_REVAP) on sediment load was negligible.

The results of the monthly discharge and TSS simulation are shown in figure 2. These simulations are based on a calibration that used monthly discharge and TSS in the objective function. The objective function used in this study is the sum of square errors. The shade region (95PPU), brackets a large amount of the measured data, which contains all uncertainties such as rainfall, soil properties and water consuming. SUFI-2 is a stochastic procedure, so statistics such as percent error, R^2 and Nash-Sutcliff, which compare two signals, are not applicable. Instead, the 95% prediction uncertainty (95PPU) was calculated for all the variables in the objective function [2]. This is calculated by the 2.5th (X_L) and 97.5th (X_U) percentiles of the cumulative distribution of every simulated point [2]. The parameter ranges leading to the 95PPU are presented in the table 3. The d-factor is the ratio of the average distance between the above percentiles and the standard deviation of the corresponding measured variable [2]. In discharge calibration, 83% of the measured data were bracketed by the 95PPU while the d-factor was 1.47.

The model was validated over 4 years, from January 1997 to December 2000. The longest–running flow gauge for the basin drains approximately 93% of the basin (station 4 in fig. 1). In addition, the three gauges that drain the smaller sub-basins were used during the calibration procedure (Station 1, 2 and 3 in fig. 1). The result of calibration and validation for TSS simulation at the main outlet of the basin is shown in figure 3.

Table 3. Initial and final values of SWAT calibration parameters for stream flow.

Parameter	SWAT variable name	Final value	
		SUFI-2 calibration	SWAT calibration
ESCO	Soil evaporation compensation factor	0.48(a),0.61(b),0.56(c)	0.40
SMFMN	Melt factor for snow on December 21 (mm H_2O/ºC-day)	2.77(a), 1.95(b),2.34(c)	2.5
SMFMX	Melt factor for snow on June 21 (mm H_2O/ºC-day)	2.82(a), 1.98(b),2.45(c)	2.6
GW_REVAP	Groundwater "revap" coefficient	0.06(a),(b),0.04(c)	0.04(a),0.06(b),0.02(c)
SMTMP	Snow melt base temperature (ºC)	+3.55	+4
ALPHA_BF	Base flow alpha factor (days)	[0.08 , 0.23]	0.118(a), 0.098(b), 0.05(c)
CH_K2	Effective hydraulic conductivity in the main channel (mm/hr)	45,71	40(a), 60(b),(c)
GW_DELAY	Groundwater delay time (days)	[43 , 100]	Varied by HRU
GWQMN	Threshold depth of water in the shallow aquifer	[-20 , 171]	40(a),(b), 20(c)
OV_N	Manning's n value for the over land flow	[-0.13 , 0.24]	0.29(a) , 0.3(b),(c)
SFTMP	Snow fall temperature (^{0}C)	1.91	2.0
REVAPMN	Threshold depth of water in the shallow aquifer for "revap"	[-33 , 118]	20(a),(b), 10(c)
PRF	peak rate adjustment factor for sediment routing in the main channel	0.38	0.5
SPEXP	channel re-entrained exponent parameter	1.04	1.05
SPCON	channel re-entrained linear parameter	0.0016	0.002
CH_EROD	channel erodability factor	0.32	0.0
CH_COV	channel cover factor	0.49	0.0

(a) The area of basin that drained into Khers abad station (Station 1 on the map of Fig. 1) (1420 km^2).
(b) The area of basin that drained into Doab merek station (Station 2 on the map of Fig. 1) (1232 km^2).
(c) The area of basin that drained into Hojat abad and Gharabaghestan stations (Station 3 and 4 on the map of Fig. 1) (2718km^2).

The simulated flow of January, February and March is more than the observed flow in 1992, and it is less than the observed flow in April and May. It seems simulated snowmelt occurs sooner than actual time. Consistent with hydrology results, figure 3 demonstrates that at the main outlet of basin the model tends to increase TSS loading sooner in the winter of 1992 associated with snowmelt. The most severe errors in predicted TSS loads all occur in months where there are large predictive errors in the monthly flow.

In the previous study, average annual sediment yield of Gharasu basin was predicted 3.4 ton/ha by SWAT model, but in this study it is predicted 3.2 ton/ha by SUFI-2. Comparison of the values of hydrologic components that were calculated using SUFI-2 and SWAT showed the lateral flow and base flow changed more than other hydrologic components. Therefore, the change of sediment load was negligible, because it is not affected by lateral and base flows.

