Article

Soil Erosion Modelling and Risk Assessment in Data Scarce Rift Valley Lake Regions, Ethiopia

Alemu O. Aga [1],* [ID], Bayou Chane [1] and Assefa M. Melesse [2] [ID]

[1]   School of Civil and Environmental Engineering, Addis Ababa Institute of Technology (AAiT), Addis Ababa 1000, Ethiopia; bayoumedi@gmail.com

[2]   Department of Earth and Environment, Florida International University, Miami, FL 33199, USA; melessea@fiu.edu

*   Correspondence: alemu.osore@aait.edu.et; Tel.: +251-985-414-699

check for updates

Abstract: To prolong the useful life of lakes and reservoirs, prioritizing watersheds by severity and risk of soil erosion is an essential index to develop sound sediment management plans. This study aims to predict soil erosion risk and sediment yield using Soil and Water Assessment Tool (SWAT) model in Lake Ziway basin, Ethiopia, and the model result is validated with lake bathymetric changes. The SUFI-2 program was applied for a model calibration and the performance of the model was assessed. The catchment prioritization study indicated that some sub-basins having the same soil type and land use but a higher slope gives higher sediment yield. This confirms that, in the basin, the upland is the main source of sediment for the lake, hence the variation of sediment yield is more sensitive to terrain slope. Furthermore, the soil conservation scenarios demonstrated in SWAT that reduce the slope length of the watershed by 50% for a slope greater than 5% are decreasing the sediment yield of the basin by 55%. The bathymetric differencing of the lake indicates that the sediment was accumulating at a rate of 3.13 t/ha/year while a calibrated SWAT model resulted in 5.85 t/ha/year. The identified reasons for these variations are the existence of outlet for the lake, floodplain depositions and abstraction of sediment (sand mining) from the tributary rivers before flowing to the lake.

1. Introduction

Land degradation and soil erosion is a serious threat in agroecosystems and is one of the main global environmental crises [1]. It has both onsite effects (loss of fertile topsoil) and offsite effects (sedimentation of lake and reservoirs). Loss of top fertile soil will reduce the productive capacity of the land and thereby create risk to global food security. The most significant and broadly impacting effects of sedimentation on lakes and reservoirs are changes in water balances, thereby reducing the live storage of the reservoir [2]. Reservoir storage is vitally important for agricultural irrigation, power generation, municipal water supply and other uses. To prolong the useful life of lakes and reservoirs, analyzing soil erosion risk is an important task to plan land use and soil conservation measures.

Erosion risk assessment and sediment risk maps, particularly at the catchment scale, provide important insights into the linkage between soil erosion and sediment deposition in the basin. Also, it can be used for various tasks such as the identification of high risk areas (erosion hot spots), to assess the catchment's average pattern of erosion risks, to identify deposition and deposition patterns, detailed erosion and major concentrated flow areas [3]. For land use and soil conservation planners,

a soil erosion and sediment risk map is an important index for prioritizing watershed management interventions [4].

In the catchment, sediment supply is heterogeneous in space and time due to its complex interactions of many factors [5] such as land use/cover, soil type, climate, landscape, drainage conditions and human activities [6] and, hence, quantification of soil loss is often difficult and one of the greatest challenges in natural resources and environmental planning [7,8]. Due to its complexity, a computer simulation model that considers all of the factors that initiated soil erodibility and erosivity has been developed. For example, Universal Soil Loss Equation (USLE) [9], the Water Erosion Prediction Project [10], Erosion Productivity Calculator [11], the Agricultural Non-Point Source Pollution model [12], the Areal Nonpoint Source Watershed Environment Response Simulation [13], European Soil Erosion Model [14], The Chemicals, Runoff and Erosion from Agricultural Environment Systems [15], and Soil and Water Assessment Tool (SWAT) [16] have been used over many years.

Among these models, the USLE has remained the most practical method for estimating soil erosion potential and to estimate the effects of different erosion factors on soil erosion. USLE has been used for more than 40 years [17,18] whereas other process-based erosion models developed afterward have limitations in applicability due to intensive data and computation requirements [19]. On erosion quantification, USLE cannot indicate the amount of sediment delivered to the downstream points due to its limitation on calculating the sediment delivery ratio [19]. As a result, more recent physically-based models have been developed to quantify the soil loss rates. Physical-based models have the ability to predicate the soil erosion and sediment delivery ratio.

The Soil and Water Assessment Tool is one of the physical-based models and has many useful components and functions for simulating the water balance, sediment loss and land management practices [20]. SWAT is designed to consider an in-built erosion prediction algorithm [21] that accounts for the spatial variation of the system using soil, land use, terrain, and management practice data inputs to predict catchment soil erosion and sediment yield [22]. Hence, it is widely used for erosion modeling in several catchments, under different climatic conditions, including semiarid climate. Its performance was tested in different parts of the world. For example, its ability was tested in sediment prediction for the Warner Creek watershed located in Maryland and the evaluation result indicates the existence of strong agreement between yearly measured and SWAT simulated sediment load [23]. Similarly, on Big Creek watershed of Southern Illinois, [24] calibrated daily SWAT sediment yield with observed sediment yield concluded that sediment fit seems reasonable. Iowa, Raccoon River watershed, [25] found that the sediment loads predicted by SWAT were consistent with sediment loads measured. It was also tested and used in many regions in Africa [26–33] to estimate sediment yields from both gauged and ungauged watersheds and good results were reported. Similarly, the performance of SWAT model was tested in Germany [34], USA [35], China [36–40] and Jamaica [41] to predict the amount of sediment as well as stream flow from gauged and ungauged river basins

Due to its wide applicability, SWAT model was selected in this study to estimate the sediment yield of Lake Ziway basin, Ethiopia. The SWAT model is a watershed scale model that incorporates the features of several other models [42]. Identification of erosion-prone areas using a distributed physical model that estimates soil erosion rates with sufficient accuracy will be important for implementing appropriate erosion control practices [43]. SWAT has the ability to estimate erosion at different spatiotemporal scales and small contributing sub-catchments; moreover, modeling errors will be adjusted by calibrating the sensitive catchment flow and sediment parameters related to surface soil and cover conditions. The model's ability to predict catchment soil erosion and sediment yield at different scales from small to large basin-scale studies [41,44–50] and its ability to estimate the spatial heterogeneity in different land management practices are additional benefits [4].

To increase the productivity of the land and to decrease siltation rates of the water body, it is crucial to implement watershed management activities inside the basins. Because of resource limitations, implementing soil conservation measures in the entire basin at a time is impractical. Hence, prioritization of intervention areas based on the severity and risks of soil erosion is imperative. For

example, in Ethiopia, the intervention for soil conservation has been exerted since the 1970s [51]. However, the efforts did not bring significant changes to ongoing soil degradation problems of the country [1,51,52]. Most recently, watershed management is an approach followed by the government of Ethiopia to reduce soil erosion in particular and to reverse land degradation in general [1,51,53]. Although dramatic reduction has been made in arresting soil erosion [1,51,53], the approach has not been supported with intervention prioritizing techniques that identify highly susceptible erosion prone areas. The Lake Ziway basin is one of the central highland basins in the Rift Valley region of Ethiopia where soil erosion is rampant. Hence, to solve this, there is a need to identify the most erosion-sensitive areas in the basin, so that effective conservation measures can be taken. Therefore, the objectives of this study are to (1) identify and prioritize erosion hotspot sub-catchments on the basis of estimated runoff and sediment yield; (2) quantify the amount of coarse sediment delivered into the lake from contributing sub-catchments and validate the result with historical lake bathymetric data; and (3) suggest suitable land management options for alleviating soil degradation problems.

