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A NOVEL APPROACH OF NEURAL NETWORKS AND USLE IN SMART SOIL EROSION MODELING, CASE STUDY IN SOUTHERN COASTAL OF VIET NAM

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ABSTRACT

Soil erosion is a critical environmental issue with far-reaching consequences. To tackle this challenge effectively, innovative approaches are required for accurate prediction, monitoring and mitigation, such as the integration of remote sensing data and geographic information systems (GIS). In recent years, the application of machine learning techniques in smart soil erosion modeling has gained significant attention due to its ability to learn complex patterns from data without explicit programming. This paper adopted one of the neural networks - the Long Short-Term Memory (LSTM) to analyze temporal variations in erosion patterns over time, aiding in understanding erosion dynamics. Furthermore, another common soil erosion model - the Universal Soil Loss Equation (USLE) was investigated to predict annual soil loss. Our data were extracted from remotely sensed data (DEM - Digital Elevation Model and MODIS) and vector data of the study area. Our case study is located in the Southern coastal areas of Vietnam where the possibility of annual soil loss is relatively high due to the conditions of steep terrain and heavy seasonal rainfall. Our preliminary results showed that the soil erosion process is unevenly distributed over the entire examined area (Quang Nam Province): the northern region is the most highly affected area than the others. The accuracy of the current soil erosion state map and soil erosion potential map showed satisfactory performance. The integration of LSTM with USLE in a smart soil erosion model has provided valuable insights for implementing efficient soil conservation strategies and adaptive management practices, crucial for mitigating erosion's adverse effects on the environment and agricultural productivity. However, challenges related to data availability and interpretability of black-box models warrant further investigation for the continued advancement of smart soil erosion modeling.

1. INTRODUCTION

Soil erosion is a pervasive natural process that results in the detachment, transport and deposition of soil particles from the Earth's surface. It is driven by various factors, including rainfall, wind, topography, land use practices and vegetation cover. Soil erosion has far-reaching implications for both the environment and human societies. It can lead to reduced soil fertility, land degradation, sedimentation of water bodies and the contamination of aquatic ecosystems. As such, understanding and mitigating soil erosion is crucial for sustainable land management and environmental conservation.

In soil erosion research, various models play a pivotal role in deciphering the intricate dynamics of erosion processes, offering valuable insights for environmental conservation and sustainable land management. The two most common models are the Universal Soil Loss Equation (USLE) (Wischmeier et al., 1965) and the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997), which use various physical features of soil, water and terrain influenced in the erosion process. Furthermore, the Soil and Water Assessment Tool (SWAT), developed by Arnold et al., in 1998, is a comprehensive model used to simulate hydrology, water quality and erosion in large watersheds. It considers various factors such as land use, climate, soil properties and management practices to estimate erosion rates (Arnold et al., 1998). There are several Geographic Information System (GIS) projects-based erosion models that integrate GIS technology and Remotely Sensed Data for spatial analysis of soil erosion. They combined various data sources and analytical tools to assess erosion risks and develop conservation strategies (Foster et al., 2001; Montgomery, 2007; Dabral et al., 2012). The European Soil Erosion Model (EUROSEM), developed by Morgan et al., in 1998, focuses on predicting sediment transport from fields and small catchments, providing dynamic insights into erosion processes (Morgan et al., 1998). These models form a suite of tools that researchers leverage to analyze and address soil erosion challenges. They offer valuable means for understanding, assessing and mitigating soil erosion's impact on the environment and agricultural lands.

To be more specific, one of the most widely employed models is the Revised Universal Soil Loss Equation (RUSLE). This model, developed by Renard and his colleagues in 1997, provides a comprehensive framework for predicting soil erosion by water. It factors in critical variables such as rainfall, soil erodibility, slope characteristics, land cover and erosion control practices. RUSLE has proven to be a fundamental tool for assessing soil erosion risks and guiding conservation planning efforts, making it a cornerstone in the field of soil erosion research (Renard et al., 1997).

