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Environmental degradation risk by water erosion in a water producer Colombian Andes basin

Risco de degradação ambiental pela erosão hídrica em bacia hidrográfica produtora de água nos Andes Colombianos

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ABSTRACT

Globally, soil degradation by water erosion has become one of the major environmental problems in tropical regions, especially under the severe environmental conditions of the Andes. This study aims to detail the soil risk to degradation by water erosion in a water producer basin located in the Tropical Colombian Andes (Combeima River basin), applying the RUSLE model, discussing how to minimize the erosion processes under its environmental conditions (steep slope, climatic variability, soil classes and properties diversity, and alternative land uses). RUSLE was applied with the support of GIS to estimate current and potential risk to soil erosion in the basin, allowing the identification of areas more prone to degradation. It was found that currently, 50.5% of the basin's area presents, on average, annual soil losses greater than 25 Mg ha^{-1} yr^{-1}, meaning a very high risk to water erosion, with 30.4% showing a severe risk (> 100 Mg ha^{-1} yr^{-1}). It was possible to conclude that the current land uses and soil management systems have not been effective in mitigating soil erosion, mainly when situated in steep topography. Therefore, it is necessary sustainable planning for the conservation of soil, water, organic carbon, plant nutrients, and other elements (not-nutrients) in this tropical Andes region.

Index terms: RUSLE; Tropical Andes; soil and environmental degradation.

RESUMO

Mundialmente, a degradação do solo devido à erosão hídrica tem sido um dos maiores problemas ambientais nas regiões tropicais, especialmente sob as severas condições dos Andes. Este estudo objetiva detalhar o risco do solo à erosão hídrica numa bacia hidrográfica produtora de água, localizada nos Andes colombianos (Bacia do rio Combeima), usando o modelo RUSLE e discutindo como reduzir os processos erosivos nas condições ambientais da região (forte declividade, variabilidade climática, diferentes classes e propriedades de solos, e usos da terra). O modelo RUSLE foi aplicado com auxílio de SIG para estimar as taxas de erosão atual e potencial na bacia a partir de sua calibração para regiões montanhosas, identificando áreas mais vulneráveis à erosão hídrica. A taxa de erosão atual em 50,5% da área total da bacia é maior que 25 t ha^{-1} ano^{-1}, o que significa que a bacia apresenta um risco muito alto à erosão hídrica, com 30,4% de sua área com risco severo (> 100 t ha^{-1} ano^{-1}). Foi possível concluir que os atuais usos da terra e os sistemas de manejo do solo não têm sido efetivos na redução da erosão hídrica, principalmente em áreas com topografia muito declivosa, demonstrando a necessidade de planejamento sustentável para melhor controlar as perdas de solo, água, carbono orgânico, nutrientes e outros elementos (não-nutrientes) nesta região dos Andes tropicais.

Termos para indexação: RUSLE; Andes Tropicais; degradação do solo e do ambiente.

INTRODUCTION

Accelerated soil erosion has been recognized as a critical environmental problem related to land use and climatic changes. Water erosion is the main cause for degradation of the soils in the world, impacting approximately 1.1 billion hectares (56% of agricultural areas) (Correa et al., 2016). The main causes of the water erosion are the climate, landscape conditions, and human activities. Water erosion has caused physical land degradation because it leads to a reduction in porosity of the surface soil layer, constraining the soil water infiltration capacity, and resulting in increased surface runoff and sediment transport. This threats the sustainable development goals (SDG) preconized by United Nations (UN) (Keesstra et al., 2018) as water erosion causes poverty, hunger, water pollution, reduction on reservoirs' capacity, with losses on food production and soil and plant nutrients, and the productive capacity of the land. In addition, it can trigger other impacts, such as sedimentation, flooding, damage to infrastructure, and landslides (Mello et al., 2020). However, some soil management practices can be useful to reduce the impacts of water erosion in agriculture, aiming to achieve the SDG at a low cost. The practices aim to reduce the surface runoff and increase soil water storage, and one of the most widely used with notable results has been the cover crops (CC) (Novara et al., 2021). CC is capable of recovering organic matter, and then the soil's biological activity and its natural fertility.

There are several models for quantifying water erosion at regional and local scales, highlighting the Universal Soil Loss Equation (USLE) (Wischmeier; Smith, 1978), Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975), Water Erosion Prediction Project (WEPP) (Flanagan et al. 2001), Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998), among others. However, the most appropriate model depends on different factors such as the scope of the study, characteristics of the data, previous and intended land use, and mainly the availability of input data (Mello et al., 2016). One of the most used models is the USLE, a pioneer model in attempt to predict average annual losses of soil by erosion, being a practical model capable to assess the soil erosion risk (Thomas; Joseph; Thrivikramji, 2018). Despite its empirical structure, in its revised version (RUSLE), several applications have been generated at watersheds with restrict database for calibration and validation of the process-based models, using an interface with GIS (Tang et al., 2015). Recent studies have been carried out in different countries and basins using RUSLE, such as Italy (Terranova et al., 2009), Brazil (Beskow et al., 2009), Vietnam (Ranzi; Le; Rulli, 2012), Spain (Fernández; Vega, 2018), Ethiopia (Zerihun et al., 2018), Switzerland (Bircher; Liniger; Prasuhn, 2019), China (Teng et al., 2018), India (Pal; Chakrabortty, 2019), among others.

One of the zones worldwide that is vulnerable to water erosion is the Andes Cordillera due to its hydroclimatic and environmental characteristics (Correa et al., 2016; Gardi et al., 2013). This high mountain range is located alongside of western South America, covering an area of 2870596 km^2. It consists of continuous steep mountains and sloping plateau, where "Inter-Andean Valleys" converge, with agricultural and livestock activities, since the ancestral populations (Correa et al., 2016). However, water erosion has become a critical problem affecting the ecosystem services, such as species provision, climate and water regulation, fertility and soil stability, which have generated incalculable environmental, productive and economic losses.

