Journal for the Agriculture, Biotechnology and Education, 5(2), 65-78, Dec 2025
e-ISSN: 2754-7825
jabedu.com

Young Wise Publishing
youngwisepub.com
© 2025

Research Article

Community resilience and climate change adaptation based on soil erosion assessment: A case study at Loei

Jeerasak Treedat[1]* and Nirundorn Khamnu[2]

Association for Conserving and Developing the Petchaboon Range (ACDEP), Phetchaboon province, Thailand

Article Info

Received: 17 October 2025
Accepted: 20 December 2025
Online: 30 December 2025

Keywords
Climate change adaptation
Pung–Mun watershed
Soil erosion assessment

2754-7825 / © 2025 The Authors. Published by Young Wise Pub. Ltd. This is an open access article under CC BY license.

Abstract

This study investigates community resilience and adaptation strategies to mitigate the impacts of climate change, with a particular focus on soil erosion in vulnerable agricultural landscapes. Employing a Participatory Action Research (PAR) approach within the Thai Prachapijai (Participatory Research and Development: PR&D) framework, the research integrates scientific analysis with community-based problem-solving processes. Twenty community participants from climate-affected areas were actively engaged in data collection, experimentation, and knowledge exchange. The study compares agricultural plots with and without soil conservation measures to evaluate the effectiveness of erosion control practices. Eight experimental plots, each measuring one cubic meter in width, length, and depth, were established to quantify annual soil loss. Four plots were located in the upstream Man River area (Ban Mak Khaeng, Kok Sathon Subdistrict), characterized by steep-slope cultivation, while the remaining four plots were situated in the Phung Phung basin, where soil conservation practices have been implemented. Over a three-year observation period, key variables—including rainfall intensity, vegetation management, soil conservation techniques, slope gradient, soil properties, and erosion risk—were systematically monitored and analyzed. Annual soil loss data were processed to estimate erosion rates and generate spatial maps illustrating erosion severity across the study areas. The results enable identification of critical factors influencing soil erosion and assessment of the effectiveness of conservation interventions. The findings are disseminated to local communities to strengthen adaptive capacity, enhance evidence-based decision-making, and promote sustainable land management practices. Ultimately, this research contributes to practical strategies for improving soil conservation, enhancing community resilience, and reducing climate change vulnerability in smallholder agricultural systems.

To cite this article

Treedat, J., & Khamnu, N. (2025). Community resilience and climate change adaptation based on soil erosion assessment: A case study at Loei. *Journal for the Agriculture, Biotechnology and Education, 5*(2), 65-78. DOI: https://doi.org/10.5281/zenodo.18391614

Introduction

Climate change has emerged as a critical global challenge affecting food security, ecosystem stability, and the sustainability of agricultural communities, particularly in developing countries that are highly vulnerable to increasing climate variability and extreme weather events. Intensified rainfall, shifting precipitation patterns, and land-use pressures accelerate soil degradation and soil erosion processes, thereby undermining agricultural productivity and ecosystem services (IPCC, 2022; FAO, 2023). In Thailand, a substantial proportion of agricultural land is located in

1 Corresponding Author: Association for Conserving and Developing the Petchaboon Range (ACDEP), Phetchaboon province, Thailand. E-mail: dewjee9@gmail.com
2 Department of Sociology and Anthropology, Faculty of Humanities and Social Sciences, Mahasarakham University, Mahasarakham province, Thailand. E-mail: nirundorn.k@msu.ac.th

sloping and erosion-prone areas. National soil resource assessments indicate that more than half of the country's land area exhibits physical or chemical limitations for agricultural use or lies within complex mountainous terrains requiring careful soil management (Land Development Department, 2023). Continuous reliance on chemical fertilizers in intensive farming systems further exacerbates soil quality deterioration and chemical accumulation risks (Department of Agriculture, 2022).

Long-term erosion assessments reveal that although most areas experience low average soil loss, certain lowland and upland regions exhibit moderate to severe erosion risks, closely associated with rainfall intensity, topographic characteristics, and inappropriate land-use practices. These patterns align with broader trends observed across Southeast Asia under climate change conditions (Shrestha et al., 2021; Panagos et al., 2022). At the community level, the concepts of community resilience and climate change adaptation have gained increasing recognition as essential frameworks for reducing vulnerability and enhancing adaptive capacity in agricultural systems. Participatory approaches that integrate local knowledge, experiential learning, and evidence-based decision-making are increasingly emphasized for sustainable land and water management (Folke et al., 2021; Tanner et al., 2022).

Nevertheless, many existing studies primarily focus on technical modeling or macro-scale assessments, while empirical studies that integrate field-based soil erosion measurements with participatory learning processes at the community scale remain limited, particularly in mountainous watershed contexts of Thailand. This study therefore aims to enhance community resilience and climate change adaptation through a participatory action research (PAR) approach under the Thai Prachapijai (Participatory Research and Development: PR&D) framework. The research empirically quantifies soil loss in agricultural plots with and without conservation measures in the Pung–Mun watershed, Dansai District, Loei Province, Thailand. The findings are expected to strengthen community-based decision-making, improve adaptive land management strategies, and support sustainable agricultural development under changing climatic conditions.

