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Soil Erosion Risk and Mitigation Strategies in Steep and Complex Forest Ecosystems

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Abstract

The soil erosion risk on the slopes in Luong Son District, Hoa Binh Province, Vietnam, was determined to inform sustainable land management and conservation planning. Remote sensing and geographic information system (GIS) technologies were integrated with the universal soil loss equation (USLE) model to generate thematic maps of rainfall erosivity (R), soil erodibility (K), topographic factors (LS), and vegetation cover. These maps were combined to produce a comprehensive soil erosion risk map. The results showed that 65.09% of the district (23,747.61 hectares), mainly flat and midland areas, had no erosion risk. Light, moderate, and severe erosion affected 19.95%, 7.61%, and 7.35% of the region, respectively. Higher erosion risk is concentrated in mid-level mountainous and limestone regions, characterized by steep slopes and sparse vegetation. These findings highlight the influence of slope gradient and length on erosion severity and spatial patterns. Remote sensing, GIS, and USLE were integrated to spatially assess soil erosion, providing a scientific basis for targeted interventions, such as reforestation and terrace farming. This study contributes to gaps in the literature by comprehensively analyzing spatial soil erosion risk and providing practical recommendations for mitigating soil erosion in vulnerable landscapes and supporting sustainable land use planning under climate change pressures.

Keywords: Soil Erosion; Remote Sensing Technology; GIS; Universal Soil Loss Equation (USLE); Assessment of Erosion Potential.

1. Introduction

Soil erosion is a major global environmental problem because of the resulting impacts on land productivity, nutrient loss, and water body sedimentation. Erosion strips the topsoil, reduces the organic matter and nutrient contents in the soil, and diminishes the water-holding capacity of the soil, leading to impaired plant growth and reduced long-term soil productivity. Detached soil particles and the pollutants they contain degrade the quality of water and aquatic ecosystems, having local effects through reducing soil fertility and wider-ranging effects through increasing stream sedimentation and contaminating water sources. Soil erosion is a major driver of land degradation that globally threatens food security, freshwater resources, and biodiversity. The intense seasonal rain and steep slopes amplify the risk of soil erosion in

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forested uplands and mountainous areas. For example, rainfall-runoff events on steep gradients can trigger landslides and gully formation in upland forests via undercutting and rill erosion. Water erosion is widespread in South and Southeast Asia due to the heavy monsoon-driven rains and steep upland terrain. For example, approximately 21% of the land in South and Southeast Asia is affected by water erosion based on heavy rainfall, accounting for 46% of all areas of degraded land. An estimated 10% of the land in Vietnam experiences moderate to extreme erosion [1, 2]. The presence and loss of forest canopy and ground cover strongly mediate these erosion processes: dense vegetation binds soil and absorbs rainfall, whereas deforested slopes are highly vulnerable to runoff. Many upland farming systems have been built on hills and plateaus in Southeast Asia, where the monsoon rainfall exceeds 1,500 mm per year. The mountains and hills account for approximately 75% of the total land area in Vietnam [3]. Approximately 39–43% of the land in Vietnam is forested, large proportions of the total agriculture and rural population are concentrated on the remaining sloping land [1, 2]. The rural economy in Vietnam is strongly linked to upland areas, with 24 million people living in mountainous rural districts in 2007 [4]. These upland farms provide food and income for the household. The high rainfall (often 1,800–2,000 mm annually) and the steep, deforested terrain increase the susceptibility of the forested uplands in Vietnam to soil loss. The soil in these regions must thus be protected for sustaining agricultural productivity, preventing the sedimentation of reservoirs and streams, and conserving forest ecosystems.

Researchers have developed various models to estimate soil erosion and map the spatial erosion risk. Empirical approaches based on the universal soil loss equation (USLE) and its derivatives are widely used [5–7]. The USLE and revised USLE (RUSLE) are used to predict the long-term average sheet and rill erosion, considering rainfall erosivity (R), soil erodibility (K), topographic steepness/length (LS), vegetation coverage (C), and support practices (P). The modified USLE (MUSLE) is an extension of the RUSLE to single-event prediction that also considers the runoff volume [8]. Empirical models, such as the USLE, are widely used globally for estimating long-term inter-rill and rill erosion rates at the field or farm-scale unit under various management strategies [8–11]. The results of the USLE model robustly correlate with the site conditions that are influenced by management practices [12]. These models require relatively few inputs and have well-established factor formulations. Alternative physically based process-oriented models (such as WEPP or EUROSEM) simulate erosion mechanics in more detail but require extensive climate, soil, and management data and are less suitable for large-area application.

Advances in geographic information systems (GIS) and remote sensing (RS) have erosion risk mapping. High-resolution digital elevation models (DEMs), in-situ GPS data collection, and satellite land use/land cover (LULC) data have been used to map slope parameters and vegetation cover in detail. For example, spatially detailed LS maps are routinely computed using GISs and satellite imagery, and remote sensing indices (e.g., the normalised difference vegetation index (NDVI)) are used to update the vegetation cover-management (C) factor [13-19]. These geospatial tools enable the creation of detailed erosion risk maps for identifying areas at high risk of soil loss under different land use scenarios. Soil and field characteristics are assessed using long-term use patterns, and RS imagery reflecting various land parameters is integrated into land use maps to describe these characteristics [20–26]. GIS technologies have been used to analyse the spatial relationships among LULC patterns and their variations over time [7]. Abdi et al. (2023) integrated the RUSLE with GIS/RS imagery to quantify soil loss in mountainous regions in Iraq [12]. Combining the RUSLE factors derived from satellite and field data in a GIS framework was both cost-effective and highly accurate in estimating soil erosion. Similarly, GISs have been used to model the USLE factors of complex terrain and generate erosion hazard maps for watershed planning [27].

The USLE and GIS/RS methods require less data than other methods (WEPP (Water Erosion Prediction Project), LISEM (Limburg Soil Erosion Model), and advanced sensor and remote techniques) and are easy to use. RS layers (e.g., land cover and vegetation indices) can be incorporated into these methods, updated over time, and be overlaid with soil and topography data. GIS-based USLE studies have focused on the overall patterns of erosion potential at the regional scale. Empirical factors have been calibrated using local data to estimate the soil erosion risk and identify vulnerable areas. However, the previous studies have limitations. Simple USLE models require large assumptions (e.g., uniform rainfall input and empirical factor linearity), and processes such as gully erosion or landslides are typically ignored. Some erosion-mapping methods used in practice rely on coarse land cover classes and lack sufficient field validation, which oversimplifies the spatial variability in vegetation, soil, and land management practices. Additionally, socioenvironmental drivers (e.g., land use change, agricultural intensity, and forest policy) have rarely been incorporated into the frameworks of soil erosion models, which have focused on physical factors only. In summary, although GIS/RS-enhanced USLE models can be used to efficiently map erosion risk, their accuracy depends on input data quality and proper validation. These models must be combined with on-the-ground monitoring and adaptive management to increase the reliability of soil erosion mapping results [12, 28–31].

