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Simulation of Sediment and Streamflow in Dabus River, Blue Nile basin

Nesredin Bashewal Mangel [a*] , Bilal Kamal Harun[b*]

[a] *Hydraulic Engineering), Assosa, University Assosa, Ethiopia, P.O.BOX. 18*

[b] *Hydraulic Engineering Assosa, University Assosa, Ethiopia, P.O.BOX. 18*

[a*] *Corresponding Email: nerehwre2017@gmail.com*

Abstract: Sediment yield and streamflow are depending on land use practice. The objective of this study to simulate the sediment yield and streamflow in the Dabus river based on the available land use data, soil data, meteorological data using the SWAT model. The initial soil conservation service runoff curve number is the most sensitive parameter for the streamflow model in Dabus catchment, its alteration on the streamflow was measure by t-stat which is 7.86 and the significance of its factor indicate by p-value is 0.02. Whereas the average slope length of the sub-basins is the sensitive parameter that affects the sediment model in this catchment, where t-stat is 2.65 and the p-value is 0.045. The simulated streamflow and sediment were calibrated and validated at the outlet of the Dabus catchment. The statistical value of model performances was evaluated by R^2 = 0.97, 0.76, NS = 0.91, 0.82 and Pbais = -2.1, 17.9 for streamflow calibration and validation. Whereas for sediment model calibration and validation R2 = 0.93, 0.94, NS = 0.88, 0.9 and Pbais = 12.46, 10.14 respectively. The sediment yield estimated from the agricultural area in Dabus catchment 173.09 t/ha which is greater than 10 metric tons per hectare.

Keywords: SWAT; SWAT-CUP; Sediment; streamflow; sub-basin; catchment; Land use

1 Introduction

Sediment yield is the net result of soil erosion and sediment deposition processes. It is defined as the total sediment outflow from a catchment, measurable at a point of reference for a specific period [1][2]. Soil erosion is a natural process accelerated by human activities. It is one of the most critical environmental hazards in the world. Every year, erosion of soil surface from river basins amounts to 60 billion tons and resulting in 24 billion tons of sediment flux to the oceans in the world, and almost 25 billion tons of soil are lost from agricultural lands [3]. From a global point of view, this currently represents a redistribution of soil resources by 7% in each decade with multiple consequences.

Soil erosion by water is a major agent of land degradation in Ethiopia and more specifically in the upper Blue Nile basin. it has a significant impact on downstream flooding and reservoir sedimentation[4]. The Blue Nile is one of the river basins which originated from the steep mountains of the Ethiopia Plateau. The soil erosion from the upstream of this basin is the major source of sediment load in the Nile basin [5]. In the downstream of the Blue Nile basin, the excessive sediment load was observed which led to massive operation cost of irrigation canal desilting, sediment dredging in front of hydropower turbines. Sinar Dam has lost 65% of its original storage after62 years of operation (Shahin, 1993), Rosieres and Khashm al-Griba Dam have also lost similar proportions since construction (Ahmed, 2004).

Streamflow is the flow of water in streams, rivers, or channels. It is derived from channel precipitation, overland flow, interflow, and groundwater. Runoff of water in streams is responsible for the transport of sediment, nutrients, and pollution downstream of the river. From the upper Blue Nile basin, the estimated sediment passing the gauging station at EL-Deim across the border in Sudan ranges from 111-140 Mt/yr [1]. The relation between the discharges and sediment flow in the river can be also represented by the sediment rating curve.

The sediment rating curve describes the average relationship between the discharge and suspended sediment concentration at a certain location. Many regression functions can be used to represent the sediment rating curve. The most commonly used sediment rating curve is the power regression function (Walling, 1978). The power regression is given as (1).

$$Q_s = a \cdot Q^b \qquad (1)$$

Where Q_s is suspended sediment concentration (mg/l), Q is discharge flow (m3/s), "a" and "b" are regression coefficient.

The sediment yield and streamflow are depending on the land-use practices in the entire watershed [6]. Agricultural practices in the Dabus watershed are dominated by cereal crop cultivation, which necessities frequent plowing that leads to little ground cover during the rainy season that in turn renders the soil to be more susceptible to erosion [7].

The main objective of this study is to simulate the sediment yield and streamflow for the Dabus catchment. And to understand the response hydrology components to the existing watershed characteristics.

