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Defining required forest area for protection soil from erosion in Vietnam: a GIS-based application

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Abstract. Forests play an important role in reducing erosion. In Vietnam, destroying natural forests in mountainous areas has caused serious environmental problems for sustainable development. Required forest areas for protection of soils from erosion in Vietnam are defined in this study. An algorithm of defining required forest area for soil erosion prevention is based on a comparison of soil loss prediction and its threshold of 10 ton $ha^{-1}yr^{-1}$ (soil loss tolerance) within the GIS environment. Soil loss is predicted from rainfall erosivity index, slope, porosity and vegetation structures in which rainfall index is calculated from 30 year monthly rainfall data of 158 weather stations. A map of erosion risk for Vietnam illustrating potential to erode soil was generated from slope, rainfall index and soil porosity by using spatial interpolation and map algebra techniques in ArcGIS. Vegetation index, a function of canopy closure, height, ground cover and litter cover, is classified into four groups. Required forest areas for protection of soil from erosion are defined from an erosion risk map in comparison with categories of vegetation index. An area (a raster cell) requires forest (natural forest or the others) when its erosion risk is higher than the vegetation index.

Keywords: Soil Erosion, GIS, Required Forest Area, Erosion Risk Map, Soil Loss.

1. Introduction

Soil erosion by water is one of the most serious environmental problems in the world. It causes adverse effects on soils, agricultural production, water quality (Lal, 2001) [1]. Worldwide, soil erosion rate are highest in Asia, Africa, and South America, averaging 30 to 40 tons $ha^{-1}yr^{-1}$, and lowest in Europe and the United States, averaging about 17 tons $ha^{-1}yr^{-1}$ (Pimentel et al., 1995) [2]. However, erosion rates are low on land with natural vegetation cover, about 2 tons $ha^{-1}yr^{-1}$ in relatively flat land and about 5 $ha^{-1}yr^{-1}$ in mountainous areas (Pimentel et al., 1998) [3].

In tropical regions where mean annual sediment yield estimated is greater than 250 tons km^{-2} (Walling at al., 1983) [4], upland areas are usually protected from erosion by a dense vegetation cover. Consequently, cutting vegetation has caused an increase in runoff and erosion (Morgan, 2005) [5]. Sidle et al. (2006) [6] has summarized some key note papers about soil erosion in Southeast Asia and concludes

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that forest conversion to agriculture and exotic plantation (e.g., shifting cultivation) have significant effects on both surface and landslide erosion. The rates of surface erosion depend on the extent dynamic management practices disturb and compact soil, alter ground cover, and modify soil properties. Therefore, accurate estimation of soil loss or evaluation of erosion risk has become an urgent task. Erosion prediction can help to address long range land management planning under natural and agricultural conditions (Angima et al., 2003) [7].

Efforts to mathematically predict soil erosion by water have occurred only since the 1930s. Several models have been developed for estimating soil loss (e.g., Wischmeier and Smith, 1965; Morgan et al., 1984, 2001; Woolhiser, 1990; Quynh, 1996) [8-12]. The initial parameters in these models include susceptibility of soil to erosion, potential erosivity of rainfall and runoff, and soil protection afforded by plant cover (Renard et al., 1997) [13]. In practice, the Revised Universal Soil Loss Equation (RUSLE) model initially developed by Wishchmeier and Smith (1965) has been most widely used. It was originally developed for use on cropland. The RUSLE has been applied in different land uses (Renard et al., 1997) [13]. However, due to the complexity of defining factors of RUSLE for a given region, the application of the RUSLE in Vietnam has been challenging in term of prediction accuracy and its validation (Quynh, 1996) [12].

Traditionally, soil loss was predicted at the local scale based on the factors usually calculated from field measurement. Soil erosion prediction at large scale is often difficult due to spatial and temporal variability of model's factors (Lu et al., 2004) [14]. In recent decades, the development of GIS techniques has facilitated the estimation of soil erosion and its spatial distribution over large areas. For example, Yukel et al. (2008) [15] applied the CORINE model integrated with remote sensing and GIS to generate an accurate and inexpensive erosion risk map in Turkey. Wang et al. (2003) [16] estimated soil loss by integrating a sample ground data set, TM images, and a slope map and showed that the geostatistical method performed significantly better than traditional stratification in terms of overall and spatially explicit estimate. Several studies found applied GIS to interpolate independent factor maps in RUSLE model (or CORINE), then to overlay these maps to generate a regional erosion risk map (Bissonnais et al., 2001; Lufafa et al., 2003; Kheir et al., 2006; Qing et al., 2008) [17-20].

In Vietnam, forests have long been recognized to provide an important role in environmental protection (Lung et al., 1995; Quynh, 1996; Dien, 2006) [12,21,22]. However, under pressure of economic development, the demand land for agricultural and other sectors has increased creating conflicts between land managers. Natural forests mostly distributed in mountainous areas have experienced high deforestation rates since 1980s (FPD, 2008) [23]. Consequently, soil erosion in upland has caused serious environmental problems (Lung et al., 1995) [21]. There is an essential need to balance between agriculture and forests, and minimize as much forest land as possible while still ensuring positive environmental effects of forest. Responding to those problems, this study applies an empirical model for predicting soil loss to produce an erosion risk map, and define required forest areas for protection of soil from erosion for Vietnam. Spatial analyses and interpolation techniques in GIS are used for this study. The input data layers for mapping include DEM, rainfall and vegetative cover.

