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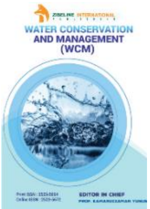

RESEARCH ARTICLE

IDENTIFYING EROSION HOT SPOT AREAS AND EVALUATION OF BEST MANAGEMENT PRACTICES IN THE TOBA WATERSHED, ETHIOPIA

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ABSTRACT

Ethiopian highlands have been increasingly exposed to the risk of soil erosion and evaluations of how various management practices can reduce the risk of soil erosion are still limited. Here, the calibrated and validated Soil and Water Assessment Tool (SWAT) is used to estimate soil loss rates, identify erosion hotspot areas and evaluate effective best management practices (BMP) to curb the risk of soil erosion. The annual sediment yield (SY) in Toba watershed varies from 0.09 t ha^{-1} yr^{-1} to 44.8 t ha^{-1} yr^{-1} with an average SY of 22.7 t ha^{-1} yr^{-1}. Cultivated lands on steep slopes are the sources of extensive soil loss rate, whereas areas with good vegetation cover have low SY. The increased population pressure, increased cultivation of steep slope and uncontrolled grazing are the causes of high SY in the watershed. 17 sub-basins with SY higher than the tolerable erosion of Ethiopia (2-18 t ha^{-1} yr^{-1}) are considered for the application of BMP scenarios. Implementing all BMPs could reduce the extent of SY but with varying degrees and combination of the BMPs are more pronounced and desirable. Reforestation with vegetative strips was the most effective management (87.8% reduction) followed by soil/stone bund with vegetative strips (83.7% reduction). These findings are important to ensure sustainable land management and promote sustainable agricultural production in a rapidly changing agricultural watershed. In general, the result highlights the need for regional developments and cooperation to urge for strong BMPs strategies for the rapid land and water resources degradation.

KEYWORDS

BMP, sediment yield, Toba watershed

1. INTRODUCTION

Regardless of the endowed diverse natural resources, Ethiopia is experiencing severe land and environmental degradation, which is a serious cause of productivity declines leading to a widespread poverty and food insecurity. Agricultural productivity in the Ethiopian highlands is strongly affected by pervasive land degradations (Haregeweyn et al., 2017; Schmidt and Tadesse, 2019; Worku and Mekonnen, 2012). Land degradation due to soil erosion in the highlands is due to the intermingling factors such as lack of effective watershed management practices, increased agricultural activities on steep slopes, land use/land cover change, heavy rainfall, climate variability and mixed crop-livestock farming systems (Dibaba et al., 2020; Hurni et al., 2005). In Ethiopia, the risk of severe soil erosion is closely associated with population density (Haregeweyn et al., 2017).

Expansion of agricultural lands, urban development and expansion and the need of extracting timber and other products to meet the needs of an increasing population is accelerating the degradations of natural resource and the environment. Soil erosion by water is the dominant forms of the degradations. This is especially problematic in the Upper Blue Nile, the source of the Nile, due to the higher erosion rate potentials (Ebabu et al., 2019). According to a study, about 39% of the upper Blue Nile basin is exposed to severe and very severe (>30 t ha-1yr-1) soil erosion, which can potentially threatens reservoirs in the downstream including Grand Ethiopian Renaissance Dam (Haregeweyn et al., 2017). In addition, excessive soil loss is posing severe challenges to the productivity of land and rural developments, operation and function of water infrastructure, products, and services of livelihoods.

This impact poses significant challenge to the agricultural system as it reduces farmers' profitability, income and employment, and poses additional risks of social, economic and environmental problems (CGIAR, 2017). Unless the current soil rate loss is averted with proper intervention, agricultural production will be disrupted and economic development will be significantly impeded. As reported by some scientist, soil erosion constitutes severe threat to the national economy owing to its dependence on agriculture (Endalamaw et al., 2021). In addition to the on-site effects of soil erosion, there are off-site effects. Soil erosion has a significant impact on the sustainability of the reservoirs and irrigation projects in the downstream and socio-economy of the local society in particular. Environmental degradation reduces the life span of hydraulic structures increasing the vulnerability of the structures to siltation and scoring (Endalamaw et al., 2021; Tefera and Sterk, 2010).

The loss of vegetation and the consequent soil erosion causes dam to fill up with sediment more quickly, resulting in poor energy production. Sediment accumulation hampers proper operation of dams and also causes reservoirs to submerge more area resulting in loss of land use, biodiversity and social impact. The recurrent power-cuts of electric power distribution recently experienced in Ethiopia are partially attributed due

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to the loss of storage capacity of hydroelectric power reservoirs which is a consequence of sedimentation. In order to increase the life of the reservoir and to best achieve the purpose for which it has been constructed, reducing sediment inflow is very important. To this end, reducing sediment and nutrient inflow through different management approaches is of paramount importance.

Moreover, the application of effective and sustainable watershed management practices could enable to increase the life span of the reservoirs in the downstream and enhances the ecosystems services provided by terrestrial and other aquatic ecosystems (wetlands, river and streams). Cognizant of the evidence that Ethiopia has suffered a lot from natural resources degradation, the problem has urged the government to affirm a commitment to address land degradation through different policies. Example: Community-based Participatory Watershed Development (CPWD and Sustainable Land Management (SLM) Programs (Desta et al., 2005; Etsay et al., 2019; Schmidt and Tadesse, 2019). However, the evidences on the extents of the management initiatives for the activities of the conservation is not clear (Gebreselassie et al., 2016).

Moreover, the undertakings and investments to combat the problems are still lower and the magnitude of the degradation exceeds the management/conservation activities by far and soil erosion continued to be the major problem. This, therefore, implies that interventions to address the existing threats of soil degradations and thereby enhance the socio-economic and ecological resilience of the watershed that involves multidimensional and multi-sectorial approach is required. Currently, there are an increasing research reports on the estimation of soil loss rate from the Ethiopian highlands (Belayneh et al., 2019; Endalamaw et al., 2021; Gashaw et al., 2021; Negese et al., 2021; Tsegaye and Bharti, 2021). The studies have shown that the loss of fertile topsoil due to erosion limits sustainable agriculture reducing soil productivity. However, the extent of annual soil loss rate varies with agroecology, topography and climate.

