

Research Article

Prediction of Sediment Yield to Lake Ziway Reservoir and Assessing Reduction methods (Using Arc-swat)

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Abstract

Sediment accumulation in Lake Ziway is an escalating concern driven by poor land use practices, ineffective watershed management, and the absence of adequate soil and water conservation measures. This study aims to estimate sediment yield in the Lake Ziway watershed using the Soil and Water Assessment Tool (SWAT) integrated within ArcGIS. The model was calibrated and validated using meteorological and spatial data across 11 sub-basins and 116 hydrologic response units (HRUs), covering a calibration period from 2001 to 2009 and a validation period from 2010 to 2012. Calibration was performed using the Sequential Uncertainty Fitting version 2 (SUFI-2) algorithm within the SWAT-CUP interface. Model performance was satisfactory, with coefficients of determination (R^2) and Nash–Sutcliffe efficiency (NSE) values ranging from 0.72 to 0.76 for discharge and 0.72 to 0.84 for sediment yield. The average annual sediment yield was estimated at 2.69 tons/ha/year, and the gross sediment inflow into Lake Ziway was calculated at approximately 1.04 million tons/year, with a deposition rate of 38.5%. Sub-basins 4 and 5 were identified as sediment hotspots, with yields exceeding 6 tons/ha/year. Three conservation scenarios were evaluated using the current watershed condition as a baseline: terracing reduced sediment yield by 72%, filter strips by 42%, and grassed waterways by 58%. These results highlight the critical role of soil and water conservation strategies in sustaining Lake Ziway's capacity and ecosystem.

Keywords

SWAT model, SUFI-2, SWAT-CUP, Sediment Yield, Lake Ziway Watershed, Best management Practices, Soil Conservation

1. Introduction

Ethiopia's agricultural productivity remains constrained due to declining soil fertility and erratic rainfall distribution. Effective utilization of the country's soil and water resources is vital for improving agricultural performance and ensuring food security [20].

One of the key threats to water infrastructure in Ethiopia is the sedimentation of reservoirs, which reduces storage capacity and shortens the operational lifespan of dams. This, in

turn, compromises the multiple services provided by reservoirs, including irrigation, hydropower generation, flood control, water supply, navigation, and recreation. The main drivers of sedimentation include deforestation, unregulated land use, overgrazing, and the absence of adequate watershed management practices. As a result, the country loses an estimated 1.3 billion metric tons of fertile topsoil annually [17].

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Sedimentation is a critical environmental and water resource management issue, particularly in lake and reservoir systems across Ethiopia's Rift Valley [2]. Lake Ziway, a vital freshwater resource in the Central Rift Valley, is increasingly threatened by sediment influx from its catchment, driven by both natural processes and intensified anthropogenic activities [6, 26]. Over recent decades, land use and land cover (LULC) changes—primarily the expansion of agriculture and urbanization at the expense of rangeland and forest cover—have significantly altered the hydrological response of the Lake Ziway watershed, accelerating soil erosion and sediment delivery to the lake [9, 18].

The consequences of unchecked sediment yield are profound. Sediment deposition reduces the storage capacity and depth of reservoirs, impairs water quality, and disrupts aquatic habitats, thereby undermining the ecological integrity and socio-economic utility of water bodies like Lake Ziway [5]. For instance, studies indicate that the average annual sediment yield into Lake Ziway has shown a marked increase over the past three decades, rising from 3.59 t/ha/yr in the late 1980s to 4.89 t/ha/yr in the late 2010s, with corresponding sediment deposition rates causing measurable reductions in lake depth and volume [3, 19]. If current trends persist, projections suggest a continued decline in the lake's storage capacity, with potential long-term impacts on water supply, fisheries, and local livelihoods [12, 24].

Understanding and predicting sediment yield is therefore essential for the sustainable management of Lake Ziway and its watershed. However, the spatial and temporal variability of sediment sources, coupled with data scarcity and complex watershed processes, pose significant challenges to accurate assessment and effective intervention [3, 25]. In response, physically-based, distributed hydrological models such as the Soil and Water Assessment Tool (SWAT) have become indispensable tools for simulating watershed hydrology, sediment transport, and evaluating the impacts of land management practices [10, 27]. The integration of SWAT with Geographic Information Systems (GIS), as in the Arc-SWAT interface, enhances the model's capacity to spatially analyze sediment dynamics and identify critical source areas within large and heterogeneous basins [20, 7].

Recent applications of SWAT and Arc-SWAT in Ethiopian watersheds have demonstrated their robustness in simulating streamflow and sediment yield, with model calibration and validation yielding strong performance indicators (R^2 and NSE values often exceeding 0.7) [11, 1]. These models have also been instrumental in assessing the effectiveness of Best Management Practices (BMPs) such as reforestation, contour ploughing, terracing, and filter strips, which have been shown to reduce sediment yield by up to 68% in some scenarios [4, 22]. For Lake Ziway, spatial modeling has iden-

tified agricultural lands on steep slopes as primary sediment sources, while forested and grassland areas contribute significantly less to sediment yield [8, 14].

In addition to modeling, understanding the drivers of sediment yield requires integration of long-term climate variability and land use dynamics [15, 23]. Human-induced watershed changes such as deforestation and unsustainable farming practices continue to exacerbate the problem [17]. Historical data and conservation efforts in Ethiopian highlands further emphasize the need for sustained soil and water management programs [16].

