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Soil Erosion Hazards and its Mitigation Scenarios in the Bubunawan River Watershed, Bukidnon, Philippines

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Abstract: Watersheds in the Philippines are increasingly vulnerable to geohazards such as soil erosion, driven by land-use change and climate-intensified rainfall. This degradation threatens both ecosystem stability and downstream communities. To better understand the extent of erosion in a watershed in the southern Philippines, this study presents a hazard assessment framework using the Revised Universal Soil Loss Equation (RUSLE), integrated within a Geographic Information System (GIS), to quantify and map soil erosion risk in the Bubunawan River Watershed (BRW) in Bukidnon, a key tributary of the Cagayan de Oro River Basin. By processing spatially distributed parameters, namely rainfall erosivity (R), soil erodibility (K), topographic factor (LS), cover management (C), and conservation practices (P), the model estimated a mean annual soil loss of 246.50 tonnes per hectare per year. The analysis identified high-hazard zones, revealing that 21.66% of the watershed exhibits very high to extreme erosion susceptibility, thus requiring priority intervention. Scenario-based modelling further elucidated system dynamics. Simulation of potential soil loss (7,524.70 t/ha/yr) under conditions without land cover and conservation practices effectively isolates and quantifies the mitigating role of current management strategies. Additionally, simulations of future climate scenarios with rainfall increases of 10–20% indicate elevated erosion rates. In contrast, modelling of nature-based solutions, specifically the reforestation of rangelands, demonstrates a potential reduction in soil loss of 33.27%. This research presents a replicable approach for transforming geospatial data into actionable insights for hazard mitigation, providing a critical tool for sustainable watershed management and enhancing resilience to climate-related geohazards.

Keywords: Soil Erosion; Hazard Assessment; RUSLE; GIS; Watershed Management; Reforestation; Climate Change Scenarios

1.0 Introduction

Soil erosion is not merely a physical phenomenon but a complex manifestation of the coupled human–environment system. Globally, the integrity of mountainous watersheds is increasingly compromised by the interplay between natural geomorphological processes and anthropogenic pressures. In the Philippines, this tension has reached a critical threshold, with millions of hectares vulnerable to degradation (Cabico, 2023). The Bubunawan River Watershed (BRW), a vital tributary of the Cagayan de Oro River system in Bukidnon, serves as a representative case for examining these interactions. Its strategic role in regional flood forecasting is currently undermined by a lack of soil loss data, rendering sustainable management a moving target.

1.1 The Bukidnon Hazard and Landscape: Geographical Specificities

The Bubunawan River Watershed (BRW) presents a distinct erosion hazard shaped by the convergence of extreme topography and intensive socio-economic development. Bukidnon's landscape is characterised by high-altitude volcanic plateaus and steep slopes which, when combined with intense tropical rainfall patterns, establish a high baseline level of natural erosivity. However, this condition is further exacerbated by specific socio-economic drivers, particularly the expansion of high-value monocrop agriculture, such as pineapple and banana plantations, and intensive maize cultivation into marginal upland areas. This study moves beyond a conventional hazard assessment by offering a geographical analysis of how local geomorphological constraints and land-use decisions interact to generate spatial patterns of vulnerability.

1.2 Land Change Science and Spatial Resilience

Framed within the paradigms of Land Change Science, this research explicitly models the environmental consequences of land-use and land cover change (LUCC). By integrating the Revised Universal Soil Loss Equation (RUSLE) within a Geographic Information System (GIS), the study evaluates the spatial resilience of the watershed, defined as its capacity to maintain functional integrity under climatic stress. The integration of these environmental variables reveals that the spatial distribution of erosion risk is not uniform; rather, it reflects the extent and location of human interventions that disrupt natural soil stability.

1.3 Policy Scenarios and Transferability

The core contribution of this research lies in its predictive capacity through scenario-based modelling. Rather than presenting a static snapshot, the study simulates the spatial implications of divergent policy pathways:

A. Degradation pathway: Modelling continued deforestation and intensified agricultural expansion.
B. Resilience pathway: Simulating the effects of targeted reforestation and soil conservation measures (P factor).
C. External pressures: Incorporating climate change projections to evaluate the watershed's response to additional stressors.

By quantifying the interactions among rainfall erosivity (R), soil erodibility (K), topographic factor (LS), cover management (C), and conservation practices (P), the study aims to: (1) map the current spatial distribution of soil loss; (2) delineate critical hazard zones; and (3) simulate the outcomes of climate- and policy-driven land-use changes. Ultimately, the Bubunawan River Watershed (BRW) serves as a representative case for mountainous tropical watersheds across Asia, providing a transferable framework for applying geospatial tools to balance human development with environmental sustainability.