Objectives

- To collect and analyze soil loss data influenced by human activities and rainfall intensity under climate change conditions.
- To compare the magnitude and characteristics of soil erosion between agricultural plots with soil conservation measures and those without conservation practices.
- To synthesize and propose site-specific strategies for reducing soil loss and promoting sustainable soil management in agricultural areas.

Research Problem

This study addresses one main research question and four sub-research questions as follows: What are the key drivers of soil erosion and spatial patterns of soil loss in the Pung and Man watersheds and adjacent agro-ecological landscapes? The sub-questions investigate:

- How does land-use conversion to monoculture agriculture influence soil erosion rates?
- What is the relationship between rainfall variability and soil loss under climate change conditions?
- How do slope gradient, soil properties, and geological characteristics affect soil erosion susceptibility?
- Which soil and water conservation measures are most effective and context-appropriate for reducing soil erosion in the Pung and Man watersheds?

Method

Research Design

This study employed a Participatory Research and Development (PR&D) framework integrated with Participatory Action Research (PAR). The approach emphasizes active community engagement throughout problem identification, field data collection, experimental implementation, and knowledge synthesis, aiming to strengthen local adaptive capacity to climate change while generating empirical scientific evidence.

Study Area and Study Period

The study was conducted in the Pung and Man watersheds, Dansai District, Loei Province, Thailand. The region is characterized by upland terrain with slope gradients ranging approximately from 25° to 50°, making it highly susceptible to soil erosion. Data collection was carried out over a three-year period from July 1, 2020, to June 30, 2023, allowing assessment of interannual variability in rainfall patterns and soil erosion dynamics.

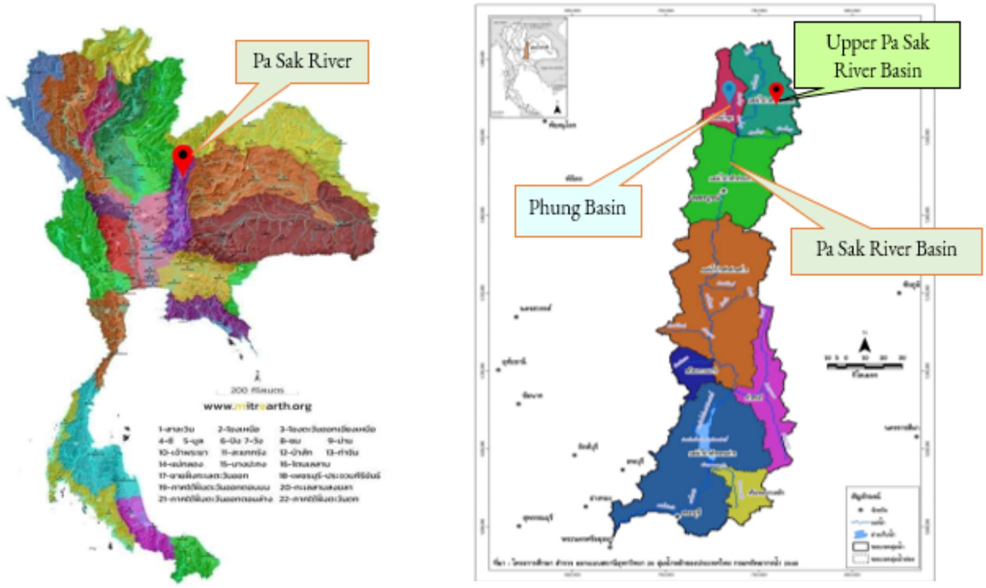

Figure 1. Location of the study area in Dansai district, Loei province, Thailand

Research Instruments

Data collection instruments included:

- rain gauges for measuring rainfall amount and intensity;
- soil sampling tools (spades, knives, measuring tapes, and sample containers);
- field tools for recording crop growth and yield;
- measuring rods for monitoring surface soil level changes; and
- leveling materials for defining plot boundaries and ensuring consistent plot conditions.

Soil Loss Monitoring Protocol

Soil loss from each experimental plot was monitored continuously and aggregated annually. After each significant rainfall event, eroded soil and sediment accumulated within plot boundaries and downslope collection zones were collected. Samples were air-dried and oven-dried at 105°C until constant weight was achieved. Dry mass was measured using a digital balance and recorded in kilograms.

Annual soil loss per plot was calculated by summing dry sediment mass from all rainfall events and converting values to soil loss rates (t ha^{-1} yr^{-1}) based on plot surface area and bulk density conversion factors. Surface soil level changes were verified using fixed reference markers installed in each plot.

Quality control included duplicate weighing, routine calibration of balances and rain gauges, and cross-checking field records by both researchers and community co-researchers.

Universal Soil Loss Equation (USLE) Factor Estimation

Annual soil loss was estimated using the Universal Soil Loss Equation (USLE):

$$A = R \times K \times LS \times C \times P$$

where A is average annual soil loss (t ha^{-1} yr^{-1}), R is rainfall erosivity, K is soil erodibility, LS is sloping length and steepness, C is cover-management, and P is supporting practice factor.

- R factor: Derived from on-site rain gauge data and nearby meteorological stations using regional erosivity equations for tropical monsoon climates.

