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Estimation of Sediment Yield and Evaluation of Management Options in the Watershed Using SWAT Model

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ABSTRACT: Land degradation and sedimentation are global issues stemming from inappropriate land management practices within watersheds, primarily due to soil erosion. The primary aim of this investigation was to estimate sediment yield, pinpoint erosion-prone areas, and determine effective strategies for reducing erosion and sediment yield within the Mormora watershed utilizing the SWAT model. The performance of the SWAT model was assessed through calibration and validation procedures employing the Sequential Uncertainty Fitting 2 (SUFI-2) algorithm within the SWAT Calibration and Uncertainty Procedures (SWAT-CUP). Calibration was conducted for the period 1993 to 2006, while validation was carried out for 2007 to 2013, focusing on streamflow and sediment yields at gauging station. Various metrics including R^2, NSE, RSR, and PBIAS were used to assess model performance. All model performance metrics indicated high accuracy. The average annual sediment yield at the outlet of the watershed was 1.19 million t/year with a spatial average of 8.54 t/ha/year. About 47.33% of the watershed was critical areas demanding implementation of soil conservation strategy. The effectiveness of five watershed management scenarios was compared to existing baseline conditions for their effectiveness in sediment yield reduction. The results indicate soil erosion decreased by 28.3% to 55.9% by applying filter strips, 61.7% to 68.4% by grassed waterways, 71.38% by terracing, 62.64% by contouring, and 46.3% by applying stone/soil bunds. Ultimately, terracing emerged as the most effective strategy for mitigating soil erosion within the study area. Consequently, the research outcomes and the developed methodology serve as a valuable resource for decision-makers, experts, and researchers involved in sustainable watershed management.

KEYWORDS: Erosion-prone areas, sedimentation, soil bund, terracing, soil erosion, watershed management

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Introduction

Soil erosion is a major environmental and economic concern on the globe (Borrelli et al., 2020) that is broadly recognized as a main ecological problem with severe monetary costs (Kopittke et al., 2019). Soil erosion and other factors caused irreversible degradation of 10 million ha of fertile land annually (Rhodes, 2014). The loss of fertile land poses a significant threat to food security by reducing yield and increasing agricultural inputs (Hossain et al., 2020; Tessema et al., 2020). The soil loss in turn causes sedimentation of the reservoir and it has also been a global challenge in reducing the capacity of the reservoir (Mulu & Dwarakish, 2015). Furthermore, in developing countries like Ethiopia overgrazing, deforestation, and agricultural practices on marginal lands and steep slopes are harming the environment and reducing agricultural productivity due to rising population pressure, increased reliance on natural resources, and inadequate land-use planning (Wassie, 2020).

Global studies show that the annual soil erosion was high (30–40 t/ha/year) in Africa, Asia, and South America (Hurni et al., 2008; Mullan et al., 2012), 10 and 20 t/ha/year in Europe (USDA 2000), and 10.8 t/ha/year in the USA (Pimentel & Burgess, 2013). The rugged topography and naturally steep slopes, improper land use management, agricultural practices, and lack of appropriate soil conservation measures facilitate soil erosion in Ethiopia's watersheds (Mhazo et al., 2016; Tesema & Leta, 2020). A study conducted by Haregeweyn et al. (2017) found that the upper Blue Nile river basin in Ethiopia experiences an average soil loss rate of 27.5 t ha^{-1} $year^{-1}$ of which at least 10% is caused by gully erosion and 26.7% leaves Ethiopia. A recent investigation by Gashaw et al. (2019) revealed that spatial soil erosion reached 55.47 t/ha/year in northern Ethiopia. The annual topsoil loss was over 1.5 billion t at the highlands of Ethiopia leading to reduced land productivity (Beyene et al., 2023). Therefore, topsoil removal necessitates urgent soil conservation interventions and management. Alongside soil erosion in the watershed, consideration of sediment load in a watercourse is crucial for addressing engineering challenges on rivers (Kasm et al., 2010).

Limited research has shown the impacts of soil management mechanisms on erosion and sedimentation reduction in the highlands of Ethiopia (dos Santos et al., 2024; Gashaw et al., 2021; Mrad et al., 2024; Sarkar et al., 2024; Zewde et al., 2024). Abebe and Gebremariam (2019) used SWAT coupled with ArcGIS to predict the spatial distribution of runoff and sediment yield in the Awash River basin of the Kesem dam watershed, in the central highlands of Ethiopia. Due to a scarcity of sediment data in Ethiopian watersheds, several studies use a single sediment rating curve for model calibration and validation, potentially introducing uncertainty in predictions (Ayele et al., 2017; Abebe et al., 2022; Jilo et al., 2019; Tadesse & Dai, 2019).

The Mormora watershed within the Genale-Dawa River basin plays a complex role in erosion, transport, and deposition processes from upstream catchments to intermediate storages (Kefay et al., 2022; Ministry of Water Resources, 2007). The unprotected Mormora watershed faces vulnerability to soil erosion due to activities like gold mining and agriculture on steep slopes. Sedimentation in the lower watershed has led to clogged stream channels, increasing bank erosion, meandering, and flooding risk. In the upper Mormora watershed, erosion and sediment transport present substantial challenges for planning and implementing national development projects in the region. Hence, it is imperative to research sediment load, pinpoint critical sediment origins, and select and implement the best soil conservation strategies. The efficacy of the management practices is contingent upon their unique design parameters, prompting the application of diverse dimension scales not previously explored in other investigations. The challenges of this study where lack of sufficient and continuous metrological and hydrological data records. This might cause a serious problem for the application of the data in model simulation.

This study aimed to estimate runoff and sediment yield, identify erosion-prone areas, and select appropriate management measures for erosion and sediment yield reduction in the Mormora watershed, Ethiopia using the SWAT model. The SWAT replicates natural hydrological processes encompassing phenomena like stream flow, evaporation, evapotranspiration, groundwater replenishment, soil saturation, sediment conveyance, chemical migration, and microbial proliferation in aquatic environments (Devia et al., 2015). By deploying specific interventions, there is a likelihood of amplifying vegetation coverage, enhancing soil quality, and augmenting agricultural output in the watershed zones, thereby safeguarding the sustainability of forthcoming water resource initiatives including water diversion infrastructures and reservoirs. Essentially, the study outcomes can inform judicious decision-making and furnish foundational data for future research endeavors within the study area, with the established research methodology and protocols ready for adoption by scholars and development practitioners globally.

Materials and Methods

Descriptions of the study area

The Mormora watershed (Figure 1) situated at coordinates 5°41′N and 38°48′E, at the upper part of the Dawa sub-basin, at 1,439 to 3,078 m elevation, encompasses 1,395 km^2 area. The gauging stations designated for monitoring this particular watershed are positioned in the Guji Zone, Oromia National Regional State, near Megado Town. The Mormora watershed is steep and mountainous in the upper part, and plane with a narrow river shape in the lower part. Detailed records of precipitation and temperature in the study region have been documented spanning from 1990 to 2019. The rainfall pattern