Another influential model worth mentioning is the Universal Soil Loss Equation (USLE). Originally developed by Wischmeier and Smith in 1965, this model provides a framework for estimating soil erosion caused by rainfall and runoff. USLE takes into account various factors, including rainfall erosivity, soil erodibility, slope length and steepness, cover and management practices and support practices to predict soil loss. The USLE model has been instrumental in assessing soil erosion risks, guiding land-use planning and facilitating the design of erosion control strategies, making it a seminal contribution to soil erosion research (Wischmeier et al., 1965). While the Universal Soil Loss Equation (USLE) is a widely used and valuable tool for estimating soil erosion, it does have some disadvantages and limitations, such as it relies on average values of various factors like rainfall, slope and land use but, does not explicitly account for variations in climate conditions like extreme weather events or changes in rainfall patterns; otherwise, there are several concerns of precision and scale - dependency of this model for large areas.

Long Short-Term Memory (LSTM) models, a type of recurrent neural network (RNN), can potentially complement the Universal Soil Loss Equation (USLE) in certain aspects, particularly in addressing the limitations associated with the USLE's temporal dynamics. In detail, LSTM models can seamlessly integrate remote sensing data, climate information and historical erosion data to create more robust predictive models. This integration allows for a more comprehensive analysis of erosion processes. Additionally, LSTM models are well-suited to capture extreme weather events and their impact on soil erosion. They can help assess how climate variability and extreme rainfall events contribute to soil loss, which may not be adequately addressed by the static USLE model. Furthermore, LSTM models can be used to optimize and calibrate USLE parameters based on historical data and temporal patterns, ensuring a more accurate representation of the dynamic erosion processes.

This study integrates the USLE and LSTM to analyze physical factors of the soil erosion process at a regional scale. This process is assessed in Southern Central Vietnam to identify locations of erosion and estimate or predict the potential mass and volume of eroded soil in the research area. The accuracy of the model is handled by using the most current research.

2. METHODOLOGIES

2.1 The study area overview

Our study area extends along the coastal area of Southern Centre Vietnam from the city of Da Nang to the province of Binh Thuan, which is approximately 3,307,000 ha large (see Figure 1). This area has been involved in the recent soil erosion research project in 2022 of which results are used to validate our ones, respectively (Nguyen Duc Lam et al., 2020).

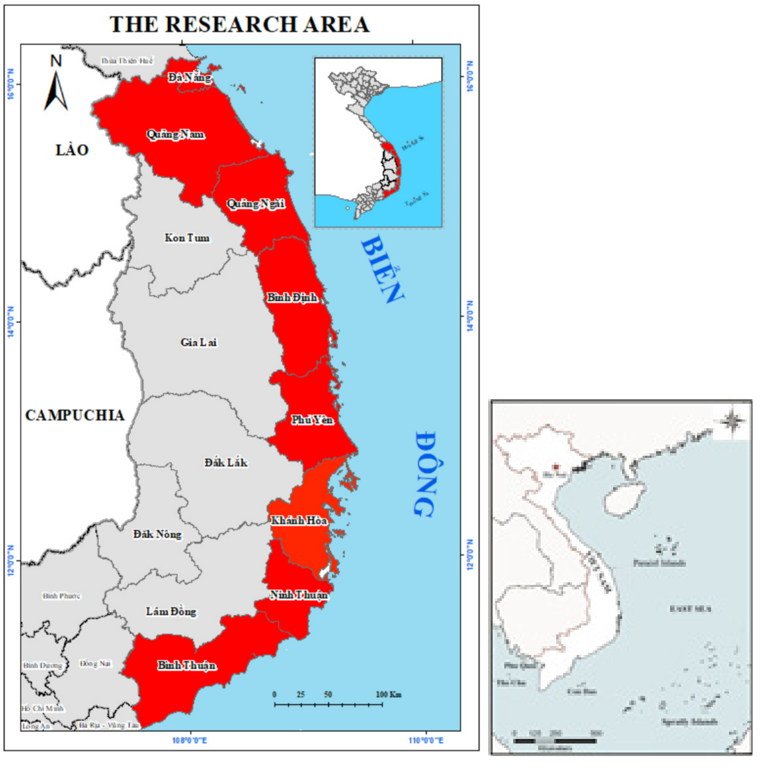

Figure 1. The study area (red shade).