Despite these advances, there remains a pressing need for comprehensive, site-specific studies that integrate high-resolution spatial data, robust model calibration, and scenario analysis to inform sediment management strategies in the Lake Ziway catchment [21]. This research aims to fill this gap by leveraging Arc-SWAT to predict sediment yield to Lake Ziway Reservoir, map sediment source areas, and assess the potential of various sediment reduction methods [13, 28]. The outcomes are expected to support evidence-based watershed management, inform policy, and contribute to the long-term sustainability of Lake Ziway and its ecosystem services [20].

The prediction and management of sediment yield in the Lake Ziway watershed is not only a scientific challenge but also a socio-economic imperative, requiring the integration of advanced modeling tools, spatial analysis, and targeted land management interventions to safeguard this critical water resource for future generations [9, 26].

Despite ongoing research in Ethiopian watersheds, limited studies have applied spatially distributed modeling approaches such as Arc-SWAT to evaluate sediment yield and assess the effectiveness of conservation strategies in the Lake Ziway watershed. This study addresses this gap by using Arc-SWAT to quantify sediment yield, identify hotspot areas, and simulate the impacts of targeted BMPs.

2. Materials and Methods

2.1. Study Area Description

Lake Ziway, located in the Central Ethiopian Rift Valley, has a total catchment area of approximately 7,285 km². Geographically, the watershed spans between 7°20'54" to 8°25'56" N latitude and 38°13'02" to 39°24'01" E longitude. The lake itself has a surface area of 423 km² with a maximum and average depth of 7.2 m and 2.5 m, respectively. Its elongated shape stretches 32 km in length and 20 km in width, making it one of the shallowest lakes in Ethiopia.

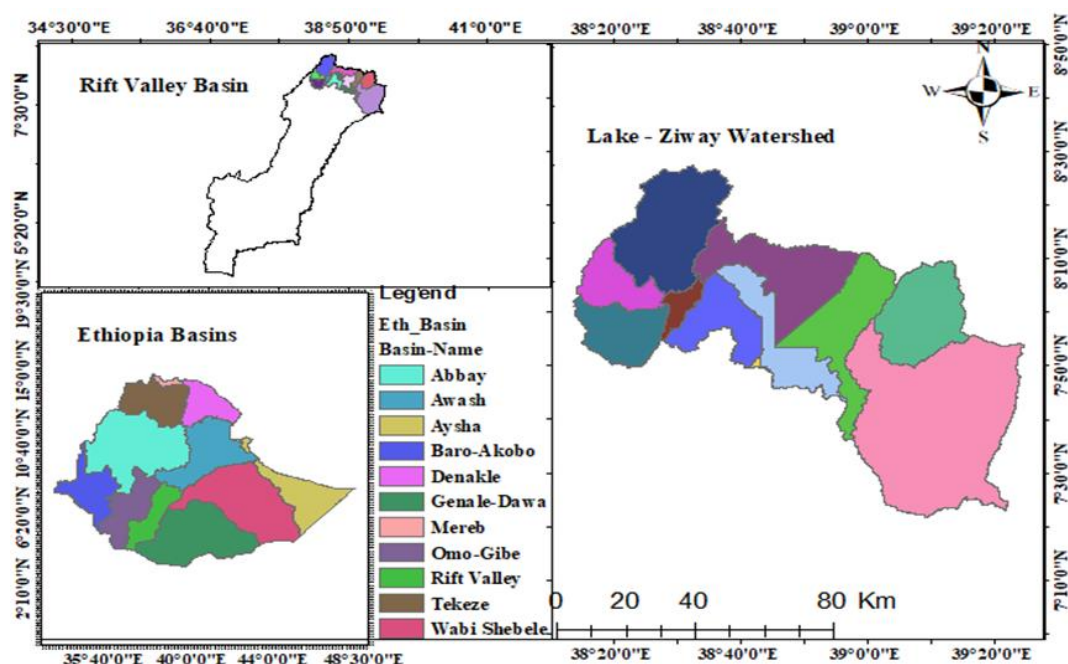


Figure 1. Locationmap of the Lake Ziway watershed.

2.2. Climate Characteristics

The Lake Ziway watershed spans multiple ecological zones:

- 1) Humid to dry humid (western highlands near Butajira and east of Assela),
- 2) Dry sub-humid (central zone between Ziway and As-

sela),

- 3) Semi-arid/arid (lowlands around the lake itself).

Average annual rainfall ranges from 620mm in the lowlands to over 1,225mm in the highlands, while daily temperatures vary between 15 °C and 25 °C across different altitudes.

