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Spatial and Temporal Distribution of Sediment Yield-Case Study Nashe, Blue Nile Basin, Ethiopia

Dereje Gizaw[1*], Megersa Kebede[2]

[1] Wollega Institute of Technology, Wollega University, Oromia, Ethiopia

[2]School of Civil and Environmental Engineering, Jimma Institute of Technology, JIT, Jimma, University, Oromia, Ethiopia

ABSTRACT

This study was applied to estimate physical based soil and water assessment tool (SWAT) model for spatial and temporal patterns of soil erosion of Nashe watershed, Western Oromia Regional State, Ethiopia. This study assesses sediment yield from Nashe watershed at outlet. The stream flow was calibrated for ten years (1991-2001) and validated seven years (2002-2008) at Nashe station using SWAT-CUP to estimate performance of the model. The model performance has been evaluated by using statistical parameters of coefficient of determination (R^2) and Nash-Sutcliffe simulation efficiency (E_{NS}) 0.79, 0.75 respectively for calibration. Model validation results 0.71 and 0.65 for R^2 and E_{NS}, respectively. Both calibration and validation results indicate that the observed values show good agreement with simulated flow. Sediment yield from each sub watershed were determined and prone soil erosion area has been identified for management planning.

Keywords: Modeling; Nashe; sediment yields; soil erosion; SWAT-CUP

1. INTRODUCTION

1.1 Background

Soil erosion is worldwide environmental crisis that threaten agricultural areas at an alarming rate. As it has direct impact on food production, global societies are considerably aware of the crisis alongside energy and global warming problem. Soil erosion occurs when natural or human induced processes decrease the ability of land to support crops and loss nutrients. The 2000 studies conducted by the Consultative Group on International Agricultural Research, soil erosion and degradation had reduced food production on 16% of the world's cropland (Pimentel, 1993). According to (Pimentel, 2006), the current rate of agricultural land degradation worldwide by soil erosion and other factors was found to be leading to an irreversible loss in productivity, ranging from 6 to 10 million hectares of fertile land in a year.

The improper management system and lack of suitable soil conservation measures have been the main causes of soil erosion and land degradation problems in the country. Soil erosion and Land degradation are resulted from increasing cultivation of mountainous and steeper slopes, without protective measures against it. Ethiopia loses about 1.3 billion metric tons of fertile soil every year and the land degradation through soil erosion is increasing at high rate (Hurni, 1989). To save soil and water resource degradation, immediate measure should be taken.

**Corresponding to*: gizawd395@gmail.com

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1.2 Statement of the problem

In 2006, due to the construction of hydropower and irrigation dam Nashe watershed, western Ethiopia, land use changes have seriously changed in the watershed. Earlier the dam was constructed, the societies living in the area were not considered, and hence have caused forests being converted to cultivated land. These changes in land cover have made widespread soil erosion. Due to this, displaced communities around the area had started convert forest to cropland on steep slope and which potentially has increased erosion problems in the area. The converted original land cover to agricultural land without using control measures and appropriate land management practice which possibly has increased soil erosion in the area. This study can prioritize, to minimize erosion and surface runoff for erosion vulnerable areas, attention to improve soil productivity and to avoid additional damage from soil erosion.

1.3 Objectives of the study

1.3.1 General objective

The main objective of this study is to estimate spatial and temporal patterns of soil erosion using Geographic Information System based version of the Soil and Water Assessment Tool model.

1.3.2 Specific objectives

- To calibrate and validate hydrological SWAT model;
- To estimate the average sediment yield from Nashe catchment;
- To identify spatial and temporal patterns of sediment yield and suggest the management practices in Nashe catchment.

2. MATERIALS AND METHODS

2.1 Study area

The study area is located in Horro Guduru Wollega Zone, East Wollega, Oromia reginal state, western basin between $9^0$50'00"-$9^0$25'00" latitude and $37^0$0'00"-$37^0$15'00" longitude is the part of Blue Nile river basin which sum of three watershed (Fincha'a, Amerti and Nashe) watersheds (Fig. 1). The study area, Nashe river sub basin, is located in the north western part of the Blue Nile basin and upper of Fincha'a valley distant 350 km from Addis Ababa. The basin is categorized by mean maximum and minimum temperatures of 11^{o}C and 18^{o}C correspondingly. The dominant soil types are Alisols and leptosols 21%, followed by Nitosoils 16%, Vertisols 15% and Cambisols 9% (Betrie et al., 2011). Regular annual rainfall in the area is about 1566.5 mm, which falls during 3-month main rainy season from mid-June to mid-September.

3. MATERIALS AND METHODS

3.1 Materials and tools used for input data preparation and analysis

Arc GIS 9.3, Arc SWAT 2009, PCPSTAT, dew02, SWATCUP, XLSTAT2005, DEM, Meteorological data, Hydrological data and Soil map data.

3.2 The method of this work

The procedure of this work will be the following component: data collecting, data processing, input data, running model, sensitivity analysis test, calibration & validation and analysis result of model.