- K factor: Determined from soil texture, organic matter, structure, and permeability using standard erodibility nomographs.
- LS factor: Calculated from field slope measurements and digital elevation models (DEM) using GIS-based analysis.
- C factor: Assigned based on crop type, vegetation cover, and seasonal management practices.
- P factor: Determined according to conservation practices such as contour farming, vegetative barriers, bamboo stabilization, mulching, and reduced tillage.

USLE estimates were compared with measured soil loss to support model validation.

Data Analysis and Spatial Mapping

Comparative analysis was conducted between conserved and non-conserved plots. Correlation analysis was applied to examine relationships between erosion drivers and soil loss. Spatial analysis was performed using Geographic Information Systems (GIS) to generate erosion severity maps and visualize spatial patterns.

Data Reliability and Validation

Data reliability was ensured through standardized protocols, periodic instrument calibration, triangulation between measured data and USLE estimates, and participatory verification with community co-researchers. Annual datasets were reviewed for anomalies and missing values prior to analysis.

Ethical Considerations

All participants provided informed consent prior to participation. Personal identifiers were anonymized in all datasets and publications. Participation was voluntary, and participants could withdraw at any time without consequence.

Operational Definitions

For clarity and consistency, key terms used in this study are defined as follows.

Soil erosion and soil loss. Soil erosion refers to the detachment and transport of soil particles by rainfall impact and surface runoff processes. Soil loss in this study specifically refers to the measured mass of detached surface soil collected from experimental plots and expressed as annual soil loss rates (t ha^{-1} yr^{-1}).

Soil and water conservation measures. Soil and water conservation measures refer to physical and biological practices applied to reduce runoff, enhance soil stability, and minimize soil erosion, including vegetative cover, reduced tillage, bamboo stabilization, mulching, contour-based practices, and agroforestry systems implemented in the study sites.

Climate change. Climate change refers to long-term alterations in average weather patterns, including temperature, precipitation, and the frequency and intensity of extreme events, driven by both natural variability and anthropogenic influences.

Climate change adaptation and community resilience. Climate change adaptation refers to adjustments in agricultural practices, land management, and community systems to reduce vulnerability and enhance adaptive capacity to climate-related risks. Community resilience refers to the ability of local communities to anticipate, absorb, adapt to, and recover from climate-related disturbances through participatory learning and adaptive management practices.

Green infrastructure (optional). Green infrastructure refers to strategically managed natural and semi-natural ecosystems that provide ecosystem services such as erosion control, carbon sequestration, biodiversity conservation, and disaster risk reduction.

Results

General Characteristics of the Study Area

The study area is located in Dansai District, Loei Province, northeastern Thailand, covering Pong and Kok Sathon subdistricts. The total study area is approximately 450 km^2, comprising 12 target villages. The landscape is predominantly mountainous with elevations ranging from 700–800 m above sea level and reaching over 1,700 m in parts of Kok Sathon.

Geologically, the area is dominated by the Sao Khua Formation (Jsk), consisting mainly of siltstone, mudstone, and sandstone, covering approximately 374.81 km^2. Secondary formations include the Phu Phan Formation (Kpp) and Phu

Kradung Formation (Jpk), which exhibit different weathering and erosion susceptibilities, influencing slope stability and landslide occurrence.

The regional climate is controlled by tropical monsoon systems with three distinct seasons: rainy (June–October), cool (November–February), and hot (March–May). Average annual rainfall ranges from approximately 1,100–1,200 mm, with peak rainfall occurring in September. Plot-level observations (2019–2021) indicate an average annual cumulative rainfall of approximately 1,540 mm and a mean annual temperature of 24.6°C, reflecting high moisture availability and rainfall variability conducive to soil erosion processes.

Soil resources are dominated by Soil Group 62, accounting for approximately 58.93% of the district area. These soils occur on steep mountainous terrain (>35% slope), are generally shallow with exposed rock fragments, and exhibit limited suitability for monoculture cropping, resulting in high erosion susceptibility. Soil Group 29 is the secondary dominant soil type, occurring on gently to moderately sloping terrain (3–25%) with greater agricultural potential.

Groundwater potential in both sub-districts ranges from moderate to high, with many areas capable of yielding 2–10 $m^3 h^{-1}$, supporting agricultural water supply during dry periods.

The study area is highly exposed to multiple natural hazards, particularly landslides and soil erosion. Approximately 67.64% of Dansai District is classified as landslide-prone. Both Pong and Kok Sathon subdistricts exhibit moderate to high landslide and erosion susceptibility. In addition, drought risk ranges from low to moderate due to seasonal rainfall variability and limited water storage infrastructure.

Overall, the combined effects of steep topography, erodible geological formations, monsoon-driven rainfall variability, and vulnerable soil conditions highlight the high sensitivity of the Pung and Man watersheds to soil erosion and climate-related risks, providing a suitable setting for evaluating conservation effectiveness and community-based adaptation strategies.

Geo-social Mapping and Participatory Water Management

Findings indicate that the Geo-social Map for integrated community-based water management serves as a practical participatory planning tool. The mapping process enhances community understanding of local environmental settings, water resources, and flood–drought problems, while systematically capturing community needs and recommendations. The resulting datasets support the development of an actionable, multi-agency action plan at village and subdistrict levels. Importantly, soil erosion risk information can be integrated as a core thematic layer within geo-social mapping to strengthen risk communication and guide context-appropriate soil and water conservation planning.

