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Sub-Watershed Prioritization for Sustainable Sediment Management in the Upper Cisokan Hydropower Catchment Using SWAT+

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ABSTRACT

Background: Sedimentation poses a critical threat to hydropower sustainability, particularly in pumped storage systems such as the Upper Cisokan Pumped Storage (UCPS) plant in West Java, Indonesia.
Aims and Methods: This study assesses the spatio-temporal dynamics of sediment yield in the Cisokan Watershed using the SWAT+ model, incorporating historical simulations (2013 and 2023) and a 2038 projection under a Business-As-Usual (BAU) scenario developed through supervised classification in Google Earth Engine (GEE).
Result: Model calibration based on observed discharge data yielded satisfactory results (NSE = 0.80 in 2013, 0.65 in 2023), validating its suitability for sediment analysis. Results reveal a nearly fourfold increase in average sediment yield from 0.61 to 2.25 tons/ha/year between 2013 and 2023, with a projected rise to 5.57 tons/ha/year by 2038. A composite prioritization index, integrating current sediment output, decadal change, and sub-watershed area, identified SW-23, SW-16, and SW-5 as the highest priority areas for erosion mitigation. These findings were validated against future projections, confirming their persistent erosion risk. The study emphasizes the importance of scenario-based watershed planning in safeguarding hydropower infrastructure. By integrating sediment modeling with scenario-based land use projection via supervised classification in Google Earth Engine (GEE), this study provides a replicable framework for proactive watershed management and hydropower sustainability planning.

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1. Introduction

Indonesia's renewable energy roadmap emphasizes the critical role of hydropower in achieving national climate targets, particularly as the country accelerates its transition toward a sustainable energy mix. Among key infrastructure projects, the Upper Cisokan Pumped Storage (UCPS) hydropower plant stands out as the first large-scale pumped storage system in the country, designed to stabilize the Java–Bali electricity grid by balancing peak and off-peak demand cycles. However, the effectiveness of this system is strongly influenced by sedimentation risks originating from the Cisokan Watershed.

Changes in land use, especially deforestation and agricultural expansion, have been shown to significantly increase sediment yield (Sadhwani *et al.*,2022; Megersa *et al.*,2020), with direct consequences on reservoir storage capacity and erosion damage to turbines (Rodriguez *et al.*,2023), underscoring the critical need for erosion management to preserve hydropower infrastructure.

Hydrological models such as SWAT+ have proven effective in simulating complex watershed processes, including erosion and sediment transport (Berhanu *et al.*,2020; Noora *et al.*,2022). Previous studies (e.g., Pusparinda & Marselina, 2025) have documented land-use impacts on sediment yield between 2013 and 2023. This study builds upon that baseline by adding a 2038 scenario projection under a Business-As-Usual (BAU) assumption using Google Earth Engine (GEE) based classification.

In addition, a composite sub-watershed prioritization framework is proposed that combines three dimensions: (1) sediment magnitude, (2) decade-long trend, and (3) contributing area size. This multi-criteria approach offers a more dynamic perspective than single-metric sediment mapping and aligns with modern risk-based watershed planning frameworks implemented in other highland basins (Berhanu *et al.*,2020; López-Pérez *et al.*,2024; Noora *et al.*,2022). The aim of this study is to assess the spatio-temporal dynamics of sediment yield in the Cisokan Watershed using the SWAT+ model.

2. Methods

This research was conducted in the Cisokan Watershed, West Java, covering the upstream Citarum Basin. It spans approximately 374 km² across West Bandung and Cianjur Regencies, characterized by steep slopes and heterogeneous land cover. Seven categories of data were used:

Table 1. Data Used.