This study has as objectives to offer a unique contribution to the Combeima River basin, a typical basin located in the tropical Andes that has a diversity of ecosystems, environmental and socio-economic issues, being highly vulnerable to climatic change and degradation. It seeks to characterize the potential water erosion and the water erosion risks in the basin, applying the RUSLE model embedded in a GIS environment. The results obtained will be of great importance for adequate land use, soil management systems and water resources in this water producer tropical Andes basin, which has faced significant alterations in recent years, such as deforestation for agriculture and changes in rainfall pattern due to climate change.

MATERIAL AND METHODS

Study area

The studied area is the Combeima River basin (CRB), which is of great importance as a strategic unit for the development of the Ibagué city (Tolima, Colombia), as it provides, among other environmental services, 80% of the water supply for the metropolitan region of this municipality (Departamento Nacional de Planeación - DNP, 2009; Peña; Barrios; Francés, 2016). In addition, this basin encompasses ecosystems of great biological and landscape diversity, being susceptible to degradation caused by the adoption of agricultural systems with inadequate management practices (Andrade et al., 2018).

CRB is located between 4º 19' 30'' and 4º 39' 57'' N and 75º 10' 11'' and 75º 23' 23'' W, on the flank east of the Colombian Andes, with a drainage area of approximately 274.22 km^2 (Figure 1). It presents altitude varying from 664 to 5,212 m, with a bimodal precipitation pattern, which includes two rainy periods (March-May and September-November) and two dry periods (December-February and June-August). The annual average rainfall is 1,800 mm and average annual temperature is 14 °C (Andrade et al., 2018). CRB drains from the "Nevado del Tolima", supplying several villages and farms across the main valley, and the city of Ibagué, which has approximately 500,000 habitants.

The soils of the basin are derived from deposits of lahars and pyroclastic fluxes that had their origin in the Nevado del Tolima volcano (Künzler; Huggel; Ramírez, 2012). In hillside areas, above 2,600 m altitude, the most important land uses encompass agricultural activities, including several productive systems (Muñoz et al., 2014).

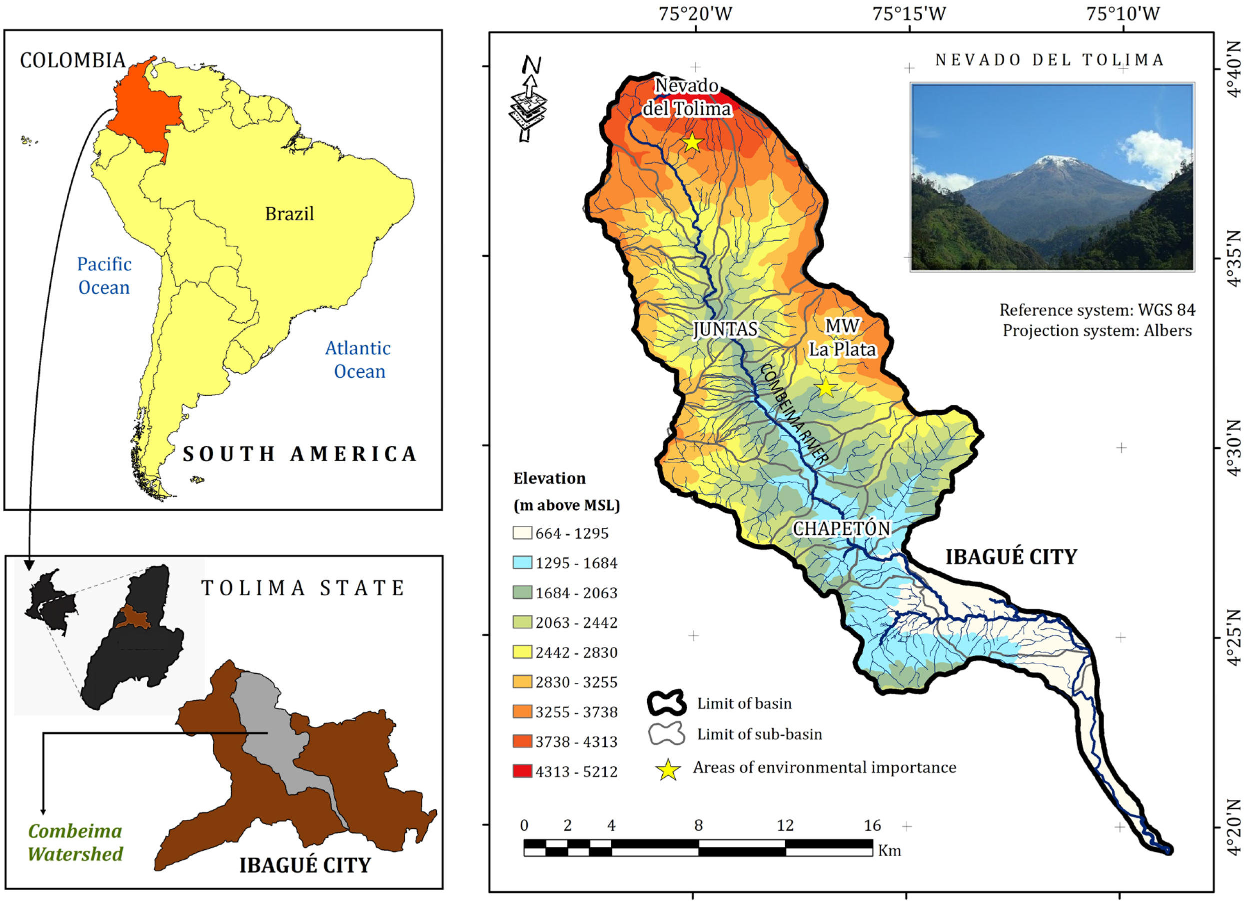

Figure 1: The geographical location of the Combeima River basin (CRB) and its respective elevation map.

