



Research Article

Evaluating Sediment Control Strategies Using SWAT Based BMP Assessment in a Tropical Highland Watershed, Northern Thailand

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Soil erosion remains a critical environmental challenge in the tropical highland watersheds of Southeast Asia, where steep terrain, intense monsoonal rainfall, and intensive land use interact to accelerate sediment generation and downstream degradation. This study aims to quantify spatial patterns of sediment yield and to systematically evaluate the effectiveness of individual and combined best management practices (BMPs) at both the watershed and subwatershed (SWW) scales using the Soil and Water Assessment Tool (SWAT) in a tropical highland watershed in northern Thailand. Baseline simulations reveal pronounced spatial heterogeneity in erosion severity, with substantial portions of the watershed exhibiting moderate to extreme sediment yield levels. Scenario-based simulations indicate sediment reduction efficiencies ranging from 42% to 85% across watershed and SW scales, demonstrating clear performance differences among BMP categories. Structural BMPs, particularly stone/soil bunds (SSB) and terracing (TRC), achieve the greatest immediate sediment reduction by shortening the effective slope length and disrupting runoff–sediment connectivity in erosion-prone areas. Vegetative and management-based BMPs, including reforestation (RFT), filter strips (FTS), and contour farming (CTF), produce more gradual yet persistent sediment reductions, thereby enhancing long-term hydrological regulation and watershed resilience. Integrated BMP implementation further improves sediment control by coupling rapid structural interception with sustained vegetative and management effects. Spatial prioritization at the SW scale demonstrates that compared with uniform implementation, targeted BMP deployment substantially enhances sediment reduction efficiency. Overall, the integration of SWAT-based modeling, multiscale evaluation, and spatial prioritization offers a transferable and decision-relevant framework for assessing BMP effectiveness and supporting climate-resilient erosion management in tropical highland watersheds.

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Introduction

Soil erosion remains a dominant driver of land degradation worldwide, undermining agricultural productivity, disrupting hydrological processes, and weakening long-term ecosystem resilience across diverse climatic and geomorphological settings (Borrelli et al., 2017; Haregeweyn et al., 2015). Globally, water-driven erosion accounts for more than half of the total soil loss, generating

substantial economic losses, accelerating soil fertility decline, and contributing to the progressive abandonment of productive agricultural land (Bouma and Batjes, 2000; Faksomboon et al., 2023; Pimentel, 2006). Erosion impacts are particularly pronounced in tropical monsoonal regions, where high rainfall intensity, steep terrain, and rapid land use change interact nonlinearly

to amplify runoff energy, soil detachment, and sediment mobilization.

In Thailand, soil erosion has been extensively documented as a critical environmental challenge, especially in northern highland watersheds characterized by complex topography and intense seasonal rainfall. Empirical studies consistently report high erosion rates associated with deforestation, the expansion of upland agriculture, shifting cultivation, and inadequate soil conservation practices (Deng et al., 2025; Gashaw et al., 2021; Haregeweyn et al., 2017). Evidence from northern Thailand further indicates that erosion processes extend well beyond onsite soil degradation, resulting in the export of large sediment loads to downstream rivers and reservoirs, thereby accelerating siltation, increasing flood risks, and degrading aquatic ecosystems and water security (Abebe et al., 2025; Betrie et al., 2011; López-Ballesteros et al., 2019; Merriman et al., 2019). These findings confirm that soil erosion in Thailand operates as a watershed-scale process governed by hydrological connectivity and sediment transfer pathways rather than as a localized field-scale problem.

Previous Thai and regional studies provide robust empirical evidence regarding the effectiveness and suitability of specific BMPs under tropical highland conditions. Practices such as CTF, vegetative buffer strips, and cover crops have been shown to substantially reduce runoff velocity and soil loss on steep cultivated slopes, primarily through the modification of flow pathways, increased surface roughness, and enhanced infiltration capacity, whereas agroforestry systems increase surface roughness, root reinforcement, and soil organic matter, thereby improving erosion resistance and hydrological regulation (Gashaw et al., 2020; 2021; Parajuli et al., 2024; Lemma et al., 2019). Structural measures, including check dams and small retention structures, have also proven effective in trapping sediment and moderating peak flows in headwater channels, particularly when implemented in combination with upstream vegetative practices (Deng et al., 2025; Lemma et al., 2019). Collectively, these studies demonstrate that BMP performance in Thailand is strongly context dependent and regulated by interactions among terrain characteristics, land use patterns, and hydrological connectivity. These Thailand-specific findings directly inform the selection of the BMP scenarios evaluated in this study and provide an empirical basis for interpreting their relative effectiveness at both the watershed and SW scales.

The Thakhunram Watershed (TKRW), a critical SW of the Ping Watershed, exemplifies these challenges. Accelerated soil erosion threatens agricultural sustainability, sediment regulation capacity, and the provision of essential ecosystem services in this mountainous landscape. Despite the expanding body of erosion

research in Thailand, site-specific assessments that explicitly integrate spatial erosion hotspot identification with quantitative, multiscenario BMP evaluation remain limited, particularly in data-scarce tropical highland watersheds.

To address this methodological gap, this study applies the SWAT model to identify erosion hotspots and evaluate the effectiveness of selected BMP scenarios within the TKRW watershed. By explicitly linking erosion hotspot analysis with multiscale BMP performance assessment and building on empirical evidence from prior Thai erosion studies, this research provides a decision-relevant and policy-oriented framework for climate-resilient soil conservation and watershed management. These findings contribute to advancing erosion science in tropical highland environments while supporting evidence-based land use planning aligned with Thailand's climate adaptation and sustainable development objectives.

Methodology

1) Description of the study area

The TKRW, a SW of the Ping River system, covers approximately 391.94 km² and is situated between 16°20'19"-16°32'24" N and 99°14'09"-99°29'53" E (Figure 1a). The elevation ranges from 70 to 575 m above mean sea level, forming a topographically heterogeneous mountainous landscape that is hydrologically partitioned into 30 SWs (Figure 1b). Located in the lower northern region of Thailand, the area represents a transition zone between upland and lowland systems, generating pronounced spatial gradients in climate, vegetation, and soil characteristics that strongly influence runoff generation and sediment transport processes.

Land use and land cover (LULC) are diverse and are dominated by agricultural systems, including paddy fields, perennial crops, and upland farming, followed by forested areas, urban and developed-up land, and other minor land classes (Figure 2a). Topographic controls further intensify hydrological responses, with 41.7% of the area having slopes exceeding 15%, 25.7% falling within 5–15%, and only 33.8% lying below 5%. These slope distributions promote rapid surface runoff, enhance hydrological connectivity, and increase susceptibility to soil erosion, particularly within cultivated uplands.

The dominant soil groups in the watershed are Soil Groups 1, 4, and 20, which account for 90.82%, 4.48%, and 4.69% of the total watershed area, respectively (Figure 2b). These soil groups differ markedly in infiltration capacity, moisture retention, and erodibility, thereby directly influencing watershed hydrology and erosion dynamics.

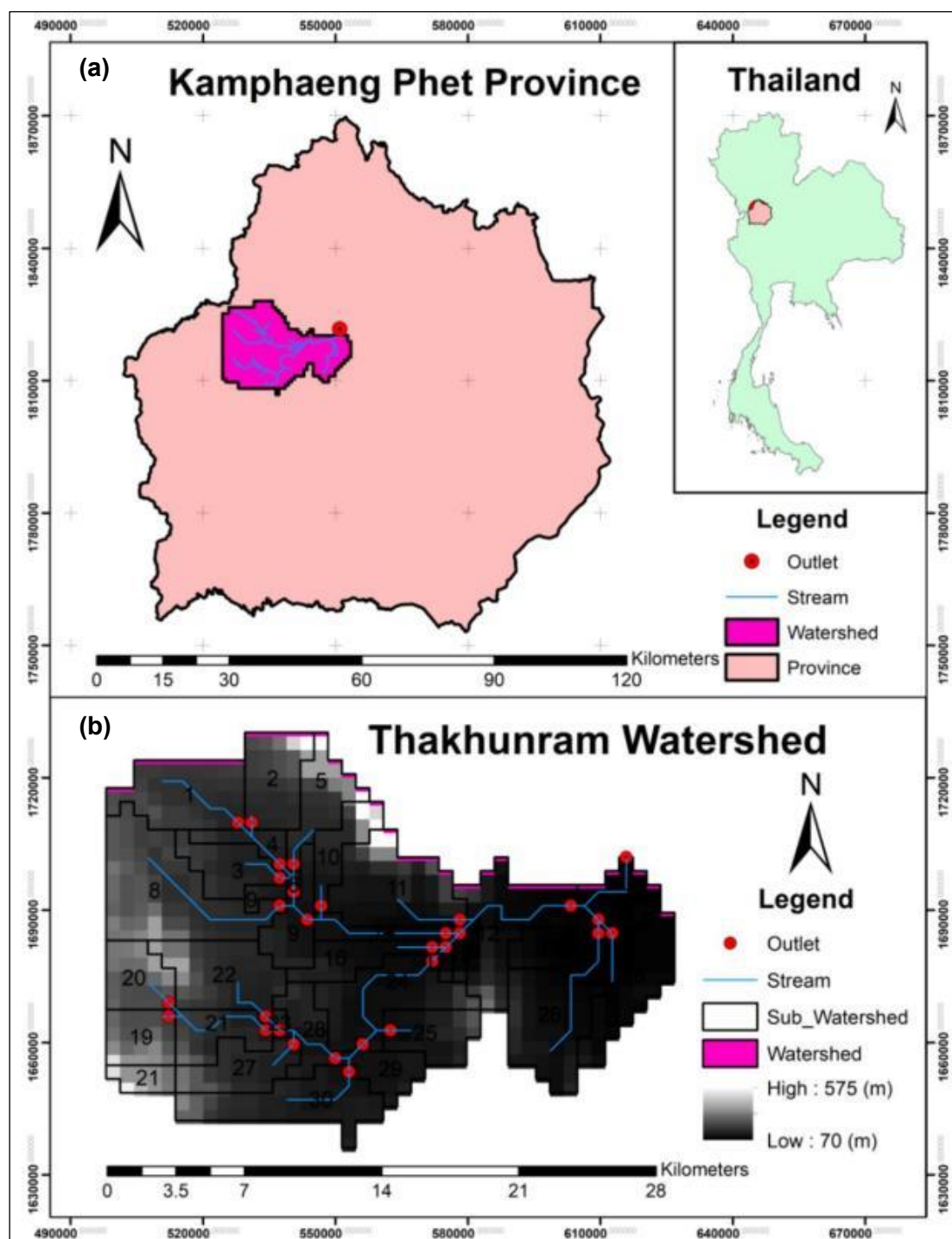


Figure 1 Location map (a) elevation and SWs (b) in the TKRW of Thailand.