The research area exhibits distinctive geographical and climatic features. To the east, it gently slopes towards the East Sea, featuring numerous deep-sea regions, while its western region enjoys a more subdued topography. Notably, this region encompasses four prominent peaks exceeding

1,000 meters in elevation, including Vong Phu, Hon Me, Hoan Con and Hoan Giao. Moreover, the topography includes transverse mountain ranges that partition the coastal region into narrow plains, giving rise to a succession of peninsulas, lagoons and numerous beaches. The climate is characterized by a climate influenced by the Annamite Range. During the summer, it experiences southwest monsoon winds, while the fall and winter seasons bring regional rains shaped by the complex interplay of topography and the influence of the tropical convergence zone. This climate results in considerable annual precipitation, particularly in areas such as Da Nang and Quang Nam, with the west part reaches of the Thu Bon river witnessing the most substantial rainfall. Nevertheless, the southern part reaches of the coastline often grapples with extended dry periods, contributing to arid conditions, notably in Ninh Thuan and Bình Thuan.

The hydrological system is characterized by a network of relatively short rivers, often marked by steep gradients, which discharge directly into the sea. However, the spatial and temporal distribution of these rivers is non-uniform, leading to fluctuations in water availability. Consequently, certain areas experience water scarcity during specific seasons, while others contend with seasonal water excesses. The brevity and steep inclines of these watercourses also render the region susceptible to flash floods during the rainy season and prolonged dry spells during the dry season, significantly impacting the daily lives, economic activities and overall livelihoods of the local populace. Within this expanse, agricultural land accounts for roughly 16.6 % of the total area, while forested land encompasses about 36.7 %. Specialized land usage represents approximately 6.6 % and residential land occupies roughly 1.3 %. Hills, mountains and sandy terrain collectively dominate the landscape, constituting roughly 83 % of the total area. These lands can be categorized into distinct groups, primarily divided into two primary systems: Alluvial soils deposited by rivers in the plains and Feralit - basaltic soils predicated on the varied geological foundations of the hilly regions.

The vegetation cover within the sandy expanses of the study area manifests substantial diversity in both species' composition and life forms. The vegetation can be categorized based on life forms, dividing it into grasslands, shrublands and forests. Shrubland stands out as the most prevalent and dominant vegetation type in the sandy terrain. Considering local conditions, the vegetation can be further classified into two fundamental categories: Vegetation distributed on dry sand and vegetation in areas subject to recurrent or frequent inundation, with the former predominating the landscape.

2.2 The process flowchart

Our model of mapping soil erosion prediction in the study area was accomplished by integrating the USLE with the LSTM algorithm in 5 steps: (1) Collecting and preparing data input; (2) Extracting 4 main sources of the model which were topography, soil, land use and climate – hydrological system; (3) Calculating parameters of the USLE (P, LS, K C, R); (4) Generating the soil erosion map and severe points; (5) Run the LSTM algorithm to determine most influenced factors and presenting the soil erosion hot spot map.

Figure 2 shows the flowchart of the study, where each color represents each step regarding different sources of data collection and extracted parameters. For example, topography was extracted from DEM and then used to determine slope, aspect and elevation. These indices, then, were used to calculate the parameters P and LS in the USLE model. They were also involved in the LSTM to identify the impact factors for the severe prediction of soil erosion hot spots. Other types of indices such as soil depth, soil AWC (available water capacity), vegetation (NDVI), rainfall and land use types were mainly extracted from satellite images (Landsat) and available regional maps. We also used several local reports for validation and data support. Details of each data collection will be presented in the next sections.