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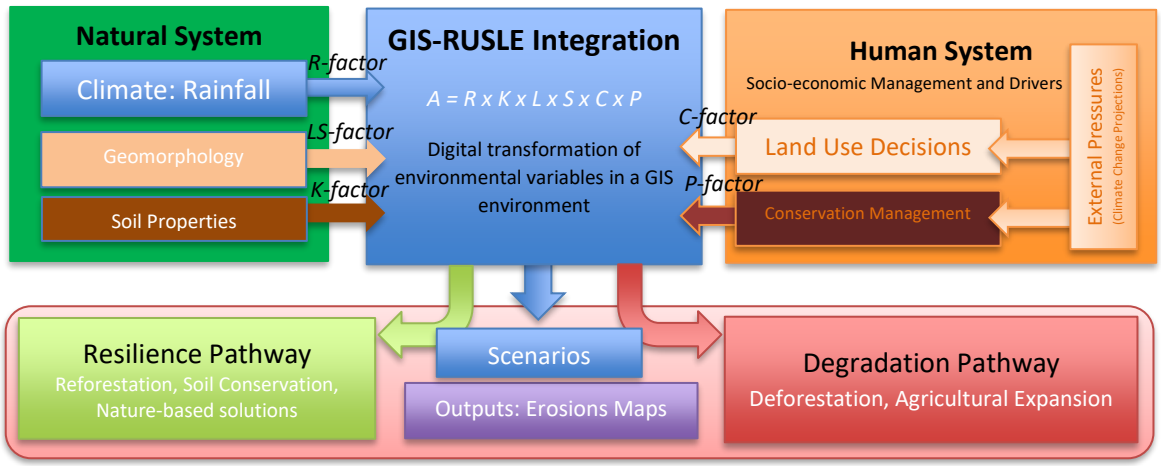


Figure 1. Conceptual framework for GIS-RUSLE of Bubunawan River Watershed.

2.0 A Digital Framework for Erosion Modeling

This study utilizes a geospatial approach, establishing a digital framework that integrates the RUSLE model with GIS to analyze soil erosion in the BRW visualized in Figure 2. The core of this framework is the spatial quantification of the five RUSLE factors to estimate annual soil loss (A), as defined by the equation: $A = R \times K \times LS \times C \times P$.

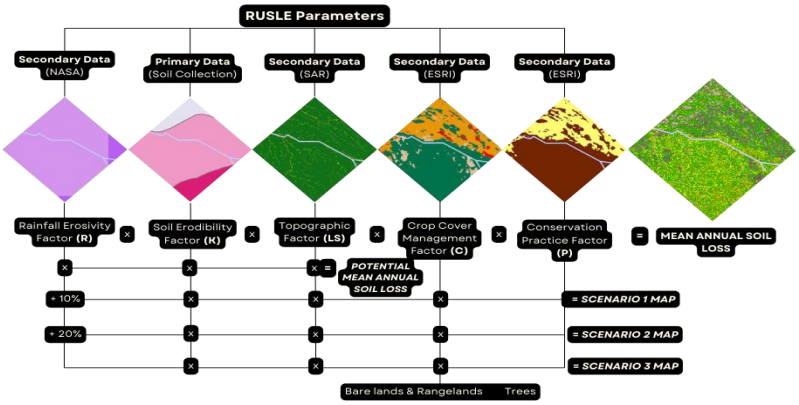


Figure 2. RUSLE conceptual framework.

Rainfall Erosivity (R factor): This factor quantifies the erosive force of rainfall. It was estimated using an empirical equation based on mean annual precipitation, capturing the spatial variability of rainfall intensity across the watershed. As a key driver in the RUSLE model, the R factor represents the cumulative impact of rainfall and associated runoff on soil detachment over time. It is particularly important under changing climate and land-use conditions, as it reflects variations in rainfall intensity and runoff dynamics (Li, He, Chen, & Sun, 2022).

Soil Erodibility (K factor): This factor represents the inherent susceptibility of soil to erosion. K values were derived from soil property data, including silt, sand, clay, and organic matter content, obtained from national soil maps and validated through field sampling.

Topographic Factor (LS factor): This factor combines the effects of slope length (L) and slope steepness (S), which influence runoff velocity and erosive potential. The LS factor was computed from a high-resolution Digital Elevation Model (DEM) within the GIS environment.

Cover Management (C factor): This factor reflects the protective effect of vegetation and land management practices. C values, ranging from 0 (full protection) to 1 (bare soil), were assigned to land cover classes derived from recent satellite imagery.

Conservation Practice (P factor): This factor accounts for the effects of soil conservation measures such as contour farming and terracing. P values were assigned based on land-use types and documented agricultural practices within the watershed.

Each factor was processed as a separate spatial data layer (raster) in ArcGIS. These layers were subsequently integrated using map algebra to produce a spatially explicit estimate of mean annual soil loss across the Bubunawan River Watershed (BRW). This workflow enables a detailed, transparent, and replicable assessment of erosion risk.

2.1 Study Area

The study focuses on the Bubunawan River Watershed (BRW), located in the province of Bukidnon, Philippines. Its outlet drains into the Cagayan de Oro River Basin in Misamis Oriental (H.R. 1455, 2022). The watershed boundaries were delineated by the researchers using geographic coordinates, approximately bounded by 124°38′E to 124°52′E longitude and 8°06′N to 8°24′N latitude, encompassing the municipalities of Libona and Baungon, Bukidnon.

