Digital elevation models (DEM) used to assess soil erosion risks: a case study in Boyaca, Colombia

Modelos de elevación digital (DEM) para evaluar los riesgos de erosión del suelo: un estudio de caso en Boyacá, Colombia

Jeiner Yobany Buitrago E.[1] and Luis Joel Martínez M.[1]

ABSTRACT

The objective of this research was to develop a model for assessing the risk of erosion, exploring the potential of DEMs from SRTM, ASTER, ALOS PALSAR and one made with interpolation of a 1:25,000 contour map to calculate the variables of the relief that have greater impact on erosion. Several geomorphometric parameters, such as slope, aspect, profile and plan curvature, topographic wetness index, stream power index, and sediment transport capacity were computed from the DEM´s elevation, some fuzzy logic functions proposed to evaluate the incidence of each parameter on erosion risk in a mountainous area of Colombia. The results showed that the use of DEM data is a relatively easy, uncostly method to identify, in a qualitative way, the risk of erosion and contribute to the enhancement of erosion information that is obtained with conventional general soil surveys.

Key words: DEM, erosion, geomorphometric, fuzzy logic.

RESUMEN

El objetivo de esta investigación fue desarrollar un modelo para evaluar el riesgo de erosión, explorando el potencial de los DEM de los sistemas SRTM, ASTER, ALOS PALSAR y uno realizado por interpolación de curvas de nivel a partir de un mapa topográfico escala 1: 25.000. De la elevación de los DEM se calcularon algunos parámetros geomorfométricos como la pendiente, el aspecto, la curvatura horizontal, la curvatura vertical, índice topográfica de humedad, capacidad de transporte de sedimentos, índice de poder de los arroyos que se consideran son tiene el mayor impacto en el riesgo la erosión. Se definieron algunas funciones de lógica difusa para evaluar la incidencia de cada parámetro de riesgos de erosión en una zona montañosa de Colombia. Los resultados mostraron que el uso de datos DEM es un método relativamente fácil y de bajo costo para identificar, de una manera cualitativa, el riesgo a la erosión y contribuir a mejorar la información erosión que se consigue mediante los levantamientos generales de suelos.

Palabras claves: DEM, erosión, geomorfometría, lógica difusa.

Introduction

Soil erosion is one of the leading environmental problems in Colombia, where about 48% of the country is affected, to some degree, by erosion (IGAC *et al*., 2010). Information regarding the areas that have some risk of erosion is critical to making decisions for implementing actions to prevent it. General soil surveys provide important information about areas that have erosion, but do not show which are at risk of being affected; additionally, the level of detail is quite general and only areas with a high incidence of erosion processes are shown. Also, some researchers believe field surveys are expensive and time consuming; therefore, alternative, less expensive approaches that predict soil erosion are desirable, especially in developing countries (Mitra *et al*., 1998).

Erosion refers to the detachment of soil particles and their transport by agents, such as water or wind; when sufficient energy is no longer available to transport the particles, deposition occurs (Morgan, 2005). Rain-splash is the most important detachment agent, while runoff is the main transport agent, with overland flow that can cause erosion in an non-concentrated flow (sheet erosion), rills that have such small concentrations of running water that they can be completely removed by normal cultivation methods, or gullies that are deeper channels that cannot be removed by normal cultivation practices (Aksoy and Kavvas, 2005).

Models are basic tools for studying erosion and predicting its occurrence; therefore, there have been significant advances on that topic. However, models differ greatly in terms of their complexity, their inputs and requirements, the processes they represent and the manner in which these processes are represented, the scale of their intended use and the types of output information they provide (Aksoy and Kavvas 2005; Merritt *et al*., 2003). Some models have limitations since that they do not involve spatial or

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[1] Department of Agronomy, Faculty of Agricultural Sciences, Universidad Nacional de Colombia. Bogota (Colombia). jybuitragoe@unal.edu.co

temporal variability; others require a significant amount of data that are not available and are difficult to obtain under our conditions; others, such as the universal soil loss equation (USLE), were developed for individual plots and cannot be applied to larger areas without modifications.

Topography is a soil-forming factor and, therefore, affects the soil characteristics that determine the use, management, conservation and degradation of this resource. In the case of erosion, topography is a factor that influences the transport and accumulation of soil by water, depending on the particular characteristics of the relief. The effect of relief on erosion has been related to variables such as slope length and steepness, shape and uniformity of the slope (Toy *et al*., 2002). Digital elevation models (DEM) are a source of data with high potential to quantitatively characterize topography as an important input for different erosion models (Mitasova *et al*., 1996; Moore *et al*., 1991). Three dimensional data for slope gradient, slope curvature and relative positions of points are determining factors in modeling erosion and water flow (King *et al*., 2005). The use of the DEM has increased as a data source for the visual and mathematical analysis of the topography and landscape and to model landforms (Martínez and Correa, 2016; Lopez, 2006; Martinez-Casasnovasa *et al*., 2004; Moore *et al*., 1991). The basic principle of geomorphometry analysis is the existence of a relationship between landforms and the numerical parameters used for its description and also with processes involved with the genesis and evolution of the landforms (Evans 2012; Pike, 2000). The primary attributes are calculated directly from the elevation data and include slope, aspect, profile and plan curvature. The secondary attributes are derived from primary attributes, are important because they offer an opportunity to describe patterns as a function of process (Wilson and Gallant, 2000; Moore *et al*., 1991) and include the topographic wetness index, stream power index, radiation and temperature indices, and sediment transport capacity, among others.