Data	Year	Source
DEM	-	tanahair.indonesia.go.id
Soil type	-	PLN UIP JBT (FAO-class)
Land use	2013, 2023	Ministry of Environment and Forestry (KLH)
Future land use	2038	Supervised classification via GEE
Climate	2013-2023	MSWEP, ERA5
Future Climate	2038	ISIMIP database
Observed river discharge	2013-2023	Cirata Hydropower Unit

All spatial layers were projected to UTM zone 48S. Land use for 2038 was derived using GEE with classifier training based on historic LUCC transitions and calibrated accuracy via visual interpretation (Gorelick *et al.*,2017).

Due to the limited availability of mid-range climate projections in the ISIMIP platform, this study utilized SSP3-7.0 as a conservative representation of BAU conditions. While SSP2-4.5 would more closely resemble a "middle-of-the-road" scenario (O'Neill *et al.*,2017), the SSP3-7.0 pathway reflects a plausible outcome under continued land use pressure and moderate mitigation efforts (Riahi *et al.*,2017).

Watershed delineation was conducted using QSWAT+, resulting in 25 sub-watersheds and 3,830 Hydrological Response Units (HRUs). Modeling scenarios were run for 2013, 2023, and projected 2038.

Observed discharge (2013–2023) was used for model calibration. The performance was assessed using Nash-Sutcliffe Efficiency (NSE) and Kling-Gupta Efficiency (KGE). The Nash–Sutcliffe Efficiency (NSE) is used to assess the predictive skill of hydrological models and is formulated as follows (Moriasi *et al.*,2007; Furqani *et al.*, 2024):

$$NSE = 1 - \frac{\sum_{i=1}^{n}\left(Q_{obs,i} - Q_{sim,i}\right)^2}{\sum_{i=1}^{n}\left(Q_{obs,i} - \bar{Q}_{obs}\right)^2}$$

Where $Q_{obs,i}$ refers to observed discharge or sediment yield, $Q_{sim,i}$ is the simulated discharge or sediment yield, and $\bar{Q}_{obs}$ is the mean value of observed data.

The Kling–Gupta Efficiency (KGE) further evaluates model robustness by combining correlation, bias, and variability components into a single metric (Gupta *et al.*,2009):

$$KGE = \sqrt{(r-1)^2 + (\beta - 1)^2 + (\gamma - 1)^2}$$

Where r is the linear correlation coefficient between observed and simulated values, $\beta = \frac{\mu_{sim}}{\mu_{obs}}$ is the bias ratio, $\gamma = \frac{CV_{sim}}{CV_{obs}}$ is the variability ratio.

Sub-watersheds were prioritized using a composite score based on sediment yield in 2023, change from 2013–2023, and area share, with 2038 projections used to validate future consistency. Scoring followed a multi-criteria framework (Halder *et al.*,2024). The total priority score was calculated as follows:

$$Priority\ Score_i = R_{SY2023} + R_{\Delta SY} + R_{Area}$$

Where R_{SY2023} is the rank score for sediment yield in 2023, $R_{\Delta SY}$ is the rank score for sediment yield change from 2013 to 2023, R_{Area} is the rank score based on sub-watershed area proportion.

The workflow of sediment yield modeling using SWAT+ is illustrated in Figure 1.