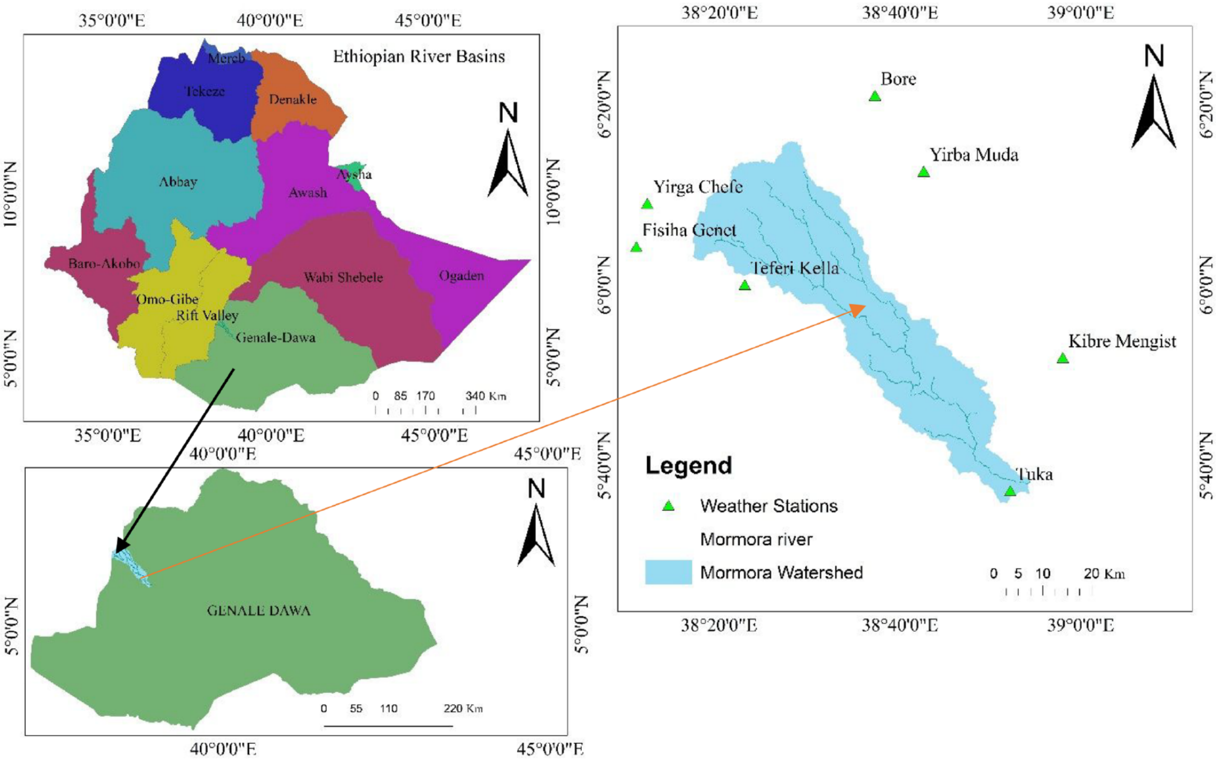

Figure 1. Map of Mormora watershed.

follows a bimodal distribution, with rainy spells occurring from April to May and September to October as reported by MoWR in 2007. The average annual rainfall varies between 1,051.9 and 1,782.28 mm, while the mean temperature ranges from 16.1°C to 18.3°C within the watershed. There is a topographic difference of about 1,639 m between the downstream part and the highlands of the study area. The upper part of the Mormora basin are steep and mountainous, while the lower basin is flat with a narrow river shape. The Elevation of the watershed shown as (Figure 2) below.

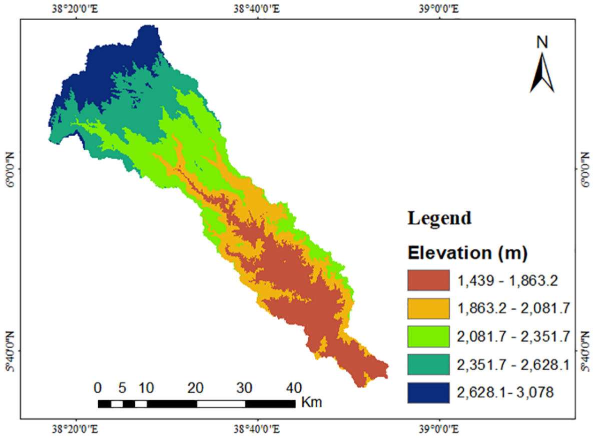

Figure 2. Elevation map of Mormora watershed.

Data used

In this study, various temporal and spatial data types were used to estimate sediment yield, identify erosion-prone areas, and propose the best watershed management options using the SWAT model. DEM, LULC, and soil attributes were spatial data employed as input for the SWAT model. A DEM serves as a fundamental tool for delineating watershed boundaries, analyzing drainage networks, generating slope profiles, and stream delineations, and identifying hydrological response units (HRUs). The DEM dataset was sourced from the ALOS-PALSAR platform accessed through ASF.alaska.edu on June 26, 2021, and resampled to a resolution of 12.5 m × 12.5 m. The slope of the watershed catchment derives from DEM. In addition to land use and soil map, parameter slope is also used to develop a Hydrological response unit in the model. Arc SWAT allows for slope class when defining a hydrological response unit. There is the possibility of choosing just a single slope class or multiple slope classes. According to Dile et al. (2016), the slope map was classified into three types by choosing multiple slope classes that were used for management practices. The slope of the study area was classified as 0% to 5%, 5% to 15%, and >15% as shown in Figure 3.

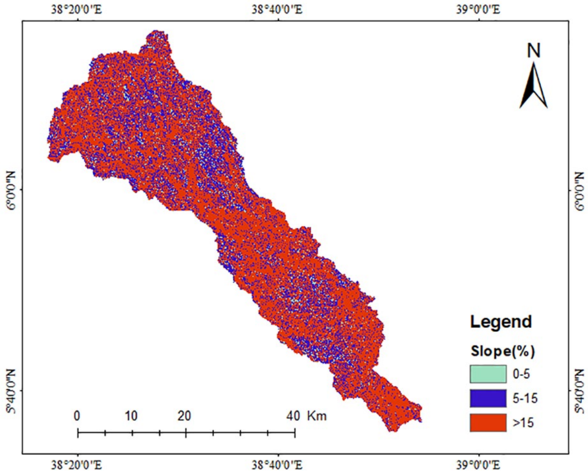

Figure 3. Slope map of the study area.

The type of land use/land cover of Mormora watershed was determined from Landsat images (Landsat 8 OLI/TIRS 2012 sensor) with a 30 m × 30 m spatial resolution downloaded from the USGS Earth Explorer website (https://earthexplorer.usgs.gov/). A supervised LULC classification technique was implemented utilizing approximately 400 ground truth points defined by the image data using ERDAS software. ERDAS software integrated with GIS has been widely used in LULC and has produced more realistic outputs (Biazin & Sterk, 2013; Dibaba et al., 2020; Hailu et al., 2020). The LULC classification accuracy was assessed using metrics such as the Kappa coefficient, producer, and overall accuracy. The study area is classified into six LULC classes using Google Earth and ERDAS IMAGINE 2015 as shown in Figure 4. As shown on this figure, area coverage of shrub land was 43.9%, agricultural land 39.4%, grassland 6.8%, forest land 4.8%, settlement 3%, and water body 2.1%. The accuracy assessment calculated by field verification and Google Earth using a field survey for land use/cover type is shown in Table 1. The Kappa coefficient, producer's accuracy, and overall accuracy showed that the LULC classification from the Landsat image using ERDAS was acceptable.

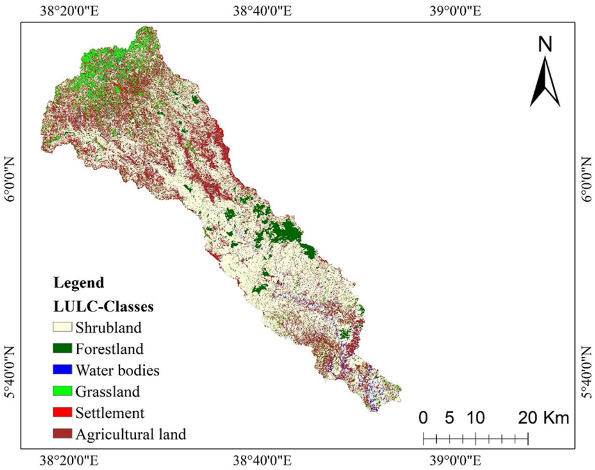

Figure 4. Land use land cover map.

Table 1. Accuracy Assessment of Land Use Land Cover Classification.