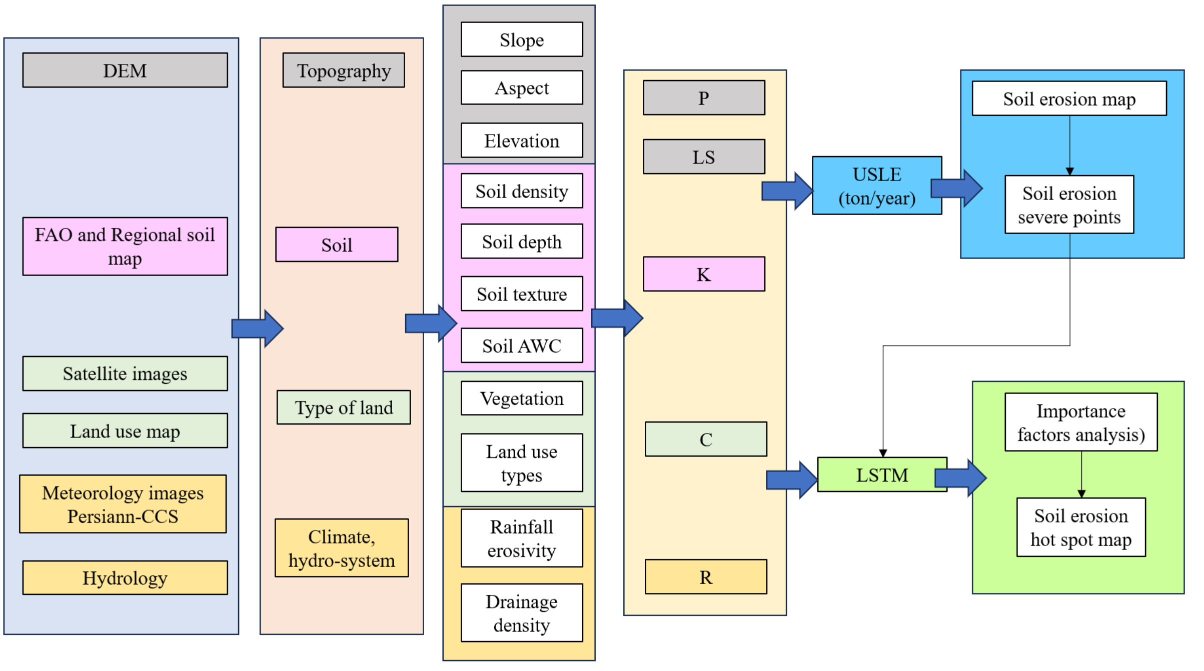

Figure 2. The flowchart of extracting and performing results.

2.3 The USLE model and key variables

The Universal Soil Loss Equation (USLE), established by Wischmeier & Smith in 1965 (Wischmeier et al., 1965), stands as one of the prevalent models employed for the computation of annual average soil erosion and the prediction of mean soil erosion on sloping terrains. The utilization of this model additionally facilitates the projection of variations in soil erosion attributed to changes within the agricultural system and the proposal or estimation of the efficacy of erosion control measures. An advantageous feature of this model lies in its ability to address the individual factors influencing soil erosion (rainfall, topography, soil characteristics, vegetation cover and tillage practices) in a closely interrelated manner, as manifested within the soil loss equation. Specifically, the equation is formulated as follows:

$$A = R \times K \times LS \times C \times P \text{ (ton/arc/year)} \quad (1)$$

where:

A: Annual soil loss (ton/ha/year)

K: Soil erodibility factor (ton.ha.h/ha/MJ/mm)

R: Rainfall erosivity factor (MJ.mm/ha.h/year)

LS: Topographic erosion factors (where L is sloping length in meters and S is sloping steepness in degrees)

C: Cover and management factor

P: Support practice factor

Table 1 represents the data sources and formulas to calculate each variable. In this study, we used QGIS software with its modules to extract, generate and perform their spatial patterns and the soil erosion map.

Table 1. USLE variables.

Variable	Formulas	Source
R	$R = 0.548257 \times P - 59.9$ P: the average annual rainfall; Unit (MJ.mm/ha/h/year)	Persian-CCS satellite images
LS	$LS = (\frac{x}{22.13})^m \times (0.0065 \times s^2 + 0.045 \times s + 0.053)$ where: x is sloping length, s is sloping steepness and m is field-parameter	DEM
K	$K = 0.0293 \times \left(0.65 - D_g + 0.24 \times D_g^2\right) \times r$ $r = e^{[-0.0021\frac{OM}{C} - 0.00037\left(\frac{OM}{C}\right)^2 - 4.02C + 1.72C^2]}$ where: OM is organic matter, C is the clay content in the soil, D_g is the average particle size of soils depending on the classes, such as: - Clay: The average particle size of clay is less than 0.002 millimeters. - Silt: The average particle size of silt ranges from 0.002 to 0.05 millimeters. - Sand: The average particle size of sand ranges from 0.05 to 2.0 millimeters.	Soil maps
C	$C = \frac{-NDVI + 1}{2}$ NDVI: Normalized Difference Vegetation Index	Landsat images
P	Human impacts regarding the slope characteristics. Table 2 illustrates that relationship.	DEM and land use map

Table 2. The P values.

