

Simulation of Sediment Yield using SWAT Model in Fincha Watershed, Ethiopia

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ABSTRACT

The soil and water assessment tool (SWAT) model was applied to simulate the sediment yield from the Fincha watershed (area 3,251 km²), located in Western Oromiya Regional State, Ethiopia. The purpose of the study was to examine the applicability of the SWAT model in a watershed with a high sediment runoff modulus. The automated calibration process was used to calibrate the model parameters using time series data from 1987 to 1996. Data from 1997 to 2006 were used to validate the model using the input parameter set. Time series plots and the statistical measures of coefficient of determination (R^2) and Nash-Sutcliffe efficiency (E_{NS}) were used to evaluate the performance of the model. The predicted and observed sediment yields generally matched well. The results of the model calibration and validation showed reliable estimates of monthly sediment yield with $R^2 = 0.82$ and $E_{NS} = 0.80$ during the calibration period and $R^2 = 0.80$ and $E_{NS} = 0.78$ during the validation period. This study showed that the SWAT model is capable of predicting sediment yields and hence can be used as a tool for water resources planning and management in the study watershed.

Keywords: SWAT application, sediment yield, Fincha watershed, Ethiopia

INTRODUCTION

Of the many resources at risk in the Ethiopian highlands, soil and water are unarguably the most critical, as nearly 85% of the population depends on subsistence agriculture (Hurni, 1990). One process that severely threatens the resource base is soil erosion and its associated effects. The Ethiopian highlands provide nearly 85% of the flow to the main Nile Basin (Swain, 1997). The Fincha watershed is a highland area with a severe soil erosion problem that drains to the Nile River. The total amounts of runoff volume and sediment

yields annually leaving the watershed are not easily quantified. The land and water resources of the area are adversely affected by the rapidly growing population and the rising demand for cultivated land. Moreover, intensive cultivation of annual crops has caused serious erosion problems in the area, resulting in soil nutrient depletion or soil fertility reduction (Ella, 2005; Bezuayehu, 2006). This process, coupled with the increasing population, has aggravated degradation in the area resulting in on-site soil erosion and off-site heavy sedimentation.

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The expansion of agricultural lands at the expense of forests, lands under communal use rights (grazing and woody biomass resources), cultivation of steep lands and overgrazing are widely practiced in the area. In addition, the ragged topography greatly contributed to the loss of huge amounts of fertile and productive soil from farm lands. The removal of nutrient-rich, fertile topsoil by erosion leads to reduced crop yields. Therefore, sound watershed management strategies are critical to wisely utilize these precious natural resources of soil and water while maintaining environmental quality.

Several studies have shown the robustness of the SWAT model in predicting sediment yields at different watershed scales. Recently, the SWAT model has been used worldwide and considered as a versatile model that can be used to integrate multiple environmental processes, which supports more effective watershed management and the development of better informed policy (Gassman *et al.*, 2005). The model has been widely applied for the simulation of runoff, sediment yield and total phosphorus losses from watersheds in different geographical locations, with varying conditions and management practices (Saleh *et al.*, 2000; Spruill *et al.*, 2000; Santhi *et al.*, 2001; Kirsch *et al.*, 2002; Van Liew *et al.*, 2003; White *et al.*, 2004; Qi and Grunwald, 2005; White and Chaubery, 2005; Wang *et al.*, 2006; Jha *et al.*, 2007; Gassman *et al.*, 2007; Parajuli *et al.*, 2007), and has been extensively used across the USA for flow and sediment yield modeling (Arnold and Allen, 1999). However, few studies have been conducted on the applicability of the SWAT model in Ethiopia, particularly in the Nile Basin (Chekol *et al.*, 2007; Tadele and Forch, 2007; Zeray *et al.*, 2007). Sediment yield simulation using the SWAT model has not been conducted in the Fincha watershed. Moreover, the lack of decision support tools and limitations of data are the main factors that have significantly hindered research and development in the area. Reliable estimates of the

various hydrological processes of a watershed such as runoff and sediment yields are tedious and time consuming when conventional methods are used, especially in remote and inaccessible areas like the Fincha watershed. Hence, it is desirable that a suitable modeling technique is used for estimating these parameters that will help provide information for the sustainable development of the land and water resources of the study watershed.

Therefore, the purpose of this study was to examine the applicability of the soil and water assessment tool (SWAT) model in estimating the runoff and sediment yields in the Fincha watershed, Ethiopia.

MATERIALS AND METHODS

Study area

The Fincha watershed is located in the Horro Guduru Wollegga Zone, Oromiya Regional State, Ethiopia, between latitudes 9°9'53" N to 10°1'00" N and longitudes 37°00'25" E to 37°33'17" E (Figure 1). The watershed has an area of 3,251 km² and covers parts of six districts—namely, Jimma Geneti, Horro, Abbay Chomen, Ababo Guduru, Guduru, and Jimmaa Rare.