Most studies have reported cultivated lands are the sources of the intolerable soil loss rate and serious soil loss urges implementation of different agricultural management practices. Some studies have reported implementation of soil and water conservation practices can significantly reduce the risk of excessive soil loss rates (Dibaba et al., 2021; Lemma et al., 2019). However, the adoption rate of soil and water conservation practices varies significantly depending on landscape conditions. This suggests that effective watershed management practices need to be identified and implemented, taking into account the rate of soil erosion, topography and landscape of the area at regional and local scales. Most of the literatures available on the estimation of soil erosion rate are based on RUSLE (Endalamaw et al., 2021; Kebede et al., 2021; Negese et al., 2021; Tsegaye and Bharti, 2021).

However, using RUSLE to estimate the soil loss rate yields higher soil loss rate than a semi distributed physical model like SWAT. For example, the average annual soil loss from the Koga watershed is reported to be 47.7 t ha-1 yr-1 using RUSLE and 24.37 t ha-1 yr-1 using SWAT (Gelagay and Minale, 2016; Ayele et al., 2017). High RUSLE estimates may be due to high topographical factors on steep slopes. RUSLE's estimation of soil loss in mountainous areas on steep slopes is highly questionable, despite its simplicity and application areas with scarce data (Dibaba et al., 2021). Due to the limited resources (human, technological and financial), proper management of watershed requires identification of sediment sources and prioritization of hotspot areas for soil erosion (Lemma et al., 2019; Ricci et al., 2018; Uniyal et al., 2020).

In this regard, it is necessary to estimate soil loss and identify various management practices that suits the agroecology of a particular study is required (Haregeweyn et al., 2015). There are two approaches for estimation of soil loss: plot/field based and watershed-based techniques (Ebabu et al., 2019; Sultan et al., 2017; Tefera and Sterk, 2010; Dibaba et al., 2021; Lemma et al., 2019; Pandey et al., 2021; Ricci et al., 2018). However, research experience has shown that a watershed-based approach is more effective than the plot-based technique for the management of soil degradation. The application of agricultural and structural based management practices called Best Management practices (BMPs) are preferred to manage soil loss from critical areas (Arabi et al., 2007; Uniyal et al., 2020). The selection of best management practices that helps to reduce soil erosion and sediment loss requires systematic research that allows to assess the effectiveness of the practices.

A physical and process-based model, Soil and Water Assessment Tool (SWAT) was used to estimate the risk of soil loss and evaluate the effectiveness of BMPs to curb the soil erosion risks and sediment loss in Toba watershed. The SWAT model was used based on its strong capability in identifying the most critical areas and spatial variability of sediment yield with in the watershed. The model also allows the use of the combined factors like land use/land cover, soil, climate, steepness of slope and simulation of different soil and water management scenarios.

2. MATERIAL AND METHODOLOGY

2.1 Study area

Toba watershed is a tributary of Didessa sub-basin in the headwater of the Ethiopian plateau, Upper Blue Nile Basin. Upper Blue Nile (named as Abbay in Ethiopia) is one of the 12 river basins of Ethiopia (Figure 1, left hand side). Geographically, Toba watershed is located between 36°2'50" to 36°37'5" East and 7°46'30" to 8°15'45" North with an altitude range from 1425 to 2596 m.a.s.l (Figure 1, right hand side). The drainage area of the watershed is 1828.4 km^2. Agriculture is the dominant activity in the watershed and forest and rangelands are the dominant cover.

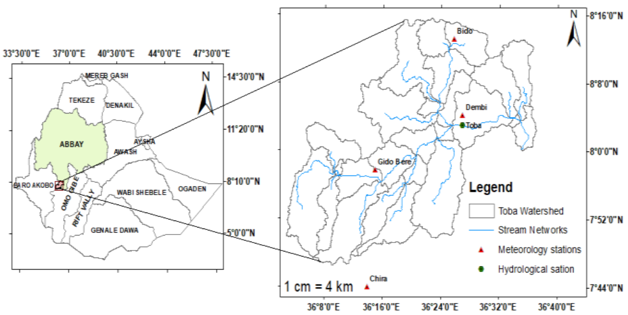

Figure 1: Map of the study area

The mean annual rainfall in the catchment varies from 1497 mm in the southwestern and 2500 mm in the northeastern part of the watershed. The watershed is characterized by humid tropical climate with heavy rainfall. The maximum and minimum temperature in Toba ranges from 18 to 36 °C and 6.5 to 17 °C (Tufa and Sime, 2020).

2.2 Input Data

The application of SWAT model to evaluate the spatial distribution of soil loss and quantify effectiveness of the BMPs requires the integration of spatial and temporal data with the application of different management practices. The spatial datasets used include Digital Elevation Model (DEM), land use/land cover and soil data (Table 1). Whereas the temporal data includes weather data, streamflow, and sediment data. The significance of different management scenario was evaluated SWAT model to curb surface runoff and soil loss. Digital Elevation Model (DEM), soil, land use/land cover, and weather data are used to develop and configure the SWAT model. Streamflow and sediment data are used to calibrate and validate the model.

The spatial maps of the Toba watershed landscape attributes are presented in Figure 2. Agriculture followed by Forest was the dominant land use/land cover in Toba watershed. The dominant soil type in Toba watershed is Dystric Nitisols followed by Dystric Gleysols (Figure 2). Elevation ranges of the watershed varies from 1425 m around the outlet to 2596m around the periphery of the watershed with majority of the watershed characterized by elevation higher than 2100m.