Spatial and Temporal Patterns of Soil Erosion Severity in the Man and Phung Watersheds

This section presents the spatial distribution and temporal dynamics of soil erosion severity in the Man and Phung watersheds based on multi-year erosion assessments and comparative analysis. The results summarize changes in erosion intensity across different severity classes, highlighting patterns of low-, moderate-, and high-risk areas over time. Comparative analysis between watersheds further illustrates how geomorphological conditions, land-use practices, and conservation interventions influence erosion trajectories. The findings provide an empirical basis for identifying erosion hotspots, evaluating long-term trends, and supporting evidence-based soil and water conservation planning at the watershed scale.

Table 1. Soil erosion severity in the man sub-watershed (2002 vs. 2020)

Class	Severity Level	Soil Loss ($t\ ha^{-1}\ yr^{-1}$)*	Area 2002 (ha)	2002 (%)	Area 2020 (ha)	2020 (%)
1	Very low	0–2	184,787	47.59	152,229	39.21
2	Low	2–5	55,104	14.19	70,430	18.14
3	Moderate	5–15	148,380	38.22	60,097	15.48
4	Severe	15–20	0	0.00	13,508	3.48
5	Very severe	>20	0	0.00	92,007	23.70
Total			**388,271**	**100.00**	**429,587**	**100.00**

Note: Original data reported in rai; values retained for consistency with official datasets.

The results indicate a substantial shift from low and moderate erosion classes toward higher severity levels over time. Areas classified as severe and very severe erosion increased markedly in 2020 compared with 2002, reflecting intensifying erosion pressure in steep upland zones. This trend suggests growing vulnerability of the Man sub-watershed to accelerated soil loss, potentially driven by land-use changes and increased rainfall intensity.

Table 2. Soil erosion severity in the Phung sub-watershed (2001, 2013, and 2020)

Class	Severity Level	Soil Loss ($t\ ha^{-1}\ yr^{-1}$)	2001 (%)	2013 (%)	2020 (%)
1	Very low	0–2	42.37	44.32	55.80
2	Low	2–5	8.72	9.02	16.99
3	Moderate	5–15	7.13	17.26	10.87
4	Severe	15–20	1.66	1.46	2.69
5	Very severe	>20	40.12	27.94	13.65
Total			**100.00**	**100.00**	**100.00**

Table 2. The Phung sub-watershed exhibited a general decline in areas classified as very severe erosion over time, accompanied by an expansion of low and very low erosion classes. These trends suggest improved land management effectiveness and gradual stabilization of erosion processes, likely associated with the adoption of soil and water conservation practices and vegetation recovery.

Table 3. Comparison of soil erosion severity between the Phung sub-watershed and the upper Pa Sak Watershed in 2013 and 2020

Class	Severity Level	Soil Loss ($t\ ha^{-1}\ yr^{-1}$)	Phung 2013 (%)	Upper Pa Sak 2013 (%)	Phung 2020 (%)	Upper Pa Sak 2020 (%)
1	Very low	0–2	44.32	30.60	55.80	50.95
2	Low	2–5	9.02	32.55	16.99	11.21
3	Moderate	5–15	17.26	10.02	10.87	10.92
4	Severe	15–20	1.46	3.07	2.69	2.46
5	Very severe	>20	27.94	23.76	13.65	24.46
Total			**100.00**	**100.00**	**100.00**	**100.00**

Table 3. Percentages represent the proportion of total watershed area falling within each soil erosion severity class derived from USLE-based raster classification and GIS spatial overlay analysis. Soil loss thresholds are expressed in tons per hectare per year ($t\ ha^{-1}\ yr^{-1}$). The table enables comparison of spatial distribution and temporal shifts in erosion risk between the Phung sub-watershed and the Upper Pa Sak watershed for the years 2013 and 2020. Minor discrepancies in totals may occur due to rounding.

Table 4. Summary trend of high-risk erosion areas (severe + very severe)

Watershed	Year	Severe (%)	Very Severe (%)	Severe + Very Severe (%)	Trend Interpretation
Man Sub-watershed	2002	0.00	0.00	0.00	Baseline low risk
	2020	3.48	23.70	27.18	▲ Sharp increase
Phung Sub-watershed	2001	1.66	40.12	41.78	Historically high risk
	2013	1.46	27.94	29.40	▼ Decreasing
	2020	2.69	13.65	16.34	▼ Continued decline
Upper Pa Sak Watershed	2013	3.07	23.76	26.83	Relatively stable
	2020	2.46	24.46	26.92	Relatively stable

Table 4. Percentages indicate the proportion of total watershed area classified as high-risk erosion zones, defined as the combined Severe (15–20 $t\ ha^{-1}\ yr^{-1}$) and Very Severe (>20 $t\ ha^{-1}\ yr^{-1}$) soil loss classes derived from USLE-based raster classification and GIS spatial overlay analysis. Trend interpretation summarizes temporal changes in the extent of high-risk erosion areas across monitoring periods for each watershed. Arrows denote increasing (▲) or decreasing (▼) trends. Slight discrepancies in totals may occur due to rounding.

