



Sediment yield modelling and prioritization of erosion-prone sub-basins in the Tekeze watershed, Ethiopia

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Abstract

Soil erosion is a major global concern due to its adverse impact on agricultural productivity and dam reservoir storage capacity. Effective land management in large watersheds is difficult, particularly in developing countries, owing to the high cost of soil conservation expenditure. Identifying the most vulnerable areas for erosion and executing remedial measures for those areas is crucial to reduce costs and improve effectiveness. The Soil and Water Assessment Tools model was used to identify weak zones for erosion from hydrologic response units to larger watersheds. The study focused on the Tekeze watershed, divided into 34 subbasins and 158 hydrologic response units, with the model performing within acceptable limits for evaluating erosion and flow. The results showed that the model is within acceptable limits for evaluating erosion and flow in the Tekeze basin, with significant differences in sediment yield across each subbasin. Due to their high sediment yield, six subbasins (viz., 1, 3, 5, 14, 17, and 28) require urgent attention. The findings of this study can guide land managers in developing effective strategies to reduce soil erosion and enhance agricultural productivity.

Keywords Erosion-prone area · Sediment yield modelling · SWAT model · Tekeze watershed

1 Introduction

Soil erosion is a significant problem worldwide (Sadeghi & Mizuyama, 2007), with severe implications for soil productivity, reservoir capacity, and water quality. Erosion predominantly affects the topsoil layer (Liu et al., 2010), which contains high levels of

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organic matter and nutrients, resulting in a decline in productivity that has considerable economic consequences. Soil erosion has been identified as the leading cause of land degradation in sub-Saharan Africa (Boj , 1996), with more than two-thirds of agricultural land degradation in the region attributed to soil erosion resulting from land-use changes and agricultural land expansion.

The impact of soil erosion is not limited to the reduction of agricultural productivity but also extends to the life of dams and the growth of the country (Pimentel, 2006). In Ethiopia, Tekeze Dam, Africa's highest arch dam (Welde, 2016), is threatened by sedimentation issues due to the steep slope and insufficient plant cover of the Tekeze watershed. Identifying the weak zone for erosion in the watershed and prioritizing the most vulnerable areas is crucial to maintaining the dam's useful life. Therefore, a comprehensive assessment of the watershed's soil erosion status is required by direct measurement in the watershed or using a hydrological model. Direct measurement of data over the entire watershed provides more precise results (Tazioli, 2009), but installing rain gauges throughout the watershed is expensive, especially in developing countries. As an alternative, the Modified Universal Soil Loss Equation (MUSLE) in the SWAT can be used to calculate the total soil erosion at the subbasin level (Chen & Mackay, 2004; Lemma et al., 2019). This formula takes into account several factors, such as rainfall intensity, slope, soil erodibility, and land use, among others. This approach is less expensive and can provide a useful estimation of soil erosion levels in the watershed, allowing for targeted erosion control measures to be implemented in the most vulnerable areas.

SWAT is a hydrological model that was initially developed by the United States Agriculture Department in 1998 (Kumar & Merwade, 2009), and it is one of the most widely used hydrological models for estimating surface runoff, streamflow, and sediment out at regional and catchment levels.

Before performing a simulation using SWAT (Strauch et al., 2012), it is essential to carry out an uncertainty analysis because there are a lot of uncertainties arising from various sources, such as input data, model parameters, and the inherent complexity of the watershed. The proportion of observed data and level of uncertainty is indicated by 95 PPU (95% prediction uncertainty), which helps to ensure that the results are reliable.

Assessment of streamflow and sediment-yield variation within a watershed is a crucial endeavor that enables the identification of the degree of impact and the development of appropriate adaptation strategies in advance. It is imperative to conduct a sub-basin-level study to comprehend the variation in streamflow or sediment yield within the watershed, enabling individuals and societies to anticipate and respond to potential future challenges. This may involve preventing worst-case scenarios from occurring or, at the very least, being well-prepared and resilient to face possible challenges. The primary objectives of this research are to assess average monthly and annual streamflow and sediment yield in the Tekeze basin, identify the most vulnerable subbasins of watersheds within the Tekeze basin to soil erosion, and evaluate the performance of the hydrological model in assessing streamflow and sediment yield. This study presents significant benefits to watershed management planners in the basin, as well as users of the SWAT hydrological model.