The climate of the Fincha watershed is 'tropical highland monsoon' with an average annual rainfall of 1,604 mm. Most of the rain falls during the months of June to September with peaks occurring during July to August and it is virtually dry from November through to April. As the watershed is located in a high rainfall area, it receives frequent torrential showers and frequent flash floods during the rainy season. The mean monthly temperature of the area varies from 14.6 to 17.7 °C (Figure 2).

The major landform of the watershed includes flat to gently sloping, undulating plains, hills and mountains. The western part of the watershed is characterized by highly rugged, mountainous and rolled topography with steep slopes and the lower part is characterized by a

valley floor with flat to gentle slopes. Elevation in the watershed varies from 1,043 to 3,196 m above mean sea level. The major portion of the watershed is under intensive cultivation and *teff*,

maize, barley and wheat are the major crops grown in the watershed. Shrub land, grazing land, forest, woodland and wetland/swamp are other land cover types in the watershed.

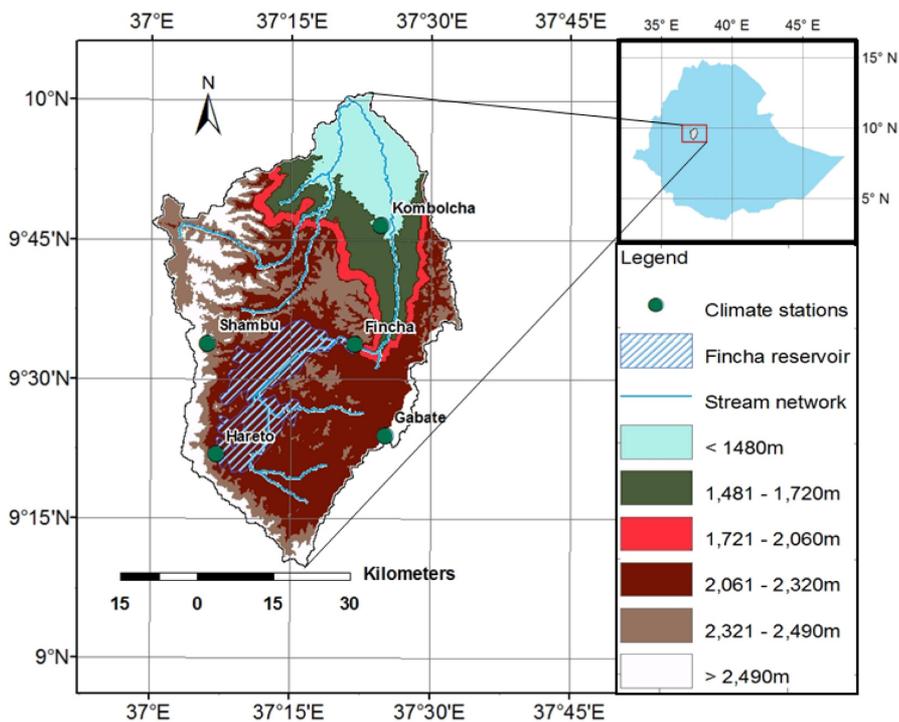


Figure 1 Location of Fincha watershed, Ethiopia.

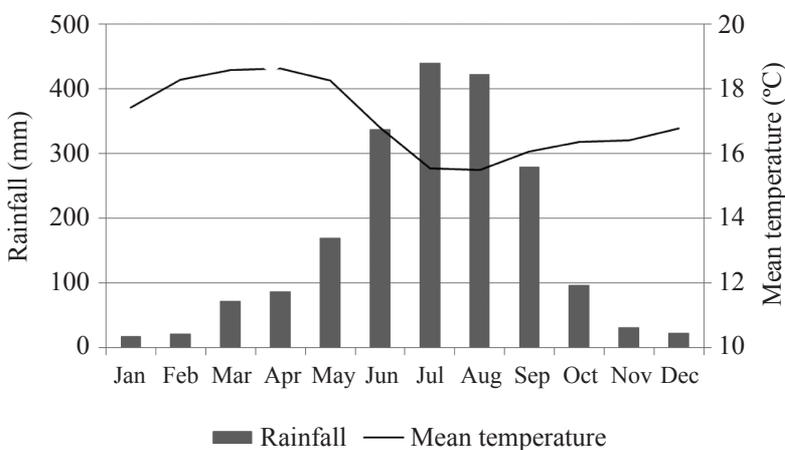


Figure 2 Mean monthly rainfall and temperature data of Fincha watershed.

The catchment has a wide range of soil types mainly dominated by clay-loam, clay, and loam soil (Bezuayehu, 2006). The largest portion of the watershed is characterized by clay soil commonly associated with swamps and temporary wetlands on the plains with good to moderate fertility. The rest of the catchment is under continuous cultivation with low fertility.

Description of SWAT model

The soil and water assessment tool was developed by the United States Department of Agriculture Agricultural Research Service (Arnold *et al.*, 1995). It is a physically based, conceptual, continuous-time and long-term river basin simulation model that originated from agricultural models with spatially distributed parameters operating on a daily time step. The model is used to quantify the impact of land management practices on water, sediment and agricultural chemical yields (nutrient loss) in large and complex watersheds with varying soils, land uses and management conditions over a long period of time (Arnold and Fohrer, 2005; Behera and Panda, 2006; Gassman *et al.*, 2007).