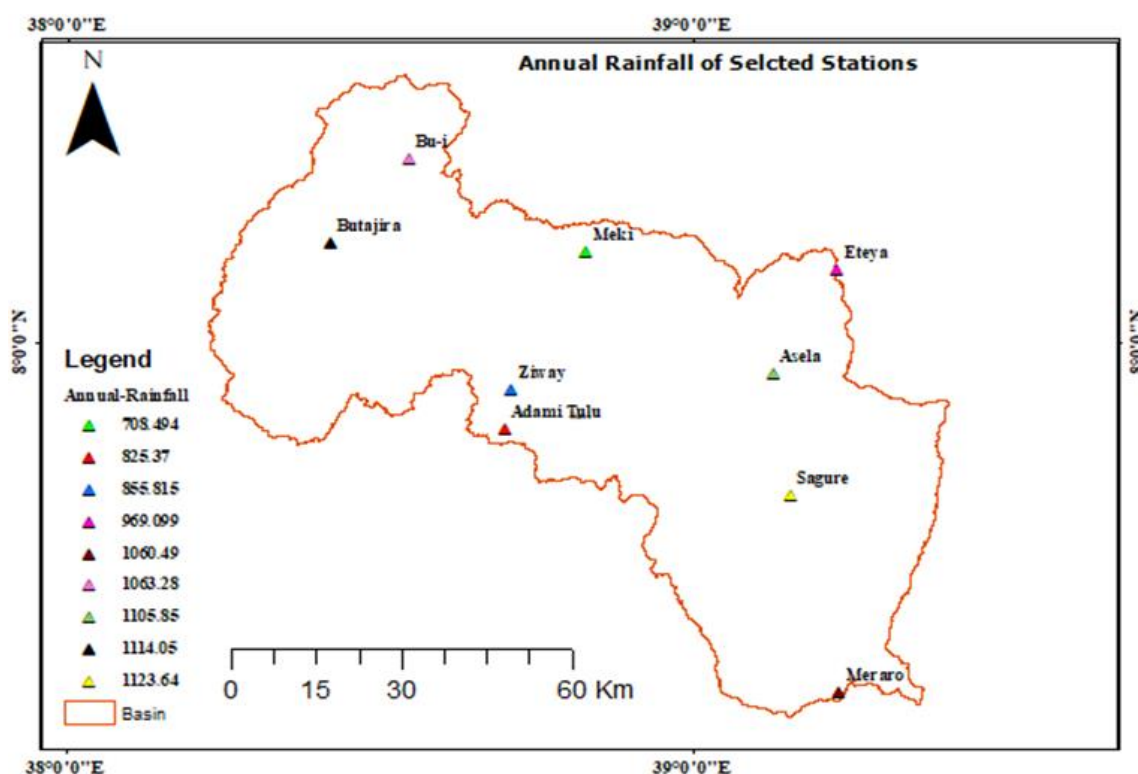


Figure 2. Annual rainfall distribution across selected stations.

2.3. Data Sources and Preparation

2.3.1. Meteorological Data

Daily meteorological data including precipitation, maximum and minimum temperature, relative humidity, wind speed, and solar radiation were collected from the Ethiopian National meteorological Agency for the years 1987–

2017. From 16 available stations, 9 were selected for their data quality and spatial distribution: Adami Tulu, Bui, Meki, Butajira, Meraro, Ziway, Assela, Eteya, and Sagure. Missing data were filled using arithmetic mean and regression methods. Data were formatted into .txt and .csv files using Microsoft Excel and the SWAT Weather Generator.

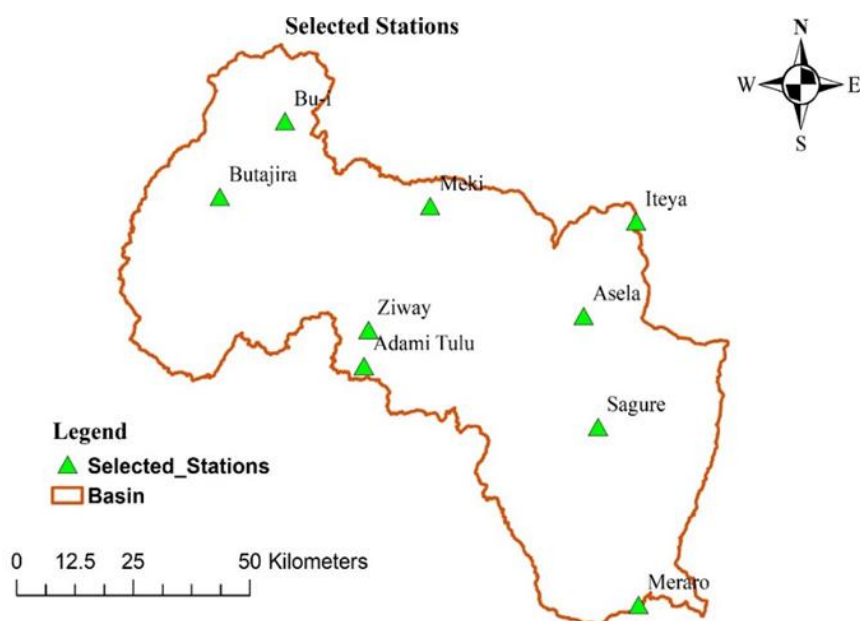


Figure 3. Meteorological station map.