Despite this progress in quantifying soil erosion, key gaps remain. First, high-resolution erosion studies on the mountainous forests in Vietnam are lacking. Most of the studies in Vietnam have focused on lowlands or agricultural settings; few studies have focused on the steep forested uplands where erosion processes differ from those in the other areas. Second, GIS/RS methods have not been fully integrated with soil loss models [32]. Many local erosion assessments have involved using traditional surveys or hydrological models; however, assessments have not combined high-resolution satellite data with the RUSLE within a spatial framework. Third, models have often omitted critical dynamic factors such as long-term climate variability (e.g., increasing extreme rainfall amount and frequency with climate change), land use changes (such as deforestation or shifting cultivation), and socioeconomic influences (e.g., farming practices and conservation policies). Finally, measures for mitigating soil erosion have not been investigated. Most erosion mapping efforts have identified the risks without linking the results to specific soil conservation strategies or engineered interventions at the site level. In summary, Vietnam lacks detailed spatial erosion analyses related to forest conditions and local management; studies providing data that can explicitly guide mitigation actions are required [33–35].

The vast majority of the land with a slope of less than 15°, which accounts for nearly 22% of the land area in Vietnam, is currently used for agriculture or forestry production. However, soil conservation measures have not been adequately implemented, resulting in higher rates of soil degradation in Vietnam than in other Asian countries. Land with slopes ranging from 15° to 25° and greater than 25° account for over 16% and 61% of the land in Vietnam, respectively [1, 2]. The sloped land across the entire country in general and in the northern provinces in particular, is diverse, supporting the livelihoods of millions of people. However, the slopes also pose challenges: the soil has eroded, the forest watersheds have been depleted, and the land quality has degraded, leading to the loss of nutrients from the soil and an increased frequency of natural disasters. Therefore, policymakers, scientists, and farmers [1, 2, 36] must focus on sustainable agricultural production to address these challenges [37].

The Luong Son District was an appropriate case for this study because of its complex terrain and various land uses. The elevation in Luong Son ranges from approximately 200 to 800 m, with steep gradients in many communities. The district has a humid subtropical monsoon climate, with a mean annual rainfall of ~1,800–2,000 mm and heavy rains often falling on steep slopes. The land cover is a mosaic of forest patches, plantations, and upland farms; smallholder agricultural farms often border natural forests. Soil loss in Luong Son has likely been serious given the high rainfall amounts, rugged slopes, and forest–agriculture interfaces. Detailed erosion mapping of the area will fill a gap in the literature as few studies have examined the soil erosion in the northern mountainous zone in Vietnam. Moreover, proposing appropriate practical conservation measures will support local planning; district authorities have identified soil degradation as a concern, but guidance is required on the appropriate interventions and their locations [37].

Nguyen and Hens reviewed the soil erosion situation in Luong Son using the findings from various studies [2]. These studies characterized the local soil erosion through identifying the influential and causal factors. The soil erosion differs across Hoa Binh, considering the slope steepness, slope length, and vegetation cover. However, researchers have seldom used the spatial analysis capabilities of GIS to model soil erosion using the USLE [8]. The potential for soil erosion in Luong Son has been exacerbated by its steep slopes and intense rainfall patterns, according to studies using the USLE model combined with GISs. The USLE model was used to quantify the average annual soil loss and predicting the impact of different land uses and cultivation systems on erosion rates [38, 39]. The soil erosion model was constructed based on methodologies established in prior studies [40–42]; the approach to deriving the maps of the individual factors contributing to the final composite map of soil erosion demonstrated the accuracy of the approach varied with the parameter considered. We tailored the development of the maps of each parameter affecting soil erosion to align with the local conditions while balancing accuracy, cost-effectiveness, and scientific rigor.

This method led to differences between the maps of the individual erosion-related factors and the maps produced with conventional methods. In addition, we integrated multiple types of approaches and data, including GIS, long-term meteorological data from local weather stations in Vietnam, DEMs [23–25] and detailed soil maps to visually represent erosion-prone areas. This approach enabled an accurate assessment of soil loss for guiding the development of conservation measures to mitigate soil erosion. We also discussed soil erosion problems and identified mitigation strategies in forested regions to limit soil erosion and ensure sustainable land use through implementing solutions based on three strategies: engineering, biology, and sustainable land use. The proposed solutions are broad in scope because the topography of the Luong Son District, a lowland semi-mountainous area in Hoa Binh Province, is typical of the northwest and northern mountains in Vietnam: low mountain ranges interspersed with limestone karsts and plains. The recommended erosion control measures align with the standard practices used in similar mountainous regions in northwest Vietnam. Different tailored strategies would be required for the plains and river basins that consider the distinct geomorphological and hydrological conditions of these areas [30, 43].

The primary objective of this study was to assess the spatial distribution of the soil erosion risk in the Luong Son District through integrating GIS, RS imagery, and the RUSLE model. High-resolution factor maps were generated using local meteorological records, DEMs, soil surveys, and satellite imagery for vegetation and land use. The potential soil loss across the district was computed. The secondary objective was to identify practical localised mitigation strategies tailored to the identified hotspots. These strategies include engineering measures (e.g., terraces and contour bunds), biological measures (e.g., reforestation and mulching), and sustainable land use practices (e.g., conservation farming). This study fills the gap in the literature on soil erosion in Vietnam and provides guidance for conversing soil conservation in the vulnerable upland regions in the country by linking erosion assessment results to mitigation planning. In section 2, the study area and datasets are presented. In section 3, the methodology employed in this study is thoroughly explained. Section 4 provides details about the outcomes resulting from the experimental work and compares this study's results with recent studies. Section 5 presents the recommended soil erosion mitigation strategies, and Section 6 includes conclusions.

2. Study Area and Datasets

2.1. Study Area

Sloped land accounts for approximately 74% of the total natural land in Vietnam. A total of 39.7% or approximately 12,931,000 hectares of Vietnam is forested. Only 4.06 million hectares of the 9.4 million hectares of agricultural land is dedicated to rice cultivation, whereas over 5 million hectares are located on sloping land. Of the latter, approximately cover 640,000 ha is upland fields used for rice cultivation, and the remaining area is forestland or unused. Arable land can only be expanded into mountainous areas with the potential because all the flat land is already being extensively used. Therefore, using sloping land for agricultural and forestry plays a crucial role in the economy [1, 2].

The Luong Son District is located in northeast Hoa Binh Province, covers an area of approximately 36488.85 ha, and includes 11 administrative units: 10 communes and 1 town (Figure 1). The district is bordered by the Ky Sơn District to the west, the Kim Boi and Lac Thuy Districts to the south, the districts of My Duc and Chuong My to the east, and Quoc Oai District (Hanoi) to the north. The district is situated from 105° 25' 14" to 105° 41' 25" east and 20° 36' 32" to 20° 57' 22" north [44].