2 Material and methodology

2.1 location of research area

Tekeze watershed is a geographical location that is situated between $36^{\circ}48'19.28''$ and $39^{\circ}51'13.12''$ East and $12^{\circ}14'23.42''$ and $14^{\circ}47'51.26''$ North (Fig. 1). This area spans two Ethiopian regional states, Amhara and Tigray, and encompasses a total area of 56,898.39 km². The watershed is characterized by rugged and mountainous terrain, with elevations ranging from 695 m in the lowlands to 4523.76 m in the highlands (Fig. 1b). The Tekeze River is the primary river that flows through the watershed and is an important source of water for irrigation and hydropower generation.

The Tekeze watershed is an essential area for Ethiopia's agricultural and energy production. The watershed is home to the Tekeze Dam, which is Africa's highest arch dam (Welde, 2016), standing at 180 m tall and producing 300 megawatts of electricity. The dam was built to provide energy and be used for irrigation, but sedimentation issues caused by the watershed's steep slope and insufficient plant cover threaten its useful life.

Despite the challenges posed by its rugged terrain, the Tekeze watershed supports a diverse range of flora and fauna. The area's unique ecosystems are home to various wildlife species, including monkeys and birds, and the fertile soil and favorable climate provide ideal conditions for crop production.

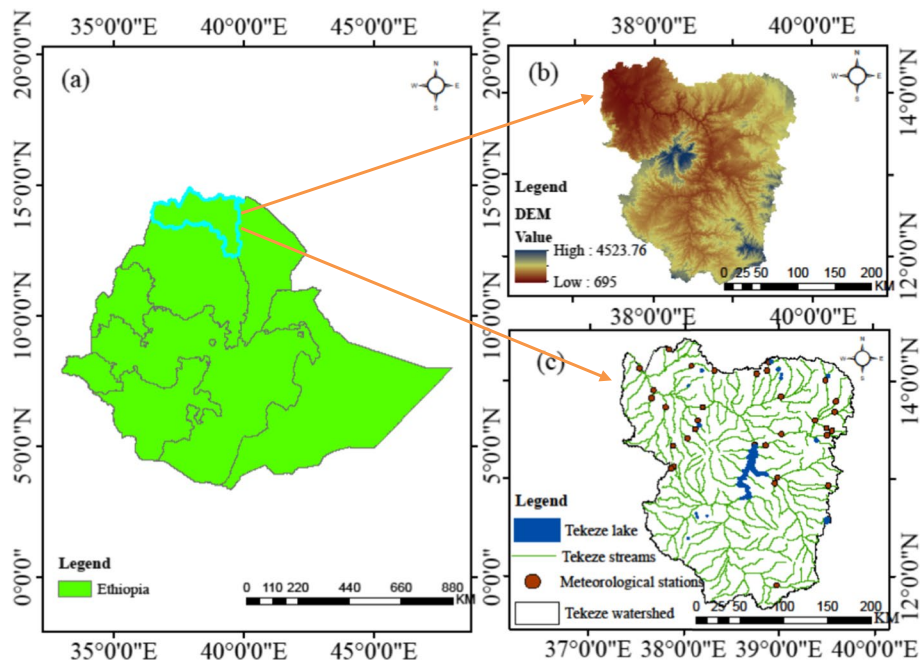


Fig. 1 Location of the research area **a** Ethiopia map; **b** Tekeze DEM; **c** Tekeze watershed

2.2 Hydrological model selection

The selection of a hydrological model is a critical step in hydrological modelling (Butts et al., 2004), as different models have different strengths and weaknesses that can affect the accuracy and reliability of the results. The choice of model should be based on careful consideration of several factors, including research objectives, data availability, model complexity, spatial and temporal resolution, model validation, and model transparency.

In the case of this study, the goal is to assess erosion and land management practices in a specific watershed. Based on the research objectives and available data, the Soil and Water Assessment Tool (SWAT) was chosen as the hydrological model for the study. SWAT is a widely used and well-validated model that can simulate the hydrological cycle and water quality processes in watersheds with varying land use and management practices (Qiu & Wang, 2014). It is capable of accounting for various hydrological processes such as infiltration, runoff, and groundwater flow, and can also simulate sediment and nutrient transport.

