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Identification of Soil Erosion Using the SWAT Model for Prioritizing Conservation Measures of Si Satchanalai Sub-Watershed in Thailand

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Abstract

One of the major environmental challenges facing the world today is land degradation and soil erosion, which pose a significant threat to the environment. Loss of top fertile soil will decrease the land's ability to produce, posing a threat to the safety of the world's food supply. Soil erosion is one of the pressing environmental problems in Thailand. This study aimed to identify soil erosion for prioritizing conservation measures and evaluate BMPs for reducing soil erosion using the soil and water assessment tool (SWAT) model in Si Satchanalai Sub-Watershed (SS-SW) in the lower watershed of the Yom Watershed, Thailand. The SWAT model was calibrated (2016 – 2018) and validated (2019 – 2021) using streamflow and sediment data in the SWAT calibration and uncertainty program (SWAT-CUP). The coefficient of determination (R^2), the nash – sutcliffe efficiency (NSE), the percent bias (PBIAS), and the root mean square error-observations standard deviation ratio (RSR) values during flow and sediment calibration and validation periods ranged from 0.94 to 0.96, 0.82 to 0.91, -2.8% to 7.2%, and 0.28 to 0.42, respectively. The study indicates that SWAT is able to simulate streamflow and sediment with sufficient accuracy. The calibrated and validated SWAT model was used to evaluate the effectiveness of three best management practices (BMPs) against the baseline conditions (Scenario A) for reducing soil erosion, such as filter strips scenario (Scenario B), stone/soil bunds scenario (Scenario C), and reforestation scenario (Scenario D). The result indicated that about 69.44% of the watershed was identified as soil erosion, which experienced a sediment yield of 18.77 ton/rai/year. The mean annual sediment yield at the baseline Scenario A approximately was 14.05 ton/rai/year. The implementation of Scenario B, Scenario C, and Scenario D reduced the sediment yield by 8.42%, 38.90%, and 68.72%, respectively. At the SW levels, Scenario B, C, and D reduced the mean annual sediment yield from 1.5% (SW-2) to 12.30 (SW-11), 10.25% (SW-2) to 67.14 (SW-20), 28.64% (SW-1) to 68.89 (SW-21), respectively. Therefore, the study suggests implementations of Scenario C and D for effective soil erosion reduction in the study watershed and in other watersheds in Thailand in general which have similar environmental settings.

Keywords: Soil erosion; SWAT model; Best management practices; Watershed

1. Introduction

Across the world, water and soil erosion is an ecosystem problem that greatly reduces the productivity of soil and water quality leading to ecosystem degradation. Human interventions, such as deforestation for agricultural food production, the cultivation of marginal lands, overgrazing, and the exploitation of soil fertility accelerate soil erosion (Wolka *et al.* 2011; Faksomboon *et al.,* 2017). Soil and water erosion degrades soil structure, and lowers soil organic matter and nutrient contents, thus reducing soil fertility. The soil erosion problem is relatively very severe in three continents of the world such as Asia, Africa, and Latin America (Borrelli *et al.,* 2017). Water-induced soil erosion is also a fundamental environmental problem in many countries (Hurni *et al.,* 2015), and undoubtedly, the Thailand highlands are among the most affected. The mean soil erosion rate in the northern parts of Thailand is a highly eroded country when compared to the other highlands region, which is due to steep slope cultivation, intensive rainfall, and topographic factors. Extreme deforestation, early settlement, burning of crop residue, and inappropriate land management practices. Soil erosion has also off-site impacts such as siltation of downstream lakes, reservoirs, and river channels, hence aggravating flooding and degradation of hydrological ecosystem services (Haregeweyn *et al.,* 2015). Investigating various land and water management practices that can reduce soil erosion is necessary given the severe soil erosion and its effects on the environment and the socioeconomic system. Such practices include intensive cultivation, extensive cultivation, filter strip, tracing, stone or soil bund, agro-forestation, soil, and water conservation measures, and area enclosure (Betrie *et al.,* 2011; Tamene *et al.,* 2017; Faksomboon et al., 2022).

Physical determination of the effectiveness of conservation methods at the watershed level is challenging and time-consuming. Modelling processes in the watershed is one approach to determining the impact of implementing structural conservation measures on water and sediment yield (Brunner *et al.,* 2008; Parajuli *et al.,* 2008; Kyalo *et al.,* 2014; Faksomboon *et al.,* 2022). Different hydrological tools including VIC, InVEST, MUSLE equation, and SWAT have been applied across the globe to model water and sediment yield from watersheds. In the present study, SWAT-a physically based model was used due to its extensive application across the world, combines both the simulation of water and sediment yield, and has good user support. The SWAT is an empirically based model; it simulates flow and sediment and nutrient loads are given elevation, land use, soils, climate, and management inputs, among others (Douglas *et al.,* 2010; Gassman *et al.,* 2007; Neitsch *et al.,* 2011). The model has also successfully been applied elsewhere in modelling ecosystem services (Bracmort *et al.,* 2006; Tuppad *et al.,* 2010; Faksomboon *et al.,* 2017, 2022). Thus, this study aimed to identify erosion for prioritization of conservation measures and evaluate BMPs for reducing soil erosion using the soil and water assessment tool (SWAT) model in the Si Satchanalai Sub-Watershed (SS-SW) of Thailand. In addition, it can be applied for a variety of activities like identifying high-risk locations, assessing the average erosion risk pattern in the watershed, identifying deposition and deposition patterns, and identifying detailed erosion and major concentrated flow areas.

2. Materials and methods

2.1 Study area

The SS-SW is the lower watershed of the Yom Watershed, in Northern Thailand, and covers an area of about 1,197.90 km^2 (Figure 1). Geographically, the watershed is located between 17◦54′30″ - 17◦16′44″ N and 99◦18′47″ - 100◦11′13″ E, and its elevation ranges from 62 to 904 meters above sea level (MSL). It has 5 districts, 4 provinces, and it is divided into 21 Sub-Watershed (SW). The SS-SW River, which is the main river drain in the watershed, originates around Mae Wa and Si Satchanalai National Park, 121.76 km^2 of the national park area is entirely within the watershed area (10.16%). The SS-SW has the wet season normally occurs between April to October and the dry season between November to March. The climate of the SS-SW area in terms of annual rainfall observed from the years 2016 to 2021 was 1,155.93 mm and the highest rainfall from April to October was between 71.07 - 233.22 mm. The study area is dominated by land use and land cover (LULC) by disturbed deciduous forest followed by deciduous forest, a forest plantation, and mixed orchard (Figure 2A), and area coverage size (Table 1). The dominant soil types are soil-20 (53.79%), soil-4 (43.54%), soil-3 (2.29%), and soil-14 (0.38%), respectively (Figure 2B). Based on the meteorological station record, including rainfall, temperatures, and humidity during the 2016 - 2021 periods. The weather data was obtained from the Sukhothai meteorological station.