2 Material and Method

2.1 Location of Study Area

The Dabus River is a north-flowing tributary of the Blue-Nile basin in southwestern Ethiopia. It bound within 34°28′53.57″W, 10°45′09.69″ N, 35°38′21.64″ E, 8°52′16.34″ S, and it joins its parent stream at 10°36′38″N 35°8′58″E. Its watershed covers an area of about 14725.39 km^2. The altitude of the Dabus watershed ranges approximately between 485 and 3150 above mean sea level. The annual rainfalls in this sub-basin range from 970mm to 1985mm and the ranges of annual maximum and minimum temperature are 20 c̊- 35 c̊ and 8.5 c̊ -20 c̊ respectively, see Figure 1.

2.2 Material

In this study, the digital elevation model (DEM 30x30m resolutions) was used in the analysis of spatial topographic parameters of the study area. Such parameters are including watershed delineation (sub-basin areas, slopes, elevations). The Sentinel-2A satellite image of 0.3km resolution land cover (2004-LULC) was used, see Table 1. Whereas the spatial soil data of the 1km resolution map obtained from a soil map of the world was used together with the land cover, and slope data of the Dabus watershed to obtain hydrologic response units (hru) parameters used in the SWAT model. According to FAO soil classification, the dominant soil group in the Dabus watershed are Ao63, Bh12, Je23, Ne12, Ne13, Re59, Vc23, Vc30, see Table 2. For the simulation of soil water of this data, the time series of meteorological data (daily precipitation, temperature, solar radiation, wind speed, relative humidity) obtain from Ethiopia national meteorology agency the selected gauging station in the Dabus watershed was used. The observed streamflow from 1997-2008 was used for simulated streamflow and sediment load calibration and validation.

