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Simulation of sediment yield and evaluation of best management practices in Azuari watershed, Upper Blue Nile Basin

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ABSTRACT

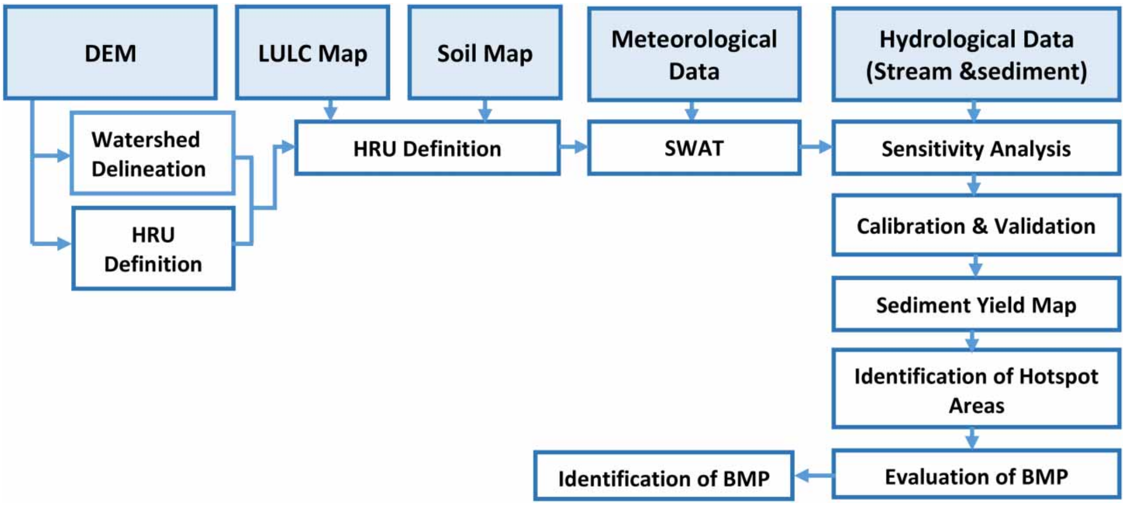
This study was conducted to simulate the sediment yield and evaluate best management practices (BMPs) for sediment control in the Azuari watershed, Upper Blue Nile basin, Ethiopia using the Soil and Water Assessment Tool (SWAT) model. As inputs for the model, 30 years (1991–2020) of daily values of meteorological data were used. For model simulation, daily stream flow and sediment data were collected for the periods from 1988 to 2012. The study area was delineated into 19 subwatersheds and the sediment yield was estimated in each subwatershed using the modified universal soil loss equation. The average simulated sediment yield in the watershed was found to be 10.81 t/ha/yr. Six subwatersheds were identified to have high to severe sediment yields and are considered hotspot areas which require prior mitigation measures to control sediment. Four soil and conservation measures were evaluated in SWAT as BMPs namely filter strip, terracing, strip cropping, and contouring. Filter strip was found to reduce sediment by 35.61%, terracing by 20.44%, strip cropping by 44.12%, and contouring by 43.6%. Thus, the implementation of strip cropping resulted in maximum sediment yield reduction. The findings of the study would help to make informed decisions on best watershed management strategies.

Key words: Azuari watershed, best management practices, Blue Nile basin, sediment yield, SWAT

HIGHLIGHTS

- The sediment yields in 19 subwatersheds of the studied watershed were estimated.
- Six subwatersheds were identified as hotspot areas.
- Four best management practices were evaluated for the control of sediments in hotspot areas.
- Identification of sediment-prone areas is required for efficient planning of watershed development.

GRAPHICAL ABSTRACT



1. INTRODUCTION

Soil erosion is the process of wearing away the topsoil of a field by erosive forces such as water and wind. Soil erosion by water is one of the most important land degradation problems, and a serious environmental threat in the world (Duru *et al.* 2018; Bhatti *et al.* 2021). When soil particles are eroded, they are moved and dumped somewhere else as they are no longer in contact with the original soil (Balasubramanian 2017). Soil erosion and sediment deposition processes combine to produce sediment yield. It is defined as the total sediment output from a watershed for a certain period, as measured at a point of reference (Bashewal & Kamal 2021). Common contributing factors for soil erosion and sediment yield include uncontrolled expansion of agricultural lands, cultivation of steep lands, urbanization, and deforestation without proper management (Kidane & Alemu 2015; Burgan 2022). Inappropriate management and soil conservation strategies lead to excessive erosion of topsoil during heavy precipitations which increases runoff and further increases sediment transport and accelerates sedimentation in lakes and storage reservoirs (Ali *et al.* 2014).

Soil erosion and sedimentation are major issues in Ethiopia due to a lack of land use planning, over-cultivation, and overgrazing (Demelash 2010; Dibaba *et al.* 2021). Rivers are observed to carry a full load of sediment showing that a considerable amount of soil is washed away from various watersheds of the country, mostly during the rainy seasons. The soil eroded from uplands is deposited in the downstream areas, which often results in the siltation of dams and water reservoirs, pollution of water sources, and the destruction of fertile agricultural land. Moreover, the deposition of sediment in natural stream channels, drainage ditches, and irrigation canals creates a loss of services and increases cleanout costs. Further, the deposition of sediment in the river channels decreases the channel capacity and results in flooding of the surrounding areas due to overflows.

Large areas of farming and deforestation are common phenomena in Ethiopia's Blue Nile River basin (Yaekob *et al.* 2020). With the constant change in land use and agricultural activities in the area, sediment generation and transport have become very complex (Tramblay *et al.* 2010). Deforestation exposes soils to increased water erosion, especially on steep terrain (Nedjai *et al.* 2013; Brown *et al.* 2014). The reduction of vegetation cover on lower slopes also increases soil erosion. This does degrade the soil fertility over time and reduces the suitability of land for agricultural use. For instance, the soil losses due to runoff within the Blue Nile River basin are recorded to reach up to 400 t/ha yr (Yaekob *et al.* 2020). The physical removal of top soils in the highlands increases sedimentation downstream (Cerdà *et al.* 2009). The eroded sediment particles by the flowing water are usually settled in reservoirs, river channels, and irrigation canals (Ali *et al.* 2014).