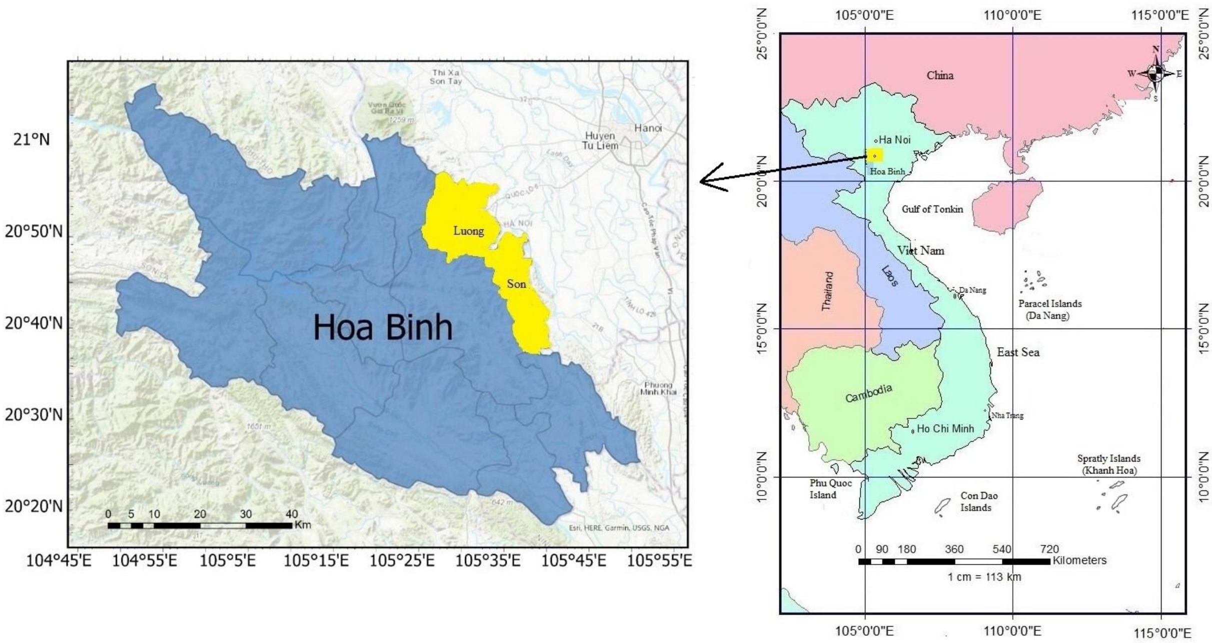

Figure 1. Location of study area Luong Son District, Hoa Binh Province, Vietnam

The topography in the district is characterised by rolling hills, with an elevation ranging between 300 and 600 m, although the district includes some plains and lower regions. The altitude of Luong Son ranges from 200 m in the lowlands to 800 m in the highest areas, comprising hilly terrain and mid-level mountains, which are prone to soil erosion during periods of heavy rainfall. The district has a tropical monsoon climate, with an average annual rainfall of approximately 1,800–2,000 mm, which mainly falls between May and October during the rainy season. Approximately 85–90% of the total rainfall occurs during this period, increasing the risk of soil erosion, particularly in agricultural and forested regions [44].

2.2. Collecting Primary Data

The primary data were collected through field surveys or satellite imagery of the Luong Son District, Hoa Binh Province.

2.2.1. Soil Data Map

The soil data map for the Luong Son District was derived from a 2022 forest inventory map of Hoa Binh Province, scaled at 1:50,000. Eight distinct soil groups were identified: alluvial, occupying 1572.53 ha or 3.18% of the total soil area; red-yellow, covering 26018.06 ha (52.64%); swampy, covering 150.72 ha (0.3%); red-brown, covering 5898.87 ha (11.93%); yellow-brown, at 2717.98 ha (5.5%); valley-colluvial, comprising 1570.10 ha, (3.18%); light yellow, covering 8082.76 hectares (16.35%); and additional soil groups, occupying 3419.33 ha (6.92%) [45].

2.2.2. Topographic Data

The topographic data for Luong Son were obtained from the 2022 forest inventory map of Hoa Binh Province at a 1:50,000 scale and a 20 m contour interval.

2.2.3. Satellite Imagery

The satellite imagery was acquired from a Landsat 8 satellite equipped with an Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) instruments. The scene, identified with code LC81270462024223LGN00, was captured on 10 August 2024 with a start time of 03:23:08 and an end time of 03:23:40 (UTC). The acquisition location corresponded to WRS Path 127 and WRS Row 046, matching the target coordinates on paths 127 and 046, respectively. The weather conditions at the time of capture indicated a cloud and land cloud cover of 6.49% and 6.13%, respectively. The imagery recorded during the daytime was classified as Level 2 OLI_TIRS_L2SP data. This satellite image was projected onto the UTM coordinate system, specifically in Zone 48, using the WGS84 datum.

2.2.4. Digital Elevation Model

The GLS DEM data were downloaded from the Landsat Collection 2 DEM repository from earthexplorer.usgs.gov, with a spatial resolution of 30 × 30 m. The scene covered a region at 20 °N and 105 °E and was stored in *.bil format. The data were processed using ArcGIS 10.8 software.

3. Research Methodology

3.1. Study Area

A soil erosion risk map for the study area was established using the USLE model and ArcGIS 10.8 software. We built maps of the rainfall erosivity, soil erodibility, topographic steepness/length, land cover, and support practices. The architecture of the developed method includes workflow and a flowchart that show the process of the methodology, are illustrated in Figure 2.

