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Integrated watershed management strategies for sustainable resource utilization using the SWAT model: case study of the Kalte River watershed, Rift Valley Basin, Ethiopia

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ABSTRACT

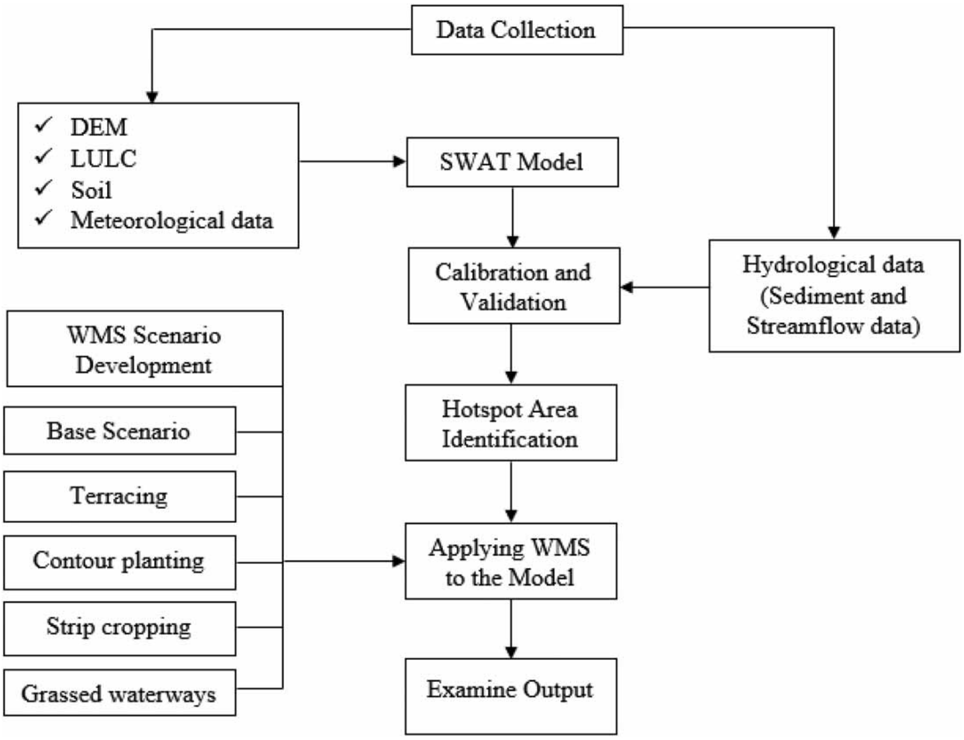
Most people who live in rural areas are highly dependent on shared access to natural resources including land, water, and forests for their food requirements and livelihoods. However, land degradation remains one of the biggest environmental problems worldwide. Therefore, this study proposed to develop integrated watershed management strategies for sustainable resource utilization in the Kalte River watershed. To achieve this, the SWAT model was simulated for 31 years (1992–2022), calibrated and validated at Wajifo and Humbo hydrological stations to determine the sediment and runoff from the watershed, highly sediment erosion-vulnerable part of the watershed was identified from the result of the model and the best watershed management practice was suggested for the study watershed. In total, 87,920 tons/year of sediment are yielded to Lake Abaya from the Kalte River watershed. The sediment yield was reduced by terracing at 64%, strip cropping at 59.32%, grassed waterway at 54.06%, and contour planting at 47.93%. Therefore, the highest efficiency management method in the Kalte River watershed is terracing. The watershed managers and scientific community are beneficiaries of the output of this study. Watershed managers and decision-makers can make use of the information to help them choose appropriate watershed management strategies and ensure sustainable watershed management.

Key words: contour planting, grassed waterway, Kalte watershed, strip cropping, terracing

HIGHLIGHTS

- The Kalte River watershed was simulated for 31 years including a 3-year warm-up period.
- The simulated model was calibrated and validated.
- Erosion hotspot area was selected based on sediment yield.
- Four watershed management practices are evaluated.

GRAPHICAL ABSTRACT



INTRODUCTION

Integrated watershed management is a scientific and resource management paradigm uniquely suited to administering natural resource challenges in densely settled landscapes where people are highly dependent on natural capital for their livelihoods (Valley 2019; Berlie & Ferede 2021). Nowadays, integrated watershed management has appeared as a new model for the planning, development, and management of surface water (rivers, lakes, and ponds), groundwater (shallow and deep wells), and vegetation resources within the watershed (Adhitama *et al.* 2022; Risal & Parajuli 2022). It is believed that integrated watershed management is a core element of better agricultural production and forest management since it can minimize land degradation, stabilize stream flows in river channels, reduce sediment load, and recharge groundwater stores (Leta *et al.* 2023). Therefore, the factors that make integrated watershed management strategically important for policy implications are the explicit effort to bridge productivity enhancement, environmental protection, and social well-being.

In Ethiopia, watershed management programmes commenced formally in the 1970s (Bishaw 2001; Bekele & Drake 2003; Yisehak *et al.* 2013). The implementation of this programme was typically a government-led, top-down, incentive-based (food-for-work) approach that prioritized engineering measures up to the late 1990s. At this stage, reducing soil erosion is the major goal. Furthermore, community-based integrated watershed conservation was introduced to encourage watershed management and livelihood improvement objectives within prevailing agroecological and socioeconomic environments in the early 2000s.

Soil erosion is a complex process and pervasive geomorphologic hazard 'earth cancer' and its rate is a comprehensive index for assessing the degree of development and sustainability of land management programmes of the countries (Gebregziabher *et al.* 2016). Due to the strong dependence of pedogenesis on geomorphic systems, there is a close relationship between geomorphic units and erosion rates at different spatial levels. The sediment in the river system is essential because it is a natural component of a riverine environment. But naturally balanced sediment supply and sediment transport in the watershed are strongly affected by human activities in many ways and in many places of the river system and the landscape (Ndomba *et al.* 2005).

In general, soil erosion is one of the major factors causing severe land degradation problems in Ethiopia, which in turn, is threatening the agricultural productivity and the very survival of the overwhelming majority of the rural population. The rate of soil loss and depletion of soil organic matter and nutrients are so high and much faster than they can be replaced. According to the Ethiopian Highland Reclamation Study, nearly 1.9 billion tons of fertile soil are moved by water erosion from highlands annually (FAO 1986).

Generally, soil erosion and sedimentation problems are strongly related to land use policy, natural resource management, level of development and degradation/deforestation of the basin as well as cultivation practices, conservation measures, etc. (Ndomba *et al.* 2008; Abebe *et al.* 2022).

Plenty of studies have investigated the extent of soil erosion in Ethiopia. Most of the studies announce that the rates of soil erosion are alarmingly high and sedimentation in reservoirs, lakes, and rivers in Ethiopia is a serious problem (Haregeweyn *et al.* 2017; Tamene *et al.* 2017; Ayele *et al.* 2021).