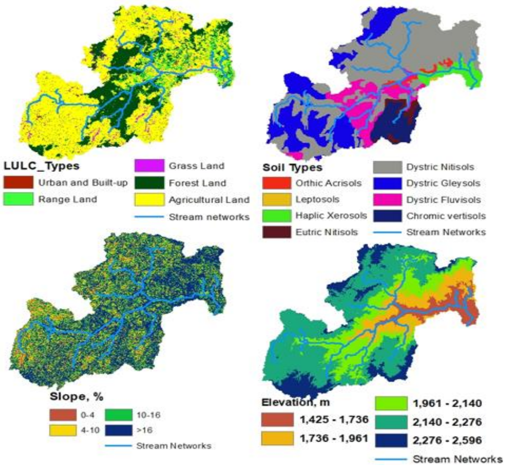

Figure 2: The spatial data attributes of Toba watershed: LULC, soil, slope and elevation

Table 1: Description of spatial and temporal data used for SWAT modelling in Toba Watershed modified (Dibaba et al., 2021).

Data Types	Description	Source	Period/Scale
DEM	DEM was used to delineate the watershed, stream networks	Shuttle Radar Topography Mission (SRTM) 1 Arc-Second Global from https://earthexplorer.usgs.gov	30 m
Land Use/ land Cover	Land use/land cover map of 2019 was used to quantify the hydrological process	LULC map derived from Landsat 8 OLI	30 m
Soil	Soil data from a vector map was processed in to a 30 m raster to match the spatial resolution of other spatial data. World digital soil map and soil grids were used to extract the Soil physico-chemical properties	Soil data processed from Ministry of Water, Irrigation and Electricity with the World digital soil map and digital soil map grids	1:50,000 and 250 m grid
Weather	Daily rainfall, temperature, wind speed, relative humidity, solar radiation of 5 stations were used to derive the hydrological balance	National Meteorological Agency, Ethiopia (NMA)	1988—2020
Streamflow	Daily stream flow data of Toba station was used to calibrate and validate streamflow	Ministry of Water, Irrigation and Electricity, Ethiopia	2000—2015
Sediment Data	Suspended sediment data of Toba stations used to calibrate and validate sediment yield	Ministry of Water, Irrigation and Electricity, Ethiopia	2000—2015

2.3 Methodology

2.2.1 Soil and Water Assessment Tool Hydrological model

SWAT is a watershed based, continuous-time and processed based model developed to allow simulation of larger and complex watershed to predict the impact of land management practices on water quality and quantity in agricultural watersheds over long periods (Arnold et al., 1998). SWAT simulates watershed hydrology in two major phases: land phase which controls the amount of water, sediment, nutrients and pesticides loading to the main channel in each sub-basin and water or routing phase which controls the movement of water, sediment and nutrients through channel network of the watershed to the outlet (Gathagu et al., 2018; Neitsch et al., 2011). The hydrological simulation of SWAT based on the water balance is given in equation 1 below:

$$SWt = SWo + \sum_{i=1}^{t}(Rday - Qs - Ea - Wseep - Qgw) \quad (1)$$

Where: SWt is the final soil water content (mm), SWo is the initial water content (mm), t is the time (days), Rday is the amount of precipitation on the i-th day (mm), Qs is the amount of surface runoff on day i (mm), Ea is the amount of evapotranspiration on day i (mm), W$seep$ is the amount of water entering the vadose zone in day i (mm), Qgw is the amount of return flow on day i (mm).

SWAT simulates soil erosion due to rainfall and runoff based on the Modified Universal Soil Loss Equation (MUSLE) using equation 2 (Neitsch et al., 2005).

$$Sed = 11.8 \times (Q_{surf} \times q_{peak} \times area_{hru})^{0.56} \times K_{USLE} \times C_{USLE} \times P_{USLE} \times LS_{USLE} \times CFRG_{USLE} \quad (2)$$

Where: Sed is the sediment yield from a given HRU on storm basis (ton/day), Q_{surf} is surface runoff volume (mm/ha), q_{peak} is peak surface runoff (m^3/s), $area_{hru}$ is the area of hydrologic response unit (ha), K_{USLE} is the soil erodibility factor (MgMJ^{-1}mm^{-1}), P_{USLE} is soil erosion control protection factors, LS_{USLE} is topography factor, C_{USLE} is crop management factor, $CFRG_{USLE}$ is coarse fragment factor.

2.2.2 Sediment Rating Curve

Sediment concentrations with the corresponding streamflow data at Toba gauging station collected from Ministry of Water, Irrigation and Electricity are available only for few months in a year. However, the application of SWAT hydrological model to simulate streamflow and sediment yield requires a continuous time step of streamflow and sediment data. Consequently, sediment rating curve was used to generate sediment load data from the streamflow using the empirical relations between the sediment concentration and their corresponding streamflow. The use of estimates derived from empirical relations between sediment concentrations and the corresponding river discharge are used often when the long-term and reliable records of sediment concentrations are limited (Choto and Fetene, 2019).

The relationship between sediment concentrations and river discharge can be written as:

$$Qs = a * Qf^{b} \quad (3)$$

Where: Qs is the sediment load in ton/day, Qf is the streamflow in m^3/s, a and b are regression constants to be determined from the suspended sediment loads and observed streamflow. The sediment concentration record was measured in mg/l and to work on equation 3, the sediment concentration was converted in to sediment load (ton/day) using the following conversion formula (Equation 4).

$$Qs = 0.0864 * C * Qf \quad (4)$$

Where, C is sediment concentration (mg/l), Qf is the streamflow (m3/s) and 0.0864 is the conversion factor. In Toba watershed, a and b are determined to be 6.8096 and 1.204 respectively. The sediment rating curve is shown by Figure 3.