CLASS NAME	WATER BODIES	FOREST	SHRUB LAND	GRASS LAND	SETTLEMENT	AGRICULTURAL LAND	TOTAL	USER'S ACCURACY (%)
Water bodies	47	0	0	0	0	0	47	100
Forest land	0	38	1	0	0	0	39	97.43
Shrub land	1	2	61	1	0	2	67	91.04
Grass land	0	1	0	49	0	0	50	98
Settlement	2	0	1	0	49	1	53	92.45
Agricultural land	1	0	1	4	0	138	144	95.83
Total	51	41	64	54	49	141	400	
Producer's accuracy (%)	92.15	92.68	95.31	90.74	100	97.87		
Overall classification accuracy = 95.5%								
Overall κ statistics = .94								

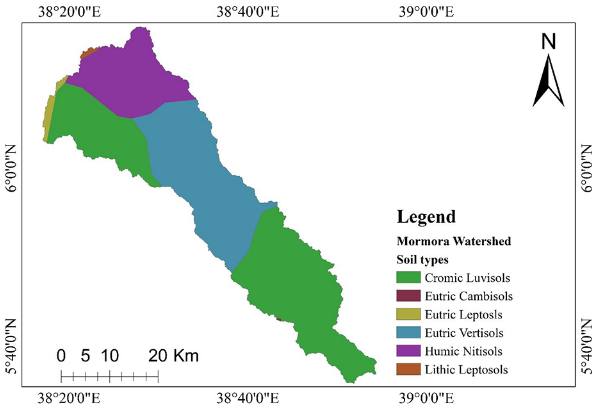

Figure 5. Soil map.

The spatial distribution of soil types sourced from the Ministry of Water Irrigation and Electricity (MoWIE; 2021) was utilized to generate the soil map for Mormora Watershed (Figure 5) and incorporated into the SWAT model for HRU delineation. The Mormora watershed exhibits a composition of six major soil groups, with Chromic Luvisols representing the predominant soil type covering 47.78% of the total area. Eutric Vertisols represent the second most prevalent soil group covering 32.06% of the overall area. Additionally, 20.16% of the total area was covered by Lithic Leptosols, Eutric Cambisols, Humic Nitisols, and Eutric Leptosols.

The meteorological datasets from different stations (Kibre Mengist, Teferekella, Yirba Muda, Bore, Fiseha Genet, Yirga Chefe, and Tuka) were acquired from the National Meteorological Service Agency (NMSA) of Ethiopia. All station data were examined by different tests to check their consistency, quality, homogeneity, and outliers. The double mass curve was used to check data consistency and the Pettit test for homogeneity. Among all stations, Kibre Mengist with comprehensive daily meteorological data emerged as a pivotal station, thus utilized as a weather generator to fill missing data at other stations. Flow and sediment data were acquired from MoWIE.

Rainfall directly influences stream flow in the short term. When rainfall occurs, water flows into streams and rivers, increasing their discharge. In regions with distinct wet and dry seasons like in Ethiopia, stream flows are typically higher during and immediately after periods of heavy rainfall. Similarly, rainfall impacts erosion processes by dislodging soil particles and transporting them overland as runoff. This eroded sediment is then carried by streams and rivers during periods of high flow. Therefore, rainfall, stream flow and, sediment have directly proportional relationships.

Hence, the sediment rating curve (Figure 6), developed using mathematical curve fitting methods as described in equation1(Morris & Fan, 1998), was utilized to generate sediment load from stream flow data due to non-continuous measured sediment concentration data.

$$S = 0.0846 \times Q \times C \qquad (1)$$

Where S is sediment load (t/day), Q is stream flow (m^3/s), C is sediment concentration (mg/L), and 0.0864 is the conversion factor.

SWAT model

The current investigation utilized the SWAT model to predict sediment yield and pinpoint critical sediment source areas along with effective management strategies. SWAT-based hydrological models aid watershed managers in setting baseline rates of hydrologic processes, crucial for predicting future hydrologic regime shifts due to land-use alteration and climate change (Al-Hussein et al., 2024; Mapes & Pricope, 2020). SWAT model is instrumental in the classification of LULC, estimation of sediment load, evaluation of effective

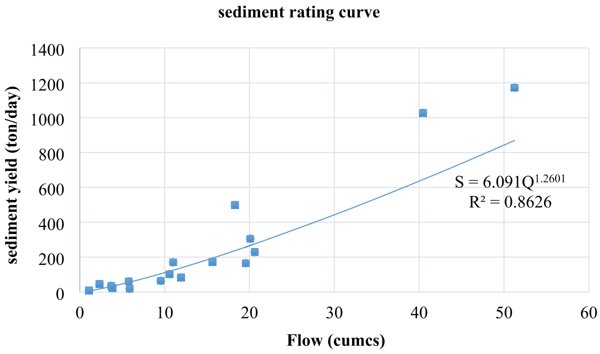

Figure 6. Sediment rating curve of the Mormora river basin at gauge station.

management scenarios, and agrochemical outputs in watersheds (Betrie et al., 2011). The inputs to this model include stream flow observations, sediment deposition measurements, LULC, DEM, soil characteristics, and meteorological data such as rainfall, temperature, wind speed, air humidity, and solar ratio.

Model setup. The watershed delineation method incorporates: DEM setup, stream definition, outlet and inlet definition, watershed outlet choice and definition, and calculation of subbasin parameters. After watershed delineation, the watershed was partitioned into hydrologic response units (HRU), which are unique occurrences of soil type, land cover, and slope class combinations within the watershed to be modeled. HRUs are used in most SWAT runs since they lighten a run by lumping all similar soil and land use areas into a single response unit. It is necessary to prepare a look-up table that refers to land use land cover classes that are found in SWAT land use land cover codes, compatible for the loading of the land use land cover of the study area. The soil layer on the map was linked to the SWAT user soil database information by loading the soil look-up table. In addition to land use and soils, a division of HRUs by slope classes was also carried out. Most of the time, when considering different slope classes for HRU definition, a multiple slope option is preferable. Once reclassifying the land use, soil, and slope in the SWAT database, all these physical properties were made to be overlaid for the HRU definition. Most modeling applications require a 20% land use threshold, 10% soil threshold, and 10% slope threshold (Neitsch et al., 2011). Below these thresholds, minor land use, soil, and slope classes within a sub-basin were dominated by the neighboring, relatively larger physical characteristics during HRU definition. For this specific study, a 5% threshold value for land use, 10% for soil, and 10% for slope were used to define the parameters by assigning multiple HRU thresholds. Finally, the Mormora watershed was created with 225 HRU. To estimate surface runoff, USDA Soil Conservation Service (1972) methodology was employed. Potential evapotranspiration was estimated using the Penman-Monteith method, stream flow in channels was simulated using variable storage routing, and sediment yield in sub-watersheds and HRUs was determined using a modified universal soil loss equation(MUSLE).

Analysis of sensitivity, calibration, and validation. Sensitivity analysis is crucial for determining the significance of each parameter on its performance. Sensitive parameters in the SWAT model are used to minimize the difference between observed data and simulated outcomes. The analysis utilized global sensitivity analysis to determine the relative significance of each parameter and objective function sensitivity using the *t*-test. The global sensitivity analysis calculates parameter sensitivities by regressing the Latin hypercube-generated parameters against the objective function values using multiple regression systems. SUFI-2 measures sensitive parameters using *t*-stat values, with larger absolute values being more sensitive. *p*-Values determine sensitivity significance, with close to zero values indicating significance. The calibration and validation of the SWAT model were carried out using the SUFI-2 technique, an extension of SWAT-CUP (Abbaspour, 2014), which accounts for uncertainties from all sources (Yang et al., 2008). The SUFI-2 algorithm offers advantages over manual calibration, expert judgment, and extensive knowledge in SWAT due to its highly parameterized description of physical processes (Eckhardt et al., 2005). The study by Mehan et al. (2017) highlights the capabilities of SWAT, including sensitivity, uncertainty, calibration, and validation. Rafiei Emam et al. (2018) and Shivhare et al. (2018) found that the SUFI-2's simple algorithm offers more accurate simulation than other algorithms. Zhou et al. (2014) found that the SUFI-2 algorithm, a semi-automated method that allows users to interact iteratively, outperformed the auto-calibration method. The calibration phase spanned fourteen years (1993–2006) excluding the warm-up period (1990–1992). The validation phase spanned 7 years of data (2007–2013) without adjusting the calibrated parameters further. Nineteen flow parameters and 12 sediment parameters were selected for sensitivity analysis. For model calibration and validation purposes, only 14 flow parameters and 9 sediment parameters were used. Performance indices: RSR, PBIAS, R^2, and ENS were used to examine the performance of SWAT model according to Moraisi et al. (2007) rating. The SUFI-2 program assesses uncertainty through the *p*-factor and *R*-factor.