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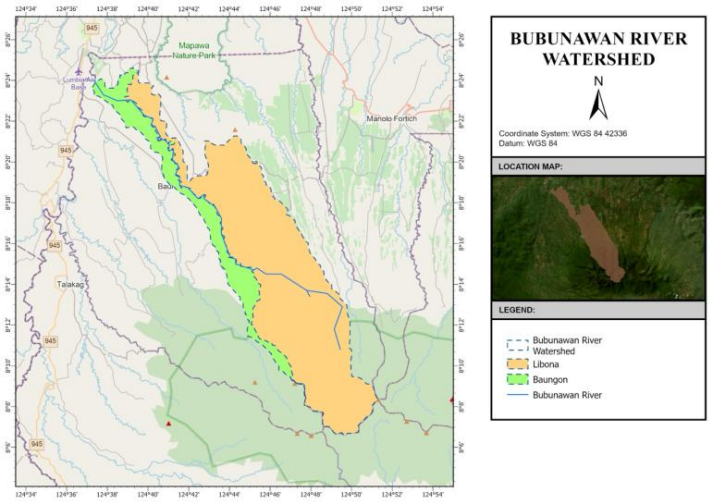


Figure 2.Study area.

The Bubunawan River Watershed (BRW) (Figure 3) is one of the major tributaries of the Cagayan de Oro River, which traverses the north-central region of Mindanao Island, Philippines (H.R. 1455, 2022). The BRW plays a significant role within the Flood Forecasting and Warning System (FFWS) due to several key characteristics. With a catchment area of approximately 223 km², it is the largest among the six primary tributaries of the basin (Japan International Cooperation Agency [JICA], 2014).

The presence of Mt. Kitanglad in the upstream region contributes to higher flood discharge compared to other tributaries, primarily due to the effects of orographic rainfall. In addition, typhoon systems affecting the watershed typically originate from the eastern direction. Owing to its geographical position in the easternmost part of the basin, the Bubunawan River can accelerate the conveyance of floodwaters towards flood-prone areas in Cagayan de Oro City, resulting in shorter response times relative to other tributaries.

According to the PAGASA flood investigation report, a significant increase in discharge was recorded in the Bubunawan River during Tropical Storm Sendong in 2011 (Canencia, et al., 2017). The river has an approximate length of 33.8 km and forms part of the larger Cagayan de Oro River system, ultimately discharging into Macajalar Bay in Misamis Oriental (19th Congress, 2022).

3.0 Materials and Methods

The research design, presented schematically below, outlines the methodological framework for analysing soil erosion factors in the Bubunawan River Watershed (BRW). The Revised Universal Soil Loss Equation (RUSLE) was applied to estimate mean annual soil loss by integrating five key input parameters: rainfall erosivity (R), soil erodibility (K), topographic factor (LS), cover management (C), and conservation practices (P).

The methodology incorporates both primary and secondary data sources. Primary data were obtained through soil sampling and laboratory analysis, while secondary data were derived from existing databases and relevant institutional sources. These datasets were used to estimate the spatial distribution of mean annual soil loss across the BRW and to generate corresponding thematic maps.

The R factor represents the kinetic energy of rainfall and its associated runoff potential. In the BRW, it was calculated using [insert specific formula or PAGASA-based method]. Given Bukidnon's tropical climate and its geographical position within the Cagayan de Oro River Basin, the watershed experiences intense, short-duration rainfall events. The resulting R-factor map (Figure 4) exhibits a gradient spatial distribution, indicating a high baseline erosive energy across the landscape. This condition constitutes a critical driver of soil detachment and contributes significantly to the region's historical flood events.

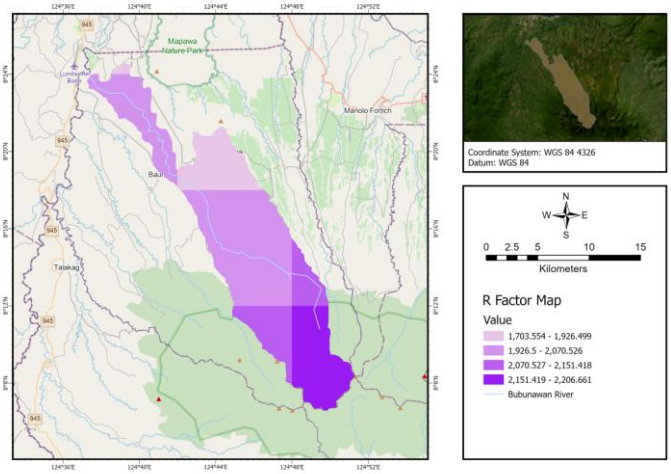


Figure 3. R-factor map.