2. Study Area

2.1. Location and Topography

Lake Ziway is located in Central Ethiopian Rift Valley basin (Figure 1), where it fills a depression at an elevation of about 1636 m above sea level. The lake is the shallowest lake in the country and drains to Lake Abiyata. It is the third largest freshwater of the Ethiopian Rift Valley Lakes and the fourth in the country. The lake has a surface area of 423 km^2 and has five islands: namely Gelila, Debre Sina, Tulu Gudo, Tsedecha and Fundro. The lake basin has a total area of 7285 km^2 and geographically it extends from $7°20'54''$ to $8°25'56''$ latitude and $38°13'02''$ to $39°24'01''$ longitude. The majority of the watershed is flat to gently undulating, but is bounded by a steep slope in the eastern and southeastern escarpments and is characterized by abrupt faults. There is a topographic difference of about 2600 m between the rift floor and the highland areas (mountains) of the basin.
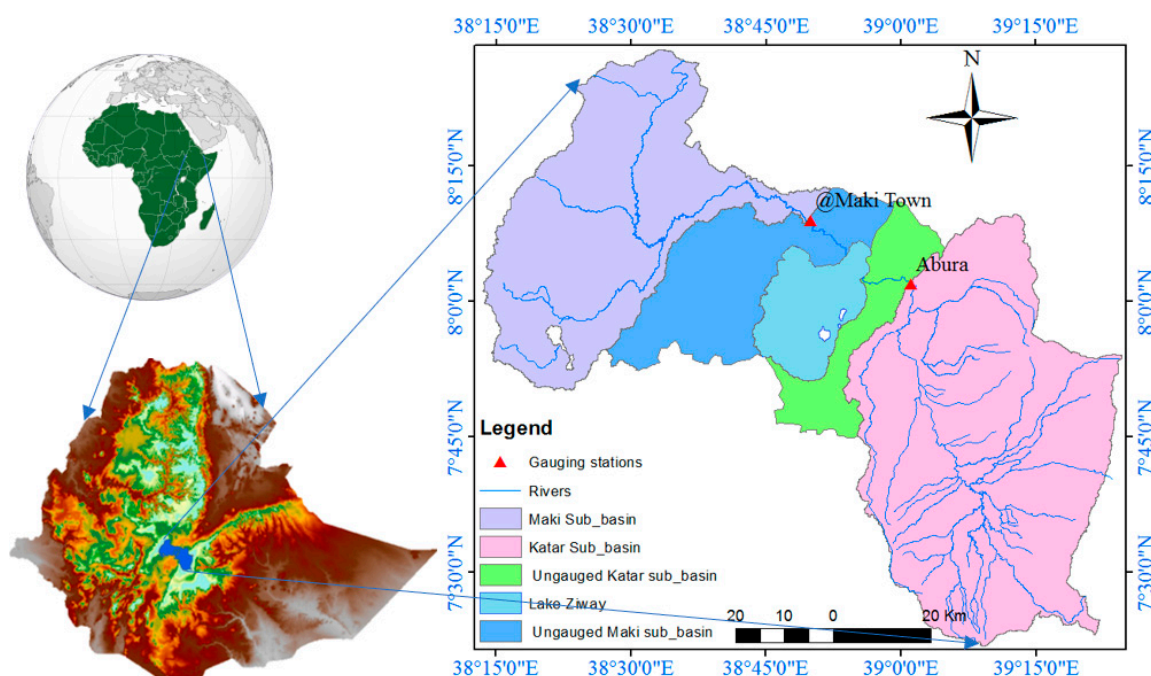

Figure 1. Location of Lake Ziway basin in Ethiopia.

2.2. Climate

The climate of Lake Ziway basin is dry to sub-humid or humid. The lowland area surrounding the lake is arid or semi-arid and the highlands are sub-dry humid to humid. The basin is classified into

three main seasons based on its rainfall [54]. The long rainy season is summer and is locally known as Kiremt. The Kiremt rain represents 50–70% of the mean annual total rainfall. The dry period extends between October–February locally known as Bega. The small rainy season known as Belg, representing 20–30% of the annual rainfall, occurs during March–May.

The long-term (1987–2016) mean annual rainfall of Arata, Bekoji SF, Ketera Genet, Kulumsa, Meraro, Ogolcho, Adamitulu, Bui, Butajra, Koshe, Meki and Ziway meteorological stations ranges from 620 to 1225 mm and the areal map of rain fall depth by using inverse distance square interpolation method (IDW) is shown in Figure 2.
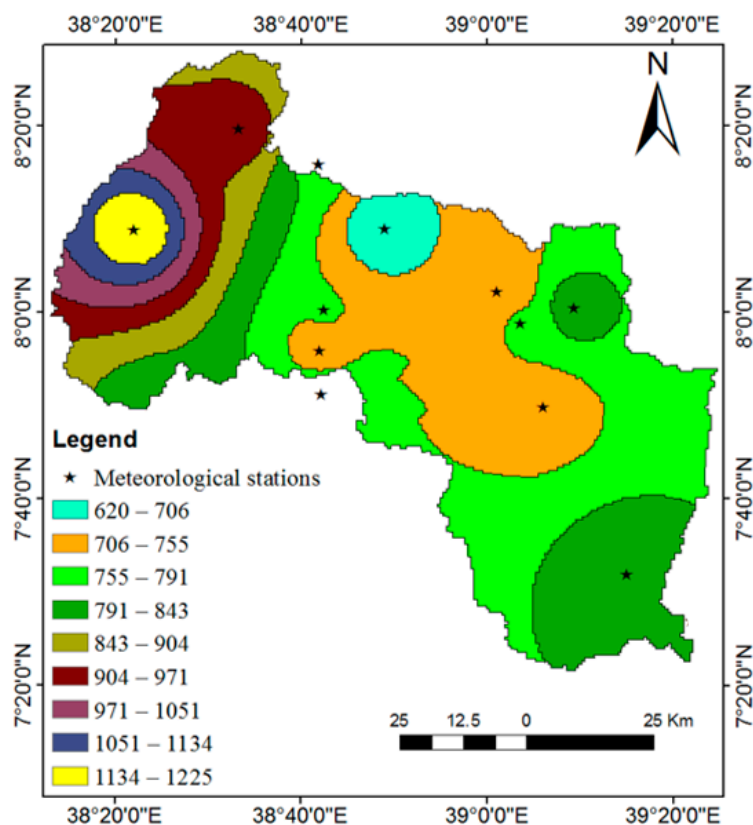

Figure 2. Average annual rainfall depth (1987–2016) in Lake Ziway Basin based on IDW interpolation of data for near meteorological rain gauges stations.

2.3. Hydrology

The lake has two main contributing rivers (Katar and Meki Rivers) and outflows to Bulbula River which flow to Lake Abiyata. Katar River is the biggest perennial river and has a total watershed area of 3350 km^2. Another tributary river, Meki, drains an area of 2433 km^2 from the west and northwest of Lake Ziway. The entire outflow from Lake Ziway is through Bulbula River, which flows in a southern direction to Lake Abiyata. Bulbula descends some 58 m over a distance of 30 km between Lake Ziway and Abiyata. Analysis of the streamflow data (1989–2008) indicated that Katar River flows to the lake with an average annual runoff volume of 401.6 million cubic meters (MCM) and Maki contributes an average annual runoff volume of 270.24 MCM. Lake Ziway discharges into the Bulbula River with a mean annual runoff volume of 116.3 MCM.

2.4. Geology, Soil and Land Use

The geology of the basin is mainly dominated by basalt. This basaltic group comprises of Wonji and Silte volcanics. The Wonji lava field is located at the eastern escarpment of Lake Ziway and the other lava field. Silte is located at the western escarpment [55]. Next to the basalt, alluvial deposits are

also scattered around the lake. Soil of Lake Ziway basin is closely related to parent material and degree of weathering [56]. The six dominant soil types include Andosols, Cambisols, Fluvisols, Leptosols, Luvisols and Vertisol [57].

Intensive agriculture is the dominant land use in the basin and a study has shown that there is dynamic land use change [57]. In the year 2010, the sediment delivery rate of the western sub-basin of the lake was assessed and from the total basin around 14% is highly eroded with an average sediment yield (SY) of 50–106 t/ha/year, 24% has an average SY of 20–50 t/ha/year and the remaining 62% of the basin is slight to moderately eroded with average SY rate of 0–20 t/ha/year [57]. The field data collection of this study has identified areas in the Katar watershed (eastern lake sub-basin) that are seriously eroded.

3. Methodology

3.1. SWAT Model

SWAT is a physical-based model that simulates surface runoff, soil erosion and sediment delivery in a river system [16]. It can be used for both gauged and un-gauged basins to estimate the runoff, sediment and chemical yields [22] with varying land-use, soil, topography and land management practices for long periods of time on a daily basis [58].

The model is suitable to simulate a single basin or multiple hydrologically connected basins. The model will divide the basin into sub-basins based on the size of the basin, the spatial detail of available input data and the amount of details required. Further, the sub-basins will be divided into small portions called "hydrological response units" (HRUs), characterized by uniformity of soil and land-use [30,49]. Hydrological processes are simulated in detail for each HRU and then aggregated for the sub-basin by a weighted average. In SWAT, the hydrologic cycle of a sub-basin is simulated based on the following water balance equation [30,49].

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

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

SWAT calculates the surface runoff from daily rain fall by using modified SCS curve number Method [59]. The surface runoff component of the water balance is determined from the SCS method as:

$$Q_{surf} = \frac{\left(R_{day} - I_a \right)^2}{R_{day} - I_a + S} \tag{2}$$

where $I_a = 0.2S$ and $S = 25.4 (1000/CN-10)$; hence the amount of surface runoff is equated as

$$Q_{surf} = \frac{\left(R_{day} - 0.2S \right)^2}{R_{day} + 0.8S} \tag{3}$$

where I is initial abstraction (mm), S is relation parameter (mm) and CN is curve number.