Slope (degree)	P
0-2	0.6
2-5	0.5
5-8	0.5
8-12	0.62
12-26	0.7
16-20	0.8
>20	0.9

2.4 LSTM algorithm

Long Short-Term Memory (LSTM) is a type of recurrent neural network (RNN) architecture designed to address the vanishing gradient problem, a limitation of traditional RNNs (Hochreiter et al., 1997). LSTM networks are capable of learning and remembering over long sequences, making them well-suited for modeling and predicting time series data, such as temporal variations in soil erosion.

LSTM networks consist of memory cells, gates and connections that allow them to capture dependencies in data across various time steps. The key components of an LSTM cell include a cell state, input gate, forget gate and output gate. These components work together to manage the flow of information, decide what to forget and store or output information over time. This architecture enables LSTMs to handle long-range dependencies and effectively model sequential data. LSTM has found application in soil erosion modeling, particularly in addressing the temporal dynamics of erosion processes. Soil erosion is not a static phenomenon; it varies over time due to factors like rainfall patterns, land use changes and land management practices. LSTM can help capture and model these temporal variations (Minacapilli et al., 2018; Pham et al., 2019; Mohammadtaghi Avand et al., 2021). Below are several approaches that LSTM can be applied in soil erosion process research:

- *Temporal Erosion Predictions*: LSTM models can predict soil erosion rates over time, allowing researchers to understand how erosion patterns change seasonally and annually. This is crucial for effective land management and erosion control.

- *Climate Impact Analysis*: LSTMs can analyze the impact of changing climate conditions, such as variations in rainfall and temperature, on soil erosion. Understanding these relationships is vital for climate change adaptation strategies.

- *Land Use Changes*: LSTM models can track the impact of land use changes on erosion patterns. For example, they can assess how deforestation or urbanization affects soil erosion in specific regions.

- *Erosion Forecasting*: LSTMs are used to create erosion forecasting models, which provide early warnings and help in planning and implementing erosion control measures.

- *Data Integration*: LSTMs can incorporate diverse data sources, such as remote sensing data, rainfall records *and* soil characteristics, to provide a holistic understanding of the soil erosion process.

In this study, we used LSTM to predict soil erosion hot spots and patterns over time. We also analyzed the factors of USLE to determine which factor was most impacted by that process. This would help to enhance understanding of the soil erosion context in the study area and to suggest applicable solutions for local authorities.

2.5 Application of LSTM

The key components of the LSTM area:

- *Cell State (C_t):* The cell state is the main horizontal line running through the top of the LSTM. It serves as a memory unit that can store and retrieve information over long sequences. It allows LSTMs to capture long-range dependencies in data.

- *Hidden State (H_t):* The hidden state is the output at a given time step and can be thought of as the current "memory" of the LSTM. It is influenced by both the current input and the previous hidden state.

- *Input Gate (i):* The input gate is responsible for determining which information from the current input and the previous hidden state should be stored in the cell state. It uses a sigmoid activation function to output values between 0 and 1, where 0 means "forget" and 1 means "remember."

- *Forget Gate (f):* The forget gate decides which information to discard from the cell state. It considers the current input and the previous hidden state and uses a sigmoid activation function to determine what to forget.

- *Output Gate (o)*: The output gate regulates what information should be passed to the hidden state and, subsequently, to the output. It uses the sigmoid function to decide what to output and a tanh activation function to produce candidate values for the hidden state.

- *Candidate Values (C~t):* This represents the new information that can be added to the cell state. It is computed using a tanh activation function.