2) Climatic conditions

Climatic conditions in the TKRW are shaped by a tropical monsoon regime that produces three distinct seasons: the climatic conditions of the study area follow the seasonal classification defined by the Thai Meteorological Department (TMD), consisting of the rainy season (May–October), the cool season (November–February), and the hot season (March–April). On the basis of long-term climatological records from the TMD (1991–2020), the mean annual rainfall in the study area typically exceeds 1,400 mm. However, observations during the recent study period (2023–2025) indicate a lower mean annual rainfall of 1,259.78 mm, reflecting pronounced

interannual variability and potential influences of recent climatic anomalies and climate change. Seasonal temperatures ranged from an average minimum of 18.14 °C during the cool period to a maximum of 38.91 °C during the hot season (Figure 3).

These climatic gradients play critical roles in regulating evapotranspiration, runoff generation, and seasonal flow dynamics, thereby directly shaping soil erosion susceptibility and agricultural performance across the watershed. Understanding these climate–land–water interactions is therefore essential for supporting integrated watershed management and climate adaptation planning.

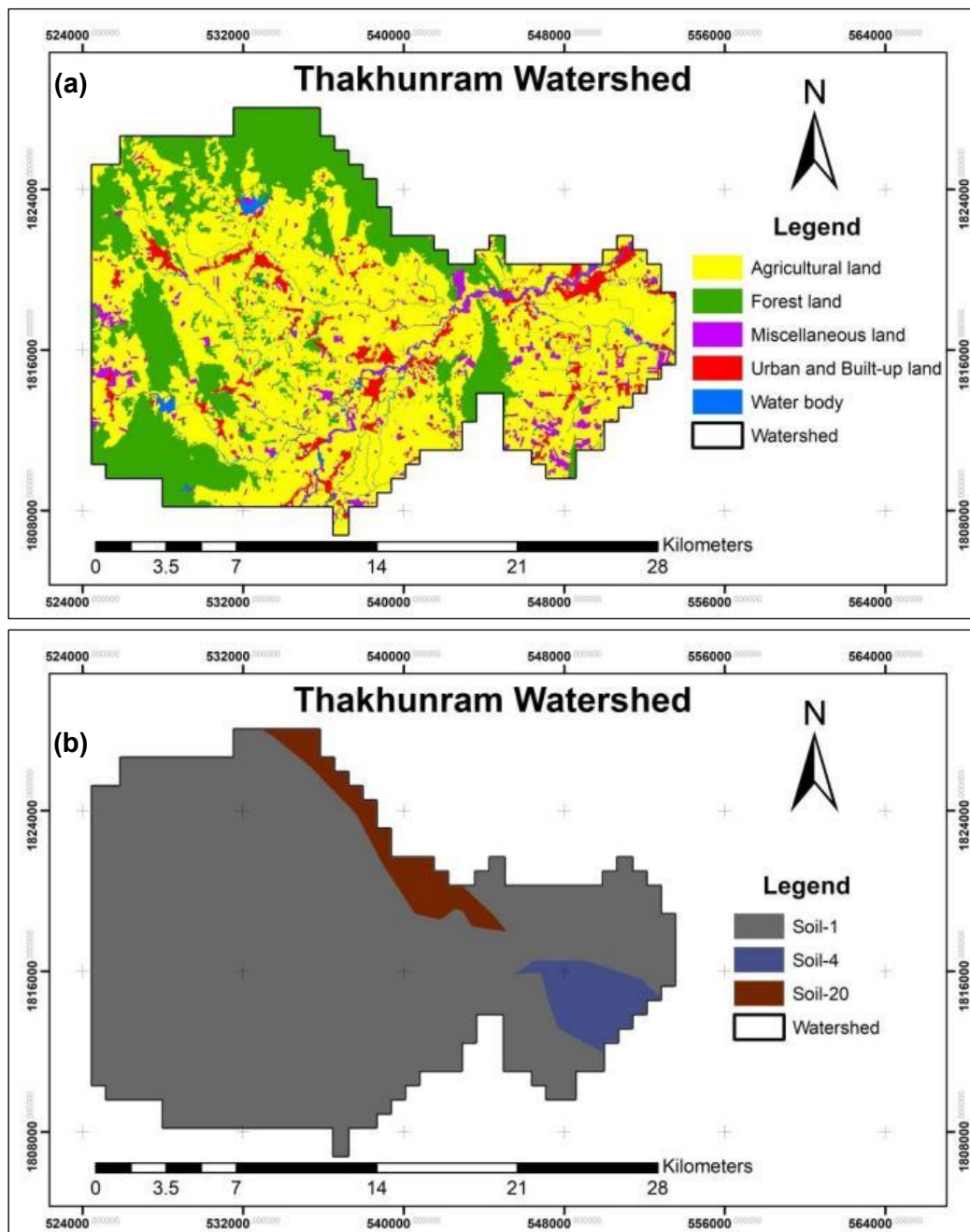


Figure 2 The LULC map (a) and soil group map (b) in the TKRW of Thailand.

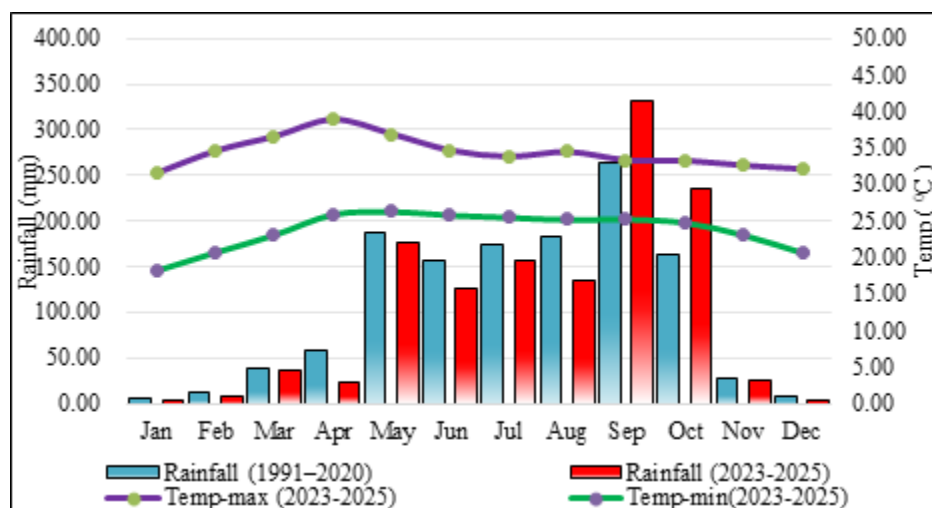


Figure 3 The 30-year average annual rainfall (1991–2020) and average annual rainfall and temperature max-min (2023–2025) in the TKRW of Thailand.

3) BMP framework and representation in SWAT

The analytical framework (Figure 4) integrates the biophysical characteristics of the TKRW with a suite of BMP scenarios implemented within the SWAT modeling environment. BMPs were represented by modifying relevant management and support-practice parameters to reflect their physical and functional mechanisms. Structural BMPs, including SSB and TRC, were simulated by reducing the effective slope length and runoff energy through adjustments to the USLE_P and slope-related parameters. Vegetative BMPs, such as RFT and FTS, were represented by increasing vegetation cover and surface protection, primarily via modification of the USLE_C factor and land cover attributes. Management-based practices, represented by CTF, were implemented by altering support-practice parameters to redirect runoff pathways and enhance infiltration.

The spatial implementation of each BMP was guided by slope class, land use type, and erosion susceptibility to ensure realistic, site-specific represen-

tation across the watershed. Vegetative BMPs mitigate erosion through canopy interception, litter accumulation, and root reinforcement, whereas structural measures rapidly reduce runoff energy and sediment connectivity in erosion-prone SWs. Together, these BMP categories function synergistically to reduce sediment yield at both the watershed and SW scales while enhancing long-term hydrological stability and ecosystem resilience.

4) SWAT model inputs

4.1) Spatial data

The key input datasets used in the SWAT model, including data type, classification, source, spatial and temporal resolution, and acquisition period, are summarized in Table 1. This standardized data compilation enhances the transparency, reproducibility, and methodological consistency of the modeling framework (Arnold et al., 2012; Deng et al., 2025; Li et al., 2025; Lopes et al., 2024; Nguyen et al., 2023; Saxton and Rawls, 2006).

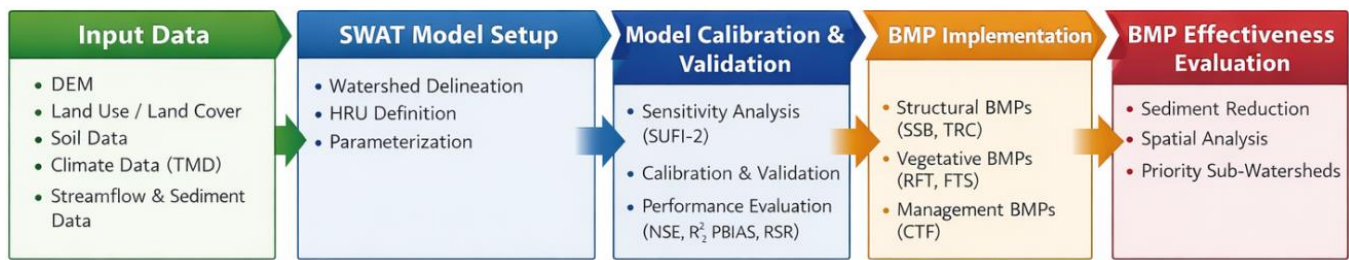


Figure 4 Conceptual framework.

Table 1 Summary of key input datasets used in the SWAT model

No.	Dataset	Description/classes	Source	Spatial resolution	Temporal resolution	Acquisition period
1	Digital elevation model	Elevation data used for watershed and stream network delineation	Shuttle Radar Topography Mission	30 m	Static	2020
2	Land use/land cover	Agricultural land (rice paddies, perennial crops, upland farming), forestland, urban/built-up areas, water bodies, miscellaneous land	Landsat 7 ETM+ (processed and classified)	30 m	Static	2023
3	Soil data	Soil Group 1, Soil Group 4, Soil Group 20 with associated physical and hydraulic properties	National soil database/ISRIC	Polygon-based	Static	2022
4	Climate data	Daily precipitation, maximum and minimum temperature	Thai Meteorological Department	Station-based	Daily	1991–2025
5	Streamflow data	Observed daily streamflow at watershed outlet	Water Resources Forecasting and Warning System Project	Station-based	Daily	2023–2025
6	Sediment data	Suspended sediment estimated using sediment rating curve	Derived from observed streamflow and sediment sampling	Station-based	Event-based/Daily	2023–2025

4.2) Temporal data and sediment reconstruction

Daily climate, streamflow, and sediment datasets were compiled from multiple sources. Long-term daily climate records (1991–2020) were obtained from the nearest TMD station. Missing values were addressed using the Carlo Monte multiple imputation method implemented in XLSTAT, after which a Weather Generator (WGEN) database was developed using the SWAT utility to ensure temporal completeness.