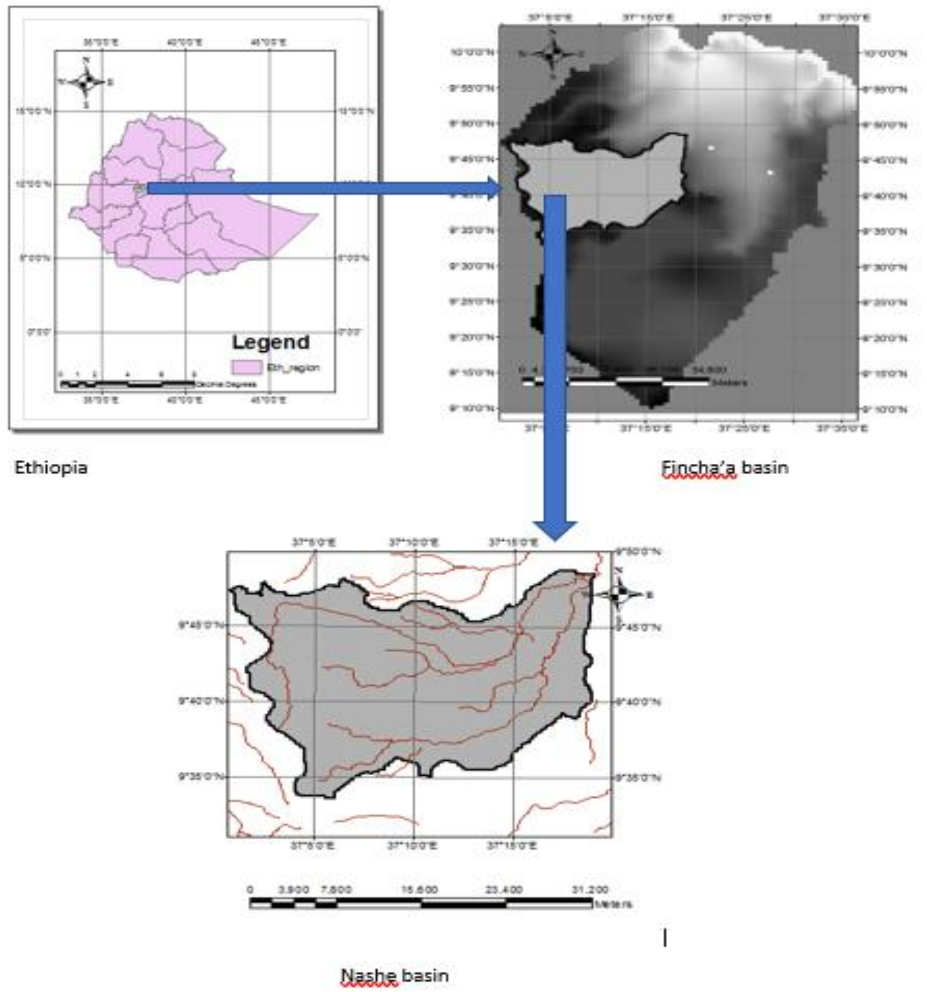

Figure 1 The location of study area

3.3 SWAT model description

The soil and water assessment tool (SWAT) are the physical based hydrological model developed by USDA Agricultural Research Service (ARS) (Arnold et al., 1998). SWAT has been employed to model watershed of different scales predict the sediment yields, runoff, stream flow and other across the world. Simulation of very large and complex basins or a variety of management strategies can be performed without excessive investment of time or money, and enables users to study long term impact. In addition, SWAT uses MUSLE to simulate sediment erosion from HRU which replace the traditional USLE equation. MUSLE uses runoff factor than rain fall factor to estimate sediment yield (Williams and Barndit, 1977).

The SWAT has recently been adapted to more effectively model hydrological processes in monsoon climates such as Ethiopia (White et al., 2008). Betrie et al. (2011) suggest that, the Soil and Water Assessment Tool (SWAT) was used to model soil erosion in the upper catchments of the Blue Nile over the Ethiopian Plateau and output result was successful calibrated and validated. Tamene et al. (2006) applied that, the Soil and Water Assessment Tool (SWAT) model to the northern highlands of Ethiopia for modeling of soil erosion in Mai-Negus catchment, Tigray regional state, northern Ethiopia. The model was successfully calibrated and validated, hence SWAT model was selected for this study.

3.4 Hydrology component

To investigate the soil erosion modeling of Nashe watershed, the Soil and Water Assessment Tool (SWAT) model was used. SWAT was developed for the purpose of simulation and to predict the impact of land management practice on water and sediment. In SWAT, the water balance is computed from the soil water content which is described by the following equation.

$$SW_t = SW_o + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \quad (1)$$

where SW_t: the final soil water content (mm), SW_o: the initial water content (mm), t: the time (days), R_{day}: the amount of precipitation on day i (mm), Q_{surf}: the amount of surface runoff on day i (mm), E_a: the amount of evapotranspiration on day i (mm), W_{seep}: the amount of water entering the vadose zone from the soil profile on day i (mm), Q_{gw}: the amount of the return flow on day i (mm).