Digital elevation models can be used to enhance soil information (Martínez and Correa, 2016) and land evaluation (Munar and Martínez 2014). Moore *et al*. (1993) found significant correlations between quantified terrain attributes and measured soil properties and Chaplot (2013)which often have severe environmental, economic and social consequences. While most of the studies on the gullying process have investigated the involved mechanisms (either overland flow incision, seepage or piping erosion analyzed the importance of terrain attributes computed from a DEM in gully erosion, and King *et al*. (2005) looked at the role played by DEM data in hydrological erosion models. Aksoy and Kavvas (2005) stated that it is possible to incorporate the physical heterogeneity in a catchment by using DEM data in a GIS environment.

Therefore, it is necessary to explore the utility of DEM as a source of data to quantitatively characterize the relief and generate information to improve the performance of erosion models and their applicability to larger areas, such as watersheds and districts, allowing for the use of spatial variability of the factors that cause erosion. This is of great importance in mountainous areas, where erosion by water most often occurs, with degrees of intensity from mild to extreme.

The objective of this research was to develop a model for assessing the risk of erosion, exploring the potential of DEM as a data source to calculate the variables of relief that have greater impact on erosion. Rather than quantifying the soil erosion losses, they try to identify areas with different risk degrees.

Methods and materials

Site characteristics

This research was conducted in the municipality of Samaca, in the department of Boyaca, at 5°29 ‘8’’ N and 73°29’31’’ W (Fig. 1). The study area covered 172.1 km^2, the dominant land uses were agriculture, livestock and coal mining (Planeacion Municipal de Samacá, 2012). There were three main landscapes: a mountain with slopes over 35%, covering 61% of the study area, a plain with slopes ranging from 7% to 20%, representing 26.4% of the extension, and a valley with slopes less than 3%, occupying 12.6% of the study area. The soils were mainly Typic Dystrudepts, Haplusterts, Inceptic Haplustalfs and Lithic Udorthents. The climate was classified as Am with the Köeppen system, which is moist with a dry period, with temperatures ranging between 13 and 18°C and an annual rainfall of 900 mm.

Data collection and analysis

Based on existing maps, an initial analysis was performed and the study area was divided into three landscape units: mountain, plain and valley, in order to consider them as layers for further analysis. Descriptive statistics for each geomorphometric parameter were calculated and an analysis of variance was performed to establish the statistical differences between the landscape units. For validation purposes, a total of 2,273 points were located in the field with a differential GPS, the elevation was recorded and used to assess the accuracy of the DEMs. The DEMs included ASTER and SRTM with a spatial resolution of 30