Daily streamflow data (2023–2025) were obtained from a hydrological station operating under the Water Resources Forecasting and Warning System Development Project. Owing to the absence of continuous sediment monitoring, sediment yield was reconstructed using a rating curve approach, following a stepwise workflow comprising data preparation, rating curve development, and subsequent SWAT calibration and validation (Figure 4). This approach remains widely applied in data-scarce watershed studies and provides a defensible basis for sediment simulation (Abebe et al., 2025; Aga et al., 2018; Batista et al., 2017; Gashaw et al., 2019).

Recent advances indicate that coupling rating curve techniques with machine learning algorithms can further increase sediment estimation accuracy in data-limited environments (Li et al., 2025; Nguyen et al., 2023). These developments are discussed here to contextualize methodological choices and highlight future improvement pathways, although such hybrid approaches were not implemented in the present study.

5) Model setup

The TKRW was delineated using a 30-m Shuttle Radar Topography Mission (SRTM) DEM (SRTM, 2020) with a flow accumulation threshold of 500 ha, selected to balance spatial detail and computational efficiency while preserving dominant drainage patterns, resulting in the subdivision of the watershed into 30 SWs. Hydrological response units (HRUs) were generated using the multiple HRU approach with 10% thresholds for land use, soil type, and slope, resulting in the production of 187 HRUs. These thresholds are widely adopted in SWAT applications to minimize parameter redundancy while maintaining hydrological representativeness, particularly in heterogeneous tropical watersheds. Slope was classified into five categories (0–2%, 2–6%, 6–12%, 12–35%, and >35%) to adequately capture the heterogeneous topographic gradients of the watershed.

Surface runoff was simulated using the Soil Conservation Service Curve Number (SCS-CN) method (United States Department of Agriculture–Soil Conservation Service, 1972), whereas potential evapotranspiration (PET) was estimated with the Penman–Monteith method (United States Department of Agriculture–Soil

Conservation Service, 1972), which incorporates both energy balance and aerodynamic components and is therefore well suited for complex tropical environments. Sediment yield was modeled using the modified universal soil loss equation (MUSLE), which integrates runoff energy and peak discharge to estimate soil erosion at the HRU scale (Arnold et al., 2012; Deng et al., 2025; Parajuli et al., 2024; Williams, 1995) (Table 2).

Recent research highlights the benefits of finer-scale HRU discretization and the integration of terrain-derived indices such as refined LS factors and topographic wetness indices to improve sediment routing accuracy in steep tropical watersheds. These approaches are discussed here to contextualize recent methodological advances; however, the present study adopts the standard MUSLE-based configuration to ensure model stability, transparency, and comparability with previous SWAT-based erosion studies.

Table 2 Model setup and parameterization of the SWAT framework for the TKRW.

6) Sensitivity analysis, model calibration and validation

Sensitivity analysis, calibration, and validation were conducted using the sequential uncertainty fitting algorithm (SUFI-2) implemented in SWAT-CUP v.5.1.6 (Abbaspour et al., 2015). Ten hydrological and eleven sediment-related parameters were selected on the basis of previous SWAT applications in comparable hydroenvironmental settings (Table 3). A global sensitivity analysis approach, in which all the parameters are varied simultaneously, was employed to capture multivariate interactions and nonlinear responses (Abbaspour et al., 2015; Abbaspour, 2018; Abebe et al., 2025). Parameter importance was quantified using t-statistics and p values, with parameters exhibiting larger absolute t values and smaller p values considered highly influential on model outputs (Abbaspour et al., 2015).

Model calibration involved iterative adjustment of the most sensitive parameters to reproduce observed daily streamflow and sediment dynamics, whereas model validation was performed to assess predictive skill using an independent dataset (Arnold et al., 2012). Calibration was performed using daily observations from 2023–2024, and validation was conducted with data spanning 2025. Daily time-step calibration was adopted to accurately represent event-scale runoff and sediment processes, which are critical for assessing BMP effectiveness in monsoon-dominated watersheds. SUFI-2 explicitly accounts for uncertainties arising from input data, model structure, parameter ranges, and observational errors (Deng et al., 2025; Gathagu et al., 2018; Gashaw et al., 2018; Worqlul et al., 2018).

Table 2 Model setup and parameterization of the SWAT framework for the TKRW.

Order	Component	Description
1	Watershed delineation	30 m DEM (SRTM, 2020); flow accumulation threshold = 500 ha; 30 SWs
2	HRUs	Multiple HRU option; 10% thresholds for land use, soil, and slope; total = 187 HRUs
3	Slope classification	Five classes: 0-2%, 2-6%, 6-12%, 12-35%, >35%
4	Surface runoff	SCS curve number method (United States Department of Agriculture–Soil Conservation Service, 1972)
5	PET	Penman–Monteith method (energy balance + aerodynamic processes) (Allen et al., 1989)
6	Sediment yield	MUSLE; integrates runoff energy and peak flow at HRU scale (Williams, 1995)

Table 3 Streamflow and sediment parameters selected for sensitivity analysis in the TKRW

Order	Parameter code	Parameter name	Description/function	Typical range/ initial value	Sensitivity ranking	Unit
Streamflow	CN2	SCS curve number	SCS curve number for runoff estimation	60–90/75	1	-
	ALPHA_BF	Baseflow alpha factor	Baseflow recession constant	0.1–1.0/0.5	2	days
	GW_DELAY	Groundwater delay	Time for water to reach river	1/30/2005	3	days
	GWQMN	Threshold groundwater level	Minimum storage required for baseflow	0–500/50	4	mm
	SOL_AWC	Available water capacity of soil	Soil water storage capacity	0.1–0.5/0.3	5	mm mm ⁻¹
	ESCO	Soil evaporation compensation factor	Adjusts soil evaporation	0.5–1.0/0.9	6	-
	EPCO	Plant uptake compensation factor	Adjusts plant transpiration	0.5–1.0/0.95	7	-
	SURLAG	Surface runoff lag coefficient	Time to reach channel	0–24/4	8	days
	REVAPMN	Threshold depth for shallow aquifer revap	Minimum water for revaporation to unsaturated zone	0–500/50	9	mm
	RCHRG_DP	Deep aquifer percolation fraction	Fraction of percolation to deep aquifer	0–1/0.1	10	-
Sediment	USLE_K	Soil erodibility factor	Soil susceptibility to erosion	0.1–0.5/0.3	1	-
	USLE_C	Cover and management factor	Effect of land cover on erosion	0–1/0.2	2	-
	USLE_LS	Slope length-gradient factor	Influence of slope on erosion	0.1–10/1.0	3	-
	SED_EM	Sediment concentration in runoff	Sediment load transported by surface runoff	0–1/0.05	4	t ha ⁻¹
	CH_K2	Channel erodibility coefficient	Sediment transport capacity of channel	0.01–0.5/0.1	5	-
	USLE_P	USLE support practice factor	Support practice factor for soil loss	0.1–1.0/0.5	6	-
	SPCON	Peak rate adjustment factor for sediment	Adjusts sediment peak flow	0.5–2/1.0	7	-
	SLSUBBSN	SWs slope length factor	Slope length influence on SWs sediment	0.1–5/1.0	8	-
	CH_COV	Channel cover factor	Effect of vegetation cover in channels on sediment	0–1/0.2	9	-
	SPCON2	Sediment concentration factor for HRU	Adjusts sediment transport from HRU	0.5–2/1.0	10	-
	USLE_P	USLE support practice factor	Support practice factor for soil loss	0.1–1.0/0.5	11	-

7) Model performance evaluation

Model performance was evaluated using widely accepted statistical indicators, including NSE, R^2 , PBIAS, and RSR, following established hydrological modeling guidelines (Moriassi et al., 2007). These indicators are recommended by Moriassi et al. (2007) for the comprehensive evaluation of hydrological and sediment simulations. As these metrics are well established, their equations are omitted, and the performance criteria are summarized in Table 4.

8) Best management practice scenarios

Details of the BMP implementation, associated SWAT parameters, and expected hydrological and sediment responses are summarized in Table 5. The selected parameters for the BMP representation (e.g., USLE_P and USLE_C) correspond directly to the most sensitive sediment-related parameters identified during SUFI-2

Model performance was analysis, ensuring internal methodological consistency between the calibration and scenario assessment.

Results and discussion

1) Sensitive streamflow and sediment parameters

A sensitivity analysis revealed that five of the ten streamflow-related parameters exerted the strongest influence on the hydrological simulations: CN2, ALPHA_BF, GW_DELAY, GWQMN, and SOL_AWC (Table 3). These outcomes align closely with previous SWAT applications in comparable hydroenvironmental settings, where parameters such as CN2, ALPHA_BF, GWQMN, EPCO, SURLAG, and ESCO were identified as dominant controls on streamflow generation (Addis et al., 2016; Faksomboon et al., 2023; Gashaw et al., 2021, Lemma et al., 2019, Mekonnen et al., 2015). This consistency reinforces the physical realism of the calibrated parameter set.

Table 4 Statistical performance indicators used for the SWAT model evaluation.

Indicator	Description	Performance criteria
NSE	Nash–Sutcliffe Efficiency coefficient used to evaluate agreement between observed and simulated values	NSE > 0.75 (Very good); 0.65–0.75 (Good); 0.50–0.65 (Satisfactory)
R^2	Coefficient of determination indicating strength of linear relationship between observed and simulated data	$R^2 > 0.70$ indicates strong correlation
PBIAS	Percent bias measuring average tendency of simulated values to be larger or smaller than observations	PBIAS < 10% (Very good); 10–15% (Good); 15–25% (Satisfactory)
RSR	Ratio of RMSE to standard deviation of observed data, combining error index and variability	RSR < 0.50 (Very good); 0.50–0.60 (Good); 0.60–0.70 (Satisfactory)

Table 5 Summary of BMP implementation and representation in the SWAT model.

