sociedade & natureza

DOI: 10.14393/SN-v34-2022- 62872
Received: August 19, 2021 | Accepted: January 05, 2022 | Published: February 07, 2022

Papers

Classification of environmental fragility in watershed using Fuzzy logic and AHP method

Karen Carrilho da Silva Lira [1]
Humberto Rodrigues Francisco [2]
Aldi Feiden [3]

Keywords:
Multi-criteria analysis
QGIS software
Environmental vulnerability

Abstract
Assessment of environmental fragility in watersheds is an important tool to assist managers in planning and interventions for sustainable production and environmental conservation. The objective of this work was to use Fuzzy logic and the Analytic Hierarchy Process (AHP) method to classify environmental fragility using data obtained from public institutions. The Marreco River watershed in western Paraná, Brazil, was the study model. To classify areas, a geographic information system (GIS) and data from a digital elevation model (DEM), as well as data on soil occupation and type were used. The analysis found that 71.3% of the basin area has average fragility. Compared to two other forms of weighing elements of the slope map, the three presented statistical difference, but all indicated that the basin under study mostly has average environmental fragility. The use of fuzzy logic allowed application of a continuous variation of weights according to the variation of environmental characteristics, which may more effectively represent the reality and, therefore, provide more reliable results. This method may represent a useful tool to appropriately manage sustainable production and environmental conservation in watershed areas.

[1] Universidade Estadual do Oeste do Paraná – UNIOESTE, Toledo, PR, Brazil. karenc@utfpr.edu.br
[2] Universidade Federal da Fronteira Sul -UFFS, Laranjeiras do Sul, PR, Brazil humberto.francisco@uffs.edu.br
[3] Universidade Estadual do Oeste do Paraná – UNIOESTE, Toledo, PR, Brazil aldi.feiden@unioeste.br

INTRODUCTION

Watersheds constitute a balanced natural system where any change may compromise their functionality (CHRISTOFOLETTI, 1980; REGGIANI AND HASSANIZADEH, 2016). As an example, the removal of vegetation cover can affect temperature, soil structure, resistance to rainfall erosion, and water regime (TRICART, 1977). In this context, environmental fragility embodies the vulnerability of the environment that can suffer erosive processes, silting, and floods (SPÖRL, 2007).

Tricart (1977) noted that the environment remains in dynamic equilibrium through its natural relations of exchange, and he suggested a model to assess the degree of instability using information about pedogenesis and morphogenesis. Ross (1994) adapted this model with information about human intervention, geomorphology, soils, vegetation cover, and climate by establishing different importance for each of these variables. Crepani (2001) used variables such as relief dissection index, rock, soil, and vegetation cover and established an equal weighting for environmental variables in the fragility study. Different results for fragility were obtained by each of these models. Dalla Corte et al. (2015) researched weighting variables and concluded that the methodology of environmental fragility analysis is highly dependent on the choice of weighting factors and is related to the context in which it is performed.

Recent studies point to the importance of analyzing environmental fragility in watershed such as dos Santos and Nascimento (2021) for the Rio de Janeiro watershed in Bahia, Albuquerque and de Medeiros (2017) in Ceará, dos Santos et al. (2021) for the Piracuruca River watershed in Piauí, in the northeast region of Brazil, and Abrão and Bacani (2018) for the Santo Antônio River watershed in Mato Grosso do Sul, in the midwest region of Brazil.

In this work, fuzzy logic was used with the objective of better representing the variation of environmental characteristics. With the mathematical structure and the property of inaccuracy of boundaries between objects, fuzzy logic can treat problems that have imprecision and abstraction in their models and concepts. Fuzzy logic can represent the variation and relative importance of each criterion in the phenomenon being studied, allowing more reliable results (BURROUGH ,1992; BURROUGH; MCDONNELL, 1998; ROSENDO, 2019). Fuzzy set theory began to be applied using geographic data in the 1980s and 1990s in the works of Burrough (1989), Kollias and Voliotis (1991), and Burrough et al. (1992), as it has become useful for data where the classification of a certain element is a matter of interpretation (BANAI, 1993). Recent research involving fuzzy logic and geographic data can be found in the Cornwell et al. (2020), Parsian et al. (2021) and Madhu et al. (2021) studies.

A multicriteria analysis method, Analytic Hierarchy Process (AHP) developed by Thomas L. Saaty, was used to support the study. AHP is a method of choice based on pairwise comparison and a predefined scale to express the importance of one criterion over the other in relation to decision-making (SAATY, 1990; SAATY, 1991; SAATY E VARGAS, 2012). In addition, it is concerned with the level of consistency of the calculations and can be applied to quantitative or qualitative information (SAATY, 1987).

In this work, characteristics such as slope, altitude, soil type, and land use/occupation were considered for the analysis of environmental fragility using the Marreco River watershed as a case study. The watershed is in western Paraná, Brazil, in a region with high grain, pig, and fish production and belongs to the Paraná 3 watershed, whose effluents release water at the Itaipu Hydroelectric Power Plant (SEAB, 2018; PMRH, 2017; PLANO DA BACIA HIDROGRÁFICA DO PARANÁ 3, 2014). Therefore, a study on the fragility of this environment is necessary to provide information for proper management.

The data obtained were processed using a Geographic Information System (GIS). GIS was developed in the 1980s and its main feature is the ability to integrate and transform spatial data with applications in several areas (SILVA, 2003; MIRANDA, 2005).

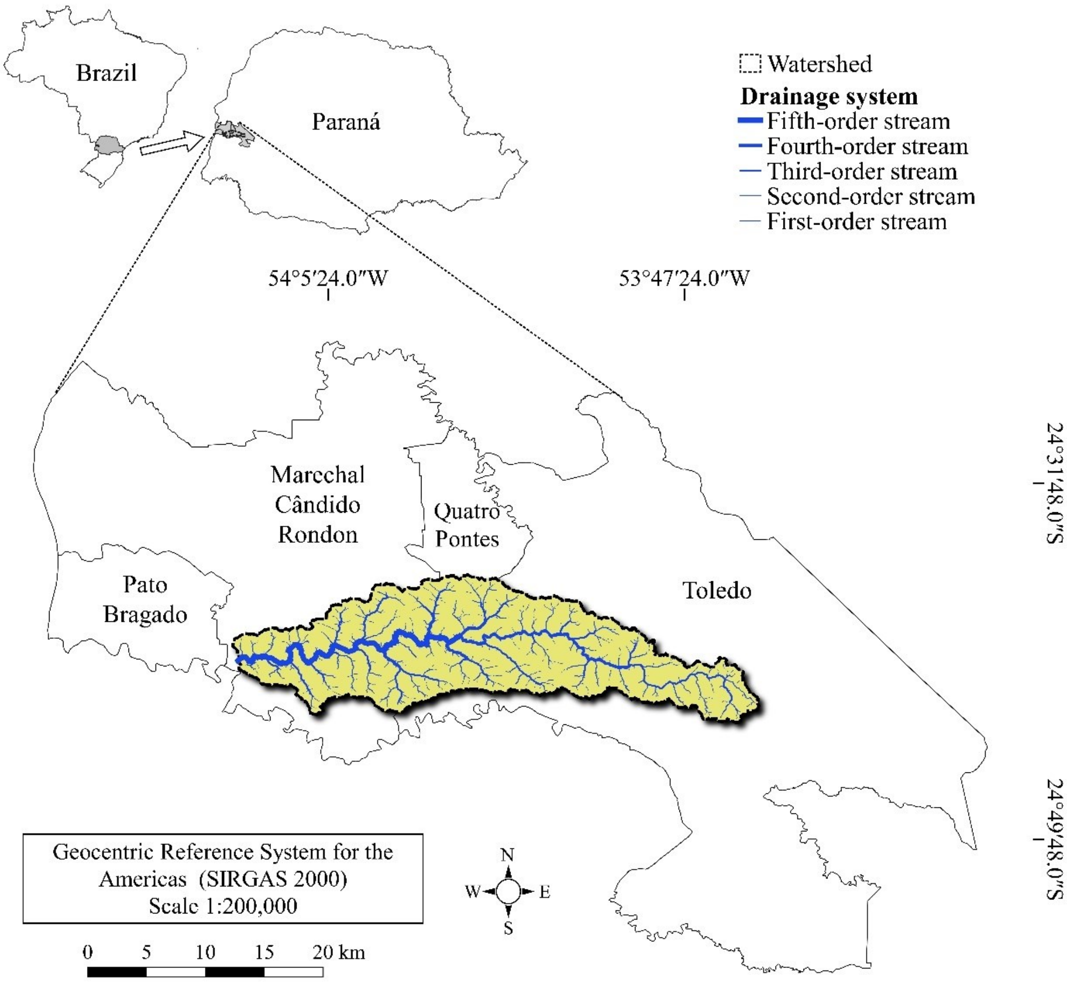
Hence, this study aimed to use fuzzy logic and the AHP method to classify environmental fragility using the Marreco River watershed as a base. Furthermore, to present the importance of using fuzzy logic to represent the variation of environmental characteristics and verify its influence on the final fragility map, a comparison was made between three different forms of weighing elements of the map with the higher weight.