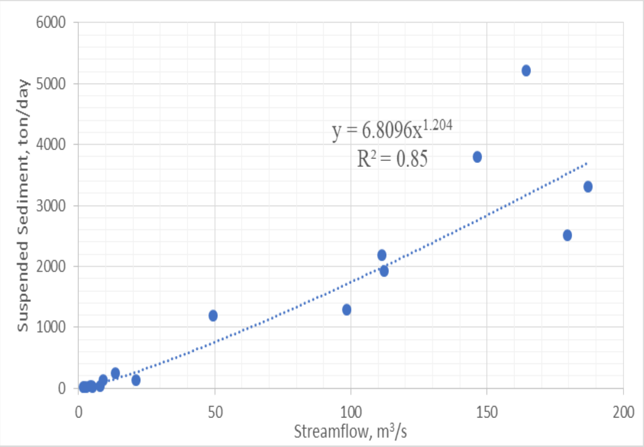

Figure 3: Sediment Rating Curve of Toba Watershed

2.2.3 Best Management Practices

Prior to the application of the BMPs, the SWAT model was calibrated and validated, and the model was parameterized to evaluate the effects of the soil and water management scenarios, which were then considered as the baseline scenario. The selection of BMPs and their parameter values is specific to topography, land use/land cover, soil and agro-ecology and the selection should reflect the actual situation of the study area (Abdelwahab et al., 2014). Therefore, the purpose of the intervention, past experience and recommendations provided in the Ethiopian Watershed Development Guidelines, and Soil and water conservation development agents guide were used to select BMPs for the simulation in the SWAT model (Desta et al., 2005; Hurni et al., 2016). Four BMPs applicable to the study area includes; filter strip, soil/stone bund, vegetative strip, reforestation and their combinations. These practices are largely under implementations in the Blue Nile basin.

a) Base line Scenario (BS): In the BS scenario, SWAT simulated the average sediment yield based on the actual watershed conditions.

b) Filter strip (FS): FS is used to reduce soil loss and its effect was simulated by increasing the width of the filter strips (FILTERW) on croplands and pasture lands.

c) Soil/stone bund (SB): This approach is the most reasonable technique commonly used in the Ethiopian highlands. SB reduces surface runoff and sediment loss by reducing the slope length and creating retention areas (Gebremichael et al., 2005). In this study, the effects of SB were simulated on steep slopes of the watershed by modifying the slope length (SLSUBBSN), the slope (HRU_SLP), the curve number (CN2) and the management support practices factor (USLE_P). USLE-P was set to 0.32 for agricultural lands, pastureland and shrublands with slope higher than 10%, CN2 was reduced by 3 units, HRU_SLP was reduced by 75% and SLSUBBSN was reduced by 50%. The modification of these parameters can also be achieved through the use of physical structures like Terraces and Fanya Juu.

d) Vegetative strip (VS): VS are established along the contour lines of the farmlands to reduce surface runoff and soil loss by reducing slope length and creating retention areas (Lemma et al., 2019). The effect of VS was simulated by modifying SLSUBBSN, HRU_SLP, USLE-P and FILTERW, as shown in Table 2.

e) Reforestation (R): Reforestation on steep slopes and degraded land can help to increase soil cover, helping to ensure the soil and water conservation (Lemma et al., 2019). In this study, the reforestation of grasslands, shrublands and cropland that are on slopes greater than 16% was applied by introducing land use/land cover in the land use update of the watershed data. We considered this scenario to restore forests that have been destroyed. Converting all crop land to forest land is not feasible. In this regard, only 5% of the crop land was considered for reforestation.

f) Combined Scenarios: Combined scenarios were evaluated based on the percent change in the sediment yield reduction by combining the applications of two scenarios. The application of Reforestation with vegetative strip, reforestation with soil/stone bund and soil/stone bund with vegetative strip was applied to compare the significance of the combined scenarios and the individual scenarios.

Table 2: Description of the BMPs scenarios and the parameter changes in the SWAT

Scenario	Parameter	Pre-BMP/ Calibrated	Post-BMP/ modified
Baseline (BL)	-	-	-
Filter Strip (FS)	FILTERW	0	1
Soil/stone bund (SB)	CN2.mgt	*	* - 3
	USLE_P	0.5	0.32
	SLSUBBSN	*	0.50*
	HRU_SLP	*	0.75*
Vegetative contour strips (VS)	FILTERW	0	1
	USLE_P	0.5	0.34
	SLSUBBSN	*	0.50*
	HRU_SLP	*	0.75*
Reforestation (R)	It is a management practice where croplands on hilly areas were changed in to plantation forests with slope >16% by 5%		

*: calibrated values

2.2.4 SWAT model setup and uncertainty Analysis

The SWAT model setup consists of the following procedures: Preparation of spatial and temporal data, watershed delineation and sub-basin discretization, HRU definition, writing weather inputs, and calibration and uncertainty analysis. A 30 by 30m resolution DEM was used to delineate the watershed. Then, HRU definition was held using a threshold value of 15%, 10%, 10% for land use, soil and slope respectively. Toba watershed was discretized into 25 sub-basin and 260 HRUs. Global sensitivity analysis was performed both for streamflow and sediment to identify the most influencing parameters. Then, SWAT model calibration and validation for stream flow and sediment was done using SUFI-2 algorithms in SWAT-CUP for the periods of 2000-2006 and 2007-2012 respectively. The model performance was evaluated using Coefficient of determination (R^2), Nash Sutcliff efficiency (NSE) and percent bias (PBIAS). These statistics were calculated using the following equation.

Coefficient of determination, R^2

$$R^2 = \frac{\sum_{i=1}^{n}\left[(Qobs - Q\bar{o}bs)(Qsim - \bar{Q}sim)\right]^2}{\sqrt{\sum_{i=1}^{n}(Qobs - Qobsm)^2 \sum_{i=1}^{n}(Qsim - Qsim)^2}}; 0 \leq R^2 \leq 1$$

Where Qobs is the observed variable, Qsim is the model simulated output, Q̄obs is the mean of the observation and Q̄sim is the mean of the simulated output and n is the total number of observations.