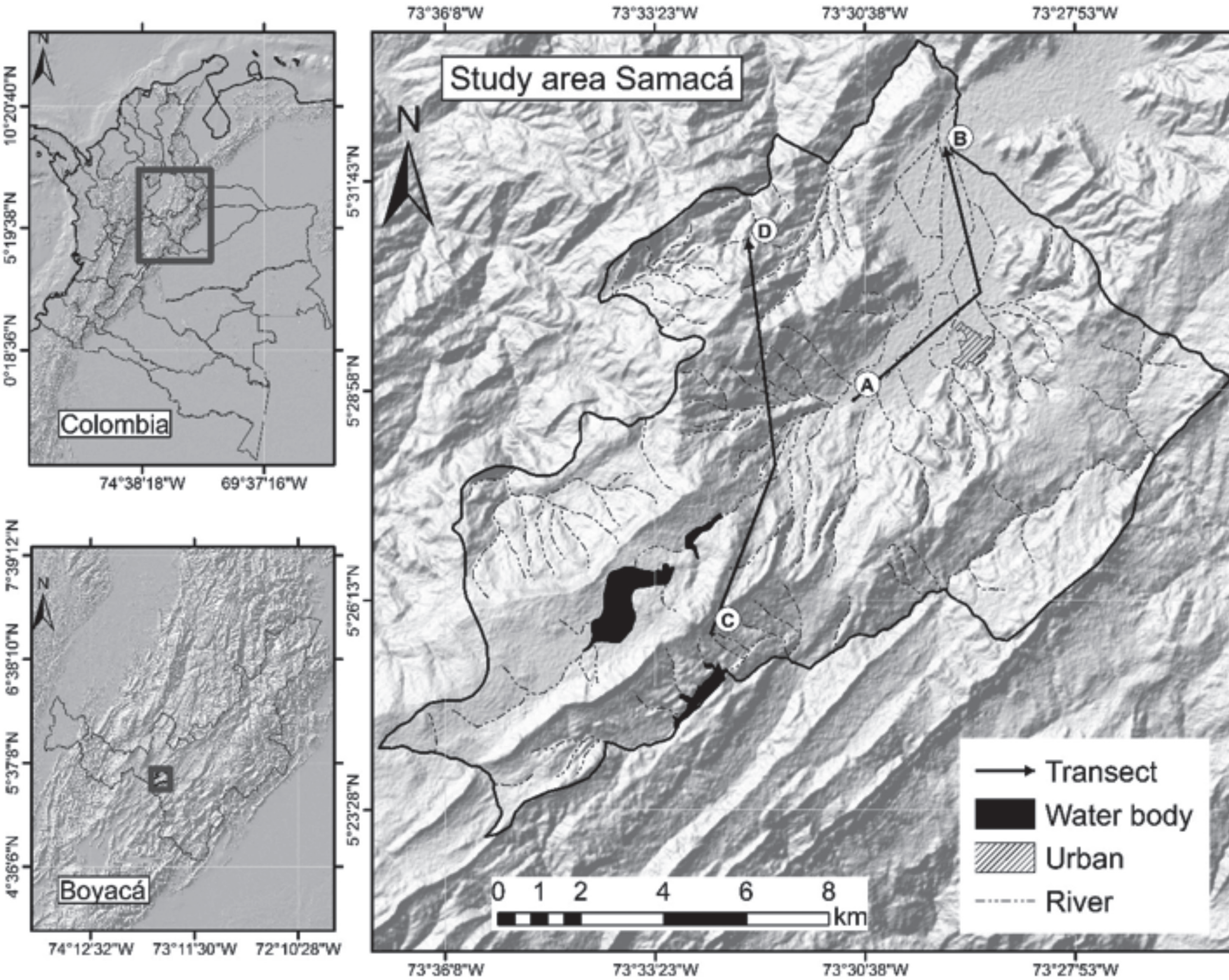

FIGURE 1. Location and transect of landscape for the study area in Samaca (Colombia).

m, ALOS-PALSAR with 12.5 m resolution and one derived by interpolation from a 1:25,000 topographic map with equidistance contours of 50 m. The following parameters were computed using SAGA (2.10) (System for Automated Geoscientific Analyses, University of Göttingen, Göttingen, Germany).

Slope

Slope is important because it influences overland and subsurface flow velocity, runoff rate and vegetation development. If we define the elevation (Z) of a point on a land's surface as a function of the location (X, Y), then the slope (S) is the first derivative of a surface and has both magnitude and direction (Chang and Tsai, 1991).

$$S = \sqrt{\left(\frac{\partial_z}{\partial_x}\right)^2 + \left(\frac{\partial_z}{\partial_y}\right)^2} \qquad (1)$$

Plane curvature

Plane curvature is the second derivative of elevation and depends on the aspect and slope. It refers to the curvature in the horizontal plane of a contour (Wilson and Gallant, 2000); when it is positive, it means that the shape of the land is convex, when it is negative, it corresponds to a concave shape and zero indicates that it is a flat surface. A convex curvature implies flow divergence and a concave one means flow convergence.

$$C_H = \frac{\theta_{xx}\theta_y^2 - 2\theta_{xy}\theta_x\theta_y + \theta_{yy}\theta_x^2}{\theta_x^2 + \theta_y^2\sqrt{\theta_x^2 + \theta_y^2 + 1}} \qquad (2)$$

where θ_x is the slope in the x direction and θ_y is the slope in y direction, θ_{xx} is the second derivative of the slope in direction x and θ_{yy} is the second derivative of the slope in direction y and θ_{xy} is the second derivative of the product of the slope in direction of x and y.

Profile curvature

Profile curvature is the curvature in the vertical plane on a flow line; it influences flow acceleration, erosion and deposition rate (Wilson and Gallant, 2000; Neteler and Mitasova, 2008; Kennelly, 2008). A convex curvature accelerates flow and erosion process, while a concave one influences the sedimentation process.

$$C_V = \frac{\theta_{xx}\theta_x^2 + 2\theta_{xy}\theta_x\theta_y + \theta_{yy}\theta_y^2}{\theta_x^2 + \theta_y^2\sqrt{(\theta_x^2 + \theta_y^2 + 1)^3}} \tag{3}$$

where θ_x is the slope in the x direction and θ_y is the slope in the y direction, θ_{xx} is the second derivative of the slope in direction x and θ_{yy} is the second derivative of the slope in direction y and θ_{xy} is the second derivative of the product of the slopes in direction of x and y.

Topographic wetness index

The topographic wetness index, also called topographic index or compound topographic index (Quinn *et al.*, 1991), is a parameter that describes the tendency of a cell to accumulate water, it was calculated as:

$$TWI = In\left(\frac{A_S}{Tan\ \theta}\right) \tag{4}$$

where TWI is the transmissivity when the soil profile is saturated, As is the specific catchment area and is a measure of surface or shallow subsurface runoff at a given point on the landscape and θ is the slope in degrees. For the ideal case of temporally and spatially uniform rainfall excess, the steady-state discharge per unit width *q* is directly proportional to A; even though this ideal condition rarely exists in the nature, this assumed relationship is used extensively in hydrology (Moore *et al.*, 1991).

Stream power index (SPI)

This parameter has been used extensively in studies of erosion, sediment transport and geomorphology as a measure of the erosive power of flowing water; it is assumed that the discharge is proportional to the drainage area (Moore *et al.*, 1991). Some authors have used a variation of this index for predicting ephemeral gullies (Moore *et al.*, 1988). The stream power index, or its derivatives, could be used to identify places where soil conservation measures that reduce the erosive effects of concentrated surface runoff, such as grassed waterways, should be used (Moore *et al.*, 1991). The calculation of this parameter is done with the following Eq. 5:

$$SPI = A_S Tan\ \theta \tag{5}$$

where A_s is the specific area of drainage and θ is the slope in degrees.