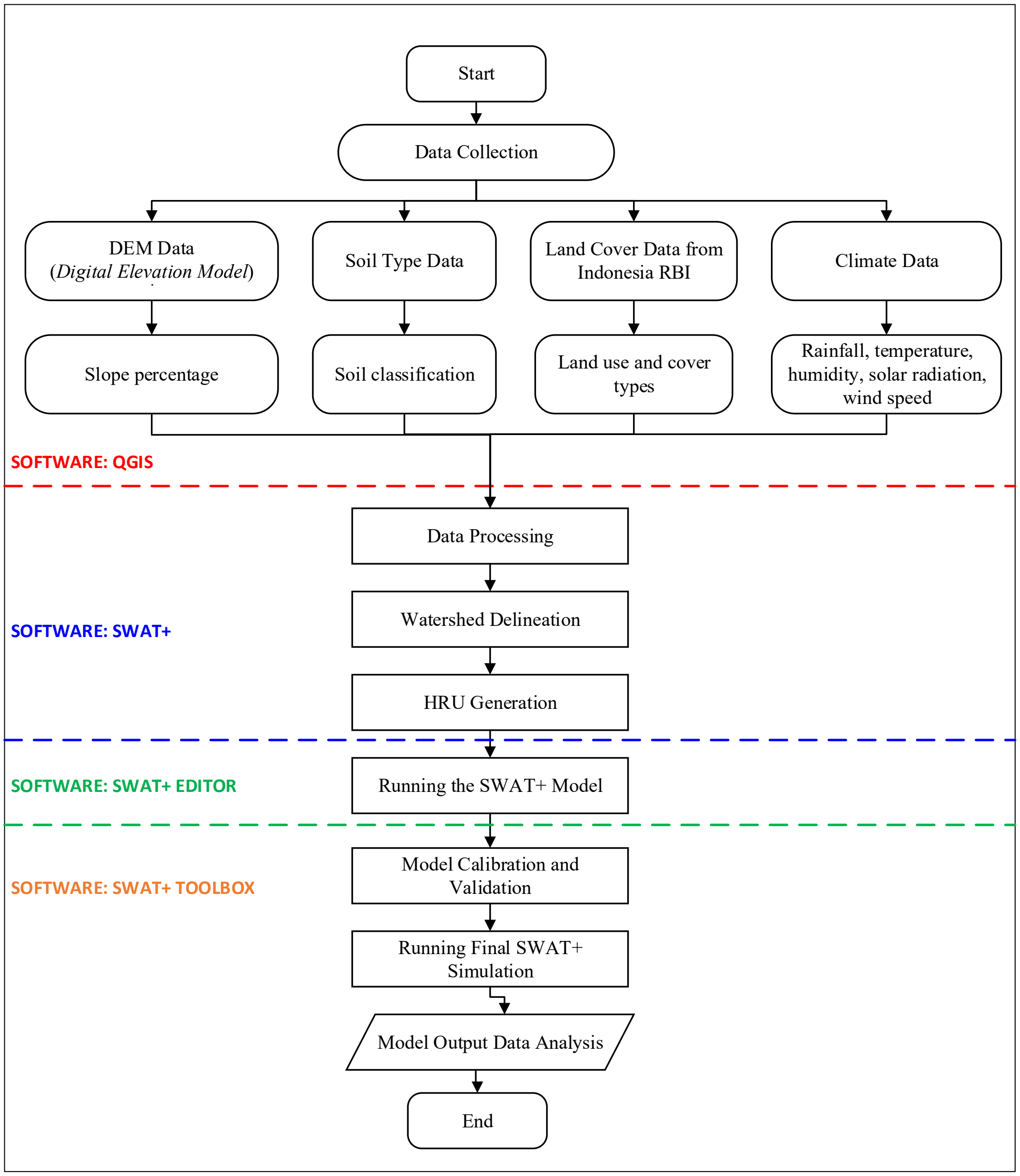

Figure 1. Research Workflow

3. Results and Discussion

3.1 Model Performance

Model calibration was conducted using observed streamflow data, as direct sediment measurements were unavailable. The SWAT+ model showed satisfactory performance (Table 1), with NSE and KGE values of 0.80 and 0.81 in 2013, and 0.65 and 0.72 in 2023, respectively. These metrics indicate that the model captures the hydrological behavior of the Cisokan Watershed with reasonable accuracy, particularly during the baseline year (Figure 2).

Streamflow-based calibration is a common approach in data-scarce regions, where sediment records are limited. Similar methods have been applied in the Xinjiang River Basin (Yuan & Forshay, 2020) and the Cantareira System in Brazil (Pontes *et al.*,2021), with reliable sediment predictions derived from calibrated flow outputs. These precedents strengthen the methodological validity of this study.