3.5 Surface runoff component

To set up the model, the amount of rainfall is one of the input parameters amongst other weather parameter which is required. The SCS curve number is used to determine runoff depth (USDA, 1972).

$$Q_{surf} = (R_{day} - I_a)^2 / (R_{day} - I_a + S) \quad (2)$$

where $I_a = 0.2S$

$$S = 25.4 \times (1000 / CN - 10) \quad (3)$$

$$Q_{surf} = (R_{day} - 0.2S)^2 / (R_{day} + 0.8S) \quad (4)$$

where Q_{surf} is the accumulated runoff or rainfall excess (mm), R_{day} is the rain fall depth for the day (mm H_2O), I_a is the initial abstraction which includes surface storage, interception and infiltration prior to runoff (mm) and commonly approximated as 0.2S, CN is the curve number for the day, Runoff only occur when $R_{day} > I_a$. The peak runoff rate is the maximum runoff flow rate that occurs with a given rainfall event. The peak runoff rate is an indicator of the erosive power of the storm and is used to predict sediment loss. SWAT calculates the peak runoff rate with modified rational method (Neitsch et al., 2005).

The corresponding equation is:

$$q_{peak} = C \times i \times A / 3.6 \quad (5)$$

where q_{peak} = runoff rate (m/s), i = rainfall intensity (mm/h), A = sub basin area (km), C = runoff coefficient.

3.6 Sediment yield component

SWAT model calculates the surface erosion and sediment yield within each HRU with the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975). The sediment supply from the individual HRU is computed by the modified universal soil loss equation.

$$Sed = 11.8 \times (Q_{surf} \times q_{peak} \times area_{hru})^{0.56} \times K_{USLE} \times C_{USLE} \times P_{USLE} \times L_{SUSLE} \times CFRG \quad (6)$$

where Sed = sediment yield (t/day), Q_{surf} =surface runoff volume (mm), q_{peak} = peak runoff rate (m/s), $area_{hru}$ = area of HRU (ha), K_{USLE} = erodibility factor, C_{USLE} = cover and management factor, P_{USLE} = support practice factor, L_{SUSLE} = topographic factor, CFRG = coarse fragment factor.

3.7 Sediment rating curve

Sediment rating historical data on suspended sediment concentrations/loads for Nashe River were obtained from the Hydrology Department of the MoWIE, Ethiopia. Data availability is limited to very few days in a year and it is highly uneven. A precise estimate of suspended sediment yields of watershed depends on the availability of long and reliable records of suspended sediment concentrations (Fig. 2). But when these records are unavailable, estimates are often derived from empirical relations between river discharges and corresponding suspended sediment concentrations / loads (Ulke et al., 2009).

$$SS = a \times Q^b \quad (7)$$

where SS is suspended sediment concentration/load, Q is stream flow rate, a and b are constants to be determined from observed discharges and suspended sediment concentrations / loads.

From the rating curve Fig. 2 coefficient a is equal to 4.417, power is equal to 1.236 and regression coefficient R^2 is equal to 0.836, and to generate the sediment concentration for Nashe is developed by below equation.

$$SS = 4.417 \times Q^{1.236} \quad (8)$$

3.8 Data collection and source

The required necessary meteorically input data for this study were daily rain fall data, max and min temperature, wind speed, radiation and relative humidity collected from Ethiopian National Meteorological Service Agency from different stations. And the required spatially data Digital Elevation Model (DEM), land use / land cover map, soil map, and soil data were collected from different sources.

The daily stream flow data for study area obtained from Ethiopian Ministry of Water, Irrigation and Energy hydrology Department. Nashe River flow daily data which is used to calibrate and validate the SWAT model were collected from Ministry of Water, Energy and Irrigation Bureau.

3.9 Data analysis and processing

After all data were collected, it was made analysis of collected data. The precipitation and temperature of all gauging stations (Nashe, Homi, Alibo and Shambu) were prepared in text format. Solar radiation, relative humidity and wind speed were used only for principal stations (Shambu). Because input data collected lacks the quality and quantity data, hydrological data missing data computation method was used. For detecting inconsistency, to correct and adjust collected data was checked by double mass curve method its consistency (Fig. 3a and 3b).