The operations within an LSTM cell are governed by the following equations:

$$i(t) = sigmoid(Wix(t) + UiH_{t-1} + bi) \quad (2)$$

$$f(t) = sigmoid(Wfx(t) + UfH_{t-1} + bf) \quad (3)$$

$$C_t = tanh(Wc(x(t) + UcH_{t-1} + bc) \quad (4)$$

$$C_t = f(t) \times C_{t-1} + i(t) \times C_t \quad (5)$$

$$o(t) = sigmoid(Wox(t) + UoH_{t-1} + bo) \quad (6)$$

$$H_t = ot(t) \times tanh\ (C_t) \quad (7)$$

In this study, our LSTM model used points extracted from the soil erosion map as the long-term memory (Cell state); the other variables generated from step 3 of each candidate time were involved in the LSTM as short-term memory (Input Gate). The model decided which insignificant factors would be sent to the "forget gate" and others would be accounted as "candidate values" in the "hidden state". A new set of predicted points were performed in the "output gate".

3. PRELIM RESULTS

3.1 Spatial patterns of USLE variables

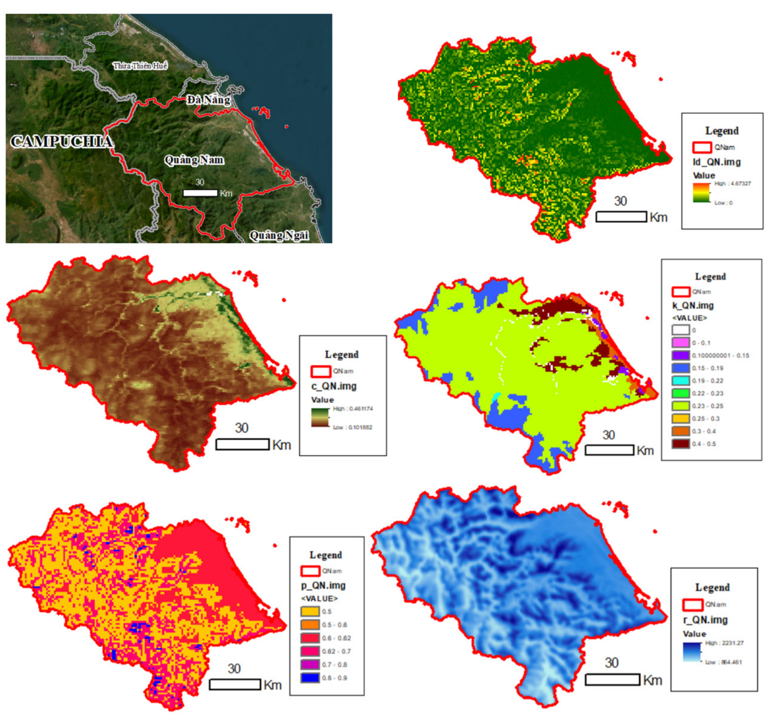

Figure 3. Our tested area - Quang Nam Province (top left) and the USLE variables (from left to right, top to bottom: LS, C, K, P and R).

Due to the high volume of data input and in order to test our proposed methods, we chose Quang Nam province as the testing site. Quang Nam province is in the North of the study area (Figure 3). Following the flowchart shown previously, we loaded data sources into QGIS and then used Raster Calculation to determine the spatial pixel values of each variable in the test site. Figure 3 represents our testing results of 5 variables of the USLE model: LS, C, K, P and R.

Generally, in terms of topography, Quang Nam province is characterized by its relatively low mountains and a gently sloping terrain towards the sea, with narrow coastal plains. There is no significant variation in slope gradients across the region. Rainfall distribution is uneven, with higher precipitation levels observed in the eastern coastal areas and lower rainfall amounts in the western region. Otherwise, there may be concerns of soil erosion along the coastline.