Table 1. Model performance statistics (NSE and KGE) for the calibration years.

Year	NSE	KGE
2013	0.80	0.81
2023	0.65	0.72

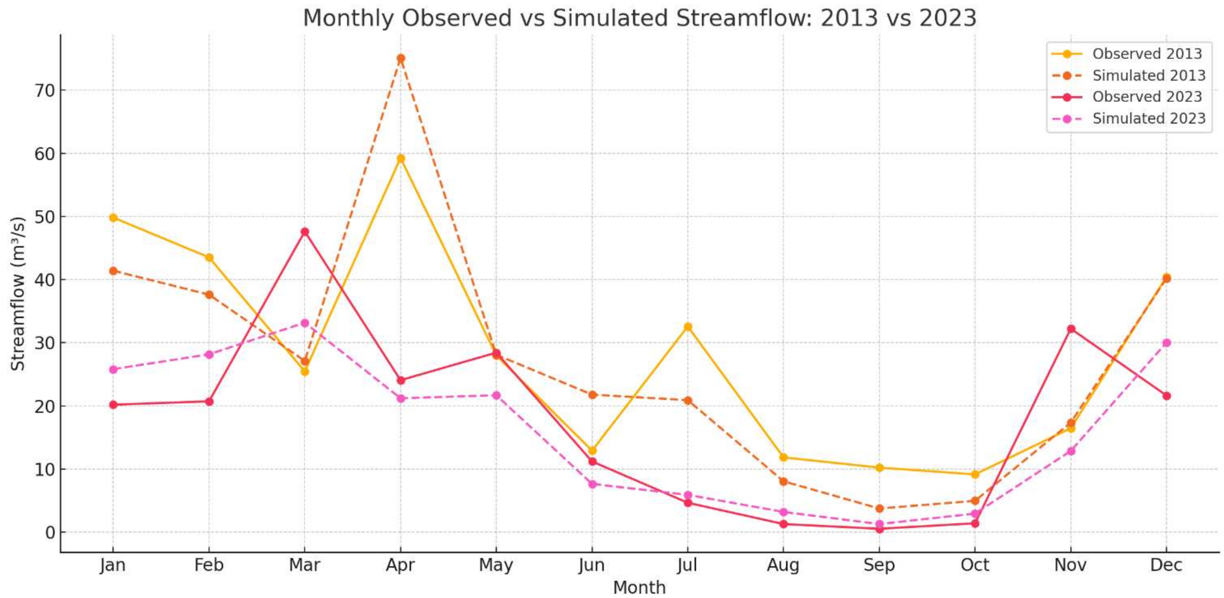

Figure 2. Comparison of observed and simulated monthly streamflow for the years 2013 and 2023

These results indicate that the calibrated model can be confidently used for further simulation of sediment yield dynamics, including long-term changes and future projections, as discussed in the following sections.

3.2 Spatio-Temporal Sediment Yield (2013–2023)

Changes in land use between 2013 and 2023 significantly affected sediment yield patterns across the Cisokan Watershed. Based on SWAT+ simulation outputs, the average annual sediment yield increased from 0.61 tons/ha/year in 2013 to 2.25 tons/ha/year in 2023.

Based on spatial distribution maps (Figure 3), sub-watersheds located in the south-central region, particularly sub-watersheds 18, 19, and 23, experienced the most significant escalation in sediment yield. These areas coincide with zones of extensive forest conversion into dryland agriculture and settlements, often occurring on steep slopes, which accelerates soil detachment and transport.

Figure 3 presents a comparative visual of the sediment yield distribution in 2013 and 2023. A noticeable expansion of localized high-yield zones (≥60 Mg/ha/year) is observed in 2023, particularly within critical sub-watersheds. It should be noted that these high-yield values represent HRU-level outputs and do not necessarily reflect sub-watershed average values, as presented in Table 2, which lists the ten sub-watersheds with the highest increase in sediment yield between 2013 and 2023. These findings emphasize the intensifying erosion risk and reinforce the importance of spatially targeted soil and water conservation interventions (Serrão *et al.,*2021; Wang *et al.,*2023).