2. Methodology

2.1. Study Sites and Data Sources

Required forest areas for protection of soil from erosion are identified for all territory of Vietnam, an S-shaped country located in the tropical monsoon area in the southeast of Asia with a great variety of deltas, mountains, forest mosaics, and climates. It has a rather high temperature and humidity, average annual temperature and humidity are above 200C and 80%, respectively. Average total annual rainfall is approximately 1940 mm. Total land area is about 330.000 km^2, three fourths of the Vietnam areas is covered by mountains causing differences in climate regime between regions (VNEA, 2006) [24]. Forest cover is about 38.2 % of which natural forests is account for 80 % and plantation forests is account for 20% (FPD, 2007) [23]. Data sources used for spatial analysis include: National Elevation Dataset (90m x 90m); 30 years monthly rainfall data gauged in 158 weather stations of Vietnam; Archives data of 63 research plots of vegetation structures and soil loss measurement. These plots are representative for different vegetation types in Vietnam (Quynh et al., 1996) [12].

2.2. Criteria for Defining Required Forest Area

The amount of soil erosion by water is an integration of the effects of vegetation cover, topographic features, climatic variables, and soil characteristics (Renard et al., 1997) [13]. In this study, to define required forest areas for soil erosion protection, average soil loss per unit areas was spatially predicted for Vietnam by applying a soil loss equation prediction developed for Vietnam (Quynh et al., 1996) [12]. The relationship between soil loss prediction and rainfall, slope, vegetation cover structures and soil porosity factors can be found expression in the following equation.

$$A = \frac{\left(2.31 * 10^{-6} * K * \alpha^2\right)}{\left(\frac{CC}{H} + GC + LC\right)^2 * P} \quad (1)$$

Where:

A = estimate average soil loss (mm year^{-1})

α = slope (degree)

CC = canopy closure (maximum is 1.0)

H = forest height (m)

GC = ground cover (maximum is 1.0)

LC = dried litter cover (maximum is 1.0)

P = soil porosity (maximum is 1.0)

K = rainfall erosivity factor, calculated based on monthly rainfall (equation 2)

$$K = \sum_{i=1}^{12} \left(\frac{R_i}{25.4}\right) * \left\{\frac{16 + 331 * \lg[(-5.8263 + 2.481 * \ln(R_i))/25.4]}{100}\right\} \quad (2)$$

Where: R_i is rainfall of month ith.

The acceptance limits of erosion is 10 ton ha^{-1} year^{-1}, this is the maximum rate of soil erosion that can occur and still permit crop productivity to be sustained economically (Hudson, 1977; Renard et al., 1997) [13,25], and approximately equivalent to 0.8mm yr^{-1}. To prevent soil degradation, annual soil loss (A) is required to less than the sustainably replacement rate (0.8 mm yr^{-1}).

Then, $$A = \frac{\left(2.31 * 10^{-6} * K * \alpha^2\right)}{\left(\frac{CC}{H} + GC + LC\right)^2 * P} \leq 0.8$$ mm yr^{-1} (3)

$$\text{Let } C_1 = \left[\frac{CC}{H} + GC + LC\right] \quad (4)$$

is index of vegetation for soil protection. An area has potential soil erosion less than replacement rate when its C_1 meets the inequality equation (5) derived from inequality (3).

$$C_1 \geq \sqrt{(2.31*10^{-6}*K*\alpha^2)/(0.8*P)} \quad (5)$$

Let $C_2 = \sqrt{(2.31*10^{-6}*K*\alpha^2)/(0.8*P)}$ (6)

is index of erosion risk. C_2 does not depend on vegetation cover structure or other changeable factors. It is only affected by stable factors (i.e., slope, rainfall factor, and soil porosity). Based on value of C_2 for a specific area, we can identify the corresponding vegetation cover structure (C_1) to protect soil from erosion.

2.3. Spatial Analysis for Defining Required Area of Protection Forest

The digital maps of elevation and rainfall of Vietnam are developed in GIS, using Spatial Analysis in ArcGIS 9.2 software (ESRI, 2008) [26]. We used these maps to produce a map that spatially identified erosion risk (C_2) of Vietnam. This was compared with the threshold of vegetation index (C_1) to generate a map of required forest area for erosion protection. Figure 1 indicates the methodology used in the model.