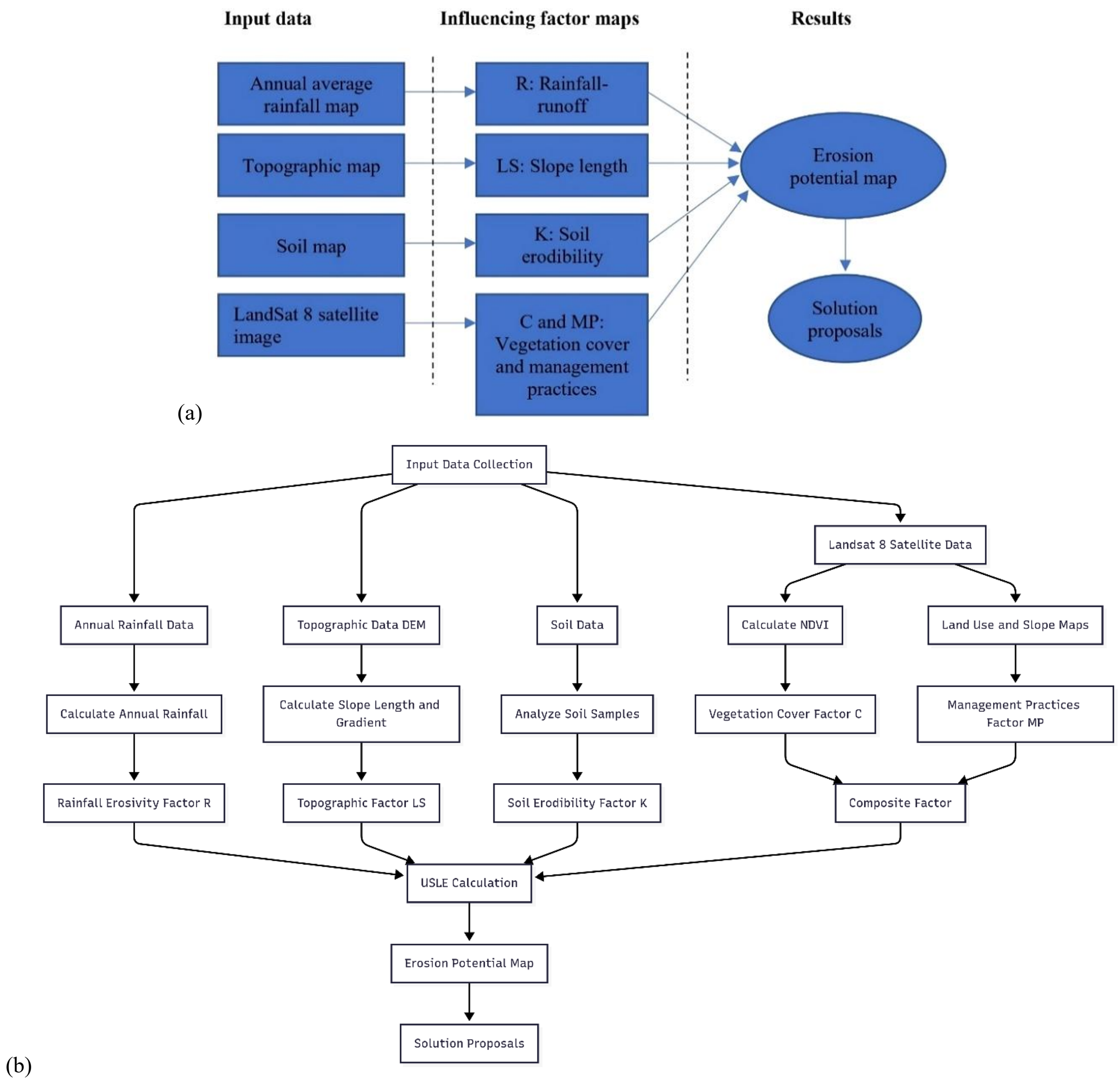

Figure 2. (a) Workflow for assessing areas at risk of soil erosion and (b) Flowchart shows the process of the methodology

3.2. Calculating the Rainfall Erosivity Factor (R)

Detailed rainfall intensity data were unavailable owing to the difficulties in collecting meteorological and hydrological data in the study region. Therefore, soil erosion was modelled based on the annual average rainfall (P) and calculating the rainfall erosivity factor using rainfall quantities and the number of rainy days over consecutive years. The only meteorological and hydrological data related to water-induced soil erosion provided by the network of stations were daily rainfall data. Therefore, we compiled the average monthly and annual rainfall and the number of rainy days using data from multiple years. An interpolation algorithm was used to generate an average annual rainfall distribution map for the study area based on the meteorological data and the average annual rainfall distribution. The average rainfall was calculated using the inverse distance weighting (IDW) interpolation technique. The rainfall erosivity factor was calculated after obtaining the interpolated annual average rainfall map as follows [37].

$$R = 0.548257 \times P - 59.5 \quad (1)$$

where R represents the rainfall erosivity factor (MJ mm/ha·h), and P denotes the annual average rainfall (mm/year)

3.3. Creating Soil Erodibility Factor (K) Map

Soil erodibility (K factor) is the inverse of the resistance of the soil to erosion. The K factor is determined as the amount of soil loss per unit of rainfall erosivity under standard conditions (i.e., a slope length of 22.4 m, 9% slope gradient, and furrow planting along the slope). The resistance of soil to erosion is highly complex and depends on the properties of the soil, such as structure, stability, permeability, organic matter content, clay mineral content, and chemical composition. The soil types in the study area were identified, and relevant documents and soil maps for the region were collected to create the oil erodibility map. This map of the Luong Son District reflects the erodibility of the different soil types in the area. We collected soil samples from the field and analysed their texture composition, organic matter content, permeability, and soil structure to determine the soil erodibility in the Luong Son District. The soil erodibility was determined based on variables that were measured and calculated from erosion monitoring plots due to resource constraints. The reader can refer to prior studies for more details [37, 46].

3.4. Creating Topographic Factor (LS) Map

The impact of topography on soil erosion in the USLE was calculated using the topographic factor (LS). Erosion increases with increasing slope gradient, which is represented by the slope length factor (L). Slope length is defined as the horizontal distance along the ground surface to the point where runoff begins that distinctly concentrates on the rills.

The slope factor (S) indicates the influence of the slope gradient on erosion. We used the following formula to calculate the slope length and gradient [47]:

$$L = \left(\frac{l}{22.13}\right)^{m} \quad (2)$$

where L is the slope length factor, l is the slope length, and m is a constant determined based on the rill erosion ratio in the study area. We selected m = 0.5m for the mountainous regions with slopes mostly above 5% and less than 21%,[48]. The topographic factor was determined as follows:

$$L = \left(\frac{l}{22{,}13}\right)^{0.5} (0.065 + 0.045S + 0.0065S \times S) \quad (3)$$

where S is the slope gradient (%).

3.5. Creating Vegetation Cover Management Factor (CP) Map

The effect of vegetation cover on soil erosion was represented using the land cover factor (C). Vegetation protects the soil by reducing the kinetic energy of rainfall, strengthening soil structure, increasing soil permeability, and mitigating or preventing runoff. The C factor is defined as the ratio of soil loss from an area with a specific amount of vegetative cover to soil loss from a bare area under similar conditions. The vegetation cover values range from 1 for bare soil to 1/1000 for forest land. The C factor was estimated using remote sensing data, specifically the normalized NDVI, as referenced in studies by [41, 42, 49]. These studies have employed NDVI to derive the C factor for soil erosion modelling. However, it's important to note that the C factor values estimated from remote sensing data have not been directly compared with values obtained from empirical field data, which may introduce uncertainties in soil erosion predictions [40]. In this study, we utilized the method proposed by De Jong (1994) to determine the C factor from Landsat 8 satellite imagery. De Jong's approach involves establishing a linear relationship between NDVI values and the C factor, facilitating the estimation of soil erosion risk based on vegetation cover derived from satellite data. We used De Jong’s formula to calculate the vegetation cover [50, 51]:

$$C = 0.43 - 0.805 * NDVI \quad (4)$$

where $NDVI$ is the normalised difference vegetation index and is calculated as follows:

$$NDVI = (NIR - Red)/(NIR + Red) \quad (5)$$

where *NIR* and *Red* are the near-infrared and red bands in remote sensing images, respectively. Landsat 8 imagery with a 30 × 30 m resolution, captured on 28 August 2024, was used for the calculations. The management practices were represented as the ratio of soil erosion on bare land without any soil conservation measures applied to that on cultivated land where soil conservation measures have been applied. The management practices were determined using two maps, the current land use and the slope gradient maps, to establish the management practices values. A composite map of the soil erosion due to vegetation cover and management practices was created by multiplying the land cover and management practices maps.

