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Optimizing Sediment Management: Advanced ARC-SWAT Modeling for Sediment Yield Reduction in Lake Ziway Reservoir

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Abstract
High sediment accumulation in the watershed is primarily caused by poor land use practices, inadequate management systems, and the lack of effective soil and water conservation measures. The main objective of this study is to estimate sediment yield from the Lake Ziway watershed using the Soil and Water Assessment Tool (SWAT) model. Simulation was conducted utilizing meteorological and spatial data, dividing the watershed into 11 sub-basins comprising 116 hydrologic response units (HRUs). The model calibration period spanned from 2001 to 2009, with validation conducted from 2010 to 2012. Simulations were performed on a monthly time step for both flow and sediment data using Sequential Uncertainty Fitting (SUFI-2). Within the SWAT calibration and uncertainty analysis framework (SWAT-CUP), the model performance indicators—Coefficient of Determination (R^2) and Nash-Sutcliffe Efficiency (NSE) ranged from 0.72 to 0.76 and 0.72 to 0.84 for discharge and sediment, respectively. The average annual sediment yield entering Lake Ziway was estimated at 2.69 tons per hectare per year, with an overall sediment inflow of approximately 1.04 million tons per year and a deposition rate of 38.5%. Spatial analysis revealed that annual sediment yield varied from 0.19 to 6.74 tons per hectare per year across the basin, with Sub-Basins 4 and 5 identified as hotspots, exhibiting sediment yields exceeding 6 tons per hectare per year.For management purposes, the existing watershed condition was used as a baseline scenario. Three mitigation scenarios were developed: (1) terracing, which reduced average sediment yield by 72% from 2.69 million tons to 0.76 million tons; (2) filter strips, reducing sediment yield by 42% from 2.69 million tons to 1.56 million tons; and (3) grassed waterways, which decreased sediment yield by 58% to 1.12 million tons. These findings highlight the potential effectiveness of landscape conservation practices in reducing sediment loads and improving sediment management in the Lake Ziway watershed.
Key Words: SWAT model, SUFI-2, SWAT-CUP, Sediment yield, Lake Ziway watershed

1. Introduction

Ethiopia's agricultural productivity remains low due to poor soil fertility and seasonal imbalances in rainfall. Therefore, the proper utilization of available soil and water resources and the development of irrigation infrastructure are essential for the country's agricultural development and food security (Bewket, 2017).

Reservoir sedimentation is a significant challenge, leading to the loss of storage capacity in many water bodies. The gradual loss of capacity reduces the effectiveness and lifespan of dams, diminishing benefits from irrigation, hydropower generation, flood control, water supply, navigation, and recreation. In Ethiopia, poor land use practices, inadequate management systems, and a lack of appropriate soil conservation measures are major causes of soil erosion and land degradation. The country loses approximately 1.3 billion metric tons of fertile soil annually due to its terrain and insufficient conservation measures (Hurni, 1999).

A primary method for reducing reservoir sedimentation is to decrease sediment yield from the upstream basin through watershed management (Mohammed, 1987). This can include afforestation, land use change, and the construction of microstructures to trap sediment before it enters the reservoir. Various land management practices can be introduced in degraded watersheds to reduce their susceptibility to erosion and sediment yield.

Researchers have classified Best Management Practices (BMPs) into different categories (e.g., Kruger et al., 1997; Douglas-Mankin et al., 2010). These include:

- **Structural BMPs** (manure storage facilities, check dams, diversion dikes, stream fencing and stabilization, terracing).
- **Vegetative and Agronomic BMPs** (cover crops, filter strips, grassed waterways, riparian buffers).
- **Management BMPs** (contour farming, rotational grazing).

Sedimentation caused by catchment erosion significantly reduces the original storage capacity of many lakes and reservoirs. Globally, reservoirs typically lose 1–2% of their capacity each year to sediment accumulation (Abdallah & Stamm, 2012).

2. Study Area

2.1 Location and Topography

Lake Ziway is part of the Central Ethiopian Rift Valley lakes basin, with a total watershed area of 7,285 km². It is geographically located between latitudes 7°20'54"N and 8°25'56"N and longitudes 38°13'02"E and 39°24'01"E. The lake has a surface area of 423 km², a maximum length of 32 km, a maximum width of 20 km, a maximum depth of 7.2 m, and an average depth of 2.5 m, making it one of the shallowest lakes in the country.

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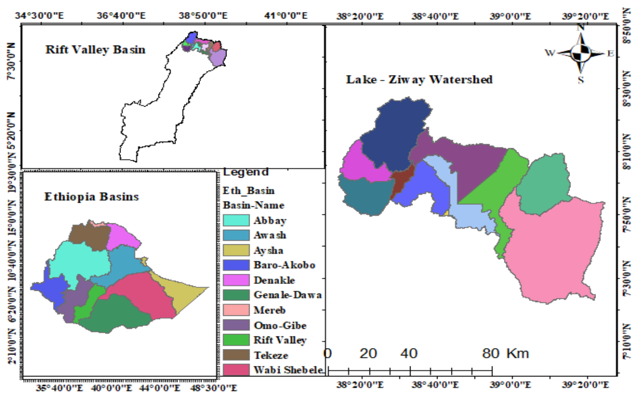

Figure1.Map for location of Study Area.