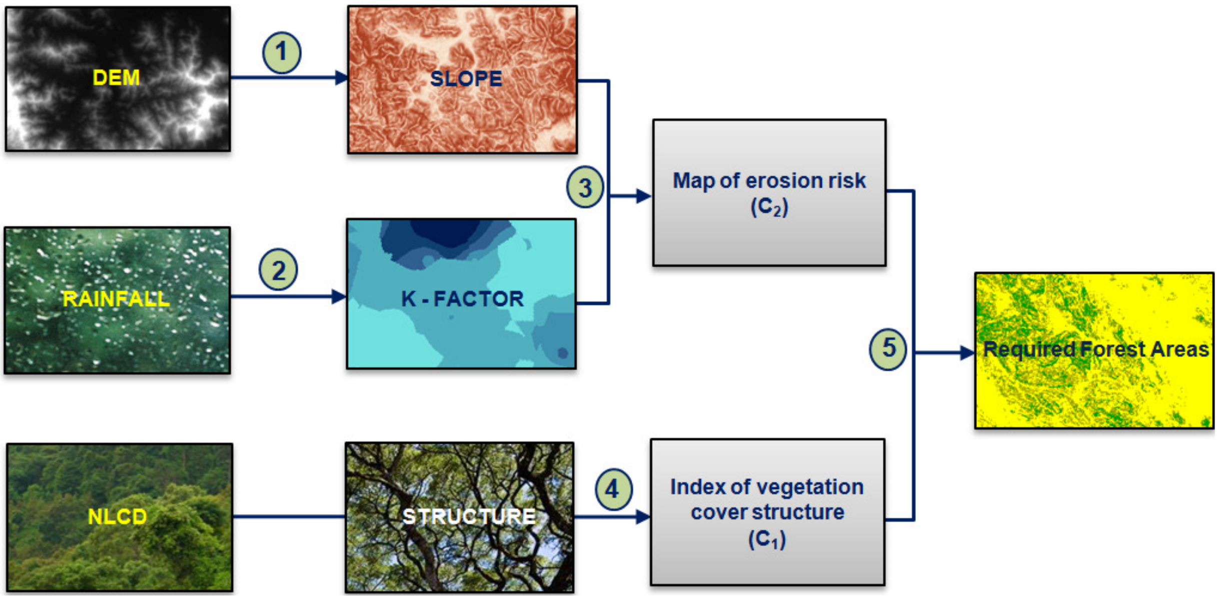


Figure 1. Analytical methodology for defining required forest area.

The explanations of each procedure in the model will be followed:

(1) Slope data layer was derived from National Elevation Dataset (DEM)

(2) Calculated average monthly rainfall for 158 meteorological stations in Vietnam, then spatially interpolated 12 monthly rainfall maps from these point data. A map of rainfall erosivity factor (K) for Vietnam was generated by overlaying 12 monthly rainfall maps based on a raster calculation in equation (2).

(3) An erosion risk map (C_2) for Vietnam was produced from three input layers (i.e., porosity, slope, and rainfall erosivity maps), in which P was assumed to equal 0.4, this is equivalent to the average porosity of fallow land following one year of traditional swidden cultivation (Quynh at al., 1996) [12]. The raster

calculation for the erosion risk map was based on equation (6).

(4) From the data of vegetation cover structures (i.e., canopy closure, ground cover, litter cover, and height) of previous study (Quynh et al., 1996) [12], calculate C_1 for different main cover types in Vietnam (equation 4). Index of vegetation covers (C_1) are classified into five classes based on their relationship with soil loss (Table 1).

Table 1. Classes of vegetation cover structure index in Vietnam

Cover types	C_1
Natural Forests	>1.7
Plantation forest, agro-forests	1.3 - 1.7
Industrial plants, fruits	0.9 - 1.3
Agriculture	0.6 - 0.9

(5) Defining required protective forest area

Algorithm of this step is based on a comparison between actual value of erosion risk (C_2) and threshold of vegetation index (C_1) in Table 1. An area (a raster cell) is required natural forest when its C_2 is greater than 1.7 (i.e., C_1 of natural forest). It is required natural forest, or plantation forest, or agro-forest, when its C_2 is less than 1.7, but greater than 1.3 (i.e., C_1 of plantation forest, agro-forest). These conditional statements were executed by Map Algebra functions (i.e., If Then Else) in Spatial Analyst Tool of ArcGIS 9.2 (Theobald, 2003) [27]. Total areas of forested cells are required forest areas for protection soil from erosion in Vietnam.

2.4. Rainfall Interpolation

Monthly rainfall maps are interpolated from 30-year averaging rainfall data of 158 weather stations relative evenly distributed in Vietnam (Fig. 2). The interpolation method used is Inverse Distance Weighted (IDW), in which an unknown point is interpolated from usually scattered set of known points (Bartier et al., 1996) [28].

$$\hat{Z}(s_0) = \frac{\sum_{i=1}^{n} Z(s_i)\lambda_i}{\sum_{i=1}^{n} \lambda_i} \quad (7)$$

Where:

$Z(s_i)$ is rainfall of station i^{th}

$\hat{Z}(s_0)$ is interpolated rainfall for location s_o

n is number of the nearest stations used for interpolation, n is chosen equal 3.

λ_i is weighted value for station i^{th}, $\lambda_i = 1/d_i^2$, where d_i is distance from location s_i to location s_o.