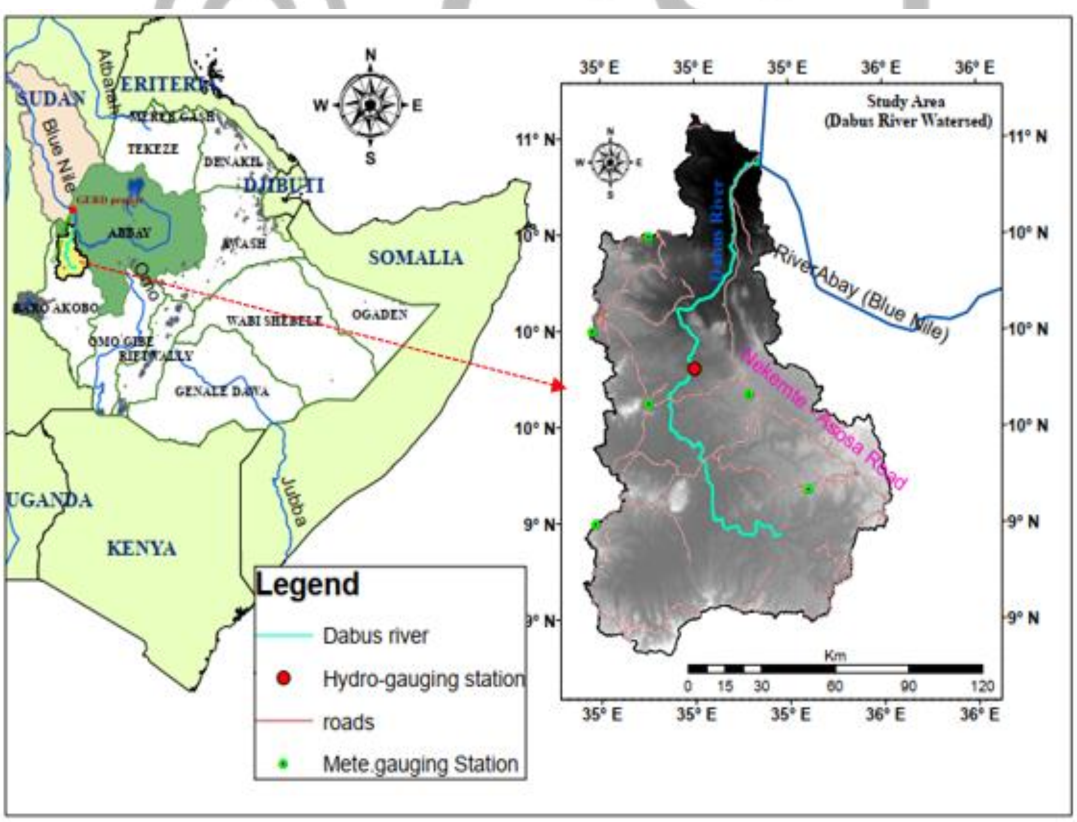


Figure 1 Location of the study area, source: generated from geographic shapefile

Table 1. Land use or land cover data and classification of Dabus catchment

2004-LULC	SWAT-code	Covered Area (%)
Rain feed crop (Crested wheat, Maize, Sorghum)	CWGR	0.03
Mosaic cropland (Agricultural land)	AGRL	32.06
Grassland (Range grass)	RNGE	11.04
Every green forest	FRSE	3.43
Deciduous Forest	FRSD	15.49
Shrub/bushland (Range bush)	RNGB	37.66
Water bodies	WATR	0.03
Barren land	BARR	0.09

Table 2. Soil data and its properties on Dabus catchment

Soil type /SWATcode/	Area(%)	k(m/hr)	AWC (%)	Sand (%)	Silt (%)	Clay (%)	USLE_K
Je23-a-121	8.42	36.21	36.21	33	37	30	0.26
Re59-2c-246	4.75	37.21	37.21	47	31	22	0.3
Bh12-3c-31	24.4	22.04	22.04	37	26	36	0.27
Ne13-3b-158	16.91	8.64	8.64	27	26	47	0.23
Ao63-3b-6	3.48	13.58	13.58	26	33	41	0.28
Vc30-3a-269	13.72	7.69	7.69	25	33	41	0.23
Ne12-3b-156	18.01	8.12	8.12	26	31	43	0.25
Vc23-3a-262	10.32	3.11	3.11	27	27	46	0.21

Note:- The dominant soil name corresponding to soil code in table 2: Eutric-fluvisols-Je23, Eutric-Regosols-Re59, Eutric-Nitosols-Ne12, Ne13, Orthic-Acrisols-Ao63, Humic-Combisols-Bh12, and Chromic-Vertisols-Vc23, Vc30 (Dewitte et al., 2013). k-soil hydraulic conductivity (m/hr), AWC- available moisture content in soil (%), USLE-K-soil erodibility factor.

2.3 Methods

SWAT (Soil Water Assessment Tool) model is a continuous-time, process-based river basin model. It was developed to evaluate the effects of alternative management decisions on water resources and non-point source pollution in large river basins[8]. The major components of the SWAT model include weather, hydrology, erosion, soil temperature, plant growth, pesticide, nutrients, land management, channel, and reservoir routing. The model divided the catchment or basins into sub-basins, each sub-basin is connected through a stream channel and further divided into hydrologic response units (hru). Based on hru developed for each sub-basin, then the model simulates hydrology, water, sediment, and other pollution components in the watershed of the given river. In SWAT, there are two alternative methods (SCS, and Green & Ampt infiltration methods) for simulation of surface runoff in the catchment. SCS-curve number method uses monthly rainfall data for estimation of surface runoff of catchment for this study. The SCS-curve number is given as (2).

$$Q_{Sur} = \frac{\left[P - 0.2S\right]^2}{\left[P - 0.8S\right]} \quad (2)$$

Whereas

$$s = 25.4\left[\left(100\frac{1000}{CN}\right) - 10\right] \quad (3)$$

Where Q_{sur} is surface runoff (mm), P is rainfall depth for the day (mm), S is the retention parameter(mm) and CN is curve number.

The streamflow of river channel routing methods is available in SWAT. The used routing method is either a variable storage routing method or the Muskingum routing method.

The variable storage routing method is given as (4).

$$V_{in} - V_{out} = \Delta V_{stored} \quad (4)$$

or

$$\left(\frac{q_{in,1} + q_{in,2}}{2}\right)\Delta t - \left(\frac{q_{out,1} + q_{out,2}}{2}\right)\Delta t = V_{stored,2} - V_{stored,1}$$

$$tt = \frac{V_{stored}}{q_{out}} = \frac{V_{stored,2}}{q_{out,2}} = \frac{V_{stored,1}}{q_{out,1}} \quad (5)$$

Where: V_{in} and V_{out} are volumes of water entered in (m^3) and left the reach respectively, *tt* is travel time in (s) q_{in} and q_{out} are the flow rate entered in (m^3/s) and left the reach with a given time step *t*.