3.6. Soil Erosion Risk Map

The soil erosion risk was calculated using the USLE method. This equation was used to estimate the average annual soil erosion rate based on influencing factors such as rainfall, soil type, slope gradient, and land use practices.

$$A = R * K * (L * S)(C * MP) \quad (6)$$

where A represents the annual soil loss (tons/ha/year), R is the rainfall erosivity factor (MJ mm/ha·h), K is the soil erodibility (tons·ha·h/ha·MJ mm), L is the slope length, S is the slope steepness, C is the vegetation cover (representing the soil protection provided by vegetation, crops, and cultivation systems), and MP is the management practices representing the soil protection provided by the erosion control measures.

3.7. Study Area

The data from the soil erosion risk map were used for calculation and analysed according to the Vietnamese national standard, which provides methods and formulas for quantifying soil erosion due to rainfall, which is similar to the USLE approach [52]. The results were used to categorise the level of soil erosion, which are shown in Table 1.

Table 1. Classification of soil erosion levels

Classification Symbol	Average Soil Erosion (ASE) (tons/ha/year)	Evaluation
I	ASE ≤ 1	No erosion
II	1 ≤ ASE ≤ 5	Light erosion
III	5 ≤ ASE ≤ 10	Moderate erosion
IV	10 ≤ ASE ≤ 50	Severe erosion
V	ASE ≥ 50	Very severe erosion

4. Results and Discussions

4.1. Mapping the Factors Influencing Soil Erosion (R, K, LS, CP)

4.1.1. Erosion Due to Rainfall-Runoff

We used GIS interpolation tools, using the average rainfall from seven stations across Hoa Binh Province for the period of 2016–2023 as input data to calculate the isohyets for constructing the rainfall erosion factor map.

Table 2. Average rainfall (cm) at meteorological stations in Hoa Binh province (general statistics office of Vietnam, 2021)

Station \ Month	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Annual Avg.
Hoa Binh Meteorology	5.1	0.6	4.4	9.9	24.2	15.4	42.4	40.3	21.9	22.3	3.9	2.9	193.2
Mai Chau Meteorology	3.4	0.3	3.1	9.0	19.7	14.3	35.7	51.8	23.7	20.9	2.1	2.0	186.0
Kim Boi Meteorology	6.7	2.1	6.1	11.1	21.8	20.8	41.8	47.6	27.5	28.8	6.3	3.7	224.2
Chi Ne Meteorology	6.4	1.6	5.3	10.2	13.9	15.5	32.4	42.1	27.1	29.2	5.3	2.3	191.3
Lac Son Meteorology	7.7	1.6	4.8	10.1	18.3	17.2	38.4	44.4	29.2	21.9	4.0	3.9	201.5
Hung Thi Meteorology	6.9	1.4	3.4	9.9	14.8	14.1	33.3	38.1	25.2	24.7	3.5	2.5	177.7
Lam Son Meteorology	5.4	0.9	4.5	7.3	15.0	17.1	40.2	43.7	19.0	22.6	4.0	3.3	183.1

The average rainfall was calculated using the inverse distance weighting interpolation technique. The isohyetal regions were then generated. The boundary map of the Luong Son district was overlaid on the rainfall map, the study area was clipped, and the rainfall erosion factor map for the Luong Son district in Hoa Binh Province for 2016–2023 was established using Equation 1.

Figure 3 shows the average annual rainfall ranged from 1768.5 to 1854.8 mm in the Luong Son District during the study period. The rainfall primarily concentrated in the northwest of the district, in the Hoa Son Commune, Tan Vinh Commune, and Luong Son Town. The highest annual rainfall recorded was 1854.8 mm, corresponding to a rainfall erosion factor of 957.407 (MJ mm/ha·h). The rainfall in the northeast, southeast, and southwest areas was medium–high. The lowest annual rainfall was approximately 1768.5 mm in the southern Luong Son District in the Thanh Cao and Thanh Son Communes, corresponding to a rainfall erosion factor of 910.092 (MJ mm/ha·h).

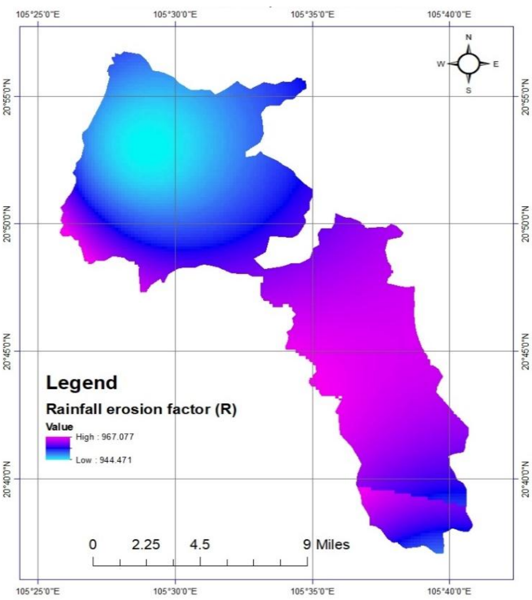

Figure 2. Rainfall erosion (R) map of Luong Son District for 2016–2023

4.1.2. Soil Erodibility (K)

We identified the soil types to create a map of the soil erodibility in Luong Son District, Hoa Binh Province, using field surveys and GIS technologies, as well as collecting data. The results are shown in Table 3.

Table 3. Statistical results of soil types in Luong Son District and erodibility of each soil type

No.	Symbol	Soil Group	Soil Type	Area (ha)	K-Factor
1	Pg	Alluvial	Gley Alluvial Soil	1154.63	0.34
2	P		Unfertilized Alluvial Soil	708.15	0.3
3	Py		Stream Alluvial Soil	347.09	0.44
4	Fl	Red-Yellow	Red-Yellow Soil Modified by Wet Rice Cultivation	4145.69	0.28
5	Fs		Red-Yellow Soil on Shale Rock	21872.38	0.31
6	J	Swampy	Swampy Soil	150.72	0.44
7	Fk	Red-Brown	Red-Brown Soil on Basaltic and Intermediate Magma	5436.87	0.22
8	Fv		Red-Brown Soil on Limestone	461.10	0.23
9	Fp	Yellow- Brown	Yellow-Brown Soil on Ancient Alluvium	2717.98	0.23
10	D	Valley-Colluvial	Valley Soil Formed by Colluvial Deposits	1570.10	0.28
11	Fq	Light Yellow	Light Yellow Soil on Sandstone	8082.76	0.26
12	Nui da, Song	Other Types	Rocky Mountains, Rivers, Lakes	341.93	0.1

A soil erodibility value was assigned to each soil type in Luong Son District to compile a soil erosion map. The soil erodibility ranged from 0.1 to 0.44 (Figure 4), with most of the values falling between 0.29 and 0.34 (58.33%). The soil erodibility values minimally varied, indicating that the erosion resistance of the soil types in the region was similar. Only the Py soil type had a distinctly different soil erodibility, but this soil type covered only 347.088 ha.