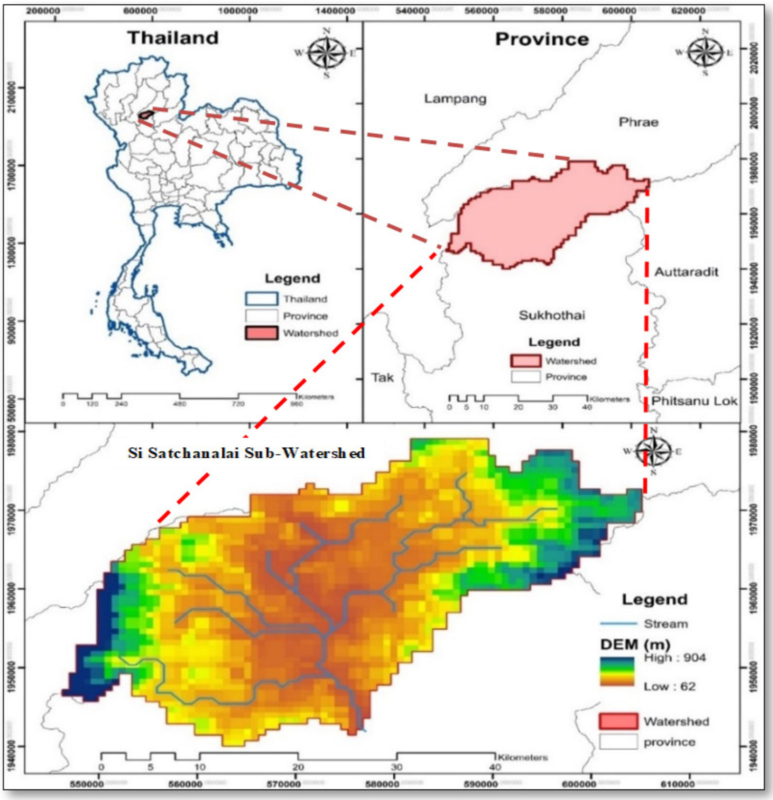


Figure 1. Location map of Si Satchanalai Sub-Watershed in Thailand

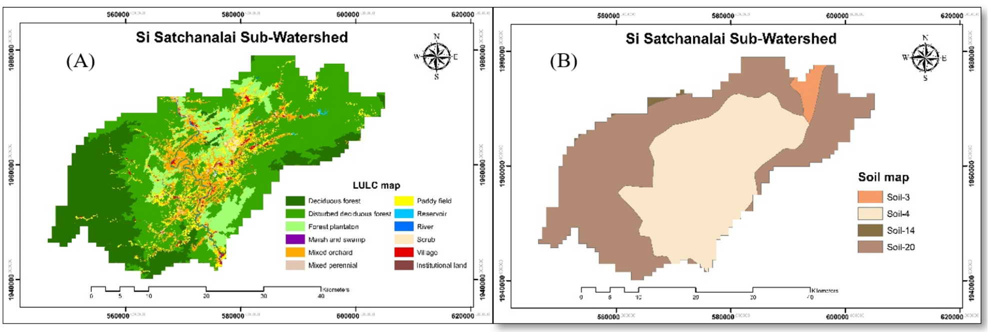


Figure 2. Land use and land cover (A), and soil maps (B) of the Si Satchanalai Sub-Watershed

Table 1. Land use and land cover type, and area coverage size in the Si Satchanalai Sub-Watershed

Order	LULC type	Area (km^2)	% of watershed
1	Paddy field	75.31	6.29
2	Mixed perennial	6.99	0.58
3	Mixed orchard	99.06	8.27
4	Deciduous forest	296.13	24.72
5	Disturbed deciduous forest	588.48	49.13
6	Forest plantation	108.77	9.08
7	Scrub	7.06	0.59
8	Marsh and swamp	0.04	< 0.01
9	Village	9.01	0.75
10	Institutional land	1.20	0.10
11	River	4.77	0.40
12	Reservoir	1.08	0.09
	Total	1,197.90	100.00

2.2 The SWAT model inputs

The SWAT is a physical-based model that simulates surface runoff, soil erosion, and sediment delivery in a river system. The model is suitable to simulate a single watershed or multiple hydrologically connected watersheds. It required spatial and temporal input data for simulating hydrological processes and sediment yield. The types of spatial data needed by the SWAT model include the digital elevation model (DEM), soil groups, LULC maps, and daily climate data. In SWAT, the hydrologic cycle of a SW is simulated based on the following water balance, in Equation 1.

$$SW_t = SW_0 + \sum_{i=1}^{t} (R_{day} - Q_{surf} - E_a - W_{seep} - Q_{gw}) \quad (1)$$

Where, SW_t is the final soil water content; SW_0 is the initial soil water content (mm); t is time; R_{day} is the amount of precipitation; Q_{surf} is the mount of surface runoff; E_a is the amount of evapotranspiration; W_{seep} is the amount of percolation and bypass flow exiting the soil profile bottom; and Q_{gw} is the amount of return flow.

2.2.1 The spatial data

The study used a 30 m spatial resolution DEM from the Shuttle Radar Topographic Mission database. The DEM was used to delineate the watersheds and SW, create stream networks, and calculate surface and channel slopes. The DEM was also used for creating hydrological response units (HRUs). The LULC map of the study area was prepared from a cloud-free 30 m resolution Landsat 8 image. Classification of the Landsat image into LULC classes was undertaken using a supervised classification technique with a maximum likelihood classification (MLC) algorithm in ERDAS IMAGINE 2014. Training points that are used for classifying the image and calculating the accuracy assessment of the classified image were collected from each LULC type from the corresponding time of period google earth image. The study attained an overall accuracy of 88.4% and a kappa coefficient of 0.87. The obtained overall classification accuracy (> 85%) showed a very good performance of classification result (Monserud, 1990). A soil map and the physical-chemical properties data of each soil type for the three soil layers are another input of the SWAT model. The study obtained the soil map of the study watershed, and organic carbon content and textural class data were collected from the Land Development Department (Table 2).