The Muskingum routing method used in SWAT is based on Muskingum Cung. It is given as (6).

$$Q_2 = C_1 I_2 + C_2 I_1 + C_3 Q_1 \quad (6)$$

Where

$$C_1 = \frac{-2k\theta + \Delta t}{2k(1-\theta) + \Delta t} \quad (7)$$

$$C_2 = \frac{2k\theta + \Delta t}{2k(1-\theta) + \Delta t} \quad (8)$$

$$C_3 = \frac{2k(1-\theta) - \Delta t}{2k(1-\theta) + \Delta t} \quad (9)$$

Where k is storage time constant for the reach (s), θ is weighting factor (0-0.5), I_2 is inflow at the end of time step (m3/s), I_1 is inflow at the beginning of time step (m3/s), Q_2 is the outflow at the end of time step (m3/s), Q_1 is the outflow at the beginning of time step (m^3/s).

Sediment in streams is transported in two patterns, first, the sediment is immersed in and moved with water, which is called suspended sediment, and its amount crossing a section of river per time unit is called suspended sediment load. Second, the sediment is in the forms of slip, rolling, or jumping motions which are called bed load [9]. The sediment yield in SWAT is estimated with MUSLE, which is developed by [10]. The MUSLE is applied for each hru and sediment yields will be route down through the main channel by using a stream power equation. The MUSLE is applied for each hru and sediment yields will be route down through the main channel by using a stream power equation, which is the modified Bagnold's equation (1977) as reported in [11]. The sediment routing method is given as equation (10).

$$Q_{sed} = 11.8 \cdot K \cdot LS \cdot C \cdot P \cdot (Q \cdot q \cdot A)^{0.56} \quad (10)$$

Where Q_{sed} is the sediment yield for given events (metric tons), Q is surface runoff ($mmH_2O\ ha^{-1}$), A is the area of hru within the basin (ha), q is the peak runoff rate (m^3/s), K is the soil erodibility, LS is topography factor, C is the cover and management and P is the support factor.

SWAT-CUP was for calibration and validation of the SWAT model output. SWAT-CUP stands for SWAT calibration uncertainty, program, which is developed to analyze the prediction of the uncertainty of SWAT model calibration and validation results [12].

2.4 Model Performance

The accuracy, consistency, and adaptability performance of the model must be evaluated [13]. In this study, the statistical methods used to evaluate the performance of the model are: Nash-Sutcliffe model efficiency coefficient (NSE), coefficient of determination (R^2), and PBIAS measure the model quantitatively.

$$NSE = 1 - \frac{\sum_{i=1}^{n}(O_i - S_i)^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2} \quad (11)$$

$$R^2 = \frac{\left[\sum_{i=1}^{n}(O_i - \bar{O})(S_i - \bar{S})\right]^2}{\sum_{i=1}^{n}(O_i - \bar{O})^2 \sum_{i=1}^{n}(S_i - \bar{S})^2} \quad (12)$$

$$Pbias = \frac{\sum_{i=1}^{n}(O_i - S_i)}{\sum_{i=1}^{n} O_i}.100\% \quad (13)$$

Where S_i and O_i are simulated and observed values during model evaluation at time step i^{th} respectively, $\bar{O}$ is the average observed value, and "*n*" is the number of values.

3 Result and Discussion

3.1 Sensitivity Parameters Analysis

SWAT-CUP enables the sensitivity analysis, calibration, validation, and uncertainty analysis of the SWAT model [12]. In this study, the sensitivity parameters analysis for both streamflow and sediment in the Dabus river basin was done with 13 input parameters selected to streamflow, see in Table 3, 10 input parameters were selected to sediment, see in Table 4.