SWAT can also calculate the sediment rate from each HRU by suing the Modified Universal Soil Loss Equation as the following equation [60].

$$Sed = 11.8 \times \left(Q_{suef} \times q_{peak} \times Area_{hur} \right)^{0.56} \times K_{USLE} \times C_{USLE} \times P_{USLE} \times LS_{USLE} \times FRG_{USLE} \tag{4}$$

where, Sed is yield of sediment in t/day; Q_{surf} is Volume of surface runoff (mm/ha); q_{peak} is the greatest surface runoff rate (m^3/s); $Area_{hru}$ is Hydrologic response unit area (ha); KUSLE is USLE soil erodibility factor; C USLE is USLE topography factors cover; LSUSLE is USLE topography factors and PUSLE is USLE soil protection factors; and CFRG accounts for stoniness.

For channel networks, SWAT computes the sediment flow as [58]

$$Sed_{ch} = Sed_{ch,i} - Sed_{deep} + Sed_{deg} \tag{5}$$

where Sed_{ch} is the amount of suspended sediment in the reach; Sed_{deg} is the mount of sediment that reenters the reach segment; Sed_{dep} is the amount of sediment deposited in the reach segment; and $Sed_{ch,i}$ is the amount of suspended sediment in the reach at the beginning of the time period.

Similarity, SWAT calculates the amount of sediment transported out of reach as [42]

$$Sed_{out} = Sed_{ch} \times (V_{out}/V_{ch}) \tag{6}$$

where Sed_{out} is the amount of sediment transported out of the reach; Sed_{ch} is the amount of suspended sediment in the reach; V_{ch} is the volume of water in the reach segment, and V_{out} is the volume of outflow during the time step.

3.2. Model Development and Input Description

To develop the SWAT model, two types of dataset are required: meteorological and catchment characteristics datasets (topography, soil and land use maps).

To set up a SWAT model for our study Area, 30 m × 30 m digital elevation model (DEM), land use map, soil maps and soil laboratory analyzed results of the basin major soils types were obtained from the Ministry of Water Irrigation and Electricity of Ethiopia (MoWIE). Prior to the application of the maps in the model, preprocessing work was carried out. The land use map has been re-classified into SWAT land use classes. The soil properties required to set up SWAT-model is soil texture, grain size percentage, soil saturated hydraulic conductivity, bulk density, soil available water and texture class. Therefore, these soil characteristics were obtained from a laboratory analyzed result done under Rift valley Lake basin Master Plan study document [47]. During the study of Ethiopian Rift Valley Lake Basin Master Plan, the soil samples were collected from all soil units of the basin and its physical and chemical laboratory analyses were conducted in the Ethiopia Water Works Design and Supervision Enterprise (WWDSE) laboratory. From out of 12 soil units of the basin, 203 soil samples were collected and its physical and chemical properties were analyzed. Hence, the soil database of the SWAT model was set-up for the basin using the analyzed soil properties. The basin's soil erodibility (K) factor was calculated using the equation shown in EPIC [61] from the analyzed soil parameters.

The meteorological data included daily precipitation, maximum and minimum temperature, daily wind speed, daily sunshine hours and daily relative humidity, and they were obtained from meteorological stations (Figure 2) available within and nearby the study area. Daily data of 31 years (1987–2017) were collected for the study.

To fill the missing values of climate elements, a weather generator model was used. The required statistical parameters were computed using the computer program developed by Reference [62]. In the Lake Ziway basin, two meteorological stations (Ziway and Bui) were analyzed and used to establish the weather generator database.

3.3. Sub-Watershed Delineation

Katar and Meki Rivers are the two major tributary rivers in Lake Ziway watershed. Before joining the lake, there are stream gauging stations namely Maki and Abura along the Maki and Katar Rivers, respectively. Using the 30 × 30 m resolution DEM data, contributing areas upstream of the two stations were delineated using ArcGIS 10.2 (Esri, Redlands, CA, USA). Accordingly, the entire study area has been divided into 51 sub-watersheds of which 26 are inside Maki and 25 in Katar Rivers sub-basins.

Based on the model setup with land use, soil and slope, and minimum area threshold values set as 5%, 10% and 10%, respectively, 550 Hydrological Response Units (HRU) were identified, which are unique combinations of land use, soil type and slope (Figure 3).
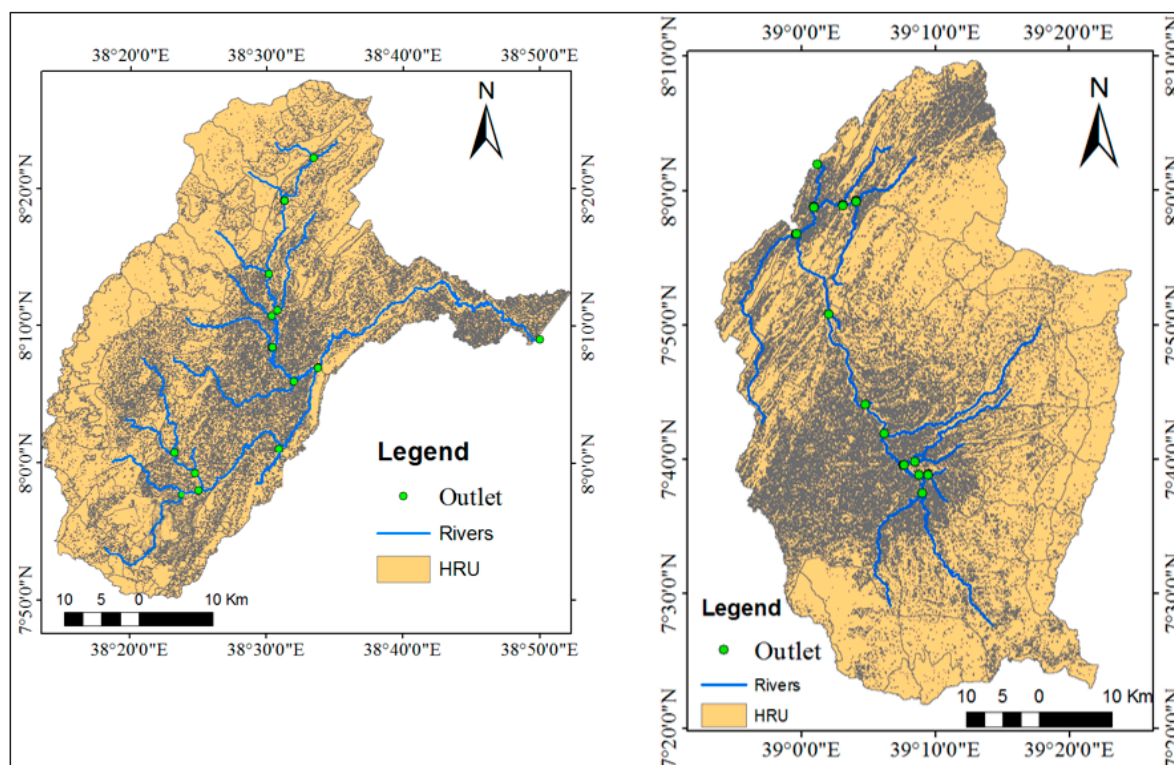

Figure 3. Hydrologic response unit (HRU): Maki (**Left**) and Katar (**Right**) Sub-watersheds.

3.4. Model Calibration, Validation and Evaluation

To calibrate and validate the model, the daily stream flow data was obtained from MoWIE and the sediment data were generated by using sediment-discharge rating curves developed for the sites. As SWAT simulates total sediment load including bed load, it is necessary to include the bed load component on the suspended load to have total sediment load for the model calibration and validation. However, in most studies in Ethiopia, the bedload component is frequently ignored due to measurement constraints. In most rivers, bed load to suspended load ranges from 10 to 30% [63]. Maki and Katar flow on a moderate to gentle slope throughout their course. Hence, we assumed the bedload as 10% of the suspended sediment load obtained from the rating curve and added for model calibration.

To prioritize the sub-basins based on their sediment contribution, the adequacy of the SWAT model was tested by calibrating and validating the model. For Maki River, at Maki gauging station, the model was run for the simulation period of 1 January 1996 through December 2013. The stream flow and sediment data of 10 years from 1999 to 2008 were used for calibration and the subsequent 5 years (2009–2013) were then used for validation period. Similarly, for Katar River, the model was run for the period of 1987 to 2010 with 11 years (1990 to 2000) calibration and 10 years (2001 to 2010) validation period. For both rivers, the first 3 years in the calibration run were used for model warm-up. In this study, the length of the time period used for calibration and validation were determined based on the existing observed data records. During calibration, sensitivity analyses were conducted automatically using the SUFI-2 program in SWATCUP software.