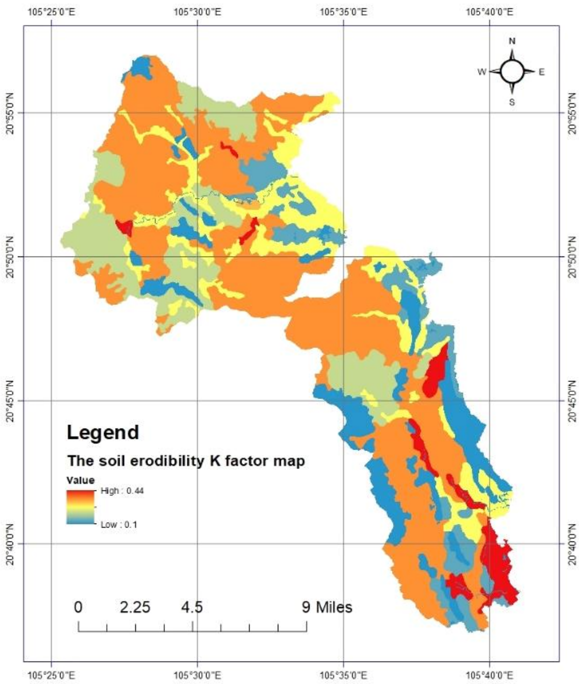

Figure 3. Soil erodibility map of Luong Son District, Hoa Binh Province

4.1.3. Topographic Erosion Factors: Slope Length and Steepness

A GLS DEM model and GIS technologies were used to create the topographic erosion factor map (LS) of Luong Son District (Figure 5). The topographic erosion factor, commonly known as the LS-factor, is a crucial component in soil erosion modeling. It combines slope steepness (S) and the effects of slope length (L) on soil erosion. The slope values in the district were interpolated from the DEM map, and a diagram of the slopes in Luong Son District was produced (Elshewy et al., 2024; Osama et al., 2021, 2023, 2024; Sadek et al., 2020) using Equation 3. The resulting map reflected the slope length and steepness. Figure 5 shows that the length and steepness of the slopes widely varies across the district. The slopes are steep and long in the middle and western regions of Luong Son District, whereas moderate values are observed in the northern and western regions. The slope steepness and length are smaller in the eastern region due to the flat or gently sloping terrain.

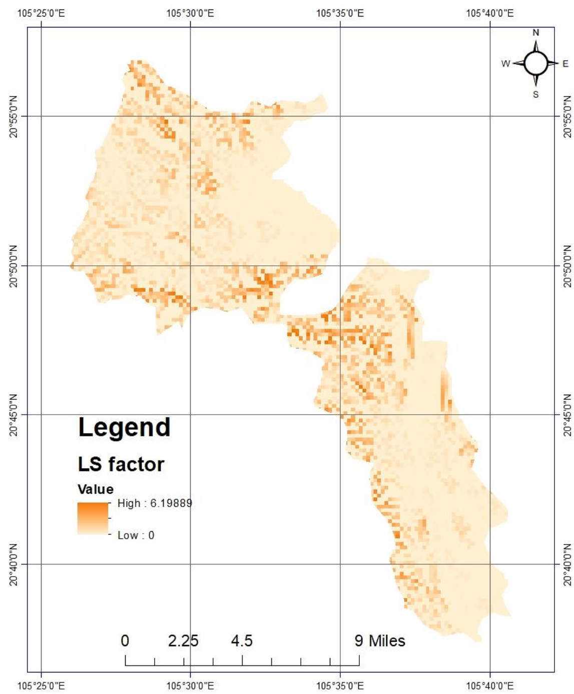

Figure 4. Distribution map of the Erosion Factor (LS) due to slope length and steepness of the topography in Luong Son District, Hoa Binh Province

4.1.4. Land Cover and Management Practices (C and P Factors)

The C-factor (cover and management factor) measures the combined effect of land cover, crops, and crop management practices on soil erosion. C-factor values range from 0 to 1, where lower values indicate greater protection against erosion, while higher values represent increased vulnerability. The P-factor (support practice factor) reflects techniques that reduce runoff and erosion, such as contour plowing, terracing, and strip cropping. P-factor values range from 0 to 1, where lower values indicate more effective erosion control practices; conversely, a value of 1 represents unmanaged areas.

In this study, we used Landsat 8 imagery (30 m spatial resolution) acquired on August 28, 2024 to calculate the NDVI for the study area (Figure 6). The NDVI values were converted to C-factor values using Equation 4. The P-factor was derived from a DEM by extracting slope information and assigning P-values according to both slope gradient and land use characteristics, with spatial processing performed in ArcGIS 10.8. The final CP-factor map (Figure 6) was generated by multiplying the P and C factor raster maps. The CP-factor mapping results reveal significant spatial variability across the landscape. Most areas of Luong Son District show lower CP values, corresponding to dense vegetation or effective erosion control practices. However, higher CP values are observed in the upper northern region and at the junction between two landmasses in the central area (Figure 6), likely due to bare soil or inadequate agricultural management practices.

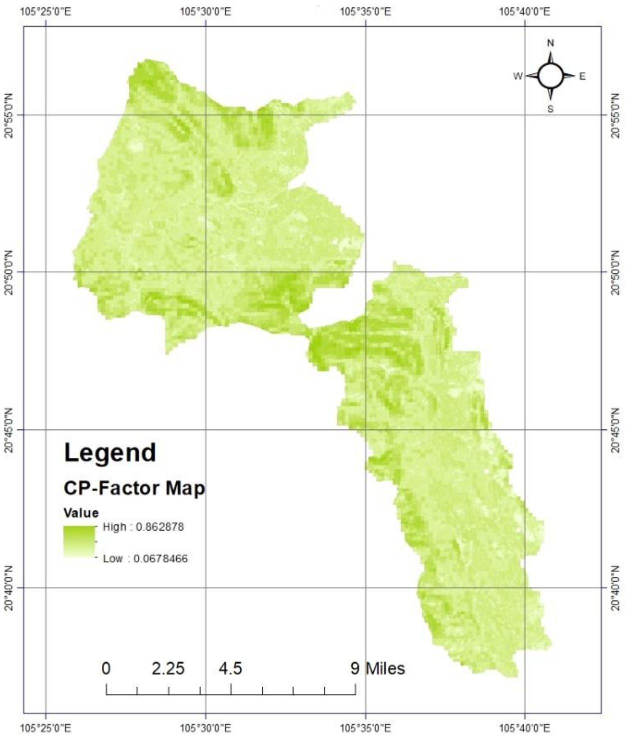

Figure 5. CP-factor map integrating land cover and management practices in Luong Son District, Hoa Binh Province

4.2. Creation of the Potential Soil Erosion Map for Luong Son District, Hoa Binh Province

The four USLE factor maps—rainfall erosivity (R), soil erodibility (K), slope length-steepness (LS), and cover-management (CP)—were stored as separate GIS layers. These layers were multiplied (Equation 6) to calculate annual soil loss (A), then converted from raster to vector format. The resulting potential soil erosion map was classified into risk levels using the Vietnamese Standard TCVN 5299:2009 (Figure 7), revealing spatial patterns of erosion susceptibility across Luong Son District.