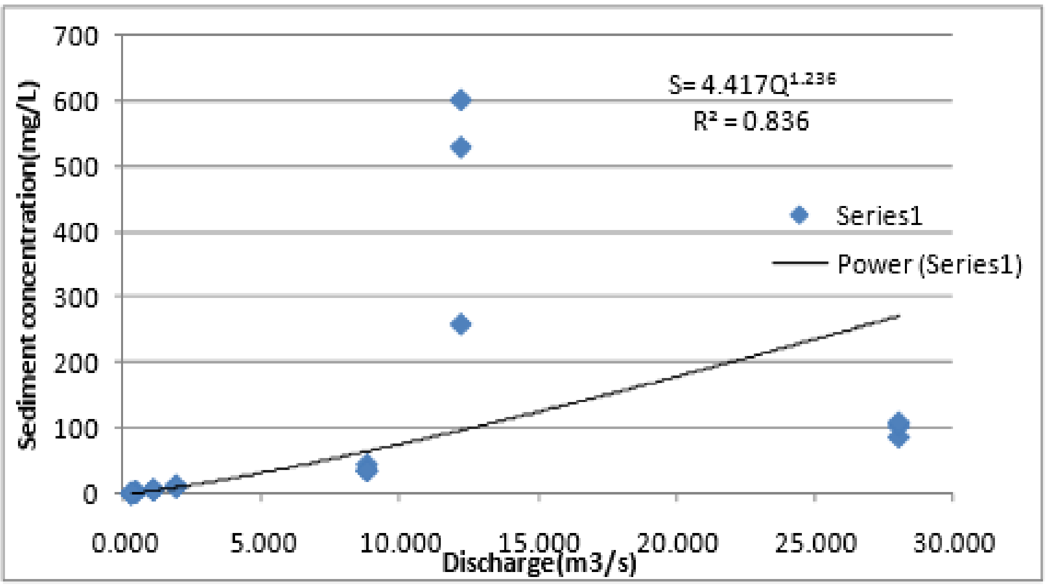

Figure 2 Sediment discharge rating curve for Nashe station

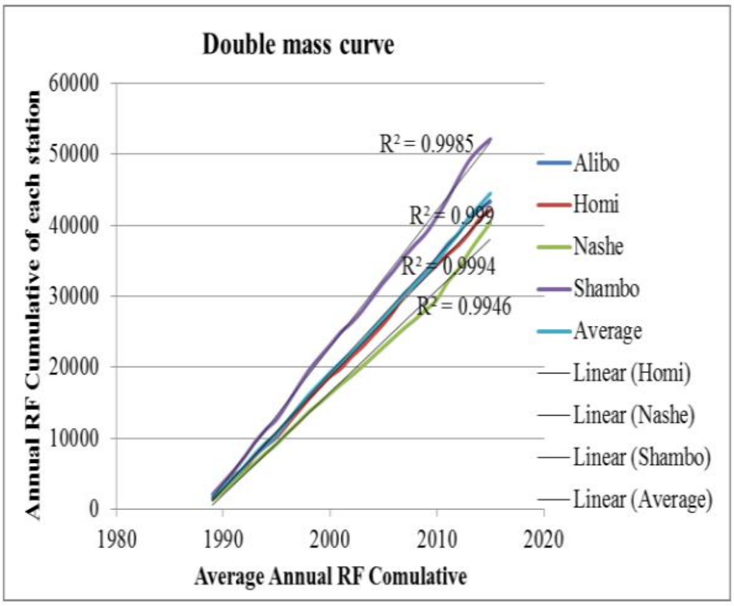

Figure 3a Double mass curves of average station

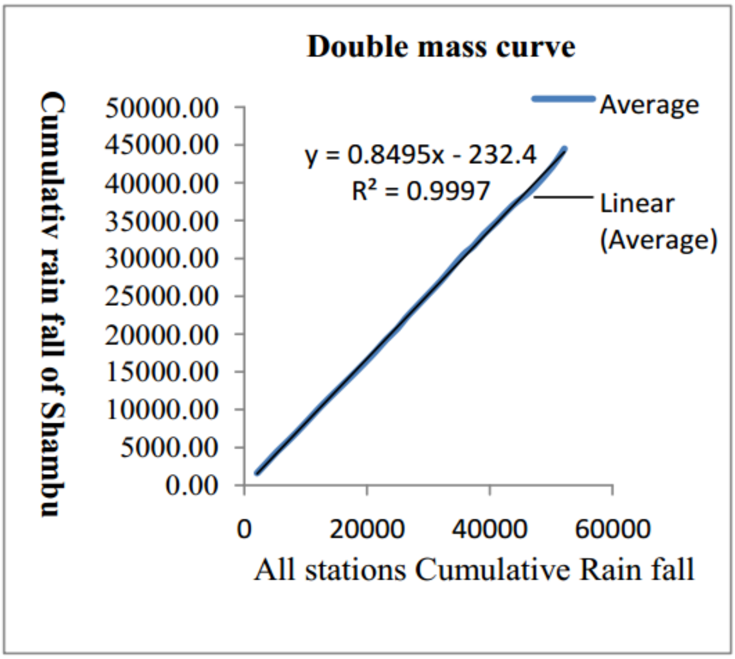

Figure 3b Double mass curves of all stations

3.10 SWAT simulation

Finally, the SWAT model has been run and read the SWAT model output by importing files to database and saving to place of interest or by opening the output. std. For this study, the SWAT simulation performed output times step (monthly) and rainfall distribution (skew normal) for the watershed. SWATCUP is used for sensitivity analysis, calibration and validation.