Sediment transport capacity (STC)

Sediment transport capacity is physically based on the length-slope factor, derived using the unit stream power theory to describe the erosion processes associated with sheet and rill flow on hill-slopes (Moore and Burch, 1986). For landscapes with a complex relief, it is more suitable than the original equation LS factor of the USLE because it explicitly takes into account the convergence and divergence of the flow through the drainage area (Wilson and Gallant, 2000; Moore *et al.*, 1991). The calculation of this parameter is done with the following Eq. 6:

$$STC = \left(\frac{A_S}{22.1}\right)^{0.6}\left(\frac{Sin\theta}{0.0896}\right)^{1.3} \tag{6}$$

where A_s is the specific area of drainage and θ is the slope in degrees.

Soil erosion risk

The actual erosion risk is the combined effect of rainfall erosivity, soil erodibility, topography sensitivity to erosion and land cover (Van Der Knijff *et al.*, 2000).

Topography sensitivity to erosion was assessed with the Hamacher fuzzy function, which allows for the integration of the effect of geomorphometric parameters on soil erosion. This function uses fuzzy connectives to combine the effect of several parameters in multi-criteria decision making (Canuto *et al.*, 2003). It has been used in digital assessments of soil based on its properties(Gruijter *et al.*, 2011). Eq. 7 was used:

$$E.R. = \left(\frac{\mu_A(x) + \mu_B(x) - 2[\mu_A(x)\mu_B(x)]}{1 - \mu_A(x)\mu_B(x)}, \dots, \frac{\mu_E(x) + \mu_F(x) - 2[\mu_E(x)\mu_F(x)]}{1 - \mu_E(x)\mu_F(x)}\right) \tag{7}$$

where *E.R. = Sensitivity of topography to erosion*; *geomorphometric parameters* (θ, C_H, C_V, *TWI, SPI, STC)*

The soil erodibility was assessed by the nomogram method (Kirby, 1980) for cartographic soil units and the degree of incidence on risk to erosion was assessed with Eq. 8:

$$\mu(\boldsymbol{x}) = \begin{cases} 0;\ x \leq 0.05 \\ \frac{1}{1+e^{(3.77-11.2*X)}};\ 0.05 \leq x\ \leq 5 \\ 1;\ Otherwise \end{cases} \tag{8}$$

The rainfall erosivity was computed as a Fournier index (Lal, 1988). A land cover map was made based on aerial photographs and a Spot image; the effect of land cover on the erosion was judged based on the values established by Hoyos (2005). Since the map showed classes, the fuzzy degrees of memberships were not assigned by means of fuzzy function, but the cover management factor was taken into account (Tab. 1).

TABLE 1. Protecting values of the different land covers (adapted from Hoyos, 2005).

Land cover type	Score
Grass	0.25
Tree grass	0.20
Annual crops associated with permanent crops and complex cultivation patterns and pastures	0.30
Complex cultivation, pastures and areas natural vegetation	0.10
Forest nature	0.05
Shrubs and bushes and coniferous forest	0.10
Paramo and subparamo vegetation	0.10
Bare lands	1.00
Water	---

The calculation of risk of erosion was performed with a fuzzy equation that integrates the effect of the above-mentioned factors. In conventional fuzzy logic, an AND operation is implemented mathematically as a minimum function on the set of logical antecedents. In this case, the Eq. 9 proposed by Reynolds (2001), was used

$$AND(x) = Min_{(x)} + \frac{(Mean_{(x)} - Min_{(x)})(Min_{(x)}+1)}{2} \qquad (9)$$

$Min_{(xi)}$ = i=1,..,n the minimum value for erosion factors

$Mean_{(xi)}$= the weighted average of $_{xi}$ for erosion factors

Where AND is a minimum-biased weighted average of the logical antecedents. According to Reynolds (2001), this equation gives a conservative estimate of the degree of accuracy.

Results and discussion

Overall, the results indicated only a slight variation in the elevation among the DEMs; the ASTER DEM showed the lower mean height values and ALOS the highest mean height. The coefficients of variation were higher in the mountain areas, indicating a larger variation of the data compared to the valley; however, the variation was generally low (Tab. 2).

Two profiles were defined, one for each landscape unit, to analyze the spatial variability of the elevation, which is the primary parameter for estimating geomorphometric variables. The profile in direction A-B corresponded to the valley and showed that the ASTER model varied greatly in elevation over short distances (Fig. 2), with height differences in some cases more than 50 m, while the ALOS and SRTM presented smaller variations, which were generally less than 10 m. The contour model had a constant elevation in this landscape unit due to the fact that the topographic map, 1:25,000, from which it was derived, had equidistance contours of 50 m; therefore, after interpolation with IDW (Munar and Martínez, 2014), a flat area will be obtained. Comparing results with field data from the study area, it can be seen that the ALOS and SRTM models were closer to reality because there the valley is a flat area with very small variations in elevation. ASTER GDEM accuracy depends on the number of used stacks per DEM-point, which varies depending on the area and, therefore, it usually has a lower vertical accuracy than SRTM height models (Jacobsen, 2010)close to worldwide covering SRTM C-band height models several problems of the remote sensing community have been solved or made simpler. With the ASTER GDEM now another free of charge available height model can be used, covering the earth from 83\u00b0 southern up to 83\u00b0 northern latitude filling the partially larger gaps of the origi-nal SRTM digital surface models (DSMs.

TABLE 2. Descriptive statistics of elevation for the DEMs used for a Samaca area (Colombia).