Two representative study areas were selected as experimental sites to monitor soil loss from surface erosion processes over a three-year period. These sites represent the headwater environments of the Man and Phung watersheds, capturing contrasting landscape characteristics, slope gradients, land use patterns, and erosion susceptibility. As presented in Table 5, the experimental plots were designed to reflect spatial variability in upland agricultural fields and community forest systems. Field-based measurements of sediment loss provide empirical evidence that complements watershed-scale erosion modeling, allowing evaluation of localized erosion dynamics, temporal variation, and the effectiveness of site-specific land management and soil conservation practices. The results presented in the table contribute to a detailed understanding of micro-scale soil erosion behavior within headwater ecosystems.

Study Sites:

- Ban Makkhaeng Yensira (Village No. 4, Koksathon Subdistrict, Dansai District, Loei Province) – Representative of the Man headwater area (8 experimental plots). (T1-T4)
- Ban Nam Phung (Village No. 3, Pong Subdistrict, Dansai District, Loei Province) – Representative of the Phung headwater area (4 experimental plots). (T5-T8)

Table 5. Soil loss from experimental plots in representative villages of the man and Phung headwaters (three-year observation)

Plot ID	Plot Location and Land Use Description	Average Slope (C°)	Erosion Severity Class	Soil Loss (m^3) Year 1	Soil Loss (m^3) Year 2	Soil Loss (m^3) Year 3	Observed Erosion Characteristics
T1	Agricultural plot, Ban Makkhaeng, Huai Dong Nguek (Man headwater tributary)	40–50	Very low	0.10	0.05	0.05	Minor surface runoff erosion
T2	Agricultural plot, Ban Makkhaeng, Huai Tham Men	35–50	Very low	0.05	0.05	0.05	Stable soil surface
T3	Agricultural plot, Ban Makkhaeng, Huai Tham Men	35–50	Severe	Sinkhole formation	0.50	Sinkhole	Localized soil collapse
T4	Agricultural plot, Ban Makkhaeng, Huai Tham Men	35–50	Very severe	Large sinkhole	Sinkhole expansion	Further expansion	Progressive land instability
T5	Agricultural plot, Ban Thung Thoeng (Phung headwater)	~35	Very low	0.10	0.05	0.05	Minor sheet erosion
T6	Agricultural plot, Ban Nam Phung	25–35	Low	0.10	0.25	0.20	Seasonal runoff erosion
T7	Agricultural plot, Ban Nam Phung	25–35	Low	0.10	0.30	0.20	Concentrated flow erosion
T8	Community forest plot, Ban Nam Phung	25–35	Very severe	1.00	1.00	1.00	

Overall Soil Loss Patterns: Across the three-year monitoring period, experimental plots exhibited substantial variability in soil loss magnitude and erosion mechanisms, reflecting differences in slope gradient, land use, vegetation cover, and subsurface stability.

- Very low erosion plots (T1, T2, T5) consistently showed minimal soil loss (≤0.10 m^3 per year), indicating that stable ground cover and moderate runoff control can effectively suppress erosion even on steep slopes (35–50°).
- Low erosion plots (T6, T7) demonstrated moderate fluctuation in soil loss (0.10–0.30 m^3), likely driven by seasonal rainfall variability and localized flow concentration.
- Severe and very severe plots (T3, T4, T8) exhibited nonlinear erosion behavior characterized by sinkhole formation, mass soil displacement, and persistent high soil loss (>1.0 m^3 annually in T8), highlighting the influence of subsurface instability and concentrated hydrological pathways.

Spatial Differences between Headwater Zones:

Man Headwater (Ban Makkhaeng Yensira)

- Plots T1 and T2 remained stable despite steep slopes (40–50°), suggesting that appropriate land management and vegetation cover can mitigate erosion risk.

- In contrast, plots T3 and T4 experienced severe erosion due to sinkhole development and progressive subsurface collapse, indicating geological vulnerability rather than surface slope alone as the dominant erosion driver.

Phung Headwater (Ban Nam Phung)

- Agricultural plots (T5–T7) showed low to moderate soil loss, reflecting relatively better soil structure and drainage stability.
- The community forest plot (T8) exhibited consistently high soil loss despite vegetative cover, implying that geomorphological conditions (e.g., shallow soils, fractured bedrock, or subsurface flow concentration) may override surface vegetation protection.

Temporal Trends (Three-Year Observation)

- Several plots demonstrated declining soil loss over time (T1, T5), possibly due to natural soil surface stabilization and minor conservation practices.
- Some plots showed fluctuating trends (T6, T7), indicating sensitivity to interannual rainfall variability.
- Severe plots exhibited progressive degradation rather than linear trends (T3, T4), reinforcing the need for structural interventions rather than solely agronomic measures.

The three-year experimental monitoring revealed strong spatial heterogeneity in soil erosion dynamics across representative headwater villages. Plots classified as very low erosion consistently recorded minimal soil loss (<0.10 m^3 yr^{-1}), even under steep slope conditions, highlighting the effectiveness of surface cover and stable land management practices. Conversely, plots exhibiting severe and very severe erosion displayed nonlinear degradation patterns dominated by sinkhole formation and mass soil displacement, indicating that subsurface geological instability plays a critical role beyond surface slope and vegetation cover.

Moderate erosion plots showed temporal variability associated with rainfall intensity and runoff concentration, underscoring the sensitivity of upland agricultural systems to climatic fluctuations. The contrasting responses between the Man and Phung headwater areas further emphasize the importance of site-specific conservation strategies rather than uniform watershed-wide interventions.