Azuari watershed is one of the watersheds in the North Gojam sub-basin of the Upper Blue Nile River basin. The watershed drains to the Azuari River, which is the tributary of the Blue Nile River. The area receives heavy rainfall with mean annual values ranging between 908.68 and 1,539.64 mm. As the topography of the area is mountainous, it is highly susceptible to erosion and environmental degradation. The main causes of such environmental problems in the watershed are the expansion of cultivated land and deforestation (Fisseha *et al.* 2011). There are many studies on erosion and sediment problems in the different sub-basins of the Upper Blue Nile River basin (Ayele *et al.* 2017; Moges *et al.* 2018; Leta *et al.* 2023). However, very few studies are available on sediment transport and its management in the Azuari watershed. Thus, understanding sediment transport mechanisms, its deposition level downstream, and evaluation of mitigation techniques to control it are crucial for long-term water resource development (Betrie *et al.* 2011).

It is known that the sediment transport mechanism is directly related to precipitation and runoff in a hydrological basin (Burgan 2022). Different hydrological models are available for the simulation of sediment and evaluation of different watershed management practices from hydrometeorological data. However, the choice of an appropriate model is largely influenced by the function that the model must fulfill (Ayele *et al.* 2017). Many recent studies in various parts of the world highlighted the use of the Soil and Water Assessment Tool (SWAT) model to assess sediment yield and evaluate different management practices to control sediments in river basins. Azari *et al.* (2016) evaluated the watershed sediment yield using the SWAT model in the Northern Forests of Iran. Similarly, Sok *et al.* (2020) reported the use of the SWAT model to assess sediment yield in the Upper Mekong Basin, China. Recently, Nepal & Parajuli (2022) also reported the good performance of the SWAT model to assess the best management practices (BMPs) to control sediment at a watershed in Mississippi. Furthermore, Ricci *et al.* (2018) assessed the SWAT model's applicability for simulating runoff and sediment loss in the Carapelle Mediterranean watershed. The SWAT model has also been used in the Blue Nile Basin, Ethiopia, to assess factors such as soil productivity loss, water-induced erosion and unsustainable land management practices, and the impact of land use changes and reforestation on sediment yield in the region (Van Griensven *et al.* 2012; Sultana *et al.* 2019; Abebe *et al.* 2022; Leta *et al.* 2023).

Therefore, the SWAT model was selected for this study to simulate sediment yield and evaluate the BMPs to control soil loss and sediment transport in high-risk areas due to its computational efficiency, data requirements, and application level (Himanshu *et al.* 2019).

2. METHODS

2.1. Description of the study area

The study area is the Azuari watershed. It is located in the North Gojam sub-basin of the Upper Blue Nile basin, Ethiopia. The watershed is geographically located at 10°58′0.012″N to 11°10′.0″N latitude and 37°50′.0″E to 38°10′.0″E longitude (Figure 1). The total area of the watershed is 678.57 km^2. The area receives a uni-modal rainfall, most of which falls from June to September, with the peak amount in July and August. The annual rainfall ranges approximately between 908.68 and 1,539.64 mm. The mean daily temperature of the area ranges from 10.48 to 23.82 °C. The topography of the study area represents diversified elevations ranging from 1,269 m at the outlet of the Azuari River that joins the Blue Nile River to 4,049 m a.m.s.l at the highest point near Choke Mountain. Very steep slopes dominate, covering large parts of the area.

2.2. Data collection

2.2.1. Spatial data

2.2.1.1. Digital elevation model. A digital elevation model (DEM) with a 20 m by 20 m resolution was used in Arc GIS 10.4.1 to delineate the study area and the subwatersheds. The DEM was taken from the Ethiopian Mapping Agency (EMA) and was projected to UTM 37 North and D_WGS_1984 datum using Arc GIS 10.4.1 software for analysis. Figure 2 shows the DEM of the study area.

2.2.1.2. Land use and land cover data. Other important GIS input layers needed by SWAT include land use and land cover (LULC). To get the LULC map, the 2020 satellite images were downloaded from the USGS earth explorer website. The satellite images were taken during the dry season (January to April) to get good quality and cloud-free images, and easy visualization of LULCs. The land use classes found in the SWAT model were

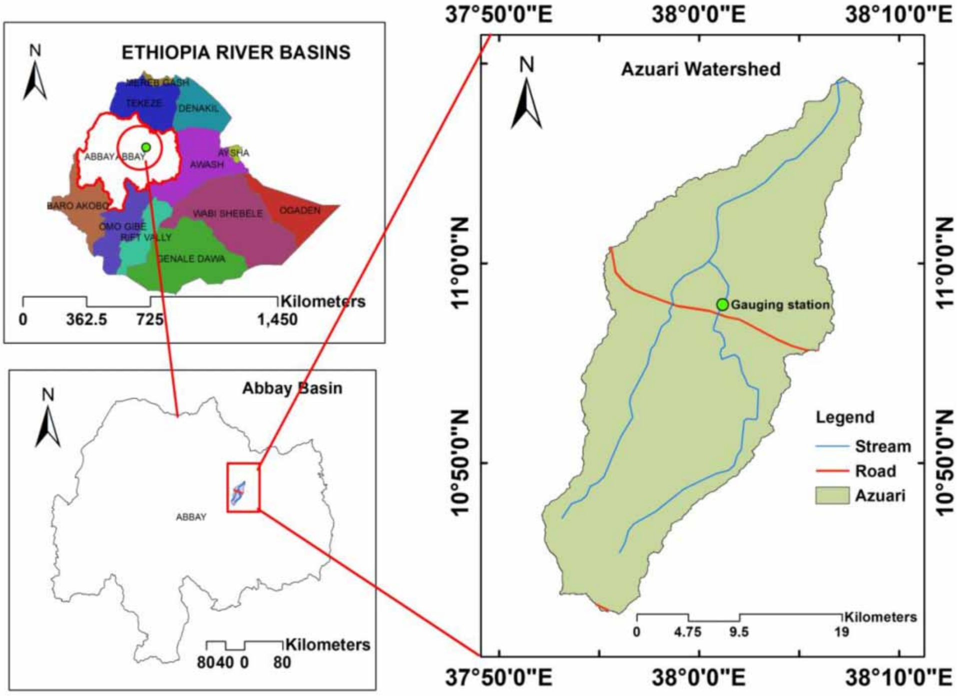


Figure 1 | Location of the study area.