3.11 Model performance assessment

To evaluate the accuracy of overall model calibration and validation, different statistical indicators are used for SWAT model. Coefficient of determination (R^2): is the indicator of relationship between the measured and simulated values. R^2 ranges from 0 to 1; with higher value the more approach to 1 indicating better agreement and value less than 0.5 indicates a poor performance of the model.

$$R^2 = \frac{\sum_{i-1}^{n}(Oi - O')(Si - S')}{\sqrt{\sum n_{i-1} - (Oi - O')^2}\sqrt{\sum n_{i-1} - (Si - S')^2}} \quad (9)$$

where Oi = Observed stream flow, Si = Simulated stream flow, S' = Mean Simulated stream flow, O' = Mean Observed stream flow, n = Number of observations.

Nash-Sutcliffe Efficiency (N_{SE}): NSE measures the degree of fitness of the observed and simulated data variance. The more the NSE approaches to 1, indicates the better will be the model performance.

$$NSE = 1 - \sum^{n}_{i=1}(Si - Oi)^2 / \sum^{n}_{i=1}(Oi - O')^2 \quad (10)$$

4. RESULTS AND DISCUSSION

4.1 Sensitivity analysis

The result from sensitivity analysis was provided by ranking of input parameters that have most impact on stream flow output. Out of these parameters only ten of them, which have greatest influence on model output are CN2, ESCO, SOL_AWC, SOL_BD, GW_REVAP, CH_K2, CH_N2, SFTMP, GWQMN and GW_DELAY, were selected as parameters for calibration process.

4.2 Model calibration

The statically result for the calibration model performance displayed satisfactory (coefficient of determination R^2 and the Nash-Sutcliffe equation N_{SE}) between simulated and observed flow was 0.79 and 0.75 respectively. This indicates that results were estimated by evaluating the modeled results are within the acceptable level with the measured stream flow at Nashe River gauging station.

The visual comparison of graphs also other measures of the model performance during calibration for stream flow (Fig. 4 and Fig. 5) which is important to identify model partiality and variation in the timing and amount of peak flows simulated. It shows the relationship between the model simulation output and observed data for model calibration.

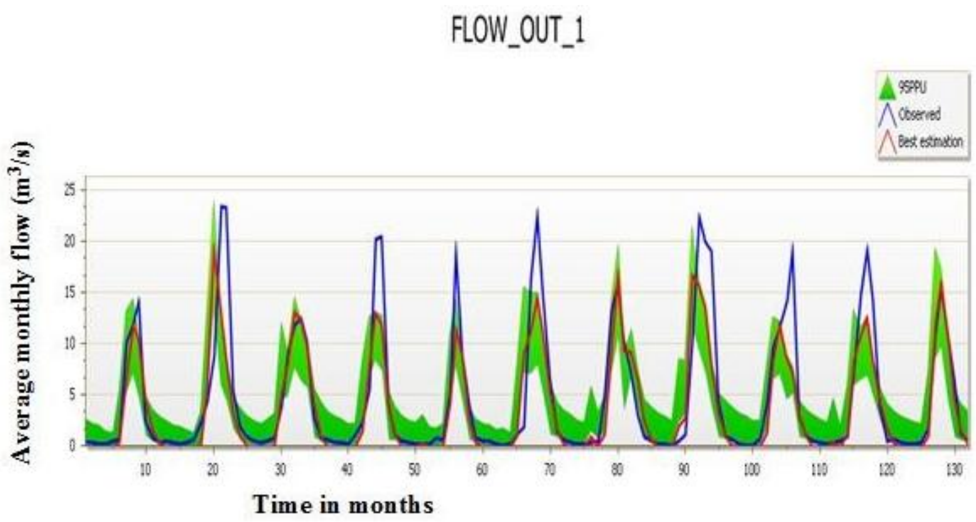

Figure 4 Calibration results of monthly observed and simulated flows by SUFI-2 of Nashe watershed

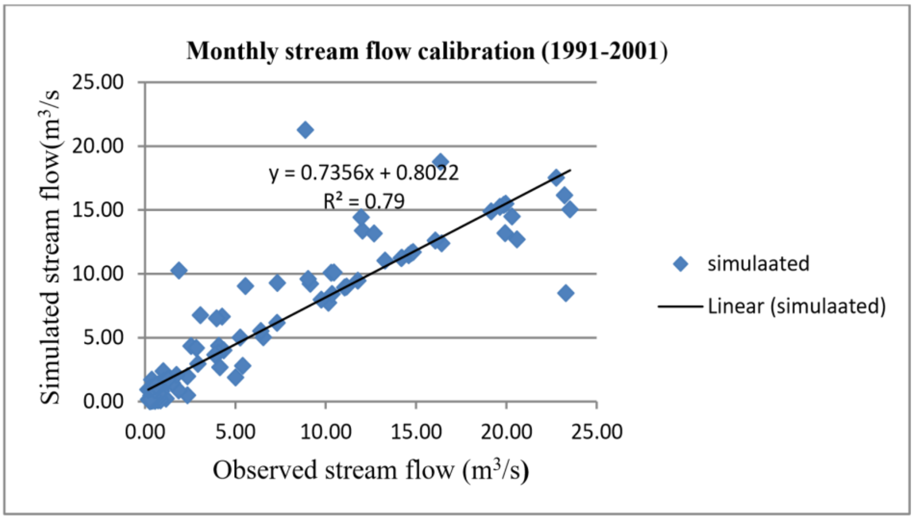

Figure 5 Scatter plot of observed and simulated stream flow for Nashe watershed during calibration period