Nash Sutcliff efficiency, NSE

$$NSE = 1 - \frac{\sum_{i=1}^{n}(Qobs - Qsim)^2}{\sum_{i=1}^{n}\left(Qobs - Q\bar{o}bs\right)^2}; -\infty \leq NSE \leq 1$$

Percent Bias, PBIAS

$$PBIAS = 100 * \left(\frac{\sum_{i=1}^{n} Qobs - \sum_{i=1}^{n} Qsim}{\sum_{i=1}^{n} Qobs}\right)$$

The use of deterministic approach that results in a single set of parameters as best simulation is an outdated approach in calibration as it doesn’t recognize the errors and uncertainties in the modelling works. Consequently, any model calibration must include the analysis of the uncertainty with propagations of parameter uncertainties in addition to the statistics R^2, NSE and PBIAS (Abbaspour, 2015). Parameter uncertainty in SUFI-2 expressed as ranges accounts for all sources of uncertainty from conceptual model, parameters, measured data and uncertainty in driving variables (Abbaspour, 2015). Two statistics, *P-factor* and *R-factor* were used to quantify the fit between the simulation result expressed as 95% prediction uncertainty (95PPU) and the observation. the degree to which all uncertainties are accounted for is designated by *P-factor* whereas, *R-factor* is the average thickness of the 95PPU envelop (Abbaspour et al., 2017). For *P-factor,* the value of greater than 70% and *R-factor* of around 1 could be acceptable for stream flow whereas, smaller value of *P-factor* and a larger value of *R-factor* could be acceptable for sediment.

3. RESULT

3.1 Sensitivity Analysis, Calibration and Validation

Relative sensitivity analysis of streamflow and sediment was performed on a monthly timescale at subbasin 11 where the gauging station is located. With t-stat and *p*-value, parameter sensitivity and ranking are determined. A low *p*-stat and a high absolute t-stat value indicates the most significant parameter. Global sensitivity using Latin hypercube ‘one-at-a-time’ regression system was used to evaluate the relative sensitivity using the *p*-value and t-stat. The sensitive streamflow and sediment in Toba watershed are described in Table 3. From Table 3, the four most sensitive streamflow parameters were SCS curve number (CN2), Deep aquifer percolation fraction (RCHRG_DP), saturated hydraulic conductivity (SOL_K) and Groundwater delay (GW_DELAY).

The most sensitive parameters for sediment yields are the management support practice factor (USLE_P), Channel cover factor (CH_COV2), Linear factor for channel sediment routing (SPCON), Channel erodibility factor (CH_COV1) and Exponential factor for sediment routing (SPEXP). These are also reported by similar studies in Upper Blue Nile River Basin (Ayele et al., 2017; Lemma et al., 2019). The sensitive parameters were calibrated with the recommended ranges and the fitted value shown in Table 3 were used to compute the amount of sediment yield from Toba watershed.

Monthly streamflow and sediment datasets were used to calibrate the model from 2000 to 2006 and validate the model from 2007 to 2012. The performances of the SWAT model is considered to be acceptable for streamflow and sediment load simulation on the bases of R^2 and NSE >0.5 and PBIAS ≤ ±55% for sediment load and PBIAS ≤ ±25% for streamflow for a monthly time step evaluation (Ayele et al., 2017; Moriasi et al., 2007). Accordingly, estimation of streamflow and sediment load showed satisfactory performance both in calibration and validation periods. However, there is relatively lower statistical measures during the validation process. Table 4 presents the summary of performance statistics for streamflow and sediment load simulations. The lower statistical measures for sediment calibration and validation could be related to the quality and scarcity of observed data, parameters, streamflow process and model prediction uncertainty. The negative PBIAS value during calibration and validation showed that the model slightly overestimated the predicted streamflow and the positive PBIAS during validation of sediment data showed under estimation.

Table 3: List of parameters used for streamflow and sediment calibration with the parameter ranges, fitted values and sensitivity ranks using SUFI-2.

	Parameter	Description	Range	Fitted value	Rank
Stream flow	1: R__CN2.mgt	SCS curve number	±25%	-10%	1
	2: V__RCHRG_DP.gw	Deep aquifer percolation fraction	0-1	0.063	2
	11: R__SOL_K(..).sol	Saturated hydraulic conductivity	±25%	8.02%	3
	4: A__GW_DELAY.gw	Groundwater delay	±10	-8.43	4
	5: A__GWQMN.gw	Treshold depth of water in the shallow aquifer required for return flow to occur (mm)	0-5000	822	5
	6: A__GW_REVAP.gw	Groundwater "revap" coefficient	±0.036	0.0096	6
	8: V__CH_K2.rte	Effective hydraulic conductivity in main channel alluvium	5-130	15.42	7
	3: V__ALPHA_BF.gw	Baseflow alpha factor (days)	0-1	0.94	8
	19: V __USLE_P.mgt	USLE support practice factor	0-1	0.50	1
Sediment	23: R__CH_COV2.rte	Channel cover factor	0.001-1	0.205	2
	21: V__SPCON.bsn	Linear factor for channel sediment routing	0.0001-0.01	0.0036	3
	22: R__CH_COV1.rte	Channel erodibility factor	0.01-0.6	0.353	4
	20: V__SPEXP.bsn	Exponential factor for sediment routing	1-2	0.653	5

To determine the degree of uncertainty and goodness of fit and the model strength, *p-factor* and *R-factor* and 95PPU calculated at the 2.5% and 97.5% levels of cumulative distribution. The results show that, 76% and 58% of the measured streamflow are bracketed by the 95PPU whereas, *R-factor* has a reasonable value of 0.87 and 1.01 during calibration and validation respectively. For sediment yield, 38% and 42% of the observed data was bracketed by the 95PPU and the *R-factor* was 0.56 and 0.81. compared to streamflow, higher level of uncertainty (38%) was reported during calibration. In general, the model performance in Toba watershed have shown higher superiority during validation and the results are comparable with studies in highlands of Ethiopia (Ayele et al., 2017; Lemma et al., 2019).