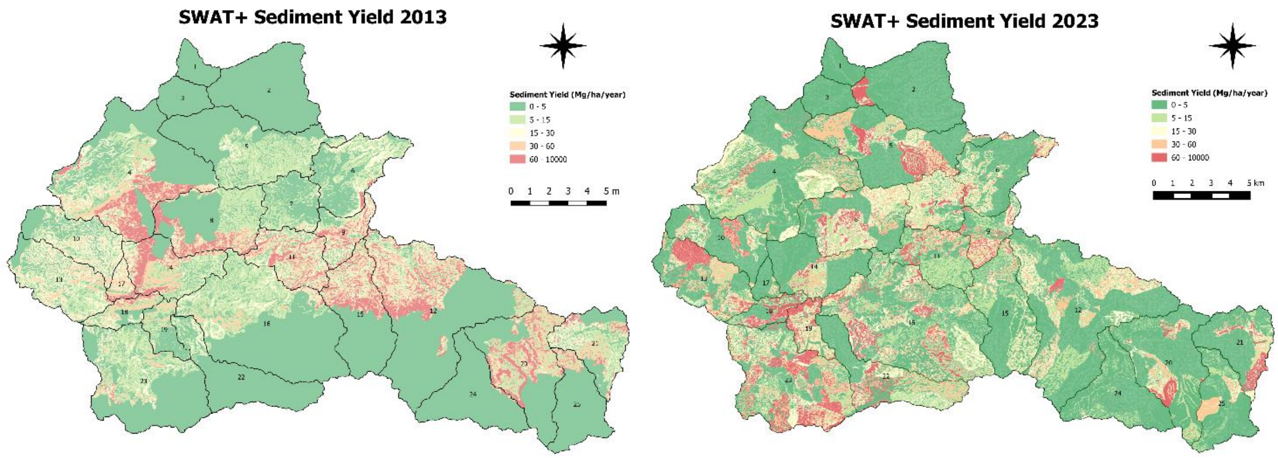

Figure 3. Spatial distribution of simulated sediment yield in the Cisokan Watershed for the years 2013 (left) and 2023 (right), highlighting the emergence of critical erosion zones.

Table 2. Sub-watersheds ranked by the largest absolute increase in sediment yield between 2013 and 2023, based on SWAT+ simulation outputs.

Sub basin	Landuse 2013	Landuse 2023	SY 2013 (Mg/ha/year)	SY 2023 (Mg/ha/year)	Δ Yield
19	frse_suhf; rice	agrl; agrr; frse_suhf; urml	0.58	18.77	18.19
23	agrl; agrr; frse_suhf; rice	agrl; agrr; frse_suhf; frst_sums; orcd; rice; urml	0.90	7.73	6.83
18	agrl; agrr; frse_suhf; rice	agrl; agrr; frse_suhf; rice; urml	1.48	7.84	6.36
7	agrl; rice	agrr; frst_sums; rice; urml	0.67	4.65	3.99
9	agrl; rice	agrl; frse_suhf; frst_sums; rice; urml	1.73	5.08	3.36
16	agrl; barr; frse_suhf; rice	agrl; agrr; frse_suhf; frst_sums; rice; shrb; urml	0.37	2.96	2.60
13	agrl; agrr; frse_suhf; rice	agrl; agrr; frse_suhf; orcd; rice; urml	0.87	3.09	2.22
22	frse_suhf; rice	agrl; agrr; frse_suhf; frst_sums; urml	0.03	2.11	2.07
5	frse_suhf; rice	agrl; agrr; frse_suhf; urml	0.18	2.25	2.07
10	agrl; agrr; frse_suhf; rice	agrl; frse_suhf; rice; urml	0.75	2.48	1.73

Note: Land use abbreviations, agrl: dryland agriculture; agrr: mixed dryland agriculture; frse_suhf: secondary dryland forest; frst_sums: mixed forest; orcd: orchard; rice: paddy field; urml: low-density urban; barr: barren land; shrb: shrub.