SUFI-2-algorithm was used to execute the parameters within 200 iterations of simulations during calibration and validation of streamflow and sediment. In the SUFI-2 algorithm, the assessment of the sensitive parameters is measured using the t-stat values[14]. The high value of t-stat indicated that the corresponding parameter is the most sensitive for selected model output and P-value is used to indicate the significance of that parameter affect the selected model output. Therefore, the only "R_CN.mgt" was determined as the most sensitive parameter for the SWAT streamflow model output, see Table 5, whereas, "R_SLSU-BBSN in sub-basin-1, 3,7, 12, 15, 16,20 were the most sensitive parameters sediment, see in Table 5

Table 3 Selected parameters for sensitive analysis to streamflow model in Dabus river

Parameters Name	Description of parameters	Range	Fitted Value
R__CN2.mgt	Initial SCS runoff curve number for moisture condition-II	-0.4	0.05
V__ALPHA_BF	Baseflow alpha factor (days)	0.0 - 1	0.74
V__GW_DELAY	Groundwater delay (days)	30– 450	42.35
V__GWQMN	Threshold depth of water in the shallow aquifer (mm)	0.0 – 2	1.94
V__GW_REVAP	Ground water "Revap" coefficient	0.0 – 0.2	0.03
V__ESCO.	Soil evaporation compensation factor	0.8 – 1	0.98
V__CH_N2.	Manning's "N" value for the main channel	0.0 – 0.3	0.13
V__CH_K2.	Effective hydraulic conductivity (mm/hr)	5– 130	67.5
V__ALPHA_BNK.	Baseflow alpha factor for bank storage (days)	0.0 – 1.0	0.85
R__SOL_AWC	Available water capacity for soil layer	-0.2 – 0.4	0.35
R__SOL_K	Soil Conductivity (mm/hr)	-0.8 – 0.8	0.09
R__SOL_BD	Soil moisture bulk density	-0.5 – 0.6	0.31
V__SFTMP	Snowfall temperature	-5 – 5	-2.94

Table 4 Selected parameter for sensitive analysis to sediment model in Dabus river

Parameters Name	Description of parameters	Range	Fitted Value
R_HRU_SLP.hru	Average slope steepness of sub-basin_1, 3, 7, 12, 15, 16, 20	0-0.2	0.088
R_OV_N	Manning's "n" value for overland flow on sub-basin_1, 3, 7, 12, 15, 16, 20	-0.2	-0.088
R_SLSUBBSN	Average slope length of sub-basin_1, 3, 7, 12, 15, 16,20	0-0.2	0.053
V_CH_N2	Manning's "n" value for the main channel	0-0.3	0.115
V_CH_K2	Effective hydraulic conductivity in main channel alluvium	5-130	8.676
SPCON	Linear parameter for calculating the maximum amount of sediment that can be re-entrained during channel sediment routing	0.0001-0.01	0.005
SPEXP	Exponent parameter for calculating sediment re-entrained in channel sediment routing	1-1.5	1.02
RSIDN	Initial residue cover (kg/ha)	0-1000	0.05
CH_COV1	Channel erodibility factor	0.05-0.6	0.07
CH_COV2	Channel cover factor	0.001-1	0.009

Table 5 Analyzed sensitive parameters for streamflow and sediment model in Dabus river

Type of model	Parameter Name	t-Stat	P-Value
Streamflow model	R__CN2.mgt	7.86	**0.02**
	V__GW_DELAY.	1.65	0.2
	R__SOL_BD	1.59	0.21
	V__ESCO	1.5	0.23
	V__ALPHA_BF	0.86	0.45
	V__ALPHA_BNK	0.85	0.46
	V__CH_K2.	0.66	0.56
	R__SOL_K	-0.65	0.56
	V__GWQMN	-0.38	0.73
	V__GW_REVAP	0.19	0.86
	V__SFTMP	0.14	0.9
	R__SOL_AWC	0.02	0.98
	V__CH_N2	0.01	0.99
Sediment model	R_SLSUBBSN_1,3,7,12,15,16,20	2.657	**0.045**
	R_OV_N_1,3,7,12,15,16,20	2.366	0.064
	R_HRU_SLP.hru_1,3,7,12,15,16,20	2.262	0.073
	V_CH_N2	-2.124	0.087
	V_CH_K2	-1.983	0.104
	SPCON	-1.847	0.124
	SPEXP	1.329	0.241
	RSIDN	1.166	0.296