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The equation proposed by El-Swaify et al (1987) was employed in this study since it has been suggested as a viable alternative for estimating the R factor in regions with limited data availability. Originally developed for tropical climates, this model is particularly suitable for scenarios characterized by a scarcity of data (Po, Sabines, & Taat, 2018). The model can be described as follows.

$$R = 38.5 + 0.35P$$

where,

P = Precipitation in millimeters per year

R = Rainfall erosivity factor $\frac{(MJ)(mm)}{(ha)(h)(yr)}$

The precipitation intensity data obtained from Huffman et al from the GIOVANNI/GSFC/NASA platform (2024) were initially recorded at a half-hourly temporal resolution and quantified in millimeters per hour. To harmonize the unit dimensionality with mean annual soil loss calculations, a standardization conversion factor of 17,520 was applied to derive the precipitation (P) factor, which was subsequently averaged across a decadal interval, as described below:

$$(2)\left(\frac{24\ hr}{1\ day}\right)\left(\frac{365\ days}{1\ yr}\right) = 17520\frac{mm}{yr}P$$

Following the unit transformation, the refined factor was systematically integrated to compute the rainfall erosivity (R-factor) values. The resultant spatial dataset underwent geospatial processing, specifically resampling to a uniform grid resolution of 30 meters by 30 meters to facilitate consistent spatial analysis and modelling.

The K-factor represents how soil typically responds to rainfall and runoff in the long run. Further, it represemnts inherent susceptibility of soil particles to detachment and transport. Unlike studies relying solely on global datasets, this research utilized primary soil sampling to validate erodibility. The K-map highlights the volcanic origins of the watershed, dominated by Adtuyon clays followed by undifferentiated Mountain soils mostly volcanic in origin. These soils possess high productivity but exhibit significant erodibility when the protective vegetative canopy is removed, particularly in the south-central agricultural zones. The fact that rainwater dislodges soil particles, which are then carried away by runoff, supports this theory. The repeated occurrence of this phenomenon causes soil erosion, and the K-factor is used to measure this erosion. Based on a unit rainfall erosion index, this factor specifies the amount of soil loss for a specific soil type. (Waseem, Humayun, Javed, & Kebede, 2023). The equation developed by David (1988), which is a modified version of the equation proposed by Wischmeier and Mannering (1969), has been utilized in subsequent studies to determine K-values (DENR, 2015). The simplification and adaption of the study to the Philippine context were conducted by taking into account factors such as particle size distribution, content of organic matter, and pH levels.

$$K = Si \times \left[(0.043 \times pH) + \frac{0.62}{OM} + (0.0082 \times S) - (0.0062 \times C)\right]$$

where,

K = Soil Erodibility Factor
Si = Silt content of soil in percentage
pH = pH level of soil
OM = Organic matter content of soil in percentage
S = Sand content of soil in percentage
C = Clay ratio of soil in percentage.

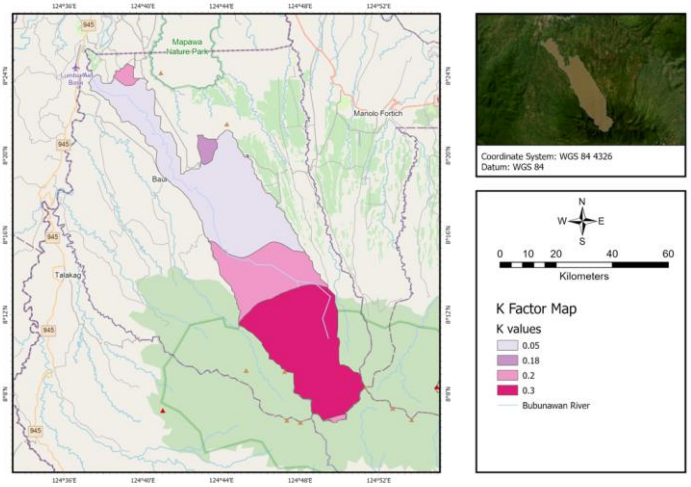


Figure 4. K-factor map.

For the primary data, collection of soil samples are done for the soil erodibility value of the RUSLE factors. Farmlands are the areas where the soil samples are collected and analyzed through laboratory experiments, as elevated farming areas are susceptible to soil erosion (Po, Sabines, & Taat, 2018). Hence, areas other than farmlands in Libona and Baungon, Bukidnon are the limitations of this study. Furthermore, since the samples of soils are from farmlands, the presence of pesticides and chemical fertilizers are excluded in the analysis of the soil sample. The method in collecting the soil samples does not include the top soil— where most of the pesticides and chemical fertilizers are present— since the samples are undisturbed soils. This is to prevent the effect of pesticides and chemical fertilizers, as these contribute to soil acidification consequently decreasing the organic matter content and changing the soil's pH level (Bisht & Chauhan, 2020)

To classify the soil samples collected, ASTM D2487 was used. This procedure describes how to classify mineral and organo-mineral soils for engineering purposes. It is based on laboratory evaluations of particle-size characteristics, liquid limit, and plasticity index. In addition, "ASTM D2488- Standard Practice for Description and Identification of Soils (Visual-Manual Procedures)" was used as the procedure includes

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methods for characterizing soils for engineering purposes. It also describes a procedure for identifying soils at the user's discretion using the classification system outlined in Test Method D2487. Visual inspection and manual tests are used to make this determination. If ever there is a need to refer to ASTM D2488, it is essential to state clearly in the reports that soil identification is done through visual-manual procedures (ASTM D2488, 2017). The Unified Soil Classification System (USCS) is a type of engineering classification of soils where it is “Based on particle size distribution, liquid limit, soil plasticity, and organic matter concentrations” that is used frequently by geotechnical engineers (Garcia-Gaines & Frankenstein, 2015). The USCS method utilizes a two-letter method to identify different soil types. It classifies soils into two categories; “Coarse-grained soils that are gravelly and sandy in nature with less than 50% passing through the No. 200 sieve.” and “Fine grained soils are with 50% or more passing through the No. 200 sieve.”