The Revised Universal Soil Loss Equation (RUSLE)

The RUSLE (Equation 1) (Renard et al., 1997) is one of the most worldwide models used to estimate the average soil erosion rates generated by rainfall and runoff (Borrelli et al., 2013). It is based on the Universal Soil Loss Equation (USLE) (Wischmeier; Smith, 1978), including alterations in the LS factor calculation, a balance involving rill-interrill erosion, and a new equation for rainfall kinetic energy (Renard et al., 1997). Its expression consists of a linear combination of the factors that characterize water erosion as follows:

$$A = R \cdot K \cdot LS \cdot CP \quad (1)$$

Where A is the annual average soil loss rate (Mg ha^{-1} yr^{-1}); R is the rainfall-runoff factor (MJ mm ha^{-1} h^{-1} yr^{-1}); K is the soil erodibility factor (Mg h MJ^{-1} mm^{-1}); LS is the length and slope factors (dimensionless); C is the cover- management factor (dimensionless); and P is the soil management practices factor (dimensionless).

The R-factor is defined as the long-term annual average of the rainfall erosivity (EI_{30}). EI_{30} is calculated per rainfall event and consists of the product between total rainfall energy (E) and the maximum consecutive 30-min rainfall intensity (I_{30}) (Wischmeier; Smith, 1978; Renard et al., 1997). However, 10-min rainfall recording datasets are necessary to apply this procedure, and such data are very scarce in most of the developing tropical countries. To overcome this limitation, the R-Factor for a given location can be estimated based on simplified models that relate R-factor and the average monthly and annual precipitation, or other related indexes, mainly the Modified Fournier Index (MFI, in mm; Equation 2). These relationships are fitted based on datasets from stations with 10-min rainfall available data. Then, this type of equation is extrapolated for the area under study using the monthly rainfall datasets, which are commonly available (Fayas et al., 2019).

$$MFI = \frac{\sum_{i=1}^{12} pi^2}{P} \quad (2)$$

Where pi is the average monthly precipitation (mm) and P is the average annual precipitation (mm). For the present study, a linear regression between R-factor and MFI for the central region of the Colombian Andes was used (r = 0.84**) (Rivera; Gómez, 1991) (Equation 3):

$$R = \sum_{I=1}^{12} 38.4(MFI) + 28.3 \quad (3)$$

Where R is the mean annual rainfall erosivity (MJ mm ha^{-1} h^{-1} yr^{-1}) and MFI is the Modified Fournier Index (mm).

In order to calculate the R-factor, data from 30 years of precipitation records (1989-2019) were collected in 14 stations of the Institute of Hydrology, Meteorology and Environmental Studies - IDEAM (acronyms in Spanish), located inside and outside of the basin. The Empirical Bayesian Kriging (EBK) tool was used to interpolate the R-factor data to cover the entire basin using ArcGIS (10.2 version). The EBK method predicts more accurate standard errors than other kriging methods and allows obtaining accurate predictions (Brychta; Janeček, 2017).

The C-Factor refers to the effect of the soil cover on water erosion. In this study, the C-Factor was determined based on Andrade et al. (2018) study, which spatially described the types of cover in the CRB on a scale of 1: 10,000 (Figure 2a), developed based on the Landsat 8 images, and (Corporación Autónoma Regional del Tolima - CORTOLIMA, 2007), from which the C-factor values were extracted (Table 1). Regarding the P-factor, we assigned the value 1.0 for the entire area, since no erosion control practices have been adopted in the basin.

Soil erodibility (K-factor) represents the soil intrinsic susceptibility to water erosion. The basic information for K-factor determination was the soil maps, which was derived from the (Instituto Geográfico Agustín Codazzi – IGAC, 2004) for this study in a scale of 1:100,000 (Figure 2b). The K-factor values for the different soil classes were obtained from CORTOLIMA (2007) (Table 2). The raster map of the K-factor was performed by interpolating the coefficient values according to the soils existing in the basin.

Length and slope (LS-factor) are fundamental for estimating soil erosion rates and the sediment transport capacity (Renard et al., 1997). In RULSE, LS calculation takes into account the upward area contribution and a rill-interrill erosion ratio (Bircher; Liniger; Prasuhn, 2019). The methodology applied in this study was initially based on Pelton, Frazier and Pickilingis (2012) proposal, with the support of Algebra map, which allows the application of the equation developed by Mitasova et al. (1996) (Equation 4). The DEM for the studied basin was based on the survey of the topographic transfer radar (NASA / SRTM), with a spatial resolution of 30 m.

$$LS = (m+1) \cdot \left[\frac{(\mathrm{Fa})\,\mathrm{x}\,(\mathrm{Cs})}{22.13}\right]^{m} \cdot \left[\frac{\mathrm{Sin}(\mathrm{Sl})}{0.0896}\right]^{n} \quad (4)$$