Table 4: Monthly streamflow and sediment calibration (2000-2006) and validation (2007-2012)

	Process	p-factor	r-factor	R^2	NSE	PBIAS	RSR
Streamflow	Calibration	0.76	0.87	0.89	0.89	-5.8	0.34
	Validation	0.58	1.01	0.71	0.52	-22.5	0.69
Sediment	Calibration	0.38	0.56	0.67	0.66	-8.4	0.58
	Validation	0.42	0.81	0.65	0.64	9.8	0.72

Graphical analysis of streamflow simulation showed that, the model predictions have shown both over estimation and under estimation during calibration and validation (Figure 4). However, the general prediction of the model is good enough to simulate the streamflow except the peak flow in most of the calibration and validation years.

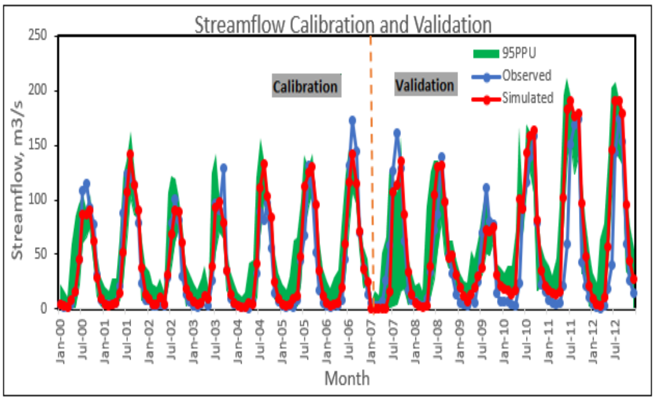

Figure 4: Observed and simulated streamflow calibration and validation

The graphical analysis of observed and the predicted sediment yield indicated that, the model has shown both overestimation and underestimation during calibration and underestimated sediment yield during validation (Figure 5). The SWAT model was unable to predict the peak sediment yield throughout the years of validation period and in some years of calibration period. However, the model is able to properly simulate the rising and falling limb in both cases.

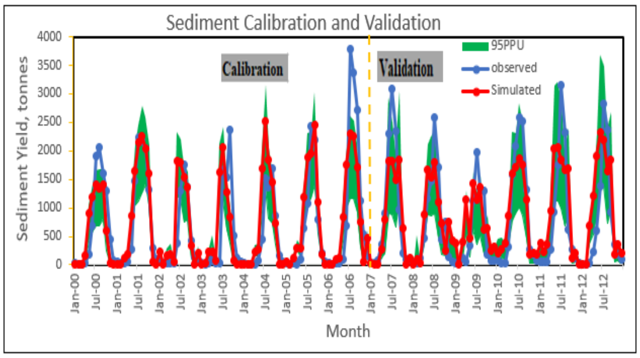

Figure 5: Observed and simulated sediment yield calibration and validation

3.2 Prioritizations of Toba watershed to sediment yields

Soil erosion by water has become the responsible factor for the degradation of fertile topsoil in agricultural areas. This is a major challenge for agricultural productivity in the highlands of Ethiopia, where agriculture is the dominant activity of the community. Toba watershed is one of the highland watersheds where soil erosion has become a challenging problem for agricultural activities. The annual sediment yield in the watershed ranges from 0.09 t ha^{-1} yr^{-1} to 44.8 t ha^{-1} yr^{-1} with an average sediment yield of 22.7 t ha^{-1} yr^{-1}. The annual SY of the watershed was classified into six severity classes: very low (0-5 t ha^{-1} yr^{-1}), low (5-10 t ha^{-1} yr^{-1}), moderate (10-18 t ha^{-1} yr^{-1}), high (18-30 t ha^{-1} yr^{-1}), very high (30-40 t ha^{-1} yr^{-1}) and severe (>40 t ha^{-1} yr^{-1}) (Table 5). The very low and low class represents the level of erosion less than the rate of soil formation. Very high and severe classes of SY is higher than the average SY.

Table 5: Annual average SY, severity classes and area of contribution

SY- t ha^{-1} yr^{-1}	Area, ha	Area, %	Severity
0 - 5	9481.14	5.2	Very Low
5_11	5434.29	3.0	Low
11 - 18	34472.5	18.9	Moderate
18 - 30	83835.0	45.9	High
30 - 40	37652.2	20.6	Very high
>40	11960.4	6.5	Severe

The spatial distribution of the sediment sources indicates that the very low and low SY (<11 t ha^{-1} yr^{-1}) in the watershed was generated from sub-basin 18, 19 and 14 (Figure 6). These sub-basins accounted about 8.2% of the total watershed and they are dominantly covered by forest land. The highest contributor of SY (>40 t ha^{-1} yr$^{-1)}$) are sub-basin 1 and 2 located in the highland areas, northern part of the watershed. These sub-basins are characterized by cultivated slopes. This indicates that human activities on higher slopes was the main driving factor of SY. In general, areas with good vegetation coverage around the central part of the watershed are characterized by low SY, and agriculturally sloping areas are the dominant sources of high SY. The study shows that SY is more sensitive to land use classes, with minimally disturbed areas are not causing significant erosion and areas under extensive agriculture are the sources of high erosion.