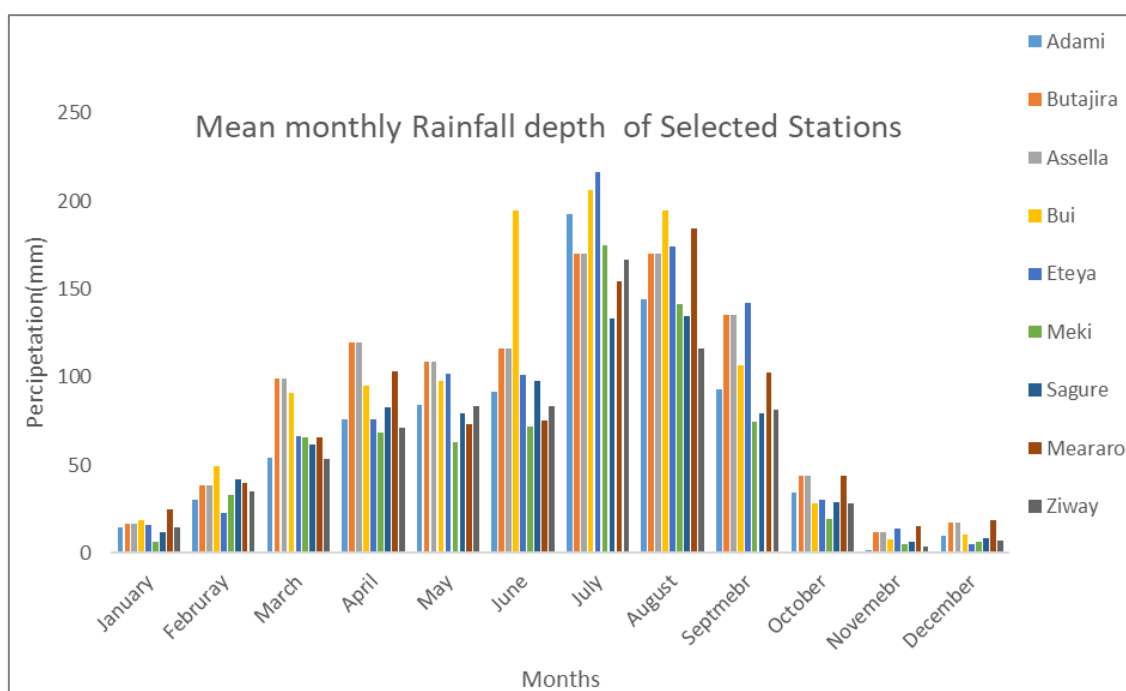


Figure 4. Mean monthly precipitation of selected stations.

2.3.2. Spatial Data

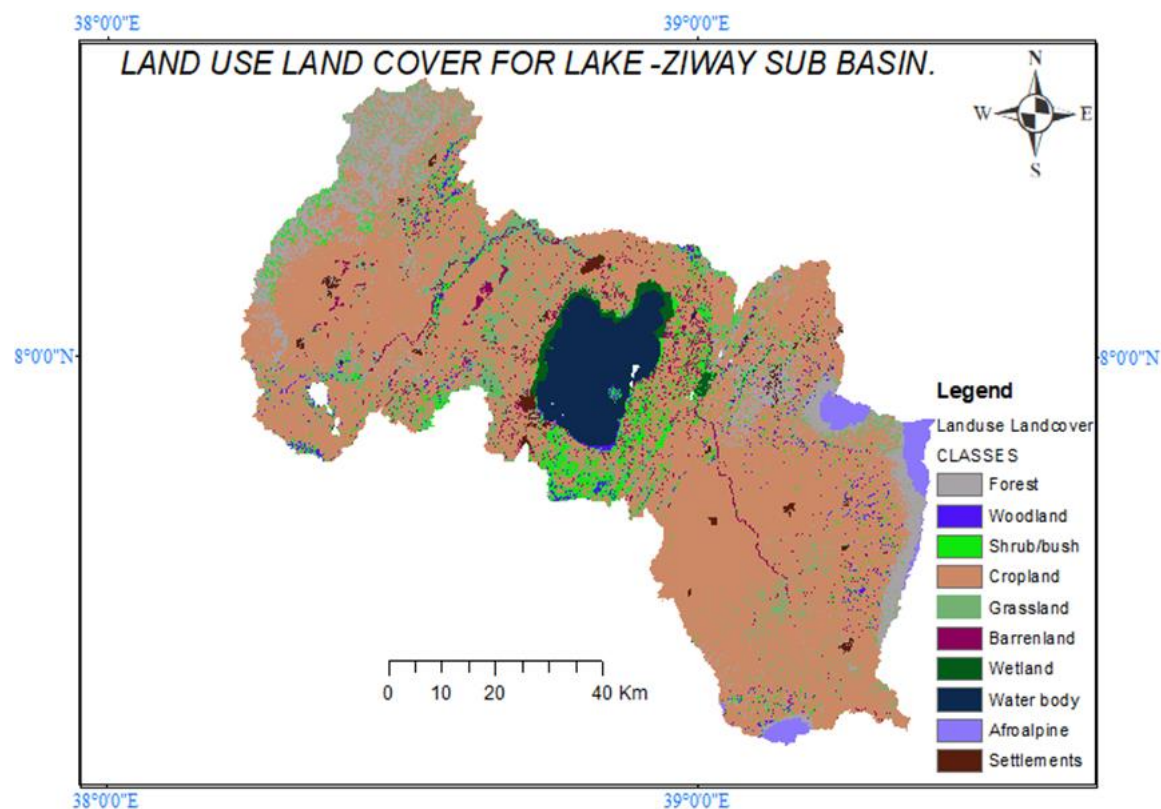


Figure 5. Land use/land covermap.