Data available for the study area included meteorological, hydrological, land use, soil, and DEM, which are important inputs for the SWAT model. The model's complexity was appropriate for the available data and research objectives, and the spatial and temporal resolution was adequate for the study area. The SWAT model was validated using observed data from the study area, and the results showed good agreement between the simulated and observed hydrological processes.

Furthermore, the SWAT model is a transparent model, with a well-documented methodology and parameters, which increases its credibility and reliability for stakeholders and decision-makers. This transparency ensures that the results of the model can be easily communicated to relevant parties, which is essential for informed decision-making.

2.3 SWATmodel

SWAT is a semi-distributed and physically-based hydrological model that was developed in the early 1990s by the United States Department of Agriculture's Agriculture Research Service (USDA) (Arnold et al., 1998). It is designed to simulate the hydrological processes of watersheds, ranging in size from small to large scales, to assess sediment yield, streamflow, water quality, and quantity.

The model works on a process-based approach, where the watershed is divided into smaller portions known as hydrological response units (HRUs), based on stream drainage areas, as well as the land cover, slope, and soils of the watershed. The hydrologic process of the watershed is then simulated by the water balance equation.

SWAT provides two options for assessing surface runoff: the SCS-CN and Green-Ampt infiltration methods. The SCS-CN method considers the total volume of rainfall, independent of the duration and intensity of rainfall, while the Green-Ampt method is time-based and requires sub-daily rainfall data. For this study SCS-CN approach was selected because only daily recorded data was available or no sub-daily data was available.

$$Q_{sf} = \frac{(Pd - Ia)^2}{(Pd - Ia + S)} \quad (1)$$

where Q_{sf} represents cumulative runoff rainfall surplus (mm), P_d represents a depth of daily precipitation (mm), I_a initial abstraction before the start of runoff (mm), and S represents a parameter of retention (storage) in millimeters.

S Retention (storage) parameter is determined by the CN equation, which varies globally due to variations in land use land cover, soils, slope, and land management.

$$S = 25.49 \left(\frac{1000}{CN} - 10 \right) \quad (2)$$

where CN represents curve number, and commonly $I_a \approx 0.2S$. Then Eq. (3) becomes,

$$Q_{sf} = \frac{(P_d - 0.2S)^2}{(P_d - 0.8S)} \quad (3)$$

In SWAT the quantity of soil erosion that happens in upland areas as a result of sheet and rill erosion is predicted using the mathematical formula Universal Soil Loss Equation (USLE) (Benavidez et al., 2018; Gwapedza et al., 2021). This formula takes into account several factors that contribute to soil loss, such as the slope of the land, the type of soil, the amount of vegetation cover, and the intensity and duration of rainfall. The USLE formula is expressed as:

$$A = R K L S C P \quad (4)$$

where

A = the potential soil loss in tons per acre per year.

R = the rainfall erosivity factor, which takes into account the amount and intensity of rainfall.

K = the soil erodibility factor, which measures the susceptibility of the soil to erosion based on its texture, structure, and organic content.

LS = the slope length and steepness factor, which reflects the effect of the slope on the amount of soil loss.

C = the cover and management factor, which considers the amount and type of vegetation cover and the farming practices used on the land.

P = the support practice factor, which represents the effectiveness of conservation practices in reducing soil loss.

2.4 Assessment of model performance

In this study, the effectiveness of the model was assessed through a comprehensive evaluation of its performance using various statistical measures. These measures included the coefficient of determination (R^2), Nash–Sutcliffe coefficient (NSE), and percent bias (PBIAS) (Ghezelsolfloo et al., 2022). R^2 is a measure of the correlation between the simulated and observed values of the parameter being modeled. A value of 1 for R^2 indicates a perfect correlation between the two sets of data, while a value of 0 indicates no correlation. NSE measures the similarity between the observed and simulated values, with a value of 1 indicating a perfect match, and a value of 0 indicating that the simulated values are equal to the average observed values. PBIAS measures the overall deviation of the simulated values from the observed values as a percentage. The higher the PBIAS value, the greater the deviation from the observed values. These

statistical measures are important tools for evaluating the performance of models, and can help researchers to determine the accuracy and reliability of their models.