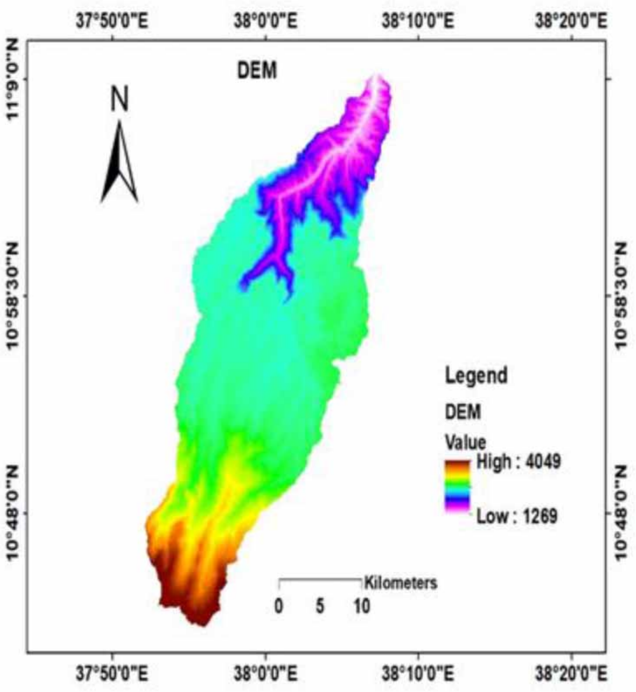


Figure 2 | DEM of the study area.

used for the hydrologic response unit (HRU) definition. Table 1 shows the different land use types in the study area and their area coverage. Further, Figure 3 depicts the LULC map of the study area.

2.2.1.3. Soil data. The soil parameters of the basin are the other key inputs required by the SWAT tool when modeling watersheds. Due to their effects on the catchment's infiltration rate, soil types have a significant impact on runoff potential. The soil map of the Azuari watershed was obtained from the world harmonized soil map database (FAO/IIASA/ISRIC/ISS-CAS/JRC 2012). Eutric Nitosol (Ne12-3b-156) was found as the major soil type in the study area. Figure 4 shows the soil map of the study area.

2.2.1.4. Slope. The slope map is also one of the input data used in the model to define HRUs. During the definition of HRUs, the slope was classified into five reasonable ranges. These were 0–10%, 10–15%, 15–20%, 20–25%, and above 25%. Based on these classes, the slope map of the area was developed (Figure 5).

2.2.2. Weather data

Meteorological data were obtained from the National Meteorological Agency (NMA) of Ethiopia. The SWAT model requires daily values of rainfall, maximum and minimum temperature, solar radiation, relative humidity, and wind speed. The daily values of these data for the periods from 1991 to 2020 were collected from four meteorological stations in the area, namely, Motta, Gundowin, Debrework, and Robgebeya. The selection of

Table 1 | LULC type and area coverage in the Azuari watershed

No	LULC	SWAT code	Area coverage in km^2	Percentage coverage
1	Agriculture	AGRL	438.53	64.63
2	Forest	FRST	50.08	7.38
3	Grassland	PAST	101.39	14.94
4	Shrub land	RNGB	49.82	7.34
5	Woodland	FRSD	27.58	4.06
6	Settlement	URBN	11.17	1.65

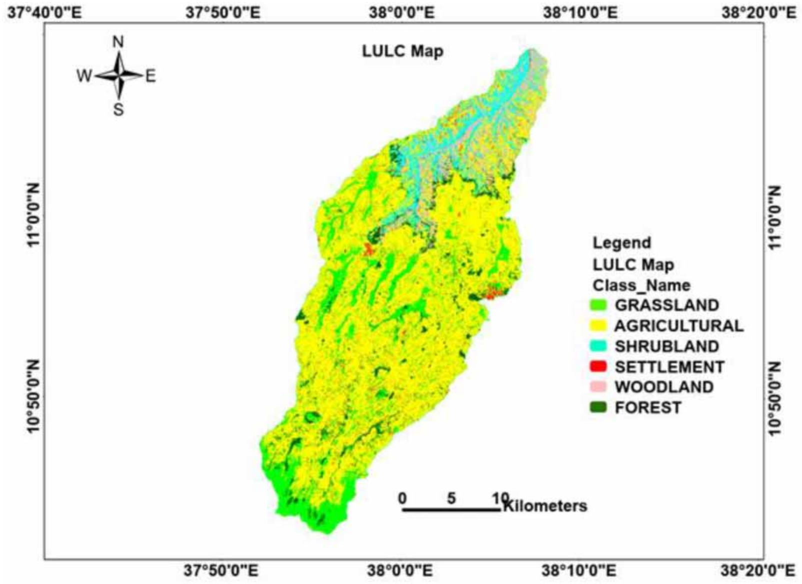


Figure 3 | LULC map of the study area.

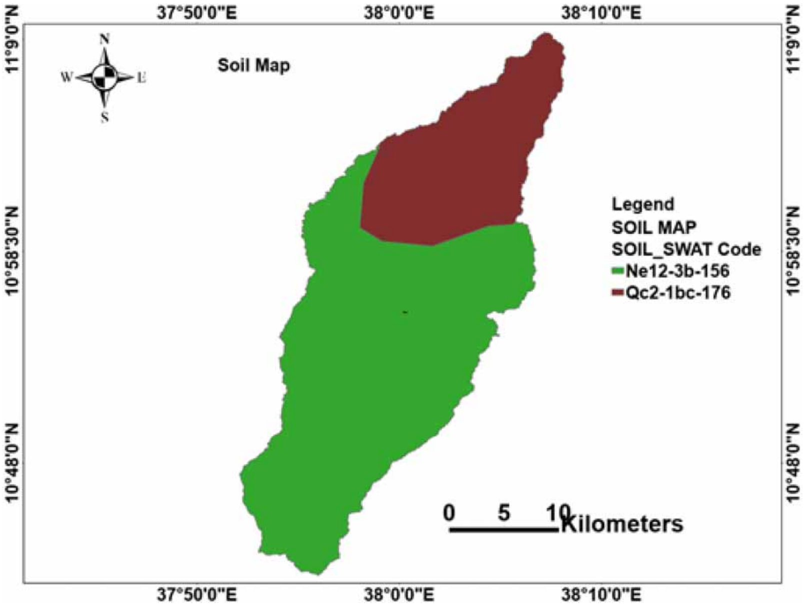


Figure 4 | Soil map of the study area.

meteorological gauging stations was typically chosen based on physical similarities and regionalization approaches to calibrate and validate the SWAT model.