Best management practices scenarios

Based on community-based Participatory Watershed Development Guidelines of Ethiopia (Desta et al., 2005), best management practices (BMPs) were selected due to their practical implementation and local research familiarity in specific Ethiopian watersheds (Ayele & Gebremariam, 2020). Five BMP scenarios including filter strips of various widths, grassed stream widths, contouring, terraces, and stone/soil bunds were

Table 2. Descriptions of BMPs and the Changes in Parameters Within the SWAT Database.

SCENARIOS	DESCRIPTION	ADJUSTED PARAMETER		VALUE
		PARAMETER	CALIBRATED	MODIFIED
Baseline	Current situation	*	*	*
Filter strips	1 m wide grass installed at the edge	FILTERW	0 (m)	1 (m)
Grassed		GWATN	a	0.1
Waterway (GW)	Water channel	GWATW	a	2.5
		GWATD	a	0.3
		GWATSPCON	a	0.005
		GWATL	a	b
		GWATS	a	HRU_SLP*0.75
Contouring	Ridges constructed on contours	CN2	*	
		USLE_P	0.7	slope (13%–16%
Terraces	Embankments and channels on contours	CN2	*	–6*
		USLE_P	0.14	(13%_16%)
		SLSUBBSN	*	–50*
Stone/soil bund	Stone/Soil or stone faced structures	CN2.mgt	*	–3*
		USLE_P	0.32	Slope > 8%.
		SLSUBBSN	*	–50*

Note. "*" indicate the representation of flow calibrated and sediment values; "a" the SWAT given values; "b" indicated the length of GWs based on HRUs lengths.

chosen for evaluation. These scenarios are suitable for the agro ecological setting and utilize locally available resources. The baseline scenario, without any BMPs, represents the initial condition before scenario simulations were conducted. Filter strips of 1, 5, and 10 m width were selected based on research experience in Ethiopian watersheds (Arabi et al., 2008; Ayele & Gebremariam, 2020).

This particular scenario is employed to replicate conservation methods for all Hydrological Response Units (HRUs) within chosen sub-watersheds of the watershed. A variety of filter widths were allocated to imitate the effects of filter strips on sediment retention. Particularly, grassed Waterways where increased roughness reduces both maximum flow rate and velocity of flow in the channel serve as the third BMP. The configurations of grassed waterways are set and adjusted with an average depth of 0.3 m, active GWAT, reduction in channel slope (HRU slope × 0.75), GWATSPCON of 0.005, and a recommended roughness coefficient of 0.1 as suggested by Sang and Maina (2018) and Waidler et al. (2011). Moreover, the average width of the grass waterways of 5, 10, 15, and 20 ms were used while keeping other parameters constant, to evaluate the increase in width on sediment reduction.

Contour farming was the fourth watershed management strategy that reduced soil erosion caused by surface runoff by providing opportunities for infiltration through water impoundment in small depressions. In this method, parameters like the initial curve number II and USLE_P values are adjusted from calibrated values. For this research, the initial curve number II is decreased by three units from its calibration value as utilized in Dibaba et al. (2021). Terracing is the fifth BMP scenario where horizontal ridges are constructed on a hillside with channels and embankments to direct runoff safely and control overland flow. Modifications to USLE_P, SLSUBBSN, and CN_II can be made based on cover type, hydrological conditions, and hydrological soil groups to reflect this conservation practice in the SWAT model (Arnold et al., 2012). The SCS curve number was rearranged by decreasing the CN_II at the treated sub-watershed by 6 units, and the USLE practice (TERR_P) is set at a *p*-factor of 0.14 to represent terracing practice as suggested by Sang and Maina (2018). A reduction of 50% in slope length (TERR_SL) as suggested by Arnold et al. (2012) was put forth.

The sixth scenario used was the stone bund. The effect of soil bund in reducing runoff and erosion was simulated using CN2, SLSUBBSN, and USLE_P parameters as recommended by Betrie et al. (2011). Accordingly, CN2 was decreased by 3 units from the calibrated value, SLSUBBSN was decreased by 50% and USLE_P was reduced to 0.32 from the calibrated values for slope classes greater than 8% as shown in Table 2.

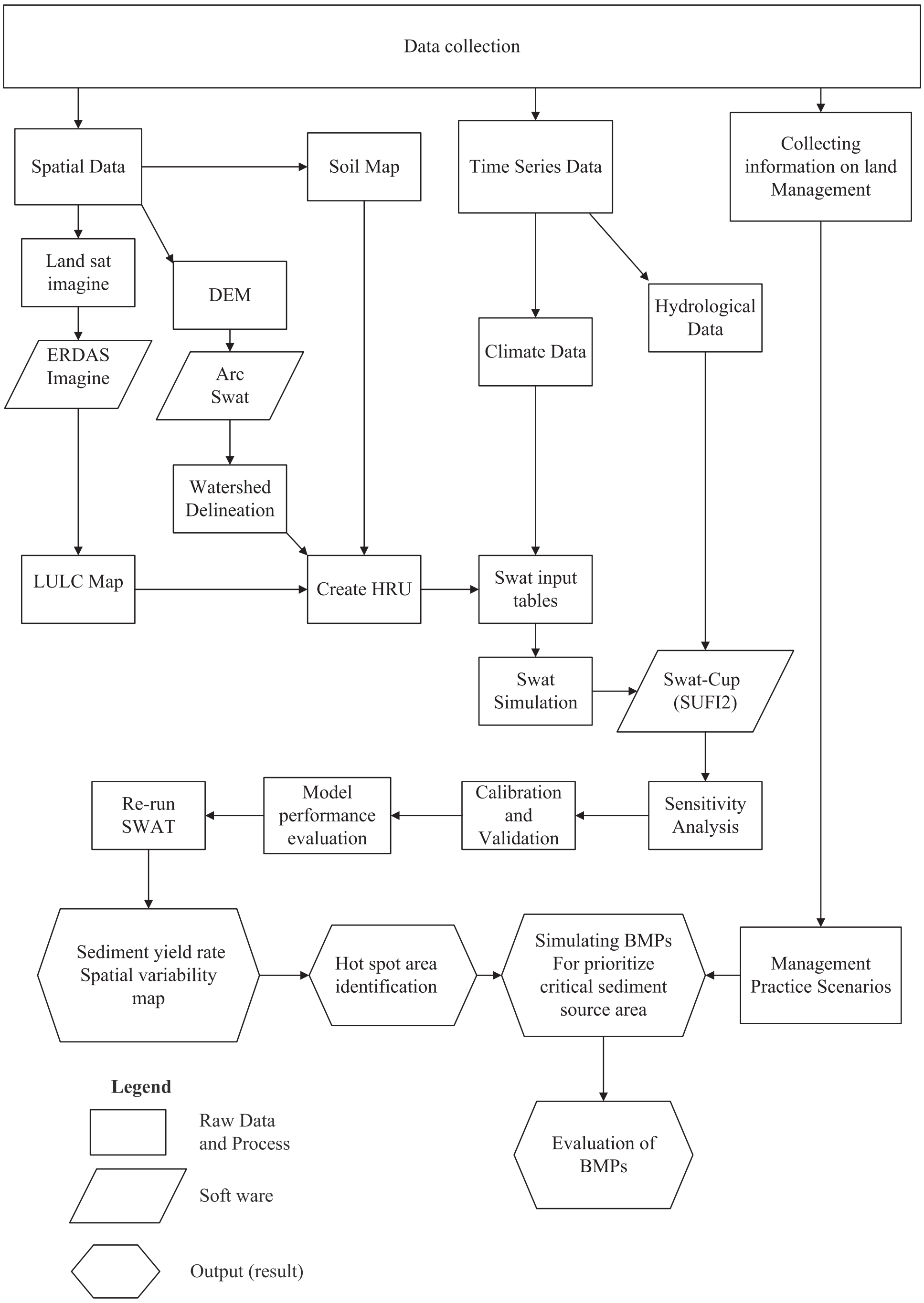

Figure 7. Overall framework of the methodology.