$$R^2 = 1 - \frac{\sum_{i=1}^n (Qp - \overline{Qo})^2}{\sum_{i=1}^n (Qo - \overline{Qo})^2} \quad (5)$$

$$NSE = 1 - \frac{\sum_{i=1}^n (Qo - Qp)^2}{\sum_{i=1}^n (Qo - \overline{Qo})^2} \quad (6)$$

$$PBIAS = \frac{\sum_{i=1}^n (Qo - Qp)}{\sum_{i=1}^n (Qo)} * 100 \quad (7)$$

where Qo refers to the observed flow data, \overline{Qo} denotes average measured flow data, Qp denotes predicted runoff data, \overline{Qp} represents average predicted runoff data, and n represents the number of measured data points.

2.5 Model input datas

In this study, SWAT model was utilized to evaluate the streamflow and sediment yield in the watershed. The model requires a variety of input data, including daily meteorological data such as maximum and minimum temperature, precipitation; spatial data, such as Digital Elevation Model (DEM), land use-landcover, and soil data; hydrological data, and sediment data. These data were collected from various sources, and their details are presented in Table 1.

2.6 Methodology

SWAT model involves several steps. First, the study area is delineated into sub-watersheds, and the required data is collected, including meteorological data, land use and soil data, topographical data, and hydrological data. The collected data is then processed and pre-processed for input into the model.

Once the data is collected and pre-processed, the model is set up by defining the sub-watersheds and hydrological processes in each sub-watershed. The model parameters are calibrated to match the observed streamflow data, and then the model is validated by comparing the simulated and observed data for another period.

Once the model is calibrated and validated, it can be used to evaluate different management scenarios, such as land use changes, water resource development, and climate change impacts. The model output can help identify critical areas where erosion and sedimentation are high and can aid in the selection of appropriate land management practices. The following flowchart presents the general methodology and step-by-step procedure used in this study. (Fig. 2).

Table 1 Input data and its source

Input data	Description	Source	References
Meteorological data 33 years data (1986–2018)	Max and Min temperatures, solar radiation, wind speed, and relative humidity	Ethiopian National Meteorology Service Agency (ENMSA)	Dile & Srinivasan (2014), Gebrehiwot et al. (2011)
Special data	DEM LULC and Soil data	Earth explorer.usgs.gov Ethiopia Ministry of Water, Irrigation, and Electricity (EMWIE), and additional image classification is performed using Erdas software	Endalamaw et al. (2021), Mariye et al. (2022) Kenea et al. (2021), Negesse et al. (2021)
Hydrological data 13 years data (1994–2006)	Discharge and sediment data	Ethiopia Ministry of Water, Irrigation, and Electricity (EMWIE)	Kenea et al. (2021), Negesse et al. (2021)