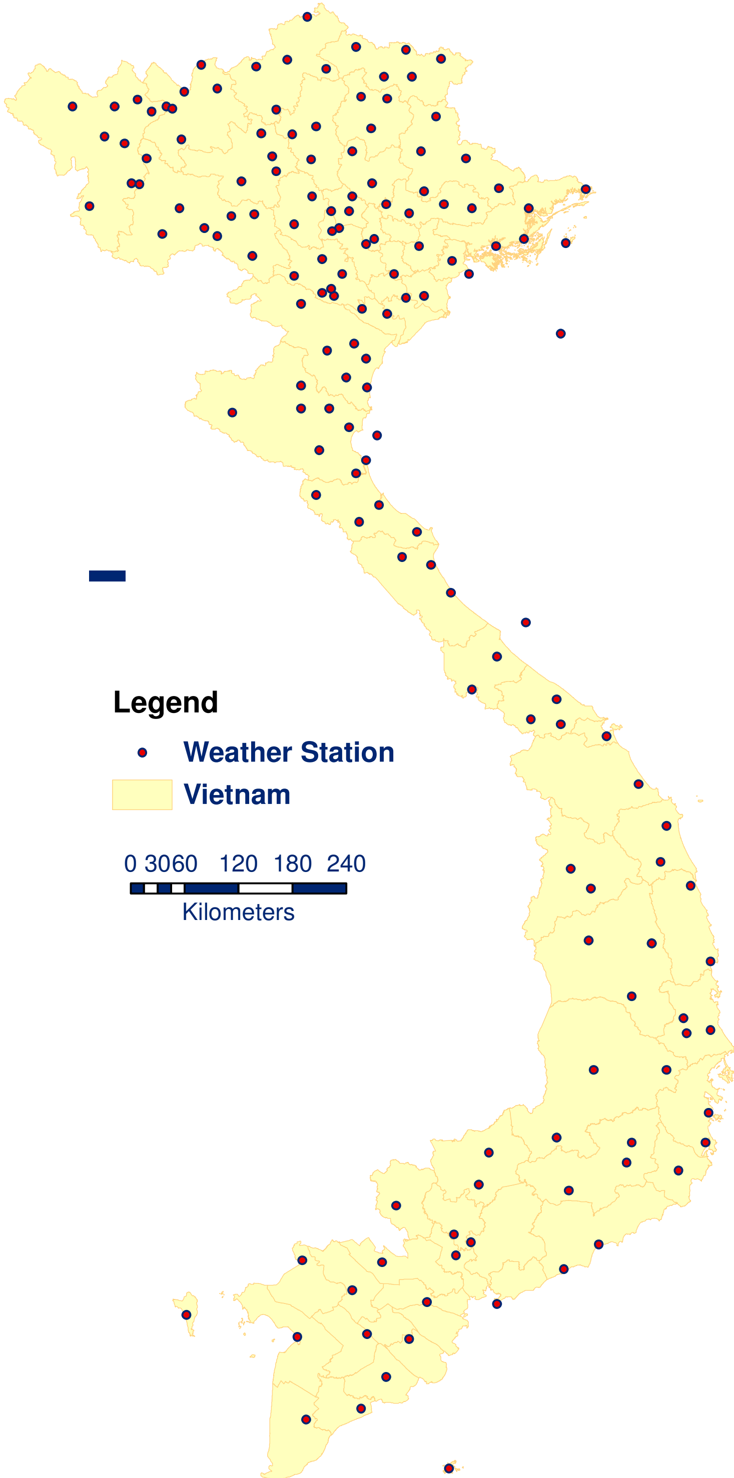
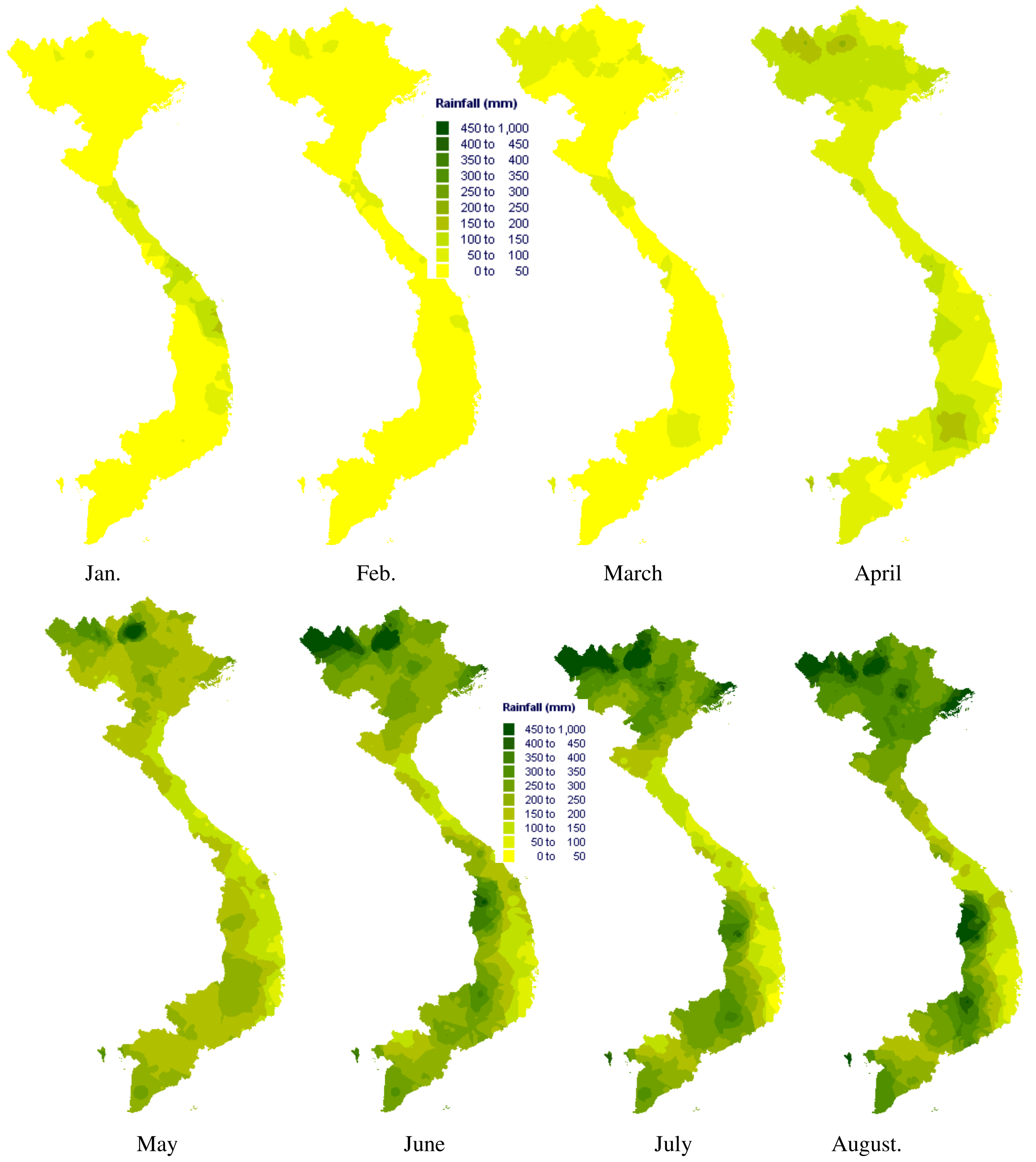