Lastly, the model performance for fitting measured constituent data was evaluated by using three widely used statistical indices: coefficient of determination, Nash–Sutcliffe coefficient and RSR (the ratio of root mean square error (RMSE) to the standard deviation of the measured data).

3.5. Validating SWAT Model Results with Lake Sedimentation Rate

One of the most conventional techniques and an accurate determination of sedimentation rate in the reservoir is a periodic bathymetric survey of the lake [64]. Temporal comparison of bathymetry maps is an indicator for environmental changes like lake or reservoir sedimentation [65–67].

For Lake Ziway, two historical bathymetric data are available. The oldest one is the 1976 lake bathymetry map and the recent one is in 2005 by the MoWIE. In order to estimate the sediment accumulation rates during the period (1976 to 2005), the total volume predicted from 1976 bathymetry elevation-volume relation curve has been subtracted from total volume calculated from the 2005 bathymetric map. Hence, to determine the volume of the lake for 2005, the contour map of the lake was georeferenced in ArcGIS10.2 and the volume was calculated for each elevation (contours) by creating triangulated irregular network (TIN) using the polygon volume calculation technique available in ArcGIS10.2.

4. Results and Discussion

4.1. Flow Calibration and Validation

A sensitivity analysis was conducted and 12 major parameters were selected for both sub-catchments (Abura and Maki). To obtain optimal fitting with the measured data, calibration was conducted manually and automatically by SUFI-2 program. The most sensitive parameters identified for both stations during calibration are SCS runoff curve number (CN2.mgt), effective hydraulic conductivity in main channel (CH_K2.rte), saturated hydraulic conductivity (SOL_K.sol), Ground water "revap" coefficient (GW_REVAP.gw), available water capacity of the soil layer (mm H_2O/mm soil) (SOL_AWC.sol), surface runoff lag time (SURLAG.bsn), threshold depth of water in the shallow aquifer required for return flow to occur (mm) (GWQMN.gw), soil evaporation compensation factor (ESCO.hru), slope of water shed (HRU_SLP.hru), base flow alpha factor (days) (ALPHA_BF.gw), groundwater delay (days) (GW_DELAY.gw), and moist bulk density (SOL_BD.sol) with different sensitivity ranks. The sensitivity result shows the SCS runoff curve number (CN2.mgt) as a major critical parameter for both stations. Curve number in a watershed is directly related to land use/cover and soil characteristics.

The calibration and validation greatly improved the agreement between the observed and predicted daily discharges. The graphical representation of measured and simulated daily stream flows matched well for both calibration and validation periods (Figures 4 and 5). The goodness-of-fit analysis of the calibration and validation stages is shown in Table 1. As shown in Table 1, all the numerical model performance indicators designated for the model performance evaluation are concordant with NSE values from 0.71 to 0.85, R^2 values from 0.72 to 0.86, and RSR from 0.39 to 0.54 in the basin. Hence, all numerical model performance measures are in the acceptable range that the SWAT model accurately simulated the measured stream flow on both stations. SWAT developers recommend an acceptable calibration for hydrology at a $R^2 > 0.6$, NSE > 0.5 and RSR < 0.7 [68]. Similarly, its performance is very good compared with the statistical performance value recommended by Reference [69].
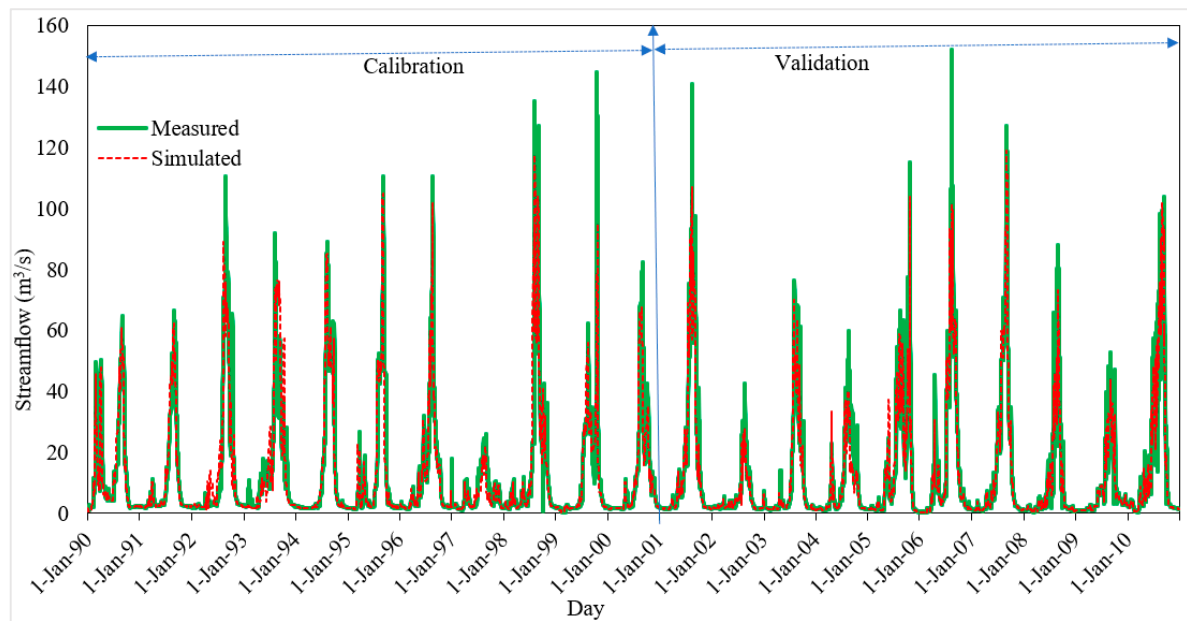
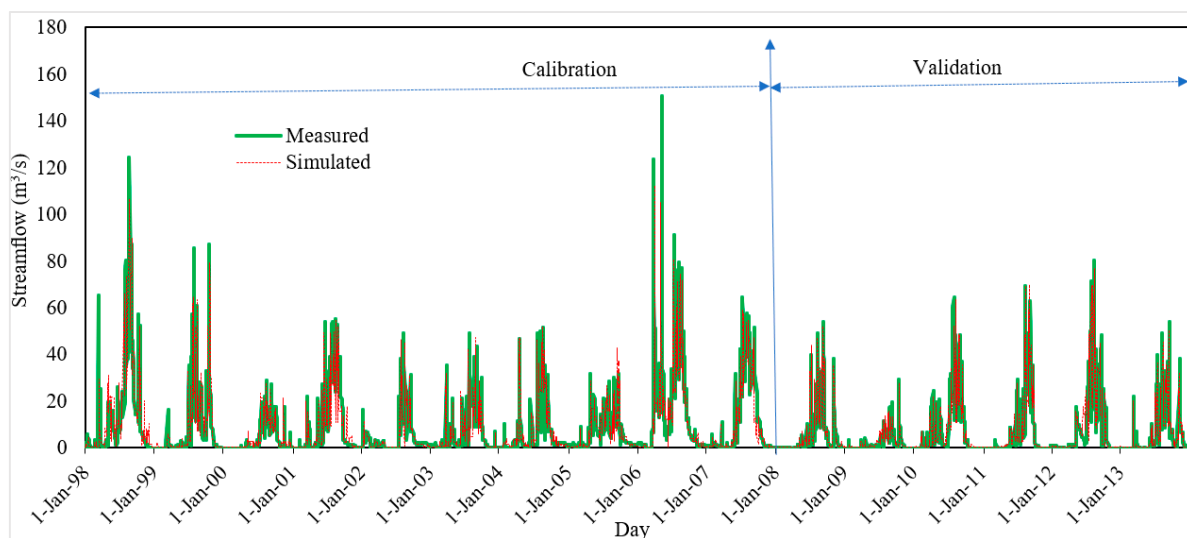**Figure 4.** Daily stream flow calibration and validation at Abura gauging station.

Figure 5. Daily stream flow calibration and validation at Maki gauging station.

Table 1. Daily streamflow calibration and validation model performance statistics.