So far, on-site soil and water conservation (SWC) measures on agricultural areas in the catchment have been focused on most studies and development activities that aim to reduce the sediment load in the reservoirs (Wolka *et al.* 2011; Berlie & Ferede 2021). Off-site soil conservation measures are largely disregarded. In addition, such SWC measures are never designed to eliminate sediment loss and transport. At their best, these measures reduce soil loss to a tolerable level. Hence, there will always be drainage out of a catchment that is loaded with some sediment.

Nowadays, hydrological models are implemented for modelling watershed sediment yields (Ndomba *et al.* 2008; Abebe *et al.* 2022). The study conducted by Abdul Razad *et al.* (2020) was to predict reservoir sedimentation using the Soil Water Assessment Tool (SWAT) towards the development of sustainable catchment management. This study highlights how the SWAT model is used to determine runoff variation and sediment yield from different sub-basins of Cameron Highlands' catchment. This paper describes the theory of SWAT, study area, model set-up, sensitivity analysis, model calibration and validation, and simulation of sediment yield at sub-catchments of Cameron Highlands and total sediment load into Ringlet Reservoir.

The study was conducted in the Maroon-Dam Catchment to determine runoff and sediment yield using the SWAT hydrological model. The result depicted that measured and simulated discharge and sediment had relatively good fitness. The discharge and sediment exhibited nearly 70 and 76% for Nash–Sutcliffe (NS) efficiency and R^2, respectively. Overall, the simulation of runoff and sediment is satisfactory using the SWAT model (Zalaki-badil *et al.* 2017). Furthermore, the SWAT model was used to model hydrology and sediment with limited data in the Abbay (Upper Blue Nile) Basin (Abebe *et al.* 2022). They aimed to estimate sediment yield and assess erosion-prone areas of the Andasa watershed having scarce sediment concentration records. The data used in this study were meteorological, hydrological, suspended sediment concentration, 12.5 m digital elevation model (DEM), 250 m resolution African Soil Information Service (AfSIS) soil, and 30 m resolution land cover data. The sediment yield was estimated as a sediment rating curve developed using the limited sediment concentration data.

This study was conducted to control the soil erosion in the Kalte River watershed by developing best-integrated watershed management strategies (WMSs). The SWAT was selected to do this task. The specific objectives addressed in this study were to model the quantity of sediment yield towards Lake Abaya using the SWAT model, to assess the sediment hotspot area in the study landscape, and to evaluate the efficiency of watershed management practices on the study watershed and finally recommend the best methods for the study area.

MATERIALS AND METHODS

Study area description

The Kalte River is a part of the Rift Valley Lake basin situated between 37°36′35″ to 37°53′21″E longitude and 6°27′41″ to 6°54′37″N latitude (Figure 1). It extends from Mount Damota to Lake Abaya and covers a drainage area of 528 km^2. Runoff initiates from southeast of Mount Damota drains to Kalte River and joins Lake Abaya.

The study area includes Sodo town, Bodereda, and Humbo Tebela Wereda of the Wolaita zone in the southern Ethiopia regional state of Ethiopia. The elevation of the Kalte River watershed ranges from 1,180 to 2,971 m. Most of the area was occupied by agricultural practices which led to extensive soil erosion. According to meteorological stations around the Kalte River watershed, the average annual rainfall ranges from 1,280 to 1,339 mm. The maximum and minimum temperatures are 34.9 and 14.2°C, respectively.

Data collection and analysis

Hydro-metrological data, DEM, soil map, land use/land cover (LULC) map, on-site Global Positioning System (GPS) data, etc.are required for this study. These data were collected from respective sectors and freely accessible internet sites (Table 1).

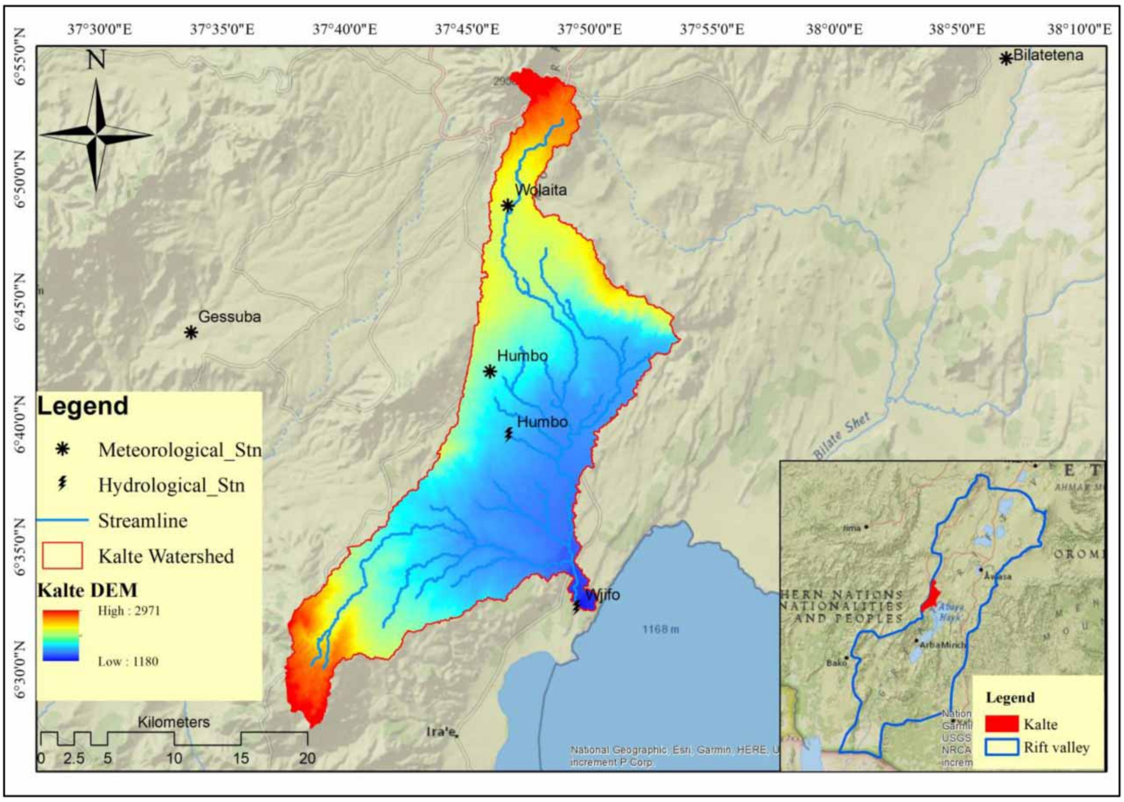


Figure 1 | Geographic location of the Kalte River watershed.

Table 1 | Required data and their respective source

Data	Respective sector or website	Application
Stream flow and sediment load data	MoWE	For the SWAT model calibration and validation
Metrological data (rainfall, temperature, relative humidity, solar radiation, etc.)	NMA	Input for the SWAT model for hydrological simulation
DEM (12.5 m × 12.5 m resolution)	http://vertex.daac.asf.alaska.edu	Use in the GIS tool for spatial analysis and the SWAT model
Soil map	Digital Soil Map of the World (DSMW) in FAO web	Input for the SWAT model
LULC	MoWE	Input for the SWAT model
GPS data	Site survey	For watershed management

Note: In the table, NMA: National Meteorology Agency and MoWE: Ministry of Water and Energy.