BMP category	BMP type	Description and management objective	Implementation in SWAT	Key parameters adjusted	Expected effect on hydrology and sediment
Structural BMPs	Stone/soil bunds (SSB)	Physical barriers constructed along slopes to reduce runoff velocity and soil detachment	Represented by modifying support-practice and slope-related parameters	USLE_P, slope length factor	Reduced runoff energy and sediment detachment
Structural BMPs	Terracing (TRC)	Conversion of long slopes into stepped surfaces to shorten effective slope length	Implemented by reducing effective slope length and runoff transport capacity	USLE_P, slope-related parameters	Decreased slope-driven erosion and sediment yield
Vegetative BMPs	Reforestation (RFT)	Establishment of permanent vegetation cover on erosion-prone areas	Simulated through changes in land use and vegetation cover parameters	USLE_C, land cover attributes	Enhanced surface protection and increased infiltration
Vegetative BMPs	Filter strips (FTS)	Vegetated strips designed to trap sediment before entering streams	Implemented by increasing surface roughness and filtering capacity	USLE_C, runoff attenuation parameters	Reduced sediment delivery to channels
Management BMPs	Contour farming (CTF)	Cultivation along contour lines to slow runoff and improve infiltration	Represented by adjusting support-practice parameters	USLE_P	Altered runoff routing and reduced erosion potential

Mechanistically, CN2 governs surface runoff generation by integrating land use, soil characteristics, and antecedent moisture conditions, which is a particularly critical function in monsoon-driven watersheds where rainfall intensity strongly interacts with land cover dynamics. ALPHA_BF and GW_DELAY regulate baseflow recession and groundwater recharge timing, shaping low-flow behavior during dry seasons. GWQMN defines the minimum aquifer storage required for baseflow activation, whereas SOL_AWC controls the soil water holding capacity, thereby influencing infiltration–runoff partitioning across contrasting hydrological seasons. Collectively, these sensitivities highlight the dominant role of coupled surface–subsurface interactions in determining the streamflow response in the TKRW.

For sediment simulations, seven of the eleven parameters examined exhibited strong sensitivity: USLE_K, USLE_C, USLE_LS, SED_EM, CH_K2, USLE_P, and SPCON. Similar sensitivity rankings have been consistently reported in diverse watershed studies, emphasizing their central roles in sediment detachment, transport, and deposition across varying terrain and land use settings (Abebe et al., 2025; Ayalew and Bharti, 2020; Faksomboon et al., 2023; Gashaw et al., 2021; Lemma et al., 2019). USLE_K represents the intrinsic soil erodibility, indicating the susceptibility to detachment under rainfall impact. USLE_C captures the protective effect of vegetation cover, rendering it highly responsive to land use changes such as deforestation or crop intensification. USLE_LS, which integrates slope length and steepness, is particularly influential in steep upland landscapes typical of the TKRW, where gravitational forces amplify sediment transport potential. Channel-related parameters, including SED_EM, SPCON, and CH_K2, govern sediment routing efficiency, deposition, and downstream delivery, reflecting the combined

influence of channel geometry and hydraulic conductivity.

Overall, the pronounced sensitivity of both the hydrological and sediment parameters underscores the necessity of the simultaneous calibration of coupled runoff–erosion processes. This sensitivity structure directly supports the selection of key parameters modified during BMP scenario implementation.

2) Calibration and validation results

A comparison between the observed and simulated daily streamflows during the calibration and validation periods is shown in Figure 5. Daily outputs were intentionally retained to evaluate short-duration runoff responses and peak flow behavior, which are critical characteristics of monsoon-driven tropical watersheds. Lower simulated flows during May–August of 2023/2024 correspond to reduced antecedent soil moisture following prolonged dry conditions, resulting in rainfall being preferentially allocated to soil moisture replenishment rather than direct runoff generation. In contrast, higher flows during the same months in 2025 reflect wetter antecedent conditions combined with more frequent high-intensity rainfall events, leading to enhanced runoff generation efficiency.

The model performance for streamflow is consistently strong, with $R^2 = 0.90$ – 0.93 , $NSE = 0.85$ – 0.91 , $PBIAS = -0.51\%$ to 6.14% , and $RSR = 0.24$ – 0.28 (Table 6), all of which meet the “very good” performance thresholds (Deng et al., 2025; Begou et al., 2016; Moriasi et al., 2007). The combination of low RSR values and near-zero PBIAS confirms that the model accurately reproduces both the flow magnitude and temporal variability with minimal systematic bias.

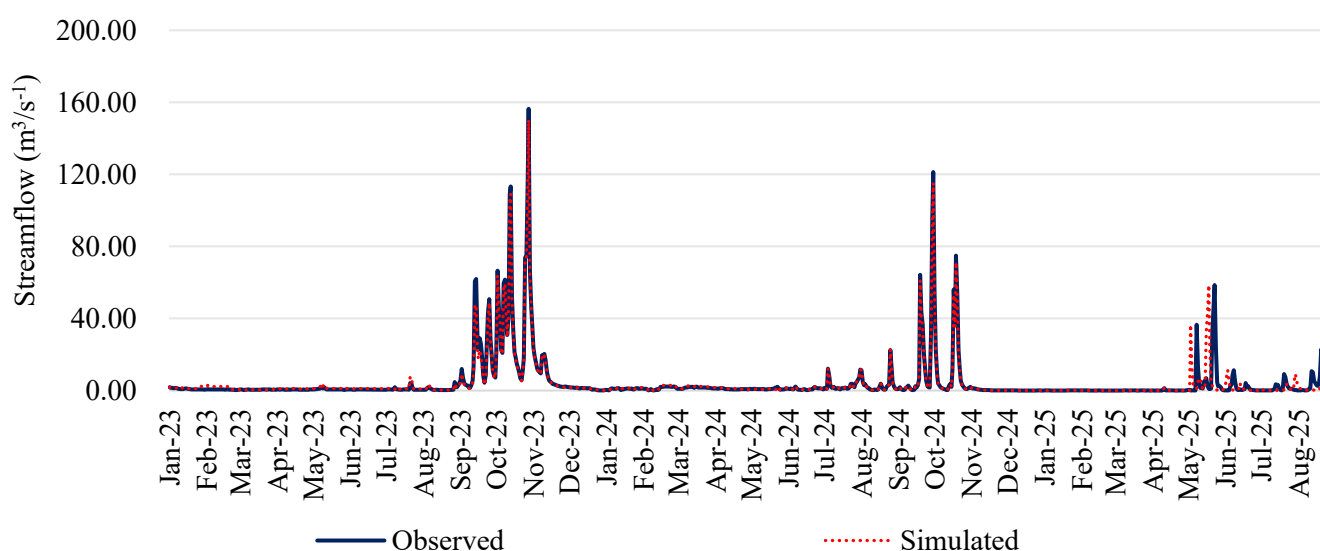


Figure 5 Daily streamflow simulations (2023–2025) in the TKRW during the calibration and validation periods. Daily time-step outputs are presented to capture event-scale runoff variability and peak flow dynamics under monsoon-dominated conditions.

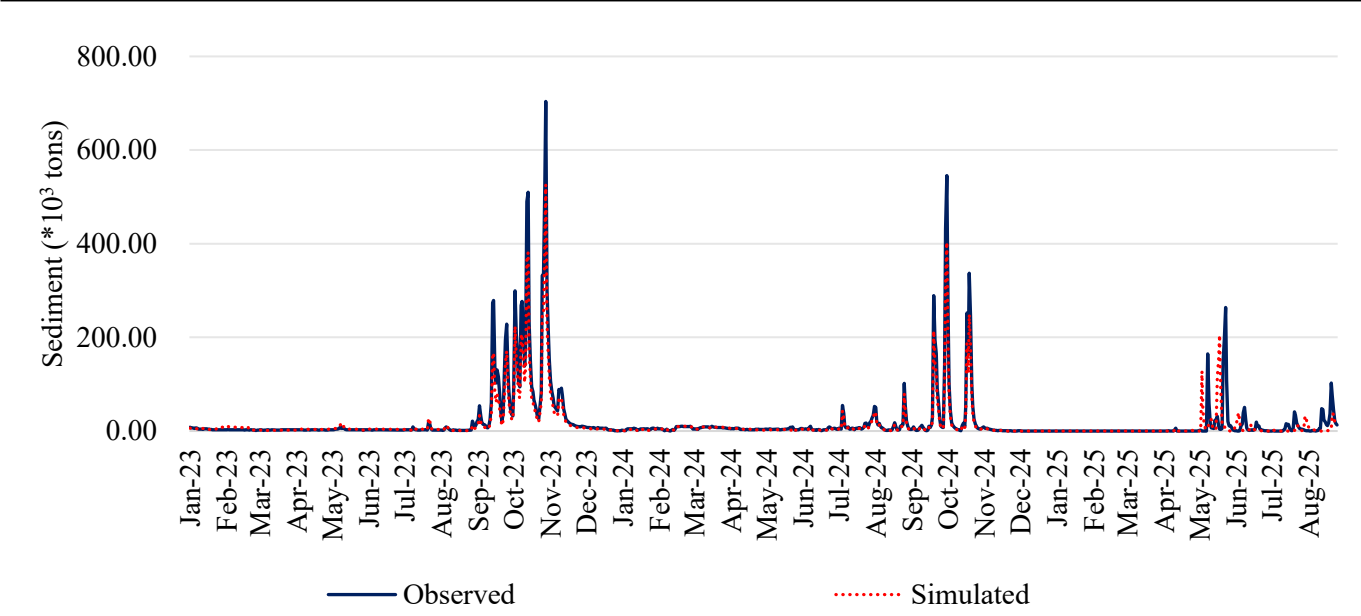


Figure 6 Daily sediment simulations (2023–2025) in the TKRW during the calibration and validation periods. Daily outputs are retained to capture event-scale sediment mobilization and transport dynamics driven by short-duration runoff events under monsoon conditions.

Table 6 The performance of the SWAT model in TKRW during the calibration and validation periods

Parameter	Simulation period	Evaluation statistics value			
		NSE	PBIAS	R ²	RSR
Sreamflow	Calibration	0.85	-0.51	0.90	0.28
	Validation	0.91	6.14	0.93	0.24
Sediment	Calibration	0.74	10.56	0.82	0.47
	Validation	0.80	12.85	0.86	0.42

Sediment simulations likewise exhibit strong predictive ability, with $R^2 = 0.82\text{--}0.86$, $NSE = 0.74\text{--}0.80$, $RSR = 0.42\text{--}0.47$, and $PBIAS = 10.56\text{--}12.85\%$ (Figure 6). Daily sediment outputs were retained to enable process-based evaluation of sediment detachment and transport during short-duration runoff events. Reduced sediment yield during May–August of 2023/2024 reflects limited runoff energy under dry antecedent conditions, whereas higher sediment outputs in 2025 correspond to enhanced runoff-driven transport capacity under wetter conditions. Although the PBIAS indicates moderate overestimation, the improved NSE and reduced RSR during validation demonstrate an enhanced ability to capture storm-driven sediment pulses, which is an expected outcome given the strong sensitivity of sediment parameters to rainfall intensity, slope gradient, and land cover.

Overall, the consistent performance across both hydrological and sediment components underscores the robustness of the SWAT model in simulating coupled runoff–erosion processes in the TKRW. This performance provides a reliable foundation for subsequent BMP scenario analysis and supports the application of SWAT as a decision-support tool in data-limited tropical highland watersheds.