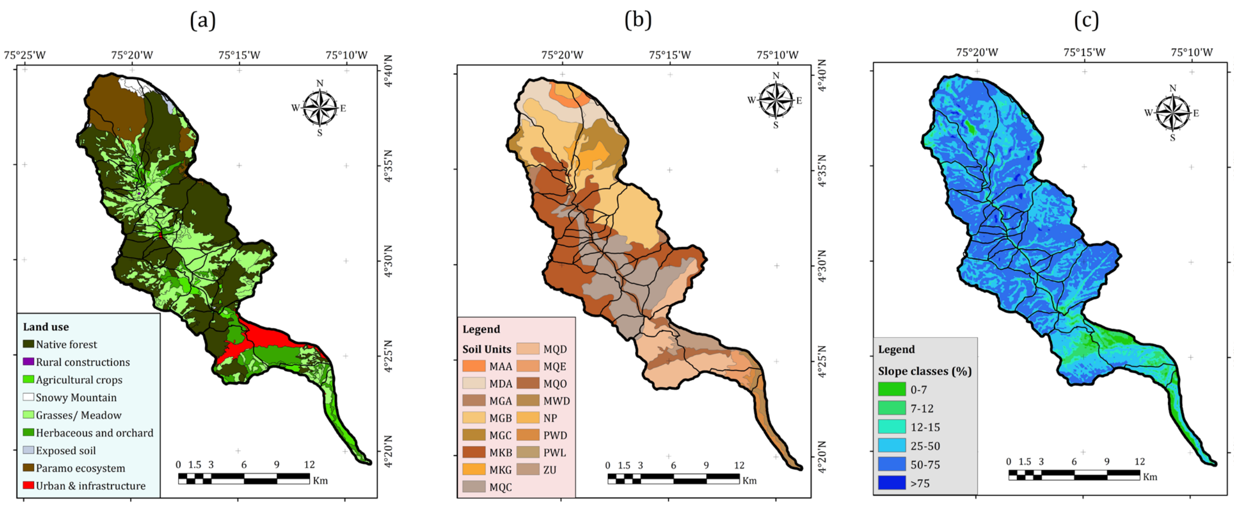

Figure 2: Maps of the land use (a), soil classes (b), and slope (c) for Combeima River basin.

Where Fa is the flow accumulation, Cs is the cell size (pixel); Sl is the slope; and m and n are the empirical coefficients. For the purposes of this study, the cumulative flow and slope maps were obtained from the slope map (Figure 2c). The values of m and n were adopted as 0.4 and 1.4, respectively, for areas with mountainous characteristics, meaning a greater participation of the rill erosion on the process (Mello et al., 2016; Renard et al., 1997).

Table 1: Land use and C-Factor for the Combeima River basin.

Symbol	Land use	C- Factor	Area	
			(km^2)	(%)
NF	Native forest	0.001	121.05	44.15
RC	Rural constructions	0.039	0.05	0.02
AC	Agricultural crops	0.045	9.22	3.36
SM	Snowy mountains	0.031	3.62	1.32
GR	Grasses/ Meadows	0.005	75.86	27.67
HO	Herbaceous and orchards	0.025	23.82	8.69
ES	Bare soil	1.000	1.37	0.50
PE	Paramo ecosystem	0.670	27.47	10.02
UI	Urban and infrastructure	0.890	11.74	4.28
	Total		274.22	100

Table 2: Soil classes and respective erodibility factors in the Combeima River basin.

Soil unit	Classification[1]	K-Factor ($Mg\ h\ MJ^{-1}\ mm^{-1}$)	Area	
			(km^2)	(%)
MKB	Alic hapludands	0.026	61.05	22.25
MGB	Lithic troporthents + Lithic hapludands + Lithic tropofolists	0.039	53.21	19.39
MQC	Typic humitropepts + Typic troporthents	0.045	46.23	16.85
MQD	Typic eutropepts + Typic troporthents + Entic hapludolls	0.031	31.07	11.32
MDA	GI: Thaptic haplocryands; Lithic cryorthents; Typic cryaquents	0.027	17.18	6.26
MGC	C: Typic hapludands	0.025	14.49	5.28
MQO	A: Typic troporthents; Typic dystropepts	0.021	12.94	4.72
ZU	Urban area	0	7.49	2.73
PWD	Typic haplustalfs	0.026	5.96	2.17
MKG	Typic hapludands	0.024	5.65	2.06
MWD	Rock outcrops + Typic ustorthents	0.033	4.97	1.81
MQE	Typic eutropepts + Typic troporthents + Entic hapludolls	0.028	4.86	1.77
MAA	Terrain type - Perpetual snows	0.007	3.57	1.30
MGA	Typic melanudands	0.034	2.83	1.03
NP	Other terrain types	0.007	2.80	1.02
PWL	Typic ustifluvents + Vertic haplustalfs + Typic ustipsamments	0.036	0.11	0.04
	Total		274.22	100

[1] US Soil Taxonomy (United States Department of Agriculture - USDA, 2014).

Water erosion risk maps

The average soil erosion risk map was obtained by applying RUSLE (Equation 1), combining the maps of the R, K, LS, and CP factors for the studied basin, using the Algebra map of the ArcGIS 10.2 version. For the determination of the potential risk of water erosion, C and P factors were considered equal to 1, corresponding to RUSLE's simulated soil losses, disregarding any type of vegetation cover and anthropic interference (Farhan; Nawaiseh, 2015). We adopted the soil erosion risk classification from Beskow et al. (2009) (Table 3).

RESULTS AND DISCUSSION

Spatial distribution of RUSLE factors in the CRB, Colombian Tropical Andes

In Figure 3, the maps of RUSLE factors (a. R-factor; b. K-factor; c. LS-factor; d. CP-factor) for CRB are presented. Rainfall erosivity is the active factor in generating water erosion (Mello et al., 2016) and in CRB, the R-factor ranged from 1,777.33 to 2,443.71 MJ mm ha^{-1} h^{-1} yr^{-1}, with an average value of 2,110.52 MJ mm ha^{-1} h^{-1} yr^{-1}. The distribution of the R-factor in CRB shows that it decreases as the altitude changes from the mountain areas to the lowland areas (Figure 3a). CRB is influenced by low R-factor values (between 1,000 and 5,000 MJ mm ha^{-1} h^{-1} yr^{-1}) due to the low amount of rain at the highest areas of the basin. Riquetti et al. (2020) modeled the R-factor for South America and observed significant correlation between altitude and R-factor in almost all the region, demonstrating that R-factor can be influenced by the elevation of mountainous regions in the continent. They observed the lowest R-factor values along the Andes Cordillera due to reduced rainfall amount at the highest elevation. Pérez-Arango (2012) conducted a study in Colombia, using the R-factor estimation method based on a random cascade model for the temporal rainfall disaggregation. For the CRB, they found approximately 3,000 MJ mm ha^{-1} h^{-1} yr^{-1}, a value similar to that obtained in this study. Therefore, we can highlight the coherence of the R-factor values for CRB in relation to other studies for the Tropical Andes region.