The slope of the study watershed

The slope of the Kalte watershed is generated from the 12.5*12.5 m DEM obtained from Alaskan Satellite Facility 'http://vertex.daac.asf.alaska.edu'. The gradient of the area ranges from 0 to 65.19% (Figure 2(c)). Most of the watershed is gently sloped; however, the origin of the stream was from a highly raised mountain called Damota.

Soil of the study watershed

As the soil map obtained from Food and Agricultural Organization (FAO), the Kalte River watershed contains three types of soil: Ochric andosols cover 57.23% of the total area, Haplic xerosols cover 30.67% of the total area, and Eutric nitosols cover 12.1% of the total area (Figure 2(b)).

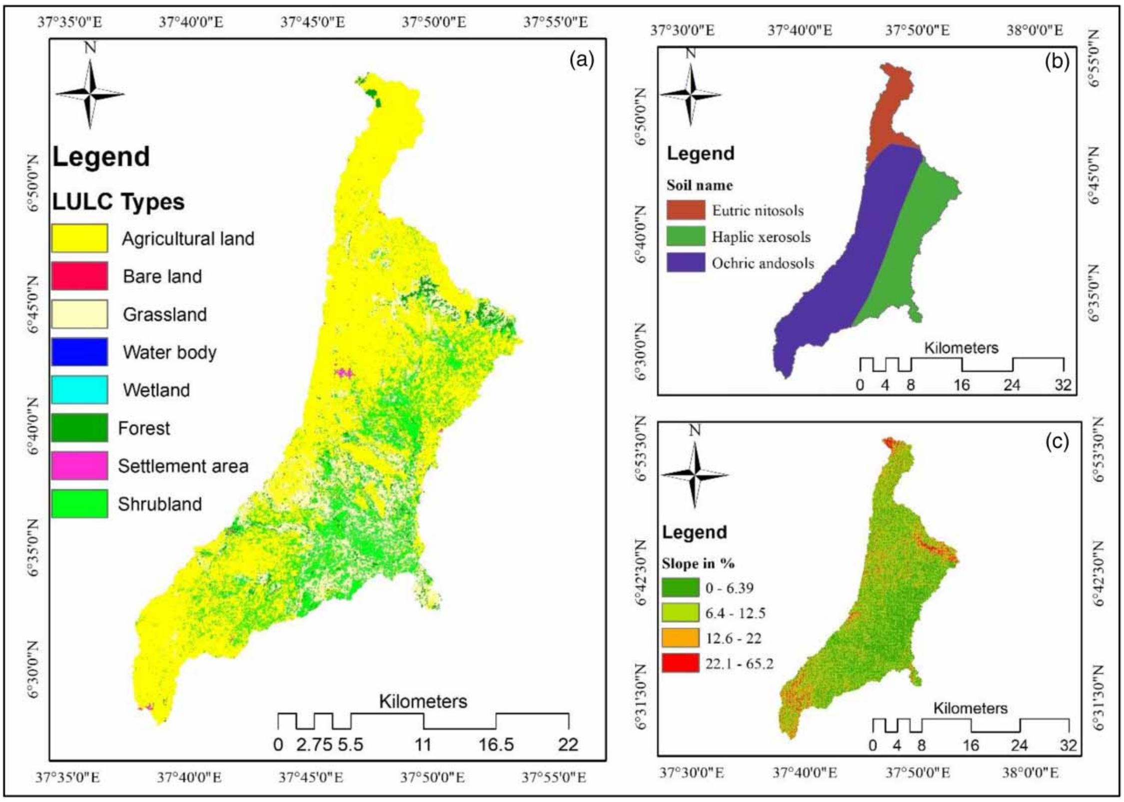


Figure 2 | (a) The LULC map, (b) the soil map, and (c) the slope map of the Kalte watershed.

Land use/land cover of the study watershed

Most of the Kalte River watershed is occupied by agriculture which covers around 53.13% of the total drainage area. Shrub land covers 14.15% of the Kalte River watershed, and 12.3 and 2.14% of the watershed are covered by grass and forest, respectively. The remaining 18.28% of the watershed is a constituent of bare land, waterbody, settlement area, and wetlands (Figure 2(a)).

Meteorological data

The meteorological data (precipitation, maximum and minimum temperature, relative humidity, sunshine hours, and wind speed) recorded in and around the study watershed were obtained at the Ethiopian Meteorology Institute in the daily time step. The data from the gauging stations are from 1992 to 2022 and the recorded weather parameters in each station are described in Table 2.

Missing data may be a very common problem in hydrometeorology, which affects the standard of results that will be afforded in hydrological studies and water resource management. The incompleteness of hydrometeorological data may be because of damaged measuring instruments, measurement errors, and geographical rareness

Table 2 | Meteorological stations and their information

S.No.	Station	Lat	Long	Alt	PRCP	TMP	RHUM	SUNHR	WNDS	% missing
1	Bilate Tena	6.92	38.12	1,496	✓	✓	X	X	X	11.5
2	Bodity	6.96	37.86	2,043	✓	✓	X	X	X	9.6
3	Dara malo	6.32	37.30	1,183	✓	✓	X	X	X	3.2
4	Humbo	6.70	37.77	1,618	✓	✓	X	X	X	9.2
5	Gessuba	6.73	37.56	1,552	✓	✓	X	X	X	13.5
6	Morka	6.42	37.31	1,221	✓	✓	X	X	X	7.8
7	Wolaita	6.82	37.78	1,854	✓	✓	✓	✓	✓	4.9

Note: In the table PRCP: precipitation, TMP: temperature, RHUM: relative humidity, SUNHR: sunshine hours, and WNDS: wind speed.

of data (data gaps) or changes to instrumentation over time, a change in the measurement site, a change in data collectors, the irregularity of measurement, or severe tropical changes within the climate. There are several methods to fill missing hydro-metrological data: the arithmetic averaging method, the normal ratio method, the inverse distance interpolation method, the multiple linear regression analysis methods, and the multiple imputation method.

In this study, the missing meteorological data were filled using the inverse distance interpolation method. In this method, weights for each sample are inversely proportionate to their distance from the point being estimated. The inverse distance method is the most accurate among all methods listed above as it is a function of rainfall measured at the surrounding index stations and the distance to each index station from the ungauged location (Shepard 1968; Moshe & Tegegne 2022).

$$P_x = \sum_{i=1}^{n} w_i P_i \tag{1}$$

$$w_i = \frac{d_i^{-2}}{\sum_{i=1}^{n} d_i^{-2}} \tag{2}$$

where P_x is the missing parameters, P_i is the recorded parameters in nearby stations, w_i is the weight from geographical location, d_i is the distance between the missing and recorded stations, and n is the number of gauged stations.

From the mean monthly rainfall, the study watershed is bimodal climate conditions: April and May is the first main rainy season and July and August is the second main rainy season in the year (Figure 3).

Hydrological data

Streamflow data

Streamflow data gauged in the Kalte watershed are obtained from the Ministry of Water and Energy (MoWE). The study watershed was gauged at the outlet named Wajifo and at the middle named Humbo. The data length obtained from these stations is from 1995 to 2015 in daily time steps.