MATERIAL AND METHODS

The Marreco River watershed lies in the municipalities of Toledo, Quatro Pontes, Marechal Cândido Rondon, and Pato Bragado (Figure 1) in western Paraná, in the southern region of Brazil, and is approximately 338.8 km^2

in area. The source of the Marreco River is in the urban area of Toledo and its mouth is on the São Francisco River located on the border between the municipalities of Pato Bragado and Marechal Cândido Rondon. According to Köppen's climate classification system, the basin is in a region of Cfa climate, i.e., subtropical climate with hot summer (IAPAR, 2020).

Figure 1 - Geographic location of the Marreco River watershed.

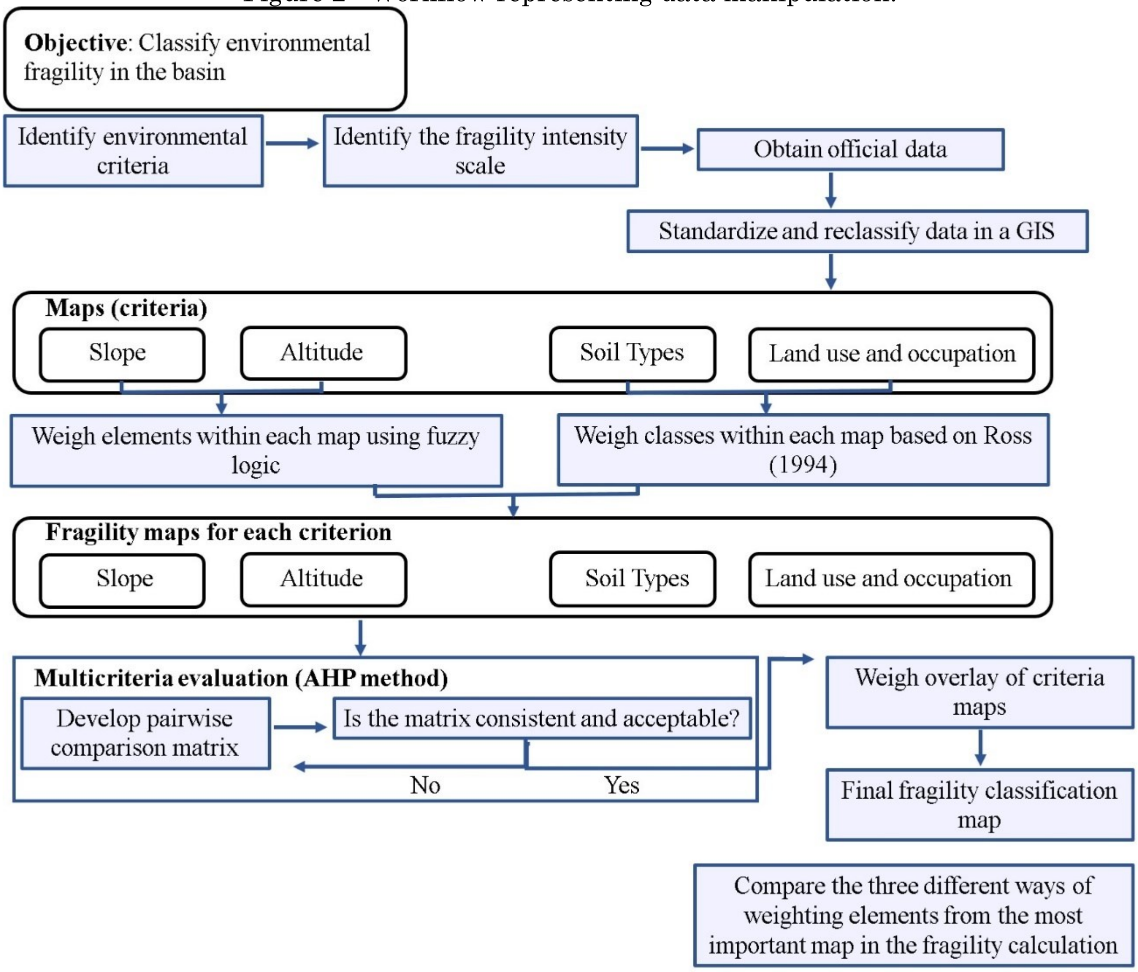


Source: The authors (2021).

The analysis methodology included the following steps (Figure 2):

- Define the environmental criteria, the fragility intensity scale, acquisition of data, and processing in a GIS;
- Weigh the elements and classes within maps based on scientific literature and using fuzzy logic;
- Weigh each criterion using the AHP method;
- Weigh overlay of criteria;
- Compare three different ways of weighting elements from the most important map in the fragility calculation.

Figure 2 - Workflow representing data manipulation.



Source: The authors (2021).

Software

This study used data provided free by public institutions that were organized through information plans represented by maps. All data were analyzed and processed in the QGIS Las Palmas software, version 2.18.28.

Data acquisition

The delimitation of the basin as well as the information on slope and altitude were obtained through the acquisition of two images (SRTM1S25W054V3 and SRTM1S25W055V3) using digital elevation model (DEM) from Shuttle Radar Topography Mission (SRTM), with spatial resolution of 1Arc-Second equivalent to 30 m. The scenes were acquired from the United States Geological Survey (USGS, 2019) and were processed through the QGIS software. To delimitate the watershed, hydrological analyses based on DEM were performed using the Terrain Analysis Using Digital Elevation Models (TauDEM) tool from QGIS according to Tarboton (2011).

The cartographic data in vector format (shp) of the region soil type were obtained directly from the Empresa Brasileira de Pesquisa Agropecuária (EMBRAPA, 2020), it is a brazilian corporation responsible for the agricultural research and development, on a 1:250,000 scale, Universal Transverse Mercator (UTM) projection, Zone 22 South, Reference System: Córrego Alegre. The classes of the second categorical level were considered to reclassify and identify soil types.

Information on land use and occupation was obtained in raster format from the Mapbiomas collection 5, on a 1:100,000 scale and at a spatial resolution of 30 m (MAPBIOMAS, 2020).

Data standardization

The data were reprojected to SIRGAS 2000 (Geodesic Reference System for the Americas 2000), UTM (Zone 22 South). After converting the soil type to the raster format, all files were standardized: spatial resolution with 30 m (pixel), a signed 16-bit datatype, row, and column dimensions with 464 and 1564 pixels, respectively, and a value was set for no data area to hide undesirable border. The objective of these procedures was to simplify metric quantifications and standardize parameters for performing multicriteria analysis (FRANCISCO et al., 2019).