Parameter	Maki Sub-Basin (At Station Maki)		Katar Sub-Basin (At Station Abura)	
	Calibration	Validation	Calibration	Validation
NSE	0.73	0.71	0.79	0.85
R^2	0.74	0.72	0.80	0.86
RSR	0.52	0.54	0.45	0.39

4.2. Sediment Yield Calibration and Validation

After stream flow calibrations, sediment flow calibration was conducted using sensitive parameters related to soil loss from each HRU. To determine the magnitude of catchment sediment yield, initial sensitive sediment parameters were calibrated using the global sensitivity analysis procedure. Besides, six sensitive sediment parameters were identified. Those are USLE support practice factor (USLE_P.mgt), USLE equation soil erodibility (K) factor (USLE_K.mgt), Channel Erodibility

factor (CH EROD.rte), Exponential factor for channel sediment routing (SPEX_P.bsn), Linear factor for channel sediment routing (SPCON.bsn) and Channel Cover factor (CH COV.rte)

As shown in Figures 6 and 7, for both stations, calibration of the SWAT model was successfully achieved using the observed daily sediment flow. Similarly, during the validation stage, the SWAT model mimicked well the sediment inflow from the two tributaries.
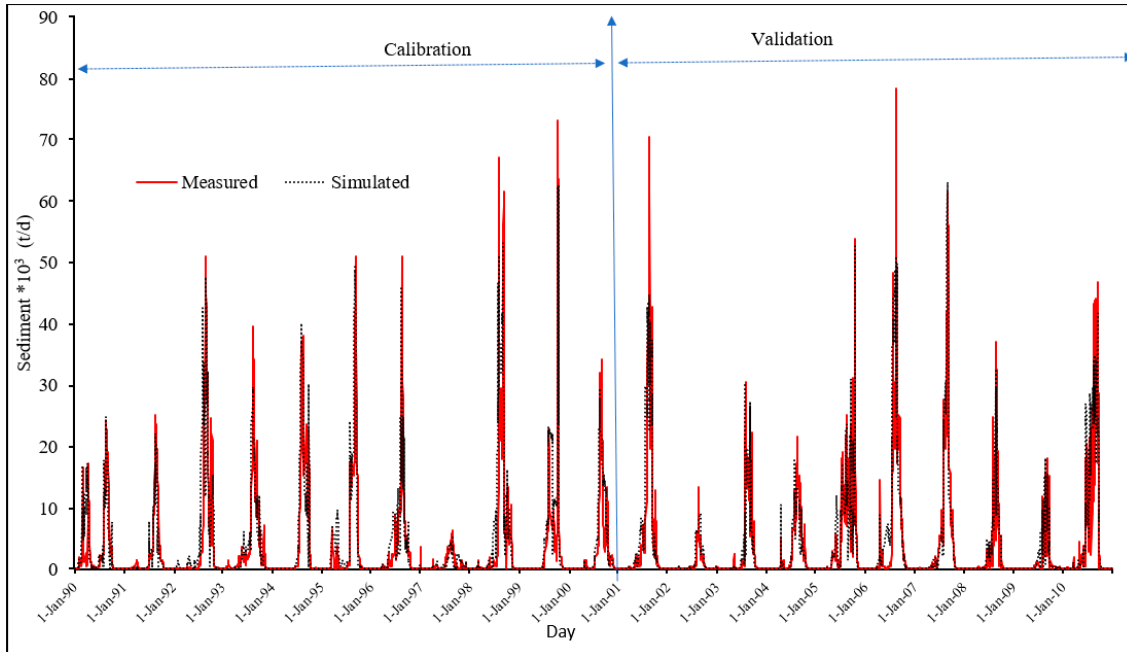

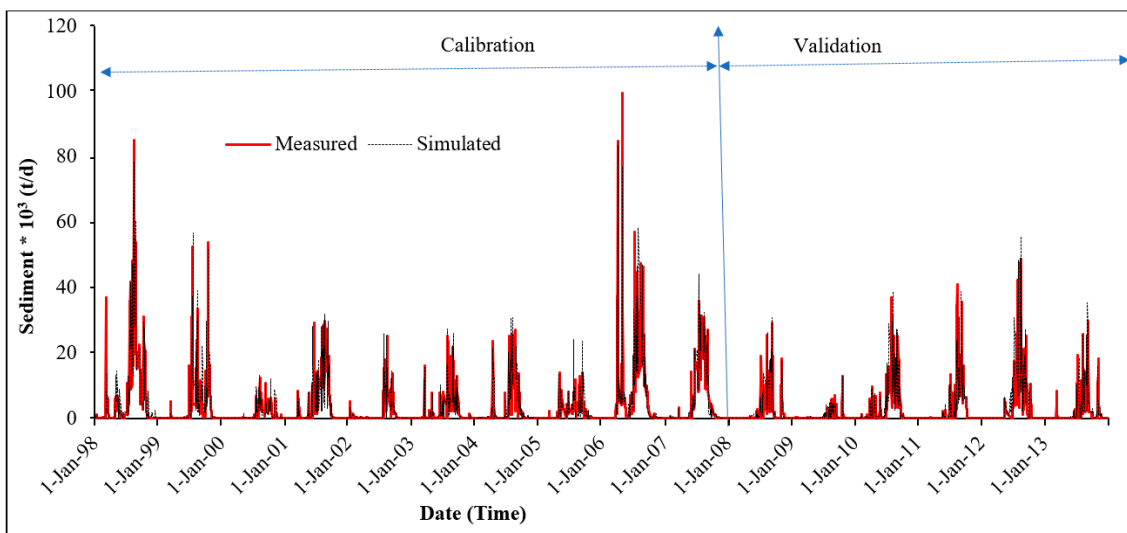**Figure 6.** Sediment yield calibration and validation at Abura gauging station.

Figure 7. Sediment yield calibration and validation at Maki gauging station.

Based on the calibration and validation results, the model performance was evaluated in terms of the statistical indicators (Table 2).

Table 2. Daily measured and simulated sediment yield calibration and validation model performance statistics.

Parameter	Maki Sun-Basin (At Station Maki)		Katar Sub-Basin (At Station Abura)	
	Calibration	Validation	Calibration	Validation
NSE	0.74	0.75	0.72	0.79
R^2	0.71	0.71	0.67	0.75
PBIAS	−7.87	−12.25	−16.68	−16.25
RSR	0.54	0.53	0.58	0.50

As can be seen in Table 2, all numerical model performance measures are in the acceptable range indicating that the SWAT model replicates the measured sediment yields. Similarly, the graphical representation of measured and simulated flows matched well for both calibration and validation periods (Figures 6 and 7). Hence, the result can be used to identify major sediment source areas within the sub-watersheds.

4.3. Spatial Distribution of Sediment Generation Hotspot Area

The calibrated SWAT modeled was used to simulate the effect of management/conservation measures on water and sediment yield in Lake Ziway basin. The annual average suspended sediment yield in Maki sub-watershed was estimated to be 6.9 t/ha/year and 4.8 t/h/year for sub-watershed Katar. The spatial variability of erosion rate was identified (Figure 8).
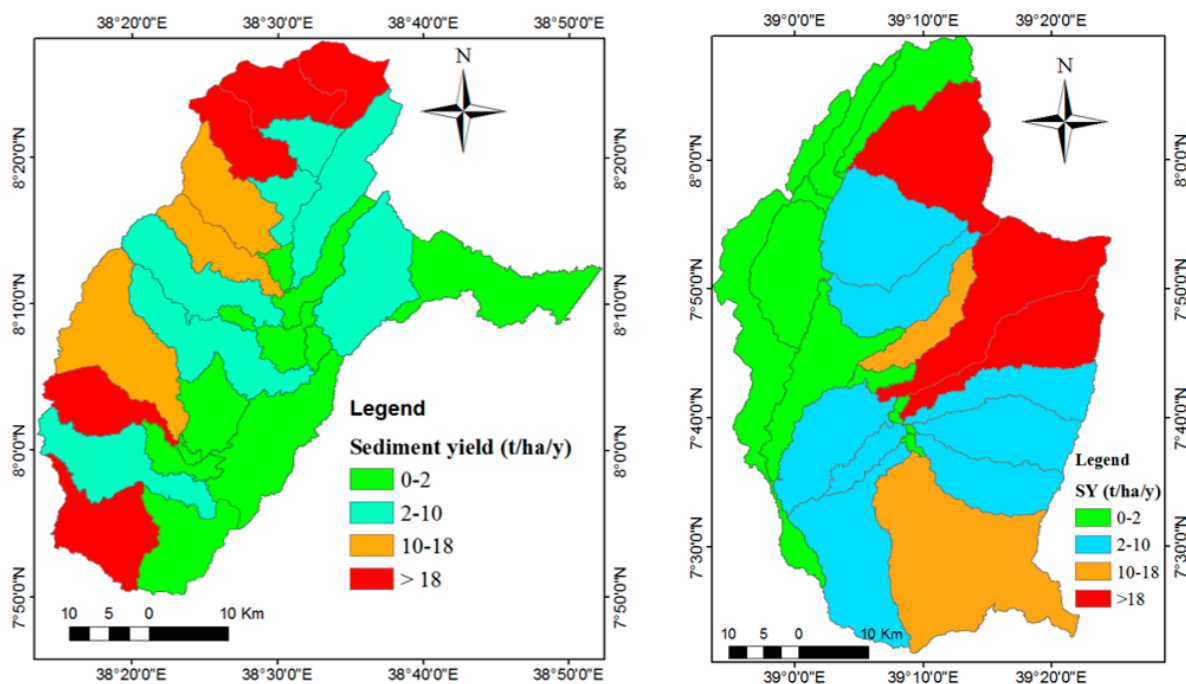

Figure 8. Spatial distribution of soil loss severity classes: Maki (**Left**) and Katar (**Right**) sub-watersheds.