Sediment data

The sediment concentration of the Kalte River watershed is measured at the streamflow gauging stations while the data are a continuity problem. The sediment yield data are calculated from the concentration data and the corresponding streamflow data using Equation (3). To avoid continuity problems, a sediment yield rating curve is developed, as shown in Figure 4. The power equation obtained from the rating curve is used for estimating continuous sediment yield which is a function of streamflow discharge (Equation (4)).

$$Q_s = kQ_w * C_s \tag{3}$$

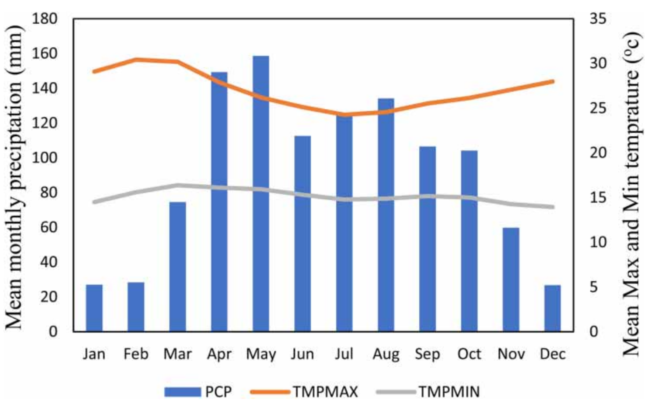


Figure 3 | Mean monthly rainfall and temperature in the year.

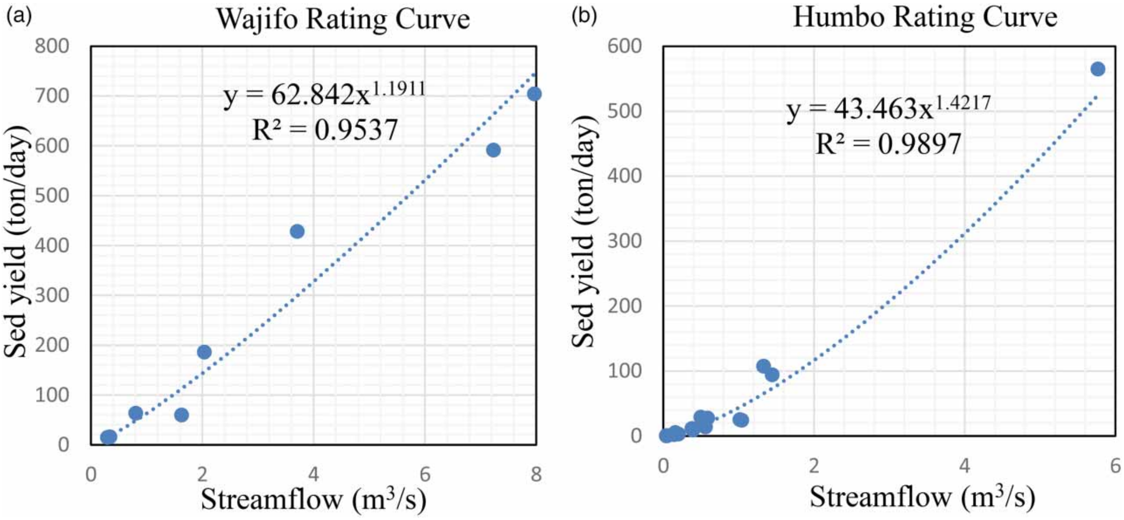


Figure 4 | Sediment yield rating curve.

where Q_s is the sediment yield in ton/day, Q_w is the streamflow in m^3/s, C_s is the average sediment concentration in mg/l, and K is the conversion factor 0.0864.

$$Y = aX^b \quad (4)$$

where a and b are constants shown in Figure 4.

SWAT model set-up

Watershed delineation

Automated watershed delineation embedded in the Arc SWAT interface was used to delineate the watershed. Delineation of the watershed and sub-watershed has been done using DEM data. The normal SWAT watershed delineation process includes five major steps: DEM set-up, stream definition, outlet and inlet definition, watershed outlets selection, and definition and calculation of sub-basin parameters. For the stream definition, the threshold-based stream definition option was used to define the minimum size of the sub-watershed to minimize uncertainty associated with model outputs.

Hydrologic response unit analysis

After watershed delineation, sub-basins were subdivided into areas having unique land use, soil, and slope so-called hydrologic response units (HRUs). Although the individual fields with specific land use, soil, and slope were scattered over the sub-basin, when lumped together they form HRUs. The land use, soil, and slope datasets were projected into the same projection as DEM. After the projection of the land use, soil, and slope datasets were reclassified, overlaid, and linked with the SWAT databases and ready for HRU definition. To define the distribution of HRUs, a multiple HRUs option with a 5% threshold value was selected (Bitew & Kebede 2023).

Writing input tables for SWAT

After all, geoprocessing is done on DEM, land use, and slope data to create sub-basins and HRUs, the next step is to build database files that include information needed to generate other input for the SWAT model including weather data. Daily time series of weather data, which include precipitation, maximum and minimum air temperature data, relative humidity, solar radiation, and wind speed are required for the SWAT modelling. The periods of the measured weather data, obtained from the National Meteorology Institute of Ethiopia (NMI), differed from station to station. The SWAT database is updated to generate other weather variables using other stations that have full records of weather variables. Then, input database files using land use, soil, DEM, and weather data of the study were created as input data and all commands were written to create the initial values of the model.

SWAT simulation

Once the creation of input files for the model, the simulation toolbox was activated to run the model. First simulation period from 01/01/1992 to 31/12/2022; three years were set for warm-up to mitigate the unknown initial conditions and were excluded from the analysis; printout setting was selected as a daily and monthly option; rainfall distribution was selected as skewed normal distribution; the Penman/Monteith method was selected to calculate potential evapotranspiration and the variable storage method was selected for channel water routing. Another option was kept as default, and then the model was the main procedure followed for this specific study. The model output data were imported to the database and the simulation results were saved as an output in the scenario folder. The flow out and sediment yield for each sub-watershed are found in the 'textinout' folder in the 7th and 11th columns, respectively, used for calibration and model verification.

SWAT model calibration and validation

Calibration is the process of adjusting parameter values to improve model performance according to a set of predefined criteria. There are several calibration methods, including manual and automated procedures using the shuffled complex evaluation method. Recently, the SWAT calibration and uncertainty programme (SWAT-CUP) was established, which is a public domain programme that may be used and copied freely. The programme links sequential uncertainty fitting (SUFI2), particle swarm optimization, generalized likelihood uncertainty estimation, parameter solution, and Markov chain Monte Carlo procedures to the SWAT. It allows sensitivity analysis, calibration, validation, and uncertainty analysis of the SWAT models (Abbaspour 2015).