The following figures present representative photographs documenting three years of field observations (Year 3) of soil erosion processes and sediment yield across experimental plots T1–T8. These plots are located in two headwater areas of Dan Sai District, Loei Province: Ban Makkhaeng Yensira (Man watershed; T1–T4) and Ban Nam Phung (Phung watershed; T5–T8). The visual evidence captures contrasting erosion responses—including surface runoff patterns, sediment displacement, and sinkhole development—under varying slope conditions, vegetation cover, and conservation measures. These images provide qualitative support for the quantitative research analysis and illustrate the temporal evolution of land stabilization and erosion dynamics within their specific environmental and management contexts.

Ban Makkhaeng Yensira, Village No. 4, Koksathon subdistrict, Dansai district, Loei province

T1

T2

T3

T4

Ban Nam Phun, Village No. 3, Pong subdistrict, Dansai district, Loei province

T5

T6

T7

T8

Discussion

Comparative Dynamics of Soil Erosion under Different Watershed Contexts

The comparative analysis of soil erosion severity between the Phung sub-watershed and the Upper Pa Sak sub-watershed was not intended to determine which watershed experienced greater erosion intensity. Rather, the objective was to examine how internal biophysical conditions and land management interventions influence erosion dynamics under changing climatic conditions. Each watershed exhibits distinct controlling factors, including geological structure, slope gradient, soil depth and texture, land-use patterns, rainfall characteristics, soil moisture regimes, and geomorphological configuration. These interacting factors operate in a nonlinear manner, limiting direct one-to-one comparisons between watersheds (Tongdeenok, 2023).

A salient finding from this study is the substantial reduction in high-risk erosion areas (Severe + Very Severe classes) in the Phung sub-watershed between 2013 and 2020. The proportion of very severe erosion (>20 t ha^{-1} yr^{-1}) declined markedly, indicating a tangible improvement in landscape stability following the intensified implementation of soil and water conservation measures. These measures included reduced tillage practices, vegetative cover enhancement, agroforestry systems, and community-based watershed rehabilitation. Mechanistically, such interventions increase surface roughness, enhance soil aggregate stability, reduce raindrop impact energy, and improve infiltration capacity, thereby decreasing surface runoff and sediment transport.

These findings are consistent with empirical and modeling studies in Thailand and comparable tropical watersheds, which demonstrate that vegetative cover management and conservation-oriented land use can significantly reduce soil erosion rates and sediment yield (Phomcha et al., 2012; Sirikaew et al., 2020). Similar conclusions have been reported for upland agricultural landscapes, where conversion from conventional tillage to conservation agriculture improves soil structural resilience and reduces erosion susceptibility (Kongkhiaw et al., 2021).

In contrast, the Upper Pa Sak sub-watershed exhibited relatively stable but persistently high proportions of very severe erosion areas between 2013 and 2020, with a slight increase in high-risk zones. This pattern suggests that conservation interventions in this watershed may be insufficient to offset ongoing erosion drivers, such as land-use intensification on steep slopes, limited vegetative buffering, and fragmented institutional coordination. Previous watershed-scale assessments in Thailand similarly indicate that without sustained and spatially coherent conservation strategies, erosion risk tends to remain elevated even when isolated mitigation measures are implemented (Tongdeenok, 2023).

The divergent trajectories observed between the two watersheds highlight the importance of adaptive governance and locally appropriate intervention strategies. While the Phung sub-watershed demonstrates the potential effectiveness of integrated conservation practices, the Upper Pa Sak watershed underscores the risks associated with delayed or uneven implementation. These contrasting cases provide valuable opportunities for cross-watershed learning and policy transfer.

Climate Variability, Rainfall Extremes, and Implications for Erosion Risk

Climate projection analysis based on Global Climate Models (GCMs) downscaled using Regional Climate Models (RCMs) for the Dansai District indicates a consistent warming trend accompanied by increasing climate variability (Jirasorn et al., 2017). Maximum temperatures are projected to rise steadily, while minimum temperatures show an even stronger upward trend, implying higher evapotranspiration demand, increased soil moisture stress, and greater vulnerability of rainfed agricultural systems to drought conditions.

Rainfall projections reveal substantial interannual variability rather than a consistent increase in total precipitation. Although certain years may experience exceptionally high rainfall associated with flood and landslide risks, the long-term trend suggests shortening rainy seasons and increasing rainfall concentration within shorter time windows. Such rainfall concentration significantly amplifies erosion processes by increasing rainfall erosivity (R-factor in USLE), surface runoff velocity, and sediment transport capacity.

Historical climate observations from Thailand further support this pattern, showing relatively stable annual rainfall totals but a shift in seasonal distribution toward late rainy-season concentration (Land Development Department, n.d.; Thai Meteorological Department, 2025). Field observations during recent years similarly indicate shorter rainy seasons combined with higher rainfall intensity. These climatic dynamics interact with watershed characteristics to intensify erosion mechanisms through stronger raindrop impact, reduced soil infiltration capacity during extreme events, and vegetation stress during prolonged dry periods.

Previous modeling studies in Thailand have demonstrated that even modest increases in rainfall intensity can significantly elevate predicted soil loss when combined with steep slopes and shallow soils (Sirikaew et al., 2020). Therefore, climate variability acts as a critical amplifying factor that can either undermine or enhance the effectiveness of conservation interventions, depending on land management resilience.