SWAT incorporates the effects of weather, surface runoff, evapotranspiration, irrigation, sediment transport, groundwater flow, crop growth, nutrient yielding, pesticide yielding and water routing, as well as the long term effects of varying agricultural management practices (Neitsch *et al.*, 2002, 2005). In the hydrological component, runoff is estimated separately for each subbasin of the total watershed area and routed to obtain the total runoff for the watershed. Runoff volume is estimated from daily rainfall using modified SCS-CN and Green-Ampt methods. Sediment yield is estimated using a modified universal soil loss equation (MUSLE).

In the SWAT model, the watershed is partitioned into subbasins that are further subdivided into one or several homogeneous hydrological response units (HRUs) with

relatively unique combinations of land cover, soil and topographic conditions. The hydrological component of the model calculates a soil-water balance at each time step based on daily amounts of precipitation, runoff, evapotranspiration, percolation and baseflow. The simulations of sediment yield are computed with the MUSLE at the HRU level and summarized in each subbasin. The simulated variables (water, sediment, nutrients and other pollutants) are routed through the stream network to the watershed outlet.

Preparation of model inputs

The basic spatial input datasets used by the model include the digital elevation model (DEM), land use/cover data, soil data and climatic data.

Digital elevation model

The DEM is one of the main inputs of the SWAT model. Topography was defined by a DEM that describes the elevation of any point in a given area at a specific spatial resolution. A 30 m grid DEM was downloaded from ASTER (Advanced Spaceborne Thermal Emission and Reflection Radiometer) GDEM (Global Digital Elevation Model). The DEM was used to delineate the boundary of the watershed and analyze the drainage patterns of the land surface terrain. Terrain parameters such as slope gradient and slope length, and stream network characteristics such as channel slope, length and width were derived from the DEM.

Land use/cover data

The land use of an area is one of the most important factors that affect surface erosion, runoff, and evapotranspiration in a watershed during simulation (Neitsch *et al.*, 2005). The land use map of the study area was obtained from the Ministry of Water Resources of Ethiopia. The major land use classes of the study area are presented in Table 1.

Table 1 Major land use classes in Fincha watershed.

Land use	Area (ha)	% Total
Agricultural land	173,692	53.43
Forest	35,531	10.93
Grazing land	38,267	11.77
Water body	39,790	12.24
Swamp area	18,885	5.81
Shrub land	18,911	5.82
Total	325,076	100.00

Soil data

The soil textural and physicochemical properties required by the SWAT model include soil texture, available water content, hydraulic conductivity, bulk density and organic carbon content for each soil type. These data were obtained from FAO (1998; 2002; 2005) and the Ministry of Water Resources of Ethiopia (2002). Some of the physical and hydrological properties of the major soil types of the Fincha watershed are presented in Table 2.

Weather data

The weather variables required by the SWAT model for driving the hydrological balance are daily rainfall and minimum and

maximum temperatures. These data were obtained from a compact disk provided by the National Meteorological Service Agency of Ethiopia. The time series data were collected from five stations (Fincha, Shambu, Hareto, Gabate, and Kombolcha) that are located within the watershed (Figure 1) and covered a period of 22 years (January 1985 to December 2006).

Hydrological data

The observed daily runoff and sediment yield data at the outlet of the watershed (Figure 1) from 1985 to 2006 were obtained from the Hydrology Department of the Ministry of Water Resources of Ethiopia. These data are required for calibration and validation of the SWAT model.

Table 2 Physical and hydrological properties of major soils in Fincha Watershed.

Soil type	Bulk Hydrol. group	AWC density (g.cm ⁻³)	Hydraulic (mm H ₂ O /mm soil)	conductivity (mm.hr ⁻¹)	Textural composition (% by weight)			Organic carbon (% by weight)
					Clay	Silt	Sand	
EutricCambisols	C	1.31	0.096	60	35	36	29	2.00
RhodicNitisols	C	1.28	0.128	250	51	34	15	2.12
EutricLeptosols	C	1.37	0.097	500	26	34	40	1.58
Chromic Luvisols	C	1.10	0.109	50	65	26	9	1.78
EutricVertisols	C	1.20	0.151	1000	36	54	10	0.63
HaplicLuvisols	D	1.13	0.119	55	60	28	12	1.75
HaplicAlisols	C	1.15	0.151	150	50	30	20	1.64
HaplicArenosols	D	1.61	0.142	100	45	40	15	1.72
HaplicPhaezems	D	1.43	0.121	65	60	25	15	1.74

Methodology

Model set-up

The ArcSWAT interface was used for the setup and parameterization of the model. A digital elevation model (DEM) was imported into the SWAT model. A masking polygon (in grid format) was loaded into the model in order to extract the area of interest, delineate the boundary of the watershed and digitize the stream networks in the study area. In this study, the minimum threshold area required to discretize the watershed into subbasins was selected as 5,000 ha. The land use/cover and soil maps of the study area (in grid format) were also imported into the model and overlaid to obtain a unique combination of land use, soil and slope within the watershed to be modeled. In this study, multiple HRUs with 10% land use, 20% soil, and 10% slope thresholds were used. These threshold levels were set to eliminate minor land uses and soil and slope classes in each subbasin so that a maximum of 10 HRUs with unique land use/soil/slope combinations would be created in each subbasin, as recommended in the SWAT user manual (Neitsch *et al.*, 2002).