3) Mechanistic interpretation of the calibration results

Mechanistically, the strong streamflow performance indicates that the SWAT model effectively captures the dominant hydrological processes controlling runoff generation and seasonal flow variability. The accurate simulation of infiltration–runoff partitioning, baseflow recession, and groundwater–surface water exchanges is largely attributable to the sensitivity and successful calibration of parameters such as CN2, ALPHA_BF, and GW_DELAY. These parameters regulate the balance between rapid surface runoff during monsoon events and delayed subsurface contributions during the dry season, enabling the model to represent both fast and slow flow pathways. This process-based behavior is particularly critical in monsoon-driven watersheds, where strong differences between wet and dry seasons govern the hydrological response. This interpretation aligns with previous findings emphasizing the central role of parameterization in representing watershed storage dynamics and producing reliable streamflow simulations (Abbaspour, 2018; Arnold et al., 2012; Guzman et al., 2015).

Sediment simulation performance similarly reflects the model’s capacity to capture mechanistic erosion and transport dynamics. The calibrated USLE-based

parameters (e.g., USLE_K, USLE_C, and USLE_LS) effectively represent hillslope detachment processes driven by rainfall intensity, vegetation cover, and slope gradients, whereas in-stream processes regulated by CH_K2, SPCON, and SED_EM govern sediment transport, deposition, and re-entrainment. The joint calibration of upland and channel-related parameters enables the model to reproduce the nonlinear, event-driven sediment pulse characteristics of steep tropical watersheds. Such mechanistic coherence is consistent with studies demonstrating that accurate sediment prediction requires simultaneous calibration of hillslope erosion and channel transport components (Betrie et al., 2011; Lin et al., 2017).

Overall, the calibrated SWAT configuration demonstrates strong process fidelity, reproducing both hydrological and sediment responses across contrasting seasons and flow regimes in the TKRW. This mechanistic robustness supports the model’s suitability for scenario-based analysis, BMP evaluation, and long-term watershed planning, particularly in mountainous and data-limited environments where coupled runoff–erosion interactions are highly dynamic and difficult to observe directly.

4) Identifying soil hotspot areas in the study watershed

Erosion hotspot identification was conducted through a spatially explicit analysis of SWAT-simulated sediment yield at the SW scale. The mean annual sediment yield (2023–2025) was extracted for each SW and classified into erosion severity classes. SWs contributing disproportionately to total sediment export were identified by jointly considering sediment yield magnitude, the spatial extent of high-severity classes, and their spatial correspondence with slope and land use characteristics. Under baseline conditions (2023–2025), the TKRW exhibited a spatially averaged sediment yield of approximately

135.62 t ha⁻¹ year⁻¹ (Figure 7), corresponding to severe to extremely severe erosion intensity. This value reflects the dominance of erosion hotspots rather than uniform basin-wide erosion and indicates high vulnerability to accelerated soil degradation in specific SWs. Recent advances in high-resolution spatial modeling and remote sensing underscore the importance of such spatially explicit hotspot detection approaches (Gashaw et al., 2018; Borrelli et al., 2021), particularly in tropical mountainous regions where steep elevation gradients and rapid land use transitions amplify geomorphic sensitivity.

Spatial analysis revealed substantial heterogeneity in sediment yield, with pronounced hotspot clusters in the middle and lower watershed zones. Although these zones are generally characterized by flat to gently undulating terrain, the identified hotspots coincide with localized steep slope segments, particularly along hillslope–channel transition areas within cultivated landscapes. In these areas, seasonal agricultural practices result in limited effective vegetative cover during critical rainfall periods, thereby enhancing soil detachment and sediment connectivity to the channel network. Mechanistically, this pattern reflects the dynamic coupling among topography, land cover, and rainfall erosivity in governing sediment detachment, transport, and deposition processes (Borrelli et al., 2021; Gashaw et al., 2018; Li et al., 2025; Silabi et al., 2025).

These findings highlight the need for spatially targeted soil and water conservation strategies, particularly in erosion-prone SWs. Priority interventions such as RFT, SSB, TRC, CTF, and FTS can substantially reduce sediment export when strategically implemented within identified hotspot zones. Targeted BMP deployment not only mitigates soil loss and downstream water quality degradation but also enhances long-term watershed resilience under increasing land use pressure and climatic variability.

Table 7 Classification of sediment yield severity in the TKRW under baseline conditions (2023–2025), defined following commonly adopted SWAT-based erosion severity thresholds and watershed prioritization frameworks.

Order	Class	Sediment yield (t ha ⁻¹ year ⁻¹)	Description
1	Very slight	< 12.50	Stable soils with negligible risk of detachment or transport (Minimal erosion).
2	Slight	12.50-31.25	Occasional erosion risk, influenced by seasonal factors or land use activities (Moderate erosion).
3	Moderate	31.25-93.75	Regular soil loss, particularly in sloped or intensively cultivated areas (High erosion).
4	Severe	93.75-125.00	Frequent and substantial soil loss, affecting land productivity and stability (Very high erosion).
5	Extremely severe	> 125.00	Severe and continuous erosion, with high sediment export and landscape degradation (Extreme erosion).

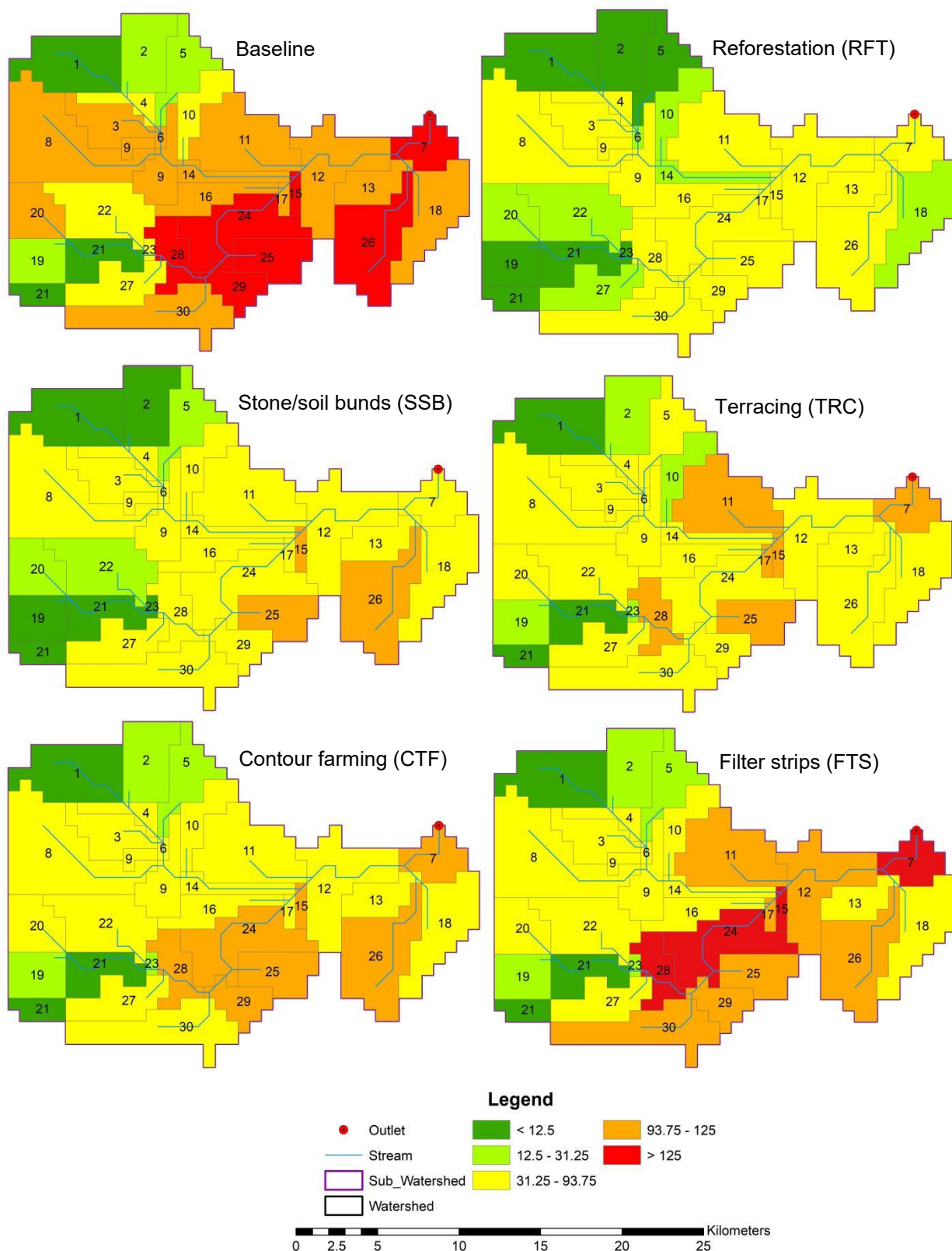


Figure 7 The mean annual sediment yield of the baseline, RFT, SSB, TRC, CTF, and FTS at the SW scale of TKRW.

The spatial distribution of sediment yield under baseline conditions was further classified into five erosion severity classes (Table 7). These classes were defined using a combination of distribution-based thresholds derived from SWAT-simulated sediment yields within the TKRW and severity ranges commonly adopted in SWAT-based erosion and watershed priori-

tization studies. Although Thailand does not prescribe a unified national sediment yield classification scheme, similar class ranges have been widely applied and validated in tropical and monsoon-dominated watersheds (Betrie et al., 2011; Gashaw et al., 2021; Lemma et al., 2019; Moriasi et al., 2007).

5) Soil erosion hotspot areas and management implications

Spatial variations in sediment yield across the TKRW reflect the combined effects of steep slopes, intensive agricultural land use, and limited effective vegetative protection, all of which accelerate soil detachment and sediment routing. In contrast, gentler slopes and depositional zones attenuate downstream sediment export. These spatial gradients, as resolved by the calibrated SWAT model, demonstrate that erosion risk is highly heterogeneous and cannot be reliably inferred from land use or slope information alone. Consequently, targeted interventions, particularly BMPs applied within erosion-vulnerable SWs, are essential to reduce sediment losses and sustain overall watershed functioning.

The analysis identifies SWs-7, SWs-15, SWs-24, SWs-25, SWs-26, SWs-28, and SWs-29 as disproportionately contributing to total sediment yield. These SWs are characterized by steep cultivated hillslopes, high runoff potential, and limited conservation practices, collectively driving elevated sediment connectivity from hillslopes to channel networks. The spatial clustering of these high-risk SWs highlights the role of geomorphological and hydrological connectivity in controlling sediment source distribution, which is consistent with findings from other tropical highland watersheds (Abebe et al., 2025; Gashaw et al., 2019; 2021; Lemma et al., 2019; Li et al., 2025). The SWAT-derived sediment risk map therefore provides a defensible, process-based basis for prioritizing soil and water conservation measures.