2.2.2 The temporal data

The long-term daily meteorological data were collected from the Sukhothai meteorological station (2016-2021). The five meteorological elements required by the SWAT model (rainfall, minimum and maximum temperature, solar radiation, wind speed, and relative humidity) were all simultaneously recorded by the station's measurement equipment. The missing meteorological data were filled using the Carol Monte Multiple Imputation methods in the XLSTAT software (REF). The weather generator (WGEN) SWAT database was

Table 2. Soil type and area coverage size in the Si Satchanalai Sub-Watershed

Order	Soil type	Soil description	Fertile soil	Area (km^2)	% of watershed
1	Soil-3	Rock rubble, gravel, gravel mixed in the soil layer, good drainage.	Slight	27.43	2.29
2	Soil-4	Sandy soil with water during the rainy season	Slight	521.60	43.54
3	Soil-14	Gravel, stone, or gravel in the soil layer with good drainage in the irrigation area	Slight	4.53	0.38
4	Soil-20	Loamy to sandy loam. with good drainage and high rainfall	Moderate	644.34	53.79
		Total	-	1,197.90	100.00

prepared using the SWAT weather generator tool. The monthly rainfall and temperature (2016 - 2021) characteristics of the Sukhothai meteorological station (Figure 3). Daily streamflow data collected from the 2016 to 2021 periods at the Lower Northern Region Irrigation Hydrology Center was obtained from the Royal Irrigation Department for calibration and validation of the SWAT model. Since there are no continuously measured sediment data at this hydro-gauging station, the study derived a continuous daily sediment yield by establishing a sediment-rating curve using the available flow and sediment concentration data. Due to the absence of continuously monitored sediment data, other studies in the world have also followed a similar method for obtaining continuous sediment yield (Batista *et al.,* 2017; Aga *et al.,* 2018; Gashaw *et al.,* 2021).

2.3 Model setup

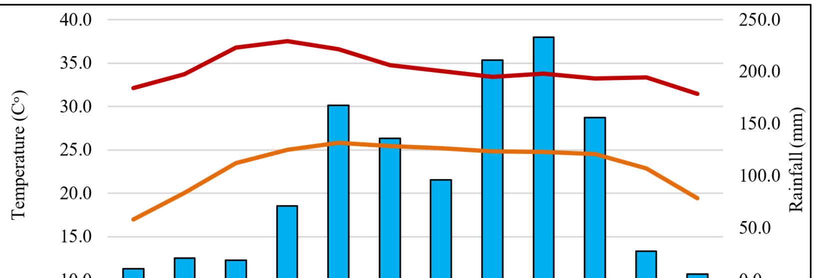
The watershed delineation was undertaken using a 30 m resolution DEM by assigning a flow accumulation threshold area of 1,197.90 km^2, which has created 21 SW. The multiple HRUs option, which follows combinations of 10% land use, 10% soil, and 10% slope classes, have created 185 HRUs in the study watershed. The use of 10% (land use), 10% (soil), and 10% (slope class) was because these combinations produce a reasonable number of HRUs that provide reasonable streamflow estimation in the SS-SW. Similar to this study, the land use-soil-slope class combinations in previous studies were selected considering the characteristics of the watershed. For example, Lemma *et al.* (2019) in the Lake Tana Watershed applied 10% land use, 20% soil, and 10% slope classes. Faksomboon (2022) applied respect of 5% for land use, 10% for soil, and 10% for slope classes of the Lamtakong Watershed. On the other hand, Gashaw *et al.* (2021) in the Gumara Watershed employed 20% land use, 10% soil, and 10% slope classes. This study used three slope ranges, namely 0 - 5%, 5 - 15%, and > 15%, respectively. Sediment yield was determined following the modified universal soil loss equation (MUSLE) (Williams, 1995) in Equation 2.

$$S_y = a\,(Q_{surf} * q_{peak} * A_{HRU})^{\beta} * K_{USLE} * C_{USLE} * P_{USLE} * LS_{USLE} * CFRG \quad (2)$$

Where, S_y is HRU sediment yield; *a* and β are location coefficients; Q_{surf} is daily surface runoff volume; q_{peakis} runoff peak discharge; A_{HRU} is HRU area; K_{USLE} is the USLE soil erodibility factor, C_{USLE}, P_{USLE}, and LS_{USLE} are dimensionless factors accounting for HRU crop cover, soil protection, and topography as defined in the original Universal Soil Loss Equation, and *CFRG* is a dimensionless factor to account for coarse fragment cover.

2.4 Sensitivity analysis, model calibration, and validation

The weather data was obtained from the Thai Meteorological Department of Thailand, and employed in simulations of AET and PET utilizing the model. A weather generator built inside the SWAT model was used to create additional meteorological data in order to meet the simulation's data requirements.



	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Rainfall	10.8	21.2	18.9	71.1	167.9	136.0	96.3	211.3	233.2	156.2	27.5	5.7
Temp-Max	32.1	33.7	36.8	37.5	36.6	34.8	34.1	33.4	33.8	33.2	33.3	31.4
Temp-Min	17.0	20.1	23.5	25.0	25.8	25.4	25.2	24.8	24.8	24.5	22.9	19.4

Figure 3. Monthly rainfall and temperature (2016-2021) of the meteorological station

2.4.1 Sensitivity analysis

Sensitivity analysis calibration and validation of the SWAT model were performed using the sequential uncertainty fitting (SUFI-2) algorithm, which is a built-up algorithm in the SWAT calibration and uncertainty program (SWAT-CUP) version 5.1.6. SUF-2 is the most widely applied calibration and uncertainty analysis program in Thailand and elsewhere in the world (Gathagu *et al.,* 2018; Gashaw *et al.,* 2018, 2021; Worqlul *et al.,* 2018; Lemma et al., 2019; Faksomboon *et al.,* 2022). In this study, thirteen streamflow and seven sediment parameters (Table 3) were selected for sensitivity analysis from previous studies in the SS-SW (Faksomboon *et al.,* 2017, 2022; Worqlul *et al.,* 2018; Gashaw *et al.,* 2018, 2021; Lemma *et al.,* 2019; Ayalew and Bharti, 2020), which allows changing all parameters were applied in this study. Sensitivity streamflow and sediment parameters were identified using t stat and *p*-value. Parameters with absolute values of a higher t stat and a smaller *p*-value are highly sensitive (Abbaspour *et al.,* 2015).