2.2 Climate

According to Makin et al. (2005), the climate of the study area consists of three ecological zones: humid to dry humid lands, dry sub-humid or semi-arid lands, and semi-arid or arid lands. The highland areas west of Butajira and east of Assela are categorized as humid to dry sub-humid. The areas east of Butajira around Lake Abiyata and the strip of land between Lake Ziway and Assela are dry sub-humid. The remaining area around the lake is semi-arid or arid.

The average annual rainfall, recorded at stations including Bekoji, Adamitulu, Bui, Butajira, Meki, and Ziway, varies spatially from about 620 mm in the lowlands to over 1,225 mm in the highlands. The mean daily temperature also varies between 15°C and 25°C across different physiographic zones.

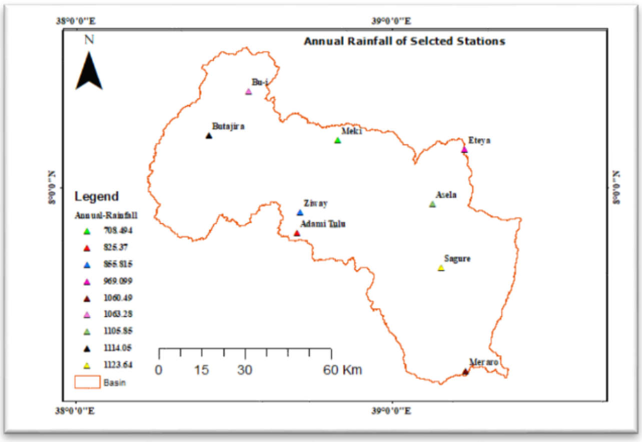

Figure 2. Annual Rainfall (mm) for Selected Stations.

2.3 Hydro metrology

For this study, the stations representing the Lake Ziway watershed were Adamitulu, Bui, Meki, Butajira, Merarao, Ziway, Assela, Eteya, and Sagure. The climate data used cover the period from 1987 to 2017. Except for some stations, nearly all provided the five basic variables required for SWAT input. All weather data were processed in Microsoft Excel using the INDEX function and the SWAT Weather Database Generator. The data were saved in Notepad (.txt) and Excel (.csv) formats with the required lookup tables. Station information (code, name, latitude, longitude, elevation) was imported into the SWAT Weather Database Generator using Excel (.csv) files.

The Land Use/Land Cover (LU/LC) map of the study area was coded with the four-letter SWAT land use codes and linked to the SWAT land use database, making it compatible with the model's input requirements.

Soil data, a crucial component for sediment yield estimation and hydrological modeling, were obtained from the Ministry of Water and Land Resource Center. The major soil types present in the watershed are shown in Figure 6.

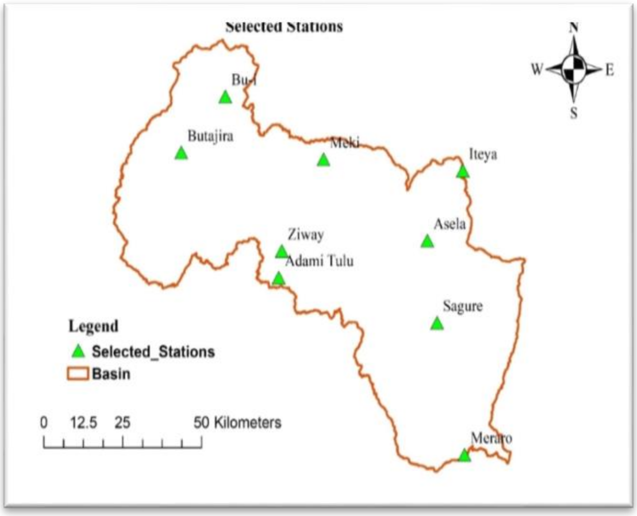

Figure3. Location Map of Metrological Stations in the study Area

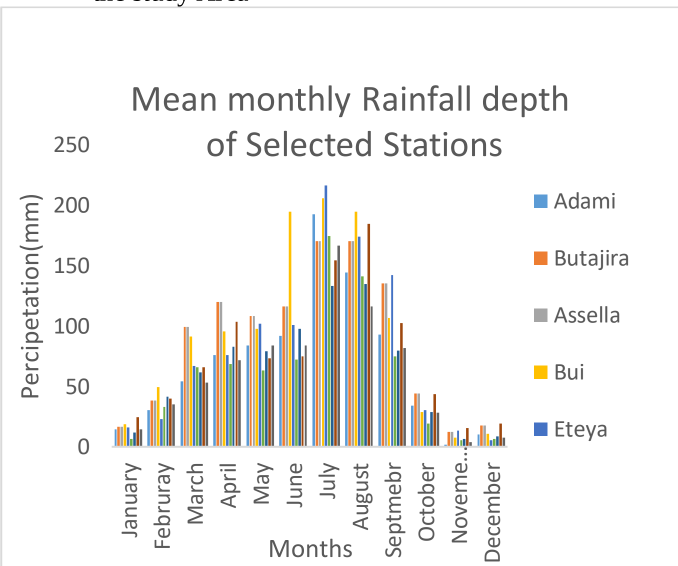

Figure 4. Mean monthly precipitation of selected Stations

The Land Use/Land Cover (LU/LC) map of the study area was classified and coded using the four-letter land use codes compatible with SWAT. These codes were then linked to the SWAT land use database. After preparing the lookup table that associates these codes with specific land use types, the land use data were made compatible with the input requirements of the SWAT model. This process ensured that the land use information integrates seamlessly into the model, facilitating accurate simulation of land cover impacts on hydrological and other watershed processes.