Figure 2. Map of Vietnam showing the locations of 158 weather stations in Vietnam.

3. Results and analysis

3.1. Rainfall Interpolation and Rainfall Erosivity Factor

The temporal and spatial distributions of monthly rainfall in Vietnam are illustrated in Figure 3 from January to December.



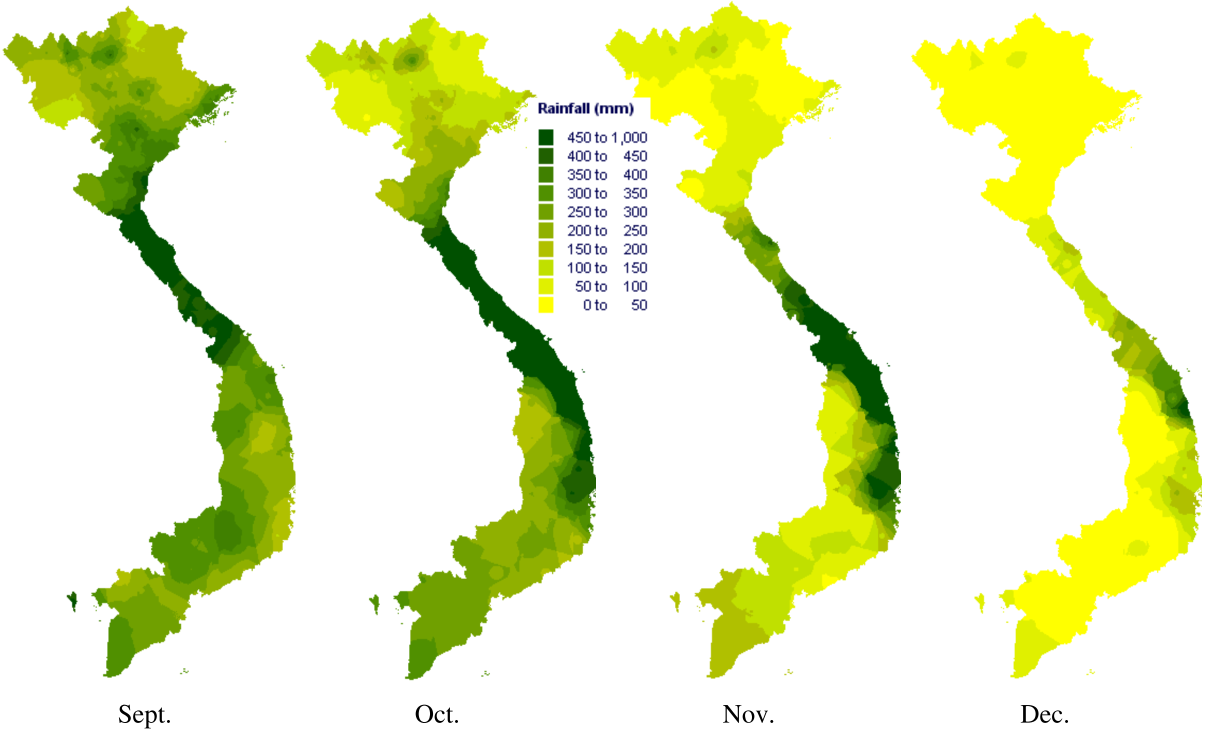


Figure 3. Interpolated average monthly rainfall for Vietnam.