Overall methodological framework

Figure 7 displays the study's overall methodological framework. The following components are part of the study's overall methodological framework such as retrieving Landsat images, processing, and analyzing different special and temporal datasets used for input for the SWAT model. Sensitivity analysis, calibration, and validation of the model and proposing best watershed management options are parts of the methodological frameworks. The work utilized remote sensing, GIS tools, applications, and hydrological models using SWAT and other measuring techniques.

Results and Discussion

Analysis of sensitive parameters for flow and sediment

The study examined the performance of each sensitive parameter for the simulation of flow and sediment load. Parameters that had large values of *t* stat and *p*-value close to zero were chosen as sensitive parameters for stream flow simulation (Table 3). From all the chosen parameters CN2, ESCO, HRU_SLP, RCHRG, GWQMN, ALPHA_BF, and GW_REVAP were highly sensitive. Similarly, SOL_K, CANMX, GW_DELAY, SOL_Z, REVAPMN, SLSUBBSN, and CH_N2

Table 3. Sensitive stream flow parameters, their range, calibrated, and Fitted Values.

PARAMETER NAME	DESCRIPTION OF PARAMETERS	RANGE VALUE	CALIBRATION RANGE	CALIBRATED VALUE
r__CN2.mgt	SCS runoff curve number	35–98	±25%	0.08%
v__ESCO.hru	Soil evaporation compensation factor	0–1	0–1	0.46
v__HRU_SLP.hru	Average slop steepness	0–1	0–1	0.30
v__RCHRG_DP.gw	Deep aquifer percolation fraction	0–1	0–1	0.16
v__GWQMN.gw	Threshold depth of water in the shallow aquifer for return flow to occur	0–5,000	0–5,000	3450.9
v__ALPHA_BF.gw	Base flow alpha factor	0–1	0–1	0.73
v__GW_REVAP.gw	Groundwater revap coefficient	0.02–0.20	0.02–0.20	0.074
r__SOL_K().sol	Saturated hydraulic conductivity	0–2,000	±25%	−0.17%
v__CANMX.hru	Maximum canopy storage	0–100	0–100	33.1
v__GW_DELAY.gw	Groundwater delay	0–500	0–500	198
r__SOL_Z().sol	Soil depth (for each layer)	0–3,500	±25%	0.079
v__REVAPMN.gw	Threshold depth of water in the shallow aquifer for revap to occur	0–500	0–500	109
r__SLSUBBSN.hru	Average slope length	0–500	±25%	0.12
v__CH_N2.rte	Manning's "n" value for the main channel	−0.01–03	−0.01–0.3	0.075

were moderately sensitive as shown below in Table 3. CH-N2 was the most sensitive parameter for flow simulation.

From those parameters, the first five parameters: USLE_P, USLE, USLE_K, USLE_C, ADJ_PKR, and LAT_SED were highly sensitive, whereas CH_COV2, CH_COV1, CH_D, and PCO were medium sensitive parameters for sediment simulation as shown in Table 4.

Stream flow calibration and validation

To calibrate and validate the SWAT Model, 23 years of stream flow data (1990–2013) were utilized and its result is shown in Figure 8. The comparison between observed and simulated values indicated favorable agreement for both the calibration and validation phases.

Calibration and validation of sediment yield

The calibration process for sediment yield simulation followed stream flow calibration and validation. The data spanning 23 years (1990–2013) was employed in the SWAT model for calibration and validation. The monthly calibrated and validated model results at the watershed's outlet are shown in Figure 9. Notably, the observed and simulated values demonstrated substantial harmony. Nevertheless, the model exhibited slight overestimations and underestimations in simulating sediment yield during peak flow and low flow periods of certain months in the calibration and validation phases, respectively, attributable to uncertain model parameters. This discrepancy arose from SWAT's primary simulation of clay, silt, and fine sand fractions of the total load, neglecting the transport of coarse material. Consequently, the observed sediment yield solely represents the fine material fraction (<0.063 mm) passing through the measuring gauging station. As indicated in Figure 10, the rainfall, stream flow, and sediment yield have a positive relationship. As the rainfall increases the stream flow increases with corresponding increases of sediment yield. On the contrary as rain fall decreases the stream flow and sediment yield. The correlation of the rainfall and sediment yield was strong ($R^2 = .71$) as shown Figure 11. Similarly, the correlation of stream flow and sediment yield was strong ($R^2 = .97$) as shown in Figure 12.

Simulation of model performance and uncertainty

Before calibrating the model, its initial simulation performance was evaluated using default model parameter values. The model showed a very good performance rate in estimating stream flow, and sediment yield and assessing soil conservation practice. According to Moriasi et al. (2007), the model's performance of this case study aligns well with monthly stream flow simulation (Tables 5 and 6). p and R-factor were used to illustrate uncertainty assessment. The SUFI-2 uncertainty analysis of stream flow indicated that approximately 77% of observed

Table 4. Sediment Parameters, Their Range, as Well as the Calibrated and Fitted Values.

PARAMETER NAME	DESCRIPTION OF PARAMETERS	RANGE VALUE	CALIBRATION RANGE	CALIBRATED VALUE
v__USLE_P.mgt	USLE support practice factor	0–1	0–1	0.547
v__USLE_K().sol	USLE soil erodibility factor	0–0.2	0.0–0.1	0.023
v__USLE_C {. . .} . Plant.dat	USLE cover and management factor	0.001–0.5	0.001–0.5	0.0035
v__ADJ_PKR.bsn	Peak rate adjustment factor for sediment	0–2.0	0–2.0	0.5962
v__LAT_SED.hru	Sediment concentration in lateral flow and ground water flow	0–1,000	0–175	163.6
v__CH_COV2.rte	Channel cover factor	0.001–1	0.001–1	0.82
v__CH_COV1.rte	Channel erodibility factor	0.01–0.6	0.01–0.6	0.32
v_CH_D.rte	Average depth of main channel	0–30	0–30	19.4
r__SPCON.bsn	Linear re-entrainment parameter for channel sediment routing	0.0001–0.01	0.008–0.01	0.0095

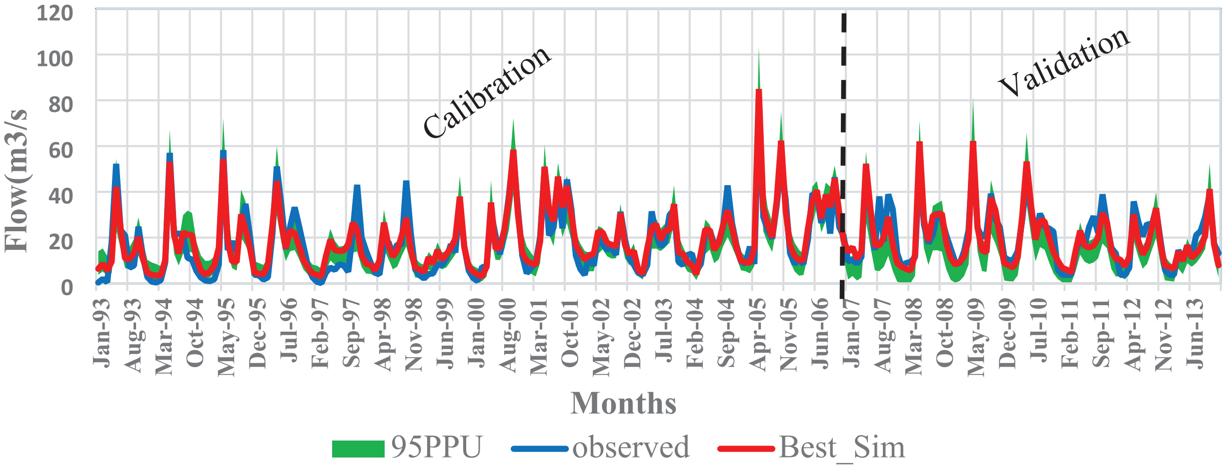

Figure 8. Calibrated and validated monthly flow results at Megado gauging station (1993–2013).