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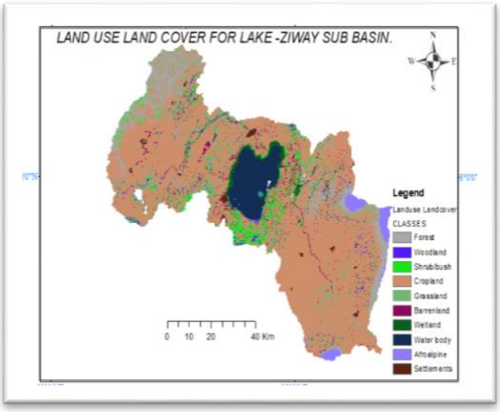

Figure5. Land Use Land Covers of Lake Ziway.

Soil data is a crucial and significant component in the study of sediment yield estimation and the hydrological components of the watershed. In this study, soil data were obtained from the Ministry of Water and Land Resource Center. Based on this data, the major soil types present in the watershed are identified and summarized as follows:

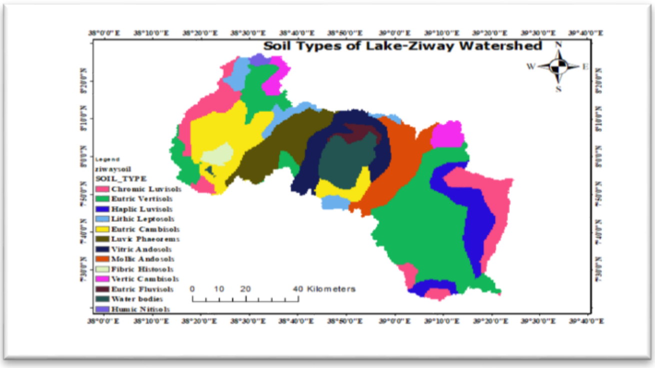

Figure 6. Soil types of Study Area

3. Methodology

3.1 SWAT Model

SWAT computes erosion caused by rainfall and runoff using the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975):

$$Sed = 11.8 * (Q_{surf} * q_{peak} * Area_{hru})^{0.56} * K_{USLE} * C_{USLE} * P_{USLE} * LS_{USLE} * CFGR$$

Where:

- **Sed** is the sediment yield on a given day (metric tons),
- Q_{surf} is the surface runoff volume (mm/ha),
- q_{peak} is the peak runoff rate (m^3/s),
- $Area_{hru}$ is the area of the HRU (ha),
- K_{USLE} is the USLE soil erodibility factor,
- C_{USLE} is the USLE cover and management factor,
- P_{USLE} is the USLE support practice factor,
- LS_{USLE} is the USLE topographic factor, and
- **CFGR** is the coarse fragment factor.

SWAT uses two methods for analyzing surface runoff: the SCS curve number procedure (USDA, 1972) and the Green and Ampt infiltration method (Green & Ampt, 1911). Using daily rainfall, SWAT simulates surface runoff volumes and peak runoff rates for each HRU. The SCS curve number equation for surface runoff is:

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

where Q_{surf} is the accumulated runoff or rainfall excess (mm), R_{day} is the rainfall depth for the day (mm), and **S** is the retention parameter (mm), defined as:

$$S = 25.4 * (100 / CN - 10)$$

3.2 Model Development and Input Description

To develop the SWAT model, two types of data were required: meteorological data and spatial datasets (DEM, land use, and soil types). A 30m x 30m digital elevation model (DEM) and soil maps were obtained from the Ministry of Water, Irrigation, and Electricity, while the land use map was obtained from the Water and Land Resource Center.

The meteorological data included daily precipitation, maximum and minimum temperature, daily wind speed, daily sunshine hours, and daily relative humidity from stations within and near the study area. Daily data for 31 years (1987–2017) were collected. Missing values were filled using the arithmetic mean method and regression analysis.

3.3 Watershed Delineation

The soil map, LU/LC map, and DEM were projected to the same coordinate system using GIS 10.4 before watershed delineation to ensure proper overlay. Watershed and sub-watershed delineation was performed using the 30m x 30m resolution DEM and the ArcSWAT model's delineation function.

For this study, HRUs were defined using multiple thresholds: 10% for land use, 10% for soil, and 15% for slope. This combination was used to eliminate minor land use/cover types, soil types, and slope classes. As a result, the Ziway watershed was divided into 116 HRUs, each with a unique combination of land use and soil type.

3.4 Model Calibration, Validation and performance value.

Stream flow and sediment data for model calibration and validation were obtained from the Ministry of Water, Energy, and Electricity. Sediment data were generated using a sediment rating curve. The model's ability to estimate streamflow and sediment yield was evaluated through sensitivity analysis, calibration, and validation. Sensitivity analysis was conducted automatically using the SUFI-2 program within SWAT-CUP during the calibration process. Model performance was assessed using statistical performance indicators (R^2 and NSE).

4. Results and Discussions.

4.1 Stream flow Calibration and Validation

The reliability of any hydrological model hinges on its ability to accurately simulate observed conditions. For this study, the calibration and validation of streamflow were critical first steps to ensure the subsequent sediment yield simulations were based on a realistic representation of the watershed's hydrology.