Recent studies have demonstrated that BMPs, including TRCs, CTFs, agroforestry systems, and vegetative buffer strips, can substantially reduce sediment loss in steep tropical landscapes. Integrating these BMPs within a scenario-based and spatially explicit modeling framework, as adopted in this study, enhances the capacity to evaluate management effectiveness and optimize conservation investments under limited resources. Such approaches also improve predictions of downstream sedimentation risks and support strategic watershed-scale planning (Deng et al., 2025; Nguyen et al., 2023; Silabi et al., 2025).

Approximately 83% of the watershed area falls within the moderate to extremely severe sediment yield classes, indicating that erosion is a pervasive watershed-scale challenge rather than a localized problem. This proportion reflects the spatial extent of high-severity erosion classes rather than uniform erosion intensity, underscoring the urgency of prioritizing conservation efforts in high-risk SWs, particularly those dominated by steep cultivated slopes, to maximize sediment reduction efficiency and downstream benefits.

Overall, the spatially explicit erosion risk classification developed in this study provides a robust decision-support tool for prioritizing interventions, guiding sustainable land use planning, and informing targeted BMP implementation across the TKRW.

6) Effects of BMPs on sediment yield at the watershed scale

Baseline simulations (2023–2025) indicate that the TKRW experiences a high sediment yield of 135.62 t ha⁻¹ year⁻¹. The implementation of BMPs resulted in substantial sediment reductions, with mean yields decreasing to 84.26 t ha⁻¹ year⁻¹ under RFT, 78.88 t ha⁻¹ year⁻¹ under SSB, 48.82 t ha⁻¹ year⁻¹ under TRC, 46.43 t ha⁻¹ year⁻¹ under CTF, and 42.38 t ha⁻¹ year⁻¹ under FTS (Figure 8; Table 8). These reductions, representing a 38–69% decline from baseline conditions, demonstrate strong consistency between SWAT-simulated responses and the physical erosion-control mechanisms of the applied BMPs.

Structural BMPs such as SSB cause substantial sediment reduction, with reported decreases of 68–81% in other highland watersheds (Demissie et al., 2013; Nyssen et al., 2007; Silabi et al., 2025) and 30–61% in Lake Tana and Gumara SWs (Gashaw et al., 2021; Lemma et al., 2019), particularly when combined with vegetative stabilization (Ebabu et al., 2019). Vegetative BMPs such as RFT exhibit similarly strong performance, which is consistent with the reduction of approximately 60% observed when cropland or bare slopes are converted to forestland (Abebe et al., 2025; Gashaw et al., 2020; Lemma et al., 2019).

In contrast, FTS provides moderate reductions (13–35%), corroborating findings from the Gumara, Gilgel Gibe, and Mediterranean catchments, where slope-focused interventions generally yield lower reductions than forest-oriented practices such as RFT do (Demissie et al., 2013; Gashaw et al., 2021; López-Ballesteros et al., 2019). TRC and CTF demonstrate particularly strong sediment mitigation, reflecting their capacity to shorten slope length, increase infiltration, and disrupt concentrated surface runoff mechanisms that are especially effective in steep, intensively cultivated terrain.

Recent research emphasizes the importance of integrating BMPs within spatially explicit modeling frameworks to optimize sediment control at the watershed scale. Hybrid or multicomponent strategies, such as the use of TRCs combined with cover crops, contour hedgerows, or riparian buffers, have resulted in 65–80% sediment reduction and greater resilience under extreme rainfall conditions (Nguyen et al., 2023). Overall, these findings indicate that multifaceted, landscape-tailored BMP portfolios outperform single interventions, particularly in complex tropical highland watersheds.

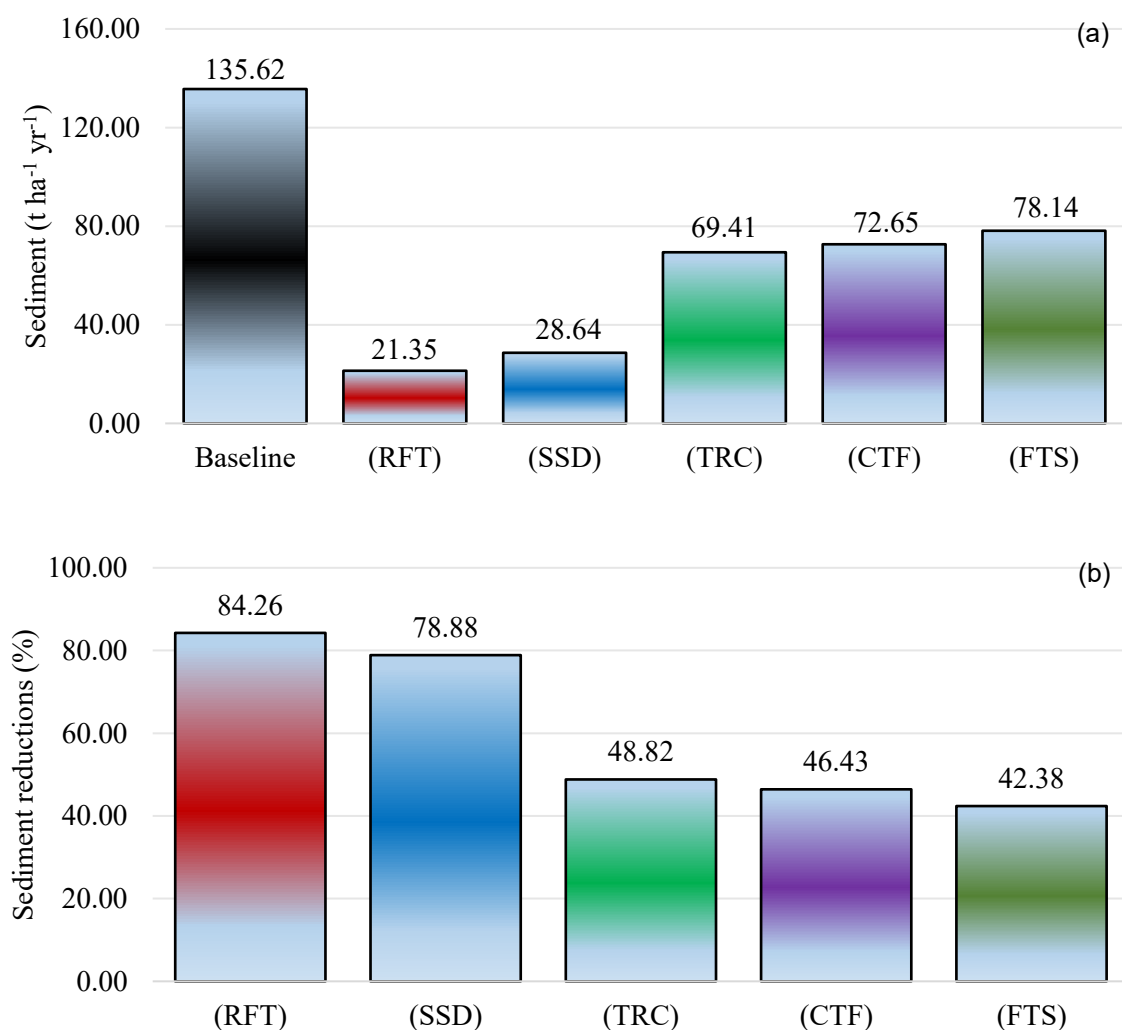


Figure 8 Mean annual sediment of the BMP scenarios (a) and sediment reductions (%) compared with the baseline of TKRW (b).

Table 8 Percentage of erosion potential areas in a given scenario and sediment yield severity classes

Order	Sediment ($\text{t ha}^{-1} \text{year}^{-1}$)	BMP scenarios						Severity class
		Baseline	RFT	SSB	TRC	CTF	FTS	
1	< 12.50	7.04	14.70	14.70	9.54	9.54	9.54	Very slight
2	12.50–31.25	10.24	20.65	10.59	11.36	12.04	13.25	Slight
3	31.25–93.75	15.42	64.65	55.36	57.24	53.28	35.24	Moderate
4	93.75–125.00	38.65	0.00	19.35	21.86	25.14	27.72	Severe
5	> 125.00	28.65	0.00	0.00	0.00	0.00	14.25	Extremely severe
Total		100.00	100.00	100.00	100.00	100.00	100.00	-

7) Effects of BMPs on sediment at the SW scale

Under baseline conditions, the mean annual sediment yield across TKRW SWs ranged from <12.50 to $>125.00 \text{ t ha}^{-1} \text{year}^{-1}$, reflecting pronounced spatial heterogeneity in erosion susceptibility. The implementation of RFT, SSB, and TRC substantially reduces sediment loads to <12.50 – $93.75 \text{ t ha}^{-1} \text{year}^{-1}$, resulting in a marked shift from moderate and severe erosion classes toward very slight and slight categories (Figure 9). Across all the BMP scenarios, the sediment reduction efficiency ranged from 42% to 85%, indicating effective but spatially differentiated responses among the SWs.

The variability in BMP effectiveness underscores the necessity of SW-specific planning. High-risk SWs exhibit disproportionately greater sediment reductions under structural (e.g., TRC and SSB) and vegetative (e.g., RFT) interventions than low-risk areas do, confirming that hotspot-based prioritization maximizes sediment reduction returns and the cost-effectiveness of conservation measures.

Mechanistically, spatial variability in BMP performance arises from interactions among slope gradient, land use intensity, soil erodibility, and vegetation cover, which collectively regulate erosion susceptibility and determine the effectiveness of a given BMP in reducing runoff

energy, intercepting sediment, and enhancing soil stability. These interactions reinforce the need for landscape-tailored BMP portfolios that respond to both biophysical constraints and management pressures specific to each SW.

Discussion

The effectiveness of BMPs in reducing sediment yield across the TKRW aligns well with findings reported in comparable tropical highland and monsoonal watersheds, reinforcing the validity of the simulated outcomes. Vegetative BMPs, particularly FTS and RFT, exhibited progressive and sustained sediment reduction, which is consistent with the

findings of previous studies demonstrating that enhanced canopy interception, litter accumulation, and root reinforcement substantially improve soil stability and erosion resistance over time (Deng et al., 2025; Lal, 2015; Morgan, 2005). These processes operate cumulatively, resulting in delayed but durable erosion control benefits, especially under repeated monsoonal rainfall. The magnitude and temporal pattern of sediment reduction observed in this study are comparable to those reported for reforestation-based BMPs in northern Thailand and similar Southeast Asian watersheds, supporting the physical realism of the modeled responses.