CH_COV1	-0.838	0.44
CH_COV2	0.801	0.459

3.2 Model Calibration and Validation

In this study, SWAT-CUP (SUFI-2 algorithm) was used to calibrate and validate the simulated streamflow and sediment in the Dabus river basin at the outlet point of the river. The observed streamflow data at the outlet point from the 2000-2005 year of the recorded period was used for calibration, see *Figure 2,* and from 2005-2008 was taken for validation of simulated streamflow, see *Figure 3*. But the recorded sediment data was not enough to calibrate and validate simulated sediment load in this basin. Therefore, because of the lack of measured the sediment rating curve method was used to obtained sediment data from the measured streamflow data for calibration and validation of sediment flow out in the river at the outlet point of the basin. The same to calibration and validation of streamflow, the obtained data has been broken from 2000-2005 of measured data was taken for calibration of simulated sediment, see *Figure 4,* and from 2005-2008 period of measured data taken for validation *Figure 5*.

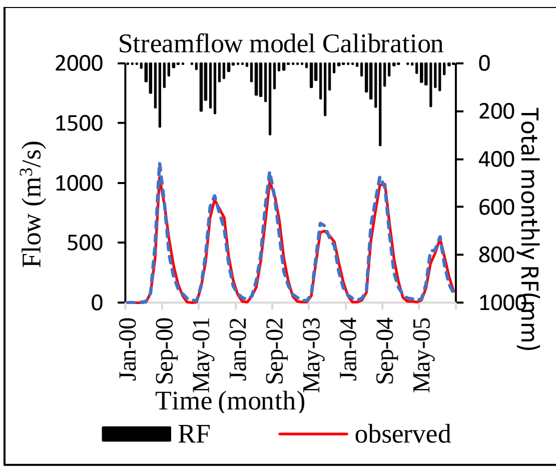


Figure 2 Calibrated streamflow at the Dabus outlet

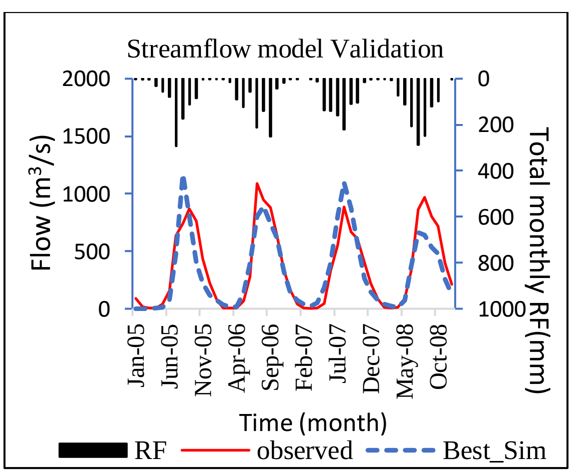


Figure 3 Validated streamflow at the Dabus outlet

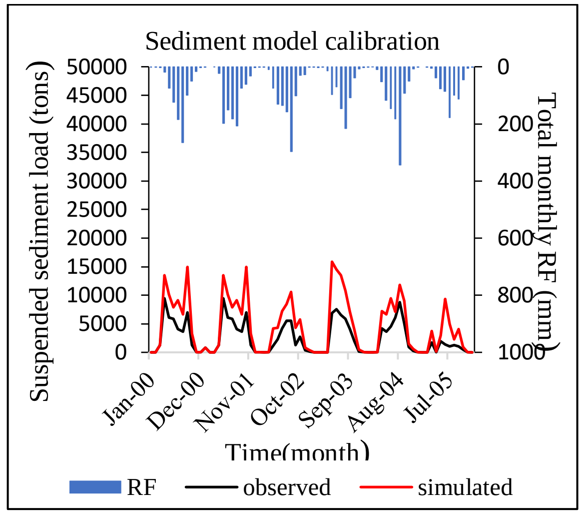


Figure 4 Calibrated sediment out at Dabus outlet

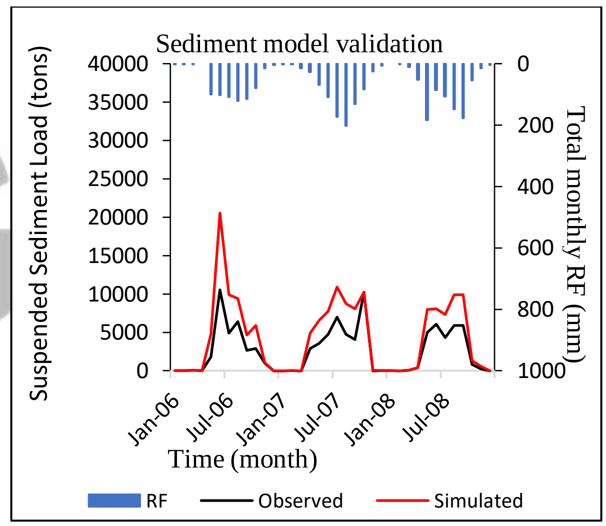


Figure 5 Validated sediment out at Dabus outlet

The performance of the model was evaluated during calibration and validation of the simulated streamflow and sediment. Therefore, the statistical value of SWAT-CUP output is summarized in *Table 6*

Table 6. Model performance

Type of models		R^2	NS	Pbais