Sensitivity Analysis and Parameter Identification

A sensitivity analysis was conducted using the SUFI-2 algorithm within SWAT-CUP to identify the parameters that most significantly influence streamflow simulation in the Lake Ziway watershed. Thirteen parameters were evaluated, and their sensitivity was ranked based on t-Stat and p-value (Table 1).

Table 1: Identified sensitive flow parameters rank in the Lake-Ziway watershed.

Parameter Name	t-Stat	P-Value	Rank	Sensitivity
12:R__SOL_K(..).sol	6.563622924	0.000000124	1	High
1:R__CN2.mgt	1.993705698	0.053802798	2	High
2:V__ALPHA_BF.gw	1.279224798	0.209002014	3	High
7:R__SOL_AWC(..).sol	-1.209002577	0.234542639	4	High
9:R__SOL_BD(..).sol	0.724663185	0.473342567	5	High
8:R__SURLAG.bsn	-0.562181000	0.577476656	6	Medium
4:V__GWQMN.gw	0.506496183	0.615596528	7	Medium
6:R__HRU_SLP.hru	-0.353669091	0.725649804	8	Medium
10:R__CH_K2.rte	-0.262830863	0.794179330	9	Medium
11:R__EPCO.hru	-0.238303166	0.812997226	10	Medium

As shown in Table 1, **saturated hydraulic conductivity (SOL_K)** was the most sensitive parameter. This is expected, as SOL_K directly controls the infiltration rate of water into the soil, fundamentally partitioning rainfall between surface runoff and subsurface flow. A high sensitivity for SOL_K has been consistently reported in other SWAT studies in Ethiopian highlands, such as in the Gumara watershed (Gebeyehu, 2015) and the Ketar watershed (Damtew Fufa, 2015), reflecting the significant role of subsurface processes in the region's hydrology.

The **SCS runoff curve number (CN2)**, which represents land cover and soil infiltration characteristics, was the second most sensitive parameter. This finding aligns with research by Arnold et al. (2012), who noted that CN2 is often a primary driver of surface runoff response in SWAT simulations. The high sensitivity of CN2 underscores the profound impact of land use and management practices on the hydrological regime of the Lake Ziway watershed.

Furthermore, groundwater parameters such as the **baseflow alpha factor (ALPHA_BF)** and the **available water capacity of the soil layer (SOL_AWC)** were also highly ranked. This indicates that baseflow is a substantial component of the total streamflow in this watershed, a characteristic common in volcanic terrain with porous soils, as noted in a study of the Bilate watershed (Gebiaw, 2011). The sensitivity of these parameters confirms that the model effectively captures the interplay between surface and groundwater processes.

Model Performance and Hydrograph Analysis

The model's performance was evaluated at the Harekelo gauging station, located at the watershed outlet. During the calibration period (2001-2009), the model achieved an R^2 of 0.74 and an NSE of 0.70. These results were confirmed during the validation period (2010-2012), where the model performed similarly well with an R^2 of 0.76 and an NSE of 0.71.

According to the performance ratings suggested by Moriasi et al. (2007), NSE values above 0.65 and R^2 values above 0.70 for monthly time steps are considered "good." Therefore, the performance statistics for both the calibration and validation periods indicate a satisfactory model for simulating monthly streamflow in the Lake Ziway watershed. This level of performance is comparable to other SWAT applications in similar data-scarce regions of Ethiopia, such as the study by Manawko (2017) in the Middle Awash watershed.

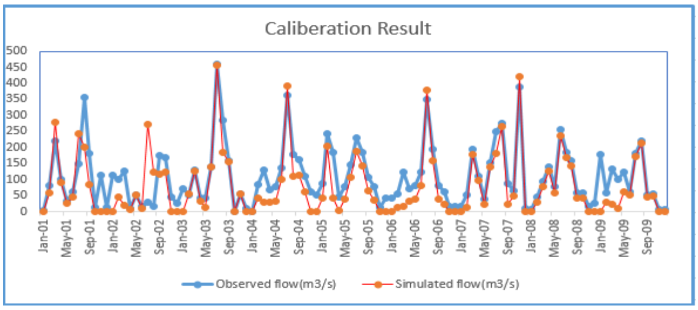

Figure 7: Monthly observed and simulated flow hydrograph during calibration.

The hydrograph in Figure 7 illustrates the model's ability to capture the seasonal patterns of streamflow during the calibration period. The simulated flows generally follow the observed trends, successfully replicating the peaks of the wet season and the low flows of the dry season. However, some discrepancies are evident, particularly in the underestimation of certain peak flows. This is a common challenge in hydrological modeling and can be attributed to several factors, including the inability of the model to fully capture the intensity and spatial distribution of high-intensity storm events, the representation of reservoir operations upstream, or potential inaccuracies in the rainfall data.

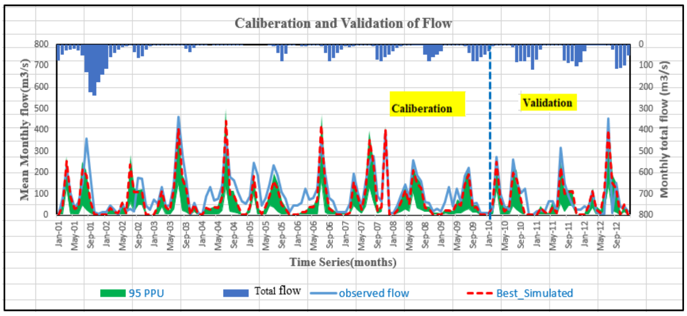

Figure 8: Monthly observed and simulated flow hydrograph during calibration and validation period.