Based on the soil erosion potential map, the research team compiled erosion area statistics across five levels, as shown in Table 4.

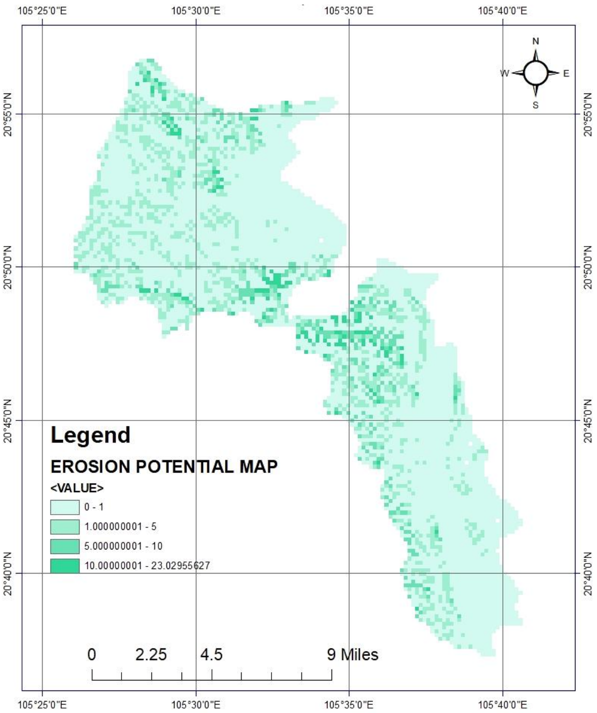

Figure 6. Potential Erosion Map of Luong Son District

Table 4. Classification of soil erosion potential in Luong Son District, Hoa Binh Province, Vietnam

No.	Soil Erosion Class Symbol	Average Annual Soil Erosion (t. ha^{-1})	Area (ha)	Percentage (%)
1	I	up to 1	23747.61	65.09
2	II	more than 1 to 5	7276.79	19.95
3	III	more than 5 to 10	2777.82	7.61
4	IV	more than 10 to 50	2679.78	7.35

Overall, Luong Son District is characterized by low mountainous terrain, with an average elevation of 251 meters above sea level. Consequently, 65.09% of the area (23,747.61 ha) exhibits no erosion, primarily in Cao Thang, Thanh Luong, and Nhuan Trach communes. Weak erosion affects 7,276.79 ha (19.95%), concentrated in Truong Son, Tan Vinh, and Cao Ram. Moderate erosion covers 2,777.82 ha (7.61%), interspersed with strong erosion in scattered areas of Tien Son, Tan Thanh, Cao Ram, and Hop Hoa. Strong erosion dominates 2,679.77 ha (7.35%), notably in Tien Son, Lien Son, Lam Son, Cao Ram, and Cao Duong communes, where mid-level mountains and limestone hills intersect with small to medium-sized fields.

The research team validated the potential soil-erosion map through in-situ datasets checked at 20 check points along the roadway corridor traversing the communes of Long Son, Hop Chau, Trung Son, Tien Son, Cu Yen, Cao Ram, and Tan Vinh (Figure 8). Due to space constraints in the paper, only key results are presented rather than extensive imagery and ancillary data. A supplementary detailed table including geographic coordinates, erosion level on the map, field verification, and accuracy assessment was added for extra explanations and verification. With the field evaluation conducted at twenty checkpoints, seventeen out of twenty points (85 %) met the accuracy criteria, demonstrating that the generated soil-erosion map achieves a satisfactory level of precision. The study's outcomes provide local authorities with a robust dataset and methodology to assess and reference the impacts of soil erosion on agricultural production. Moreover, the research offers recommendations for appropriate land-use planning strategies in subsequent development phase.

Recent work by Thi My Linh et al. (2024) focused on runoff and erosion from unpaved road segments in Truong Son Commune, Luong Son District. Their study found that road surface runoff coefficients ranged from 24–32% across 24 rainstorms, and sediment production was strongly correlated with both storm precipitation and surface runoff. Notably, they observed that sediment collected at the base of cut slopes was 52–97% of that from road surfaces, with greater sediment yield in areas of increased hillslope convergence [53-55]. In comparison, the present study provides a broader landscape perspective, quantifying the spatial extent of erosion intensities across the district, rather than focusing solely on road infrastructure. Both studies, however, highlight the critical role of topography, especially slope and convergence, in determining erosion risk.

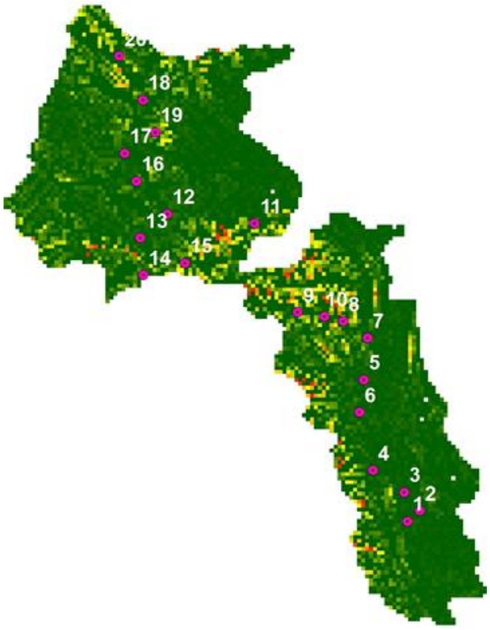

Figure 7. In-situ check-points distribution diagram through the study area

Dung et al. (2019) investigated runoff generation and soil erosion in Acacia plantations of different ages within Luong Son. They reported that younger plantations (1-year-old) exhibited higher runoff coefficients and soil loss compared to older (5-year-old) stands, indicating that vegetation maturity and ground cover significantly reduce erosion rates [56]. The present study similarly identifies areas with minimal erosion as those with stable soil structure and substantial vegetative cover, underscoring the protective effect of established vegetation.

Broader regional studies in northern Vietnam have documented highly variable soil erosion rates, with values ranging up to 2,635 t ha^{-1} yr^{-1} depending on land use, slope, and watershed characteristics. These studies also note that field plot measurements often yield higher erosion rates than catchment-scale assessments due to the buffering effects of paddy fields and landscape features [57, 58]. The present study's district-level mapping of erosion intensity is consistent with these findings, showing that strong erosion is concentrated in areas with steep slopes, shallow soils, and fragmented fields conditions known to exacerbate soil loss.

The present study corroborates earlier findings regarding the influence of slope, land cover, and land use on erosion dynamics in mountainous northern Vietnam. However, it advances previous work by providing a comprehensive spatial quantification of erosion intensities across communes, rather than focusing on specific land uses or infrastructure. The convergence of evidence from multiple studies, including the present one, emphasizes the necessity of targeted soil conservation strategies, which motivated us to propose soil erosion mitigation strategies in Section 5.