The LS factor represents the effect of terrain on the rate of erosion, where increased slope length and steepness correlate with higher overland flow. In complex terrains like the BRW, the model proposed by (Mitasova et al. ,1996, as cited in Borrelli et al., 2021)) - originally suggested by Moore and Burch - is utilized to calculate the LS factor as a function of the unit contributing area. The high-altitude volcanic plateaus and deeply incised river canyons result in high LS values, indicating that the terrain itself provides a significant physical "potential" for high-velocity overland flow. This approach is widely adopted in GIS-based RUSLE studies within the Philippines (Benavidez et al., 2018; Po et al., 2018). In this study, the LS equation incorporates the standard unit plot length of 22.13m and a slope gradient of 5.143° (0.0896 or 9%), which serve as normalization constants (Rodriguez & Gimenez Suarez, 2012). Following the work of Salino et al. (2024) and Po et al. (2018) for similar tropical mountainous regions, the exponents m = 0.4 and n = 1.3 were applied to account for the prevailing sheet and rill erosion processes in high-relief landscapes.

$$LS = \left(Flow\ Accumulation \times \frac{Cell\ Size}{22.13}\right)^{0.4} \times \left(\frac{Sin\ Slope}{0.0896}\right)^{1.3}$$

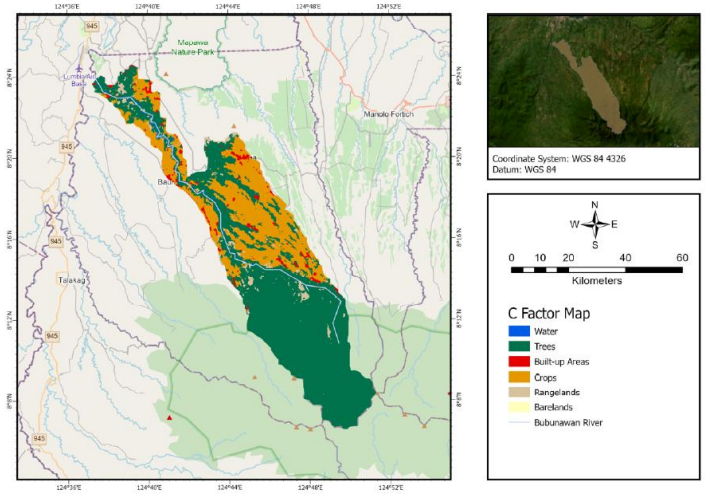


Figure 5. C-factor map derived from Sentinel 2 Mission.

The cover management factor (C), which ranges from 0 to 1, represents the protective effect of vegetation cover and its influence on soil erosion. It establishes a relationship between land use and land cover characteristics and the susceptibility of the basin to soil loss. Land-use types that are highly prone to erosion are assigned higher C values (approaching 1), whereas those offering greater protection are assigned lower values (approaching 0) (Biswas & Pani, 2015). The C factor is considered the most dynamic parameter in the RUSLE model, as it reflects the ratio of soil loss under specific vegetation or crop conditions relative to bare soil.

In this study, C values were derived from ESRI land cover datasets based on Sentinel-2 imagery. The resulting C-factor map (Figure 6) highlights the spatial imprint of human activities on the watershed. Lower values are concentrated in the forested northern regions, while higher values dominate the southern areas, where high-value monocrop plantations (e.g., pineapple and banana) and intensive maize cultivation provide limited soil protection, particularly during peak rainfall periods.

The P factor accounts for the effects of soil conservation measures on erosion rates. It modifies RUSLE estimates by incorporating land management practices such as contour farming, strip cropping, and terracing (Renard et al., 1997, as cited in Waseem et al., 2023). The P factor ranges from 0 to 1, where values closer to 0 indicate effective conservation practices, and values closer to 1 indicate minimal or no conservation efforts (Ganasri & Ramesh, 2016).

In this study, P values were assigned based on observed agricultural practices and government land-use data. In cases where field data on conservation measures were limited, values were adopted from published studies conducted under comparable environmental conditions. The generated P-factor map indicates a general lack of conservation structures in upland agricultural areas, where values approaching 1.0 (indicating absence of conservation practices) are prevalent, thereby exacerbating soil loss.

Given the complex interaction of natural and anthropogenic factors, the watershed faces significant environmental challenges, particularly soil erosion. This study employed established empirical equations from the literature that are appropriate to the study context and available data in estimating RUSLE parameters and mean annual soil loss in the BRW. The use of context-specific equations ensures that model outputs reflect the prevailing climatic conditions, terrain characteristics, soil properties, land cover, and conservation practices of the study area.