Fuzzy modeling

In this work, a classification was employed that attributes values (weights) to a region according to the variation of a given characteristic. This classification is described by fuzzy sets and defined as a generalization of Boolean algebra (ZADEH, 1965).

Let G is a space of objects represented by points and x an element of G. A fuzzy set A in G is characterized by the membership function $f_A(x)$, which associates each point x in G, a real number in the interval [0.1], where the value represents the grade of membership of x in A. That is,

$$A = (x, f_A(x)), x \in G$$

and

$$f_A: G \rightarrow A: [0.1]$$

Thus, the nearer $f_A(x)$ is to 1, the higher the grade of membership of x in A; the nearer $f_A(x)$ is to 0, the lower the grade of membership of x in A. The function $f_A(x)$ can be discrete or continuous. (ZADEH, 1965).

In the model called Boolean, the membership function is expressed with values 0 or 1, if $x \notin A$ or if $x \in A$, respectively. Inferences based on Boolean rules are often inefficient due to their rigid classification (MEIRELLES, 1997).

Fuzzy modeling can be represented by different membership functions depending on the characteristics of the set in the problem (BURROUGH ET al., 1992). The choice of this function is not arbitrary, but it is subjective and reflects the context in which the problem is inserted and how it is treated (KANDEL, 1986). Linear, quadratic, gaussian, or sigmoid functions are the most used.

Determining weights using fuzzy modeling

The information plans used were slope, soil type, land use and occupation, and altitude maps. To facilitate the calculations, we decided to use the interval [0.10] instead of [0.1] for the membership function.

Each point x represents an environmental element or class in a certain space on the map. A value (weight) in the interval [0.10] was assigned for the soil and land use and occupation classes; for the slope and altitude elements, continuous membership functions were used. This weighting was empirically performed based on Crepani et al. (2001), Ross (1994), and Spörl (2001).

The degree of fragility was adapted to fuzzy modeling based on Crepani et al. (2001) and Ross (1994) with five intensities: very low, low, average, high, and very high fragility, expressed by values in the interval [0.10] (Table 1). Therefore, the closer to 10, the greater environmental vulnerability.

Table 1- Degrees of fragility.

Degree of fragility	Values
Very low	up to 2
Low	2 to 4
Average	4 to 6
High	6 to 8
Very high	8 to 10

Source: Adapted from Ross (1994).

Environmental fragility in terms of soil type and land use and occupation

The classification of environmental fragility of different soil types and land use/occupation was based on Ross (1994) (Table 2). For soil classification, this author considered the diffuse and concentrated surface runoff of rainwater. To classify land use and occupation, he considered the protection capacity they offer to the soil. To apply the weights, a reclassification of the raster data was performed using the r.reclass algorithm in the QGIS software according to Westervelt and Shapiro(2022).

Table 2 - Classes in the soil and land use maps, degrees of environmental fragility and weights.

Variables	Degrees of Environmental Fragility and Weights				
	Very low	Low	Average	High	Very high
	2	4	6	8	10
Soil	Red and Red-Yellow Latosol, clayey texture	Yellow and Red-Yellow Latosol, medium/ clayey texture	Red Nitosol, Red Argisol, clayey texture	Red-Yellow Argisol, medium texture	Neosol, Cambisol, Gleysol
Land use	Forest formation	Pasture	Agriculture-pasture mosaic	Agriculture	Urban area

Source: Adapted from Ross (1994).

Environmental fragility in terms of slope

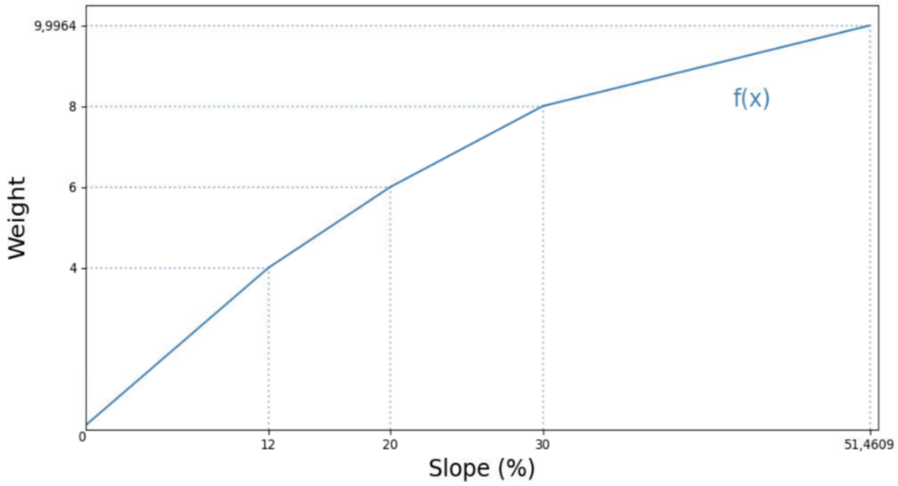
The term slope is defined as the degree of inclination of the relief in relation to the horizontal plane; the greater the slope of the terrain, the greater the speed and transport capacity of rainwater, contributing to the soil erosion process (CREPANI et al., 2001; GEMITZI et al., 2011; WU, 2014). In this work, the slope value was treated in terms of percentage.

The distribution of slope values in the fragility scale was based on Crepani et al. (2001) and Ross (1994). Fragility values closer to 0 (zero) were associated with lower slope, i.e., regions where soil-forming processes predominate. Values closer to 10 were associated with greater slope, i.e., regions where erosive and landslide processes predominate.

To elaborate the membership function $f(x)$ that attributed weights to the elements of the slope map, the minimum and maximum slope (51.46%) values found in the basin, the limits of the hierarchical categories of Ross (1994), and a linear interpolation of these limits were used (Figure 3):

$$f(x) = \begin{cases} 0.325\,x + 0.1; & 0 \leq x \leq 12 \\ 0.25\,x + 1; & 12 < x \leq 20 \\ 0.2\,x + 2; & 20 < x \leq 30 \\ \frac{20\,x + 1120}{215}; & 30 < x \leq 51.4609 \end{cases} \quad (1)$$

Figure 3 - Graph of the function $f(x)$ applied to the elements of the slope map.



Source: The authors (2021).

To apply the function to each element of the slope map, the raster calculator from QGIS software was used according to QGIS Project (2019).

Environmental fragility in terms of altitude

Signs of changes in certain altitudes, such as temperature and precipitation patterns, are clear (LÓPEZ et al., 2011). Fritzons et al. (2008), through a regression analysis between temperature and altitude for the entire set of stations in Paraná, concluded that 74% of the temperature variation can be explained by the altitude difference. Ávila et al. (2016) presented a relationship between precipitation and altitude in the South region, Brazil. Wischmeier (1959) related the amount of soil loss and energy of rains, and dos Santos and Nascimento (2021) used rainfall as one of the factors to estimate soil loss in a watershed. In addition, de Mello et al. (2020) connected rainfall erosivity and altitude.

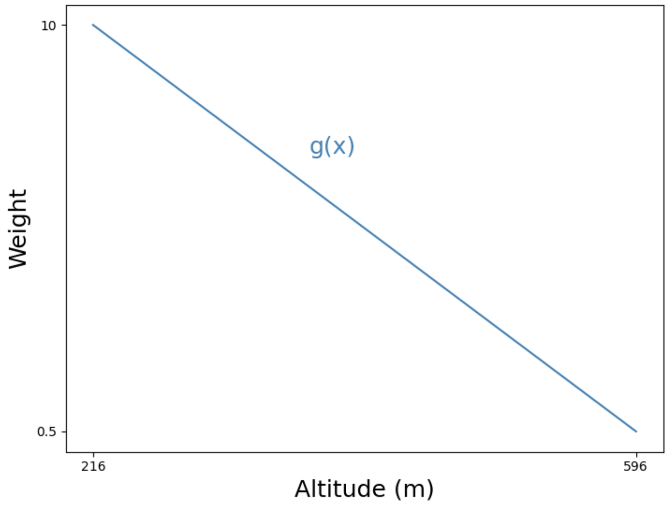
Waltrick et al. (2015) calculated an estimated rainfall erosivity in the state of Paraná and observed that the highest values occurred in the period of planting the summer crop and in the winter when there is less vegetation cover on the soil in the western and southwestern regions of the state. This result indicates the importance of using this feature in environmental studies in the region.