Figure 3b shows the K-factor map for CRB. Areas with greater erodibility values (> 0.035 Mg h MJ^{-1} mm^{-1}) are concentrated in the central region of the basin, over the MQC soil mapping unit (Typic Humitropepts + Typic Troporthents). Tropical Inceptisols are recognized as soils with high erodibility, due to their great silt/clay ratio, low permeability and high susceptibility to surface crusting (Pinto et al., 2015). In areas of steep slope and valleys, in the eastern area of the basin, the K-factor was 0.026 Mg h MJ^{-1} mm^{-1}. This area is located in the MKB soil mapping unit (Alic Hapludands), where the parent material is made up mainly of volcanic ashes. These Andisols are susceptible to surface crusting, which reduces water infiltration capacity, increasing their erodibility (Zehetner; Miller, 2006). In the upper areas of the basin, the lowest erodibility values were found, mainly because of the rock outcrops predominance. The western part of the basin, in the upper sector of the La Plata basin (Figure 1), and in the canyon of the Combeima river, the K-factor is 0.039 Mg h MJ^{-1} mm^{-1}, distributed in the MGB soil mapping unit (Lithic Troporthents + Lithic Hapludands + Lithic Tropofolists) originated mostly from igneous rocks. The intrinsic susceptibility to erosion of these shallow soils (Lithic subgroup by according to US Soil Taxonomy, USDA, 2014), decreasing the water infiltration rate and increasing surface runoff, justifies such high K-factor values.

Table 3: Classification risk for current water erosion and classification for potential water erosion (Beskow et al., 2009).

Classification risk	Current soil loss ($Mg\ ha^{-1}\ yr^{-1}$)	Classification	Potential soil loss ($Mg\ ha^{-1}\ yr^{-1}$)
Light	0 – 2.5	Light	0 – 400.0
Light to moderate	2.5 – 5.0	Moderate	400.0 – 600.0
Moderate	5.0 – 10.0	Moderate to high	600.0 – 800.0
Moderate to high	10.0 – 15.0	High	800.0 – 1600.0
High	15.0 – 25.0	Very high	1600.0 – 2400.0
Very high	– 100.0	Severe	>2400.0
Severe	>100.0		

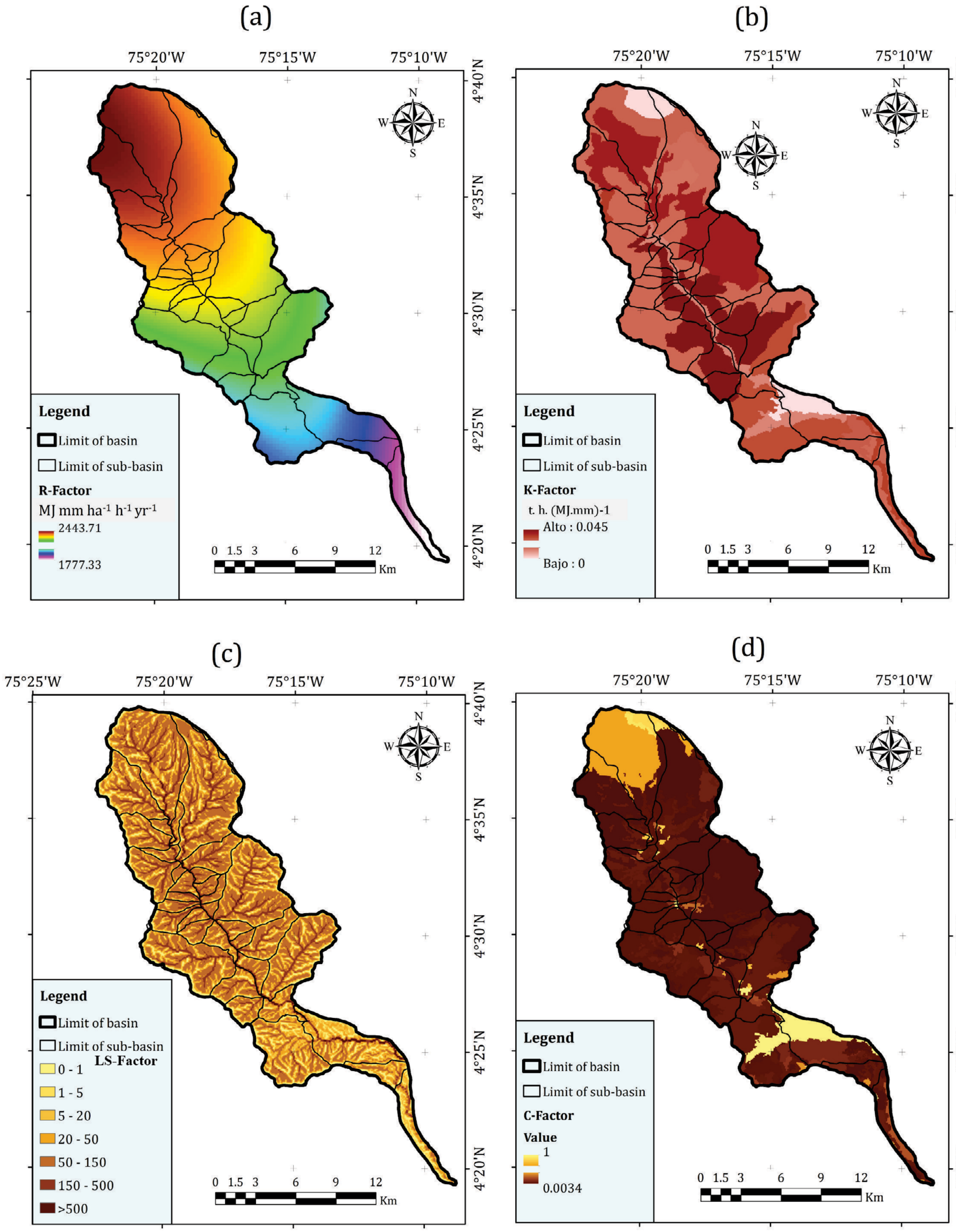

Figure 3: RUSLE factors for CRB, Colombian Tropical Andes (a. R-factor; b. K-factor; c. LS-factor; d. CP-factor).