The SUFI-2 is a semi-automated method that makes the calibration procedure easier to carry within the realizable time bounds (Sloboda & Swayne 2011; Mehan *et al.* 2017). The performance and efficiency of the model in simulating the streamflow were evaluated using the coefficient of determination (R^2), NS, per cent of bias (PBIAS), and root mean square error (RMSE) (Thavhana *et al.* 2018). The recommended value of these statistical parameters is obtained from previous studies (Abbaspour 2015; Sao *et al.* 2020; Adriel *et al.* 2021).

$$NS = 1 - \frac{\sum_{i=1}^{n} (Q_m - Q_s)_i^2}{\sum_{i=1}^{n} (Q_{m,i} - \overline{Q}_m)^2} \tag{5}$$

$$R^2 = \frac{\left[\sum_{i=1}^{n} (Q_{m,i} - \overline{Q}_m)(Q_{s,i} - \overline{Q}_s)\right]^2}{\sum_{i=1}^{n} (Q_{m,i} - \overline{Q}_m)^2 \sum_{i=1}^{n} (Q_{s,i} - \overline{Q}_s)^2} \tag{6}$$

$$PBIAS = 100 * \left(\frac{\sum_{i=1}^{n} (Q_m - Q_s)_i}{\sum_{i=1}^{n} Q_{m,i}} \right) \tag{7}$$

$$RSR = \frac{\sqrt{\sum_{i=1}^{\mathrm{n}} (Q_m - Q_s)_i^2}}{\sqrt{\sum_{i=1}^{n} (Q_{m,i} - Q_m)^2}} \tag{8}$$

where Q is a variable (discharge or sediment), m and s stand for measured and simulated variables, and i is the ith measured or simulated data.

Model parameter sensitivity and uncertainty analysis

Sensitivity analysis evaluates the influences of different parameters on the simulation result, and the response of the output variable to a change in the input parameter. It can be classified into local, in which changes in parameters are made one by one, while all the others are kept constant, and global, which promotes a multilinear regression of the entire input space (Abbaspour 2015). t-stat and p-value in the SUFI2 algorithm are used for parameter sensitivity analysis. Parameters with a larger absolute value of t-stat and p-value closer to zero, are more sensitive (Abbaspour 2015; Khalid *et al.* 2016). The global sensitivity analysis method was used in this particular study.

Tegegne *et al.* (2019) recognized that the input data error, model parameters, model structure, and spatial resolution of the physical input data are the main sources of uncertainty in hydrological modelling. *p*-factor and *r*-factors explain the uncertainties in the calibrated model, the *p*-factor being the percentage of simulation within the 95% prediction uncertainty (95PPU). The *r*-factor is the average thickness of the 95PPU band divided by the standard deviation of the data. The suggested values for the *p*-factor and *r*-factor are >0.7 and <1.5, respectively (Abbaspour 2015; Adriel *et al.* 2021).

Hotspot area identification

The hotspot area was identified based on runoff and sediment yield of sub-watersheds obtained from the calibrated and validated SWAT model. The degree of severity was decided from the previous studies (Hurni 1985; Haregeweyn *et al.* 2017; Tefera *et al.* 2020) (Table 3).

Evaluation of selected watershed management strategies

There is an effect of soil erosion and sediment production from the critical sub-watershed of the study area, which needs conservational practices. The watershed management operations were simulated in the SWAT model to observe the reduction change from the output sediment yield of the model by selecting the high sediment-yielding sub-basins. Therefore, to use the model as a tool for analyzing the effects of different activities in the study area, an alternative scenario analysis was developed. For this specific study, the following scenarios are analyzed.

Scenario-0 (base scenario)

The base scenario is evaluating sediment yield without any watershed management practice.

Scenario-1 (terracing)

A terrace is a ridge within a field designed to block runoff and control erosion. A terrace is constructed transversely on a contour and appears in the field with regular spacing. Sediment and runoff parameters are used to simulate terracing in the SWAT. The Universal Soil Loss Equation (USLE) practice (TERR_P) factor, the slope length (TERR_SL), and the curve number (TERR_CN) are adjusted to simulate the effects of terracing.

Scenario-2 (contour planting)

Contour planting is the practice of tilling and planting crops following the contour of the field as opposed to straight rows. The contours are oriented at a right angle to the field slope at any point. Small ridges, resulting from field operations, increase surface storage and roughness, reducing runoff, and sediment losses. Altering curve number (CONT_CN) to account for increased surface storage and infiltration and the USLE practice factor (CONT_P) to account for decreased erosion is employed in the SWAT model to simulate contour planting.

Scenario-3 (strip cropping)

Strip cropping is the preparation of groups of alternating crops within an agricultural field. The grouping is generally placed based on the contours of the field. Strip cropping is simulated in the SWAT by altering the Manning's *N* value for overland flow (STRIP_N) to represent increased surface roughness in the direction of runoff. The curve number (STRIP_CN) may be adjusted to account for increased infiltration. The average value for multiple crops within the field may be reflected by adjusting the USLE cropping factor (STRIP_C).

Scenario-4 (grassed waterways)

Grassed waterways are vegetated channels that transport runoff from a field. The scouring potential of concentrated flow is reduced by reducing flow velocities with the vegetation within the waterways. Grassed waterways are generally broad and shallow channels that are simulated in the SWAT and have a side slope of 8:1. Grass waterways reduce flow velocities which increase the deposition of particular contaminants by trapping sediments

Table 3 | Sediment yield severity classes

Degree of severity	Very slight	Slight	Moderate	Severe	Very severe
Sediment yield (ton/ha/year)	0–5	5–15	15–30	30–50	>50

and other contaminants. Grassed waterways were developed in the SWAT model by fixing flag for the simulation of grass waterway (GWATI), Manning's *N* value for overland flow (GWATN), the linear parameter for calculating sediment in grassed waterways (GWATSPCON), depth of grassed waterway channel form of the bank to bottom (m) (GWATD), an average width of a grassed waterway (m) (GWATW), length of grassed waterway (km) (GWATL), and average slope of dressed waterway channel (m) (GWATS).

RESULTS AND DISCUSSION

Initial model simulation output

The Kalte River watershed was simulated in the SWAT model using DEM, soil data, LULC, and weather data. As a result of the simulation, the watershed was divided into 49 sub-basins and a total of 535 HRUs. The SWAT model was set up and run on a monthly time step. The initial run was for 31 years from 1992 to 2022 with a 3-year warm-up period. The initially simulated streamflow and sediment yield were compared with those observed in the Wajifo and Humbo gauged stations located in sub-basins 43 and 22, respectively. The NS was used as the objective function to evaluate the initial model performance. The initial model performance was carried out for the calibration period 1995 to 2008 using the SWAT-CUP user manual procedure by changing the number and simulation of the parameter into 1 in the Par_inf (parameter information text file) and by setting up dummy-parameter change (ex. r__SFTMP.bsn 0 to 0) (Abbaspour 2015). According to the recommended value of evaluation indexes, the initial model performance at both gauging stations provided unsatisfactory results. Therefore, the model needs calibration.

Model parameter sensitivity analysis

Streamflow sensitive parameters

The sensitive model parameter that affects the hydrological output of simulated models is obtained from a previous similar study and evaluated in the SUFI2 algorithm of the SWAT-CUP for this study watershed (Cibin & Sudheer 2010; Eromo *et al.* 2016; Welde 2016; Moreira *et al.* 2018; Adeba & Tafese 2021; Adriel *et al.* 2021).