Landscape	DEM	Median (m)	Mean (m)	Min (m)	Max (m)	SD	CV (%)
Valley	ALOS	2,610	2,611	2,602	2,629	6.6	0.25
	SRTM	2,588	2,590	2,581	2,607	6.4	0.25
	COUNTOURS	2,595	2,597	2,595	2,610	4.1	0.16
	ASTER	2,588	2,589	2,552	2,635	16.5	0.64
Mountain	ALOS	3,051	3,081	2,747	3,427	219.4	7.12
	SRTM	3,042	3,067	2,728	3,418	221.6	7.22
	COUNTORS	3,041	3,068	2,731	3,414	221.7	7.23
	ASTER	3,025	3,054	2,740	3,422	218.5	7.16

SD, standard error; CV, coefficient of variation.

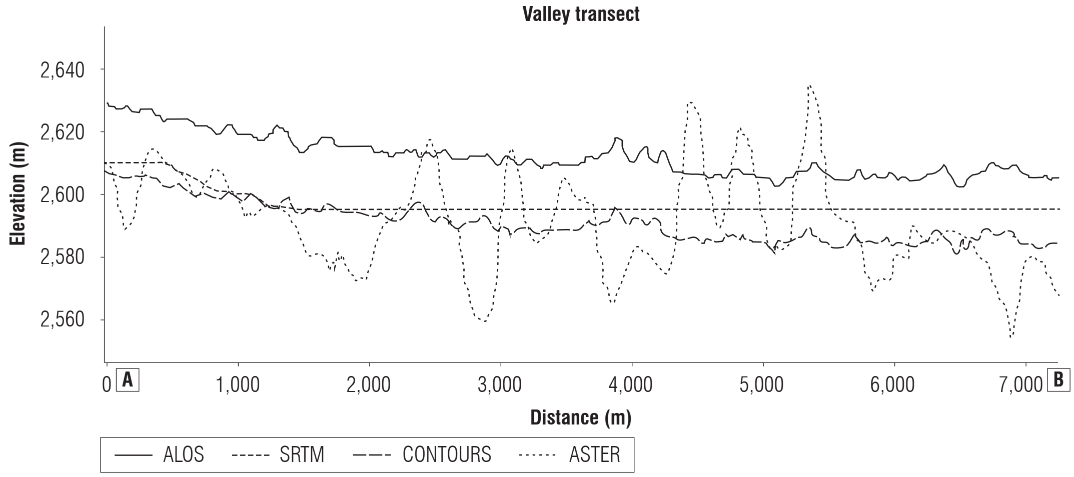

FIGURE 2. Topographic profile to the valley with different DEM's in a Samaca area (Colombia).

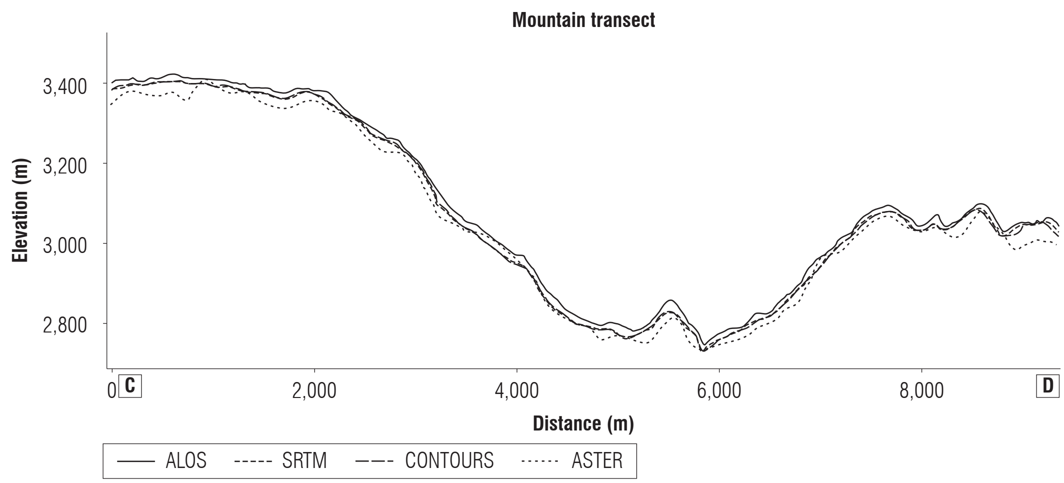

FIGURE 3. Transect to the mountain landscape with different DEMs in a Samaca area (Colombia).

In a mountainous area, the variation of elevation among DEM at short distances (Fig. 3) is also important; the ASTER presented lower values and ALOS higher ones. In both landscapes, the ALOS model had systematically higher height values, as compared with the others, while the ASTER showed the lowest height and the DEM derived from contour lines had an intermediate height.

These findings have implications for estimating geomorphometric parameters since elevation is the main variable from which other parameters are derived.

The ALOS DEM exhibited higher elevations in both landscapes when compared with the other DEM. The analysis of variance showed that there were significant differences between the evaluated DEM (Tab. 3).

From the analysis, comparing the elevation of the various DEM with data taken in the field with GPS, it was found that the highest R^2 (0.783) was seen with the DEM ALOS and the lower k^2 values were in the ASTER DEM and Contour; the SRTM also presented a high R^2 (0.71). The lowest RMSE value (Root Mean Square Error) was seen with the ALOS DEM, followed by contours and SRTM; the ASTER

TABLE 3. Average elevation for each DEM, by landscapes in a Samaca area (Colombia).