2.4.2 The model calibration and validation

The calibration is a procedure of altering model parameters using the measured data to provide a similar response over time. The monthly basis model calibration and validation were undertaken using the data recorded from the 2016 - 2018 and 2019 - 2021 periods, respectively.

2.5 The model performance evaluation

The study evaluated the performance of the streamflow and sediment data using the nash-sutcliffe efficiency (NSE), percent bias (PBIAS), root mean square error (RMSE)-observations standard deviation ratio (RSR), and coefficient of determination (R2). The calculation of NSE, PBIAS, and RSR following Equations 3, 4, and 5 (Moriasi *et al.,* 2007), while R^2 was computed based on Eq. (6), respectively (Begou *et al.,* 2016). The model performance ratings were evaluated based on a range of values for NSE, PBIAS, RSR, and R^2, respectively.

$$NSE = \left\{1 - \frac{\sum_{i=1}^{n} (Y_i^{obs} - Y_i^{sim})^2}{\sum_{i-1}^{n} (Y_i^{obs} - Y^{mean})^2}\right\} \quad (3)$$

$$PBAIS = \left\{\frac{\sum_{i=1}^{n} \left(Y_i^{obs} - Y_i^{sim}\right) * 100}{\sum_{i=1}^{n} (Y_i^{obs})}\right\} \quad (4)$$

$$RSR = \frac{RMSE}{STD_{obs}} = \left\{\frac{\sqrt{\sum_{i=1}^{n} (Y_i^{obs} - Y_i^{sim})^2}}{\sqrt{\sum_{i=1}^{n} (Y_i^{obs} - Y^{mean})^2}}\right\} \quad (5)$$

$$R^2 = \left\{\frac{\sum_{i=1}^{n} \left(Y_i^{obs} - Y^{mean}\right) \times (Y_i^{sim} - X^{mean})}{\sqrt{[\sum_{i=1}^{n} (Y_i^{obs} - Y^{mean})^2]} \times \sqrt{\sum_{i=1}^{n} (Y_i^{sim} - X^{mean})^2}}\right\}^2 \quad (6)$$

Table 3. Streamflow and sediment parameters were considered for sensitivity analysis

Order	Input file	Parameters	Descriptions
Streamflow	.mgt	CN2	SCS curve number
	.gw	ALPHA_BF	Base flow recession constant
	.gw	GW_DELAY	Delay time for aquifer recharge (days)
	.gw	GWQMN	Channel effective hydraulic conductivity (mm h^{-1})
	.hru	DEP_IMP	Depth to impervious layer in the perched water table (mm)
	.sub	CH_N1	Manning's n value for the main channel
	.bsn	ESCO	Soil evaporation compensation coefficient
	.bsn	SURLAG	Surface runoff lag time
	.hru	OV_N	Manning's ''n'' value for overland flow
	.sub	CH_S1	The average slope of tributary channels
	.hru	SLSUBBSN	Average slope length
	.rte	CH_N2	Manning's ''n'' value for the main channel
	.sol	SOL_K	Saturated hydraulic conductivity
Sediment	.mgt	USLE_P	USLE support practice factor
	.plant date	USLE_C	Min value of USLE land cover factor
	.hru	HRU_SLP	Average slope steepness (m/m)
	.bsn	SPCON	The linear re-entrainment parameter in sediment routing
	.bsn	SPEXP	Exponent re-entrainment parameter in sediment routing
	.rte	CH_COV2	Channel cover factor
	.rte	CH_COV1	Channel erodibility factor

Where, n is the total number of observations, Y_i^{obs} is the observed value, Y_i^{sim} is the simulated value, Y^{mean} is the mean of the observed data, X^{mean} is the mean of the simulate data and STD_{obs} is the standard deviation of the observed data

2.6 The best management practices scenarios (BMPs)

Identifying the effective BMPs for sediment yield reduction is one of the widely applied types of SWAT applications in the world (Lemma *et al.,* 2019; Gashaw *et al.,* 2021; Gathagu *et al.,* 2018; Briak *et al.,*2019; Himanshu *et al.,* 2019; Uniyal *et al.,*2020). In this study, the effectiveness of three BMPs for reducing soil erosion was evaluated against the baseline scenario (Scenario A). The selected Scenarios are the filter strips Scenario (Scenario B). The stone/soil bunds Scenario (Scenario C), and the reforestation Scenario (Scenario D). The descriptions of these Scenarios are provided in the following sections.

2.6.1 The baseline scenario (Scenario A)

The sediment yield obtained after calibration of the SWAT model for streamflow and sediment yield parameters (2016-2021).

2.6.2 The filter strip scenario (Scenario B)

The filter strips are vegetated areas along the cropland contours. Establishing vegetated areas such as grasses minimize the probability of rill and gully erosion formation on cultivated lands by reducing the velocity of surface runoff, and enhancing infiltration. The filter strip scenario was implemented in the SWAT model by changing the width of the filter strip to 1 m in all agricultural HRUs, soil types, and slope classes.

2.6.3 The soil/stone bund scenario (Scenario C)

The stone/soil bund is a structural conservation practice from soil and/or stone along the contours with water collection channels or watersheds in hill areas. The stone/soil bunds are the most widely implemented conservation practices in Thailand. Hence, evaluating the effectiveness of these BMPs in reducing soil erosion is imperative. The stone/soil bund Scenario was implemented in the SWAT model by modifying the Curve Number (CN2) to 57.4 and USLE_P-value to 0.38 for all cultivated lands (Table 4). Implementation of Scenario B was also done by decreasing the slope length (SLSUBBSN) and slope steepness (HRU_SLP) by 50% and 25%, respectively in each slope class.

2.6.4 The reforestation scenario (Scenario D)

Reforestation is a soil erosion control practice that involves the conversion of erosion-vulnerable cultivated lands into the forest. Plantation of steep slope areas of cultivated lands is one of the effective methods for reducing soil erosion in the Highlands. The reforestation scenario assumes that all the cultivated lands above 10% will be changed into the forest. In this study, implementation of the reforestation scenario in the SWAT model was made by changing the land use and land cover map.