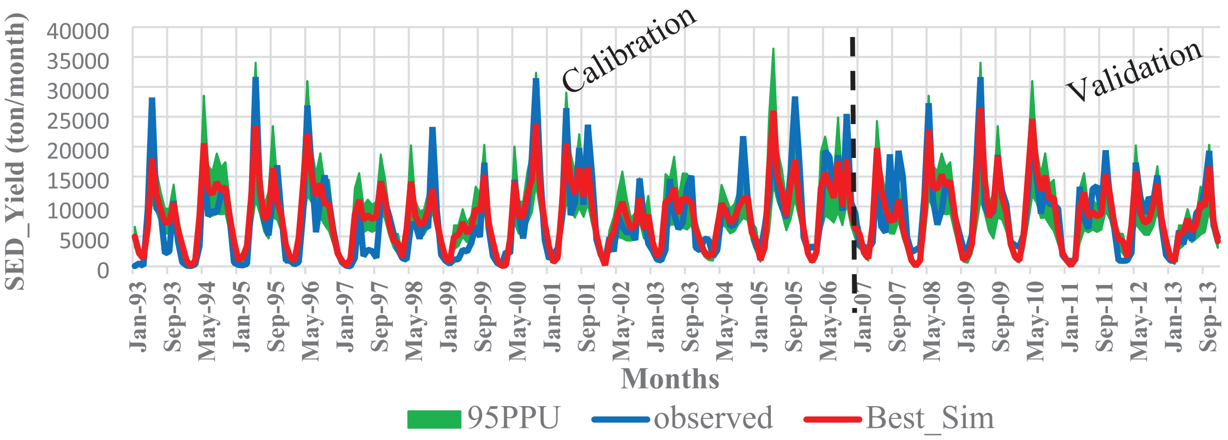

Figure 9. The calibrated and validated monthly sediment yield simulation at Megado station (1993–2013).

flow data during calibration and 67% during validation fell within the 95 PPU, demonstrating robust estimation capabilities (*R*-factor <1) for both scenarios (Table 5). Similarly, the uncertainty metric of SUFI-2 indicates that 56% and 65% of monthly sediment yield data from the station were encompassed by the 95 PPU for calibration and validation, respectively, demonstrating robustness in estimation (*R*-factor <1; Table 6). However, model performance is better in simulating flow than sediment. This phenomenon arises due to the intricate array of factors influencing sediment dynamics, impeding a comprehensive representation within the model.

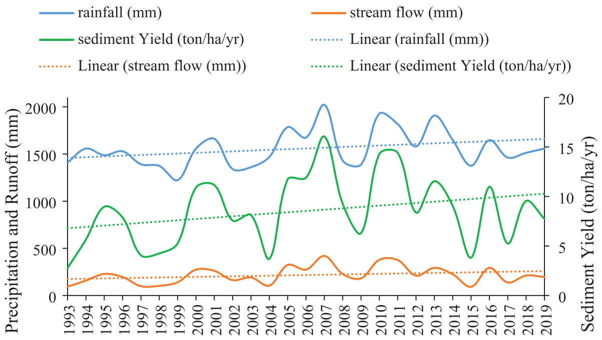

Figure 10. Rainfall, stream flow, sediment yield, and the corresponding trend lines for the entire simulation period.

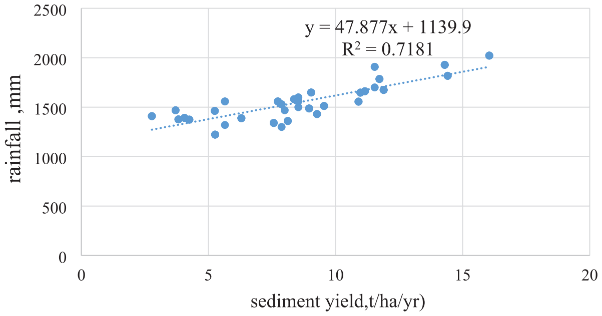

Figure 11. Correlation between rainfall and sediment yield.

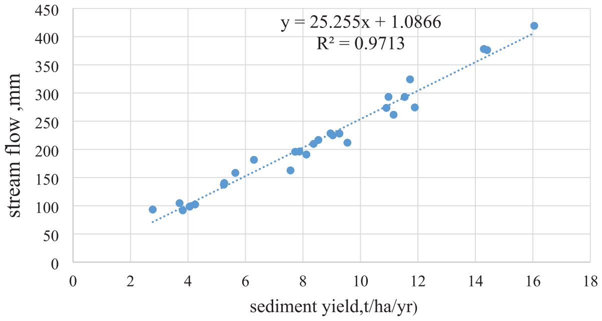

Figure 12. Correlation between stream flow and sediment yield.

Sediment yield reduction scenarios

The designated management strategies (filter strip, grassed waterway, contouring, terracing, and stone/soil bunds) were compared with baseline scenarios to evaluate their mitigation potential in reducing sediment yield using the SWAT model. Based on the model simulation, a mean annual sediment yield of 8.54 t/ha/year was estimated at the baseline scenario. This is in agreement with a sediment yield of 2.45 to 12.82 t/ha/year (average of 8.2 t/ha/year) in the Hamesa watershed, Ethiopia (Damte Darota et al., 2024). Implementation of filter strips with a width of 1, 5, and 10 m reduced the sediment yield from the critical source area by an average of 36.65%, 59.2%, and 72.17% respectively. Depending on this finding, it can be concluded that the average annual sediment yield was reduced as the filter strip width increased. Nevertheless, it was noted that augmenting the filter width twofold or threefold does not result in a proportional increase in reduction capacity. This is in alignment with a study by Arabiet al. (2008). Studies conducted by Arabi et al. (2008) found that the application of 1, 5, and 10 m filter strips reduced sediment yield by 28.23%, 45.58%, and 55.9% respectively. The study conducted by Demissie et al. (2013) at Gilgel Gibe One Dam, Ethiopia applied 1 m filter strips for critically affected sub-watersheds. This research reveals that 35% of sediment yield in critical sub-watersheds has been diminished relative to the mean annual sediment load at the baseline scenario. According to the study by Tesema and Leta (2020), the implementation of 5 m filter strips in highly affected sub-basins led to a 59.16% reduction in sediment yields compared to the baseline scenario. Similarly, Tenaw and Awlachew (2008) illustrated a 74.4% reduction in annual sediment yield with the implementation of 10 m filter strips. According to a study conducted by Bibi and Adem (2023) in the upper Gilo watershed, Ethiopia revealed that the application of filter strips reduced the watershed sediment yield by 53.2%.

Table 5. Model Performance and Uncertainty Measures for Stream Flow.

SIMULATION (MONTHS)	STATION	UNCERTAINTY MEASURES		MODEL PERFORMANCE INDICATORS			
		P-FACTOR	*R*-FACTOR	R^2	NSE	RSR	PBIAS
Calibration (1993_2006)	Megado	0.77	0.88	.86	0.86	0.38	−5.9
Validation (2007_2013	Megado	0.67	0.79	.82	0.79	0.46	6.6

Table 6. Model Performance and Uncertainty Measures for Sediment Load.

SIMULATION (MONTHS)	STATION	UNCERTAINTY MEASURES		MODEL PERFORMANCE INDICATORS			
		P-FACTOR	*R*-FACTOR	R^2	NSE	RSR	PBIAS
Calibration (1993–2006)	Megado	0.56	0.73	.75	0.74	0.51	–7.6
Validation (2007–2013	Megado	0.65	0.74	.76	0.75	0.50	3.1

The efficacy of grassed waterways in sediment reduction is attributed to their capacity to entrap silt emanating from eroded fields and curtail channel erosion progression. Therefore, in this study, grassed waterways were installed at the most eroded sub-watersheds. Implementation of 5, 10, 15, and 20 m grassed waterways reduced the sediment yield from the baseline conditions by 61.7%, 65.9%, 67.55% and 68.54%, respectively. It was observed that when increasing the width of a grass waterway, there was an increase in sediment reduction from the baseline conditions, but doubling the width of a grass waterway did not proportionally reduce the mean annual sediment yield. A similar study conducted by Ayele and Gebremariam (2020) in the Bilate watershed in Ethiopia revealed that the application of a 30 m grassed waterway reduces sediment yield to 68.04%. Manawko (2017) discovered that implementing a 30 m width grassed waterway reduces the treated sub-basins mean annual sediment yield rate by 76%. Gathagu et al. (2018) showed that the implementation of a 2.5 m width of grass waterway on the treated sub-watershed can minimize the mean sediment yield by 54%.