The highest values of LS (Figure 3c) were found in the north-central region, specifically in the area of the river canyon up to the frozen mountains in Nevado del Tolima (from 2,200 to 5,212 m altitude above sea level). The LS factor ranged from 0 to greater than 500, where the 20 to 150 values represent 54% of the total area of the basin and are classified as "moderate" to "high severity" (Correa et al., 2016). The LS-factor values were similar to those obtained by Correa et al. (2016) for a Peruvian Andes basin, under similar landscape and altitude conditions, and using the same calculation procedure. Traditionally, in CRB, agricultural and livestock production systems are carried out on the mountainside, in slopes varying from 50 to 75%, where LS is > 150. It is of great importance to determine whether the areas with the highest LS values coincide with bare soils, allowing to identify the areas with the greatest risk to degradation by water erosion and landslides, and where the conservation efforts need to be intensified.

The CP-factor map is presented in Figure 3d, and the values are distributed between 0.0034 and 1. It is possible to observe that the upper part of the basin presents relatively higher values. In areas located in the central part of the basin, there are relatively lower C values (0.0034 to 0.2), since the predominant land uses are pastures, secondary vegetation, and croplands. The C-factor values in areas with predominant land uses like well managed forestry, pastures, secondary vegetation, and croplands are generally low, as these land uses have ability to mitigate the direct impact of the rainfall drops, reducing the soil vulnerability to water erosion. It was also observed that at higher altitudes of the Nevado del Tolima there are higher values of the CP-factor associated with larger areas with bare soils. According to Correa et al. (2016), in such areas of the tropical Andes, reduced vegetation is associated with less biomass accumulation due to low temperatures and small amounts of rainfall that constrain vegetation development and, consequently, imposes reduction of the soil surface protection against the direct impact of rain drops.

Current water erosion risk in CRB

Current water erosion rate is a reflection of the effects of the land uses, relief and soil management systems in CRB. Soil erosion presents, predominantly, "high" to "severe" classes (Table 4). Approximately 50.5% of the basin's area present soil erosion risk varying from "very high" to "severe" (25 to 100 Mg ha^{-1} yr^{-1}). Also, 35.02% of the basin's area show a low (light) soil erosion rate.

Table 4: Soil erosion risk in CRB.

Classification	Soil loss (Mg ha^{-1} yr^{-1})	Area	
		(km^2)	(%)
Light	0-2.5	96.03	35.02
Light to moderate	2.5-5	0.75	0.27
Moderate	5-10	4.95	1.81
Moderate to high	10-15	13.36	4.87
High	15-25	20.62	7.52
Very high	25-100	55.01	20.06
Severe	>100	83.50	30.45
Total		274.22	100

Figure 4a shows that these areas correspondent to the city of Ibagué, as well as areas with gentler slope and forestry as the main land use, which contribute for mitigating soil erosion. It was observed that, currently, 51.98% of the basin have "high" to "severe" erosion rate (15 to > 100 Mg ha^{-1} yr^{-1}) (Figure 4a; Table 4), implying in substantial soil losses. These aspects have implied on complex systems of gullies and mass movements. In this way, by reviewing the spatial and temporal distribution of landslides in the CRB between the years of 1999 and 2015, the greatest number of the landslides (> 90 %) occurred in such areas (Leal-Villamil; Pérez-Gómez; Ortiz-Lozano, 2018).

According to IGAC (2004), the soils of the MGB soil mapping unit are Lithic Troporthents, Lithic Hapludands, and Lithic Tropofolists, which have low weathering and are shallow. Water erosion in these soils is facilitated by their weak structure and silty texture, which leads to surface sealing, reducing water infiltration and increasing the surface runoff. In these soils, native areas covered by forestry and the Páramo ecosystem are predominant, as well as agricultural crops and grasslands. According to Leal-Villamil, Pérez-Gómez and Ortiz-Lozano (2018), in the grasslands, there is high incidence of landslides. Conversely, the MKB soil mapping unit reveals different levels of soil erosion risk, being more frequent the "very low" (0-2.5 Mg ha^{-1} yr^{-1}) and "severe" (>100 Mg ha^{-1} yr^{-1}) classes, covering 8.55% of the basin's area. These soils are classified as Alic Hapludands, with abundant gravels (IGAC, 2004). Their pedological attributes in association with land uses and soil management systems make these soils randomly vulnerable to water erosion, being mainly influenced by the last two aspects.