To quantify the effects of the spatial distribution of soil type, land use and terrain slope on soil erosion, seven main erosion source areas (SY > 10 t/ha/year and indicated in red color in Figure 8) inside of Maki and three inside of Katar sub-basins were selected (Figure 8). For both sub-basins, all the selected catchments were characterized by a single land use class (agriculture) and one dominant soil type of Luvisols. In addition, the research employing catchment prioritization indicates that in low land areas with the same land use and soil type, the soil loss is low. This indicates that the variation of sediment yield is more sensitive to terrain slopes due to poor land use practices on steep slope areas.

Based on this result, potential areas of intervention were prioritized and three management or conservation measurement scenarios were developed and simulated using SWAT model in order to evaluate the most suitable management/conservation measures within the basin.

- ☞ Base Scenario (Scenario I): This scenario presents the actual condition observed in the watershed (without conservation measures)
- ☞ Scenario 2: Assume the slope length of the watershed is reduced by 25% for a slope greater than 5% by using physical conservation structures (Parallel Terraces, Fanya Juu, soil bund, etc.)
- ☞ Scenario 3: Assume the slope length of the watershed is reduced by 50% for a slope greater than 5% by using physical conservation structures (Parallel Terraces, Fanya Juu, soil bund, etc.)

Simulation was performed for each scenario for the HRUs with the corresponding conservation measures and management practices. The sediment yields were compared to the result of the baseline scenario simulation. Sediment loss reductions relative to the base scenario due to conservation practices are listed in Table 3.

Table 3. Estimated sediment reduction due to conservation structures and best management practices as compared to the baseline scenario.

Scenario	Percentage of Change in Sediment Flow	
	Maki Sub-Basin	**Katar Sub-Basin**
Base scenario	0	0
Scenario 2	−13	−12
Scenario 3	−55	−49

As shown in Table 3, for Maki sub-basin, scenario 3 is reducing the sediment yield by 55% and scenario 2 by 13%. Similarly, for Katar sub-basin, scenarios 3 and 2 reduce the sediment yield by 49% and 12%, respectively. On average, the sediment yield of Lake Ziway basin will reduce by 52% and 12.5% of scenario 3 and 2, respectively. Due to the different slope ranges between the two sub-basins, with equal slope length reduction, the effectiveness of sediment reduction has varied. In Maki sub-basin, the slope length as well as the slope gradient is slightly higher that Katar sub-basin.

Hence, this result can be used as a guideline for decision-makers to apply a suitable method to reduce the erosion load, especially from high erosion rate areas. On selected hotspot erosion areas, the required treatments may include practicing strip planting, terracing, or contour farming to reduce the effect of slope on surface runoff flow velocity and sediment transport capacity.

4.4. Sedimentation Estimate Using Historical Lake Bathymetric Differencing

Lake sediment volume calculation was done by differencing 1976 and 2005 volumes for each elevation by creating TIN using the polygon volume calculation technique available in ArcGIS10.2. Comparison of the two old bathymetric maps indicates that, within 3 decades, the lake volume has been reduced by 48.63 Mm^3. Taking the average bulk density of the basin soil as 1.25 t/m^3, the annual sediment yield is estimated as 2.14 Million t/year. For total watershed of the lake, the long-term annual average sediment load is estimated as 3.13 t/ha/year.

Global minima for specific suspended sediment yield falls well below 2 t/km^2/year. Maximum of 10,000 t/km^2/year for Lo Ho River in the People's Republic of China [70] and 23,700 t/km^2/year for Geleda watershed in Ethiopia [1] was cited. The average soil loss rate for Ethiopia is estimated as 42 t/ha/year for cultivated croplands and 35 t/ha/year for other lands [71]. Accordingly, the estimated watershed sediment yield of Ziway catchment lie is well below the maximum range, but significantly above the low sediment yield values recorded globally.

4.5. Difference between Sediment Estimated by SWAT Model and Bathymetric Differencing Techniques

The sediment yield for a watershed determined by calculating the accumulation of sediment in a lake bottom was equated as 3.13 t/ha/year. However, the annual sediment load estimated by SWAT model for Katar sub-basin is 4.8 t/ha/year and 6.9 t/ha/year for Maki. On average, the SWAT model is estimating the lake basin sediment rate as 5.85 t/ha/year. Thus, the model is slightly over estimating as compared to the bathymetric analysis which is due to the fact that all the sediment eroded from the contributing basin as well as the sediment existing in the stream channels cannot arrive at the outlet. Most parts of the sediment will be deposited in the floodplain and others will be lost on river conveyance systems [43]. Hence, the average sediment yield predicted from the lake sedimentation may under estimate the actual erosion rate of the lake basin.

Next to the floodplain deposition, the lake has an outlet through the Bulbula River in its south direction through which sediment is carried outside the lake. As shown in Figure 1, almost all of the ungauged basin is flat and its sediment contribution may be too low. The calculated sediment load for bathymetric differencing is the average of total watershed, hence the predicted low sediment yield may be reasonable.

In addition to this, there is the abstraction of sediment from its river channels/section. Sand mining and dredging activities can be seen along the two tributary rivers of the lake. Like that of lake outlet, abstraction of sediments from its tributary rivers can reduce sedimentation risk reaching the lake. On those rivers, the floodplain deposition rate is high due to the existence of such sediment abstraction along the rivers. Overall, the estimated values for both methods are reasonable and acceptable.

5. Conclusions

The aim of this study was to assess surface runoff generation and soil erosion rates for Lake Ziway basin by applying the SWAT model. Field measured soil parameters were used for calibrating and validating both runoff and sediment flows. The calibration processes considered sensitive flow and sediment parameters to evaluate the degree of agreement between measured and simulated monthly datasets. The model performance was evaluated using statistical indices and was found to be very good for both flow and sediment on both calibration and validation periods.

Sediment yield estimated with the SWAT model was found to correlate reasonably well with soil, land use, and topography for each HRU. The long-term mean annual average catchment sediment yield is 6.9 and 4.8 t/ha/year for sub-basins of Maki and Katar, respectively. Based on the sediment yield of the sub-basins, potential sediment source areas for catchment prioritization and erosion control were identified. All the sub-basins identified as source areas for sedimentation were typified by a single soil type and one land use class with different terrain slopes. This indicates that the variation of sediment yield is more sensitive to terrain slopes due to poor land management in high slope areas. Furthermore, the research showed that the best option to reduce the sediment flow of the basin is applying a soil conservation activity that reduces the basin slope length. For a scenario that reduces the slope length of the watershed by 50% for slopes greater than 5%, the sediment yield of the basin is reduced by 55%. The comparison of lake sedimentation rate from the SWAT model and old lake bathymetry differencing indicates the existence of overestimation by the model. This is slightly over estimating as compared with bathymetry results. The expected reasons for this variation are deposition of sediment on floodplain, the existence of outlet for the lake, presence of gentle slope on ungauged parts of the basin, and abstraction of sediments (sand) from the tributary rivers.

To reduce the environmental degradation of the basin and prolong the useful life of the lake, a systematic plan and policy will be needed. Hence, the developed map (Figure 8) that shows the high erosion area is a tool for decision makers to implement suitable soil conservation measures on selected areas. On selected hotspot erosion areas, the required treatments may include practicing strip planting, terracing, or contour farming to reduce the effect of slope on surface runoff flow velocity and sediment transport capacity.