5. Soil Erosion Mitigation Strategies

The results demonstrate that while soil erosion rates in Luong Son District remain below critical thresholds, prolonged inaction could lead to severe degradation. To address this, we propose three mitigation strategies based on remote sensing and GIS-derived erosion risk maps: (1) structural measures, (2) biological interventions, and (3) sustainable land management practices. The following sections will discuss these strategies in detail.

5.1. Structural Measures

Structural solutions involve the use of physical structures and techniques to control soil erosion.

5.1.1. Barriers Construction

Soil erosion prevention commonly employs barriers constructed from local materials (wood, branches, or bamboo), installed horizontally along contours and secured with stakes. Barrier spacing is adjusted based on slope gradient—steeper slopes require closer intervals. Contour lines are identified using an A-frame (three wooden/bamboo sticks, a rope, and a stone), which, when calibrated, guides barrier placement [59, 60].

5.1.2. Trenches and Banks

Farmers can use stones to build retaining walls that divide slopes into smaller sections, reducing water flow speed and force. Spacing depends on slope gradient: 3–4 m for steep slopes and 5–6 m for moderate slopes. In medium-depth soils, contour trenches reduce runoff and improve infiltration. Where trenching is impractical (rocky/shallow soils), stone walls along contours slow water flow. Construction should begin at the hilltop to prevent runoff damage [60].

5.1.3. Terraces

Terracing effectively controls erosion but requires significant time and effort. Terrace dimensions depend on slope gradient: gentler slopes require wider terraces, while steeper slopes need narrower ones. Construction involves: (1) moving topsoil aside, (2) spreading excavated soil outward to form a gradual slope, (3) building a small ridge on the outer edge, and (4) digging drainage channels along the inner edge. Finally, the fertile topsoil is returned [61].

5.1.4. Check Dams and Silt Traps

Check dams and silt traps in drainage ditches or gullies reduce flow velocity, minimize erosion, and enhance water infiltration. Check dams—small, easily maintained structures—are built along contours using stakes and woven materials (e.g., bamboo or branches) reinforced with stones. Silt traps (>1 m^3) excavated in water channels intercept runoff and promote sedimentation [60].

5.1.5. Structure Maintenance

Structural maintenance is critical for sustained effectiveness. Contour trenches require periodic sediment removal, particularly following heavy rainfall. Vegetation components demand specific attention: (1) trees and grasses need pruning to avoid crop shading, (2) green manure leaves should be soil-incorporated for rapid decomposition, and (3) contour ridge grass must be kept short (≤10 cm) to maintain livestock palatability.

5.2. Biological Strategies

Biological strategies for soil erosion control utilize organic materials and cultivated vegetation to protect and stabilize soils. These approaches not only prevent erosion but also enhance soil fertility and deliver additional ecosystem benefits.

5.2.1. Living Barriers

Living barriers represent an effective biological strategy for soil erosion control, particularly in deforested areas. Farmers can establish fast-growing vegetation—including [leguminous tree species], Pennisetum purpureum (elephant grass), and pineapples—whose deep root systems stabilize soil and improve structure. These barriers are optimally deployed in zigzag patterns along contour trenches, combining water retention with erosion control. Key benefits include: (1) physical reduction of runoff velocity and sediment trapping, (2) enhanced soil fertility through organic matter input, and (3) production of valuable byproducts (fodder, fuelwood, fruits) [62].

5.2.2. Contour Cultivation with Green Strips

Contour cultivation with green strips integrates contour farming with permanent vegetative barriers. Crops are cultivated between strips of fast-growing leguminous trees or grasses on terraces, which function as live erosion barriers while enhancing soil fertility. Selected species (primarily multi-purpose legumes and shrubs) must exhibit: (1) rapid growth, (2) deep root systems, and (3) economic utility (fodder, fuelwood, construction materials). The system provides additional agronomic benefits through nitrogen fixation and green manure from leguminous leaves [63].

5.3. Sustainable Land Use

Sustainable land management practices aim to optimize soil health while minimizing disturbance. Based on remote sensing (RS), local geoid heights modeling, and GIS-assisted erosion risk assessment, we recommend: (1) restricting agricultural expansion on steep slopes through gradual conversion to perennial crops with superior ground cover; (2) expanding forested areas via policy-driven reforestation of vulnerable slopes; (3) regulating spontaneous migration through structured settlement planning; and (4) conducting comprehensive natural and socio-economic surveys to inform land-use planning.

6. Conclusions

This study demonstrates that integrating the USLE model with remote sensing and GIS technologies provides an effective framework for quantifying and mapping soil erosion risk in Luong Son District. The methodology enabled creation of detailed spatial distribution maps for all erosion factors (R, K, LS, and CP), culminating in a comprehensive district-wide erosion assessment.

Key findings reveal that 65.09% of the study area experiences no erosion, predominantly in flat and midland regions. Erosion affects the remaining areas with varying intensity: 19.95% light erosion, 7.61% moderate erosion, and 7.35% severe erosion. The most vulnerable zones are concentrated in the communes of Tien Son, Lien Son, Lam Son, Cao Ram, and Cao Duong, where mid-mountain topography and limestone terrain predominate.

While these results provide valuable insights for land resource management, several limitations should be acknowledged. The analysis relied on medium-resolution (30×30m) remote sensing data and DEMs for calculating C and LS factors. Data constraints also included limited coverage from rainfall monitoring stations. Furthermore, the assessment did not incorporate geological and geomorphological factors or rainfall-runoff characteristics that influence erosion processes. Despite these limitations, the study outcomes offer:

- A scientific basis for soil conservation planning
- Critical inputs for sustainable land-use strategies under climate change
- Reliable reference data for water resource management

Future research should focus on:

- Incorporating higher resolution satellite imagery and DEMs
- Expanding the rainfall monitoring network
- Integrating geological and geomorphological parameters
- Validating model results with field measurements

This approach establishes a replicable methodology for erosion assessment in similar mountainous regions of Southeast Asia, while providing actionable insights for local sustainable development planning.

7. Declarations

7.1. Author Contributions

Conceptualization, P.T.T., L.H.C., and T.T.T.; methodology, P.T.T. and T.T.T.; software, P.T.T., M.A.E., M.F., and N.O.; validation, P.T.T., T.T.T., M.F., and M.A.E.; formal analysis, N.O., M.A.E., L.H.C., and T.T.T.; investigation, P.T.T., L.H.C., and M.F.; resources, P.T.T., L.H.C., M.A.E., and T.T.T.; data curation, P.T.T., L.H.C., and T.T.T.; writing—original draft preparation, P.T.T.; writing—review and editing, M.F., N.O., and M.A.E.; visualization, P.T.T., M.F., and N.O.; supervision, P.T.T. and M.F.; project administration, P.T.T. and M.F.; funding acquisition, M.F. and N.O. All authors have read and agreed to the published version of the manuscript.

7.2. Data Availability Statement

The data presented in this study are available on request from the first or corresponding author.

7.3. Funding

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7.4. Conflicts of Interest

The authors declare no conflict of interest.

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