Streamflow	calibration	0.97	0.91	-2.1
(m3/s)	Validation	0.76	0.82	17.9
Sediment	calibration	0.93	0.88	12.46
(ton)	Validation	0.94	0.9	10.14

3.3 Monthly Sediment and Streamflow

The maximum sediment yields were reported for agricultural land in the Dabus catchment*, see in Table 7*.

This shows that the soil from cultivated lands is easily detached by the overland flow during the rainy season which leads to a large amount of sediment yield occurring in this catchment. In other, the rate of erosion from cultivated land is high in this catchment. Due to this, the detached soil fragment is transported overland flow into the stream channel and deposited in the main channel where the slope in the river is low. As a result, it is possible to say that poor land use practice in this catchment is the factor for severity erosion risk that leads to high sediment problems in the Blue Nile basin.

In this study the SWAT model simultaneously, hydrology components such as water flow in the streams and sediment as well with help routing methods available in the model. As a result of sensitive parameters analyzed for both streamflow and sediment model indicate that the land use practice has an impact on the streamflow model, see Figure 6. Therefore, to reduce the impact of land use practice for both streamflow and sediment yield problems in this catchment the best management practice is necessary [1].

Table 7**.**Average sediment yield in Dabus catchment

SWAT-code	Area (%)	Sediment Yield(t/ha)
AGRL	32.06	**173.09**
FRSD	11.04	**0.72**
FRSE	3.43	**0.55**
FRST	15.49	**0.21**
RNGB	37.66	**16.2**
RNGE	0.03	**11.06**

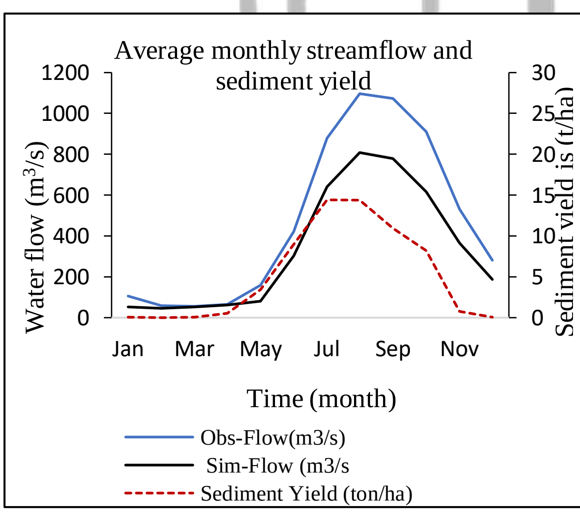
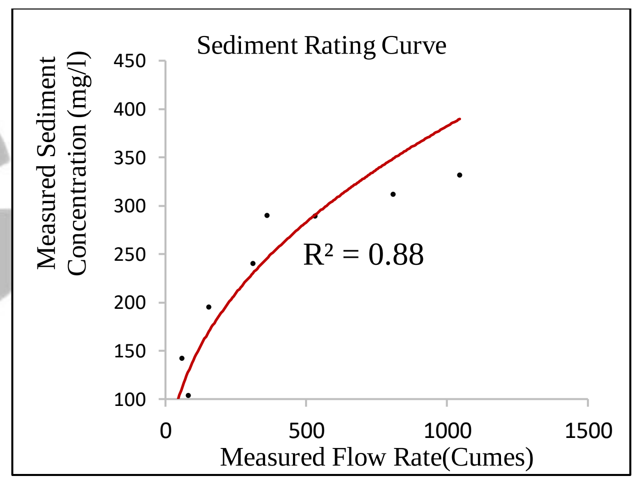