A summary of the data utilised in this study is presented in the table below.

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Table 1. Summary of collected data.

Soil Erosion Factors	Data	Data Type	Source
Rainfall Erosivity Factor (R)	Rainfall data (Annual Precipitation)	Tabulated	DOST-PAGASA
Soil Erodibility Factor (K)	Soil Data, K-factor Values (Actual soil analysis)	Raster image, Tabulated	Primary, DENR, Remote Sensing-based
Topographic Factor (LS)	Digital Elevation Model	Raster image	DOST DREAM Project
Crop Cover Management Factor (C)	Land Cover Map, C-factor values	Raster image, Tabulated	Remote-Sensing based, Literature
Conservation Practice Factor (P)	P-factor value	Tabulated	Literature

4.0 Results and Discussion

4.1 Spatial Distribution of Erosion Hazard

Soil loss varies significantly across the landscape, ranging from near zero to over 282,000 t/ha/yr in extreme cases. Spatial analysis reveals a clear pattern of hazard concentration. While approximately 65.56% of the watershed experiences slight to negligible erosion (0–5 t/ha/yr), a substantial 29.74% falls within the high to extreme soil loss categories. This demonstrates the model's capacity to identify discrete high-hazard zones, thereby enabling the prioritisation of areas requiring immediate conservation interventions.

The estimated mean annual soil loss for the Bubunawan River Watershed (BRW) is 246.50 t/ha/yr, classifying it as an area of extreme erosion hazard. Figure 7 corroborates the elevated erosion rates observed in other critical watersheds across Northern Mindanao, while also highlighting the BRW as a particularly high-risk tributary. For comparison, Salino et al. (2024) reported a mean annual soil loss of 153.20 t/ha/yr in the adjacent Tagoloan River Basin (TRB), with nearly half of the basin exhibiting high to severe erosion susceptibility.

The higher erosion rate observed in the BRW (246.50 t/ha/yr), relative to the TRB, can be attributed to the specific geographical characteristics of the study area, notably the convergence of high-altitude volcanic plateaus and the concentrated expansion of intensive monocrop agriculture (e.g., pineapple and banana plantations) on steep, marginal lands. These findings are further supported by Benavidez et al. (2018), who reported soil loss rates exceeding 300 t/ha/yr in degraded upland areas of the wider Cagayan de Oro River Basin. Collectively, these studies substantiate the severity of soil erosion in the BRW and underscore its role as a significant sediment source within the regional river system.

4.2 Digitally Isolating the Impact of Land Management

The soil loss analysis of the Bubunawan River Watershed (BRW) reveals a distinct spatial distribution across its 22,604.22 ha extent. The majority of the watershed, accounting for 65.56% (14,819.13 ha), experiences none to slight soil loss (0–5 t/ha/yr), indicating relatively stable soil conditions across most areas. However, 10.80% (2,442.06 ha) of the watershed falls within the very severe to extreme soil loss category (>300 t/ha/yr), of which 4.39% (993.24 ha) is classified as extreme (>1,000 t/ha/yr), representing critical zones that require immediate intervention. The intermediate risk categories exhibit a graded distribution: moderate soil loss (5–15 t/ha/yr) affects 4.70% (1,061.82 ha), high soil loss (15–50 t/ha/yr) impacts 8.08% (1,825.56 ha), very high soil loss (50–150 t/ha/yr) covers 8.16% (1,844.82 ha), and severe soil loss (150–300 t/ha/yr) accounts for 2.70% (610.83 ha) of the total area.

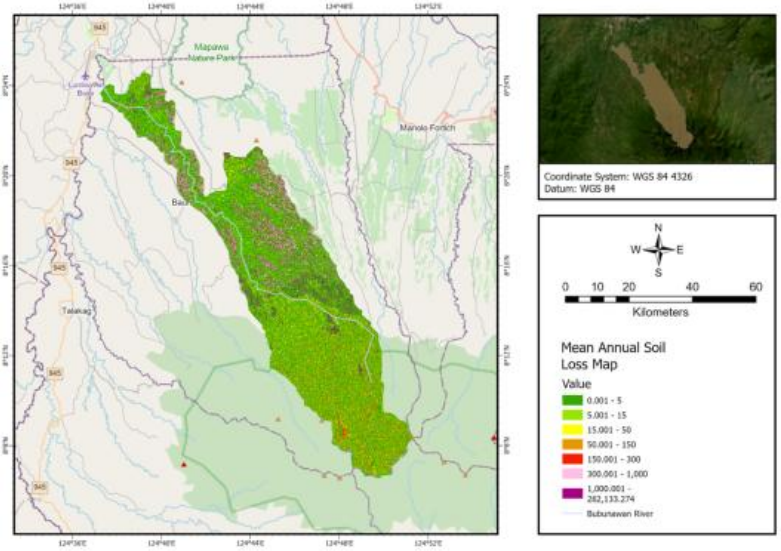


Figure 6. Mean annual soil loss map of the BRW.