Landscape	DEM	Elevation (m)
Valley C	ALOS	2,611 a
	SRTM	2,590 c
	CONTOURS	2,597 b
	ASTER	2,589 c
Mountain	ALOS	3,081 a
	SRTM	3,067 b
	CONTOURS	3,068 b
	ASTER	3,054 c

Means with different letters indicate significant differences according to the Tukey test ($P \leq 0.05$).

showed the highest RMSE. These results were due to the higher resolution seen with the ALOS DEM (12.5 m) and a better representation of the Earth's surface, with no effects from clouds, as was the case with the ASTER model, meanwhile the DEM derived from the interpolation curve generalized the heights.

Based on the previous analyses, the DEM ALOS was selected for computing the geomorphometric parameters.

Geomorphometric parameters

Slope

In the study area, the slope varied between 0.9% and 89.4%; in the valley, the slopes had an average of 4.4%, while, on the mountain, the dominant slope was greater than 30%, presenting an average of 28.7%. After applying the fuzzy function (Fig. 4A) to the slope map, the influence of the slope on risk of erosion was obtained (Fig. 5B). When the slope was less than 3%, it was considered to have a low incidence of risk of erosion and, therefore, the degrees of membership in the fuzzy function was equal to 0, when the slope increased, the impact on the erosion risk was also higher and, therefore, the membership degrees presented values close to 1.

Slope is a factor of higher incidence in erosion studies therefore, a reliable estimate of the slope degree is required as an input for erosion models. Slope obtained from a DEM is more accurately than the obtained from maps as part of general soil surveys (Munar and Martínez, 2014)

Plane curvature

The plane curvature varied between -0.04 and 0.06. The highest incidence corresponded to the convex forms with values greater than zero (Fig. 4B) and, according to the fuzzy function (Fig. 5C), the degrees of membership increased, up to 1. These forms corresponded to ridges and upper parts of the slopes in the mountain. Meanwhile, the lowest incidence of this parameter in the risk of erosion corresponded to curvature values under zero; therefore, there were low degrees of membership that corresponded to concave shapes. The flat surfaces had an intermediate degree of incidence.

The concave curvature implied a greater convergence of water flow, facilitating the transport of materials and accumulation, while the convex surfaces promoted divergence of water flow, influencing dispersion, and, therefore, had less effect on erosion (Olaya, 2008).

Profile curvature

Values less than zero presented a low incidence in the risk to erosion and corresponded to a concave shape in the vertical direction to the slope, while the convex shapes had a higher incidence and the flat slopes had an intermediate effect (Fig. 4C). The curvature profile influences the flow acceleration, erosion and deposition rate; a convex curvature accelerates flow and erosion process, while a concave one influences the sedimentation process (Wilson and Gallant, 2000; Neteler and Mitasova, 2008; Kennelly, 2008).

Topographic Wetness Index

In the study area, the TWI ranged from 1.9 to 24.0. Higher TWI values represent depressions in the landscape, where water is likely to concentrate through runoff, while lower values represent crests and ridges (Martínez and Correa, 2016). TWI was the factor with more incidence in the risk of erosion since higher degrees of incidence covered larger areas (Fig. 4E and Fig. 5E).

Stream power index (SPI)

The Stream Power Index varied between 0 and 6.2. Higher values correspond to lower and concave shapes of the terrain, indicating a greater erosive power of the water flow and, therefore, presents values of membership degree close to 1 (Fig. 4E), while lower values indicate a less likely occurrence of concentration to runoff, presenting membership values close to zero. This parameter has been used extensively in studies of erosion, sediment transport and geomorphology as a measure of the erosive power of flowing water, it is assumed that the discharge is proportional to the drainage area (Moore *et al*., 1991). Some authors have used a variation of this index for predicting ephemeral gullies (Moore *et al*., 1988). The SPI or its derivatives, could be used to identify places where soil conservation measures that reduce the erosive effects of concentrated surface runoff, such as grassed waterways, should be used (Moore *et al*., 1991). Sediment delivery decreases with increasing basin sizes because large basins have more sediment storage sites where eroded sediment is kept. Sediment delivery can be limited by reducing either the detachment rate or the transport capacity, depending on which has a lower value (Aksoy and Kavvas, 2005) (Fig. 5F).

Sediment transport capacity (STC)

The sediment transport capacity varied between 0 and 70.2. Lower values correspond to convex terrain that hinders the concentration of water flow and, therefore, has low values in degrees of membership (Fig. 4F). An increased transport index indicates a higher concentration of water flow and,