The daily rainfall and daily minimum and maximum temperature data were prepared in the appropriate file format (as a .dbf database file) required by the model and imported into the model.

Model calibration and validation

The SWAT model included a large number of parameters that describe the different hydrological conditions and characteristics across the watershed. During the calibration process, model parameters were subjected to adjustments, in order to obtain model results that correspond better to the measured datasets. The current study used the auto-calibration process and the model was calibrated on a monthly basis from January 1987 to December 1996. The hydrological component and the erosion component of the model were calibrated sequentially until the

average simulated and measured values were in close agreement.

The procedure for calibrating the model for flow and sediment yields is shown in Figure 3. The flow was the first output calibrated by adjusting the curve number (CN) parameter because the results of many studies indicated CN as the most sensitive parameter (Das *et al.*, 2007; Parajuli *et al.*, 2007; Arabi *et al.*, 2008; Wang *et al.*, 2008). CN is a soil moisture balance parameter that allows the model to modify the moisture condition of the soil to estimate the surface runoff. The runoff curve numbers (CN) were adjusted within $\pm 10\%$ from the tabulated curve numbers to reflect the conservation tillage practices and soil residue cover conditions of the watershed.

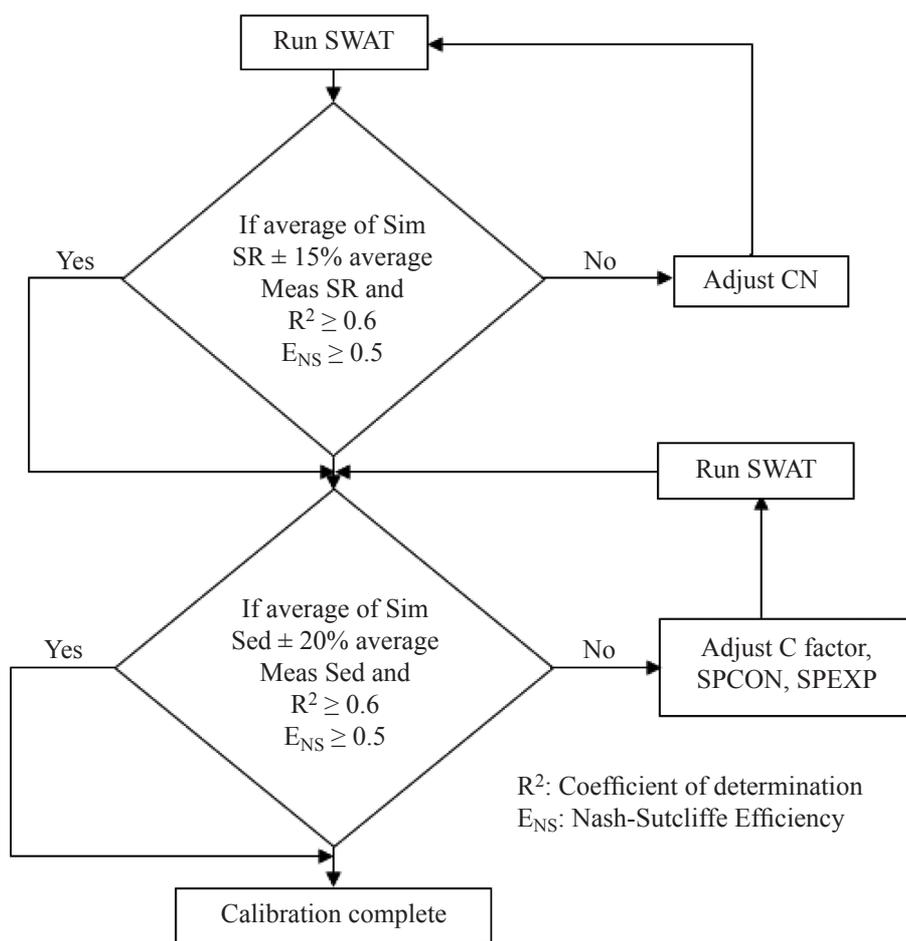
As SWAT uses MUSLE (Williams, 1975), sediment was calibrated by adjusting the MUSLE crop cover and the management factor. The C-factor was adjusted to represent the surface cover better for grazing and agricultural lands. Channel sediment routing variables, such as the linear factor for calculating the maximum amount of sediment during channel sediment routing (SPCON) and the exponential factor for calculating the sediment in the channel sediment routing (SPEXP), were also adjusted during the calibration.