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The analysis of the Bubunawan River Watershed (BRW), employing the A=RKLS equation, revealed substantial variability in potential mean annual soil loss, ranging from 0 to 1,127,267.12 tonnes per hectare per year, with a mean of 7,524.70 tonnes per hectare per year (SD=36,870.73).

Table 2. Mean annual soil loss values and their proportions in the BRW.

		MASL		PMASL	
Soil Loss Class	Soil Loss (t/ha/yr)	Area (ha)	Area (%)	Area (ha)	Area (%)
None to Slight	0 – 5	14,819.13	65.56	14,022.81	62.04
Moderate	5 – 15	1,061.82	4.70	21.06	0.09
High	15 – 50	1,825.56	8.08	51.39	0.23
Very High	50 – 150	1,844.82	8.16	117.45	0.52
Severe	150 – 300	610.83	2.70	152.55	0.67
Very Severe	300 – 1000	1,448.82	6.41	571.68	2.53
Extreme	> 1000	993.24	4.39	7,667.28	33.92
Total		22,604.22	100.00	22,604.22	100.00

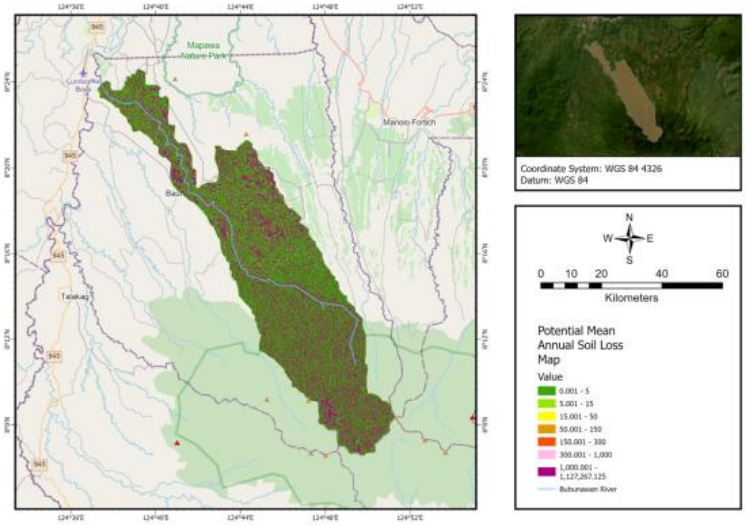


Figure 7. Potential mean annual soil loss map of the BRW.

In the absence of land cover management and soil conservation practices, the RKLS formulation represents the potential soil loss within the watershed. The Bubunawan River Watershed (BRW), bisected by the Bubunawan River, exhibits a pronounced south-to-north gradient in erosion vulnerability. Figure 6 illustrates the contrast between relatively stable conditions (0–5 t/ha/yr, shown in dark green) and zones of extreme erosion risk (>1,000 t/ha/yr, represented by red patches). This marked spatial heterogeneity, influenced by topography and the river network, highlights the need for targeted soil conservation strategies, particularly in high-risk areas and critical riparian zones where extreme erosion potential coincides with the river system.

A key strength of the digital framework lies in its capacity to simulate hypothetical scenarios. By excluding the C factor (cover management) and P factor (conservation practices) from the RUSLE computation, the model estimates “potential” soil loss based solely on natural drivers, namely rainfall, soil properties, and topography. This scenario yields a potential mean annual soil loss of 7,524.70 t/ha/yr. The substantial difference between the potential (7,524.70 t/ha/yr) and the estimated actual soil loss (246.50 t/ha/yr) provides a robust quantitative indication of the critical role played by vegetation cover and land management practices in mitigating erosion. This comparison offers strong empirical support for the effectiveness of existing conservation measures.

4.3 *Modeling Future Scenarios: Climate Change and Mitigation*

The digital framework was further employed to assess the watershed’s sensitivity to future changes. To simulate the effects of climate change, rainfall inputs were increased by 10% and 20%, representing projected intensification of precipitation. The model indicates a corresponding rise in soil erosion, with the proportion of the watershed classified as “extreme” risk increasing from 4.39% to 5.13% under the 20% rainfall scenario (Table 3). This analysis translates the abstract threat of climate change into a quantifiable escalation in erosion hazard.

Table 3. Mean annual soil loss with increase in rainfall and their proportions.

		No Increase		With 10% increase		With 20% increase	
Classes	Soil Loss (t/ha/yr)	Area (ha)	Area (%)	Area (ha)	Area (%)	Area (ha)	Area (%)
None to Slight	0 – 5	14,819.13	65.56	14,763.69	65.31	14,715.09	65.10
Moderate	5 – 15	1,061.82	4.70	1,017.27	4.50	977.49	4.32
High	15 – 50	1,825.56	8.08	1,686.69	7.46	1,602.54	7.09
Very High	50 – 150	1,844.82	8.16	1,980.99	8.76	2,046.78	9.05
Severe	150 – 300	610.83	2.70	630.63	2.79	670.32	2.97
Very Severe	1000	1,448.82	6.31	1,447.2	6.40	1,431.9	6.33
Extreme	>1000	993.24	4.39	1,077.75	4.77	1,160.1	5.13
TOTAL		22,604.22	100.00	22,604.22	100.00	22,604.22	100.00

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Nature-based mitigation: A mitigation scenario was modelled by converting all areas currently classified as rangelands and bare land (characterised by high C-factor values) into forest cover (assigned a low C-factor value of 0.003). The simulation indicates that this targeted reforestation strategy could reduce total soil loss within the watershed by 33.27%. This result demonstrates the utility of the modelling framework as a decision-support tool, enabling the evaluation and validation of potential interventions prior to their implementation.