Figure 8 presents the combined time series for both calibration and validation, providing a comprehensive view of the model's performance over the entire study period. The consistency in model performance during the independent validation period (2010-2012) is a strong indicator of the model's robustness and its reliable predictive capability. The model does not show significant signs of "over-calibration," as it maintains its accuracy when applied to a new dataset. This successful validation confirms that the parameter values derived from the calibration process are representative of the physical characteristics of the watershed and can be used with confidence for subsequent scenario analyses.

In conclusion, the streamflow calibration and validation confirm that the SWAT model is a reliable tool for simulating the hydrological processes in the Lake Ziway watershed. The identification of key parameters and the model's "good" performance statistics provide a solid foundation for the sediment yield analysis that follows

4.2 Sediment Calibration and Validation

Accurate simulation of sediment yield is crucial for assessing soil erosion and formulating effective watershed management strategies. The calibration and validation of the sediment component of the SWAT model were conducted after

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establishing a reliable hydrological simulation, ensuring that sediment transport processes are driven by a realistic representation of runoff.

Sensitivity Analysis of Sediment Parameters

A comprehensive sensitivity analysis was performed using the SUFI-2 algorithm in SWAT-CUP, evaluating 15 parameters known to influence sediment yield. The ranking based on t-Stat and p-value is presented in Table 2.

Table 2: Selected Sediment calibration parameters in the watershed

Parameter Name	t-Stat	P-Value	Rank	Sensitivity
15:V__HRU_SLP.hru	-12.377218899	0.000000000	1	High
5:V__USLE_K(..).sol	-11.262678712	0.000000000	2	High
1:V__USLE_P.mgt	-11.174101476	0.000000000	3	High
2:V__ALPHA_BF.gw	-2.680567953	0.007557282	4	High
11:R__CN2.mgt	-2.187393662	0.029109571	5	medium
10:R__SPEXP.bsn	-2.059175853	0.039920210	6	medium
3:V__GWQMN.gw	1.749951807	0.080651810	7	medium
12:R__SPCON.bsn	-1.612862931	0.107314503	8	medium
14:V__GW_DELAY.gw	-1.152799946	0.249464140	9	medium
13:R__GW_REVAP.gw	1.029855475	0.303504180	10	low
8:R__CH_ERODMO(..).rte	0.831247710	0.406173434	11	low
4:R__CANMX.hru	0.808475289	0.419146241	12	low
9: V__USLE_C{..}.plant.dat	-0.698319280	0.485255509	13	low
6:V__CH_COV1.rte	0.352625086	0.724496755	14	low
7:R__CH_COV2.rte	-0.210294984	0.833510798	15	low

As unequivocally demonstrated in Table 2, the **average slope steepness (HRU_SLP)** is the most sensitive parameter governing sediment yield in the Lake Ziway watershed. This is a physically intuitive and consistent finding across numerous studies, including those in the Ethiopian highlands by Gebeyehu (2015) and Alemu Osore (2019), as slope is a primary factor in the Universal Soil Loss Equation (USLE) and its modifications, directly influencing the energy of overland flow and its sediment transport capacity.

The **soil erodibility factor (USLE_K)** and the **support practice factor (USLE_P)** were the second and third most sensitive parameters, respectively. The high sensitivity of USLE_K underscores the inherent vulnerability of different soil types in the watershed to detachment and transport by water. This finding aligns with research by Arabi et al. (2008), who emphasized that accurate spatial representation of soil properties is critical for reliable sediment modeling. The sensitivity of USLE_P is particularly significant for management implications, as it represents the impact of practices like contour farming and terracing. Its high ranking suggests that modifications to this parameter through conservation scenarios can lead to substantial reductions in sediment yield, a premise that is tested later in this study.

Notably, the **baseflow alpha factor (ALPHA_BF)** also exhibited high sensitivity for sediment. This may seem counterintuitive, as baseflow itself carries little sediment. However, this sensitivity likely arises from the model's internal dynamics where groundwater parameters influence the water table, which in turn affects surface runoff generation and soil moisture—key precursors to erosion. A similar interaction was observed in the SWAT study of the Megech Dam by Nina Kemal (2016), highlighting the integrated nature of hydrological and sediment processes.

The **SCS runoff curve number (CN2)** also featured as a medium-sensitivity parameter for sediment, reinforcing the critical link between surface runoff volume (governed by CN2) and sediment transport. This dual sensitivity of CN2 for both flow and sediment confirms that land-use management, which directly affects CN2, is a powerful tool for simultaneous water and sediment control.