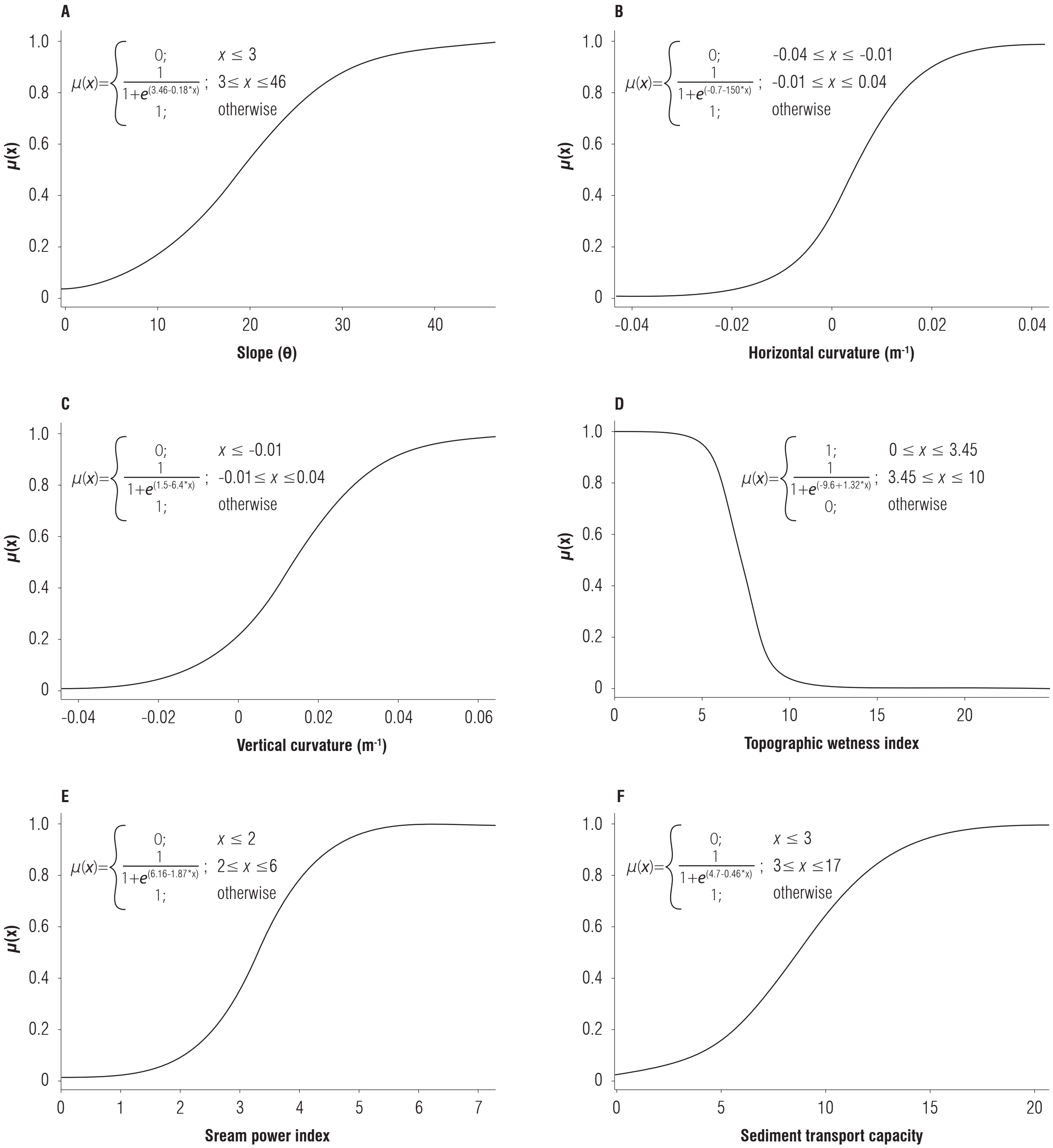

FIGURE 4. Fuzzy logic functions applied to terrain parameters in a Samaca area (Colombia).

therefore, has a greater impact on sediment transport, reaching values over 17, which is considered the greatest effect on the risk of erosion and, consequently, the degrees of membership have values of 1 (Fig. 5G).

Risk of erosion

This map demonstrates the qualitative classification of the areas according to the risk of erosion (Fig. 6). In the study area, dominant risk were high and moderate with 64.1 and 58.9 km^2 of the area respectively, and in less proportion low and very high risk with 32.9 and 16.2 km^2. According to Van Der Knijff *et al.* (2000), in some areas, erosion risk is expressed in qualitative terms rather than in actual rates of soil loss. These authors stated that a quantitative assessment is not appropriate when the data availability is not adequate. The use of fuzzy-logic in soil science has several advantages