The initial annual sediment yield of 1.19 million t at the outlet of the watershed dwindled by 62.64% to 0.474 million t/year following the implementation of contour farming in critically affected regions. The mean sediment yield at the watershed notably dropped from 1.19 to 0.639 million t/ha/year, representing a 53.7% reduction. Among all management strategies, terracing emerged as the most effective measure in sediment yield reduction, as illustrated in Figure 13. Moreover, to a certain extent, this study's findings align with research by Ayele and Gebremariam (2020) in the Bilate watershed, Ethiopia where 71.38% sediment yield reduction was observed post-terracing. Similarly, the use of a terrace reduces sediment yield by 85% (Schmidt & Zemadin, 2013), 80.57% (Manawko, 2017) as compared to the baseline scenarios. The application of stone/soil bunds decreased the sediment load by 46.33% as compared to the base line scenario. Aysheshim (2015) also proved that stone/soil bunds reduce sediment load by 60.15% from the baseline scenario.

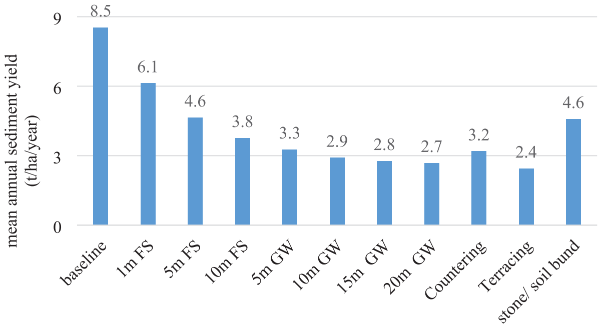

Figure 13. Average annual sediment yield at different BMPS.

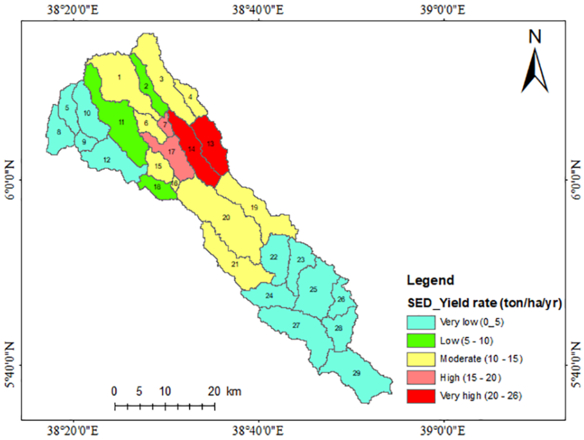

Figure 14. Spatial variability of sediment yield in the Mormora watershed.

Spatial variability of sediment yield at sub-watersheds (SW) and their proposed BMPs options

The developed spatial sediment yield map was used to identify the erosion-prone area for the implementation of soil conservation practices. The severity map of the Mormora watershed was categorized into five classes based on FAO (1988) classification. Sub-watersheds dominated by agricultural, grassland, and shrub lands mainly covered with Eutric Vertisols, Chromic Luvisols, and Humic Nitisols were key sources of annual sediment yield. Sub-watersheds with high sedimentation sources have a mean slope exceeding 5%. Ethiopian watersheds have demonstrated this, as the land's steeper slope and use for cultivation and urbanization have accelerated soil erosion and hydrological variations (Duressa et al., 2024; Tessema et al., 2020; Tola & Shetty, 2021). The sub-watershed erosion/sediment yield severity classes are shown in Figure 14. In this figure, SW-13 and SW-14 were very highly affected areas, and SW-7 and SW-17 were highly affected areas. Sub-watershed, 1, 3, 4, 6, 15, 16, 19, 20, and 21

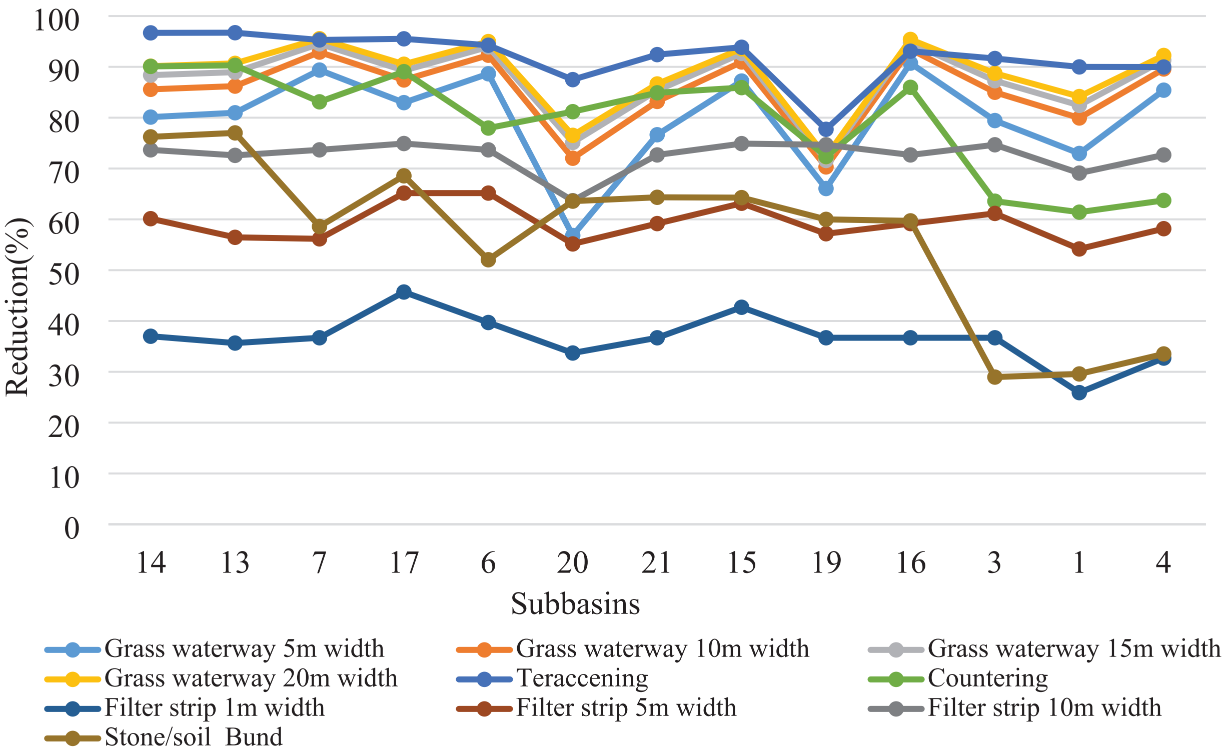

Figure 15. Evaluation of sub basins and percentage of reductions with selected BMPs.

were moderately affected areas. Sub watershed, 2, 11, and 18 were moderately erosion-prone areas and the remaining sub-watersheds 5, 8, 9, 10, 12, 22, 23, 24, 25, 26, 27, 28, and 29 were very low (negligible) erosion-prone areas.

The output of the model showed that sub-watersheds 7, 13, 14, and 17 were highly eroded areas (covering 10.88%) and contributed 15–23.47 t/ha/year of annual sediment yield from the whole watershed, which is relatively higher than the contribution of the other remaining sub-watersheds. Eight sub-watersheds of moderately eroded areas cover 36.45% of the watershed and are the sources of 10–15 t/ha/year sediment yield. The remaining sub-watersheds cover 55.17% of the whole area and are sources of 0–10 t/ha/year sediment yield. According to Ayele and Gebremariam (2020), the average annual sediment yield varies between 0 and 26 t/ha/year. From a study by Manawko (2017), a spatial average sediment yield of 7.23 t/ha/year was observed which is relatively similar to this study.