Role of Participatory Governance and Ecosystem-Based Adaptation

A distinctive contribution of this study lies in its application of Participatory Research and Development (PR&D) and Participatory Action Research (PAR) frameworks. The observed improvements in the Phung sub-watershed cannot be attributed solely to biophysical interventions but also reflect strengthened community engagement, shared learning, and local ownership of conservation practices. Participatory approaches enhance the legitimacy, continuity, and adaptive refinement of interventions, particularly in complex upland socio-ecological systems (Sengtaweesuk et al., 2025). Moreover, the integration of ecosystem-based measures—such as riparian buffer restoration, bamboo stabilization, and agroforestry systems—aligns with emerging evidence that nature-based solutions can simultaneously reduce disaster risk, enhance ecosystem services, and strengthen climate resilience (Thai–German Cooperation, 2023). These approaches also complement spatial planning instruments, such as geo-social mapping and participatory watershed planning, which enable communities and agencies to align land management decisions with ecological constraints.

Policy Implications and Limitations

From a policy perspective, the contrasting erosion trajectories between the Phung and Upper Pa Sak watersheds emphasize the need for context-specific, long-term conservation strategies supported by institutional coordination and community participation. Scaling successful practices from the Phung watershed to other vulnerable basins may enhance regional resilience to soil degradation and climate extremes. However, several limitations should be acknowledged. Soil erosion severity was estimated using USLE-based spatial modeling and GIS raster classification, which are sensitive to rainfall data resolution, land-use classification accuracy, and parameter calibration. Consequently, the results should be interpreted as spatial risk assessments rather than exact measurements of on-site soil loss (Kongkhiaw et al., 2021; Sirikaew et al., 2020). Future research should integrate higher-resolution climate datasets, sediment monitoring, and long-term experimental plots to strengthen predictive reliability.

Overall, the combined evidence underscores the necessity of adaptive, participatory, and ecosystem-based watershed management approaches to sustain soil resources, protect agricultural productivity, and enhance climate resilience in upland regions.

Micro-scale Soil Erosion Dynamics in Headwater Experimental Plots

The three-year field monitoring of experimental plots in representative headwater villages revealed strong spatial heterogeneity in soil erosion dynamics, driven by interactions among slope gradient, land use, vegetation cover, hydrological pathways, and subsurface geological conditions. Plots classified as very low erosion (T1, T2, and T5) consistently recorded minimal soil loss (<0.10 m^3 yr^{-1}), even on steep slopes exceeding 35–50°, indicating that stable ground cover and appropriate land management can effectively suppress surface erosion (Morgan, 2005; Lal, 2015).

In contrast, severe and very severe plots (T3, T4, and T8) exhibited nonlinear degradation characterized by sinkhole formation, mass soil displacement, and progressive land instability. These patterns suggest that subsurface geomorphological vulnerability—such as shallow soils, fractured bedrock, and preferential flow paths—can dominate erosion processes beyond surface slope and vegetation effects, consistent with findings in tropical upland environments (Bryan & Jones, 1997; Valentin et al., 2005; Sidle et al., 2006).

Moderate erosion plots (T6 and T7) showed interannual variability linked to rainfall intensity and runoff concentration, reflecting the sensitivity of upland agroecosystems to climatic variability (Nearing et al., 2017; IPCC, 2021). The contrasting responses between the Man and Phung headwaters emphasize that erosion control strategies must be site-specific rather than uniformly applied at the watershed scale. While some steep agricultural plots remained stable due to effective management, adjacent plots experienced severe degradation driven by geological constraints.

Overall, the experimental evidence confirms that micro-scale field observations are essential for validating watershed-scale erosion models and for designing adaptive soil and water conservation strategies under climate change. Effective mitigation requires integrating surface management practices with targeted structural interventions in geologically sensitive areas (Renard et al., 1997; FAO, 2017; Alewell et al., 2019).

Recommendations

Implement Risk-Based Spatial Zoning for Soil Erosion Management:

Soil conservation policies should shift from slope-based criteria toward integrated risk-based spatial zoning that incorporates geological structure, soil depth, subsurface hydrology, land-use intensity, and erosion history. The experimental plots revealed that severe erosion and sinkhole development occurred even under vegetated conditions, indicating that subsurface instability can override surface protection measures. High-resolution geospatial risk mapping should therefore guide prioritization of conservation investments, land-use regulation, and infrastructure placement in headwater regions.

Integrate Structural Stabilization with Nature-Based Solutions in High-Risk Areas

In geologically vulnerable zones, conservation strategies should combine engineering stabilization measures (e.g., subsurface drainage control, reinforced terraces, contour barriers, and flow diversion structures) with biological approaches such as agroforestry, perennial vegetation, and ground cover management. While vegetative practices effectively reduced erosion in stable plots, severe erosion plots exhibited nonlinear degradation requiring structural reinforcement. Integrated hybrid solutions can enhance slope stability, reduce concentrated runoff, and improve long-term ecosystem resilience.