As shown in Figure 3, average annual rainfall varies dramatically ranging approximately from 1000mm in Nha Ho to 4000mm in Bac Quang. The rainfall is unevenly spatio-temporally distributed. The variation of rainfall is the main cause of droughts in the dry season and floods in the rainy season. In some areas like Ham Tan, Phan Thiet there is either no rain for 2-3 months or very little rainfall. The highest monthly rainfall occurring in August and September is 900–1000mm (e.g., Bac Quang, Nam Dong). The rain season starts from April to October, particularly from July to December in the central coastal area. The rainfall in rainy season accounts for 80% of the total annual rainfall.

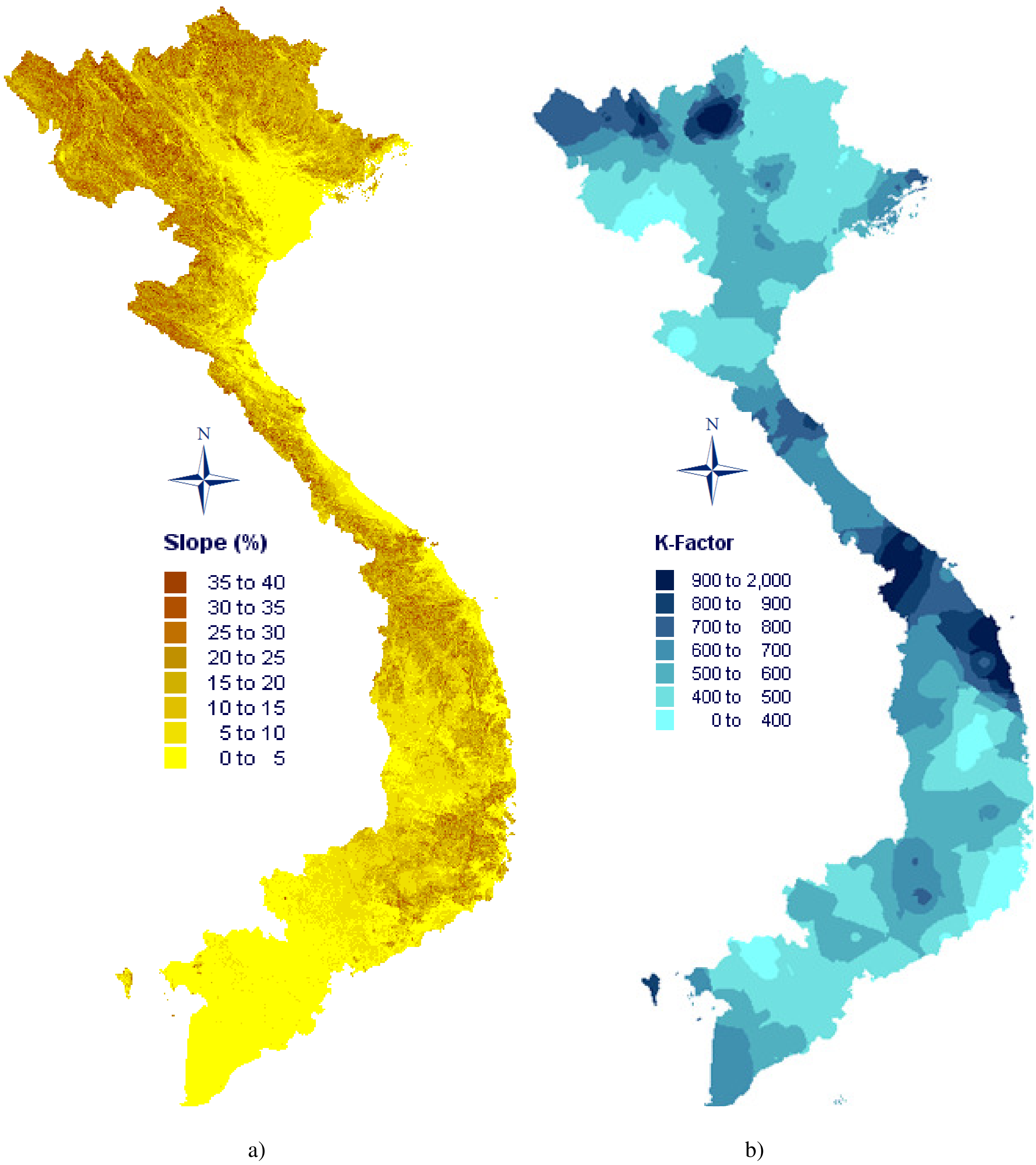


Figure 4. Map of slope (a) and rainfall erosivity factor (b).

3.2. Erosion Risk and Required Forest Areas

As indicated above, about three fourths of the total natural land area of Vietnam is covered by hills and mountains, with a general downward slope from west to east (Fig. 4a). A high gradient of slope, together with unevenly distribution of rainfall erosivity (Fig. 4b), consequently created a great variability within erosion risk map of Vietnam (Fig. 5a). The northwest and central west areas of Vietnam (red color) have the highest potential to erode soil. The two large areas having the lowest erosion risk (blue color) are located in Red River Delta (northern) and Mekong River Delta (southern).