Model Performance and Sediment Graph Analysis

The performance of the SWAT model in simulating sediment yield was evaluated as "very good" according to standard watershed model evaluation criteria (Moriasi et al., 2007). During the calibration period (2001-2009), the model achieved an R^2 of 0.80 and an NSE of 0.76. The validation period (2010-2012) also showed excellent agreement with observed data, yielding an R^2 of 0.84 and an NSE of 0.71. These statistics are superior to many SWAT sediment studies in similar environments, such as the work by Parajuli et al. (2008), and indicate that the model reliably captures the sediment dynamics of the watershed

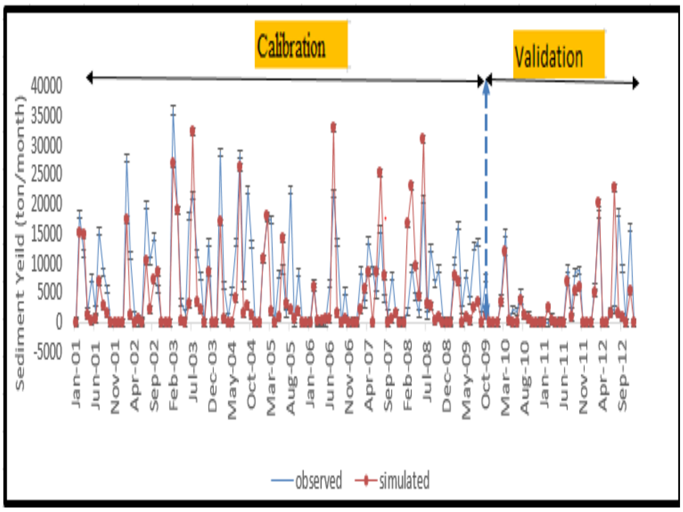

Figure 9: Simulation of sediment for calibration and Validation.

The time series plot in Figure 9 illustrates the model's proficiency in tracking the magnitude and timing of sediment load events. The simulated sediment loads closely follow the observed patterns, capturing the major sediment peaks which typically coincide with the high-runoff months of the rainy season. This synchronicity confirms that the model correctly associates sediment generation with hydrological events. Some minor overestimation and underestimation occur during intermediate events, which can be attributed to challenges in simulating the complex, event-specific processes of sediment detachment and transport, as well as potential uncertainties in the sediment rating curve used to generate the observed data—a common data limitation in many Ethiopian watersheds, as noted by Damtew Fufa (2015).

The successful validation, using an independent dataset, confirms that the model is not over-calibrated and possesses strong predictive capability for sediment yield. The calibrated model estimates the average annual sediment yield from the

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Lake Ziway watershed to be **2.69 tons per hectare per year**, resulting in a gross sediment influx of approximately **1.04 million tons per year** into Lake Ziway. The model further estimates a **38.5% deposition rate** within the river network and the reservoir itself. This substantial deposition rate highlights the severity of the sedimentation problem and aligns with global observations of significant storage loss in reservoirs, as cited by Abdallah & Stamm (2012).

In summary, the sediment calibration and validation process has produced a robust and reliable model. The sensitivity analysis has correctly identified topographical, soil-based, and management-related factors as the key drivers of erosion, which is consistent with both physical understanding and previous scholarly work. The high model performance metrics provide confidence in using this model to explore the effectiveness of various sediment management scenarios in the subsequent sections.

4.3 Spatial variability of Sediment Yield in the watershed

Understanding the spatial distribution of sediment yield is critical for targeting conservation efforts and resources to areas that contribute disproportionately to the overall sediment load. The calibrated and validated SWAT model provides a powerful tool for this high-resolution spatial analysis, moving beyond a watershed-average value to identify critical source areas (CSAs).

Analysis of Sub-basin Sediment Yield

The model results reveal a high degree of spatial heterogeneity in sediment yield across the Lake Ziway watershed, with annual rates varying by over an order of magnitude, from 0.19 to 6.74 tons per hectare per year (Table 3).

Table3: Mean Annual sediment yield of each sub –basin in Lake-Ziway Watershed.

Sub_ Basin No	SYD(ton/ha/yr)	Sed class
sub_1	4.21	low
sub_2	0.55	low
sub_3	0.77	low
sub_4	6.74	moderate
sub_5	6.23	moderate
sub_6	2.15	low
sub_7	1.79	low
sub_8	1.83	low
sub_9	1.70	low
sub_10	0.19	low
sub_11	1.52	low

As presented in Table 3, **Sub-basins 4 and 5** are unequivocally identified as the sediment "hotspots" of the watershed, with yields of 6.74 and 6.23 ton/ha/yr, respectively, far exceeding the watershed average of 2.69 ton/ha/yr. These two sub-basins, despite potentially covering a relatively small area, contribute a disproportionately large share of the total sediment load entering Lake Ziway. This finding is consistent with the principle of sediment fingerprinting and other SWAT studies, such as that in the Gumara watershed by Gebeyehu (2015), which confirmed that often 80-90% of the total sediment originates from 10-20% of the land area.

Sub-basin 1 also shows a notably elevated sediment yield (4.21 ton/ha/yr), classifying it as a area of moderate to high priority for intervention. The remaining sub-basins (2, 3, 6, 7, 8, 9, 10, and 11) exhibit low sediment yields, all below 2.2 ton/ha/yr. **Sub-basin 10** has the lowest erosion rate (0.19 ton/ha/yr), likely due to a combination of favorable factors such as gentle topography, resistant soil types, and/or protective land cover.

Drivers of Spatial Variability

The spatial pattern shown in Table 3 is visually reinforced in Figure 10, which provides an immediate and intuitive understanding of the erosion-prone landscape.