The calibrated values of parameters for various model outputs are presented in Table 3. The model outputs were calibrated for flow and sediment yields until the average simulated values fell within 15 and 20% of the average measured values, respectively.

In the validation process, the model was operated with input parameters set during the calibration process and the results were compared against an independent set of observed data to evaluate the performance of model prediction. In this study, the model was validated using data from January 1997 to December 2006 on a monthly basis.

Table 3 Calibrated values of model parameters.

Parameter	Description	Lower and upper bound	Calibrated value
CN	SCS runoff curve number	±10%	+5%
C-factor	Cover or management factor	0.003–0.45	0.2
SPCON	Linear factor for channel sediment routing	0.0001–0.01	0.0008
SPEXP	Exponential factor for channel sediment routing	1.0–1.5	1.0



SR: Surface runoff; Sed: Sediment; Sim: Simulated; Meas: Measured; CN: Curve number; C: Crop cover management factor; SPCON and SPEXP, respectively are the linear and exponential factors for calculating sediment in the channel routing.

Figure 3 Calibration procedures for flow and sediment yields in the SWAT model.

Evaluation of model performance

In this study, during both calibration and validation periods, the goodness-of-fit between the simulated and measured runoff and sediment yields was evaluated using the coefficient of determination (R^2) and the Nash-Sutcliffe coefficient of efficiency (E_{NS} ; Nash and Sutcliffe, 1970).

The R^2 value measures how well the simulated versus observed regression line approaches an ideal match and ranges from 0 to 1, with a value of 0 indicating no correlation and a value of 1 representing that the predicted dispersion equals the measured dispersion (Krause *et al.*, 2005).

E_{NS} has been reported in the scientific literature for model simulations of flow and water quality constituents such as sediment, nitrogen, and phosphorus yields (Moriassi *et al.*, 2007). It is used to assess the predictive power of hydrological models and indicates how well the plot of the observed versus simulated values fit the 1:1 line. The closer the model efficiency is to 1, the more accurate the model is. It is defined by Equation 1:

$$E_{NS} = 1 - \frac{\sum_{i=1}^n (O_i - S_i)^2}{\sum_{i=1}^n (O_i - O_{av})^2} \quad (1)$$

where E_{NS} = the Nash-Sutcliffe efficiency of the model; O_i and S_i = the observed and simulated values, respectively; and O_{av} = the average observed value.

SWAT developers in Santhi *et al.* (2001) assumed an acceptable calibration result of $R^2 > 0.6$ and $E_{NS} > 0.5$. Moriassi *et al.* (2007) also proposed that E_{NS} values should exceed 0.5 in order for the model results to be judged as satisfactory for hydrological and pollutant loss evaluations performed on a monthly time step and these values were also considered in the current

study as adequate statistical values for accepting calibration results.

RESULTS AND DISCUSSION

A SWAT model was calibrated and validated on a monthly basis to predict the flow and sediment yields from the Fincha watershed using a time series dataset of 22 years from 1985 to 2006. The first two years of the modeling period were used for 'model warm-up'. Data for the period 1987 to 1996 were used for calibration and the remaining part of the dataset was reserved for validation. The watershed was subdivided into 19 subbasins based on a chosen threshold area of 5,000 ha. The overlay of land use, soil and slope maps resulted in the definition of 72 HRUs. The simulated flow and sediment yields at the outlet of the watershed gauging station were compared with the observed flow and sediment yields.

Model calibration

During the calibration period (1987 to 1996), the simulated monthly flows matched well with the measured monthly flows ($R^2 = 0.82$ and $E_{NS} = 0.72$) as shown in Figures 4 and 5. The trends of seasonal variability and monthly average discharge were generally well captured. The adequacy of the model is further indicated by its clear response to extreme rainfall events resulting in high runoff volumes (as for example in August 1994). However, the model underestimated the peak monthly flow during the first five and the last two years of the simulation periods and overestimated the peak flows from 1992 to 1994 (Figures 4 and 5).

The model also adequately predicted the sediment yields in the study area during calibration with R^2 and E_{NS} values of 0.81 and 0.78, respectively. During this period, the simulated monthly sediment yields matched well with the measured monthly sediment yields (Figures 6 and 7). However, the monthly sediment yield values

were over-predicted by the model during the wet season from 1991 to 1995 (Figure 7) that might have resulted from the newly opened irrigation farms downstream of the reservoir. On the other hand, during the wet season from 1987 to 1990,

monthly sediment yields were under-predicted by the model which could have been due to siltation from sediment in the reservoir. Table 4 presents the monthly statistical results during both the calibration and validation periods.