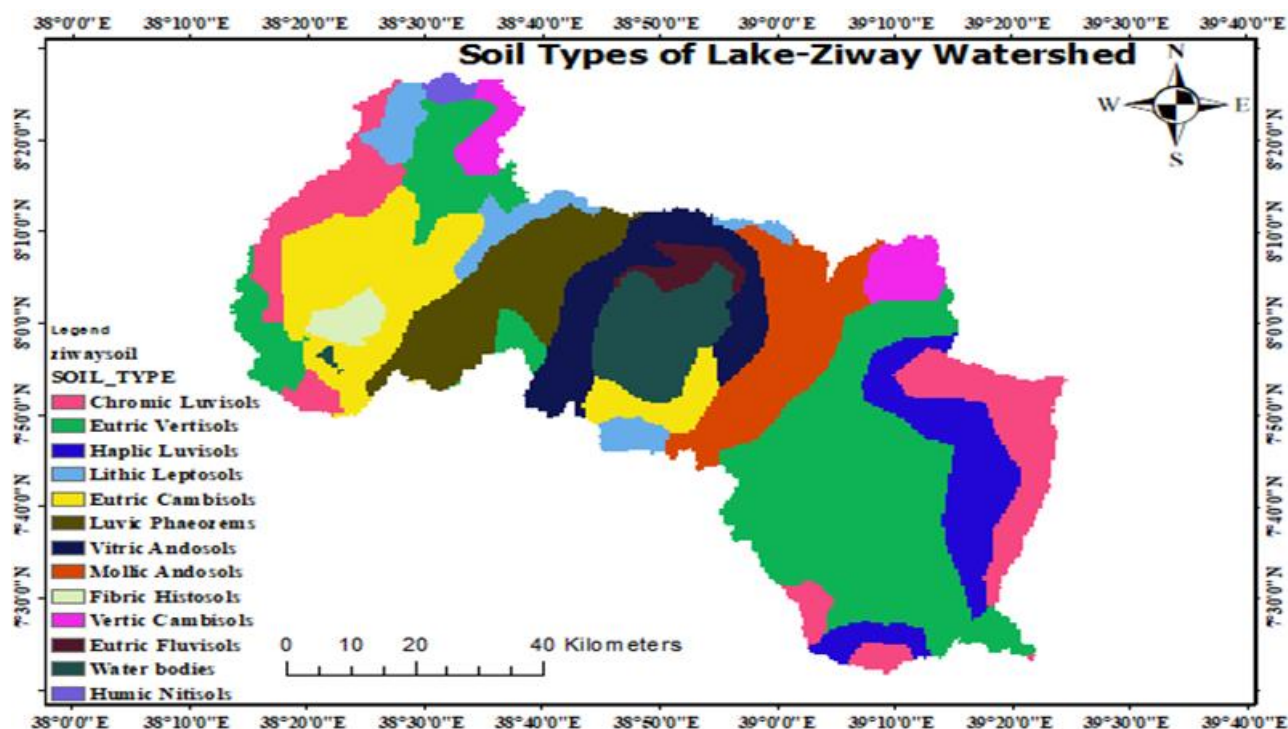


Figure 6. Soil types in the watershed.

1. Digital Elevationmodel (DEM): 30m resolution DEM used for watershed delineation.
2. Land Use/Land Cover: Reclassified using SWAT-compatible codes, with a lookup table created for integration.
3. Soil Data: Obtained from theministry of Water and Land Resource Center, including spatial soil classification.

2.4. SWATmodel Description

The Soil and Water Assessment Tool (SWAT) was used to simulate runoff and sediment yield. SWAT estimates sediment using themodified Universal Soil Loss Equation (MUSLE):

$$\text{Sed} = 11.8(Q_{\text{surf}} \cdot q_{\text{peak}} \cdot \text{AreaHRU})^{0.56} \cdot KUSLE \cdot CUSLE \cdot PUSLE \cdot LSUSLE \cdot CFRG$$

Where:

- 1) Sed: sediment yield (tons/day)
- 2) Qsurf: surface runoff (mm)
- 3) qpeak: peak runoff rate (m³/s)
- 4) AreaHRU: HRU area (ha)
- 5) K, C, P, LSK, LS: USLE factors for soil erodibility, covermanagement, support practice, and topography
- 6) CFRG: coarse fragment factor

Surface runoff was estimated using the SCS Curve Numbermethod:

$$Q_{\text{surf}} = ((R_{\text{day}} - 0.25S)^2) / (R_{\text{day}} + 0.8S)$$

$$S = 25.4 \left(\frac{100}{CN} - 10 \right)$$

2.5. Model Setup in ArcSWAT

2.5.1. Input Preparation

All spatial data (DEM, LU/LC, soilmaps) were preprocessed in ArcGIS 10.4 and projected consistently before importing into ArcSWAT 2012.meteorological data was linked to sub-basins via the SWAT Weather Generator.

2.5.2. Watershed Delineation and HRU Definition

Watershed delineation was performed using the DEM. The watershed was divided into 116 sub-basins. Hydrologic Response Units (HRUs) were defined using thresholds of 10% for land use, 10% for soil, and 15% for slope to remove less significant combinations.

2.6. Model Calibration, Validation, and Performance Evaluation

2.6.1. Streamflow Calibration and Validation

Streamflow data was acquired from theministry of Water and Energy and calibrated using the SUFI-2 algorithm in SWAT-CUP.

- 1) Calibration Period: 2001–2009
- 2) Validation Period: 2010–2012
- 3) Key sensitive parameters: SOL_K, CN2, ALPHA_BF, SOL_AWC, and SOL_BD

Table 1. Sensitivity analysis results for flow parameters.

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

Model performance:

- 1) Calibration: R² = 0.74, NSE = 0.70
- 2) Validation: R² = 0.76, NSE = 0.71

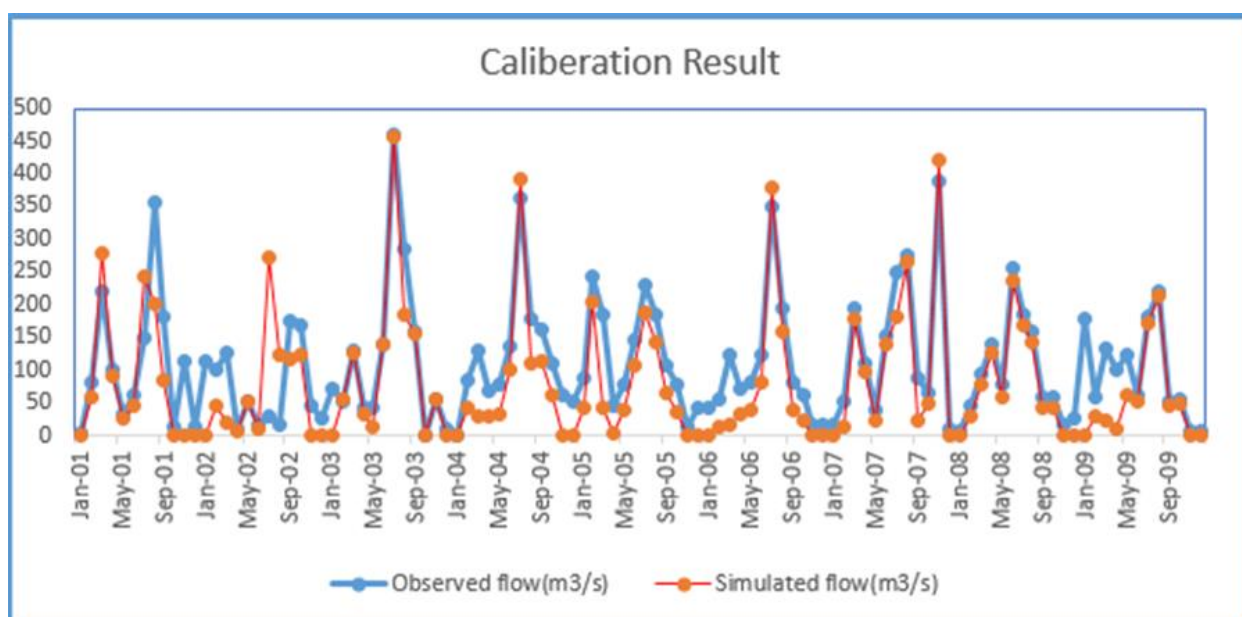


Figure 7. Observed streamflow hydrograph during calibration period.

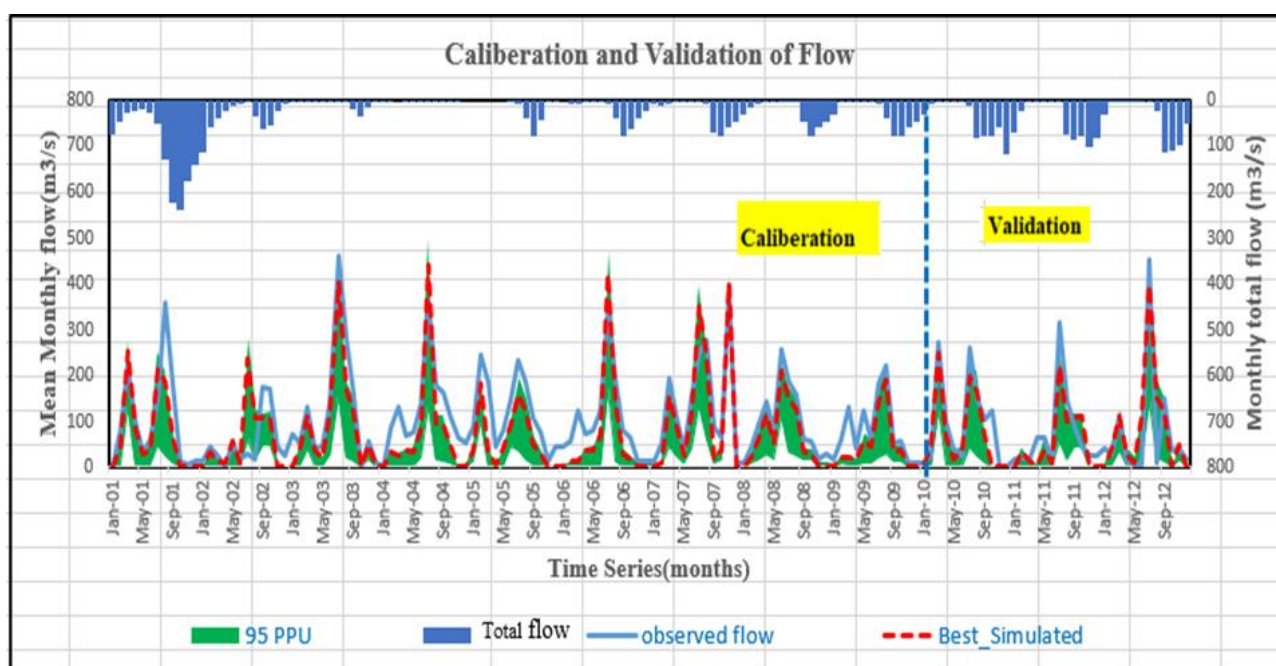


Figure 8. Simulated streamflow hydrograph during validation period.

2.6.2. Sediment Calibration and Validation

Sediment load data was estimated using sediment rating curves and calibrated via SWAT-CUP using 15 sediment-related parameters.

Table 2. Sediment parameter sensitivity analysis.