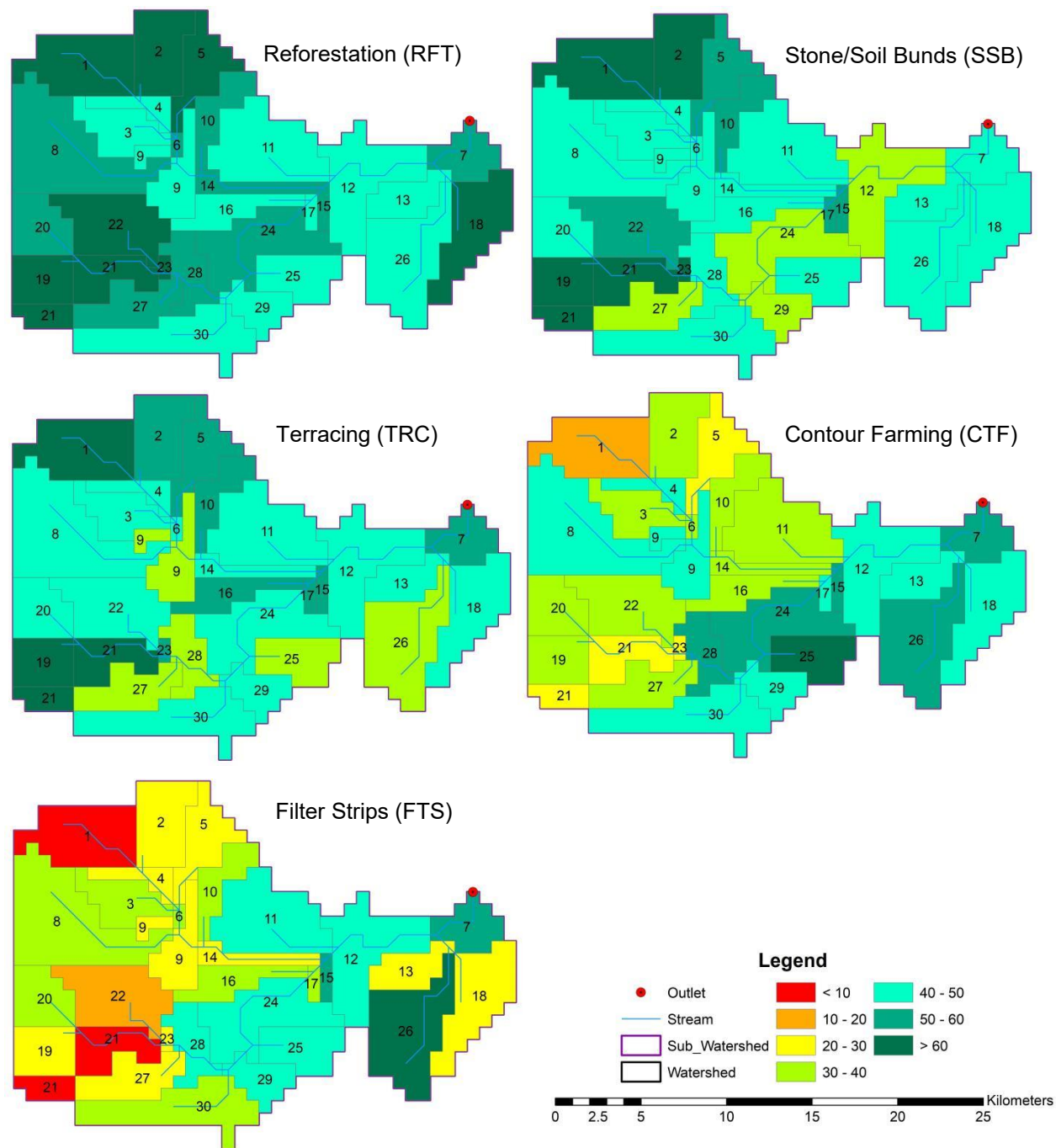


Figure 9 The sediment yield reduction (%) of RFT, SSB, TRC, CTF, and FTS at the SW scale of TKRW.

Structural BMPs, including SSB and TRC, delivered the most pronounced short-term reductions in rill and gully erosion, particularly in steep and highly connected SWs. This rapid response is consistent with earlier SWAT-based and field-scale assessments emphasizing the effectiveness of slope-length reduction and runoff interception in erosion hotspots (Gebresamuel et al., 2010; Mekonnen et al., 2015; Nyssen et al., 2007; Silabi et al., 2025). However, the sustainability of these benefits is inherently conditional on maintenance, institutional capacity, and local governance structures. The gradual decline in modeled effectiveness under scenarios of reduced maintenance reflects this dependency and highlights a key limitation of purely engineering-based interventions.

Management-based practices, notably CTF, produced moderate yet stable sediment reductions, in agreement with prior empirical and modeling studies conducted in resource-limited agricultural systems (Araya and Stroosnijder, 2010; Gassman et al., 2014). While absolute reductions were lower than those achieved by structural BMPs, the low implementation cost, operational simplicity, and adaptability of CTF increase its feasibility for widespread adoption. These results corroborate evidence that integrating CTF with conservation tillage and residue management can generate cumulative benefits, including reduced sediment export and improved soil organic matter, thereby strengthening adaptive capacity under variable climatic conditions.

SW-scale analysis revealed substantial spatial heterogeneity in BMP performance, reflecting interactions among slope gradient, land use intensity, and hydrological connectivity. The superior performance of SSB in erosion hotspots and the broader watershed-scale effectiveness of RFT are consistent with patterns reported in other tropical and semiarid watersheds, where BMP efficiency is strongly modulated by local physiographic and hydrological context. These findings further confirm that uniform BMP application is unlikely to be efficient under constrained financial and institutional resources, underscoring the necessity of spatially explicit prioritization frameworks.

The prioritization-based implementation strategy proposed herein, which combines structural BMPs in high-risk SWs (SWs-7, SWs-15, SWs-24, SWs-25, SWs-26, SWs-28, and SWs-29) with vegetative and management-based measures in moderate-risk areas, reflects best practices reported in recent watershed-scale BMP assessments. Such phased strategies are particularly effective because they deliver rapid, visible reductions in erosion risk while enabling longer-term ecological recovery and stakeholder engagement. The integration of SWAT-based simulations with spatial decision-support tools enhances confidence in the transferability of the framework, which is grounded in

multiscale analysis, process-based interpretation, and explicit prioritization logic.

Overall, a comparative evaluation confirms that TRC and SSB remain the most effective structural interventions in steep terrains, whereas CTF and FTS function as complementary, low-cost measures whose performance strongly depends on local management conditions. RFT provides the most durable long-term benefits through soil structural improvement and ecosystem recovery, albeit longer implementation periods are needed. Taken together, these findings demonstrate that site-specific integration of structural, vegetative, and management-based BMPs constitutes the most robust and realistic strategy for achieving sustained sediment reduction and long-term watershed resilience in tropical highland systems such as the TKRW.

Conclusions

This study demonstrates the complementary and scale-dependent roles of BMPs in mitigating soil erosion across the TKRW. Structural measures, notably SSB, provide rapid and substantial reductions in sediment yield, confirming their suitability for immediate prioritization in the most erosion-prone SWs. Vegetative interventions, such as RFT, enhance long-term watershed resilience while delivering additional ecosystem services, rendering them particularly effective in upland areas where soil degradation threatens ecological integrity and local livelihoods. FTS offers moderate yet cost-effective sediment control, functioning as a complementary measure in moderately vulnerable zones when integrated with other BMPs.

Given resource and implementation constraints, a phased and spatially explicit deployment strategy is essential. Immediate interventions should focus on high-priority SWs (SWs-7, SWs-15, SWs-24, SWs-25, SWs-26, SWs-28, and SWs-29), followed by progressive expansion to other erosion-sensitive areas. Integrating structural, vegetative, and management-based BMPs enables a balanced approach that couples short-term sediment reduction with long-term ecological stabilization. Such multiscale coordinated linking plot-, hillslope-, and watershed-level processes further increase sediment retention and landscape connectivity.

Future watershed management should emphasize adaptive and evidence-based BMP portfolios that explicitly account for climate variability, land use dynamics, and socioeconomic limitations. Participatory governance, institutional support, and continuous monitoring frameworks are critical for sustaining BMP performance and strengthening local implementation capacity.

Overall, this study confirms that effective BMP selection and prioritization must be spatially explicit, context sensitive, and dynamically adaptive. The integrated framework developed herein provides a

transferable and decision-relevant approach for sediment control planning in tropical highland watersheds facing accelerated erosion under changing climatic and socioeconomic conditions.

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Data availability statement

Information and data used in the study will be disclosed upon request.

Author contributions

Banchongsak Faksomboon: Conceptualization, Methodology, Software, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – Original draft, Writing – Review & editing, Visualization, Supervision, Project administration, Funding acquisition

Wilailak Suanmali: Investigation, Resources, Visualization

Conflicts of interest

The authors declare that there are no conflicts of interest in competing financial or personal relationships that could have appeared to influence the work reported in this work.