Therefore, the sensitive parameters in this study watershed are soil conservation service curve number (CN2), effective hydraulic conductivity in the main channel alluvium (CH_K2), Manning's 'n' value for the main channel (CH_N2), soil evaporation compensation factor (ESCO), average slope length (SLSUBBSN), Manning's 'n' value for overland flow (OV_N), average slope steepness (HRU_SLP), depth from the soil surface to bottom of the layer (SOL_Z), an available water capacity of the soil layer (SOL_AWC), saturated hydraulic conductivity (SOL_K), groundwater delay (GW_DELAY), baseflow alpha-factor (ALPHA_BF), threshold depth of water in the shallow aquifer required for return flow to occur (GWQMN), groundwater 'revap' coefficient (GW_REVAP), threshold depth of water in the shallow aquifer for 'revap' to occur (REVAPMN), and deep aquifer percolation fraction (RCHRG_DP). The sensitivity of each parameter was evaluated in Wajifo and Humbo streamflow gauging stations available in the study watershed and their sensitivity rank of each parameter based on *t*-stat and *p*-value obtained from the SWAT-CUP are presented in Table 4. The parameters, having the higher absolute value of *t*-stat and low *p*-value, are more sensitive.

Sediment sensitive parameters

Similarly, the parameter that affects sediment simulation is the USLE equation parameter (USLE_P), sediment concentration in lateral flow and groundwater flow (LAT_SED), the main value of the USLE_C factor, a linear parameter for calculating the maximum amount of sediment that can be re-entrained during channel sediment routing (SPCON), the exponent parameter for calculating sediment re-entrained in channel sediment routing (SPEXP), and USLE equation soil erodibility *K* factor (USLE_K). Sediment data are available at Wajifo and Humbo gauging stations and the fitted values of sensitive parameters with their sensitivity rank are provided in Table 5.

Model calibration and validation output

Streamflow calibration and validation output

The selected 16 sensitive parameters were used for calibration and validation of the hydrological model with the SWAT-CUP (SUFI-2) on monthly time steps from 1995 to 2015. The observed streamflow data from 1995 to 2008 were used for calibration and from 2009 to 2015 were used for validation. Then the value of the evaluation indexes is provided in Table 6.

Table 4 | Streamflow sensitive parameters and their fitted values

	Wajifo		Humbo	
Parameter name	**Rank**	**Fitted values**	**Rank**	**Fitted values**
R__CN2.mgt	1	−0.161	1	−0.199
R__HRU_SLP.hru	2	6.717	12	8.383
V__CH_K2.rte	3	0.842	9	2.825
R__SOL_K(..).sol	4	1.030	3	1.563
R__SLSUBBSN.hru	5	−0.596	2	−0.065
R__CH_N2.rte	6	1.433	12	1.356
R__SOL_Z(..).sol	7	2.248	14	2.389
V__REVAPMN.gw	8	0.039	8	0.057
V__ESCO.hru	9	0.936	7	0.953
V__GWQMN.gw	10	2,455	6	2,048
V__GW_DELAY.gw	11	4.708	11	1.642
V__ALPHA_BF.gw	12	0.000	4	0.000
V__GW_REVAP.gw	13	0.185	10	0.103
R__SOL_AWC(..).sol	14	0.610	5	2.090
V__RCHRG_DP.gw	15	0.001	16	0.001
R__OV_N.hru	16	−0.017	15	−0.308

Table 5 | Sediment-sensitive parameters and their fitted values

	Wajifo		Humbo	
Parameter name	**Rank**	**Fitted values**	**Rank**	**Fitted values**
V__USLE_P.mgt	1	0.0002	1	0.002
V__USLE_K(..).sol	2	0.5631	2	0.501
V__USLE_C{..}.plant.dat	3	0.3023	3	0.347
V__SPCON.bsn	4	0.0745	5	0.019
V__SPEXP.bsn	5	1.0458	6	1.438
V__LAT_SED.hru	6	1.4417	4	3.875

Table 6 | The value of the SWAT model efficiency evaluation indexes for streamflow

	Calibration (1995–2008)		Validation (2009–2015)	
Index	**Wajifo**	**Humbo**	**Wajifo**	**Humbo**
R^2	0.83	0.6	0.68	0.67
NS	0.83	0.6	0.69	0.67
PBIAS	−17.2	−3.7	−20.1	−3.6
p-factor	0.77	0.74	0.74	0.76
r-factor	0.95	1.04	0.72	0.69

According to the evaluation indexes, the observed and simulated streamflow has a good relation ($R^2 \geq 0{,}6$, NS ≥ 0.6, PBIAS $\geq -25\%$ or $\leq 25\%$, *p*-factor ≥ 0.7, and *r*-factor ≤ 1.5) showing the acceptable range of the evaluation indexes. The relation between the observed, simulated, and per cent of prediction uncertainty is elaborated in Figure 5.

Sediment calibration and validation output

The model simulation of sediment yields was calibrated and validated in Wajifo and Humbo gauging stations. The model efficiency was also checked with the evaluation indices and all values indicate a good prediction of the