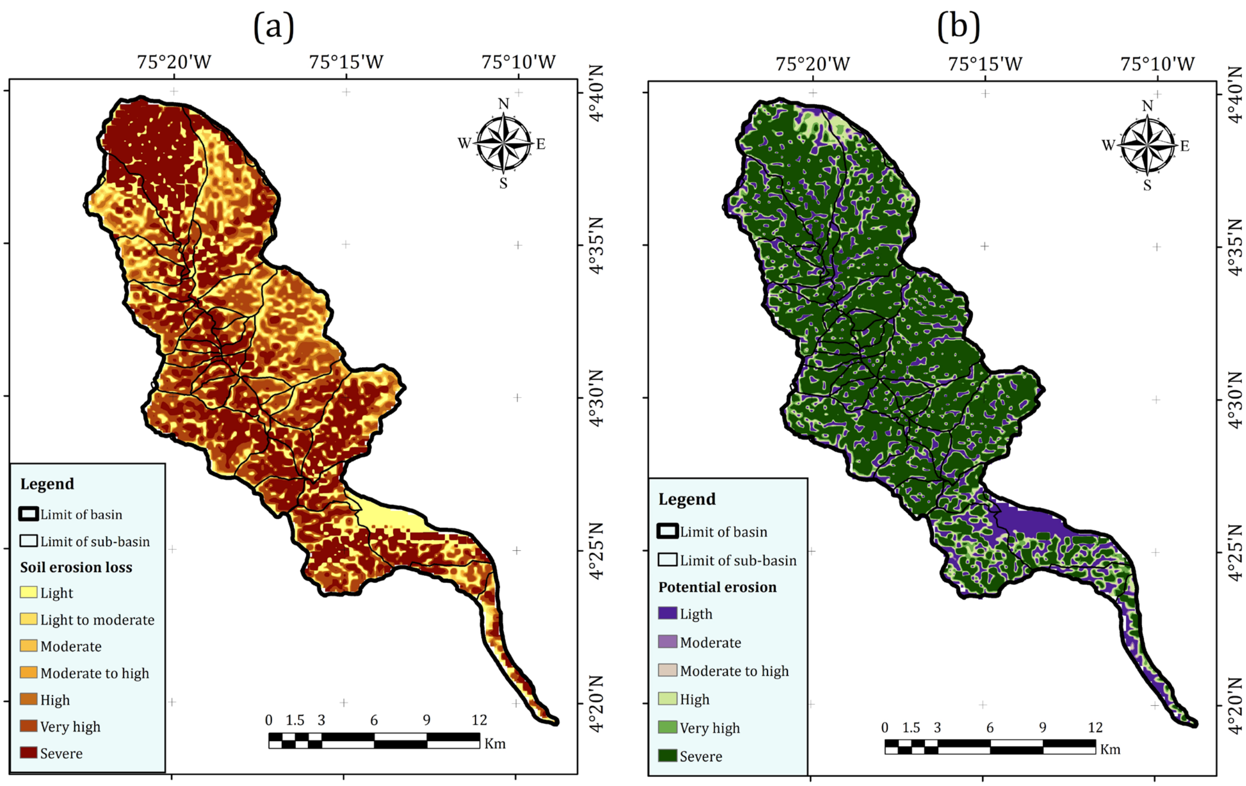

Figure 4: Current soil erosion risk map (a) and potential water erosion map (b) for CRB.

Table 5 presents an analysis of the soil erosion rate carried out by according to the soil class. The soil mapping units MGB and MKB, which correspond to 11.05% and 8.55% of the basin's area, respectively, present the highest risk to degradation by water erosion, with rates greater than 100 Mg ha^{-1} yr^{-1} of soil losses.

In MQC soil mapping unit, the "very low", "very high" and "severe" soil erosion risks are predominant, accounting for 15.59% of the basin's area. These soils are Typic Humitropepts and Typic Troporthents, which relatively reduced susceptibility to soil erosion of the first soils due to high soil organic matter (SOM) content, probably accounting for the "very low" class. The Typic Troporthents are naturally more susceptible to erosion, which in association with the current overuse of the soils, justify the occurrence of more than 40 landslides in these areas between 1999 and 2015.

Table 6 shows that 25.54% (70.03 km^2) of the grassland (GR) showed soil erosion rates varying from "high" to "very high" (15 and > 100 Mg ha^{-1} yr^{-1}). This means that these areas have the highest soil erosion rates in the basin and the greatest risk to degradation. Trampled grasslands decrease the soil infiltration capacity due to superficial compaction of the soil, increasing the surface runoff during storms, as well as the soil losses per rainfall event. Marshall et al. (2014) suggested that the transition from grasslands to sustainable forestry and well managed crops may generate reduction of the soil erosion risks and flooding, by improvements of the soil structure and water infiltration capacity.

Native forest (FN) areas predominantly have "very low" soil erosion rates (between 0-2.5 Mg ha^{-1} yr^{-1}, corresponding to 24.68% of the basin's area), being the land use less affected by erosion processes in the basin. However, 11.64% of the FN areas showed "very high" soil erosion rates (> 100 Mg ha^{-1} yr^{-1}). In steep slope areas, common characteristics of the Andes region, it is necessary to mitigate the occurrence of erosion processes. According to Elliot, Page-Dumroese and Robichaud (1998), in less disturbed forestry, greater soil erosion rates are relative to bushfires, leading to landslides, and ravines.

Table 5: Soil mapping units in CRB and respective soil losses.

Soil mapping unit	Soil Losses (Mg ha^{-1} yr^{-1})							
	0-2.5	2.5-5	5-10	10-15	15-25	25-100	>100	Total (%)
MKB	8.549	0.008	0.252	0.277	0.562	4.055	8.549	22.25
MGB	3.851	0.007	0.372	0.317	0.080	3.727	11.050	19.41
MQC	4.883	0.015	0.011	0.423	0.810	5.569	5.150	16.86
MQD	8.432	0.011	0.372	0.155	0.016	1.167	1.178	11.33
MDA	3.793	0.020	0.117	0.009	0.131	0.656	1.539	6.27
MGC	0.839	0.012	0.007	0.181	0.890	2.341	1.014	5.28
MQO	1.021	0.041	0.219	0.537	1.185	1.251	0.463	4.72
ZU	1.058	0.010	0.109	0.176	0.653	0.452	0.274	2.73
PWD	0.620	0.016	0.026	0.394	0.328	0.664	0.120	2.17
MKG	1.021	0.020	0.022	0.448	0.303	0.085	0.160	2.06
MWD	0.150	0.014	0.084	0.154	0.813	0.018	0.558	1.79
MQE	0.438	0.026	0.088	0.529	0.525	0.024	0.142	1.77
MAA	0.033	0.008	0.109	0.667	0.427	0.032	0.004	1.28
MGA	0.146	0.020	0.004	0.336	0.438	0.008	0.073	1.02
NP	0,182	0.015	0.015	0.281	0.357	0.012	0.157	1.02
PWL	0.007	0.029	0.000	0.000	0.000	0.000	0.004	0.04
Total (%)	35.02	0.27	1.81	4.88	7.52	20.06	30.43	100

Table 6: Land use mapping units in CRB and respective soil losses.