De Mello et al. (2013), through multivariate models, concluded that the erosivity can be explained by geographic coordinates and altitude and, in the South and Southeast regions of Brazil, the higher the altitude the lower the average annual rainfall erosivity. Studies such as those by Nel et al. (2010) and Hoyos et al. (2005) presented similar relationship in other countries with different environmental characteristics.

Based on this information, a linear membership function with negative angular coefficient was used to distribute weights to the elements in the altitude map. The fragility values closer to 0 (zero) were associated with maximum altitude (596 m), in regions with lower erosivity caused by rainfall. Fragility values closer to 10 were associated with the minimum altitude (216 m), according to $g(x)$ function (Figure 4).

$$g(x) = -0.025\,x + 15.4 \qquad (2)$$

Figure 4 - Graph of function $g(x)$ for weighting elements of the altitude map.



Source: The authors (2021).

To apply the function to each element of the altitude map, the raster calculator from QGIS software was used according to QGIS Project (2019).

The AHP method

The AHP method developed by Saaty (1977) was used due to its ability to analyze a problem through the construction of hierarchical levels and weight assignment to multiple criteria, while performing an intuitively and consistently paired comparison through a predefined scale (SAATY, 1987; PINESE JÚNIOR; RODRIGUES, 2012; SCHMIDT, 1995).

Determining weights using AHP

In the judgment stage, a paired comparison of the criteria was performed resulting in the weight of each, representing its importance in the classification map of environmental fragility. This importance was attributed based on the professional opinion of the authors and the scientific literature, including Tricart (1977), Ross (1994), Crepani (2001), Leandro (2013), Cereda Junior and Röhm (2014), Pinese Júnior and Rodrigues (2012), and Spörl (2001). For this comparison, the scale of relative importance developed by Saaty (1977) was used (Table 3). The comparison square matrix of reciprocal values and unit diagonal was constructed through the pairwise comparison.

Table 3 - Scale of relative importance between two criteria.

Less important	Extremely	$1/9$
		$1/8$
	Very strongly	$1/7$
		$1/6$
	Strongly	$1/5$
		$1/4$
	Moderately	$1/3$
		$1/2$
	Equally	1
More important	Moderately	2
		3
	Strongly	4
		5
	Very strongly	6
		7
	Extremely	8
		9

Source: Adapted from Hossain and Daz (2010).

The subjectivity of judgments based on researchers' experiences can result in inconsistencies in the final matrix. The inconsistency is measured through the consistency ratio (CR) that relates the consistency index (CI) of the matrix in question with the consistency index obtained from the n-order reciprocal matrix with non-negative elements randomly generated (RI) (Table 4). The value of CR must be less than 0.1 or 10% for satisfactory consistency and for the experts' judgment to be considered reliable. (SAATY, 1990).

Table 4 - Random Consistency Index (RI).

n	1	2	3	4	5	6	7	8	9	10
RI	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

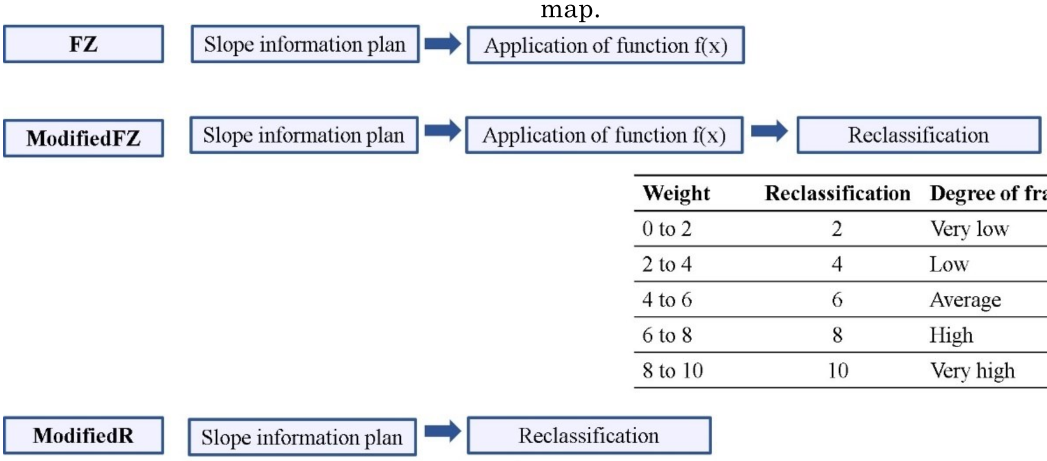
Source: Saaty (1990).

To compare each of the criteria (slope, altitude, soil, and land use/ occupation), the AHP method was combined with GIS technology using the Easy AHP complement of the QGIS software to perform a weighted linear combination according to Malczewski (2000).

Comparison of methods

A comparison was made between three different forms of weighing elements of the map with the higher weight (slope) to verify its influence on the final fragility map. The first technique is described throughout the work and determined only by the application of the continuous membership function $f(x)$; the second is determined using the function $f(x)$ and subsequent reclassification of the resulting raster file; the third is determined by the reclassification of the raster file using the hierarchical categories of Ross (1994) (Figure 5). The three ways are called Fuzzy (FZ), Modified Fuzzy (ModifiedFZ), and Modified Ross (ModifiedR), respectively.

Figure 5 - Implementation flowchart of the three ways to attribute weights to the elements of a slope map.



Weight	Reclassification	Degree of fragility
0 to 2	2	Very low
2 to 4	4	Low
4 to 6	6	Average
6 to 8	8	High
8 to 10	10	Very high

Slope	Reclassification	Degree of fragility
0 to 6%	2	Very low
6 to 12%	4	Low
12 to 20%	6	Average
20 to 30%	8	High
above 30%	10	Very high

Source: The authors (2021).

The results of each of the three techniques were used together with the other three maps (altitude, soil, and land use/ occupation) and their respective weights for the generation of fragility maps.