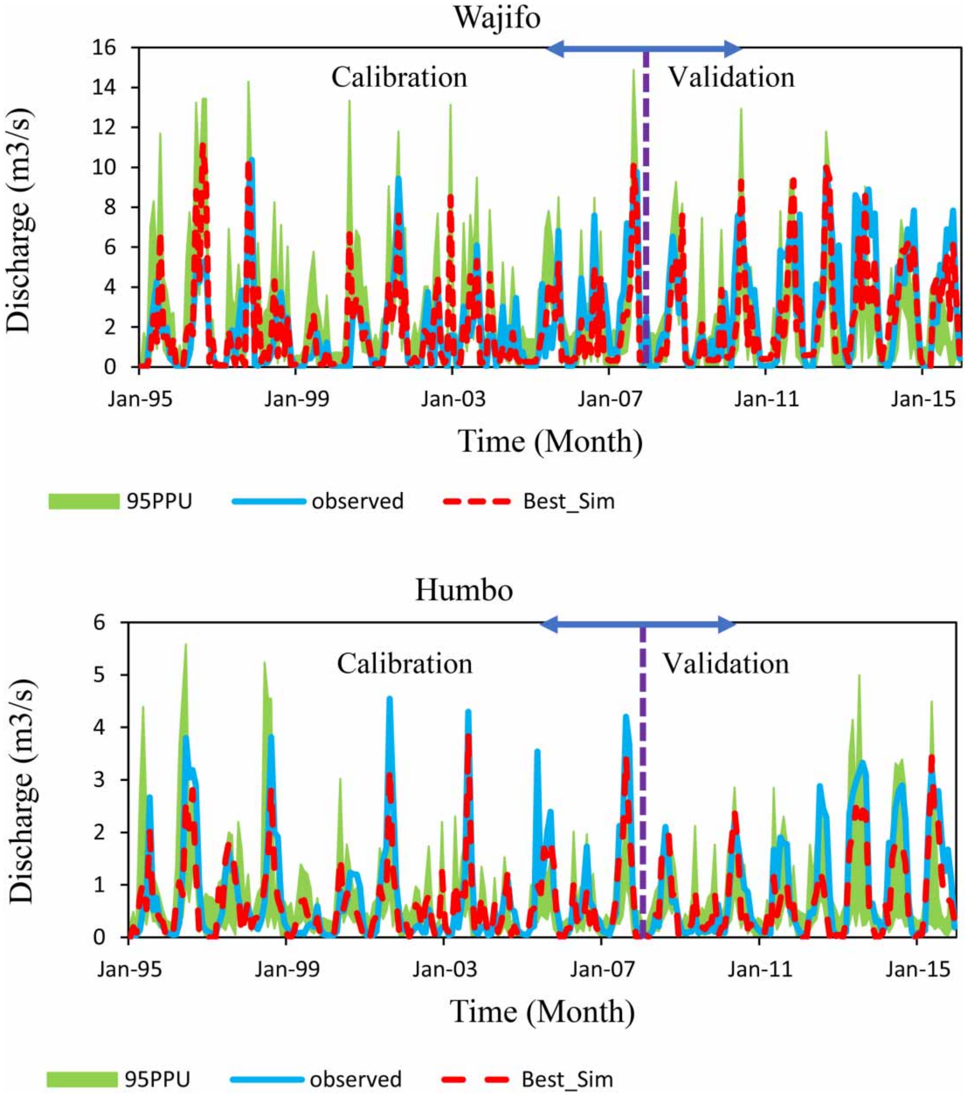


Figure 5 | Comparison graph of the observed and best-simulated streamflows.

Table 7 | The value of the SWAT model efficiency evaluation indexes for sediment

	Calibration (1995–2008)		**Validation (2009–2015)**	
Index	**Wajifo**	**Humbo**	**Wajifo**	**Humbo**
R^2	0.63	0.57	0.58	0.67
NS	0.73	0.6	0.59	0.67
PBIAS	−19.2	−13.7	−18.1	−3.6
p-factor	0.97	0.84	0.64	0.76
r-factor	0.75	1.14	1.02	1.19

model suggesting that the SWAT can be adopted for hydrological simulation in the Kalte River watershed (Table 7).

The result shows that there is a good agreement between the measured and simulated monthly sediment with some underestimation of the peak sediment yield (Figure 6).

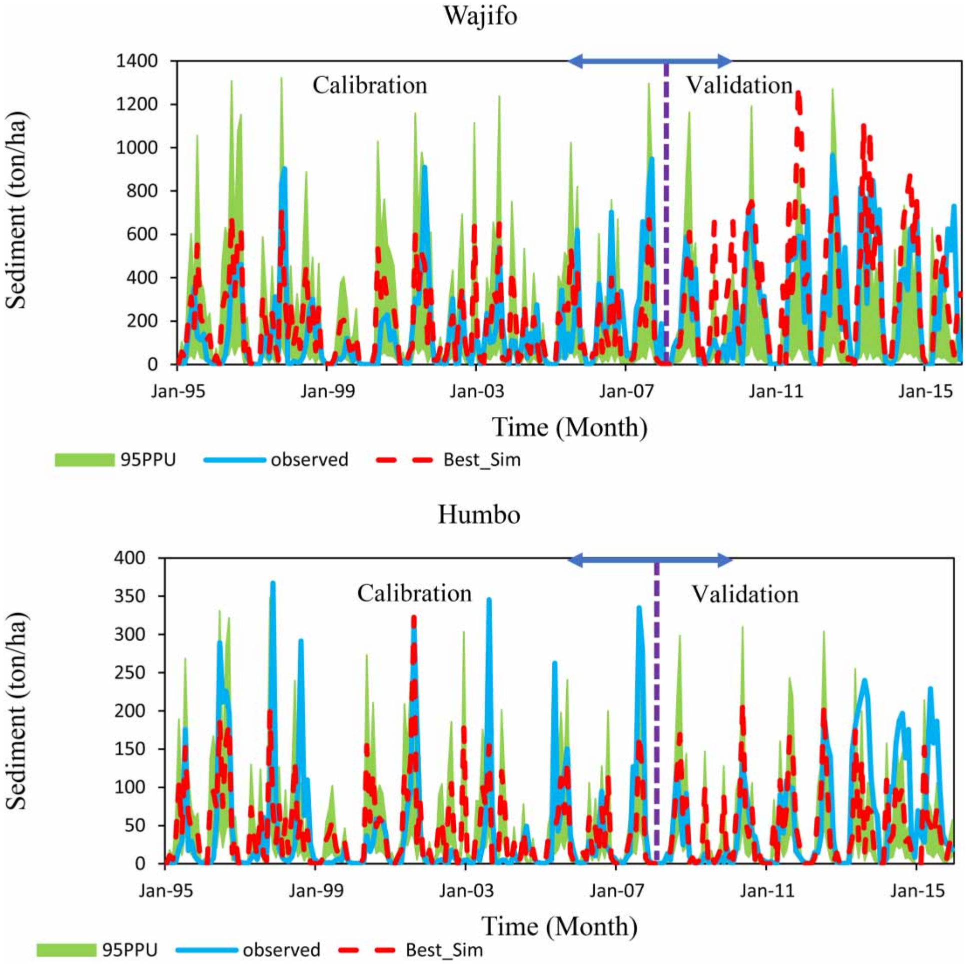


Figure 6 | Comparison graph of the observed and best-simulated sediments.

Hotspot area identification and mapping

Sediment hotspot areas are identified based on the yearly sediment yield per hectare and the severity classes are grouped according to Table 3. After the model calibration and validation of sediment, the spatial distribution of the sediment yield was identified by delineating the watershed into sub-watersheds and finding the sediment yield in each sub-watershed. The watershed was divided into 49 sub-watersheds and the sediment yield in each sub-watershed was estimated. The sediment yield varies from 0.74 to 121.58 tons/ha/year. Therefore, 26 sub-watersheds, which constituted 53.06% of the studied watershed, exhibited very low-to-moderate erosion risks. As the soil losses in the 26 sub-watershed areas are within the acceptable soil loss rate, it is less important to apply WMS. Whereas the 23 sub-watersheds exhibited severe to very severe erosion risk areas and covered 46.94% of the total area. These sub-watersheds are, therefore, identified as hotspot areas that need quick management intervention to reduce soil losses. Therefore, the hotspot area map is developed with severity groups (Figure 7).