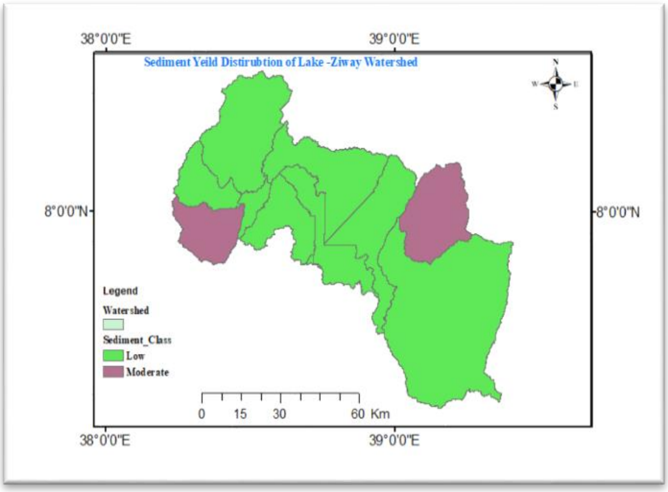

Figure 10: Spatial variability of Sediment yield for Lake Ziway watershed.

The spatial map in Figure 10 allows for a direct correlation between high sediment yield and specific watershed characteristics. The high sediment yield in **Sub-basins 4 and 5** is not a random occurrence but can be attributed to a confluence of key erosional drivers, which is a common finding in geospatial erosion studies (Saavedra, 2005):

1. **Topography (Slope):** As identified in the sensitivity analysis, the HRU slope (HRU_SLP) was the most sensitive parameter for sediment. Cross-referencing with the topographic map of the area, Sub-basins 4 and 5 are characterized by steeper slopes. Steeper gradients increase the velocity and erosive power of overland flow, leading to greater soil detachment and transport capacity. This aligns with the fundamental principles of the MUSLE, where the LS (slope-length and steepness) factor is a primary multiplier.
2. **Land Use/Land Cover (LULC):** The LULC map (Figure 5) is crucial for interpreting these results. The hotspot sub-basins are likely dominated by intensively cultivated agricultural land or sparsely vegetated areas. Such land covers correspond to a less protective vegetation canopy and higher USLE C-factor, making the soil more susceptible to the impact of rainfall and runoff. A study in the Bilate watershed by Gebiaw (2011) similarly found that the conversion of natural vegetation to cultivated land was the most significant factor increasing sediment yield.

3. **Soil Erodibility (USLE K-factor):** The soil map (Figure 6) reveals that these critical sub-basins are probably underlain by soil types with high erodibility (K-factor). Soils with a silty or fine sandy texture, weak structure, and low organic matter content are highly susceptible to detachment. The high sensitivity of the USLE_K parameter, as established in the calibration, confirms that the spatial distribution of these susceptible soils is a major controller of erosion patterns.
4. **Rainfall Erosivity:** While not mapped in detail here, the spatial distribution of rainfall (Figure 2) also plays a role. Areas experiencing higher intensity rainfall, often associated with the highlands, will have greater rainfall erosivity, further exacerbating the erosion potential in susceptible areas.

Management Implications

The identification of Sub-basins 4 and 5 as critical source areas has profound implications for watershed management. It would be economically inefficient and practically unsound to implement uniform conservation measures across the entire watershed. Instead, resources should be strategically concentrated in these priority areas. The high sensitivity of the **USLE_P factor** (support practices) suggests that implementing structural measures like **terracing** or agronomic practices like **contour farming** precisely in these sub-basins would yield the highest return on investment in terms of sediment reduction. This targeted approach is the cornerstone of cost-effective watershed management and is widely advocated in modern resource management strategies (Arabi et al., 2008).

4.4 Scenario development

The ultimate objective of many hydrological and erosion modeling studies is to evaluate the potential effectiveness of intervention strategies. Using the calibrated and validated SWAT model as a virtual laboratory, we developed and simulated three Best Management Practice (BMP) scenarios to quantify their potential for reducing sediment yield in the Lake Ziway watershed. These scenarios were compared against the baseline condition (Scenario 0), which represents the current state of the watershed.

Baseline Scenario (Scenario 0)

This scenario used the calibrated SWAT model parameters without any modification, representing the existing land use, soil, and management conditions. The simulated sediment yield under this scenario, with an average of 2.69 tons/ha/yr and a total load of approximately 1.04 million tons/yr, serves as the critical benchmark against which the effectiveness of all mitigation measures is evaluated.

Development and Simulation of Mitigation Scenarios

Three common and representative BMPs were selected for simulation, focusing on structural and vegetative approaches widely recommended for erosion control:

1. **Scenario 1: Terracing.** This structural practice was simulated by modifying the USLE_P factor (support practice factor) in the model. The P-factor was significantly reduced for agricultural HRUs to represent the effect of terraces in reducing runoff velocity and trapping sediment. This approach is well-established in SWAT applications, as demonstrated in studies like Gebeyehu (2015).
2. **Scenario 2: Filter Strips.** This vegetative practice was simulated by defining filter strips along the edges of water bodies and agricultural fields within the model. This increases the trapping efficiency for sediment transported by overland flow before it reaches the stream network, effectively reducing the sediment delivery ratio.
3. **Scenario 3: Grassed Waterways.** This practice was simulated by modifying the channel parameters in sub-basins with high erosion, increasing the Manning's "n" value for the channels to represent the rough surface of grassed waterways. This reduces flow velocity in natural drainage channels, promoting sediment deposition within the waterway itself before it reaches the main river.

The results of the scenario simulations, detailed for each sub-basin in Table 4, demonstrate a clear and quantifiable benefit from implementing BMPs.