Table 4. Mean annual soil loss with increase in reforestation.

		No Increase		With Reforestation	
Classes	Soil Loss (t/ha/yr)	Area (ha)	Area (%)	Area (ha)	Area (%)
None to Slight	0 – 5	14,819.13	65.56	14,869.44	65.78
Moderate	5 – 15	1,061.82	4.70	1,139.85	5.04
High	15 – 50	1,825.56	8.08	1,890.81	8.36
Very High	50 – 150	1,844.82	8.16	1,871.73	8.28
Severe	150 – 300	610.83	2.70	607.86	2.69
Very Severe	1000	1,448.82	6.31	1,425.96	6.31
Extreme	>1000	993.24	4.39	798.57	3.53
TOTAL		22,604.22	100.00	22,604.22	100.00

The spatial distribution of soil erosion in the Bubunawan River Watershed (BRW) (Figures 7 and 8) reveals a pronounced north–south gradient in erosion risk. The south-central region emerges as the primary hotspot, characterised by extreme soil loss rates. This pattern reflects the geographical convergence of high topographic factor (LS) values, associated with steep volcanic slopes, and elevated cover management (C) values linked to intensive maize and pineapple cultivation.

Although the northern upland areas exhibit comparable slope gradients, erosion rates remain considerably lower due to the stabilising influence of forest cover and relatively sustainable land-use practices. In contrast, the south-central sector represents a zone of low spatial resilience, where the removal of natural vegetation for agricultural expansion on marginal lands has increased the susceptibility of volcanic soils to high rainfall erosivity (R factor), a defining feature of the Bukidnon climate.

A comparison between the baseline condition and the resilience pathway (Figure 7) further highlights the effectiveness of targeted interventions. As illustrated in Figure 8, the strategic implementation of reforestation and conservation measures in these southern hotspots substantially reduces the spatial extent of extreme erosion risk. These findings emphasise that spatial prioritisation, rather than aggregate soil loss alone, should inform watershed management and policy decisions.

5.0 Discussion

This study successfully implemented a digital framework integrating the Revised Universal Soil Loss Equation (RUSLE) within a Geographic Information System (GIS) to conduct a comprehensive soil erosion hazard assessment in the Bubunawan River Watershed (BRW). The analysis extends beyond static estimation by incorporating a dynamic, spatially explicit approach, demonstrating how digital tools enhance the understanding and management of environmental hazards.

The model effectively identified and mapped high-risk erosion zones, providing a clear basis for targeted intervention. Notably, scenario-based modelling highlights the substantial value of this approach. Simulations of climate change impacts enable the anticipation of future risks, while the evaluation of mitigation strategies, such as reforestation, supports the design and validation of effective nature-based solutions. The marked disparity between potential and actual soil loss further emphasises the critical role of vegetation cover and sustainable land management in mitigating erosion.

The findings provide a robust evidence base for watershed managers and policymakers. In particular, the strategic conversion of erosion-prone rangelands and bare areas into forested landscapes emerges as a highly effective intervention. Overall, this study demonstrates that digital approaches to hazard assessment are not merely theoretical but constitute practical tools for enhancing landscape resilience and safeguarding critical water resources.

This study successfully integrated the Revised Universal Soil Loss Equation (RUSLE) within a Geographic Information System (GIS) to analyse the soil erosion hazardscape of the Bubunawan River Watershed (BRW), Philippines. By situating the analysis within the frameworks of Land Change Science and Coupled Human–Environment Systems (CHES), the research advances beyond a purely technical application to provide a deeper geographical interpretation of watershed vulnerability.

6.0 Conclusions

The results indicate a mean annual soil loss of 246.50 t/ha/yr, classifying the BRW within an extreme erosion hazard category. Importantly, the spatial distribution of erosion risk is highly heterogeneous. The south-central region is identified as a critical hotspot, where steep volcanic slopes coincide with intensive monocrop agriculture and limited conservation practices. Scenario analysis further demonstrates that the resilience pathway, characterised by targeted reforestation and enhanced soil conservation measures, can reduce the spatial extent of extreme erosion from 4.39% to 3.53% of the watershed area.

These findings highlight the necessity of place-based, spatially explicit management strategies, rather than uniform policy approaches. The BRW may serve as a representative case for other data-scarce, mountainous tropical watersheds across Asia. Ultimately, the proposed digital framework offers a replicable and transferable tool for supporting decision-making, enabling stakeholders to balance socio-economic development with environmental sustainability in high-relief landscapes

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Data Availability: The data supporting the findings of this study are available from the corresponding author upon reasonable request.

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Conflicts of Interest: The authors declare that there are no conflicts of interest in this study.

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