3.3 Projection for 2038 (BAU)

The 2038 land use/land cover (LULC) projection was developed using a supervised classification approach in Google Earth Engine (GEE), leveraging a Random Forest algorithm trained on historical land cover transitions between 2013 and 2023 (Figure 4). The model incorporated explanatory variables such as elevation (SRTM), slope, distance from roads, and temporal change patterns (Pande *et al.*,2024; Sheeba *et al.*,2023). Training and validation were conducted using stratified random sampling, achieving an overall accuracy of 99.7% and a Kappa coefficient of 0.996. The projection adopted a Business-As-Usual (BAU) scenario consistent with Indonesia's SSP2 climate development pathway, assuming current land use trends continue without significant policy shifts. Several post-classification refinements were applied, including spatial masking for reservoir inundation, partial retention of rice fields, and slope-based adjustment for forest and agricultural areas. Additionally, the expansion of water bodies was adjusted to account for the planned reservoirs in the Upper Cisokan Pumped Storage (UCPS) project, with the Lower Dam covering approximately 260 hectares and the Upper Dam around 80 hectares (PT PLN (Persero), 2021).

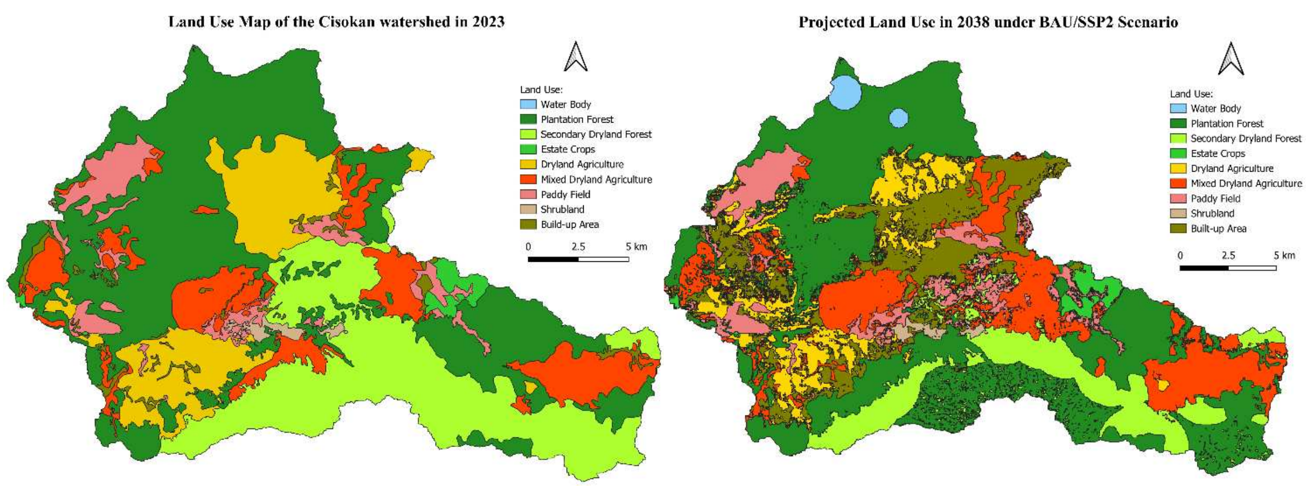

Figure 4. LULC comparison of the Cisokan watershed in 2023 (KLH) and projected 2038 (BAU/SSP2 scenario using Random Forest model in GEE)

The resulting LULC projection provides the basis for subsequent sediment yield modeling, revealing substantial shifts in erosion risk across the watershed. Model results show that average sediment yield in 2038 is expected to reach 5.57 tons/ha/year, more than double the 2023 estimate of 2.25 tons/ha/year. This increase is strongly associated with continued expansion of mixed dryland agriculture and build-up area (urban settlements) at the expense of forest cover, especially in the eastern parts of the watershed. These dynamics are further illustrated in Table 3, which summarizes the area changes for each land use class across 2013, 2023, and the projected 2038 scenario.