Table 4. List of the considered BMPs and the parameter changes in the SWAT model

Order	Scenarios	Description	Adjusted parameter value		Modified value
			Parameter name	Calibrated value	
1	Scenario A	Baseline	-	-	-
2	Scenario B	Soil/Stone bund	SLSUBBSN	a	0.25a
			HRU-SLP	b	0.61b
			CN2	75.9	57.4
			USLE-P	0.42	0.38
3	Scenario C	Filter strip	FILTERW	0	1
4	Scenario D	Reforestation	-	-	-

Remark: ‘‘-’’ represents the calibrated streamflow and sediment parameter values.
‘‘a’’ is the SWAT assigned values.
‘‘b’’ indicates the relative calibrated value of parameters.

3. Results and discussion

3.1 Sensitive streamflow and sediment parameters

Among the thirteen-streamflow parameters considered for sensitivity analysis, seven of them were sensitive to the output variable. These sensitive streamflow parameters in their order of sensitivity are CN2, CH_K2, REVAP, GW_DELAY, ESCO, GWQMN, and ALPHA_BF. Similar to this finding, a previous study undertaken in the watershed in most of the previous studies reported that CN2, ALPHA_BF, GWQMN, and ESCO are highly sensitive streamflow parameters (Faksomboon *et al.,* 2017; Worqlul *et al.,* 2018; Gashaw *et al.,* 2021; Faksomboon *et al.,* 2022). On the other hand, of the seven sediment parameters considered for sensitivity analysis, four of them were sensitive to the output variable. The sensitive sediment parameters in the order of sensitivity are SPCON, USLE_P, USLE_C, and HRU_SLP (Table 5). Similar to the findings of this study, preceding studies in the watershed also reported the sensitivity of most of these sediment parameters in the respective study sites (Faksomboon *et al.,* 2017, 2022; Lemma *et al.,* 2019; Ayalew and Bharti, 2020; Gashaw *et al.,* 2021).

3.2 The calibration and validation results

The observed and simulated streamflow and sediment were compared as show in (Figure 4 and 5). The result indicated that the model has simulated the observed streamflow and sediment reasonably.

Table 5. The identified sensitive streamflow and sediment parameters in the study watershed

Order	Parameters	Min value	Max value	Fitted value	t-stat	p-value	Sensitivity rank
Streamflow	R__CN2.mgt	- 0.02	0.2	- 0.09	- 9.65	> 0.01	1
	V__CH_K2.rte	0.01	150	58.64	2.54	> 0.01	2
	V__GW_REVAP.gw	0.02	0.20	0.15	3.45	0.11	3
	V__GW_DELAY.gw	0	350	278.66	- 1.56	0.24	4
	V__ESCO.bsn	0	1	0.37	- 0.74	0.28	5
	V__GWQMN.gw	0	2	1.22	0.66	0.37	6
	V__ALPHA_BF.gw	0.01	1	0.45	0.85	0.39	7
Sediment	V__SPCON.bsn	0.0001	0.01	0.01	- 7.41	> 0.01	1
	V__USLE_P.mgt	0.1	0.8	0.4	- 4.62	> 0.01	2
	V__USLE_C.plant.dat	0.001	0.5	0.15	- 2.74	> 0.01	3
	R__HRU_SLP.hru	- 0.2	0.2	0.17	- 1.95	0.08	4

Remark: R_: existing parameter value is to be replaced by a given value.
V_: existing parameter value is multiplied by (1 + given value).

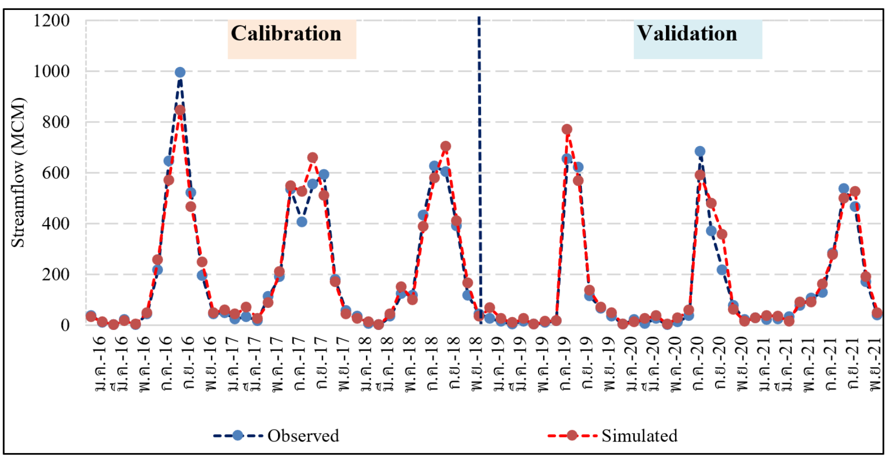


Figure 4. Monthly streamflow of the study watershed during the calibration (2016 - 2018) and validation (2019 - 2021) periods

In terms of statistical indices, R^2 of 0.96 and 0.96, NSE of 0.89 and 0.91, PBIAS of -2.8% and 5.7%, and RSR of 0.32 and 0.28 were attained during calibration (Figure 6A) and validation (2016 - 2021) periods (Figure 6B), respectively. The obtained statistical indices during the calibration (Figure 7A) and validation periods (Figure 7B) such as R^2 of 0.94 and 0.96, NSE of 0.82 and 0.85, PBIAS of 6.4% and 7.2%, RSR of 0.42 and 0.39, respectively.

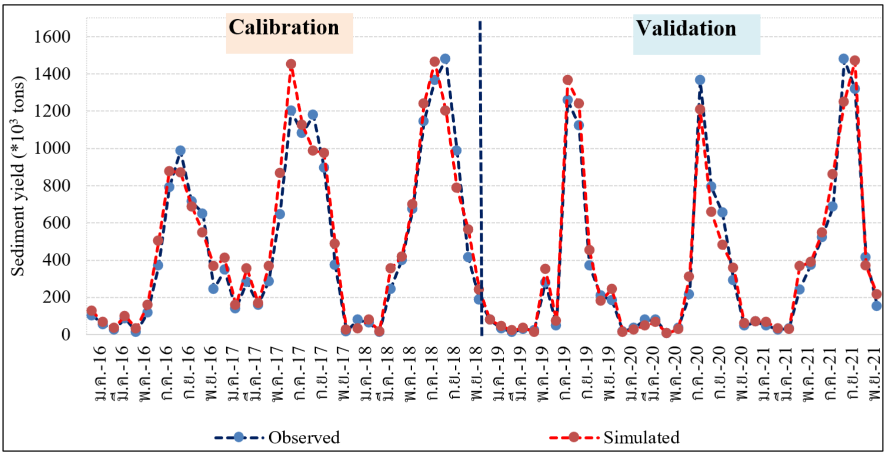


Figure 5. Monthly sediment of the study watershed during the calibration (2016 - 2018) and validation (2019 - 2021) periods