2.2.3. Hydrological data

2.2.3.1. Stream flow data. Daily stream flow data was collected from the Ministry of Water and Energy (MoWE) for the periods of 1988–2012. The data were used for the derivation of sediment yield from measured sediment concentration.

2.2.3.2. Sediment data. Sediment data for the Azuari River was obtained from the MoWE in a concentrated form. The data were collected from the periods from 1988 to 2012. As the sediment data was in a concentrated form, to change it to sediment yield, a sediment rating curve is required. The sediment rating curve is a plot of stream flow discharge and suspended sediment concentration. It is commonly used for the calculation of average sediment discharge from water discharge when sediment samples are not adequate.

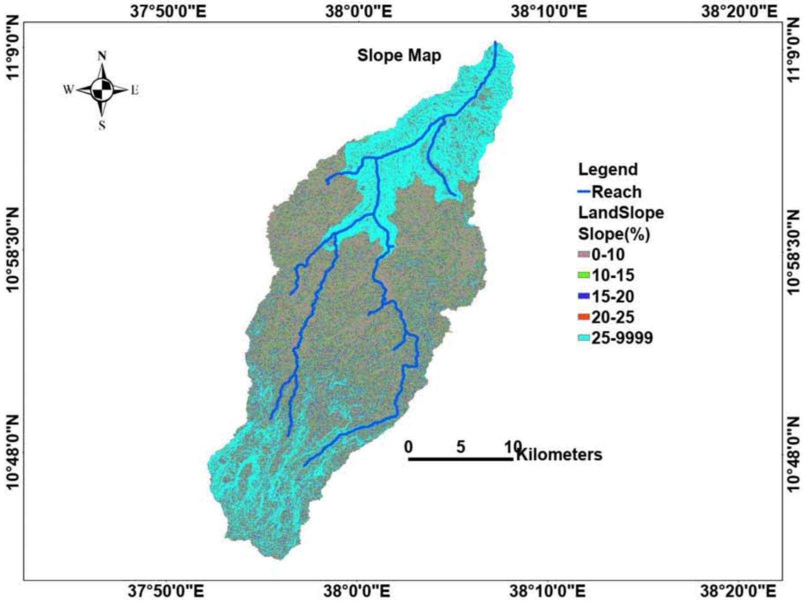


Figure 5 | Slope map of the study area.

In this study, the sediment discharge is derived from sediment concentration and measured stream flow using Equation (1). The rating curve was then developed from the relationship between the derived sediment yields and measured flow rates (Figure 6). Equation (2) shows such a relationship:

$$Q_s = 0.0864 \times C \times Q \tag{1}$$

where Q_s is sediment yield in t/day; C is sediment concentration in mg/l, and Q is stream flow in m^3/s.

$$Y = 19/405X^{1.6324} \tag{2}$$

where Y is sediment load in t/day and X is stream flow in m^3/s.

2.3. SWAT model setup

2.3.1. Watershed and subwatersheds delineation

The first step in the SWAT model setup is defining watershed boundaries from a DEM. Thus, the delineation of the studied watershed and its subwatersheds were done using DEM data and the normal SWAT watershed delineation process which includes five major steps, DEM setup, stream definition, outlet and inlet definition,

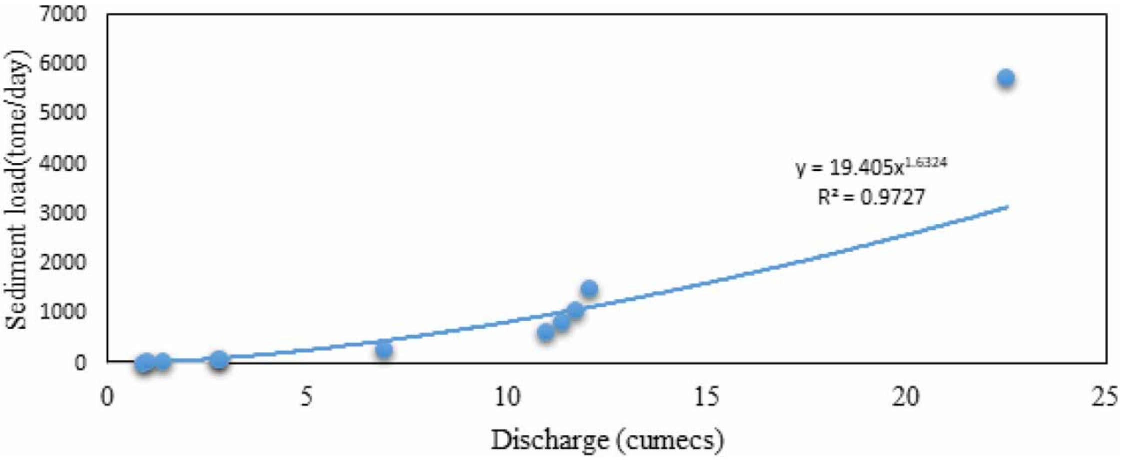


Figure 6 | Sediment rating curve.

watershed outlets selection, and definition and calculation of sub-basin parameters. For the stream definition, the threshold-based stream definition option was used to define the minimum size of the subwatershed to minimize uncertainty associated with model outputs.