The implementation of a 5 m wide grass waterway had the least sediment reduction in SW-20 and SW-19, but there was a high sediment reduction in sub-watersheds of SW-6, SW-7, and SW-16 with a percentage reduction of 88.64%, 89.37%, and 90.73%, respectively (Figure 15). The percentage of mean annual sediment yield is highly reduced in sub-watersheds of 7, 6, 16, and 15 for applications of all grass waterway widths. However, Sub-watersheds 20, 19, 1, and 21 had the least sediment reduction when compared to the other sub-watersheds. But, when applying a 20 m width of grass waterway, the average sediment yield was highly reduced from sub-watersheds of 7, 16, 6, and 15 by 95.53%, 95.39%, 94.97%, and 93.56%, respectively. The effectiveness of filter strips showed a wider spatial variability at 1, 5, and 10 m widths of the filter strip. For example, it was observed that the least reduction for 1 m width filter strips was 25.19% (SW-1) followed by 32.7% (SW-4) and 33.7% (SW-20). On the other hand, the application of a 5 m width of filter strip shows high sediment reduction on SW-17 and 15. The sediment reduction from the average sediment rate for these sub-watersheds was 65.16% and 63.26%, respectively. There is also high sediment reduction of 74.92% and 74.675% respectively on these sub-watersheds when a 10 m width filter strip was applied (Figure 15). At SW-1, SW-4, SW-3, and SW-19, 10 m width filter strips were relatively more effective than stone bund and contouring.

Application of soil bunds was most efficient in decreasing the highly eroded sub-watersheds (SW-13 and SW-14) and also more effective in sediment reduction on these sub-watersheds than applying a 10 m width filter strip. Contouring was the most sediment-reducing practice at SW-14 and SW-13 by 90.09% and 90.26%, respectively as compared to filter strip and stone/soil bunds of 10 m and grass waterways of 15 m width at those sub-watersheds. Contouring has a relatively consistent reduction property than filter strips and stone/soil bunds (Figure 15). Terracing was an effective scenario to reduce erosion at critical sub-watersheds. As shown below in Figure 15, terracing was more effective than 10 m wide filter strip, 20 m width of grass waterway, countering, and stone/soil bunds on sub-watersheds of 14, 13,17, 21, 15, and 20, but have low sediment reduction at sub-watersheds of 7, 6, 16, and 4 when compared to 15 and 20 m width of grass waterway.

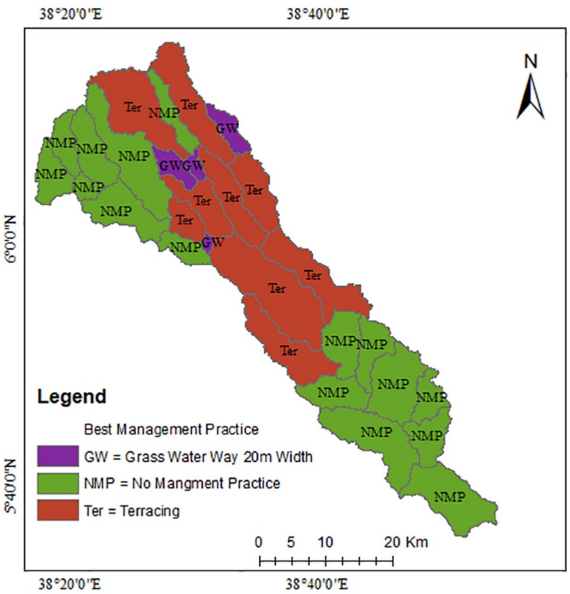

Figure 16. Spatial map of the best effective management practice in the Watershed.

Terracing was the most effective scenario in reducing sediment by 96.69%, 96.72%, 95.29%, 95.52%, and 94.25% for sub-watersheds of 14, 13, 7, and 17, respectively. The effectiveness of terracing varies between 77.71% and 96.69.4% spatially. Ayele and Ayalew (2024) have also identified that terracing as the most important watershed treatment approach among strip cropping, residue management, and contouring intervention techniques. The spatial distribution of the 20 m width of grass waterway and terracing is shown in Figure 16. The study indicated that terracing is the best soil conservation mechanism in the majority of sub-watersheds as compared to other management practices.

Conclusion

Soil erosion and sedimentation are primarily caused by improper land management techniques in the watershed and it eventually results in land degradation. This study attempted to investigate sediment yield, prioritize areas with severe sediment sources, and determine soil conservation mechanisms in the Mormora watershed. The SWAT model was examined to be very good at simulating stream flow and sediment load, as well as evaluating management mechanisms. Sequential Uncertainty Fittings (SUFI-2) which is an extension of SWAT_CUP was used for calibration and validation of stream flow and sediment yield.

The model performance was evaluated using the standard calibration and validation statistical performance efficiency indicators: the coefficient of determination (R^2), Nash-Satcliffe modeling efficiency (NSE) and Root Mean Square Error Standard Deviation Ratio (RSR) and Percent bias (PBIAS). The statistical results of the model calibration and validation displayed a very good performance with $R^2 = .86$, NSE = 0.86, RSR = 0.38, and PBIAS = –5.9%), and $R^2 = .82$, NSE = 0.79, RSR = 0.46, and PBIAS = 6.6%, respectively for stream flow. The simulation result for calibration and validation of sediment yield has also shown a good model performance rate with $R^2 = .75$, ENS = 0.74, RSR = 0.51, and PBIAS = –7.6%, and a very good model performance rate with $R^2 = .76$, ENS = 0.75, RSR = 0.5, and PBIAS = 3.1%, respectively.

The model simulated 1.19 million t of sediment yield at the watershed outlet annually. About 47.33% of the watershed are erosion-prone areas. The spatial variation of the average sediment load was 8.54 t/ha/year. The classification of the sediment yield in the watershed ranges from 1.654 to 23.47 t/ha/year. The severity class ranges from 10 to 23.47 t/ha/year as well. Among the 29 sub-watersheds, 13 were classified as critical sub-watersheds. The majority of these sub-watersheds exhibit relatively steep slopes and are predominantly covered by agricultural land, grassland, and shrub lands. These critical sub-watersheds are having predominantly eutrophic vertisols, chromic luvisols, and humic nitisols soils rendering them susceptible to severe erosion.

The SWAT model demonstrated that the adoption of BMPs yields a significant advantage in terms of sediment reduction. The application of stone/soil bunds, filter strips, contouring, grassed waterways, and terracing decreased the sediment load by 46.33%, 55.9%, 62.64%, 68.3%, and 71.38%, respectively. In the 13 treated sub-watersheds, the efficacy of selected BMPs displayed varying levels of effectiveness. Implementation of filter strips, soil bunds, and contouring on erosion risk watershed ranged from 25.9% to 63.67%, 28.96% to 77%, and 61.4% to 90.3% respectively. On the other hand, grassed waterways and terracing exhibited reductions between 56.81% to 95.53% and 77.71% to 96.71%, respectively. Generally, terracing was a more efficient reduction measure across different land uses, slopes, and soil conditions in the identified critical sub-watersheds.

Thus, the adoption of identified the best management practices (BMPs) holds promise in effectively mitigating soil erosion and reducing sediment yield in the study area. Therefore, this study would be a valuable resource or guideline for experts and policymakers involved in sustainable watershed management. However, the implementation, efficacy, and sustainability of such management practices rely on the availability of physical, financial, and human resources as well as on the cooperation of all stakeholders directly or indirectly benefitted from the watershed. Thus, the social and economic dimensions of watershed management along with the necessary resources, warrant further investigations. The result of the study can even be utilized by researchers and development agents as baseline information for further similar or related studies that will be conducted within the study area or related watershed. Future study required to determine the change in land use land cover on stream flow, the impact of climate change on stream flow, flood induction and flood mapping on the study area. Also further study is needed on how to excute mining in the study area. Filter strips, grassed water way, contouring, terracing and stone/soil bunds were studied with the aim of determining the effectiveness of solely sediment reduction ability. Further studies are required to assess the effect of these BMPs on ground water and evapotranspiration. Finally, it was recommended to assess the holistic impacts of implementing BMPs. For example, assessing the cost benefit, on and off-site ecological benefits, and farmers' preference to different BMPs. The challenges of this study where lack of sufficient and continuous metrological and hydrological data records. This might cause a serious problem for the application of the data in model simulation. Therefore, it was recommended to install sufficient hydrometer logical stations in the watershed and continuous monitoring recording of data.

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Author Contributions

The first author participated in all phases of the research and manuscript preparation. The second author participated in all phases of the research and manuscript preparation except for data collection, and the third author participated in manuscript write up.

Declaration of Conflicting Interests

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Data Availability Statement

Most datasets generated and analyzed in this study can be available upon request.

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