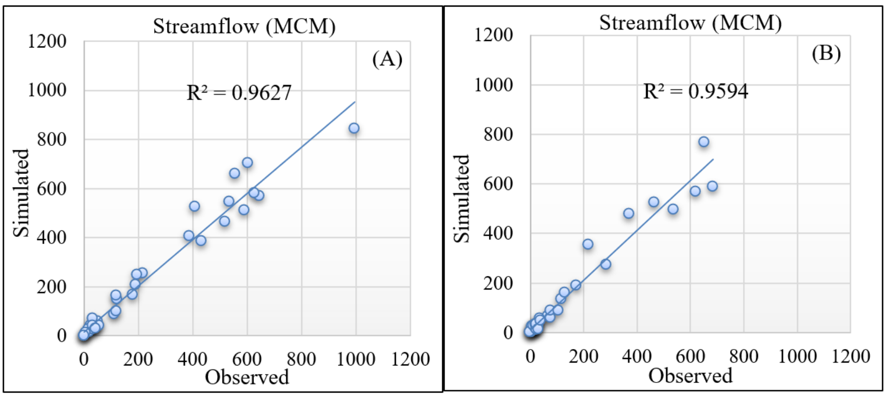


Figure 6. Coefficient of determination for the streamflow was calibrated in year 2016 - 2018 (A) and validated in the year 2019-2021 (B) periods

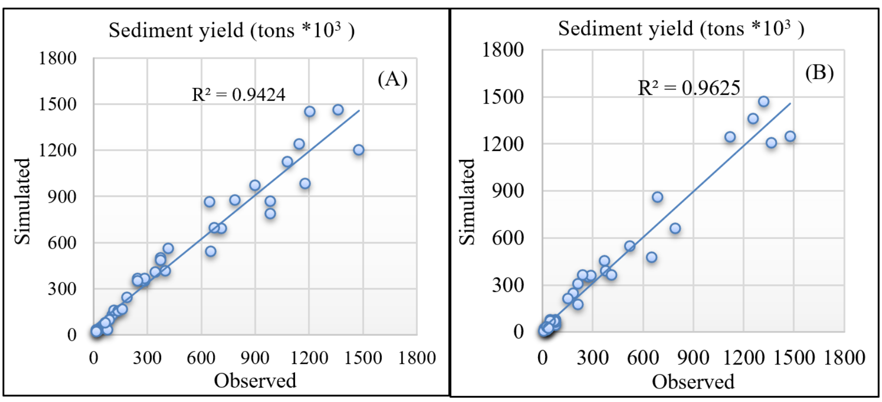


Figure 7. Coefficient of determination for the sediment yield was calibrated in year 2016 - 2018 (A) and validated in the year 2019-2021 (B) periods

The obtained statistical indices indicated the very good performance of the SWAT model for simulating the streamflow and sediment yield in the study watershed, that the values of all statistical indices were high in the period, which indicates the good quality of the entire data (Table 6).

3.3 The identifying soil erosion of the study watershed

The obtained average annual sediment yield of SS-SW was categorized into 5 sediment severity classes, such as 1) Slight, 2) Moderate, 3) Severe, 4) Very severe, and 5) Extremely severe (The Department of Land Development, 2002). The average annual sediment yield of SS-SW during the 2016 - 2021 periods at the baseline Scenario A (Figure 8). The result shows that the average annual sediment yield of the study watershed was approximately 14.05 ton/rai/year, respectively. Showing the spatial variations of sediment yield among the 21 SW, SW-11, SW-15, SW-17, SW-19, and SW-21, which cover about 12.08% of the SS-SW area, experienced the extremely severe sediment severity category. On the other hand, SW-7, SW-10, SW-12, SW-14, SW-16, SW-18, and SW-20, which represented about 40.76% of the SS-SW, were grouped in the very severe sediment severity category. The SW in the severe sediment severity category is SW-4, SW-8, and SW-13, which accounted for about 16.60% of the SS-SW. The SW in the moderate sediment were SW-1, SW-3, and SW-9, which represented about 14.34%. On the other hand, SW-2, SW-5, and SW-6, which accounted for about 10.3% of the total area, are within the slight sediment severity category, respectively. Therefore, about 69.44% of the SS-SW experienced severe to extremely severe sediment severity classes, which are identified as soil erosion (Table 7). Conversely, which represented only 30.56% of the total area, is under the severe sediment severity class.

Table 6. Performance of the SWAT model during calibration and validation periods

Order	Simulation period	Evaluation statistics			
		R^2	NSE	PBIAS (%)	RSR
Streamflow	Calibration	0.96	0.89	-2.8	0.32
	Validation	0.96	0.91	5.7	0.28
Sediment yield	Calibration	0.94	0.82	6.4	0.42
	Validation	0.96	0.85	7.2	0.39

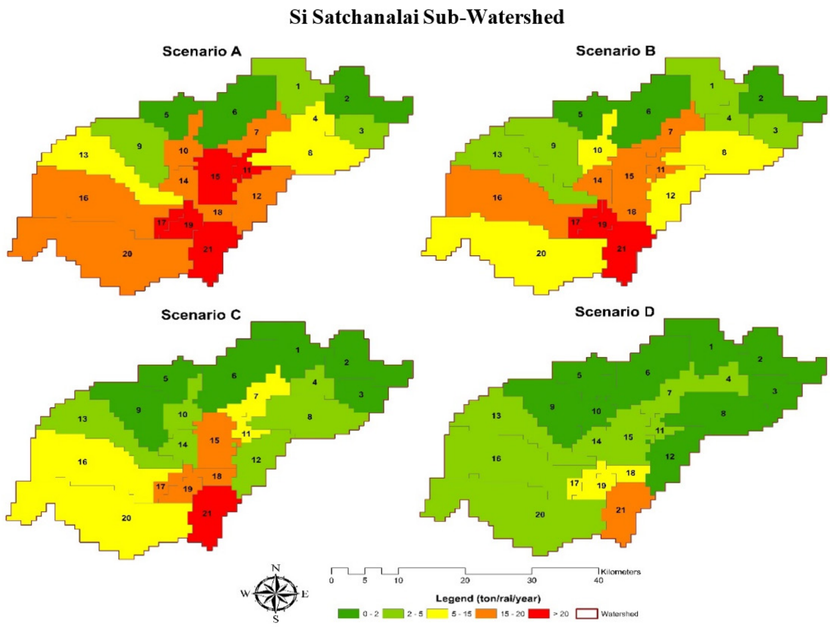


Figure 8. Mean annual sediment yield (2016 - 2021) of SS-SW at the baseline Scenario A, Scenario B, Scenario C, and Scenario D