4.3 Model validation

For this study, monthly validation of statistical analysis showed that good agreement between observed and simulated stream flow, which was explained by R^2 and N_{SE} values (0.71 for R^2 and 0.65 for N_{SE}). The validation result represents that SWAT model accurately predict stream flow (Fig. 6 and Fig. 7), by showing the relationship between the simulated output and observed data.

4.4 Sediment yield

The result indicates that good agreement between rating curve and SWAT model on predicting sediment loads. These showed that the simulated sediment yield from stream flow simulation by SWAT model was acceptable (Fig. 8 and Fig. 9).

The average annual sediment yield result obtained from stream flow SWAT model simulation was used to spatial based soil erosion map for each sub basin of watershed. The increasing of sediment yield was primarily due to increases in surface runoff. Based on this simulation, the average sediment yield at outlet (RCH 1) from the watershed was 0.285 Mton / year (Table 1 and Table 2).

In this study area, the simulated sediment yield was 60.97 ton / ha which is found in the tolerable rate range.

The temporal distributions of soil erosion have been estimated entire Nashe watershed based on the SWAT simulated average monthly sediment yields. According to the results, average sediment yields generated during (June & September), monthly severe soil erosion time and (July & August) monthly extreme soil erosion time (Fig. 10).

4.5 Conservation measure for management

For sub watersheds (N-8, 10, 11) was in bare vegetation, high relief and steep slope, that it demonstrates poorer infiltration and higher overflow than all other sub watershed of the basin. Therefore, both conservation measures have to apply consecutively. In the same way; the watershed medium priority classes (N-2, 3, 5, 6, 7, 9, 12, 13, 15) are comparatively moderate soil erosion zone and be made up of moderate slopes, less bare vegetation and shape parameters. And in-situ management were recommended. Also, for sub watersheds categorized under low priority classes (N-1, 4, 14) are very slight erosion susceptibility zone.

These sub watersheds are mild slope and flat land need measures such as Contour farming, Strip cropping and Mixed cropping during the rainy season and seeding time can reduce soil erosion (Fig. 11).

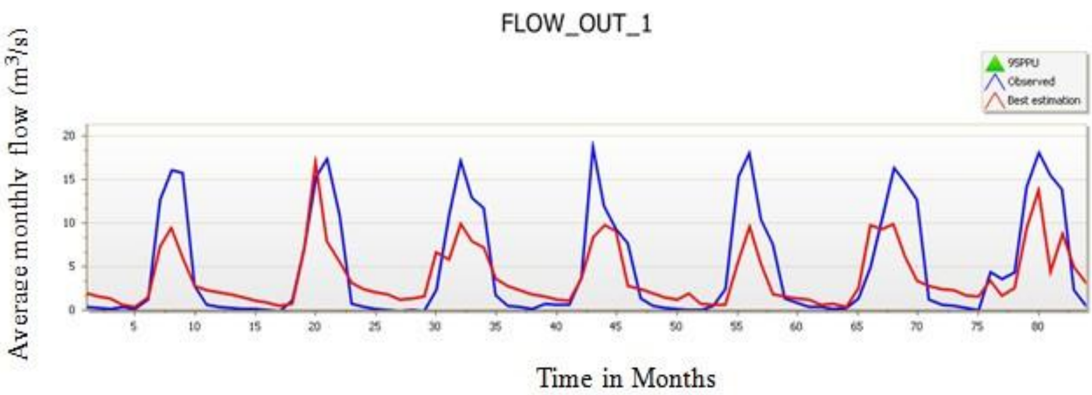

Figure 6 Validation results of monthly observed and simulated flows by SUFI-2 Nashe watershed