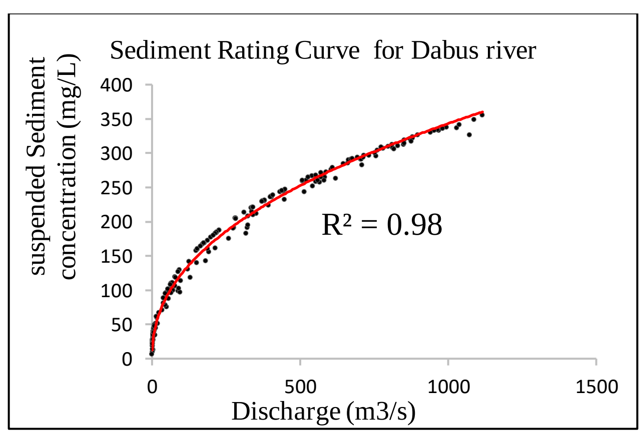
Figure 6Average monthly streamflow and sediment yield for Dabus basin

3.4 Sediment Rating curve

Sediment load is an important component in river basin management. It is usually transported in the river during extreme events related to the intensity of rainfall and high river flow[15]. During this event the difficulty face to the collection of sediment data rather than discharge flow in the river. The sediment load measurement method based on the measured suspended sediment concentration and the flow rate is a stable and reliable method for estimation of sediment load data from measure flow rate, but it requires enough or continuous measurement [16]–[18]. Because a lack of enough measured sediment data will prompt to use of the sediment rating curve method for estimating the suspended sediment load from measured discharge flow [15], [19]. In this study, the sediment rating curve was plotted for measured suspended sediment concentration and the flow rate at the outlet of the Dabus river basin, see Figure 7*a*. The fitting line for power regression was indicated with R^2 is 0.88. The rating curve for the estimated suspended sediment concentration from the measured flow rate at the outlet point of the basin is plotted, see Figure 7*b*. Then the fitting line for the power regression function is indicated with R^2 is 0.98. The correlation of estimated sediment value from the measured flow rate and simulated sediment value using the SWAT model at the outlet of the Dabus river basin was strongly fitted such as R^2 is 0.99 Figure 8. This shows that applying power regression to estimate the sediment load from the measure flow rate was a successful method of calculating sediment load for the required purpose in this study.



(a)



(b)

Figure 7**(a), (b)** Sediment Rating Curve

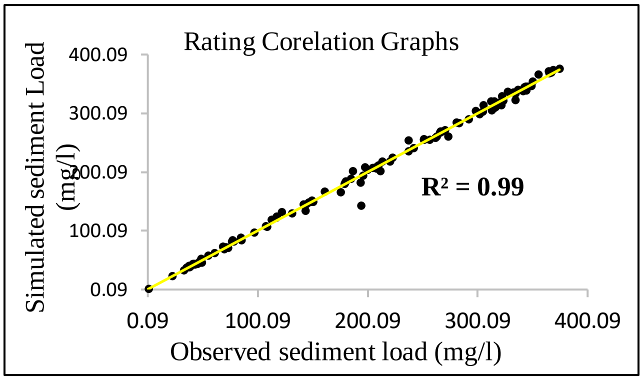


Figure 8 Sediment Rating Curve for Dabus river

4 Conclusion

Based on the available spatial land use data, soil data, meteorological data on Dabus catchment, the SWAT model was used to simulate the sediment and streamflow for the Dabus river, Blue Nile basin. SWAT CUP (SUFI-2 algorithm) is the computer program that was used to assess the sensitive parameter, calibration, and validation of streamflow and sediment model in the Dabus river basin. The runoff curve number (R_CN.mgt.) in the only parameter was the most sensitive parameter that affects the streamflow model. R_SLSUBBSN_1,3,7,12,15,16,-20 were the most sensitive to sediment model in the basin.

The measured time series flow data was used in streamflow, but estimated sediment value from measured flow by sediment rating curve was used in sediment model calibration and validation. In this study, the maximum sediment yield was estimated from agricultural land, which equals 173.09 t/ha. This implies the bad practices of land use are the major factor that the sediment yield in the Dabus watershed. The sediment rating curve is the alternative way to obtain sediment load data for the required purpose unless the measured data are available.

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