3.4 The effects of BMPs on sediment yield at the watershed scale

The average annual sediment yield of the study watershed for the period 2016 to 2021 at the baseline Scenario A was 14.05 ton/rai/year. The implementations of Scenario B, Scenario C, and Scenario D have reduced the mean annual sediment yield to 12.86, 8.58, and 4.39 ton/rai/year respectively (Figure 9A). The highest percentage of sediment yield reduction was obtained at the implementation of Scenario B (8.42%), Scenario C (38.90%), and Scenario D (68.72%) (Figure 9B), respectively. At baseline Scenario A, the severe, very severe, and extremely severe sediment severity categories, which are soil erosion, accounted for about 69.44% of the watershed. Hence, the slight and moderate sediment-affected class covers only 30.56% of the total area. In Scenario B, the severe, very severe, and extremely severe sediment severity or soil erosion affected classes accounted for about 60.03% of the SS-SW area. Hence, the slight and moderate sediment-affected class covers only 39.97% of the total area. It is also indicated that in the implementation of Scenario C, the only SW-21 was the extremely severe and very severe 4 SW (SW-15, SW-17, SW-18, and SW-19) including severe sediment severity represented about 4.24%, 7.90%, and 31.56% of the SS-SW area, respectively. Similar to Scenario D, there are no areas within the extremely severe sediment severity category. Conversely, soil erosion, which are areas affected by the very severe and severe sediment severity categories in this case, represented about 8.07% of the SS-SW area. In Scenario D, the moderate and slight sediment severity class represented about 91.93%. Therefore, Scenario D has shown better sediment reduction efficiency than Scenario B and Scenario C at the watershed scale. In the same manner, the sediment reduction efficiency of Scenario C is better than Scenario B at the watershed scale.

Table 7. A classification of sediment severity classes in Thailand

Class	Level	A		CER	Scenario (Area in %)			
		(ton/ha/yr)	(ton/rai/yr)	(mm/yr)	A	B	C	D
1	Slight	0.00 - 12.50	0.00 - 2.00	0.00 - 0.96	16.22	16.22	30.56	44.94
2	Moderate	12.51 - 31.25	2.01 - 5.00	0.97 - 2.40	14.34	23.75	25.71	46.99
3	Severe	31.26 - 93.75	5.01 - 15.00	2.41 - 7.20	16.60	30.52	31.56	3.80
4	Very severe	93.76 - 125.00	15.01 - 20.00	7.21 - 9.60	40.76	22.66	7.90	4.26
5	Extremely severe	> 125.00	> 20.00	> 9.60	12.08	6.86	4.26	-
		Total			100.00	100.00	100.00	100.00

Remark: Soil loss tolerance (Permissible soil loss) = 2 ton/rai/yr, CER = 0.96 mm/yr
Sources: Land Development Department (2002)

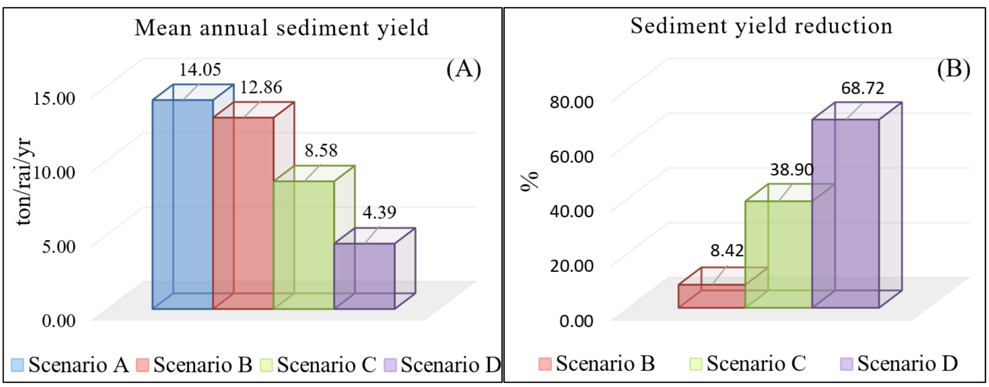


Figure 9. Mean annual sediment yield of BMPs scenarios (A) and sediment yield reductions (%) compared to the scenarios (B)

The implementations of the three considered BMPs (Scenario B, C, and D) in this study have reduced the sediment yield by 8.42, 38.90, and 68.72%, respectively. The variation of sediment yield is more sensitive to terrain slopes. The result is aligned with the findings of previous studies in the highlands of the world. For example, Lemma *et al.* (2019) study in the Lake Tana Sub-Watershed has also indicated that the implementation of stone/soil bunds on cultivated lands, grasslands, and shrublands that are located above 8% slope gradient minimized sediment yield by 61%. The implementation of stone/soil bunds on all cultivated lands of the Gumara Watershed has also decreased sediment yield by 30.5% (Gashaw *et al.,* 2021). Reforestation of cropland and bare land on the slope above 30% reduced the sediment yield of the Lake Tana Sub-Watershed by 61% (Lemma *et al.,* 2019), respectively.