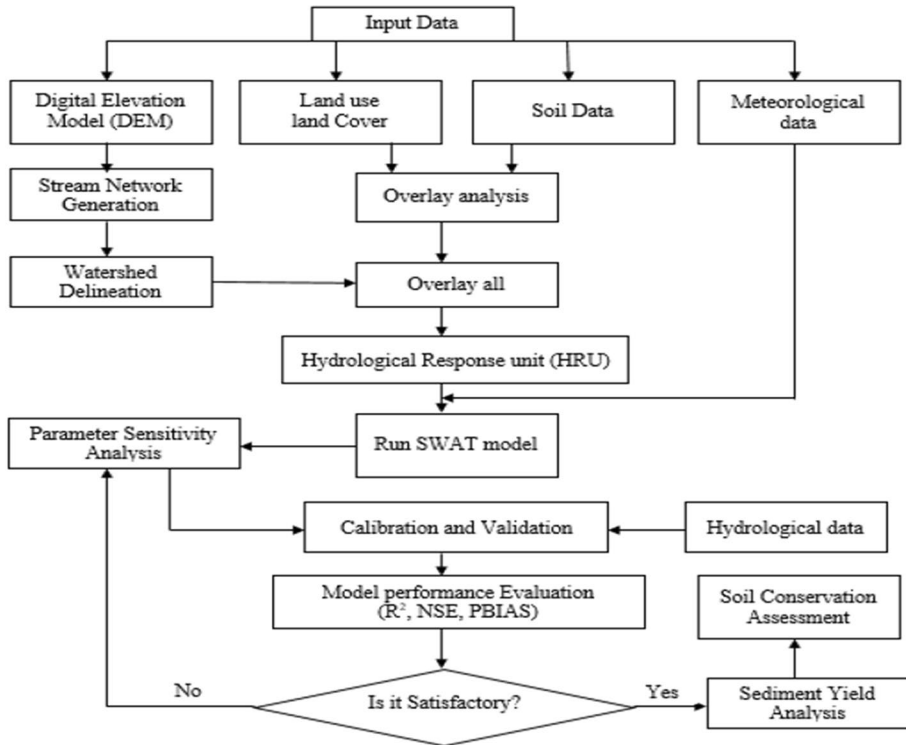


Fig. 2 Flowchart for Research Methodology

3 Result and discussion

3.1 Sensitivity analysis

In order to identify the significant parameters affecting the predicted results of stream-flow and sediment yield, a SWAT-CUP sensitivity analysis was conducted in accordance with Dong et al. (2015) and Healy and Essaid (2012). This analysis technique is used to determine the most important parameters for SWAT model calibration and validation, as reported in Dong et al. (2015) and Tesfaye et al. (2019). In this study, a set of 12 stream-flow parameters (as shown in Table 2) was selected to determine the critical parameter, following the approach of (Khalid et al., 2016; Woldesenbet et al., 2017).

3.2 Calibration and validation

Calibration and validation are crucial steps to ensure the accuracy of the SWAT model. The calibration process involves adjusting the model parameters until the simulated values match the measured values or satisfy the desired criteria (Arnold et al., 2012). On the other hand, validation is a process of verifying the performance of the calibrated model without further adjusting the parameters.

Table 2 Ranking of most sensitive flow and Sediment parameters

Hydrological data	Parameter	Description of parameter	Sensitivity Rank	Fitted value	t-stat	p-value
Discharge	R__SOL_AWC	Available water capacity of soil	1	1.15	-4.95	0.00
	V__ESCO.hru	Adjustment factor of soil	2	0.04	4.09	0.000
	V__SLSUBBSN.hru	mean slope length	3	44.3	3.49	0.001
	R__SOL_BD	bulk density of soil	4	-0.01	-3.48	0.001
	R__CN2.mgt	SCS runoff curve number	5	0.03	2.64	0.009
	R__EPCO.hru	The adjustment factor for crop uptake	6	-0.12	1.25	0.213
	V__GWQMN.gw	water depth of shallow aquifer required for return flow to occur	7	2710.9	0.57	0.569
	R__SOL_K	Permeability of saturated zone in mm/hr	8	-0.009	0.48	0.633
	V__GW_DELAY	delay of groundwater (day)	9	88.7	-0.28	0.776
	V__ALPHA_BF	base-flow alpha factor for (day)	10	0.38	-0.25	0.805
	V__REVAPMN	The minimum depth of water in the shallow aquifer required for "revap" to take	11	59.09	-0.07	0.945
Sediment	v__USLE_K.sol	soil erodibility	1	0.78	19.03	0.001
	r__HRU_SLP.hru	mean steepness slope	2	0.19	2.62	0.005
	r__FILTERW.mgt	edge-of field filter width	3	0.55	0.42	0.765
	r__LAT_SED.hru	Sediment concentration for lateral and groundwater flow	4	0.24	-0.32	0.816

V represent replace and r represent existing parameter value is multiplied with by (1+a given value)