After sureness of model validity, the erosion map of sub-basins was provided. It is schematized in figure 4 from 1997 to 2000. By using this map the critical basin were specified (fig. 5). Comparison of erosion map and DEM showed that the critical sub-basins are located in mountainous and hilly areas. Moreover, comparison of sediment yield of HRUs indicates the most erosive areas are cultivated lands with steep slope. Land use type of hilly area is very important because most of the rain-fed lands are located in this area and the type of geology is low to medium resistance to erosion. So, vulnerability to soil erosion and sediment yield in these areas are high.

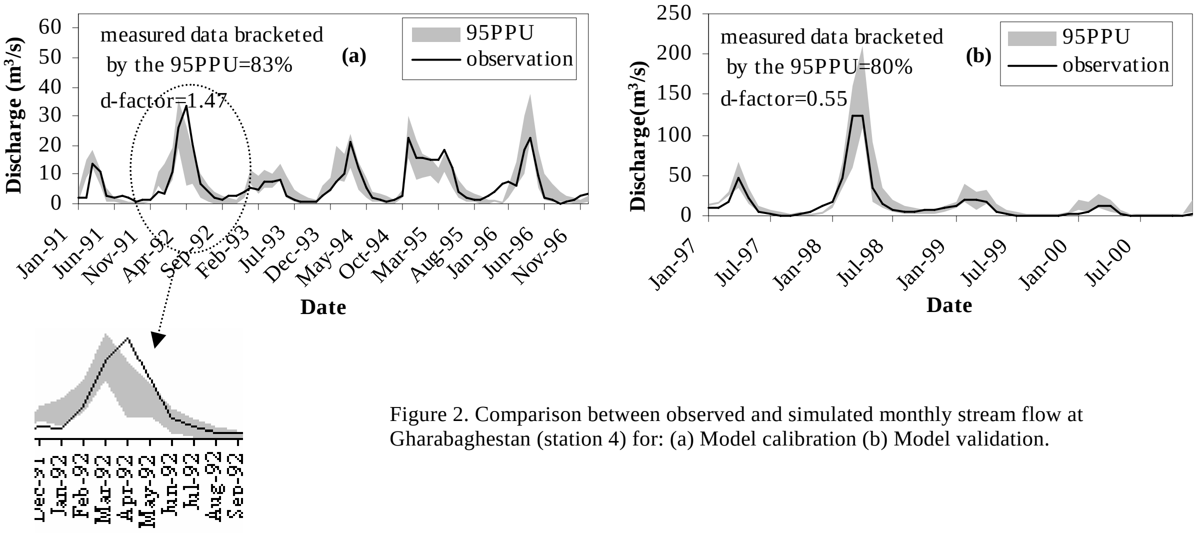


Figure 2. Comparison between observed and simulated monthly stream flow at Gharabaghestan (station 4) for: (a) Model calibration (b) Model validation.

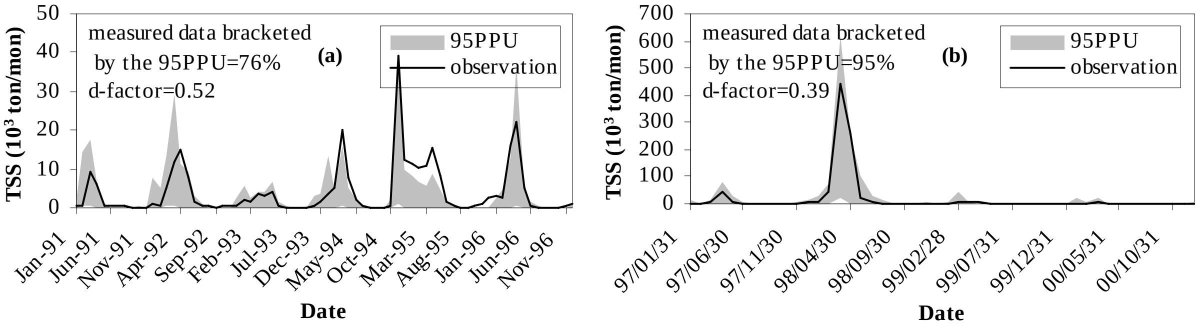
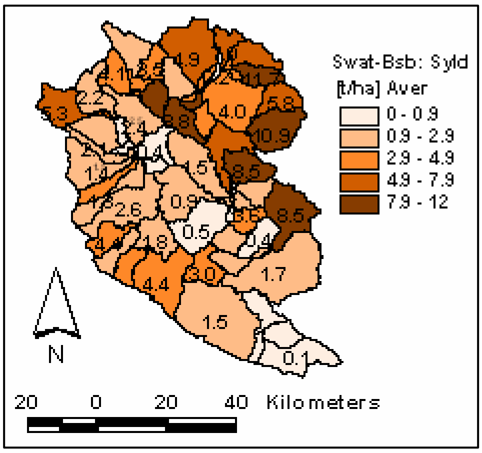


Figure 3. Comparison between observed and simulated monthly TSS at Gharabaghestan (station 4) for: (a) Model calibration (b) Model validation.