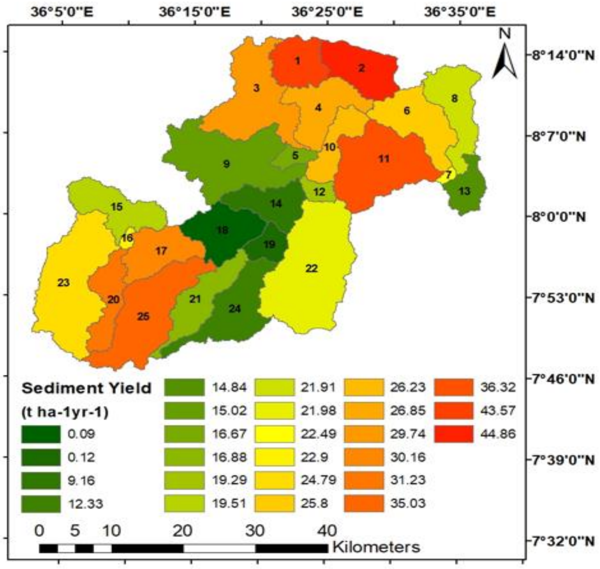

Figure 6: Spatial distribution of sediment yields in Toba watershed

The estimated annual average rate of SY in the Toba watershed was 22.7 t ha^{-1} yr^{-1}. This was higher than the tolerable soil loss (2-18 t ha^{-1} yr^{-1}) of Ethiopian agricultural land, as suggested (Hurni, 1985). However, the average annual SY predicted in Toba watershed is lower than the rates of average soil erosion rates reported in various parts of the Blue Nile Basin. Some researchers in Koga catchment, a tributary to Gilgel Abay (24.3 t ha^{-1} yr^{-1}), in Lake Tana Basin (32 t ha^{-1} yr^{-1}), in the Beshillo catchment (35 t ha^{-1} yr^{-1}) and in the Finchaa catchment (36.47 t ha^{-1} yr^{-1}) (Ayele et al., 2017; Lemma et al., 2019; Yesuph and Dagnew, 2019; Dibaba et al., 2021). The variations in soil loss in different parts of the Blue Nile reveals that, SY varies with difference in agroecology and biophysical environment. Relatively, the lower average soil loss in Toba watershed could be attributed to the good vegetation cover (forest was the second dominant land use class) compared to the other areas. Most of the soil loss estimates in Ethiopia are based on the RUSLE model. Although the model is simple and can be developed with small input parameters in areas like Ethiopia where data is limited, the outputs of RUSLE model is sensitive to the input parameters. In RUSLE model, there is no option to identify the most sensitive parameters like the other models.

3.4 Evaluation of Best management Practices

Usually, it is important to set a threshold value between tolerable and intolerable level of soil erosion to minimize the risk of soil erosion. The soil loss rate considered as tolerable based on maintenance of crop production was reported from 1 to 11 t ha^{-1} yr^{-1} (FAO, 2019). According to FAO, SY from 8.2% of the watershed is considered as a tolerable rate of erosion (FAO, 2019). In Ethiopia, the tolerable rate of soil loss in different agro-ecological conditions were reported from 2 to 18 t ha^{-1} yr^{-1} (Hurni, 1985). In this study, sub-basins that generates SY more than 18 t ha^{-1} yr^{-1} which accounts for 72.9% were considered for the BMP scenario analysis. From the total 25 sub basins, only 8 sub-basins generate the tolerable soil loss and the remining 17 sub-basins require urgent soil erosion control.

The summary of implementing the individual BMPs and their combination in Toba watershed was summarized in Table 6. The lowest SY reduction was reported as 36.1% reduction during the implementation of the filter strip (FS) and the highest reduction was reported as 80.5% by the simulation of vegetative strip (VS) followed by soil/stone bund (SB). Applying SB to steep slopes and reforesting the hills reduced SY by 69.3% and 47.5%, respectively. However, implementing a combination of the BMP scenarios improved the SY reduction. The highest reduction in SY was attained by the combination of R and VS followed by SB and VS. This finding suggests a reasonable reduction of SY requires implementation of appropriate combinations of BMPs. An improved reduction in SY by combining BMPs has been shown in similar studies (Uniyal et al., 2020).

Table 6: Estimated SY reduction due to BMPs compared to the baseline scenario

Scenarios	Percentage of change in SY, %
FS	36.1
SB	69.3
VS	80.5
R	47.5
R+SB	77
R+VS	87.8
SB+VS	83.7

Although the application of all BMPs have shown reasonable reduction of SY, the simulation of all BMPs revealed considerable spatial variability (Figure 7). Applying a combination of BMPs, SB and VS reduced SY below the tolerable soil loss across the entire erosion hotspot areas. The application of FS and R alone cannot alleviate the risk of soil erosion fully from the whole watershed within the tolerable limit of the soil loss. In particular, the seven sub-basins under FS and the two sub-basins under R still generates SY that exceeds the permissible limit of soil loss (Figure 7).

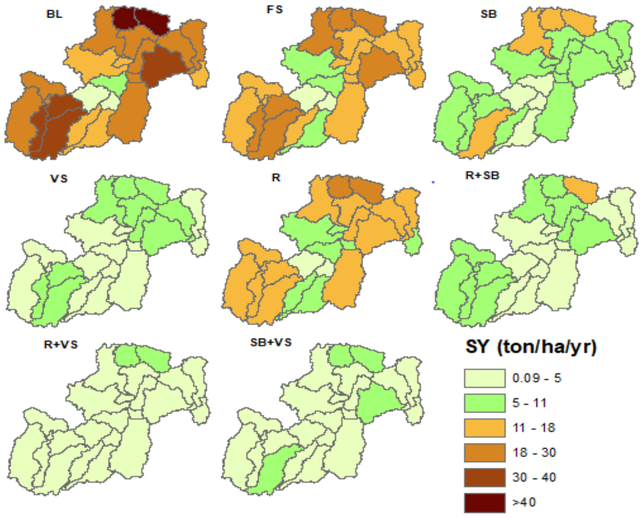

Figure 7: Impacts of BMPS on the reduction in sediment yield

3.5 Management and policy implications

Considering various alternatives for investigating the possible soil and water management practices is one of the most conceivable results of research for decision makers. The concept of management practices is that the development and management of watershed resources need to achieve sustainable production without degrading the resource base or causing any ecological imbalances. In this context, an integrative systemic approach that helps to reverse the land degradation through water erosion by regulation of hydrological and ecological processes is required as poorly planned management practice could result in complete failure.