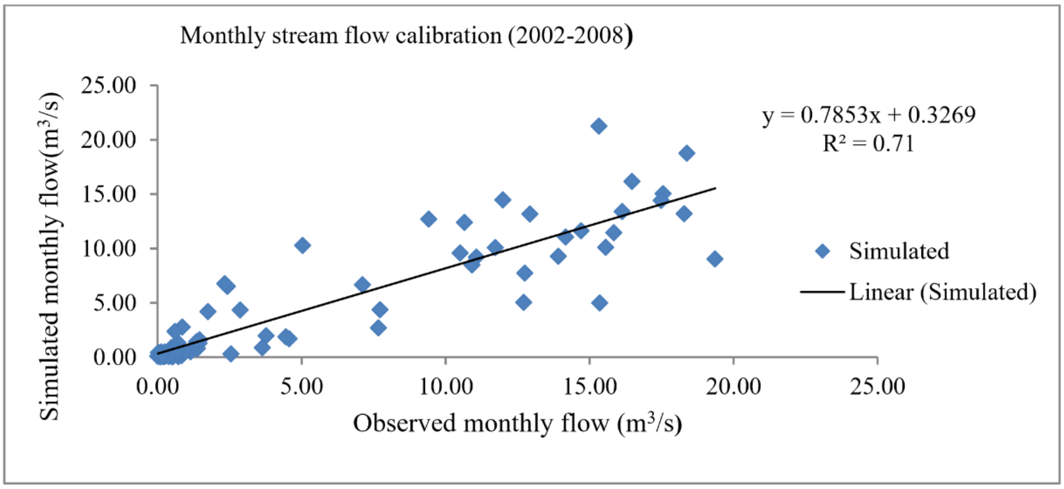

Figure 7 Scatter plot of observed and simulated stream flow during validation periods

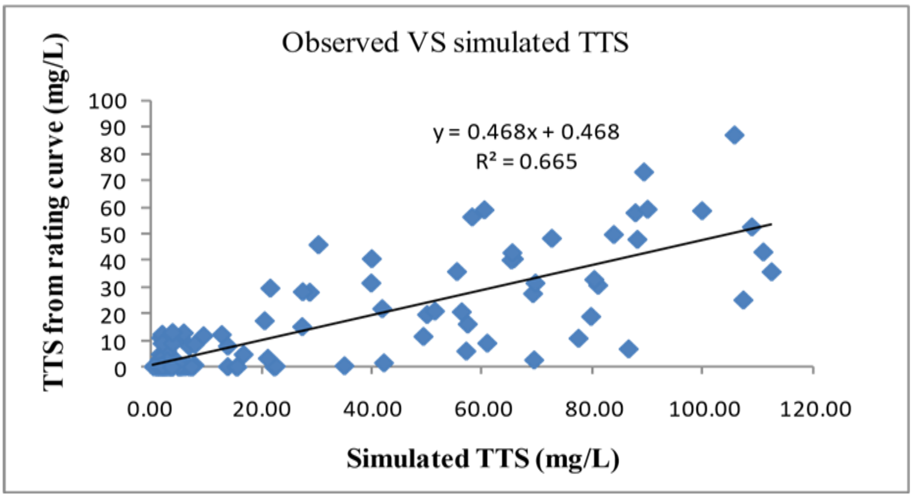

Figure 8 Simulated sediment and obtained from rating curve

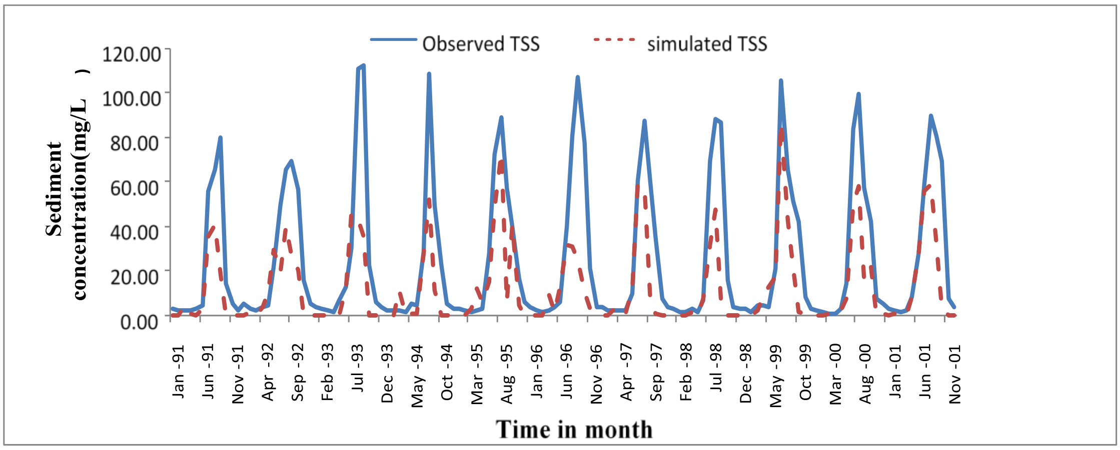

Figure 9 Simulated and computed sediment concentration

Table 1 Sediment yield at outlet of each sub-basin

Rich	Sediment yield at outlet (Mton / yr)	Sub basin by name
1	0.285	N-1
2	0.014	N-2
3	0.223	N-3
4	0.207	N-4
5	0.196	N-5
6	0.07	N-6
7	0.059	N-7
8	0.010	N-8
9	0.050	N-9
10	0.137	N-10
11	0.029	N-11
12	0.053	N-12
13	0.006	N-13
14	0.063	N-14
15	0.021	N-15