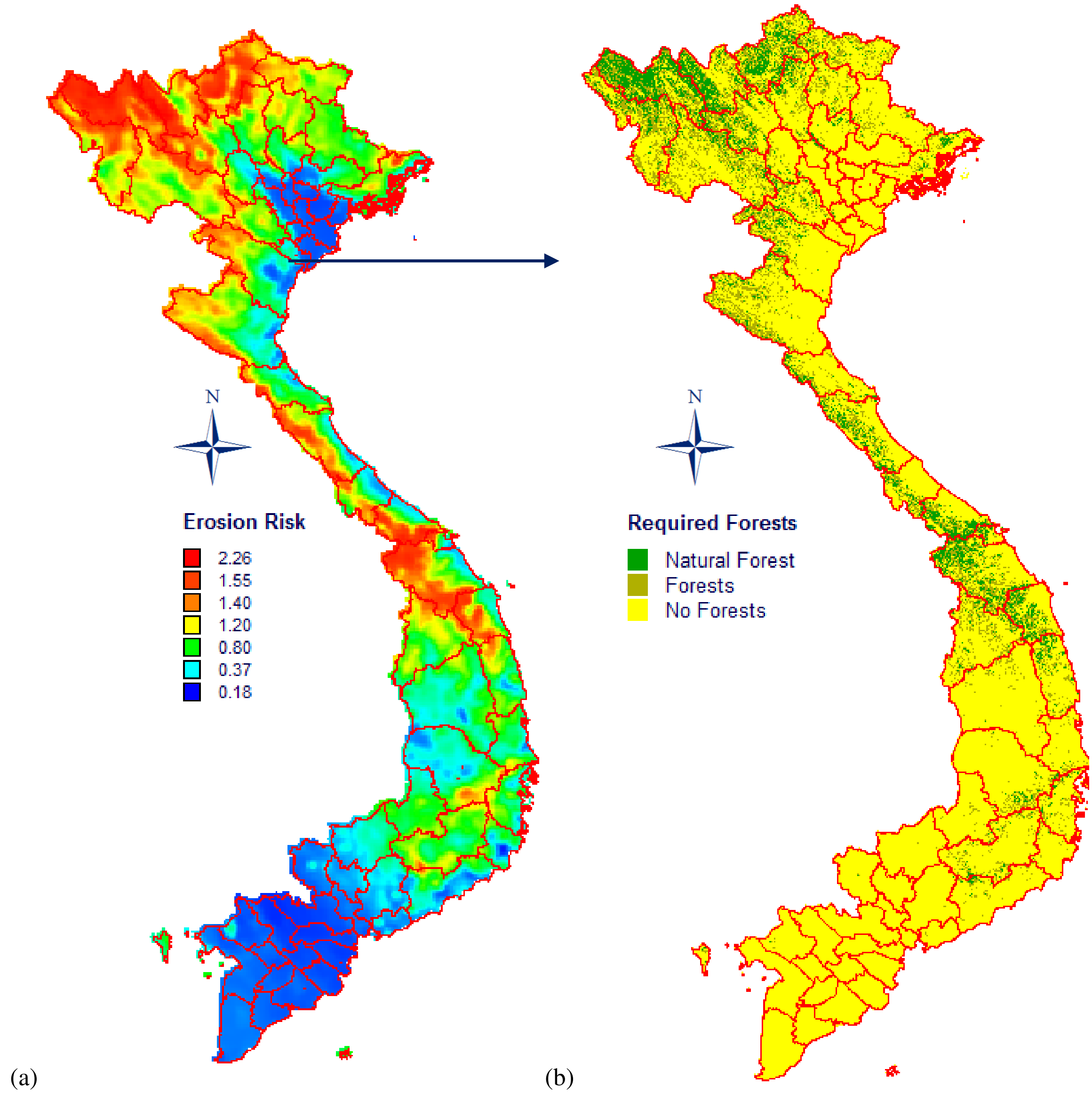


Figure 5. Maps of Vietnam showing (a) erosion risk and (b) required protective forest areas.

The map of required forest areas for Vietnam (Fig. 5b) was generated from erosion risk map in comparison with vegetation index (inequality 5). Total required forest areas for protection of soil from erosion for Vietnam are 7,191,436 ha, of which 2,469,497 ha is natural forest. Fifteen out of 64 provinces do not require forests for erosion prevention, most are distributed in the Red and Mekong river deltas. Provinces requiring high percentages of forest cover are mainly located in the northwest and south central of Vietnam.

4. Disscussion

The revised universal soil loss equation (RUSLE) is an erosion model predicting longtime average annual soil loss, it is a powerful tool that is widely used in the United States and many foreign countries (Renard et al., 1997) [13]. The RUSLE was developed initially by Wischmeier and Smith (1965, 1978) [29] for original use on cropland. It has been being applied to different land uses (e.g., rangeland, forestland). The RUSLE is expressed as:

$$A = R * K * L*S * C * P \quad (8)$$

Where: A = estimated spatial average soil loss per unit area

R = rainfall-runoff erosivity factor

K = soil erodibility factor

L = slope length factor

S = slope steepness factor

C = cover-management factor

P = support practice factor

The essence of universal soil loss equation is to isolate each variable and reduce its effect to a number. Soil loss is predicted by multiplying the numbers. For a given situation (e.g., soil type, cover, slope and length) the value of each factor in the equation is fixed, which only can be established after it has been measured (Hudson, 1977) [25]. In Vietnam, there are limited applications of the RUSLE to predict erosion from land surface due to a lack of references to qualitatively assess the factors for given circumstances. Lung et al. (1995) [21] has defined factors in the equation (8) for the Central Highlands, and also identified C factor for different forest covers in this area (Table 2). However, there are some disadvantages when applying this equation to predict soil erosion; these include: (1) there is no verification for method used to define factors; (2) vegetation classifications are not detailed enough; (3) and experimental plots were designed in a small range of the factors.