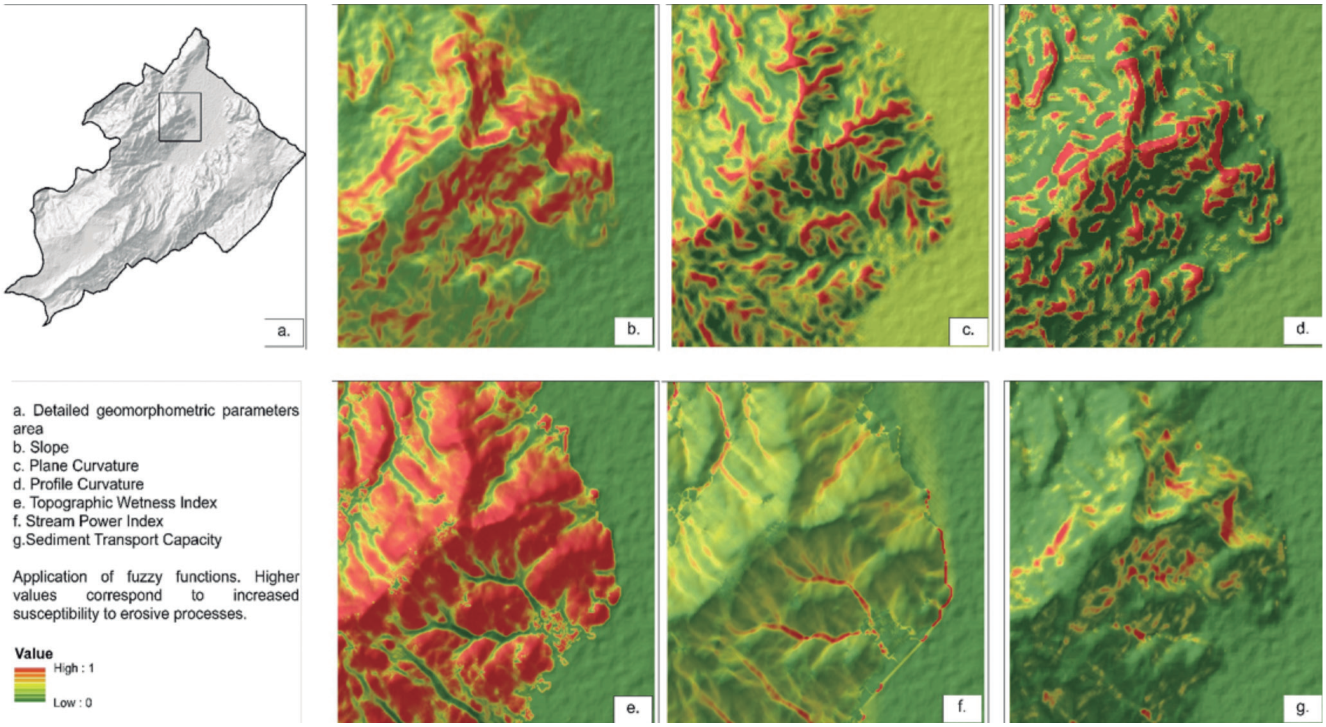

FIGURE. 5. Results of fuzzy logic functions in the terrain parameter in a Samaca area (Colombia).

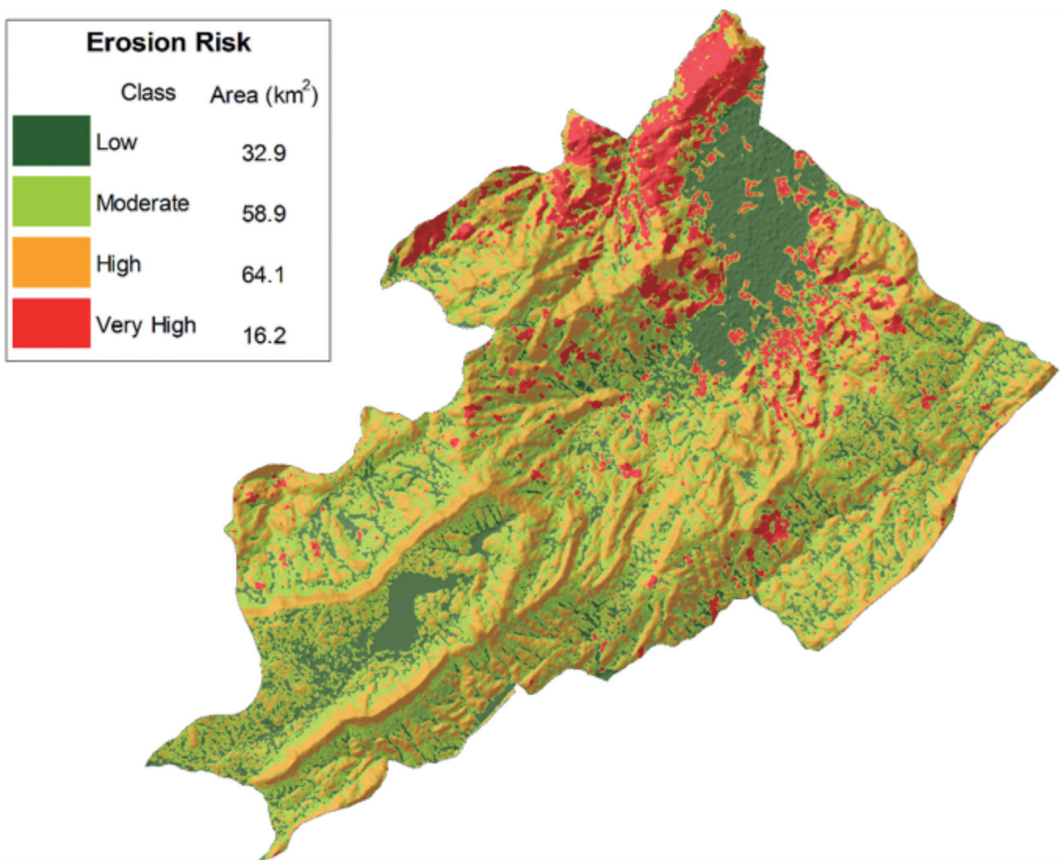

FIGURE 6. Erosion risk for a Samaca area (Colombia).

that improves the use of conventional logic, McBratney and Odeh (1997) mentioned that in complex processes with many factors influencing and data with high uncertainty, fuzzy approach has a great potential for modelling.

Conclusions

The land zoning based on the qualitative analysis of risk of erosion is an important contribution for making decisions about soil management and conservation in areas where there is insufficient data, at the level of detail required, to develop or apply very precise quantitative models. DEMs are an important data source that are low cost and have good resolution to improve information on erosion; they calculate geomorphometric parameters that facilitate a better understanding of the factors affecting erosion. In addition, it can improve the level of detail of the information offered by the general erosion soil surveys. The use of fuzzy logic provides a more realistic approach to the erosive phenomenon whose classes do not have clear and exact limits and its assessment is based on data that have considerable uncertainty. This generates information quickly and at a low cost to take measurements in order to prevent or reduce the degree of erosion.

Acknowledgments

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