2.3.2. HRU analysis

SWAT uses the concept of HRUs which refers to the portion of a subwatershed that possesses unique land use and soil attributes. After watershed and subwatersheds delineation, the HRU analysis was done. The HRU analysis requires land use, soil, and slope data. After adjusting the projection of land use and soil, and by preparing the SWAT code related to the SWAT database, the land use and soil maps together with the multiple slopes map were overlaid to create HRU feature classes. To limit the number of HRUs, a threshold of 5% land cover, 10% slope, and 20% soil was used.

2.4. Sediment yield simulation

The SWAT model contains algorithms for simulating sediment yield from the watershed. The spatial distribution of the sediment yield was estimated by delineating the watershed into subwatersheds and finding the sediment yield in each subwatershed. The sediment yield was estimated for each HRU in a subwatershed and was aggregated to find the sediment yield for each subwatershed. SWAT estimated the sediment yield for each HRU with the Modified Universal Soil Loss Equation (MUSLE) (Hidayat & Sulistyo 2019), expressed by the equation:

$$S_{\mathrm{ed}} = S_{\mathrm{ed}} = 11.8(Q_{\mathrm{surf}} * q_{\mathrm{peak}} * Areahru)^{0.56} K_{\mathrm{USLE}} * C_{\mathrm{USLE}} * P_{\mathrm{USLE}} * LS_{\mathrm{USLE}} * \mathrm{CFRG} \tag{3}$$

where S_{ed} is the sediment yield rate (t/day), Q_{surf} is the surface runoff volume (mm/day), q_{peak} is the peak runoff rate (m^3/s), *Areahru* is the area of the HRU (ha), and K_{USLE}, C_{USLE}, P_{USLE}, and LS_{USLE} are the USLE soil erodibility factor (0.013 metric ton m^2 h/(m^3-metric ton cm)), crop cover management factor, erosion control practice factor, and topographic (length and steepness) factor, respectively. CFRG is the coarse fragment factor which is obtained by

$$\mathrm{CFRG} = \exp(-0.053 \times \mathrm{Rock}) \tag{4}$$

where Rock is the percent rock in the first soil layer (%).

In MUSLE, the rainfall energy factor is replaced with a runoff factor. This improves the sediment yield prediction. Using daily rainfall, SWAT simulates surface runoff (Q_{surf}) for each HRU. In this study, the SCS curve number method was used to estimate surface runoff. The SCS curve number equation is given by

$$Q_{\mathrm{surf}} = \frac{(R_{\mathrm{day}} - 0.2S)^2}{(R_{\mathrm{day}} + 0.8S)} \tag{5}$$

where Q_{surf} is the accumulated runoff or rainfall excess (mm), R_{day} is the rainfall depth for the day (mm), and S is the retention parameter (mm). The retention parameter, S, is determined by the equation:

$$S = 25.4\left[\left(\frac{1,000}{\mathrm{CN}}\right) - 10\right] \tag{6}$$

where CN parameter is defined by the initial soil water conditions, soil permeability, and land use.

2.5. Sensitivity analysis

After sediment simulation, a sensitivity analysis was done to identify sensitive parameters for model calibration. A total of nine parameters were selected, and the ranks of sensitive parameters were made depending on global sensitivity analyses *p*-value and *t*-statistic. Then, the sensitivity analysis was ranked from most sensitive to least sensitive.

2.6. Model calibration and validation

After the sensitive parameters identification, calibration of the model was executed to evaluate the performance of the model simulation using the SWAT_CUP tool. Model calibration and validation were carried out by minimizing the difference between the observed and simulated sediment. Due to limited data, sediment calibration was conducted for the years 1988 and 2004 on a monthly basis. But the first 2 years were considered for a model warm-up period. For validation, sediment data from the year 2005 to 2012 were used.

2.7. Model performance analysis

The performance of the model for sediment simulation was measured using the coefficient of determination (R^2), Nash–Sutcliffe efficiency (NSE), and root mean square error observations standard deviation ratio (RSR).

The R^2 number indicates the degree to which the observed and simulated values are related. R^2 was obtained by

$$R^2 = \frac{\sum_{i=1}^{n}(Q_s - \bar{Q}_s)[(Q_o - \bar{Q}_o)]^2}{\left[\sum_{i=1}^{n}(Q_s - \bar{Q}_s)\right]^2\left[\sum_{i=1}^{n}(Q_o - \bar{Q}_o)\right]^2} \tag{7}$$

where Q_o is observed flow, Q_s is simulated flow, $\bar{Q}_o$ is the average of observed flow, and $\bar{Q}_s$ is the average of simulated flow. R^2 value ranges between 0 and 1, with higher values suggesting less error variance and values larger than 0.5 commonly regarded as acceptable (Moriasi *et al.* 2007).

The NSE was obtained by Equation (1) (Nash & Sutcliffe 1970):

$$\mathrm{NSE} = 1 - \frac{\sum_{i=1}^{n}(Q_o - Q_s)^2}{\sum_{i=1}^{n}(Q_o - \bar{Q}_o)^2} \tag{8}$$

The NSE value ranges between 0 and 1. It is 1 if the measured value perfectly matches all forecasts. The forecasts are poor if the NSE is negative, indicating that the average output value is a better estimate than the model forecast (Sahu *et al.* 2020). Moriasi *et al.* (2007) stated that an NSE value larger than 0.50 is satisfactory for SWAT model simulation.

RSR standardizes root mean square error (RMSE) using the observations' standard deviation (Moriasi *et al.* 2007). It was obtained by Equation (9):

$$\mathrm{RSR} = \frac{\sqrt{\sum_{i=1}^{n}(Q_o - Q_s)^2}}{\sqrt{\sum_{i=1}^{n}(Q_o - \bar{Q}_o)^2}} \tag{9}$$

RSR varies from the optimal value of 0, which indicates zero RMSE or residual variation and therefore perfect model simulation, to a large positive value. The lower the RSR, the lower the RMSE, and the better the model simulation performance. Moriasi *et al.* (2007) stated that an RSR value larger than 0.60 is satisfactory for SWAT model simulation.

2.8. Identification of sediment-prone areas

In this study, the identification of hotspot (sediment-prone) areas was done based on the sediment yield of each subwatershed. Based on Hurni (1985), the severity of erosion-prone areas was evaluated based on Table 2.