References

1. Gashaw, T.; Tulu, T.; Argaw, M. Erosion risk assessment for prioritization of conservation measures in Geleda atershed, Blue Nile basin, Ethiopia. *Environ. Syst. Res.* **2017**, *6*, 1–14. [CrossRef]
2. Elsawwaf, M.; Willems, P. Analysis of the climate variability on Lake Nasser evaporation based on the Bowen ratio energy budget method. *J. Environ. Biol.* **2012**, *33*, 475–485. [PubMed]
3. Blinkov, I.; Kostadinov, S. Applicability of various erosion risk assessment methods for engineering purposes. In Proceedings of the BALWOIS 2010, Ohrid, Macedonia, 25–29 May 2010.
4. Ayele, G.T.; Teshale, E.Z.; Yu, B.; Rutherfurd, I.D.; Jeong, J. Streamflow and Sediment Yield Prediction for Watershed Prioritization in the Upper Blue Nile River Basin, Ethiopia. *Water* **2017**, *9*, 782. [CrossRef]
5. Yu, B.; Neil, D. Temporal and spatial variation of sediment yield in the Snowy Mountains region, Australia. In *Variability in Stream Erosion and Sediment Transport*; IAHS Publ. No. 224; International Association of Hydrological Sciences (IAHS): London, UK, 1994.
6. Marttila, H.; Bjørn, K. Dynamics of erosion and suspended sediment transport from drained peatland forestry. *J. Hydrol.* **2010**, *388*, 414–425. [CrossRef]
7. Arekhi, S.; Niazi, Y.; Kalteh, A. Soil erosion and sediment yield modeling using RS and GIS techniques: A case study, Iran. *Arab. J. Geosci.* **2010**, *5*, 285–296. [CrossRef]
8. Salsabilla, A.; Kusratmoko, E. Assessment of Soil Erosion Risk in Komering Watershed, South Sumatera, Using SWAT Model. In *AIP Conference Proceedings*; American Institute of Physics: College Park, MD, USA, 2017; Volume 1862.
9. Wischmeir, W.H. Predicting Rainfall-erosion Losses from Cropland East of the Rocky Mountain, Guide for Selection of Practices for Soil and Water Conservation. *Agric. Handb.* **1965**, *282*, 47.
10. Nearing, M.; Foster, G.; Lane, L.; Finkner, S. A process-based soil erosion model for USDA-Water Erosion Prediction Project technology. *Trans. Am. Soc. Agric. Biol. Eng.* **1989**, *32*, 1587–1593. [CrossRef]
11. Jones, C.; Dyke, P.; Williams, J.; Kiniry, J.; Benson, V.; Griggs, R. EPIC: An operational model for evaluation of agricultural sustainability. *Agric. Syst.* **1991**, *37*, 341–350. [CrossRef]
12. Young, R.A.; Onstad, C.A.; Bosch, D.D.; Anderson, W.P. AGNPS: A nonpoint-source pollution model for evaluating agricultural watersheds. *J. Soil Water Conserv.* **1989**, *44*, 168–173.
13. Beasley, D.; Huggins, L.; Monke, E. ANSWERS: A model for watershed planning. *Trans. ASAE* **1980**, *23*, 938–944. [CrossRef]
14. Morgan, R.; Quinton, J.; Smith, R.; Govers, G.; Poesen, J.; Auerswald, K.; Chisci, G.; Torri, D.; Styczen, M. The European Soil Erosion Model (EUROSEM): A dynamic approach for predicting sediment transport from fields and small catchments. *Earth Surf. Process. Landf.* **1998**, *23*, 527–544. [CrossRef]
15. Knisel, W. *CREAMS: A Field-Scale Model for Chemicals, Runoff and Erosion from Agricultural Management Systems*; United States Department of Agriculture (USDA): Washington, DC, USA, 1980; 640p.
16. Arnold, J.G.; Srinivasan, R.; Muttiah, R.S.; Williams, J.R. Large Area Hydrologic Modeling and Assessment Part I: Model Development. *J. Am. Water Resour. Assoc.* **1998**, *34*, 73–89. [CrossRef]
17. Dennis, M.; Rorke, M. The relationship of soil loss by interill erosion to slope gradient. *Catena* **2000**, *38*, 211–222. [CrossRef]
18. Kinnell, P. AGNPS–UM: Applying the USLE–M within the agricultural nonpoint source pollution. *Environ. Model. Softw.* **2000**, *15*, 331–341. [CrossRef]
19. Lim, K.J.; Sagong, M.; Engel, B.A.; Tang, Z.; Choi, J.; Kim, K.-S. GIS-based sediment assessment tool. *CATENA* **2005**, *64*, 61–80. [CrossRef]

20. Bisantino, T.; Bingner, R.; Chouaib, W.; Gentile, F.; Trisorio Liuzzi, G. Estimation of runoff, peak discharge and sediment load at the event scale in a medium-size mediterranean watershed using the Annagnps Model: An AGNPS evaluation for runoff, peak discharge and sediment load. *Land Degrad. Dev.* **2015**, *26*, 340–355. [CrossRef]

21. Taguas, E.V.; Gómez, J.A.; Denisi, P.; Mateos, L. Modelling the rainfall-runoff relationships in a large olive orchard catchment in Southern Spain. *Water Resour. Manag.* **2015**, *29*, 2361–2375. [CrossRef]

22. Arnold, J.; Fohrer, N. SWAT2000: Current capabilities and research opportunities in applied watershed modelling. *Hydrol. Process.* **2005**, *19*, 563–572. [CrossRef]

23. Chu, T.W.; Shirmohammadi, A.; Montas, H.; Sadeghi, A. Evaluation of the SWAT model sediment and nutrient components in the piedmont physiographic region of Maryland. *Trans. ASAE* **2004**, *47*, 1523–1538. [CrossRef]

24. Muleta, M.K.; Nicklow, J.W. Decision support for watershed management using evolutionary algorithms. *J. Water Resour. Plan. Manag.* **2005**, *131*, 35–44. [CrossRef]

25. Jha, M.K.; Gassman, P.W.; Arnold, J.G. Water quality modeling for the Raccoon River watershed using SWAT. *Trans. ASABE* **2007**, *50*, 479–493. [CrossRef]

26. Dessu, S.; Melesse, A.M.; Bhat, M.; McClain, M.E. Assessment of water resources availability and demand in the Mara River basin. *CATENA* **2014**, *115*, 104–114. [CrossRef]

27. Dessu, S.; Melesse, A.M. Modelling the rainfall–runoff process ofthe Mara River basin using the soil and water assessment tool. *Hydrol. Process.* **2012**, *26*, 4038–4049. [CrossRef]

28. Dessu, S.; Melesse, A.M. Impact and uncertainties of climate change on the hydrology of the Mara River basin, Kenya/Tanzania. *Hydrol Process.* **2013**, *27*, 2973–2986. [CrossRef]

29. Setegn, S.; Dargahi, B.; Srinivasan, R.; Melesse, A.M. Modeling of sediment yield from Anjeni-Gauged Watershed, Ethiopia using SWAT model. *J. Am. Water Resour. Assoc.* **2010**, *46*, 514–526. [CrossRef]

30. Setegn, S.; Srinivasan, R.; Dargahi, B.; Melesse, A.M. Spatial delineation of soil erosion vulnerability in the Lake Tana Basin, Ethiopia. *Hydrol. Process.* **2009**, *23*, 3738–3750. [CrossRef]

31. Setegn, S.G.; Rayner, D.; Melesse, A.M.; Dargahi, B.; Srinivasan, R. Impact of climate change on the Hydroclimatology of Lake Tana Basin, Ethiopia. *Water Resour. Res.* **2011**, *47*, W04511. [CrossRef]

32. Setegn, S.G.; Srinivasan, R.; Melesse, A.M.; Dargahi, B. SWAT model application and prediction uncertainty analysis in the Lake Tana Basin, Ethiopia. *Hydrol. Process.* **2010**, *24*, 357–367. [CrossRef]

33. Yesuf, H.M.; Assen, M.; Alamirew, T.; Melesse, A.M. Modeling of sediment yield in Maybar gauged watershed using SWAT; Northeast Ethiopia. *CATENA* **2015**, *127*, 191–205. [CrossRef]

34. Nguyen, V.; Dietrich, J.; Uniyal, B.; Tran, D.; Nguyen, V.T.; Dietrich, J.; Uniyal, B.; Tran, D.A. Verification and correction of the hydrologic routing in the soil and water assessment tool. *Water* **2018**, *10*, 1419. [CrossRef]

35. Parajuli, P.B.; Nelson, N.O.; Frees, L.D.; Mankin, K.R. Comparison of AnnAGNPS and SWAT model simulation results in USDA-CEAP agricultural watersheds in south-central Kansas. *Hydrol. Process.* **2009**, *23*, 748–763. [CrossRef]

36. Qi, Z.; Kang, G.; Chu, C.; Qiu, Y.; Xu, Z.; Wang, Y. Comparison of SWAT and GWLF model simulation performance in humid south and semi-arid north of China. *Water* **2017**, *9*, 567. [CrossRef]

37. Li, D.; Qu, S.; Shi, P.; Chen, X.; Xue, F.; Gou, J.; Zhang, W.; Li, D.; Qu, S.; Shi, P.; et al. Development and integration of sub-daily flood modelling capability within the SWAT model and a comparison with XAJ model. *Water* **2018**, *10*, 1263. [CrossRef]

38. Chang, C.-H.; Harrison, J.F.; Huang, Y.-C.; Chang, C.-H.; Harrison, J.F.; Huang, Y.-C. Modeling typhoon-induced alterations on river sediment transport and turbidity based on dynamic landslide inventories: Gaoping River Basin, Taiwan. *Water* **2015**, *7*, 6910–6930. [CrossRef]

39. Guo, S.; Zhu, Z.; Lyu, L.; Guo, S.; Zhu, Z.; Lyu, L. Effects of climate change and human activities on soil erosion in the Xihe River Basin, China. *Water* **2018**, *10*, 1085. [CrossRef]

40. Mishra, Y.; Nakamura, T.; Babel, M.S.; Ninsawat, S.; Ochi, S.; Mishra, Y.; Nakamura, T.; Babel, M.S.; Ninsawat, S.; Ochi, S. Impact of climate change on water resources of the Bheri River Basin, Nepal. *Water* **2018**, *10*, 220. [CrossRef]

41. Grey, O.; St, F.; Webber, D.; Setegn, S.; Melesse, A.M. Application of the soil and water assessment tool (SWAT model) on a small tropical island (Great River watershed, Jamaica) as a tool in integrated watershed and coastal zone management. *Int. J. Trop. Biol. Conserv.* **2014**, *62*, 293–305.