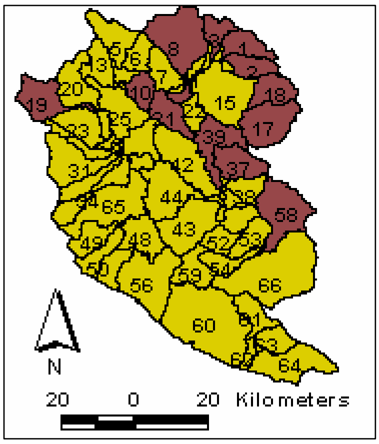


Figure 4. SWAT model predicted sediment yield Per hectare of sub-basin from 1991-1996.

Figure 5. Sensitive sub-basins to erosion (Dark color).

Irrigated agricultures are concentrated in the alluvial area and along the valley due to gentle slopes and its productive soils. Because of the gentle slope and heavy soil texture, little erosion occurs in these regions.

With consideration of the above explanations, some management scenarios are recommended for soil conservation:

1- Support practices such as contouring and terracing.

2- Land use change in hilly and mountainous areas of basin with due consideration of land capability.

First scenario: With due attention to topographic conditions and possibility of "contouring" or "contouring and terracing" the critical sub-basin 16, 17, 19, 37 and 39 are suitable for land management practices. Reduction of erosion in the agricultural HRUs located in lower parts of these critical sub-basins is presented in table 4. As shown in table 4, contouring and terracing is more effective than contouring.

Second scenario: Because land management practices in hilly and mountainous areas are impracticable, land cover changing of these areas is recommended for soil conservation. The hilly areas are suitable for afforestation. Therefore, rain-fed lands and other land uses located in hilly areas are converted to forest. The land cover of hillsides is converted to orchard. Finally, the mountainous areas are suitable for pasture and range.

The results of land use conversion are presented in table 5. The best effect of the land use conversion on sediment yield reduction occurs in sub-basins that rain-fed lands on hillsides are predominate land use (sub-basin 3, 8 and 19). Sediment yield reduction of mountainous sub-basins is negligible (sub-basin 10, 16, 37 and 39). In these sub-basins the main factor of erosion is steep slope, and land use conversion is not effective.

Table 4. Summary of support practices results on sediment yield.

Sub-basin	Area of HRU (%)	Initial sediment yield (ton/ha)	Predicted sediment yield (ton/ha)		Sediment yield reduction of sub basins (%)
			Contouring (Reduction %)	Contouring and Terracing (Reduction %)	
16	9	25.0	19.5 (22)	15.1 (40)	5
	3	0.6	0.28 (53)	0.28 (53)	
17	3	29.0	25.1 (13)	18.8 (35)	1
19	4	13.8	9.8 (29)	7.5 (46)	2
37	3	42.1	34.3 (19)	16.8 (60)	4
	4	22.6	20.3 (10)	13.7 (39)	
	1.5	1.3	0.0 (100)	0.65 (50)	
39	5	28.0	22.9 (18)	17.7 (37)	5
	6	7.8	5.1 (35)	3.2 (59)	

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Table 5. Summary of land use conversion results on sediment yield.

Sub-basin	Initial sediment yield (ton/ha)	Predicted sediment yield after land cover changing (ton/ha)	Sediment yield reduction of sub-basins (%)
3	6.83	0.42	94
19	4.12	0.25	94
8	4.63	0.33	93
17	7.52	2.98	60
1	5.12	2.13	58
18	4.63	2.05	56
2	10.21	6.94	32
58	6.32	4.73	25
21	6.15	5.24	15
37	8.75	8.85	0.03
39	7.93	7.83	0.03
10	6.71	6.52	0.01
16	3.42	3.51	0.01

Conclusions

In this study SUFI-2 was used for model calibration and validation. By using SUFI-2, we could perform uncertainly analysis and calibrate the model for more number of parameters. Also, the duration of model calibration was reduced from four months to one week. Two different management scenarios for soil conservation were considered in order to evaluate the effects on sediment yielding in Gharasu river basin. Contouring and terracing will effectively reduce sediment loading of rain-fed lands in hillsides. Changing agricultural practices such as increasing forest, conversion of rain-fed area in steep slope land to orchards and woods will reduce erosion about 5 percent within hilly and mountainous sub-basins. Finally, this study showed that the SWAT model is a capable tool for simulating hydrologic components and erosion in Gharasu river basin.

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