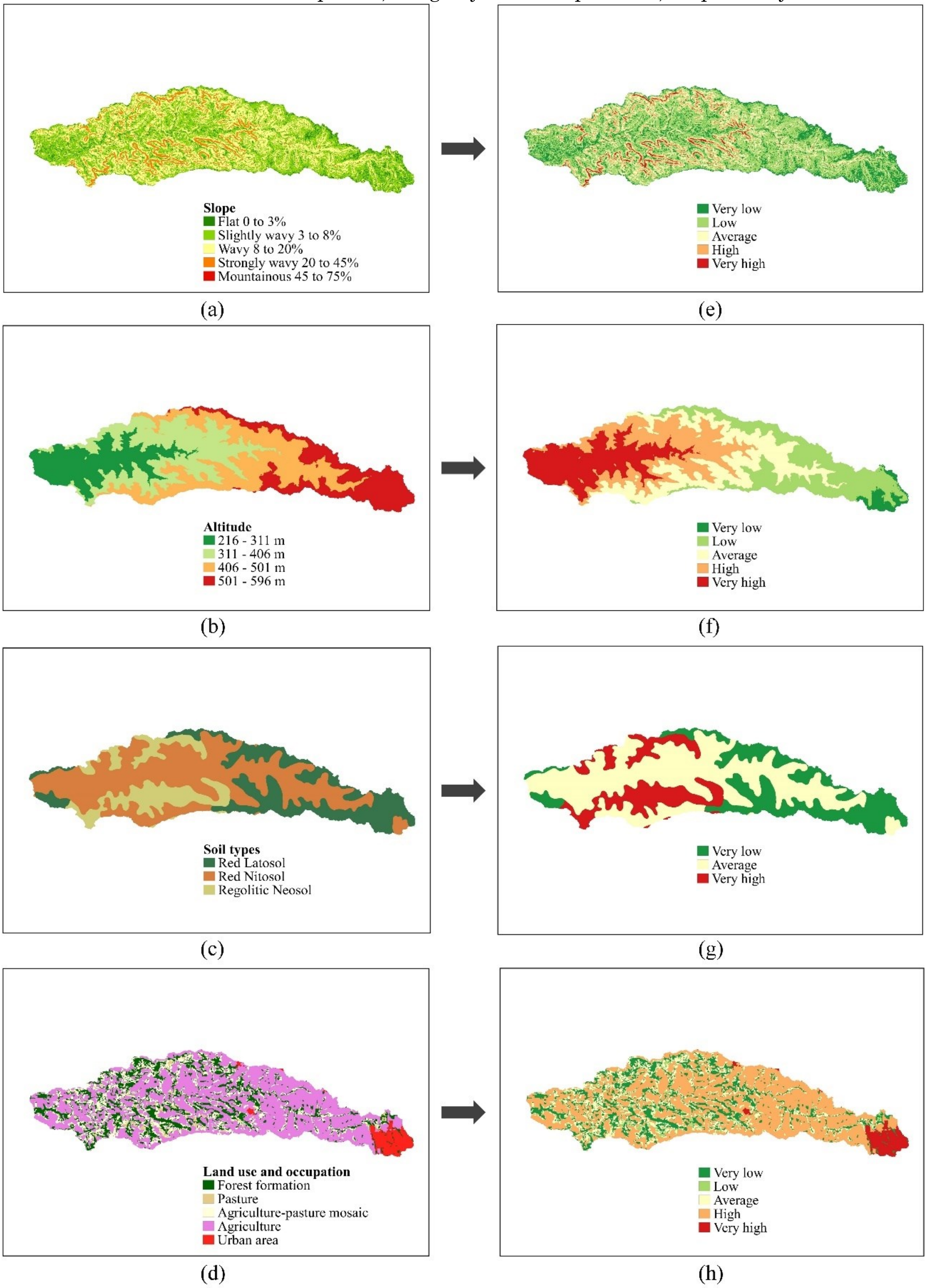
In each fragility map, sampling points were distributed equally spaced (30 m) using the QGIS Regular Points tool. Subsequently, the points were determined in relation to the boundary layer of the Marreco River watershed, concentrating the points within the polygon. The Point Sampling tool algorithm was used to extract the values contained in each of the fragility maps at the specified sampling points. The extracted values resulting from each method were put into a spreadsheet and then statistical analysis was performed (Analysis of Variance of Main Effects) using the R software (RCORE TEAM, 2020).

RESULTS

In the first step, the characteristics of the region of the Marreco River basin were analyzed. Thematic maps were generated for slope, altitude, soil type, and land use/occupation, (Figure 6, a – d). The predominant slopes of the basin are classified as slightly wavy and wavy (Figure 6a). The lowest altitude is located near Marechal Cândido Rondon city, and the beginning of the basin in Toledo city has an altitude of 596 m (Figure 6b). The soil types found are Red Latosol, Red Nitosol, and Neosol (Figure 6c). The studied area is widely used for agriculture (Figure 6d).

Figures 6 e – h present reclassified maps according to the degree of fragility provided in Tables 1 and 2 and the membership functions $f(x)$ and $g(x)$. The soil types in the basin mostly have average fragility regions (54.5%) with the Red Nitosol. Land use and occupation mostly contain high fragility regions (57.1%) represented by agriculture (Table 5). According to slope and altitude, the predominant degree of fragility is low, with 50.4% and 25.7%, respectively (Table 6).

Figure 6 - Thematic maps of the Marreco River watershed: a) Slope; b) Altitude; (c) Soil types; d) Land use and occupation; Fragility scale maps: e – h, respectively.



Source: The authors (2021).

Table 5 - Degrees of environmental fragility related to soil types as well as land use and occupation found in the Marreco River watershed.

Degree of fragility	Soil			Land use and occupation		
		Area(km²)	%		Area(km²)	%
Very low	Red Latosol	93.5	27.6	Forest formation	63.9	18.9
Low	-	0.0	0.0	Pasture	8.1	2.4
Average	Red Nitosol	184.6	54.5	Agriculture-pasture mosaic	59.2	17.5
High	-	0.0	0.0	Agriculture	193.3	57.1
Very high	Neosol	60.7	17.9	Urban area	14.3	4.2
∑		338.8	100		338.8	100

Source: The authors (2021).

Table 6 - Degrees of environmental fragility in the Marreco River watershed calculated for slope and altitude using the membership functions $f(x)$ and $g(x)$, respectively.

Degree of fragility	Slope		Altitude	
	Area (km²)	(%)	Area (km²)	(%)
Very low	70.2	20.7	9.6	2.8
Low	170.6	50.4	86.9	25.7
Average	65.6	19.4	85.4	25.2
High	24.7	7.3	83.7	24.7
Very high	7.7	2.3	73.2	21.6
∑	338.8	100	338.8	100

Source: The authors (2021).

The most important parameter through the AHP method was slope (51.42%), followed by land use and occupation (29.55%), soil (12.14%), and altitude (6.89%) (Table 7).

Table 7 - Paired comparison matrix used to evaluate the relative importance of each criterion in relation to environmental fragility.

	Comparison matrix				Normalized comparison matrix [a]				$(\boldsymbol{\omega})$ [b]
	S	T	U	A	S	T	U	A	
S	1	4	2	7	0.5283	0.4706	0.5581	0.5000	0.5142
T	$1/4$	1	$1/3$	2	0.1321	0.1176	0.0930	0.1429	0.1214
U	$1/2$	3	1	4	0.2642	0.3529	0.2791	0.2857	0.2955
A	$1/7$	$1/2$	$1/4$	1	0.0755	0.0588	0.0698	0.0714	0.0689
∑	1.893	8.5	3.583	14					1
			$\boldsymbol{\lambda max}$ [c]	**CI** [d]	**RI** [e]	**CR** [f]			
			4.02285	0.0076	0.90	0.0085			

S=slope; T=soil type; U=land use/occupation; A=altitude. [a] The normalized comparison matrix is obtained by dividing each element of the comparison matrix by the sum of all elements in its column. [b] The eigenvector (ω) is the weights of each criterion and is obtained by averaging values of each row of the normalized comparison matrix. [c] λmax is the highest eigenvalue of the comparison matrix. [d] The CI consistency index is calculated as $\frac{\lambda max - n}{n-1}$, where n is the matrix order. [e] The RI random consistency index is 0.90 for $n = 4$. [f] The consistency ratio is defined by $CR = CI/RI$.