Table 2 The severity of soil erosion corresponding to area in Nashe watershed

Soil erosion condition	Sediment yield (ton / ha / yr)	Percent of area coverage (%)	Watershed Area
Low erosion	0 - 25	20	N-1, 4, 14
Moderate erosion	25 - 75	60	N-2, 3, 5, 6, 7, 9, 12, 13, 15
Severe erosion	75 - 150	20	N-8, 10, 11
Extreme erosion	Above 150	0	None

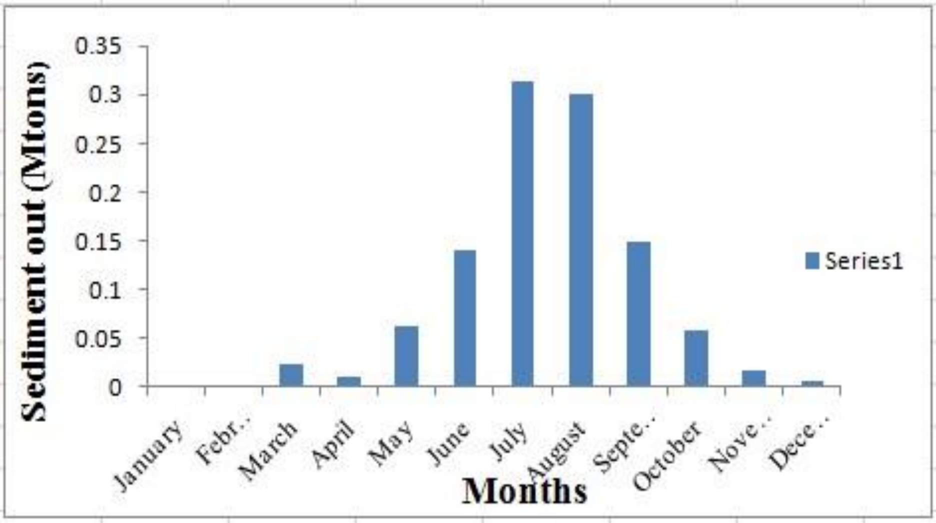

Figure 10 Spatial distribution of sediment yield in Nashe watershed

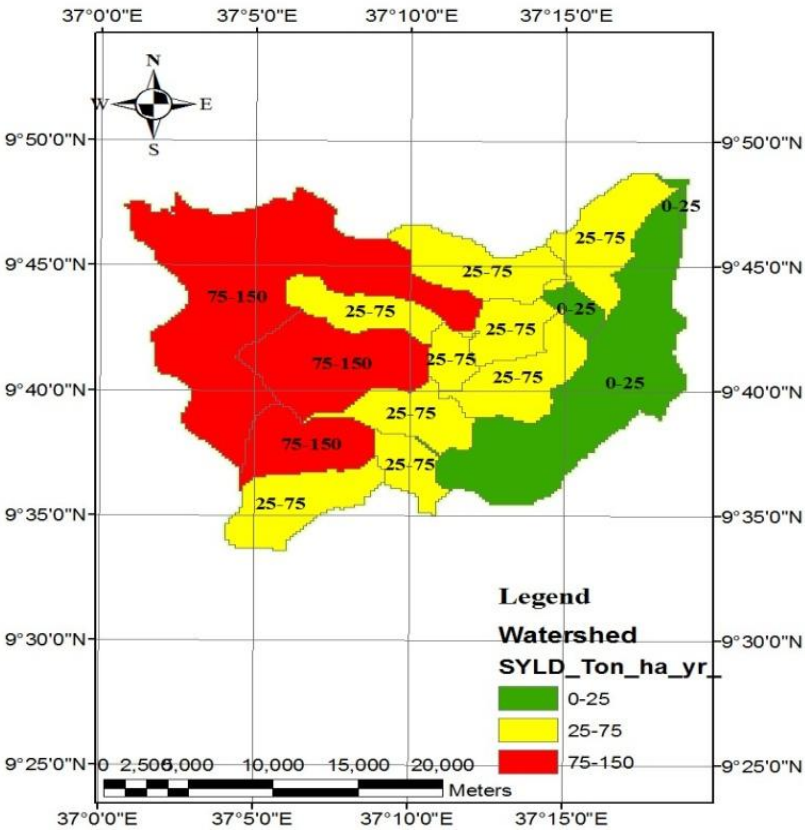

Figure 11 Temporal distribution of sediment yield in Nashe watershed

CONCLUSIONS

The average monthly simulated flows were compared with the average monthly observed values using graphical and statistical methods. As the measured data were not available on sediment yield, the simulated data has been used to determine sediment yields from sub basin.

In this study, sub basin was categorized in terms of their sediment yield per hectare which is very important data with high erosion rates leading to land degradation where conservation measures are required. According to generation of sediment yields soil erosion prone areas have been identified and priority sub watershed required are suggested to reduce maximum soil erosion.

In general, the ability of SWAT model performance was adequately to simulate stream flows from Nashe sub basin and successfully result were obtained. Therefore, SWAT model is an acceptable tool for extra study of the hydrological response in Nashe sub basin.

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