3.5 The effects of BMPs on sediment yield at the sub-watershed scale

The sediment reduction efficiency of each scenario against the baseline Scenario A at SW of SS-SW. The mean annual sediment yield of SW in the SS-SW at the implementations of Scenario B ranges from 0.5 to 27.87 ton/rai/year. Scenario B has changed the sediment severity classes of SW-15 and SW-11 from extremely severe to very severe, and SW-10, SW-12, and SW-20 from very severe to severe sediment severity categories. The application of Scenario B has also changed SW-4 and SW-13, from severe to moderate sediment severity categories, respectively. However, the application of Scenario B did not change the sediment severity classes of SW-1, SW-2, SW-3, SW-5, SW-6, SW-9, SW-17, SW-19, and SW-21, respectively. The sediment reduction efficiency of Scenario B ranges between 1.5% in SW-2 to 12.3% in SW-11 (Figure 10A). The implementation of Scenario C provides a mean annual sediment yield between 0.45 to 20.03 ton/rai/year. Scenario C has reduced the areas experienced by the extremely severe, very severe, and severe sediment severity categories to moderate and slight sediment severity levels. The sediment reduction efficiency at the application of Scenario C ranges from 10.25% to 67.49% (Figure 10B). The maximum sediment yield reductions were obtained in SW-20, in which the area is covered by cultivated land.

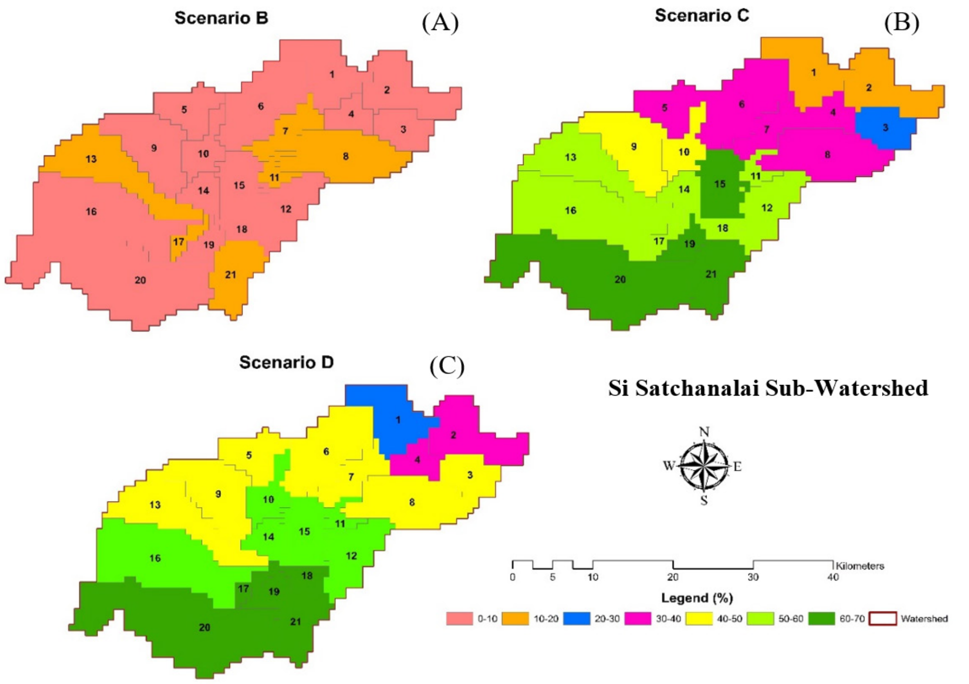


Figure 10. Sediment yield reduction (%) at the implementations of Scenario B (A),Scenario C (B), and Scenario D (C) at a sub-watershed scale of the Si Satchanalai Sub-Watershed

In contrast, the lowest sediment reduction in SW-2 is because it is covered with forest and slopes higher than 30%. Similar to Scenario D, the mean annual sediment yield of the study area at the implementations of Scenario D is between 0.98 to 15.45 ton/rai/year. The implementation of Scenario D has changed the areas affected by the extremely severe, very severe, severe, moderate, and slight sediment severity categories. The application of Scenario D has also changed the extremely severe sediment severity affected areas into very severe (SW-21), severe (SW-17 and SW-19), and moderate (SW-11 and SW-15) sediment categories, respectively. The sediment reduction efficiency of Scenario D is between 28.64 to 68.89% (Figure 10C).

When compared to the simulations of the effectiveness of three BMPs for reducing soil erosion, it was found that Scenario D is more efficient for Scenario B and Scenario C. This study is consistent with many previous studies. Although Scenario D is effective at the watershed scale compared to Scenario B and Scenario C, it is not effective in all SW for reducing the ongoing soil erosion in the study area. On the other hand, for some SW, Scenario C has a better sediment reduction effect compared to Scenario D (SW-13 and SW-15). Thus, suggestions of effective BMPs for each SW, since implementing the suggested effective BMPs in the SW at the same time is impractical, prioritizations of SW are imperative. The first prioritization for implementing the effective BMPs should be made to the remaining erosion-vulnerable SW.

4. Conclusion

Soil erosion is a fundamental environmental problem in SS-SW and other watersheds, which is causing onsite and offsite negative impacts. Therefore, this study identified soil erosion of the SS-SW and evaluated the effectiveness of Scenario B, Scenario C, and Scenario D against the baseline Scenario A for reducing ongoing soil erosion using the SWAT model. The result indicated that about 69.44% of the SS-SW are erosion, which experienced a mean annual sediment yield higher than 18.77 ton/rai/year. The mean annual sediment yield of the study area is approximately 14.05 ton/rai/year. The implementation of Scenario B, Scenario C, and Scenario D reduced the baseline Scenario A sediment yield by 8.42%, 38.90%, and 68.72% at the watershed scale, respectively. At the SW levels, the sediment reduction efficiency of Scenario B ranges between 1.5% (SW-2) to 12.30% (SW-11). On the other hand, the applications of Scenario C and Scenario D reduced the mean annual sediment yield from 10.25% (SW-2) to 67.14% (SW-20) and 28.64% (SW-1) to 68.89% (SW-21), respectively. Though Scenario D has shown better sediment reduction efficiency than Scenario B and Scenario C at the watershed scale, Scenario D is not effective in all erosion-vulnerable SW. Thus, implementing the suggested BMPs for each soil erosion are fundamental. The identified effective BMPs in this study can be used for reducing soil erosion in the highlands, which have similar environmental settings. It also recommends further studies on the negative effects of BMPs when applied to reduce ongoing soil erosion in the watershed. This affects people living in the SS-SW, as well as surrounding areas and all living things. To reduce the environmental degradation of the watershed, a systematic plan and policy will be needed to focus on offering technical assistance to farmers in selecting soil and water conservation practices that are best suited to their local conditions. Furthermore, the decision-makers or watershed managers should involve stakeholders to support improved BMPs for balanced and sustainable natural resources.

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