2.9. Best sediment management practices scenario

Implementing appropriate BMPs in severely affected or hot spot areas is critical for reducing sediment movement and soil erosion in watersheds. But the selection of BMPs and the values of their parameters depend on the study

Table 2 | Methods of identification of sediment-prone areas

Erosion risk class	Very low	Low	Moderate	High	Very high	Severe
Soil loss (t/ha/yr)	0–5	5–8	8–10	10–15	15–25	>25

area reality (Betrie *et al.* 2011). From research experience in the Ethiopian highlands (Hurni 1985), the following five scenarios were considered for the selection of BMPs.

2.9.1. Scenario 0 (Baseline scenario)

This scenario indicates the present condition of the watershed without any consideration of management practices.

2.9.2. Scenario 1 (Filter strips)

Filter strips reduce overland flow velocity which results in the deposition of particles. Filter strips were placed on all agricultural HRUs, all soil types, and slope classes. An appropriate model parameter used for the representation of the effect of filter strips was the width of the filter strip (FILTERW). FILTERW was modified by editing the HRU (.hru) input table of default 0 value by 1 m filter width value.

2.9.3. Scenario 2 (Terracing)

A terrace is an embankment within a field designed to intercept runoff and prevent erosion. A terrace is constructed across the slope following the general contour lines. Terraces were placed on all soil types, slope classes, and agricultural HRUs. Appropriate model parameters used for the representation of the effect of terraces are average slope length (SLSUBBSN) and USLE support practice factor (P USLE). The P USLE value was modified by editing the HRU (.hru) and management (.mgt) input table values, respectively. The SWAT model assigns the SLSUBBSN parameter value based on the slope classes. In this application, the SWAT assigned values were 61, 24, 18.3, 15.24, and 9.14 m for slope classes 0–10%, 10–15%, 15–20%, 20–25%, and above 25%, respectively. The modified parameter values for SLSUBBSN are equal to 10 m for all 0–25% and not modified for slopes greater than 25% slope classes. Hurni (1985) recommended that the minimum *P* factor be adjusted to 0.5 for terracing practice throughout Ethiopia. So PUSLE was modified from the calibrated value of 0.59–0.5 by editing the (.mgt) input table.

2.9.4. Scenario 3 (Strip cropping)

Strip cropping is simulated in SWAT by changing Manning's *n* value for overland flow (STRIP-N) to represent increased surface roughness in the direction of runoff. Curve number (STRIP-CN) was adjusted to account for increased infiltration. USLE Cropping factor (STRIP-C) was adjusted to reveal the mean value for multiple crops within the field. The USLE practice factor (STRIP_P) may also be updated to represent strip cropping conditions. STRIP-N, TERR-CN, STRIP-CN, STRIP-C, and STRIP-P were modified by adding and editing the operations (.Ops) input table of their default values of 0.15, 60, 0.4, and 0.7 by 0.15, 59, 0.2, and 0.5, respectively (Table 3).

2.9.5. Scenario 4 (Contouring)

Contour planting parameters were modified in SWAT by changing the curve number (CONT-CN) for surface storage and infiltration and the USLE practice factor (CONT_P) for erosion. Initial SCS curve number II

Table 3 | SWAT parameters used for different BMPs

		SWAT parameter used		
Scenarios	**Description**	**Parameter name (input file)**	**Calibration value**	**Modified value**
Scenario 0	Baseline	–	-	-
Scenario 1	Filter strip	FILTERW (hru)	0	1
Scenario 2	Terracing	SLSUBBSN (hru) 0–10% slope	61	10
		10–15% slope	24	10
		15–20% slope	18.3	10
		20–25% slope	15.24	10
		>25% slope	9.14	9.14
		USLE_P(mgt)	0.59	0.5
Scenario 3	Strip cropping	STRIP_N	0.15	0.15
		STRIP_CN	60	59
		STRIP_C	0.4	0.2
		STRIP_P	0.7	0.5
Scenario 4	Contouring	CONT_CN	60	59
		CONT_P	0.6	0.5

(CONT_CN) and contouring PUSLE factor (CONT_P) model parameters were used for adjustment of the effect of contouring. Contouring parameters were modified by adding and editing the operations (.Ops) input table of the default values of 60 and 0.6 for CN and P by 59 and 0.5, respectively (Table 3).

3. RESULTS AND DISCUSSION

3.1. Sediment yield modeling

3.1.1. Sediment-sensitive parameters

The sensitivity parameters for sediment simulation in SWAT were ranked based on *p*-value and *t*-statistics. The larger absolute value *t*-stat and *p*-value close to zero is the most sensitive parameter. The most sensitive parameters for sediment identified in this study are Manning's *n*, the crop cover factor, and the soil erodibility factor (Table 4).

3.1.2. Calibration and validation

The model simulation of sediment yields was calibrated and validated. The result shows that there is a good agreement between the measured and simulated monthly flows with some underestimation of the peak flows (Figure 7). The model efficiency was also checked with the statistical values and all values indicate a good prediction of the model suggesting that SWAT can be adopted for hydrological simulation in the study area (Table 5).

3.2. Identification, prioritization, and mapping of sediment-prone areas

Identification of the spatial variability and ranking of critical sediment-prone (hotspot) areas is useful for the implementation of best management strategies and long-term use of natural resources in a more sustainable

Table 4 | Sensitivity analysis of sediment yield

Parameter name	Sediment parameters name	*t*-stat	*p*-value	Rank	Min	Max	Fitted
4:V__CH_N2	Manning's *n* value	9.21	0.00	1	0.01	0.23	0.08
9:V__USLE_C	USLE cover factor	– 3.98	0.00	2	0	0.01	0.0045
8:V__USLE_K	USLE soil edibility (*K*) factor	– 3.75	0.00	3	0.03	0.08	0.049
2:V__SPCON	Linear factor for channel sediment	– 1.64	0.1	4	0.00038	0.0011	0.000546
3:V__SPEXP	Exponential factor for sediment routing	1.27	0.2	5	1.04	1.135	1.07
1:V__USLE_P	USLE support practice factor	– 1.1	0.26	6	0.5	0.8	0.6863
5:V__CH_K2	Effective hydraulic conductivity (mm/h)	0.19	0.84	7	0	20	8.74
7:V__CH_COV2	Channel cover factor	– 0.19	0.85	8	0.72	0.907	0.86
6:V__CH_COV1	Channel erodibility factor	– 0.08	0.93	9	0.00038	0.001	0.00082