3.2 Spatial distribution of soil erosion

Figure 4 illustrates the current and predicted state of spatial distribution of soil erosion in the tested area. Based on soil erosion maps in conjunction with statistical data on the extent of eroded land across the entire research area, it is evident that the process of soil erosion is not uniformly distributed throughout the study region. From a spatial distribution perspective, regions such as the mountainous region of Quang Nam province may exhibit extensive soil erosion with rates exceeding 3,200 tons/ha/year and over 100 tons/ha/year, accounting for approximately 60 % of the provincial land areas. The primary reason for this phenomenon is the substantial impact of topography. With a topography that channels the northeasterly winter winds and the southwestern summer winds, these areas experience substantial rainfall, leading to a rapid increase in soil erosion. Furthermore, based on the land cover factor (C), it can be observed that these regions have relatively low C values, indicating a diminishing vegetation cover. Consequently, when it rains, water runs across surfaces without encountering the impediment of vegetation cover, leading to an escalating soil erosion rate.

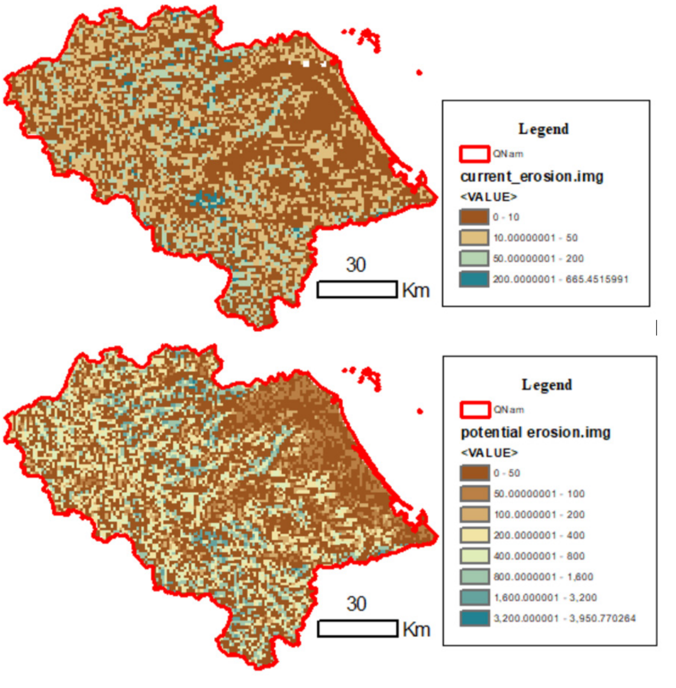

Figure 4. The spatial distribution of the current status of soil erosion in Quang Nam (upper image) in 2022 and a prediction of soil erosion impacts (lower image) projected for 2030.

Unit: ton/ha/year.

In addition, the average annual rainfall in this region is considerably high, owing to their topographical orientation. When these factors are combined, it becomes evident that these areas are highly susceptible, with high levels of soil erosion exceeding 3,200 tons/ha/year for potential soil erosion and over 200 tons/ha/year for current soil erosion, representing a substantial hazard.

3.3 Future plan

Since we were able to conduct the current and projected state of soil erosion patterns over the tested site, there was a lack of analysis of the role of each factor (P, LS, C, K and R) in the eroded process. Otherwise, the LSTM has not been able to determine the significant “candidate values” due to several uncertainties of data missing and the pixel size. In the next steps, we will investigate (1) analyzing the multi-collinearity of each factor to reveal the relationship between them, (2) determining the most impacted factor in the study area, (3) interpolating and calibrating the hot spots of the model to assess soil erosion risk zone with validation and (4) last but not least, test and apply our strategies entirely the study area.

4. DISCUSSION

The maps of potential soil erosion and current soil erosion in the Quang Nam region are the outcomes of the complex interactions of various natural factors through erosion indices. However, due to our limited time of testing and data resources, the main driving factors have not been revealed yet. Based on our current USLE and LSTM results, we are currently leaning toward the R factor. Rainfall distribution exhibits significant variability and the specific characteristics of each soil type, in conjunction with the influence of the terrain conditions, combined with vegetation cover and land management practices, contribute to the distinct variations in the degree of soil erosion across different regions. Our next steps will test these hypotheses and derive the analysis.

We expect to provide a comprehensive spatial depiction of the susceptibility of various areas to soil erosion, offering invaluable insights for land management and conservation efforts. The integration of these erosion factors, in conjunction with their spatial distribution, serves as a vital tool for understanding the dynamic and complex nature of soil erosion processes not only in the Quang Nam province but also in the South-Central region of Vietnam.

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