Table 3. LULC in the Cisokan Watershed in 2013, 2023, and Projected 2038 under the BAU Scenario.

Class	2013 (ha)	2023 (ha)	2038/BAU (ha)
Water Body	2.45	2.34	323.19
Plantation Forest	16,739.11	15,083.86	14,814.77
Secondary Dryland Forest	-	8,963.60	4,279.18
Estate Crops	0.51	464.05	432.36
Dryland Agriculture	3,156.87	5,016.58	3,428.01
Mixed Dryland Agriculture	8,127.87	4,900.07	6,170.26
Paddy Field	9,405.64	2,147.02	2,796.31
Shrubland	45.58	255.11	292.21
Open Area	98.96	-	-
Built-up Area	-	744.37	5,040.55
Total	37,577	37,577	37,577

3.4 Sub-Watershed Prioritization

The prioritization analysis revealed significant spatial variability in erosion contribution across the 25 sub-watersheds. Based on the composite scoring system, which integrates sediment yield in 2023, change from 2013 to 2023, and relative area size, three sub-watersheds (SW-23, SW-16, and SW-5) were classified as Very High Priority (Table 4). These sub-watersheds consistently exhibited high sediment yield, notable positive trends over the past decade, and considerable areal coverage. These findings underscore their critical role in the overall sediment load entering the UCPS reservoir.

Table 4. Composite prioritization of sub-watersheds based on sediment yield, change over time, and area proportion.

Sub-Watershed	SY 2023	Δ SY	Area (%)	Total Score	Priority Class
SW-23	7.73	6.83	0.07	15	Very High
SW-16	2.96	2.60	0.10	13	Very High
SW-5	2.25	2.07	0.06	13	Very High
SW-9	5.08	3.36	0.02	12	High
SW-7	4.65	3.99	0.02	12	High
SW-22	2.11	2.07	0.04	12	High
SW-19	18.77	18.19	0.01	11	High
SW-18	7.84	6.36	0.01	11	High
SW-13	3.09	2.22	0.04	11	High
SW-10	2.48	1.73	0.03	11	High
SW-12	1.10	0.47	0.10	11	High
SW-8	1.43	0.45	0.05	10	Medium
SW-6	1.61	1.17	0.04	9	Medium
SW-20	0.93	0.30	0.05	9	Medium
SW-21	1.48	0.85	0.03	8	Medium
SW-4	0.90	- 0.13	0.10	8	Medium
SW-15	0.72	0.23	0.04	8	Medium
SW-11	0.94	0.01	0.03	7	Low
SW-2	0.14	0.14	0.05	7	Low
SW-14	0.50	- 0.30	0.03	6	Low
SW-24	0.28	0.12	0.04	6	Low
SW-25	0.34	0.17	0.03	5	Low
SW-17	0.41	- 3.59	0.01	4	Very Low
SW-1	-	-	0.01	3	Very Low
SW-3	-	-	0.01	3	Very Low

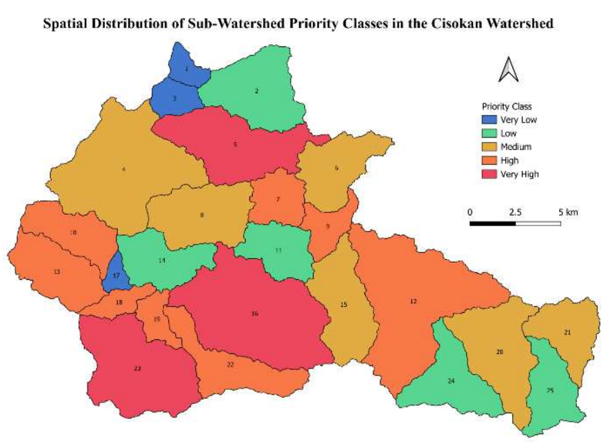

Figure 5. Spatial distribution of sub-watershed prioritization based on composite sediment yield scoring in Cisokan Watershed