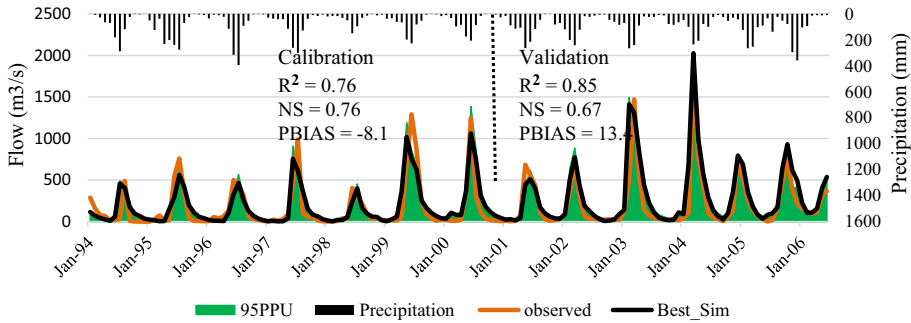


Fig. 3 Flow Hydrograph for Observed and Simulated Flow during 1994–2006

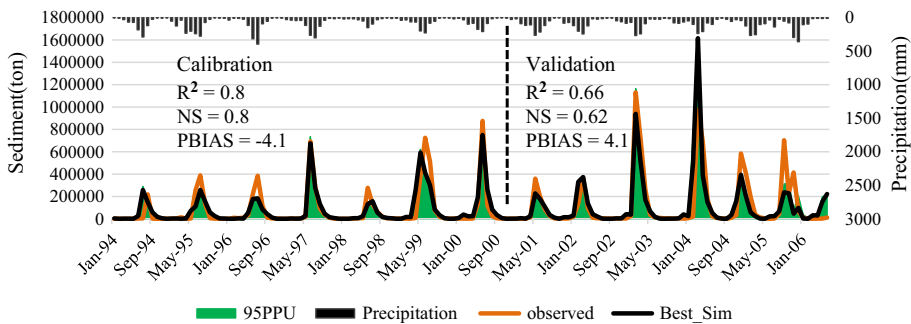


Fig. 4 Observed and simulated sediment load for period (1994–2006)

To evaluate the performance of the SWAT model, calibration and validation were performed for 13 years, with 7 years (1994–2000) for calibration and 6 years (2001–2006) for validation. Figures 3 and 4 illustrates the calibration and validation results for both measured and simulated data, with statistical performance values of $R^2=0.76$ for calibration and 0.85 for validation, $NS=0.76$ for calibration and 0.69 for validation and $PBIAS=-8.1$ for calibration and 13.4 for validation. These results indicate that the model's quality is excellent, with a significant correlation between the measured and simulated data, which is in line with the model evaluation standards reported by Yuemei et al. (2008).

3.3 Criteria and ranges of soil erosion

In order to assess the severity of soil erosion in a particular area, it is essential to have a set of criteria to evaluate the extent of the problem. Table 3 provides a comprehensive guide that outlines the criteria and ranges of soil erosion that can be used to identify the areas that require immediate attention. By using this table, decision-makers can accurately assess the level of soil erosion and prioritize their conservation efforts accordingly.

Once the vulnerable areas have been identified, the next step is to implement the appropriate soil conservation and management techniques. These techniques can include the use of cover crops, contour farming, terracing, and conservation tillage practices, among

Table 3 Class of soil erosion (Uniyal et al., 2020)

Soil erosion Type/class	Rate (ton/ha/year)
Extremely low	$0 < X \leq 5$
low	$6 \leq X \leq 10$
Medium	$11 \leq X \leq 15$
Large/high	$16 \leq X \leq 20$
Very Large/high	$21 \leq X \leq 40$
Very Serious	Greater than 41

others. The selection of the most suitable technique will depend on the specific requirements of the area, such as soil type, land use, climate, and topography.

3.4 Assessing sediment yield and surface runoff variations

Assessing the variations in sediment yield and surface runoff is a crucial aspect of watershed management and hydrological studies (Zuo et al., 2016). In the Tekeze basin, which is a critical natural resource that supports the livelihoods of people and the ecosystem in the region, the SWAT model was employed to evaluate the amount of annual erosion occurring within the watershed. To provide detailed assessments of specific regions, the subbasin analysis approach was utilized.

SWAT model divides the watershed into smaller subbasins using a digital elevation model (DEM) and a stream network delineation algorithm. The DEM is used to calculate the flow direction and accumulation, and a stream network is delineated by identifying the cells that have the highest flow accumulation values and defining them as stream segments. The subbasins are then defined by delineating the drainage area between adjacent stream segments. This process is repeated until all the subbasins are identified within the watershed. The size of the subbasins can be adjusted by specifying the minimum and maximum drainage area thresholds during the subbasin delineation process.