Table 2. An example of USLE factors calculated for the central highland of Vietnam

Locations	R	K^a	LS	C	P
Konhanung	872.5	0.021	2.37 (10^0)	0.0083^b	1.0
Pleiku	943.3	0.024	4.38 (15^0)	0.0076^c	1.0

Sources: Lung et al. (1995) [21]

[a] K factor for Bazan soil; [b] C factor for bamboo forest; [c] C factor for grass

These disadvantages are resolved by applying the erosion prediction equation (1) used in this study. This equation was established based on observations of 63 field plots of different cover types, including natural forests, plantation forests, orchards, abandoned land, grazing land and paddy field (Quynh et al., 1996) [12]. Soil erosion in each plot is measured and estimated by using the triangle of three steel poles. In the middle of each pilot plot, place three steel poles in a triangle form. The length of each side of the triangle (the distance from each pole) is 3 m. Each pole is placed deeply into the soil and left about 20 cm higher than the surface of the land. Use a long plastic durable string to connect the three poles at the height of 10 cm from the surface, then measure the distance at 9 points (3 points in each side of the triangle) from the string to the surface before and after each rain event to estimate the thickness of soil layer eroded by each rain (mm). Soil loss depth was analyzed in relation to vegetation structures (e.g., height, canopy closure, ground cover, and litter cover), slope, and rainfall. The authors have found a close relationship among these variables (Fig. 8a). They used monthly rainfall as a replacement of rainfall intensity (Fig. 8b) for calculation of rainfall erosivity factor. The root mean squared error (RMSE) of soil loss prediction by using the equation (1) is about 16%. Recently, the equation has been widely applied in Vietnam (Quynh et al., 2006) [12].

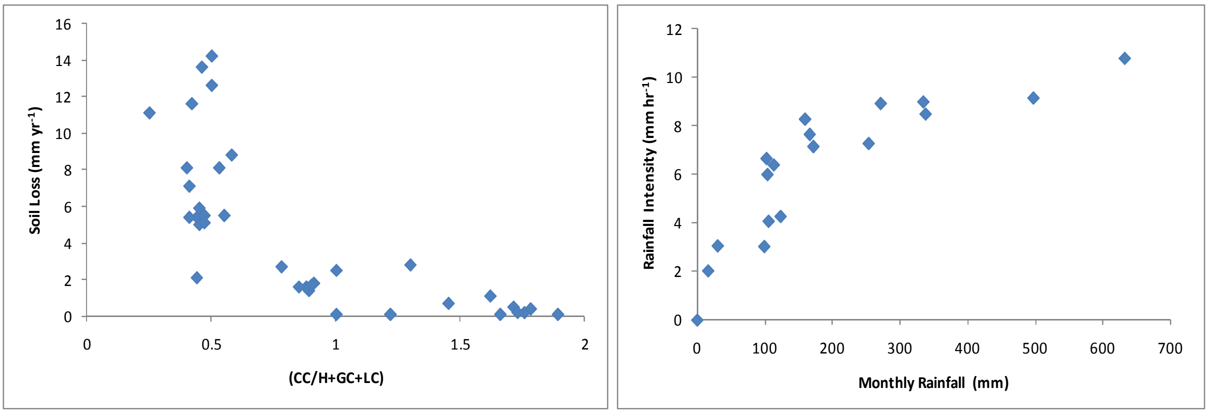


Figure 6. Bivariate plots of (a) vegetation cover structure (i.e., canopy closure, height, ground cover, and litter cover) and soil loss (mm yr^{-1}), R^2 =0.73; and (b) monthly rainfall (mm) and rainfall intensity (mm hr^{-1}), R^2=0.78, (Quynh at al., 1999) [30].

5. Conclusions

Soil erosion by water continues to be serious environmental problems in Vietnam. The primary objectives of this study were applying GIS techniques to define required forest areas for protection soil from erosion in Vietnam.

Due to difficulties in identifying factors for Revised Universal Soil Loss Equation (RUSLE) in Vietnam, the spatially potential soil loss was predicted by an equation developed by Vietnam itself, in which soil erosion prediction is a function of vegetation cover structures, slope, erosivity rainfall index, and soil porosity. Based on the selected soil loss equation and the threshold for soil loss in tropical regions (10 ton ha^{-1} yr^{-1}), we have established two criteria to define required forest area, one is index of erosion risk (C_2), the other one is index of vegetation (C_1). The map of erosion risk was interpolated from mean 30-year monthly rainfall data, slope, and porosity. The index of vegetation was calculated for main cover types in Vietnam from available data (i.e., height, canopy closure, ground cover, and litter cover). Applying raster analysis techniques in ArcGIS, the map of required forest areas for soil erosion prevention was generated from erosion risk map in comparison with vegetation index. This map is a spatial distribution of required natural forests, other forests, or non forests.

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