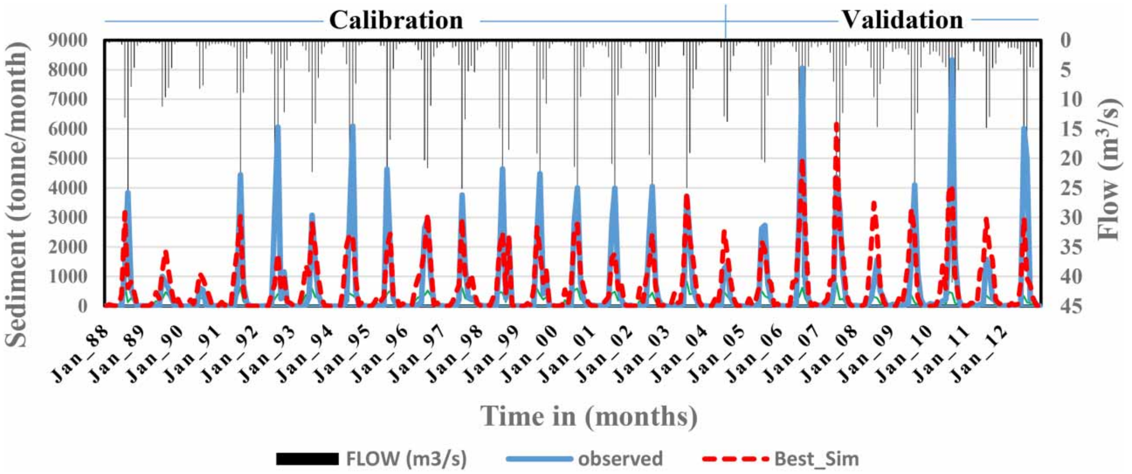


Figure 7 | Sediment yield calibration and validation.

Table 5 | Sensitivity analysis of sediment yield

	Model efficiency		
Model test	R^2	**NSE**	**RSR**
Calibration	0.65	0.64	0.6
Validation	0.58	0.58	0.65

way. After the model calibration and validation of sediment, the spatial distribution of the sediment yield was identified by delineating the watershed into subwatersheds and finding the sediment yield in each subwatershed. The watershed was delineated into 19 subwatersheds and the sediment yield in each subwatershed was estimated. The sediment yield varies from 0.72 to 36.56 t/ha/yr (Figure 8).

From Table 6, 13 subwatersheds which constituted 68.23% of the studied watershed exhibited very low to moderate erosion risks. In Ethiopia, acceptable soil loss that can maintain the economy and a high level of production is below 11 t/ha/yr (Husen & Abate 2020). As the soil losses in the 13 subwatershed areas are within the acceptable soil loss rate, it is less important to apply BMPs. Whereas the six subwatersheds which are coded as SW-1, SW-2, SW-4, SW-5, SW-6, and SW-7 exhibited high to severe erosion risk areas and covered a total of 31.77% of the total area. These subwatersheds are, therefore, identified as hotspot areas which need quick management intervention to reduce soil losses. Accordingly, the subwatersheds are prioritized into six classes (very low, low, moderate, high, very high, and severe) according to their severity of erosion and are shown in Figure 9.

3.3. Best sediment management scenario analysis

The resource considerations for the implementation of watershed management programmes may limit the implementation to a few watersheds. Thus, it is always better to start management measures from the highest priority subwatershed. There are different sediment mitigation measures in the SWAT model. In this study, four BMPs (scenarios) were evaluated on the six critical subwatersheds, namely SW-1, SW-2, SW-4, SW-5, SW-6, and SW-7. The four BMPs applied on these subwatersheds are filter strip, terracing, strip cropping, and contouring (Table 7). The effects of BMPs on sediment reduction were compared with a baseline scenario (scenario 0) (no management practices).

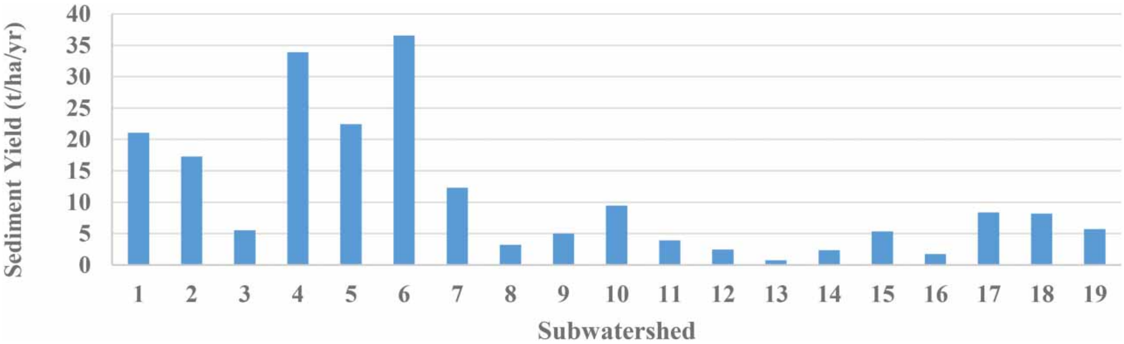


Figure 8 | Spatial variation of sediment yield.