References

- Abbaspour, K. C., Rouholahnejad, E., Vaghefi, S., Srinivasan, R., Yang, H., & Kløve, B. (2015). A continental-scale hydrology and water quality model for Europe: Calibration and uncertainty of a high-resolution large-scale SWAT model. *Journal of Hydrology*, 524, 733–752.
- Abbaspour, K. C. (2018). *SWAT-CUP: SWAT calibration and uncertainty programs – A user manual*. Swiss Federal Institute of Aquatic Science and Technology (Eawag), Dübendorf, Switzerland.
- Abebe, T. G., Lemma, T. M., & Meshesha, T. W. (2025). Exploring best soil conservation practices using the tolerable soil loss limit in central highland of Ethiopia: A case study of Andit Tid watershed. *International Soil and Water Conservation Research*, 13, 348–361.
- Addis, H. K., Strohmeier, S., Ziadat, F., Melaku, N. D., & Klik, A. (2016). Modeling streamflow and sediment using SWAT in Ethiopian highlands. *International Journal of Agriculture and Biology*, 9(5), 51–66.
- Aga, A. O., Chane, B., & Melesse, A. M. (2018). Soil erosion modelling and risk assessment in data scarce Rift Valley Lake regions, Ethiopia. *Water*, 10(11), 1684.
- Allen, R. G., Jensen, M. E., Wright, J. L., & Burman, R. D. (1989). Operational estimates of reference evapotranspiration. *Agronomy Journal*, 81(4), 650–662.
- Araya, T., & Stroosnijder, L. (2010). Effects of tied ridges and mulch on barley (*Hordeum vulgare*) rainwater use efficiency and production in Northern Ethiopia. *Agricultural Water Management*, 97(6), 841–847.
- Arnold, J. G., Moriasi, D. N., Gassman, P. W., Abbaspour, K. C., White, M. J., Srinivasan, R., Santhi, C., Harmel, R. D., van Griensven, A., Van Liew, M. W., Kannan, N., & Jha, M. K. (2012). SWAT: Model use, calibration, and validation. *Transactions of the ASABE*, 55(4), 1491–1508.
- Ayalew, L. T., & Bharti, R. (2020). Modelling sediment yield of Rib watershed, northwest Ethiopia. *ISH Journal of Hydraulic Engineering*, 28, 491–502.
- Batista, P. V. G., Silva, M. L. N., Silva, B. P. C., Curi, N., Bueno, I. T., Júnior, F. W. A., Davies, J., & Quinton, J. (2017). Modelling spatially distributed soil losses and sediment yield in the upper Grande River Basin, Brazil. *Catena*, 157, 139–150.
- Begou, J., Jomaa, S., Benabdallah, S., Bazie, P., Afouda, A., & Rode, M. (2016). Multi-site validation of the SWAT model on the Bani catchment: Model performance and predictive uncertainty. *Water*, 8(5), 178.
- Betrie, G. D., Mohamed, Y. A., van Griensven, A., & Srinivasan, R. (2011). Sediment management modelling in the Blue Nile Basin using SWAT model. *Hydrology and Earth System Sciences*, 15(3), 807–818.
- Borrelli, P., Robinson, D. A., Fleischer, L. R., Lugato, E., Ballabio, C., Alewell, C., Meusburger, K., Modugno, S., Schütt, B., Ferro, V., Bagarello, V., Van Oost, K., Montanarella, L., & Panagos, P. (2017). An assessment of the global impact of 21st century land use change on soil erosion. *Nature Communications*, 8(1), 2013.
- Borrelli, P., Robinson, D. A., Fleischer, L. R., Lugato, E., Ballabio, C., Alewell, C., ... & Montanarella, L. (2021). An assessment of the global impact of 21st century land use change on soil erosion. *Science of the Total Environment*, 780, 146494.
- Bouma, J., & Batjes, N. H. (2000). Trends of world-wide soil degradation. *Hohenheimer Umwelttagung*, 3, 3–43.
- Demissie, T. A., Saathoff, F., Seleshi, Y., & Gebissa, A. (2013). Evaluating the effectiveness of best manage-

- ment practices in Gilgel Gibe Basin Watershed—Ethiopia. *Journal of Civil Engineering and Architecture*, 7(10), 1240–1252.
- Deng, Y., Ou, Y., Pang, S., Yan, B., Zhu, H., Yan, L., & Cui, Q. (2025). Multi-objective optimization of best management practices at watershed scale: A case study of drinking water source watersheds in northeast black soil region of China. *Agricultural Water Management*, 318, 109736.
- Ebabu, K., Tsunekawa, A., Haregeweyn, N., Adgo, E., Meshesha, D. T., Aklog, D., Masunaga, T., Tsubo, M., Sultan, D., Fenta, A. A., & Yibeltal, M. (2019). Effects of land use and sustainable land management practices on runoff and soil loss in the upper Blue Nile basin, Ethiopia. *Science of the Total Environment*, 648, 1462–1475.
- Faksomboon, B., Chaivino, N., & Phadpin, A. (2023). Identification of soil erosion using the SWAT model for prioritizing conservation measures of Si Satchanalai Sub-watershed in Thailand. *EnvironmentAsia*, 16(3), 117–132.
- Gathagu, J. N., Sang, J. K., & Maina, C. W. (2018). Modelling the impacts of structural conservation measures on sediment and water yield in Thika-Chania catchment, Kenya. *International Soil and Water Conservation Research*, 6, 165–174.
- Gashaw, T., Tulu, T., Argaw, M., & Worqlul, A. W. (2018). Modeling the hydrological impacts of land use/land cover changes in the Andassa watershed, Blue Nile Basin, Ethiopia. *Science of the Total Environment*, 619–620, 1394–1408.
- Gashaw, T., Tulu, T., Argaw, M., & Worqlul, A. W. (2019). Modeling the impacts of land use/land cover changes on soil erosion and sediment yield in the Andassa watershed, upper Blue Nile Basin, Ethiopia. *Environmental Earth Sciences*, 78, 679.
- Gashaw, T., Worqlul, A., Dile, Y., Addisu, S., Bantidar, A., & Zeleke, G. (2020). Evaluating potential impacts of land management practices on soil erosion in the Gilgel Abay watershed, upper Blue Nile Basin, Ethiopia. *Heliyon*, 6, e04777.
- Gashaw, T., Dile, Y. T., Worqlul, A. W., Bantider, A., Zeleke, G., Bewket, W., & Alamirew, T. (2021). Evaluating the effectiveness of best management practices on soil erosion reduction using the SWAT model: For the case of Gumara watershed, Abbay (upper Blue Nile) Basin. *Environmental Management*, 68, 240–261.
- Gassman, P. W., Reyes, M. R., Green, C. H., & Arnold, J. G. (2014). The soil and water assessment tool: Historical development, applications, and future research directions. *Transactions of the ASABE*, 57(5), 1421–1449.
- Gebresamuel, G., Singh, B. R., & Dick, Ø. B. (2010). Land-use changes and their impacts on soil degradation and surface runoff of two catchments of Northern Ethiopia. *Acta Agriculturae Scandinavica, Section B-Soil & Plant Science*, 60(3), 211–226.
- Guzman, J. A., Jenkins, M. W., & Sanders, J. H. (2015). Mechanistic interpretation of SWAT parameter sensitivity for hydrologic modeling. *Environmental Modelling & Software*, 68, 39–48.
- Haregeweyn, N., Tsunekawa, A., Nyssen, J., Poesen, J., Tsubo, M., Meshesha, D. T., Schütt, B., Adgo, E., & Tegegne, F. (2015). Soil erosion and conservation in Ethiopia: A review. *Progress in Physical Geography*, 39(6), 750–774.
- Haregeweyn, N., Tsunekawa, A., Poesen, J., Tsubo, M., Meshesha, D. T., Fenta, A. A., Nyssen, J., & Adgo, E. (2017). Comprehensive assessment of soil erosion risk for better land use planning in river basins: Case study of the upper Blue Nile River. *Science of the Total Environment*, 574, 95–108.
- Lal, R. (2015). Restoring soil quality to mitigate soil degradation. *Sustainability*, 7(5), 5875–5895.
- Li, Z., Xue, W., & Sereewatthanawut, I. (2025). Evaluation of best management practices (BMPs) for mitigating non-point source pollution in the Wang River Basin of Thailand based on the SWAT Model. *Environmental Technology & Innovation*, 39, 104327.
- Lin, Z., Radcliffe, M., & Xu, Y. (2017). Mechanistic modeling of sediment detachment and transport in SWAT for improved erosion prediction. *Hydrological Processes*, 31(12), 2130–2145.
- Lemma, H., Frankl, A., van Griensven, A., Poesen, J., Adgo, E., & Nyssen, J. (2019). Identifying erosion hotspots in Lake Tana Basin from a multisite soil and water assessment tool validation: Opportunity for land managers. *Land Degradation & Development*, 30, 1449–1467.
- Lopes, A., Gouveia, s., Serpa, D., Keizer, J., & Vieira, D. (2024). Exploring the inclusion of soil management practices in erosion models towards the improvement of post-fire predictions. *Geomorphology*, 466, 109452.
- López-Ballesteros, A., Senent-Aparicio, J., Srinivasan, R., & Pérez-Sánchez, J. (2019). Assessing the impact of best management practices in a highly anthropogenic and ungauged watershed using the SWAT model: A case study in the El Beal watershed (southeast Spain). *Agronomy*, 9(10), 576.
- Mekonnen, M., Keesstra, S. D., Stroosnijder, L., Baartman, J. E. M., & Maroulis, J. (2015). Soil conservation through sediment trapping: A review. *Land Degradation & Development*, 26(6), 544–556.
- Merriman, K. R., Daggupati, P., Srinivasan, R., & Hayhurst, B. (2019). Assessment of site-specific agricultural best management practices in the upper East River watershed, Wisconsin, using a

- field-scale SWAT model. *Journal of Great Lakes Research*, 45, 619–641.
- Morgan, R. P. C. (2005). *Soil erosion and conservation* (3rd Eds.). Blackwell Publishing.
- Moriasi, D., Arnold, J., Van Liew, M., Bingner, R., Harmel, R., & Veith, T. (2007). Model evaluation guidelines for systematic quantification of accuracy in watershed simulations. *Transactions of the ASABE*, 50(3), 885–900.
- Nguyen, H. T., Le, T. D., & Pham, Q. H. (2023). Prioritization of erosion-prone sub-watersheds using SWAT and BMP scenario analysis. *Catena*, 228, 107136.
- Nyssen, J., Poesen, J., Gebremichael, D., Vancampenhout, K., Daes, M., Yihdego, G., Govers, G., Leirs, H., Moeyersons, J., Naudts, J., Haregeweyn, N., Haile, M., & Deckers, J. (2007). Interdisciplinary on-site evaluation of stone bunds to control soil erosion on cropland in Northern Ethiopia. *Soil and Tillage Research*, 94, 151–163.
- Parajuli, P., Gallagher, T., Cristan, R., Danial, M. L., Mitchell, D., McDonald, T., Rijal, A., & Zheng, J. (2024). Postharvest evaluations of soil erosion, ground cover, and best management practice implementation on integrated biomass and conventional clearcut harvest sites. *Forest Ecology and Management*, 556, 122041.
- Pimentel, D. (2006). Soil erosion: A food and environmental threat. *Environment, Development and Sustainability*, 8, 119–137.
- Saxton, K., & Rawls, W. (2006). Soil water characteristic estimates by texture and organic matter for hydrologic solutions. *Soil Science Society of America Journal*, 70, 1569–1578.
- Silabi, M. Z., Sadeghi, S. H., & Vafakhah, M. (2025). Soil erosion elasticity initiative for prioritizing sub-watersheds. *International Soil and Water Conservation Research*, 13, 277–289.
- SRTM. (2020). *Source of the 30 m resolution Shuttle Radar Topography Mission (SRTM) digital elevation model (DEM)*. <https://earthexplorer.usgs.gov/> (Accessed 12 September 2019)
- United States Department of Agriculture–Soil Conservation Service. (1972). *National engineering handbook: Section 4 Hydrology*. USDA, Washington D.C.
- Williams, J. R. (1995). Chapter 25: The EPIC model. In V. P. Singh (Eds.), *Computer models of watershed hydrology* (pp. 909–1000). Water Resources Publications.
- Worqlul, A. W., Ayana, E. K., Yen, H., Jeong, J., MacAlister, C., Taylor, R., Gerik, T. J., & Steenhuis, T. S. (2018). Evaluating hydrologic responses to soil characteristics using SWAT model in a paired-watersheds in the upper Blue Nile Basin. *Catena*, 163, 332–341.