Strengthen Community-Based Monitoring and Adaptive Watershed Governance

Localized plot monitoring captured erosion dynamics and threshold behavior that are not fully detected by watershed-scale models. Institutionalizing community-based monitoring networks and linking them with GIS platforms can enhance early-warning capacity, validate erosion models, and support adaptive decision-making. Embedding erosion risk information into geo-social mapping and participatory planning processes will strengthen stakeholder ownership and improve long-term maintenance of conservation interventions.

References

Alewell, C., Borrelli, P., Meusburger, K., & Panagos, P. (2019). Using the USLE: Chances, challenges and limitations of soil erosion modelling. *International Soil and Water Conservation Research, 7*(3), 203–225.

Bryan, R. B., & Jones, J. A. A. (1997). The significance of soil piping processes. *Geomorphology, 20*(3–4), 209–218.

Department of Agriculture. (2022). *Sathanakan kan nam khao pui khemi khong prathet Thai* [Situation of chemical fertilizer imports in Thailand]. Ministry of Agriculture and Cooperatives.

FAO. (2017). *Voluntary guidelines for sustainable soil management*. FAO.

FAO. (2023). The state of the world's land and water resources for food and agriculture 2023. Food and Agriculture Organization of the United Nations.

FAO. (2023). *The state of the world's land and water resources for food and agriculture 2023*. Food and Agriculture Organization of the United Nations.

Folke, C., Polasky, S., Rockström, J., Galaz, V., Westley, F., Lamont, M.,. Walker, B. (2021). Our future in the Anthropocene biosphere. Ambio, 50(5), 834–869. https://doi.org/10.1007/s13280-021-01544-8.

Folke, C., Polasky, S., Rockström, J., Galaz, V., Westley, F., Lamont, M., … Walker, B. (2021). Our future in the Anthropocene biosphere. *Ambio, 50*(5), 834–869. https://doi.org/10.1007/s13280-021-01544-8.

IPCC. (2021). *Climate Change 2021: The Physical Science Basis*. Cambridge University Press.

IPCC. (2022). Climate change 2022: Impacts, adaptation, and vulnerability. Cambridge University Press.

Jirasorn, C., et al. (2017). Climate projection using global and regional climate models for northeastern Thailand. Faculty of Engineering, Ramkhamhaeng University. *(in Thai).*

Kongkhiaw, P., et al. (2021). Quantification and prediction of soil losses using the Universal Soil Loss Equation (USLE). *Naresuan University Journal of Science and Technology*, 29(3), 78–95.

Lal, R. (2015). Restoring soil quality to mitigate soil degradation. *Sustainability, 7*(5), 5875–5895.

Land Development Department. (2022). *Thailand soil status report 2022*. Land Resources Survey and Planning Division, Ministry of Agriculture and Cooperatives.

Land Development Department. (n.d.). *Thailand climate and land resource statistics*. Ministry of Agriculture and Cooperatives.

Morgan, R. P. C. (2005). *Soil erosion and conservation* (3rd ed.). Blackwell.

Nearing, M. A., Yin, S., Borrelli, P., & Polyakov, V. O. (2017). Rainfall erosivity. *Catena, 157*, 357–362.

Panagos, P., Ballabio, C., Poesen, J., Lugato, E., Scarpa, S., Montanarella, L., & Borrelli, P. (2022). Soil erosion modelling: A global review and statistical analysis. Science of the Total Environment, 823, 153522. https://doi.org/10.1016/j.scitotenv.2022.153522.

Panagos, P., Ballabio, C., Poesen, J., Lugato, E., Scarpa, S., Montanarella, L., & Borrelli, P. (2022). Soil erosion modelling: A global review and statistical analysis. *Science of the Total Environment, 823*, 153522. https://doi.org/10.1016/j.scitotenv.2022.153522

Phomcha, P., Wirojanagud, P., Vangpaisal, T., & Thaveevouthti, T. (2012). Modeling the impacts of alternative soil conservation practices for an agricultural watershed with the SWAT model. *Procedia Engineering*, 32, 1205–1213.

Renard, K. G., et al. (1997). *RUSLE handbook*. USDA.

Sengtaweesuk, A., et al. (2025). Application of GIS and participatory action research for watershed management in northern Thailand. *Journal of Environmental Management and Sustainability*. *(forthcoming / in press)*

Shrestha, R. P., Nepal, P., & Bhatta, B. (2021). Soil erosion risk assessment under climate change scenarios in Southeast Asia. Environmental Monitoring and Assessment, 193(6), 1–17.

Sidle, R. C., et al. (2006). Preferential flow systems. *Hydrological Processes, 15*(4), 633–655.

Sirikaew, U., et al. (2020). Impact of climate change on soil erosion in the Lam Phra Phloeng watershed using USLE-based approaches. *Water*, 12(12), 3527.

Tanner, T., Bahadur, A., & Moench, M. (2022). Challenges for resilience policy and practice. Climate and Development, 14(3), 189–199.

Thai Meteorological Department. (2025). *Seasonal climate outlook and rainfall statistics for Thailand*.

Thai–German Cooperation. (2023). *Lessons from piloting monitoring and evaluation of ecosystem-based adaptation (EbA) in Thailand's water sector*.
Tongdeenok, P. (2023). Watershed management and classification in Thailand. *BIO Web of Conferences*, 61, 03024.
Valentin, C., et al. (2005). Gully erosion. *Catena, 63*(2–3), 132–153.