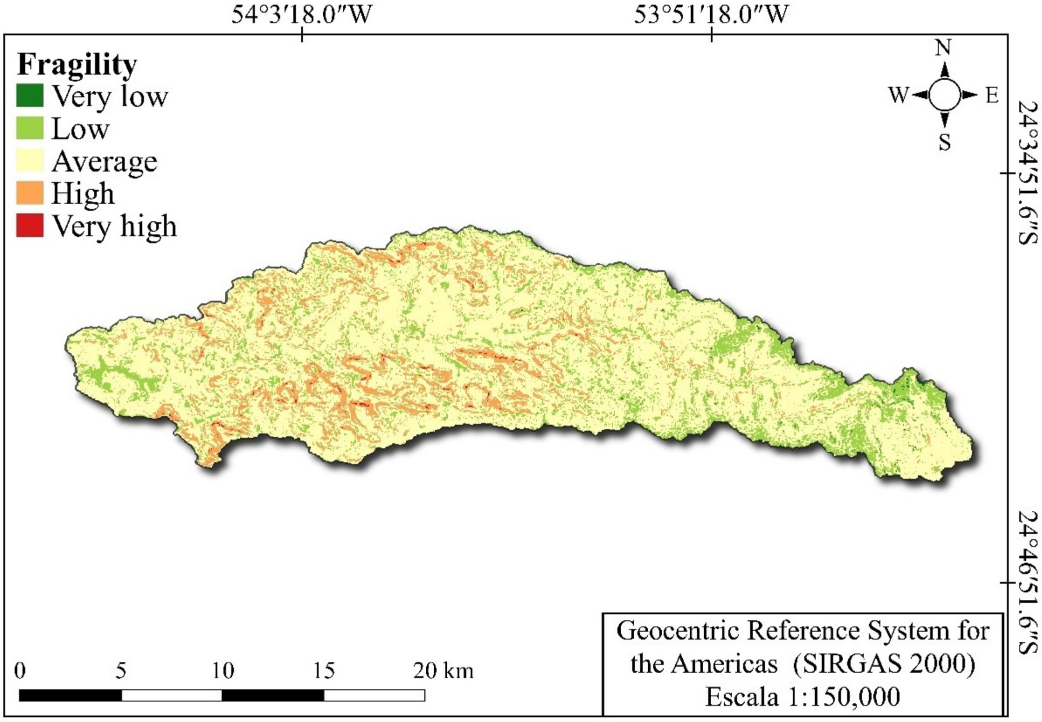
Source: The authors (2021).

Environmental fragility was calculated by weighted overlay of the four fragility maps (result of using Table 2 and functions $f(x)$ and $g(x)$) using Easy AHP and equation 3 in QGIS.

$$Environmental\ fragility = 0.5142 \times (Slope) + 0.1214 \times (Soil) + 0.2955 \times (Land\ use/occupation) + 0.0689 \times (Altitude) \quad (3)$$

The result of this calculation indicates that 71.3% of the basin area was considered to have average fragility, followed by 15.1% with low fragility, and 13.2% with high fragility (Figure 7 and Table 8).

Figure 7 - Environmental fragility classification map for the Marreco River watershed.



Source: The authors (2021).

Table 8 - Area of the different degrees of environmental fragility in the Marreco River watershed.

Degree of fragility	Area (km²)	(%)
Very low	0.5	0.2
Low	51.2	15.1
Average	241.6	71.3
High	44.7	13.2
Very high	0.8	0.2
∑	338.8	100

Source: The authors (2021).

The comparison of three different forms of weighing the elements of the slope map indicated that the basin mostly has average environmental fragility (Table 9). The FZ method classified a larger area as very low (0.2%) and low (15.1%) fragility than the ModifiedFZ (0% and 3.4%, respectively) and ModifiedR method (0% and 4.6%, respectively). This difference can be explained by the variation of weights according to variation of the elements on the slope map in the FZ method in contrast to the other two that classified different elements with the same weight (Figure 5).

The extraction fragility map values from each method resulted in three spreadsheets with each having 845,209 data, totaling 2,535,627 data. To compare the results, the R software was used to calculate 999 analyses of variance of the main effects, each performed for a sampling of 999 points in each spreadsheet. The analysis was performed based on the mean of the values found, considering a significance level of 5%. Thus, it was possible to infer that there is a significant difference between the methods and the geographical position. The method used to apply the weights on the slope map influences the degree of environmental fragility calculated ($\boldsymbol{F_{position}} = \mathbf{8.807}, \boldsymbol{p - value_{position}} = \mathbf{1.383 \cdot 10^{-310}}$ and $\boldsymbol{F_{method}} = \mathbf{484.015}, \boldsymbol{p - value_{method}} = \mathbf{1.391 \cdot 10^{-146}}$; $\boldsymbol{p - valor}$ = statistical significance and $\boldsymbol{F}$ = F statistic).

Soc. Nat. | Uberlândia, MG | v.34 | e62872 | 2022 | ISSN 1982-4513

Table 9 - Effect of methods to assign weight to the elements on the slope map on the degree of environmental fragility.

Degree of fragility	Method of assigning weight to slope map elements		
	FZ	ModifiedFZ	ModifiedR
	Area (%)	Area (%)	Area (%)
Very low	0.2	0	0
Low	15.1	3.4	4.6
Average	71.3	57.2	63.1
High	13.2	37.7	31.1
Very high	0.2	1.7	1.3
∑	100	100	100
Mean calculated for degree of fragility *	5.94_c	6.80_a	6.60_b

*Different letters on the same line indicate a significant difference between the means by the Tukey test at 5% of significance.

Source: The authors (2021).

DISCUSSION

The theory of fuzzy sets has been important for geographic data since the 1980s to deal with imprecision and abstraction in classifications (BANAI, 1993).

The conventional classification through fixed values assigned to an area may propagate errors in landscape modeling. Geotechnologies and multicriteria analysis with fuzzy logic have played an important role in environmental studies because they allow representation of the variation and relative importance of each environmental characteristic in the phenomenon studied. (MEIRELLES, 1997; ROSENDO, 2019).

Examples of studies include Junior et al. (2016), who used data such as soil, slope, population, altitude, and landforms to study the susceptibility to landslides in watersheds and concluded that fuzzy logic and AHP are essential for solving problems related to the empirical knowledge of experts. Cereda Junior and Röhm (2014) used the fuzzy model to determine environmental fragility employing variables such as soil, vegetation cover, and rainfall behavior, presenting satisfactory results compared to field research and previous studies. Miara and Oka-Fiori (2007) studied environmental fragility through AHP and fuzzy standardization with the erosivity, geology, soils, and slope variables; their results correlated with the reality on the ground. Guerrero et al. (2021) elaborated a natural vulnerability chart using fuzzy inference and AHP employing relief, geology, rainfall, land use, and slope variables, and they considered the method effective, with satisfactory results. Cheng et al. (2020) analyzed the health of the ecosystem of a desert using the fuzzy concept, physiological, ecological, and environmental criteria, and they obtained precision, objectivity, and reliability in the results. Rosendo (2019) analyzed socio-environmental vulnerability to drought in Brazilian regions using fuzzy sets and environmental variables such as rainfall anomaly index, crop areas, and degraded areas. Therefore, several variables can be added to the model to cover the proposed objectives.

In this work, the weights of the elements within the slope and altitude maps using fuzzy logic through the functions $f(x)$ and $g(x)$, respectively, considered the potentials for landslides and erosivity caused by the rains. The function $f(x)$ classified 50.4% of the basin with low fragility in terms of slope, and the function $g(x)$ classified approximately 25% of the basin for each degree of low, average, and high fragility in terms of altitude (Table 6). Linear interpolation was used to construct the functions due to the simplicity of execution and easy adaptation in other areas and contexts. The functions chosen depend on the dataset and in what context these data are treated (BURROUGH et al., 1992; KANDEL, 1986).

The AHP method resulted in the slope as the most important criterion, followed by land use and occupation, soil, and altitude (Table 7). Spörl (2001) compared models and indicated the most detailed map supported by the slope map. Our analyses found the predominant degree of environmental fragility is average (71.3%) in the Marreco River watershed (Table 8).

The ways of weighting the elements of the slope map elucidated a statistical difference, but all indicated that the basin under study has mostly average environmental fragility, although the FZ method classified a larger area with a lower degree of fragility (Table 9). This can be explained by the fact that the FZ method allows representation of the variation of map elements while FZmodified and Rmodified assign fixed values to regions with different characteristics.

FINAL CONSIDERATIONS

This work considered the slope, soil type, altitude, land use and occupation to classify and analyze environmental fragility in the Marreco River watershed, located in western Paraná, Brazil.