The assessment of sediment yield and surface runoff variation is essential for several reasons. Firstly, it aids in comprehending the impact of land use changes, climate variability, and hydrological interventions on soil erosion and river systems. Secondly, it is critical for designing and implementing soil and water conservation measures that can decrease sediment yield and surface runoff variations. Finally, it is crucial for managing water resources and planning infrastructure projects such as dams and irrigation systems.

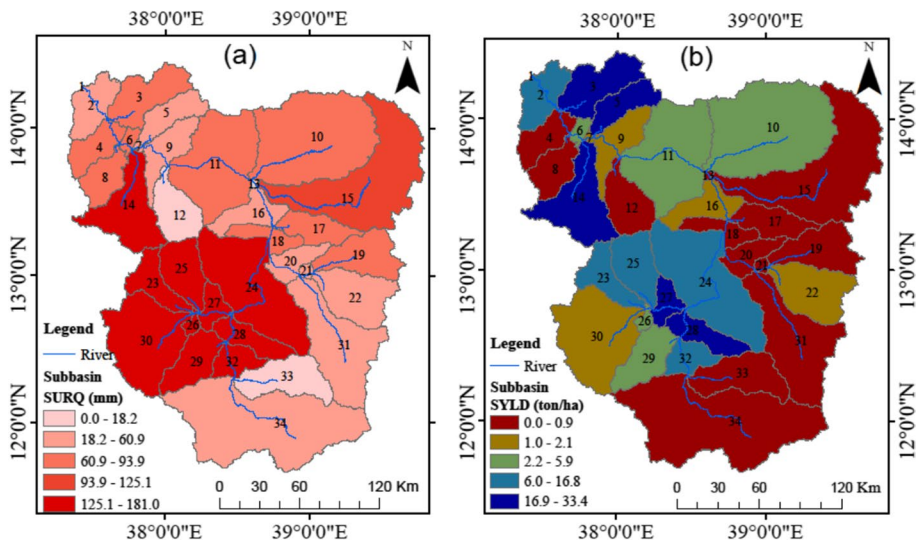
The results of the model indicate significant variation in sediment yield among the subbasins within the Tekeze watershed. This variation is attributed to the differences in land use/land cover, watershed management, soil types, rainfall, and slope variability. The analysis has revealed that sediment yield varies from 0 to 39 tons per hectare. The detailed results are presented in the (Table 4 and Fig. 5).

3.5 Identifying erosion prone area

The identification of erosion-prone areas is a crucial step in effective watershed management. In the Tekeze basin, the analysis has revealed that there are 11 subbasins with a very low sediment yield of 0–5 ton/ha, four subbasins with a low sediment yield of 6–10 ton/ha, one subbasin with a medium sediment yield of 11–15 ton/ha, two subbasins with a

Table 4 Amount of surface runoff and sediment yield in each subbasin

Sunbasin	SURQ (mm)	SYLD (ton/ha)	Subbasin	SURQ (mm)	SYLD (ton/ha)
1	56.4	24.9	18	74.7	0.5
2	60.2	7.8	19	88.3	0.5
3	64.4	23.0	20	49.2	0.1
4	93.9	0.4	21	43.6	0.1
5	47.5	21.4	22	54.1	1.3
6	84.9	3.1	23	164.0	10.6
7	33.6	2.1	24	170.5	8.6
8	74.9	0.9	25	156.3	8.4
9	60.9	1.1	26	170.6	4.3
10	77.9	5.9	27	177.3	31.8
11	81.5	3.4	28	169.2	33.4
12	0.0	0.0	29	174.5	4.9
13	18.2	0.7	30	178.6	1.1
14	181.0	19.3	31	43.3	0.7
15	125.1	0.7	32	164.9	16.8
16	38.6	2.1	33	0.0	0.0
17	66.7	0.2	34	39.5	0.4

**Fig. 5** Result of (a) surface runoff and (b) Sediment yield at Tekeze watershed

high sediment yield of 16–20 ton/ha, and four subbasins with a very high sediment yield of 21–39 ton/ha (Table 5).