To validate the robustness of the prioritization results, sediment yield projections for the year 2038 under the BAU scenario were examined for the three sub-watersheds classified as Very High Priority: SW-23, SW-26, and SW-5. All three sub-watersheds demonstrated a consistent or increasing trend in sediment yield (Table 5). These findings suggest that the prioritization framework not only reflects current erosion pressures but also aligns with projected long-term sediment dynamics, thereby supporting its applicability for forward-looking watershed management strategies.

Table 5. Sediment yield validation for Very High Priority sub-watersheds (2013–2038, BAU).

Sub-Watershed	SY 2013 (Mg/ha/yr)	SY 2023 (Mg/ha/yr)	SY 2038 (Mg/ha/yr)
SW-23	0.90	7.73	8.57
SW-16	0.37	2.96	8.11
SW-5	0.18	2.25	12.50

3.5 Implications for UCPS Sustainability and Conservation Planning

The increasing trend of sediment yield observed between 2013 and 2023, as well as the projected escalation under the 2038 Business-As-Usual (BAU/SSP2) scenario, presents a tangible risk to the long-term sustainability of the Upper Cisokan Pumped Storage (UCPS) hydropower plant. As a closed-loop facility dependent on dual reservoirs, UCPS is particularly vulnerable to sediment accumulation, which can reduce effective storage volume, compromise turbine efficiency, and necessitate costly maintenance or dredging (Shrestha & Shrestha, 2019; Noon & Kim, 2021). The simulation results underscore the need to treat sediment control not only as an environmental imperative but also as a fundamental operational safeguard for large-scale energy infrastructure.

The prioritization framework developed in this study provides a targeted strategy for erosion mitigation, highlighting sub-watersheds that contribute disproportionately to current and future sediment yield. Sub-watersheds such as SW-23 and SW-16 emerged as consistent high-priority areas across both historical and projected scenarios, indicating persistent erosion pressure. Integrating these insights into watershed management planning enables stakeholders to allocate conservation resources more effectively, focusing on upstream interventions such as agroforestry, land cover restoration, and slope stabilization (Halder *et al.,*2024). Furthermore, the use of temporal and scenario-based prioritization strengthens the adaptive capacity of erosion control measures, supporting the long-term reliability and efficiency of UCPS operations under dynamic land use conditions.

4. Conclusions

This study assessed sediment yield dynamics in the Cisokan Watershed using SWAT+ simulations for the years 2013, 2023, and a 2038 projection under the Business-As-Usual (BAU/SSP2) scenario. The results show a significant increase in sediment yield driven by land use change, particularly the expansion of dryland agriculture and settlements. A composite prioritization index incorporating sediment magnitude, decadal change, and sub-watershed area successfully identified critical erosion zones (e.g., SW-23, SW-16, SW-5) for targeted intervention. These findings underscore the importance of integrating sediment management into long-term hydropower planning, especially for the Upper Cisokan Pumped Storage (UCPS) system. Future research should explore alternative land use scenarios, such as afforestation and sustainable land management, to compare their mitigation potential, and extend the modeling scope to reservoir sedimentation and routing processes. Importantly, future model validation should utilize observed sedimentation data, including sediment trap measurements, turbidity-based monitoring, or bathymetric surveys, to enable direct comparison with simulated outputs and improve the model's accuracy and operational reliability. This study contributes a replicable, forward-looking framework for erosion risk assessment under dynamic land use pressures, supporting more adaptive and evidence-based watershed management in tropical upland regions.

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