Parameter Name	t-Stat	P-Value	Rank	Sensitivity
15:V__HRU_SLP.hru	-12.377218899	0.000000000	1	High

Parameter Name	t-Stat	P-Value	Rank	Sensitivity
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	midium
10:R__SPEXP.bsn	-2.059175853	0.039920210	6	midium
3:V__GWQMN.gw	1.749951807	0.080651810	7	midium
12:R__SPCON.bsn	-1.612862931	0.107314503	8	midium
14:V__GW_DELAY.gw	-1.152799946	0.249464140	9	midium
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

Sediment simulation performance:

- 1) Calibration: $R^2 = 0.80$, NSE = 0.76
- 2) Validation: $R^2 = 0.84$, NSE = 0.71

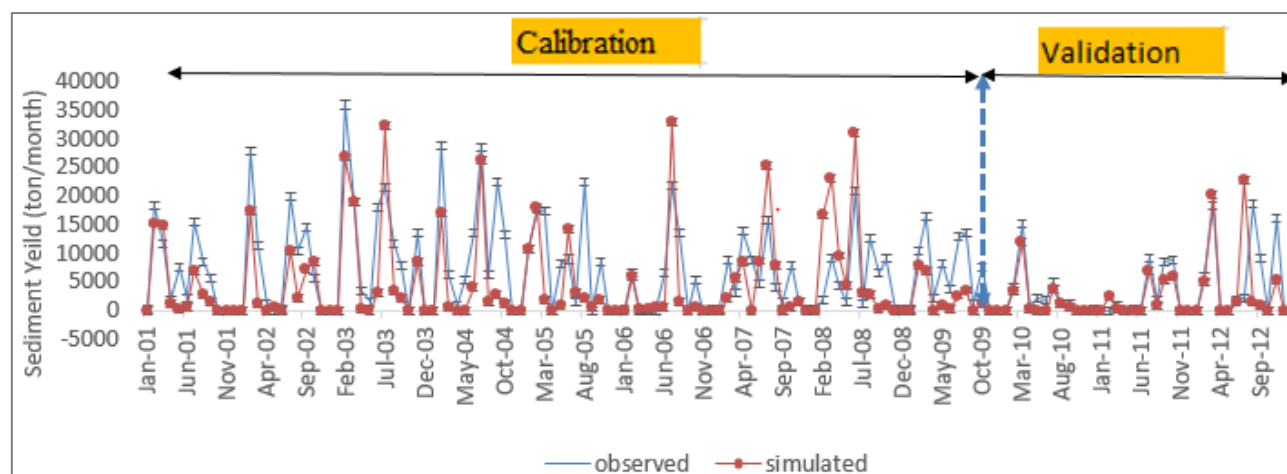


Figure 9. Simulation of sediment for calibration and Validation.

3. Results and Discussion

3.1. Sediment Yield Estimation

The SWATmodel simulation revealed that the Lake Ziway watershed produces a total sediment yield of 1,170,431 tons

per year, equivalent to 2.69 tons/ha/year during the 2001–2012 simulation period. This sediment yield is not uniformly distributed across the watershed; some sub-basins contribute significantly more than others due to differences in land use, slope, soil type, and rainfall intensity.

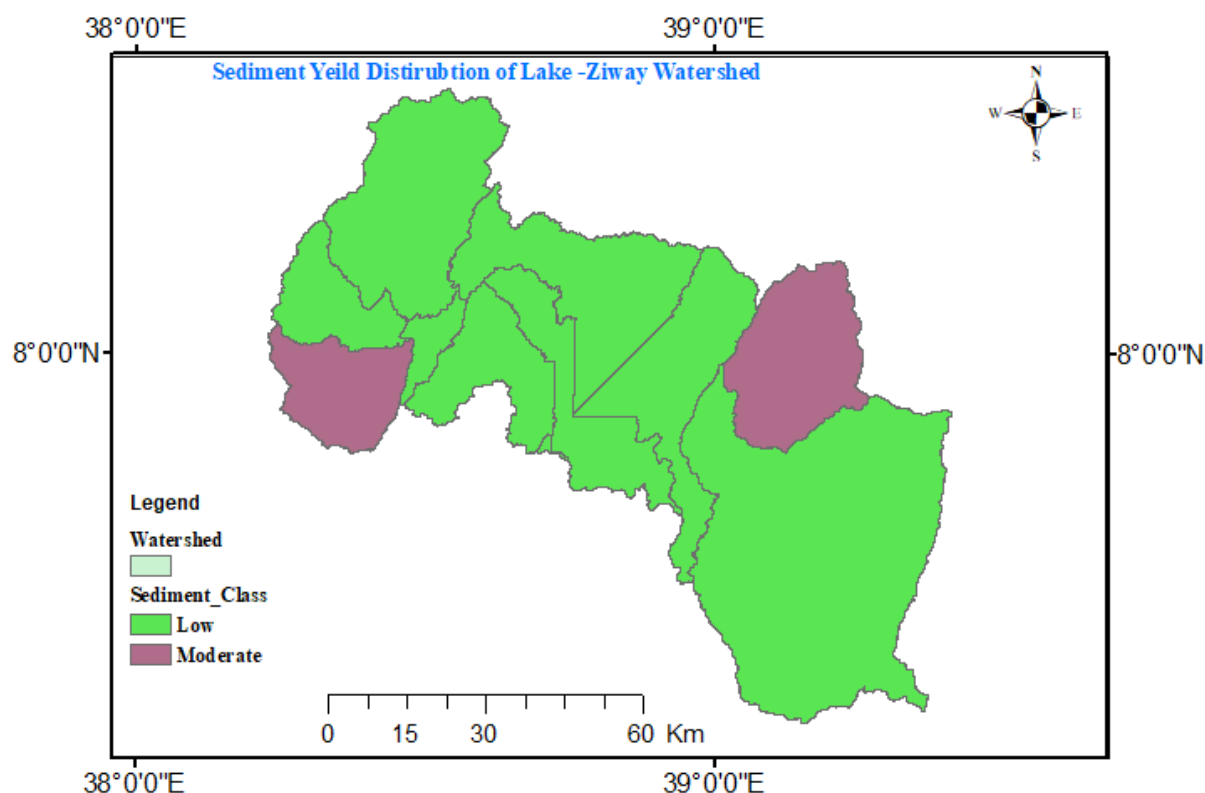


Figure 10. Annual sediment yields distribution map of the watershed.