Watershed management strategy scenarios output

The implementation of various WMS exhibits considerable improvement in sediment yield reduction. The cost of implementation of WMS may limit the implementation to a few watersheds. Thus, it is always better to start management measures from the highest priority sub-watershed. In the Kalte watershed, 53.06% of sub-basins yield 30 tons/ha/year and more. Therefore, the WMS is applied for these sub-basins. The sediment output reduction by implementing WMS was compared with the model outcomes in the current conditions (base scenario) as listed in Table 8. Therefore, compared to the base scenario the average sediment yield is 25.64 tons/ha/year reduced to 9.23 tons/ha/year or 64% reduction by terracing. In a previous study conducted on the Bilate watershed, the sediment reduction capability of terracing was 60–80% (Amaru Ayele & Gebremariam 2020). In the

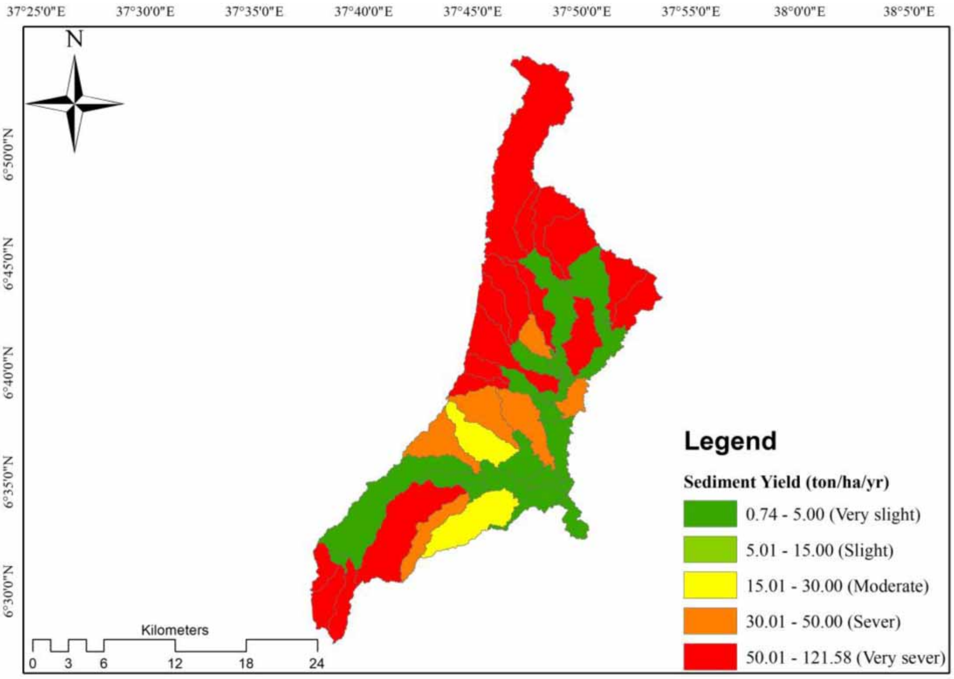


Figure 7 | Sediment yield map of the Kalte watershed.

Table 8 | WMS scenarios and their efficiency in the Kalte watershed

Scenarios	Description	Parameters	Calibrated value	Modified value	Average sediment yield (ton/ha/year)	Reduced sediment	% Reduction
Scenario_0	Base scenario	–	–	–	25.64		
Scenario_1	Terracing	TERR_P	0.6	0.55	9.23	16.41	64.00
		TERR_CN	60	59			
		TERR_SL					
		0–5% Slope	56	15			
		5–15% Slope	42	15			
		15–30% Slope	20	15			
		>30% Slope	9.75	8			
Scenario_2	Contour planting	CONT_CN	60	59	13.35	12.29	47.93
		CONT_P	0.6	0.5			
Scenario_3	Strip cropping	STRIP_N	0.15	0.35	10.43	15.21	59.32
		STRIP_CN	60	58			
		STRIP_C	0.4	0.2			
		STRIP_P	0.7	0.5			
Scenario_4	Grassed waterway	GWATI	–	1	11.78	13.86	54.06
		GWATN	0.1	0.35			
		GWATSPCON	0.005	0.005			
		GWATD	1	3/4*GWATW			
		GWATW	10	15			
		GWATL	1,000	1,000			
		GWATS	0.005	HRU_SLP*0.75			

second scenario contour planting implementation can reduce the sediment yield by 47.93% and strip cropping will reduce 59.32% soil erosion. Contour planting and strip cropping methods are evaluated in different watersheds in Ethiopia and reported their efficiency of 40–60% reduction (Bitew & Kebede 2023; Zantet *et al.* 2023). Grassed waterways are mostly in small watersheds and urban watersheds due to their complexity and cost of implementation and their sediment reduction capability is 50–60% (Parajuli 2022). In this study, compared to the base scenario the grassed waterway reduces 54.06% of sediment yield.

The study also evaluates the integrated methods firstly integrating the terracing and contour planting. At this condition, terracing was applied for very severe sub-basins and contour planting was applied for severe sub-basins. The 50.46% sediment yield is reduced by terracing plus contour planting. Secondly, terracing and strip cropping were integrated and reduced the 60% of sediment yield.

CONCLUSION

This study attempted to develop a comprehensive integrated WMS by employing a methodological framework with a physically based, spatially distributed, and the public domain SWAT model. The model was adopted to the Kalte River watershed using calibration and validation by observed data through the SWAT-CUP and SUFI2 algorithm. According to statistical evaluation indexes (R^2, NS, and RSR), the SWAT model has good performance in the study watershed as streamflow and sediment wise.

The result depicts that 87,920 tons/ha/year of sediment are yielded to Lake Abbaya from the Kalte River watershed. Moreover, sub-basins in the Kalte River watershed have an average sediment yield value of 25.64 tons/ha/year (0.74–121.58 tons/ha/year). The Kalte River watershed was discrete into 49 sub-watersheds during modelling, of which 53.06% (26) exhibited very low-to-moderate sediment yield, and severe-to-very-severe recording covered 46.94% (23) of the watershed. These results implicate that the Kalte River watershed is vulnerable to extensive agricultural soil loss and imposes the risk on Lake Abbaya sediment deposition. Therefore, integrated WMSs are employed in the sediment yield-prone area (sub-basin yielding severe to very severe).

However, lack of long-term continuous data in the study area different types of WMSs were evaluated in this study including terracing, contour planting, strip cropping, and grassed waterway. The efficiency of applying these WMSs was evaluated against the base scenario. Therefore, this study found that terracing reduces sediment yield by 64%, strip cropping reduces the sediment yield by up to 59.32%, grassed waterways reduce the sediment yield by up to 54.06%, and up to 47.93% of sediment yield is reduced by contour planting. Hence, terracing is more efficient and the best management strategy in the Kalte River watershed is terracing. The findings of this study are beneficial to watershed managers and the scientific community. Watershed managers and decision-makers can make use of the information to help them choose appropriate WMS and ensure sustainable watershed management.

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AUTHORS CONTRIBUTION

A.M., M.B., H.D., and M.C. contributed to conceptualization; A.M. and M.B. contributed to methodology; A.M. contributed to software development; A.M. validated the work; A.M. and M.B. participated in formal analysis; A.M. M.B., H.D., and M.C. investigated the work; A.M. M.B., H.D., and M.C. were involved in resource preparation; A.M. and M.B. participated in data curation; A.M. prepared the original draft; M.B., H.D., and M.C. wrote the original draft and reviewed and edited the manuscript; and A.M., M.B., H.D., and M.C. visualized the published work. All authors agreed to the published version of the manuscript.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

CONFLICT OF INTEREST

The authors declare that there is no conflict.

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