The use of fuzzy logic allowed representing the variation of environmental characteristics and their degree of importance in the analysis of fragility. Moreover, the AHP method established hierarchical levels for the criteria through consistent calculations.

The analysis found that the basin mostly has average environmental fragility, indicating that the region requires adequate planning of actions. The discussions confirm that the combination of fuzzy logic, AHP method, and geotechnologies can be a promising tool to assist in decision making and adequate management of anthropic activities in watershed areas. The further deepening and exploration of fuzzy logic in analyzes at the level of environmental planning are suggested.

ACKNOWLEDGMENTS

To the Unioeste and GEMAq for the structure for the development of the research. To the doctoral student Jhony Ferry Mendonça da Silva for the collaborations related to the use of the QGIS software.

SOURCE FUNDING

This research did not receive any funding from funding agencies in the public, commercial or non-profit sectors.

REFERENCES

ABRÃO, C. M.R., BACANI, V. M. Diagnóstico da fragilidade ambiental na bacia hidrográfica do Rio Santo Antônio, MS: subsídio ao zoneamento ambiental. *Boletim Goiano De Geografia*, v.*38, n.* 3, p. 619–645, 2018. https://doi.org/10.5216/bgg.v38i3.56362

ALBUQUERQUE, E. L.S., de MEDEIROS, C. N. Vulnerabilidade socioambiental em bacias hidrográficas no Setor Leste Metropolitano de Fortaleza, Ceará, Ateliê Geográfico, v. 11, n. 1, p.109–126, 2017. https://doi.org/10.5216/ag.v11i1.39018

ÁVILA, A.; JUSTINO, F.; WILSON, A.; BROMWICH, D.; AMORIM, M. Recent precipitation trends, flash floods and landslides in southern Brazil, *Environmental. Research. Letter, v.* 11, 114029, 2016. http://dx.doi.org/10.1088/1748-9326/11/11/114029

BANAI, R. Fuzziness in Geographical Information Systems: contributions from the analytic hierarchy process. International Journal of Geographical Information Systems, 7:4, p. 315-329, 1993. https://doi.org/10.1080/02693799308901964

BURROUGH, P. A. Development of intelligent geographical information system. International Journal of Geographical Information Systems, v.1, p. 1-11, 1992. https://doi.org/10.1080/02693799208901891

BURROUGH, P. A.; McDonnell, R. A. Principles of Geographic Information Systems. Oxford: Oxford University, 1998.

BURROUGH, P.A.; MCMILLAN, R.A.; DEURSEN, W. Fuzzy Classification Methods for Determining Land Suitability from Soil Profile Observation and Topography. Journal of Soil Science, v. 43, p. 193-210, 1992. https://doi.org/10.1111/j.1365-2389.1992.tb00129.x

BURROUGH, P. A. Fuzzy mathematical methods for soil survey and land evaluation. Journal of Soil Science, v. 40, p. 477-492, 1989. https://doi.org/10.1111/j.1365-2389.1989.tb01290.x

CEREDA JUNIOR, A, RÖHM, S.A. Analysis of environmental fragility using multicriteria analysis (mce) for integrated landscape assessment. Journal of Urban and Environmental Engineering, v.8, n.1, p.28-37, 2014. https://doi.org/10.4090/juee.2014.v8n1.028037

CHENG, W.; Xi, H.; SINDIKUBWABO, C.; SI, J.; ZHAO, C.; YU, T.; LI, A.; WU, T. Ecosystem health assessment of desert nature reserve with entropy weight and fuzzy mathematics methods: A case study of Badain Jaran Desert, Ecological Indicators, v. 119, 2020. https://doi.org/10.1016/j.ecolind.2020.106843.

CHRISTOFOLETTI, A. Geomorfologia. 2a ed. São Paulo, Edgard Blücher, 1980.

CORNWELL E., SPOSITO V., FAGGIAN R., Land suitability projections for traditional sub-alpine cropping in the Australian Alps and Chilean Dry Andes. A combined biophysical and irrigation potential perspective, Applied Geography, v. 121,2020. https://doi.org/10.1016/j.apgeog.2020.102248

CREPANI, E.; MEDEIROS, J.S.; AZEVEDO, L.C.; DUARTE, V.; HERNANDEZ, P.; FLORENZANO, T.; BARBOSA, C. Sensoriamento Remoto e geoprocessamento aplicados ao zoneamento Ecológico-Econômico e ao ordenamento territorial. INPE, São José dos Campos, São Paulo, 2001. Available: http://sap.ccst.inpe.br/artigos/CrepaneEtAl.pdf . Accessed: February 13,2020.

DALLA CORTE, A. P.; KLEIN HENTZ, A. M; DOUBRAWA, B.; SANQUETA, C.R. Environmental fragility of Iguaçu river watershed, Paraná, Brazil. Bosque, vol. 36, n. 2, p. 287-297, 2015. https://doi.org/10.4067/s0717-92002015000200014

de MELLO, C.R.; ALVES, G.J.; BESKOW, S.; NORTON, L.D. Daily rainfall erosivity as an indicator for natural disasters: assessment in mountainous regions of southeastern Brazil, Natural Hazards, v. 103, p. 947–966, 2020. https://doi.org/10.1007/s11069-020-04020-w

dos SANTOS, F. de A., MENDES, L. M.S., da CRUZ, M. L.B. Suscetibilidade biofísica a inundações da Sub-bacia Hidrográfica do rio Piracuruca. Ateliê Geográfico, v. *15*, n.1, p.266–285, 2021 https://doi.org/10.5216/ag.v15i1.64590

dos SANTOS, J. Y.G., NASCIMENTO, R.Q. Efeitos das alterações no uso e ocupação do solo nas perdas de solo da bacia do Rio de Janeiro, Oeste da Bahia, Boletim Goiano De Geografia, v. 41, n.1, 2021. https://doi.org/10.5216/bgg.v41.65397

EMBRAPA, Empresa Brasileira de Pesquisa Agropecuária. Sistema Brasileiro de Classificação de Solos, 2ªed. Available: https://www.embrapa.br/solos/sibcs . Accessed: February 17,2020.

FRANCISCO, H.R.; CORRÊIA, A.F.; FEIDEN, A. Classification of areas suitable for fish farming using geotechnology and multi-criteria analysis, *ISPRS* International Journal of Geo-Information, *v.8,* p.394, 2019. https://doi.org/10.3390/ijgi8090394

FRITZSONS, E.; MANTOVANI, L. E.; AGUIAR, A. V. Relação entre altitude e temperatura: uma contribuição ao zoneamento climático no estado do Paraná. Revista de estudos ambientais, v.10, n. 1, p. 49-64, 2008. http://dx.doi.org/10.7867/1983-1501.2008v10n1p49-64

GEMITZI, A.; FALALAKIS, G.; ESKIOGLOU, P.; PETALAS, C. Evaluating landslide susceptibility using environmental factors, fuzzy membership functions and gis. Global NEST Journal, v. 13, n.1, p. 28-40, 2011. https://doi.org/10.30955/gnj.000734

GUERRERO, J.V.R; PESTANA, L.F.A.; SOARES, J.A.H.; RUIZ, I.H.; MOSCHINI, L.E. Carta de vulnerabilidade natural como instrumento de apoio ao Zoneamento Ecológico-Econômico do município de Pirassununga (São Paulo), Revista Brasileira de Sensoriamento Remoto, v.2, n.2, p.25-42, 2021. https://zenodo.org/record/5548230. Accessed: October 08, 2021

HOSSAIN, M.S.; DAS, N.G. GIS-based multi-criteria evaluation to land suitability modelling for giant prawn (Macrobrachium rosenbergii) farming in Companigonj Upazila of Noakhali. Computers and Electronics in Agriculture, Bangladesh, v.70, p.172–186, 2010. https://doi.org/10.1016/j.compag.2009.10.003

HOYOS, N.; WAYLEN, P.R.; JARAMILLO, A. Seasonal and spatial patterns of erosivity in a tropical watershed of the Colombian Andes. Journal of Hydrology, v.314, p.177–191, 2005. https://doi.org/10.1016/j.jhydrol.2005.03.014

IAPAR, Instituto Agronômico do Paraná. Köppen's classification. Available: http://www.iapar.br/modules/conteudo/conteudo.php?conteudo=2533 . Accessed: April 30, 2020.