Subbasin one stands out as particularly problematic, with a high sediment yield of 24.9 ton/ha, and its critical role as a pass-through for surface runoff from all other subbasins makes it even more pressing to address. To effectively manage erosion in this subbasin,

Table 5 Most sensitive subbasins for erosion

Yield type	Subbasin number	YIELD (ton/ha)
Extremely low	12,33,20,21,17,4,34,19,18,31,13, 15,8,30,9,22,16,7,6,11,26,29	0–4.9
Low	10,2,25,24	5.9–8.6
Medium	23	10.6
Large/high	32	16.8–19.3
Very Large	5,3,1,14,27,28	21.4–33.4

targeted management strategies are necessary. Additionally, subbasins 5, 3, 1, 27, and 28 require urgent attention in terms of land management practices to protect the watershed.

4 Conclusion and recommendation

4.1 Conclusion

The study successfully utilized the SWAT model to accurately identify the most vulnerable areas for erosion in the Tekeze watershed at the sub-basin level. This was made possible by using digital elevation model (DEM) data to provide spatial information on slope, elevation, and watershed features.

Previous research conducted in the Tekeze basin did not analyze erosion susceptibility at the sub-basin level, which made it challenging to pinpoint exact locations and prioritize mitigation efforts. However, this study divided the watershed into 34 sub-basins, enabling the identification of erosion-sensitive zones and providing a roadmap for effective land management.

The identified sub-basins that require immediate attention for soil conservation and management are 1, 3, 5, 14, 27, and 28, with sediment yields ranging from 19.34 to 33.36 tons/ha. Meanwhile, sub-basins 2, 23, 24, 25, and 32, with sediment yields of 7.85 to 16.76 tons/ha, require attention as a secondary priority.

By targeting specific locations, land management efforts can be more effective and cost-efficient. The results of this study can be used as a basis for designing erosion control measures in the Tekeze basin and similar large watersheds. Overall, the sub-basin level analysis proved to be a crucial step in accurately identifying erosion-prone areas and developing effective soil conservation and management strategies.

4.2 Recommendation

Prioritize erosion-prone sub-basins: The study identified specific sub-basins that require immediate attention for soil conservation and management. Therefore, the first step is to prioritize these sub-basins and allocate resources accordingly.

Land-use management: Appropriate land management practices such as agroforestry, contour farming, and conservation tillage should be promoted in sub-basins that are identified as erosion-prone to reduce sediment yield.

Public awareness: Awareness campaigns should be launched to educate the public and farmers about the importance of soil and water conservation, and the need for sustainable land use practices to minimize soil erosion and sediment yield.

Further research: Further research could be conducted to assess the effectiveness of various soil and water conservation practices in reducing sediment yield in the Tekeze Watershed, and to identify other factors that contribute to soil erosion and sediment yield in the region.

By implementing the above recommendations, it is possible to minimize soil erosion, improve soil quality, and sustainably manage the natural resources in the Tekeze basin.

5 Innovative contributions of the study

The study made several innovative contributions. Firstly, the study identified specific sub-basins in the Tekeze Watershed that are prone to erosion using a rigorous modelling approach. By using the SWAT model and sub-basin level analysis, the study provided a detailed understanding of the erosion patterns within the watershed. This approach helped to identify specific regions within the watershed that are prone to erosion, allowing for more targeted and efficient management efforts.

Secondly, the study conducted an uncertainty analysis of the model outputs to ensure that the results are reliable and robust. This is a critical step in modelling studies, as it helps to quantify the level of uncertainty in the results and ensures that the model outputs are trustworthy.

Thirdly, the study demonstrated the importance of sub-basin level analysis for identifying vulnerable areas for erosion, which had not been explored in previous research in the Tekeze watershed. By dividing the watershed into 34 sub-basins, the study provided a more comprehensive understanding of the sediment-prone regions and prioritized sub-basins for conservation measures.

Finally, the study provided practical recommendations for soil conservation and management, such as prioritizing the sub-basins requiring immediate attention for soil conservation and management. These recommendations are crucial for policymakers and practitioners who are tasked with implementing conservation measures effectively.

Data availability Data and material will be given when a request has been made.

Declarations

Conflict of interest There is no conflict of interest by the authors.

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