Sub-basins with steep slopes, sparse vegetation cover, and cultivated lands were found to be the most significant contributors to sediment yield. These areas are particularly vulnerable to surface runoff and soil erosion and should therefore be prioritized for intervention.

3.2. Identification of Critical Erosion-prone Areas

The sediment yield map was used to classify sub-basins into four priority classes based on erosion severity:

- 1) Very High (Class I): >15 tons/ha/year
- 2) High (Class II): 10–15 tons/ha/year
- 3) Moderate (Class III): 5–10 tons/ha/year
- 4) Low (Class IV): <5 tons/ha/year

Out of the total 116 sub-basins:

- 1) 19 sub-basins (16.4%) fall under Class I, indicating critical erosion zones,
- 2) 24 sub-basins (20.7%) fall under Class II,
- 3) 35 sub-basins (30.2%) fall under Class III,
- 4) 38 sub-basins (32.7%) fall under Class IV.

The highest sediment-yielding sub-basins are in the northern and western highland portions of the watershed, where the combination of steep terrain and intensive agricultural activity has accelerated soil loss. These areas are major contributors to sediment delivery into Lake Ziway and should be considered for immediate soil and water conservation measures.

3.3. Sediment Yield Reduction Scenarios

Three sediment reduction scenarios were simulated to assess the effectiveness of conservation practices:

1. Scenario 1: Reforestation in Critical Areas

Critical sub-basins (Class I) were targeted for afforestation, converting cultivated and bare land into forest. This scenario reduced the sediment yield by 38.7%, demonstrating the effectiveness of vegetative cover in reducing soil detachment and surface runoff.

2. Scenario 2: Terracing and Contour Farming

Support practices (P-factor) were adjusted to reflect the implementation of terracing and contour plowing. This scenario showed a 24.5% reduction in sediment yield.

3. Scenario 3: Combined measures This scenario integrated reforestation and terracing in high-priority sub-basins. It resulted in a 52.3% reduction in sediment yield, highlighting the synergistic effect of combining structural and vegetative measures.

3.4. Discussion

The results confirm that sediment yield is strongly influenced by topography, land use, and soil type. Areas with steep slopes and extensive agricultural activity, especially those lacking conservation measures—are the primary contributors to sediment transport into Lake Ziway.

The findings are consistent with previous studies conduct-

ed in Ethiopian highlands and support the assertion that implementing site-specific soil and water conservation practices can significantly reduce sediment delivery to reservoirs.

Furthermore, the scenario analysis demonstrates that integrated watershed management, which combines reforestation, terracing, and proper land use planning, is the most effective strategy to control sediment yield.

4. Conclusion

This study assessed the spatial and temporal distribution of sediment yield in the Lake Ziway watershed using the ArcSWAT model, with a focus on identifying erosion-prone areas and evaluating the effectiveness of sediment reduction strategies. The model, calibrated and validated using streamflow and sediment data from 2001–2012, demonstrated strong performance with R^2 and Nash–Sutcliffe efficiency values ranging from 0.72 to 0.85. The simulation revealed that the average annual sediment yield across the watershed was 2.69 tons/ha/year, contributing a total of 1.04 million tons of sediment to the lake annually, with a deposition rate of 38.5%. Sediment distribution varied significantly across sub-basins, with the highest yields occurring in steeper, intensively cultivated areas—particularly sub-basins 4 and 5—marking them as critical erosion hotspots.

Sensitivity analysis identified key hydrological and sediment-related parameters, including saturated hydraulic conductivity (SOL_K), curve number (CN2), soil erodibility factor (USLE_K), and slope length factor (HRU_SLP), which significantly influenced sediment yield outputs. Scenario analysis showed that implementation of Best Management Practices (BMPs) can effectively reduce sediment yield across the watershed. Among the tested scenarios, terracing emerged as the most effective intervention, reducing sediment yield by 72%, followed by grassed waterways (58%) and filter strips (42%). These results underscore the value of spatially targeted conservation strategies, with terracing recommended as the primary intervention in erosion-prone sub-basins.

To improve future modeling accuracy and inform sustainable watershed management, it is recommended that hydrometeorological monitoring infrastructure be expanded and improved, with a focus on increasing the frequency and coverage of sediment gauging stations. While this study relied on secondary data, future research would benefit from primary, high-resolution datasets, particularly to assess sediment dynamics under changing climatic conditions. Moreover, extending this modeling approach to adjacent watersheds could support regional-scale planning and fill knowledge gaps. Continued integration of SWAT-driven conservation planning with local land use policy will be critical to safeguarding the long-term ecological and economic functions of Lake Ziway.

Abbreviations

BMP	Best Management Practices
DEM	Digital Elevation Model
HRU	Hydrologic Response Unit
NSE	Nash–Sutcliffe Efficiency
R^2	Coefficient of Determination
SWAT	Soil and Water Assessment Tool
SUFI-2	Sequential Uncertainty Fitting Version 2
MUSLE	Modified Universal Soil Loss Equation

Author Contributions

Alemayehu Kassa Ewentie: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing

Peniel Bafe Unto: Conceptualization, Data curation, Formal Analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing

Conflicts of Interest

The authors declare no conflicts of interest.

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