42. Melesse, A.M.; Graham, W.D.; Jordan, J.D. Spatially distributed watershed mapping and modeling: GIS-based storm runoff and hydrograph analysis: (part 2). *J. Spat. Hydrol.* **2003**, *3*, 2–28.

43. Anwar, A.A.; Seifu, A.T.; Essayas, K.A.; Abeyou, W.W.; Tewodros, T.A.; Shimelis, B.D.; Melesse, A.M. Climate change impact on sediment yield in the upper Gilgel Abay Catchment, Blue Nile Basin, Ethiopia. In *Landscape Dynamics, Soils and Hydrological Processes in Varied Climates*; Springer International Publishing: Basel, Switzerland, 2015; Volume 7, pp. 615–644.

44. Arnold, J.G.; Williams, J.R.; Maidment, D.R. Continuous-time water and sediment-routing model for large basins. *J. Hydraul. Eng.* **1995**, *121*, 171–183. [CrossRef]

45. Maalim, F.K.; Melesse, A.M. Modelling the impacts of subsurface drainage on surface runoff and sediment yield in the Le Sueur Watershed, Minnesota, USA. *Hydrol. Sci. J.* **2013**, *58*, 570–586. [CrossRef]

46. Mekonnen, M.; Melesse, A.M. Soil erosion mapping and hotspot area identification using GIS and remote sensing in Northwest Ethiopian Highlands, Near Lake Tana. In *Nile River Basin*; Springer: Dordrecht, The Netherlands, 2011; pp. 207–224. ISBN 978-94-007-0688-0.

47. Wang, X.; Garza, J.; Whitney, M.; Melesse, A.; Yang, W. Prediction of sediment source areas within watersheds as affected by soil data resolution. In *Environmental Modelling*; Nova Science Publishers, Inc.: Hauppauge, NY, USA, 2008; pp. 151–185.

48. Hunink, J.; Niadas, I.; Antonaropoulos, P.; Droogers, P.; de Vente, J. Targeting of intervention areas to reduce reservoir sedimentation in the Tana catchment (Kenya) using SWAT. *Hydrol. Sci. J.* **2013**, *58*, 1–15. [CrossRef]

49. Msaghaa, J.J.; Melesse, A.M.; Ndomba, P.M. Modeling sediment dynamics: Effect of land use, topography, and land management in the Wami-Ruvu Basin, Tanzania. In *Nile River Basin*; Springer: Cham, Switzerland, 2014; pp. 165–192. ISBN 978-3-319-02719-7.

50. Msaghaa, J.J. Sediment yield modeling and dentification of erosion hotspots in Tropical Watersheds: The case of upper Ruvu Catchment in Tanzania. Master's Thesis, Florida International University, University Park, FL, USA, 2015.

51. Haregeweyn, N.; Berhe, A.; Tsunekawa, A.; Tsubo, M.; Meshesha, D.T. Integrated watershed management as an effective approach to curb land degradation: A case study of the Enabered Watershed in Northern Ethiopia. *Environ. Manag.* **2012**, *50*, 1219–1233. [CrossRef] [PubMed]

52. Osore, A.; Moges, A. Extent of gully erosion and farmer's perception of soil erosion in Alalicha Watershed, Southern Ethiopia. *J. Environ. Earth Sci.* **2014**, *4*, 74–81.

53. Tongul, H.; Hobson, M. *Scaling up an Integrated Watershed Management Approach through Social Protection Programmes in Ethiopia: The MERET and PSNP Schemes*; Food and Agriculture Organization: Rome, Italy, 2013.

54. Legesse, D. Analysis of the Hydrological Response of the Ziway–Shala Lake Basin (Main Ethiopian Rift) to Changes in Climate and human Activities. Ph.D. Thesis, Aix-Marseille University, Aix-en-Provenece, France, 2002.

55. Ayenew, T. The Hydrogeological System of the Lake District Basin, Central Main Ethiopian Rift. Ph.D. Thesis, Free University of Amsterdam, Amsterdam, The Netherlands, 1998.

56. Makin, M.J.; Kingham, T.J.; Waddams, A.E.; Birchall, C.J.; Eavis, B.W. *Prospects for Irrigation Development around Lake Zwai, Ethiopia*; Wageningen University and Research: Wageningen, The Netherlands, 1976.

57. Federal Democratic Republic of Ethiopia Ministry of Water Resources (MOWR): Rift Valley Lakes Basin Integrated Resources Development Master Plan Study Project. Integrated Watershed Management of Western Lake Ziway Sub-basin Prefeasibility Study. Part II Prefeasibility Studies. Addis Ababa, Ethiopia. Unpublished work. 2010.

58. Neitsch, S.; Arnold, J.; Kiniry, J.; Williams, J. *Soil and Water Assessment Tool Theoretical Documentation Version 2009*; Texas Water Resources Institute: College Station, TX, USA, 2011.

59. Setegn, S.G.; Melesse, A.M.; Wang, X.; Vicioso, F.; Nunez, F. *Calibration and Validation of ArcSWAT Model for Prediction of Hydrological Water Balance of Rio Haina Basin, Dominica Republic*; GIS & Water Resources: Orlando, FL, USA, 2010; Volume VI.

60. Williams, J. Sediment-yield prediction with Universal Equation using runoff energy factor. In *Present and Prospective Technology for Predicting Sediment Yield and Sources*; U.S. Department of Agriculture: Washington, DC, USA, 1975; Volume ARS-S-40, pp. 244–252.

61. Sharply, A.; Williams, J. *EPIC-Erosion/Productivity Impact Calculator I, Model Documentation*; United States Department of Agriculture: Washington, DC, USA, 1990.

62. Stefan, L. *Program pcpSTAT: User's Manual*; Scribd, Inc.: San Francisco, CA, USA, 2003.

63. Church, M. Bed material transport and the morphology of Alluvial River Channels. *Annu. Rev. Earth Planet. Sci.* **2006**, *34*, 325–354. [CrossRef]

64. Limgis, L. *Winter School on Essentials in Limnology and Geographic Information System (GIS)*; Centre for Ecological Sciences: Karnataka, India, 2001.

65. Hajigholizadeh, M.; Melesse, A.M.; Fuentes, H.R. Erosion and sediment transport modelling in shallow waters: A review on approaches, models and applications. *Int. J. Environ. Res. Public Health* **2018**, *15*, 518. [CrossRef] [PubMed]

66. Yesuf, H.; Alamirew, T.; Melesse, A.; Assen, M. Bathymetric mapping for Lake Hardibo in Northeast Ethiopia using sonar. *Int. J. Water Sci.* **2012**, *1*, 1–9. [CrossRef]

67. Yesuf, H.; Alamirew, T.; Melesse, A.; Assen, M. Bathymetric study of Lake Hayq, Ethiopia. *Lakes Reserv. Res. Manag.* **2013**, *18*, 155–165. [CrossRef]

68. Santhi, C.; Arnold, J.; Williams, J.R.; Dugas, W.; Srinivasan, R.; Hauck, L. Validation of the SWAT model on a large river basin with point and nonpoint sources. *J. Am. Water Resour. Assoc.* **2001**, *37*, 1169–1188. [CrossRef]

69. Moriasi, D.N.; Arnold, J.G.; Liew, M.W.V.; Bingner, R.L.; Harmel, R.D.; Veith, T.L. Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Trans. ASABE* **2007**, *50*, 885–900. [CrossRef]

70. Walling, D.; Hadley, R..; Lal, R.; Onstad, C.; Yair, A. *Recent Developments in Erosion and Sediment Yield Studies*; UNESDOC: Paris, France, 1985.

71. Hurni, H. Land degradation, famine, and land resource scenarios in Ethiopia. In *World Soil Erosion and Conservation*; Cambridge University Press: Cambridge, UK, 1993; pp. 27–62.