Land use mapping unit	Soil Losses (Mg ha^{-1} yr^{-1})							
	0-2.5	2.5-5	5-10	10-15	15-25	25-100	>100	Total (%)
NF	24.68	0.08	0.85	1.90	1.81	3.18	11.64	44.15
RC	0.00	0.01	0.00	0.00	0.00	0.00	0.01	0.02
AC	0.00	0.00	0.22	0.06	0.07	1.33	1.68	3.36
SM	0.20	0.02	0.11	0.40	0.06	0.32	0.20	1.32
GR	1.42	0.01	0.35	0.35	4.81	9.44	11.29	27.67
HO	3.79	0.01	0.01	0.31	0.01	3.73	0.82	8.69
ES	0.01	0.02	0.00	0.01	0.01	0.06	0.39	0.50
PE	4.10	0.08	0.25	1.21	0.16	0.74	3.47	10.02
UI	0.81	0.04	0.01	0.78	0.60	1.19	0.85	4.28
Total (%)	35.02	0.27	1.81	5.03	7.52	20.01	30.35	100

Other native land uses, such as the Páramo ecosystem (PE), show different levels of soil erosion rate varying from “very low” to “severe” classes. This ecosystem is located between 3,500 and 4,800 m asl, under extreme cold and dry conditions, on a very steep relief with scarce vegetation, where diverse human activities have been carried out. Studies by Diaz-Granados, Navarrete and Suárez (2005), Otero et al. (2011) and Poulenard et al. (2001) indicated that undisturbed PE has high water infiltration capacity and low soil erosion rates. However, anthropic practices such as tillage and burning have increased the surface runoff, triggering the soil erosion processes. This fact places emphasis on the need to carry out sustainable practices to control surface runoff and, consequently, to maintain the hydrological regulation of this very important ecosystem.

Agricultural crops (AC) occupy only 3.36% of the basin's area and do not show high soil erosion rates. However, it is worth mentioning that, out of the basin's area, 3.01% showed "very high" to "severe" soil erosion classes. These results point out the rationale of the planning of the rural territory of the basin, by adopting an agroecological approach, i.e., increasing the areas of afforestation under several sustainable agroforestry systems with the use of few invasive agricultural practices to decrease the risks of degradation of the basin by water erosion.

Potential water erosion in CRB

In the map of the potential soil erosion (Figure 4b), the physical factors intrinsically linked to the physical conditions of the basin (soil erodibility and topography) and the active factor (rainfall erosivity) were considered, keeping the C and P factors equal to 1 (bare soil). According to the classification used by Beskow et al. (2009), soil erosion rates greater than 2,400 Mg ha^{-1} yr^{-1} means a severe potential water erosion, and 59% of the CRB area are in this class (Table 7).

Table 7: Potential soil erosion in the CRB (CP = 1).

Classification	Soil erosion (Mg ha^{-1} yr^{-1})	Area	
		(km^2)	(%)
Light	0-400	94.24	34.37
Moderate	400-600	0.29	0.11
Moderate to high	600-800	1.09	0.40
High	800-1600	6.28	2.29
Very high	1600-2400	10.31	3.76
Severe	> 2400	162	59.08
Total		274.22	100

In general, CRB area is predominantly under "severe" potential water erosion once the land uses and soil management systems are not adequately planned. Considering that for the calculation of the potential water erosion it is important to mention that the LS factor plays a key role as a determining factor for the soil erosion processes in the Andes region. One can see in Figure 4b that potential water soil is concentrated in areas with steeper slope (> 50%), decreasing in areas with undulated and flat topography, with a predominance of rill erosion. In RUSLE, this factor has been better modeled than USLE, especially considering the upstream contribution areas, determining the accumulated flow paths and attributing a greater weight for rill erosion, which is especially relevant for a better characterization of the hydraulic sediment capacity transport.

It can be observed that the predominant high potential to water erosion increase the risk to degradation due to the high values of K-, and LS-RUSLE factors, which can be controlled with the establishment of the appropriate vegetation cover and adequate soil management, especially the use of cover crop strategies that improve the quality of the soil. In this way, sustainable land uses and soil management systems are crucial and must be analyzed to maintain the minimum possible exposure of the soil to the direct impact of heavy rainfalls.

CONCLUSIONS

The RUSLE can be used to estimate current soil erosion behavior and the risks to degradation by water erosion in this high mountain basin of the Tropical Andes region. It was found that the current soil erosion rate in CRB is framed as "very high" to "severe" classes in 62.84% of the area, indicating that the current land uses and soil management systems have not been effective in mitigating soil losses in most part of the basin. The critical areas in terms of degradation are associated with the K- and LS-factors, since R-factor does not have a high degree of variability and aggressiveness in the basin. These areas can be controlled with appropriate establishment of CC to reduce soil erosion and landslide occurrences. The current soil erosion risk map allowed the establishing the CRB's areas with accelerated soil erosion rate, providing background for sustainable planning towards to SDG of the United Nations in this typical water producer tropical Andes basin.

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