The limited and slow response to the multifaceted issues of community and the need for integration and comprehensive action are yet exacerbating the environmental problems. There are some efforts towards natural resources management like integrated water and soil conservation practices.

However, the lack of cooperation and coordination in the design and implementation of comprehensive and integrated development interventions that can fully support sustainable development remains a bottleneck that must be observed and focused by all involved. In most cases, the development interventions in our country, the study area in particular are overlooked to provide a detailed analysis and understanding about the environment-population nexus. Consequently, the severity of the environmental problem related to soil erosion currently emerging in the watershed and the region at large is caused by the uncontrolled population-environment nexus outcomes. The peculiar characteristic of the population of the Oromia region where the study is located is that very limited size of land holding to the farmers is the cause for cultivation of steep slope which has become a source of erosion and sediment loss in the watershed as shown in sub basin 1 and 2 in Figure 6. The emphasis of the local government on expanding agriculture lands every year so as to ensure food security of the area and also create job opportunity for youths could be the main reason for uncontrolled extensive agricultural expansion.

The main problem of management in Ethiopia is that interventions are taking place without prior investigation and the need for local population for conservation. Moreover, there is no sort of organizational structure to the grass root level, for instance watershed committee for watershed conservation and most of the activities were done through mass mobilization. The relevance of policy and program tools for land conservation through mobilization however depends on whether or not the farm households are convinced of the need to to invest in nature conservation. On the other hand, the implementation of various management practices is strongly influenced by the agro-ecological variations, technology used by the community and institutional supports, research supports and public awareness (Etsay et al., 2019; Miheretu and Yimer, 2017). Most of the factors are still the factors that trigger the failure of natural resources management. In this regard, management practices require commitment to long-term practices regardless of the underlying biophysical conditions or environment.

This offers an opportunity to achieve consistency of guidelines and measures at all levels and areas, from local to global. Collaborative planning and action at the landscape level is an important foundation for maximizing cross departmental synergy. Effective inter-sectoral coordination requires stakeholders to share evidence, information, and best practices; and coordinate the planning, implementation, and monitoring processes are harmonized at the landscape level. Integrated landscape or catchment management ensures that by managing the underpinning natural resource base and ecosystem services in a coordinated way, societal needs can be met in the short and long term. Therefore, the application of best management practices described in chapter 3 for enhancing the socio-ecological resilience of Toba watershed can be aligned with the integrated landscape approach of addressing multiple goals of sustainable development.

When implementing BMPs, coordinated development and management of land and water should be considered with the broader upstream and downstream interests. Three important pillars have to be developed: developing proper policies, strategies and legislation with proper finance and incentive structures, forming a framework for institutions through which policies can be implemented and set up management systems for the institutions to do their job.

Strategic Goal 1: Improve the ecological resilience of the watershed by improving the management of biophysical resources (mainly soil and vegetation) and restoring degraded ecosystems and sites.

Strategic Goal 2: Improve socio-economic development and the livelihoods of communities in targeted watershed by promoting small-scale and community owned green businesses to improve socio-economic resilience. Therefore, intervention packages that can be linked to this strategic goal of enhancing socio-economic resilience should logically be targeting on improving and/or modernizing the agricultural production system through intensification, among others. An important consideration of these interventions is that they have to contribute to the realization of eco-friendly or climate-smart agricultural production systems.

4. CONCLUSION

Water induced soil erosion poses challenge to agricultural production in agricultural watersheds. The increased risk of soil erosion and the associated environmental problems have increased the need for research on sustainable management of land and water resources. This study investigated soil erosion status in the Toba watershed and sought to identify hotspot areas for effective intervention to reduce the risk of sediment generation. Considering various alternatives to investigate the possible soil and water management practices is one of the conceivable outcomes of the study for decision policy. The estimated annual sediment yield varies from 0.09 t ha^{-1} yr^{-1} to 44.8 t ha^{-1} yr^{-1} with an average sediment yield of 22.7 t ha^{-1} yr^{-1}. The highest SY was contributed by the steep farmland.

The severity of erosion at the very low, low and moderate severity levels covering 27.1% of the watershed area was within the tolerable ranges of soil erosion in Ethiopia (2 to 18 t ha^{-1} yr^{-1}). Seventeen sub-basins, which represent about 72.9% of the watershed area, have been identified as critical areas that require implementation of proper measures. Regardless of the considerable SY by all scenarios, the simulation of the individual BMPs in reducing SY over Toba watershed has varied appreciably. The application of certain scenarios (FS and R) cannot reduce the risk of soil erosion below the tolerable limit of the soil loss. However, the combination of scenario is more prominent and more desirable for SY reduction.

Therefore, this result suggests that a reasonable reduction in SY requires the implementation of an appropriate combinations of BMPs. Overall, this study showed how SWAT model can be used to support systematic watershed management planning using erosion hotspot area prioritization. Coordinated development and management of land and water with the broader upstream and downstream interests could help to achieve better implementation of best management practice. Therefore, this study recommends, creating awareness of the risk of soil degradation in order to persuade and ensure the long-term engagement of the community and stake holders in management activities.

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AUTHORS' CONTRIBUTIONS

Wakjira T Dibaba have developed the concept of the study, methodology, and formal analysis. Dessalegn G Ebsa conducted field works, investigation. Both authors involved in writing review and editing the manuscript. All authors have read and agreed to the published version of the manuscript.

AVAILABILITY OF DATA AND MATERIALS

The data used during the current study are available from the corresponding author upon reasonable request.

COMPETING INTEREST

The authors declare that they have no competing interests.

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