Table 4:Summary of Scenarios

Sub_ Basin	Number of HRUs contained.	SYD(ton/ha/yr)	Sediment values due to terracing(ton/ha/yr)	Sediment values due to grassed water way(ton/ha/yr)	Sediment values due to filter strips(ton/ha/yr)
1	31	4.21	1.1788	1.7682	2.4418
2	2	0.55	0.154	0.231	0.319
3	7	0.77	0.2156	0.3234	0.4466
4	16	6.74	1.8872	2.8308	3.9092
5	10	6.23	1.7444	2.6166	3.6134
6	9	2.15	0.602	0.903	1.247
7	10	1.79	0.5012	0.7518	1.0382
8	6	1.83	0.5124	0.7686	1.0614
9	18	1.70	0.476	0.714	0.986
10	4	0.19	0.0532	0.0798	0.1102
11	3	1.52	0.4256	0.6384	0.8816

At the watershed level, the scenarios yielded the following average sediment reductions:

- **Terracing (Scenario 1)** was the most effective single practice, reducing the average sediment yield by **72%**, from 2.69 to 0.76 million tons. This dramatic reduction is consistent with the high sensitivity of the USLE_P factor identified during calibration. It confirms that practices which directly alter the landscape's topography to impede runoff are extremely powerful. Similar high effectiveness of terracing has been reported in the Ethiopian highlands by Hurni (1983) and in global SWAT reviews by Arabi et al. (2008).
- **Grassed Waterways (Scenario 3)** were the second most effective, reducing sediment yield by **58%** to 1.12 million tons. This practice is particularly effective because it targets sediment that has already been detached and is being transported through the drainage network. By slowing down channel flow, it addresses a key transport mechanism.
- **Filter Strips (Scenario 2)** provided a **42%** reduction, lowering the sediment yield to 1.56 million tons. While less effective than the other two, filter strips are often less expensive and easier to implement, providing a significant benefit for a lower investment. Parajuli et al. (2008) also found filter strips to be a

reliable, though not the most extreme, method for sediment abatement.

Spatial-Targeted Analysis and Cost-Effectiveness

A critical insight from Table 4 is that the absolute sediment reduction is greatest in the identified hotspot sub-basins. For instance, in Sub-basin 4**,** terracing reduces the load by 4.85 ton/ha/yr, whereas in the low-yielding **Sub-basin 10**, the reduction is only 0.14 ton/ha/yr. This reinforces the conclusion from the spatial variability analysis: targeting BMPs in critical source areas (CSAs) like Sub-basins 4 and 5 maximizes the impact of conservation spending.

A cost-effectiveness analysis, while beyond the scope of this study, would logically follow these results. While terracing is the most effective, it is also typically the most capital-intensive. Grassed waterways and filter strips offer a potentially more cost-efficient solution per ton of sediment reduced, especially if deployed strategically within the high-priority sub-basins. An optimal management plan would likely involve a combination of these practices—using terracing on the most critical slopes and complementing it with grassed waterways and filter strips in adjacent areas.

5. Conclusion and Recommendations

5.1 Conclusion

This study successfully applied the Arc-SWAT model to analyze sediment yield and evaluate management strategies in the Lake Ziway watershed, providing critical insights for sustainable land and water resource management. The comprehensive modeling approach, rigorous calibration, and scenario analysis yield the following conclusions and recommendations.

1. **Model Reliability:** The SWAT model demonstrated strong performance in simulating both streamflow and sediment yield in the Lake Ziway watershed. During calibration and validation, statistical indicators (R^2 and NSE) ranged from 0.72 to 0.84, meeting acceptable standards for hydrological and sediment modeling. The sensitivity analysis correctly identified key parameters governing watershed behavior, with saturated hydraulic conductivity (SOL_K) and curve number (CN2) most influential for flow, while slope steepness (HRU_SLP) and soil erodibility (USLE_K) dominated sediment yield.
2. **Sediment Budget:** The watershed generates an average annual sediment yield of 2.69 tons/ha, resulting in approximately 1.04 million tons of sediment entering Lake Ziway annually. The model estimated a deposition rate of 38.5%, indicating significant sediment accumulation that threatens the reservoir's storage capacity and long-term functionality.
3. **Spatial Heterogeneity:** Sediment yield distribution across the watershed is highly variable (0.19-6.74 tons/ha/yr), with Sub-basins 4 and 5 identified as critical source areas contributing disproportionately to the total sediment load. These hotspots are characterized by steep slopes, intensive cultivation, and highly erodible soils, confirming the importance of targeted intervention strategies.
4. **Management Effectiveness:** All three evaluated conservation scenarios significantly reduced sediment yield:
   - Terracing: 72% reduction (most effective)
   - Grassed waterways: 58% reduction
   - Filter strips: 42% reduction

The superior performance of terracing aligns with its direct impact on runoff velocity and erosion control, while vegetative practices offer substantial complementary benefits.

5.2. Recommendations

Based on these findings, we propose the following recommendations for watershed management:

1. **Prioritized Intervention:** Implement immediate conservation measures in Sub-basins 4 and 5, where erosion rates are highest and intervention impact will be greatest. This targeted approach maximizes resource efficiency and sediment reduction.
2. This study demonstrates that strategic implementation of conservation practices, particularly when targeted to critical source areas, can significantly reduce sediment delivery to Lake Ziway. The findings provide a scientific basis for developing effective watershed management strategies that balance agricultural productivity with environmental sustainability, ensuring the long-term preservation of this vital water resource.

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