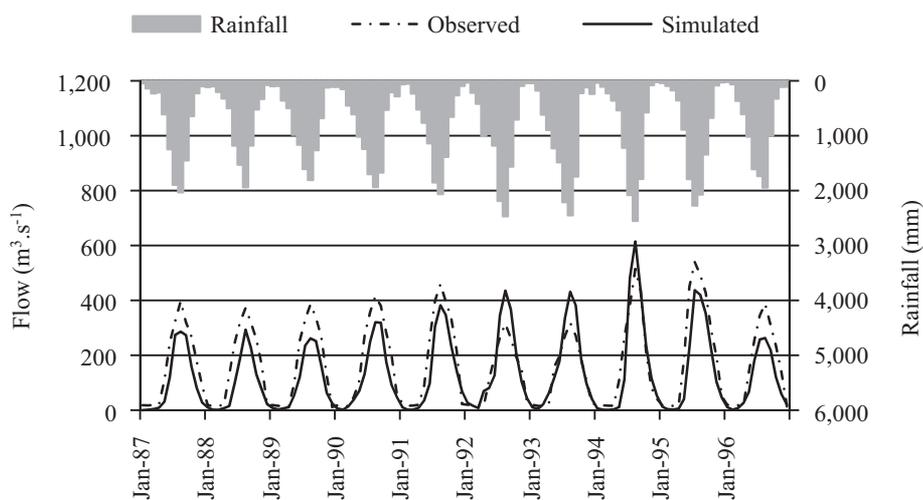


Figure 4 Simulated and observed monthly flow superimposed with monthly rainfall during calibration period (1987–1996).

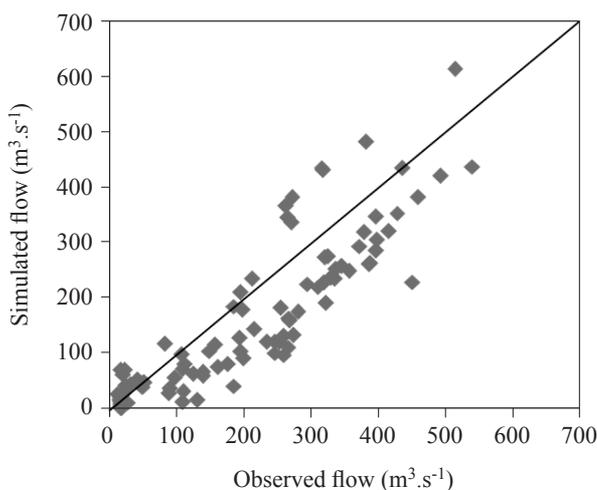


Figure 5 Simulated versus observed monthly flow during calibration period (1987–1996).

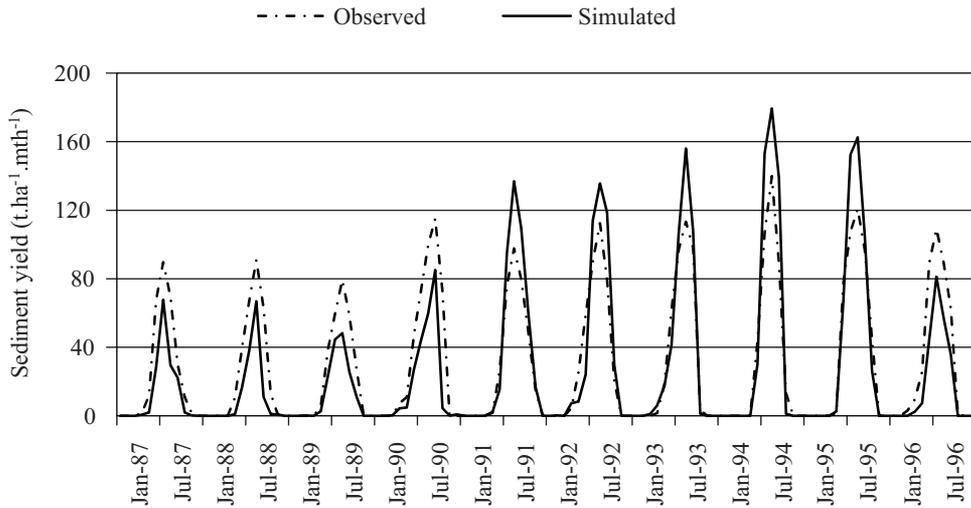


Figure 6 Simulated and observed monthly sediment yields during calibration period (1987–1996).

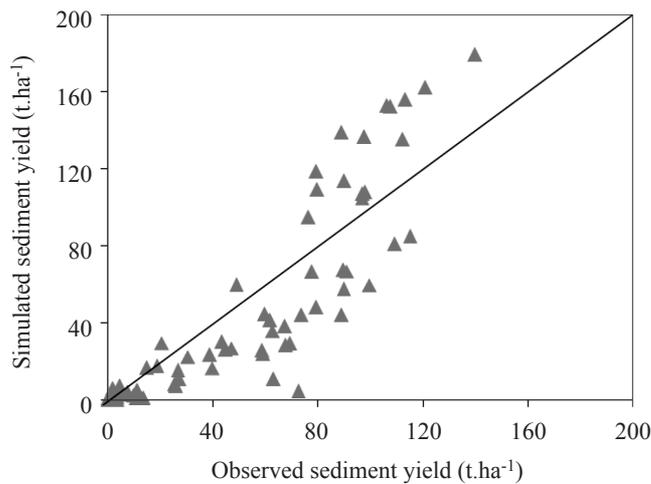


Figure 7 Simulated versus observed monthly sediment yields during calibration period (1987–1996).