Table 6 | Identification of sediment-prone areas

Severity level	**very low**	**Low**	**Moderate**	**High**	**Very high**	**Severe**
Soil loss (t/ha/yr)	0–5	5–8	8–10	10–15	15–25	> 25
Sub watershed	8, 11, 12, 13,14, 16	3, 9, 15, 19	10, 17, 18	7	1, 2, 5	4, 6
Area (ha)	19,315	17,583	9,195	2,191	11,738	7,532
Area (%)	28.59	26.03	13.61	3.24	17.38	11.15
Severity ranks	6	5	4	3	2	1

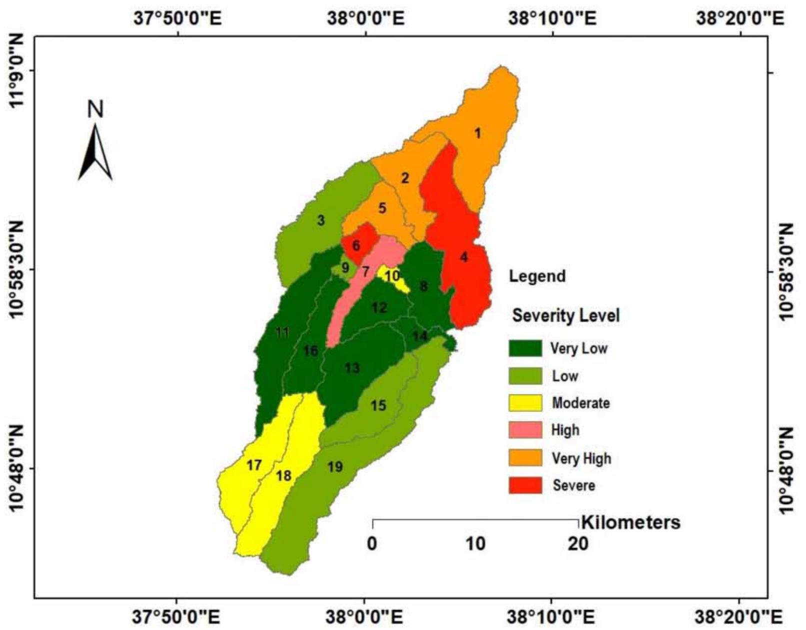


Figure 9 | Severity levels of erosion in subwatersheds of Azuri watershed.

Table 7 | Best sediment management scenario result

		SWAT parameter used					
Scenarios	**Description**	**Parameter name (input file)**	**Calibration value**	**Modified value**	**Mean sediment (t/ha/yr)**	**Reduced sediment load (t/ha/yr)**	**% Sediment reduction**
Scenario 0	Baseline	–	-	-	10.81	0	0
Scenario 1	Filterstrip	FILTERW (hru)	0	1	6.96	−3.85	−35.61
Scenario 2	Terracing	SLSUBBSN (hru)					
		0–10% slope	61	10			
		10–15% slope	24	10			
		15–20% slope	18.3	10			
		20–25% slope	15.24	10			
		>25% slope	9.14	9.14			
		USLE_P (mgt)	0.59	0.5	8.6	− 2.21	− 20.44
Scenario 3	Strip cropping	STRIP_N	0.15	0.15			
		STRIP_CN	60	59			
		STRIP_C	0.4	0.2			
		STRIP_P	0.7	0.5	6.04	− 4.77	− 44.12
Scenario 4	Contouring	CONT_CN	60	59			
		CONT_P	0.6	0.5	6.1	− 4.71	− 43.6

Without receiving any management practices, the average simulated sediment yield of the watershed was 10.81 t/ha/yr. However, with the application of the filter strips with a 1 m width of strips (scenario 1), the mean sediment yield was found to be 6.96 t/ha/yr, which exhibited a reduction of the sediment by 35.61% from the baseline. By applying terracing (scenario 2), the average sediment yield was found to be 8.6 t/ha/yr, which is a reduction of 20.44%. Similarly, with the applications of terracing (scenario 2), strip cropping (scenario 3), and contouring (scenario 4), the average sediment yields were found to be 8.6, 6.04, and 6.1 t/ha with corresponding reductions of the sediment from the baseline scenario by 20.44, 44.12, and 43.6%, respectively. Thus, the critical subwatersheds are suggested to be better managed using strip cropping with a strip width of 1 m on agricultural lands for the control of sediments. Strip cropping is one of the biological SWC measures. As the biological measures are generally more economical than the structural measures, the use of strip cropping is also advantageous from the viewpoint of cost.

4. CONCLUSION

The SWAT model has gained widespread acceptance in recent years as a tool for analyzing sediment production in river basins and watersheds. The model has been applied in numerous studies to evaluate sediment yield in various contexts. Modeling using SWAT is significant because it offers an in-depth understanding of the effects of water erosion on agricultural land and water resources. This study was conducted to simulate the sediment yield and develop BMPs in the Azuari watershed, Upper Blue Nile basin, Ethiopia using the SWAT model. The necessary hydrological and metrological data for model inputs were collected from MoWE. As the sediment data was in concentrated form, the sediment yield was derived from measured stream flow using a rating curve. The performance of the SWAT model for sediment simulation was checked by the R^2, NSE and RSR. The study area was delineated into 19 subwatersheds and the sediment yield was estimated in each subwatershed using the MUSLE in ArcSWAT. The model parameters for sediment were calibrated using sediment load data from 1988 to 2005 and were validated using data from 2006 to 2012. The model performed well for monthly sediment yield with R^2, NSE, and RSR values of 0.65, 0.64, and 0.6 during calibration and 0.58, 0.58, and 0.65 during validation, respectively. The sediment yield in the subwatersheds was found to vary from 0.72 to 36.56 t/ha/yr with an average sediment yield of the watershed of 10.81 t/ha/yr. The sediment yields in the 13 subwatersheds were found lower than the acceptable soil loss rate, whereas six subwatersheds which are coded as SW-1, SW-2, SW-4, SW-5, SW-6, and SW-7 were identified as critical or hotspot areas as they exhibited high to severe soil erosion. Four soil and conservation measures were evaluated in SWAT as BMPs to control sediment in the identified hotspot areas, namely filter strip, terracing, strip cropping, and contouring. The effect of applying these BMPs was checked against the baseline scenario. It was found that filter strip reduces sediment up to 35.61%, terracing up to 20.44%, strip cropping up to 44.12%, and contouring up to 43.6% from the baseline. Thus, the critical subwatersheds are advised to be managed using strip cropping for effective control of sediments in the area. Overall, using the SWAT model to examine sediment yield offers useful insights into how different land use and soil management methods affect the health of ecosystems and water quality. The findings of this study will also help to make well-informed decisions for developing the best watershed management strategies.

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DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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