Table 4 Monthly calibration and validation statistical results.

Description	R ²	E _{NS}	Mean		Standard Deviation	
			Observed	Simulated	Observed	Simulated
Flow (m ³ .s ⁻¹)						
Calibration	0.82	0.72	140.35	129.73	145.84	139.58
Validation	0.81	0.77	121.26	114.95	124.73	122.29
Sediment yield (t.ha ⁻¹)						
Calibration	0.82	0.80	30.18	26.94	39.85	44.93
Validation	0.80	0.78	25.38	22.84	35.79	36.77

Model validation

The SWAT model also successfully validated the flow from 1997 to 2006 (Table 4). Monthly flow rates were well predicted, and the measured and simulated monthly flows matched well ($R^2 = 0.81$ and $E_{NS} = 0.77$) as shown in Figures 8 and 9. The model under-predicted the flow during the years from 1997 to 2000 and

from 2003 to 2004; and over-predicted from 2001 to 2002 and from 2005 to 2006. However, the trends of seasonal variability and monthly average discharge were generally well captured.

The model validation results also showed that the monthly predicted and observed sediment yields matched well with R^2 and E_{NS} values of 0.80 and 0.78, respectively (Table 4) except for

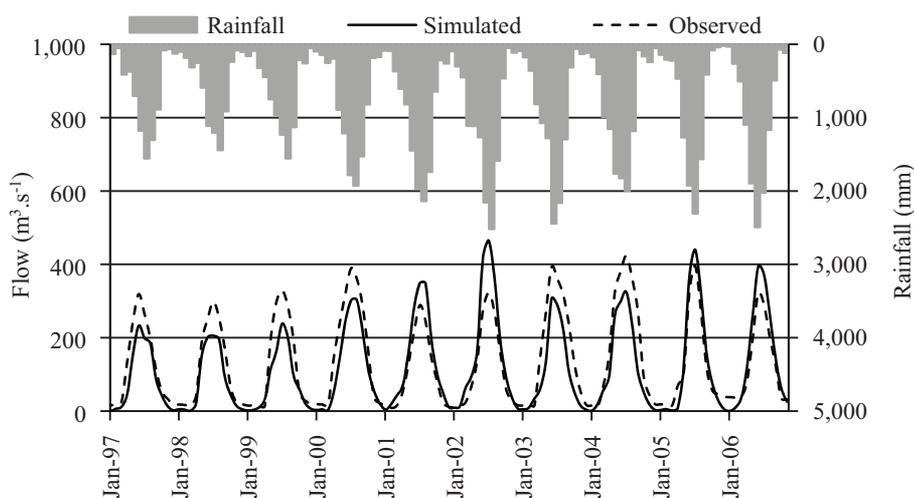


Figure 8 Simulated and observed monthly flow superimposed with monthly rainfall during validation period (1997–2006).

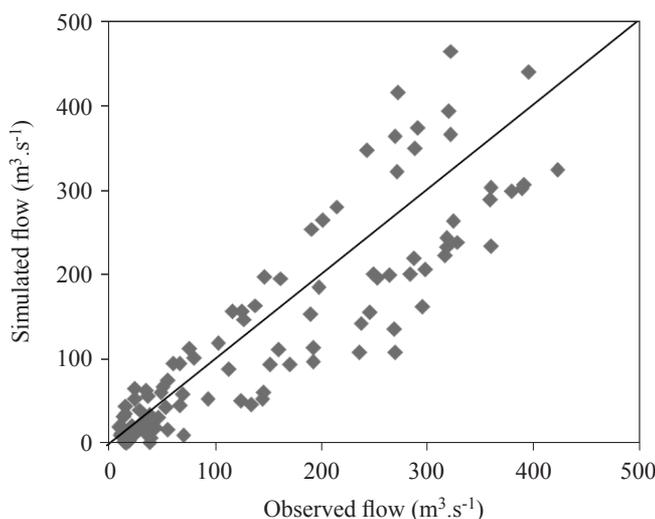


Figure 9 Simulated versus observed monthly flow during validation period (1987–1996).

July 2002 when the flow was also overestimated by the model. Figure 10 shows the simulated and observed sediment yields during the validation period. The scatter plot of the observed versus the simulated sediment yields is displayed in Figure 11.

During both the calibration and validation periods, the difference between the simulated

and observed values might be attributed to the inadequate representation of rainfall inputs, due to: the uneven distribution of rain gauge stations in the catchment; the spatial variability of rainfall; errors during data recording; or local rainfall storms that were not well represented by the rainfall data used in the hydrological simulations. Another possible reason might be the lack of data on the

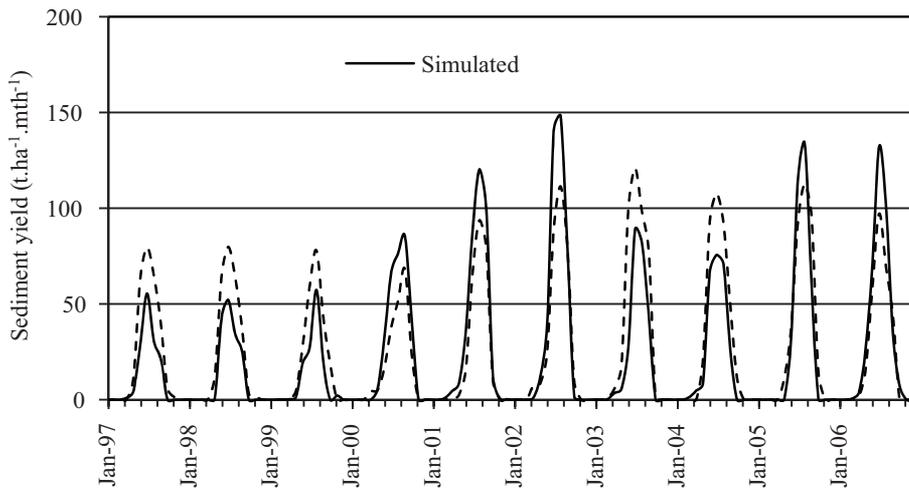


Figure 10 Simulated and observed monthly sediment yields during validation period (1997–2006).

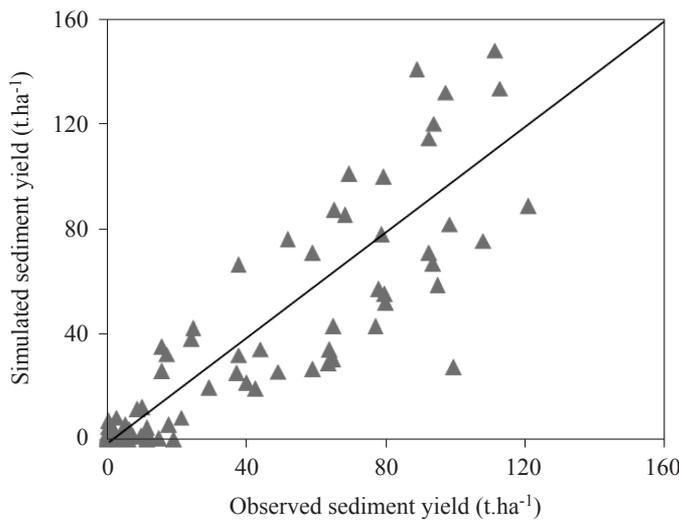


Figure 11 Simulated versus observed monthly sediment yields during validation period (1987–1996).

management and various water use abstractions from the reservoir, such as water for domestic use and irrigation projects, and these water uses were not included in the simulation.

The results of this study agreed with that conducted by Tadele and Forch (2007) using SWAT for simulating stream flows from the Hare watershed in Ethiopia, where the flows were predicted with R^2 and E_{NS} values of 0.74 and 0.69, respectively. Chekol *et al.* (2007) applied SWAT for the assessment of the spatial distribution of water resources and the evaluation of the impacts of different land management practices on the hydrological response and soil erosion in the upper part of the Awash River Basin in Ethiopia; their model performed well with both R^2 and E_{NS} values greater than 0.79 during both the calibration and validation periods. They concluded that the SWAT model accurately tracked the measured flows and simulated the monthly sediment yield well.

CONCLUSION

The SWAT model was calibrated from 1987 to 1996 and validated from 1997 to 2006 on a monthly basis to examine its applicability for simulating flows and sediment yields from the Fincha watershed. The average monthly simulated flows and sediment yields were compared with the average monthly observed values using graphical and statistical methods. The results showed reliable estimates of average monthly flow and sediment yields with a high coefficient of determination (R^2) and Nash-Sutcliffe model efficiencies (E_{NS}) during both the calibration and validation periods.

The R^2 values were 0.82 and 0.81, respectively, for the flow during the calibration and validation periods. The respective R^2 values for the monthly sediment yield were 0.82 and 0.80. A good agreement between the measured and simulated average monthly flows was also demonstrated by E_{NS} values of 0.72 and 0.77, respectively, during the calibration and validation

periods. The corresponding E_{NS} values for sediment yields were 0.80 and 0.78. In most instances, the simulated average monthly flows and sediment yields were close to the average monthly measured values during both the calibration and validation periods. The differences between the simulated and observed values might be attributed to inadequate representation of rainfall inputs and the utilization of surface water from the reservoir such as for water supply and irrigation projects and these water uses were not included in the simulation. However, the seasonal variability of the monthly average runoff and its maximum values were generally well captured.

In general, the SWAT model performed well in predicting both the flow and sediment yields from the study watershed and the results were acceptable. It is a capable tool for further analysis of the hydrological responses in the watershed. The study can be further extended to similar watersheds in the country, particularly in the Blue Nile Basin of Ethiopia, where quantifying the total volume of runoff and sediment yields is urgently required for better land and water resources planning and management purposes.

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