JUNIOR, C.H.L.S, BEZERRA, D.S., ANDERSON, L.O.,DE ANDRADE, M.R.M., PEREIRA, D.C.A., BEZERRA, V.L.A.R., SILVA, F.B., de ARAGÃO, L.E.O.C. Zoneamento da susceptibilidade a deslizamentos induzidos com base na lógica fuzzy e no processo analítico hierárquico (AHP): o caso da bacia hidrográfica do Rio Anil, São Luís – MA, Revista Brasileira de Cartografia, n.68/9, p. 1819-1837, 2016. Available: https://seer.ufu.br/index.php/revistabrasileiracartografia/article/view/44445. Accessed: January 21, 2022.

KANDEL, A. Fuzzy mathematical techniques with aplications. Boston: Addison-Wesley Publishing Company, 1986.

KOLLIAS, V. J.; VOLIOTIS, A. Fuzzy reasoning in the development of geographical information systems. International Journal of Geographical Informalion Systems, v.5, p.209-223, 1991. https://doi.org/10.1080/02693799108927844

LEANDRO, D. Modelagem de fragilidade ambiental usando índices baseados em dados especiais e com suporte de sistema especialista, Tese (Doutorado em Ciências Geodésicas), Universidade Federal do Paraná, Curitiba, 2013.

LÓPEZ, A.; AQUINO, A.M.; ASSIS, R. Agricultura de montanha: uma prioridade latente na agenda da pesquisa brasileira. Embrapa Informação Tecnológica, Brasília, 2011.

MADHU, A.; KUMAR, A.; JIA, P. Exploring Fuzzy Local Spatial Information Algorithms for Remote Sensing Image Classification, Remote Sensing, v. 13, 4163, 2021. https://doi.org/10.3390/rs13204163

MALCZEWSKI, J. On the use of weighted linear combination method in GIS: Common and best practice approaches, Transactions in GIS,4, 5–22, 2000. https://doi.org/10.1111/1467-9671.00035

MAPBIOMAS. Coleção da Série Anual de Mapas de Cobertura e Uso de Solo do Brasil. Available: https://plataforma.mapbiomas.org/map#coverage. Accessed: February 17,2020.

MEIRELLES, M.S.P. Análise Integrada do Ambiente Através de Geoprocessamento – Uma Proposta Metodológica Para Elaboração de Zoneamentos, Tese (Doutorado em Geografia), Universidade Federal do Rio de Janeiro, 1997.

MELLO, C.R.; VIOLA, M.R.; BESKOW, S.; NORTON, L.D. Multivariate models for annual rainfall erosivity in Brazil, Geoderma, 202–203, 2013. https://doi.org/10.1016/j.geoderma.2013.03.009

MIARA, M.A.; OKA-FIORI, C. Análise por múltiplos critérios para a definição de níveis de fragilidade ambiental – um estudo de caso: bacia hidrográfica do rio Cará-cará, Ponta Grossa/PR, Revista RA´E GA, Curitiba, n. 13, p. 85-98, 2007 http://dx.doi.org/10.5380/raega.v13i0.6642

MIRANDA, J.I. Fundamentos de Sistemas de Informações Geográficas, Brasília,DF, Embrapa Informação Tecnológica, 2005.

NEL, W.; REYNHARDT, D.A.; SUMNER, P.D. Effect of altitude on erosive characteristics of concurrent rainfall events in the northern KwaZulu-Natal Drakensberg. Water AS, v. 36, p.509–512, 2010. https://doi.org/10.4314/wsa.v36i4.58429

PARSIAN, S.; AMANI, M.; MOGHIMI, A.; GHORBANIAN, A.; MAHDAVI, S. Flood Hazard Mapping Using Fuzzy Logic, Analytical Hierarchy Process, and Multi-Source Geospatial Datasets. Remote Sensing, v.13, 4761, 2021. https://doi.org/10.3390/rs13234761

PINESE JÚNIOR, J. F.; RODRIGUES, S. C. O método de análise hierárquica – AHP – como auxílio na determinação da vulnerabilidade ambiental da bacia hidrográfica do Rio Piedade (MG). Revista Do Departamento De Geografia, v.*23*, p.4-26, 2012. https://doi.org/10.7154/RDG.2012.0023.0001

PLANO DA BACIA HIDROGRÁFICA DO PARANÁ 3, Águas Paraná, 2014. Available: http://www.aguasparana.pr.gov.br/arquivos/File/Parana_3/plano_de_bacia/Produto_01_Caracteristicas_Gerais_da_Bacia_BP3_2014_v07_Final.pdf . Accessed: April 08, 2020.

PMRH, Plano Municipal de Recursos Hídricos de Toledo, 2017. Available: https://www.toledo.pr.gov.br/portal/plano-municipal-de-recursos-hidricos/plano-municipal-de-recursos-hidricos . Accessed:October 12, 2018.

QGIS Project, QGIS User Guide, Release 2.18, 2019. Available: https://docs.qgis.org/2.18/pdf/en/QGIS-2.18-UserGuide-en.pdf Accessed: February 04, 2022

R CORE TEAM. R: A language and environment for statistical computing. R foundation for Statistical Computing, Vienna, Austria. Available: https://www.R-project.org/. Accessed: July 15, 2020.

REGGIANI, P.; HASSANIZADEH, S.M. MEGASCALE thermodynamics in the presence of a conservative field: The watershed case. Advances in Water Resources., v.97, p.73–86, 2016. https://doi.org/10.1016/j.advwatres.2016.09.002

ROSENDO, E.E.Q. Vulnerabilidade à seca nas regiões semiárida brasileira e portuguesa: uma avaliação baseada em lógica fuzzy, Tese (Doutorado em Geografia), Universidade do Porto, Portugal, 2019.

ROSS, J. L. S. Análise empírica da fragilidade dos ambientes naturais e antropizados. Revista do Departamento de Geografia. São Paulo, n. 8, 1994. https://doi.org/10.7154/rdg.1994.0008.0006

SAATY, T.L. A scaling method for priorities in hierarchical structures. J. Math. Psychol., v.15, p.234–281, 1977. https://doi.org/10.1016/0022-2496(77)90033-5

SAATY, R.W. The analytic hierarchy process—What it is and how it is used. Math. Model., v. 9, p.161–176, 1987. https://doi.org/10.1016/0270-0255(87)90473-8

SAATY, T.L. How to make a decision: The analytic hierarchy process. European Journal of Operational Research, v.48, p.9–26, 1990. https://doi.org/10.1016/0377-2217(90)90057-I

SAATY, T. L. Método de Análise Hierárquica, Tradução de Wainer da Silveira e Silva, São Paulo: McGraw-Hill, 1991.

SAATY, T.L.; VARGAS, L.G. Models, Methods, Concepts & Applications of the Analytic Hierarchy Process. International Series in Operations Research & Management Science, Berlin/Heidelberg: Springer, 2012. https://doi.org/10.1007/978-1-4614-3597-6

SCHMIDT, A.M.A. Processo de apoio a tomada de decisão abordagens: AHP e MACBETH, Dissertação (Mestrado em Engenharia de Produção), Universidade Federal de Santa Catarina, Florianópolis, 1995.

SEAB, Secretaria de Estado da Agricultura e do Abastecimento, Departamento de Economia Rural, 2018. Available: http://www.agricultura.pr.gov.br . Accessed: July 14, 2019.

SILVA, A.B. Sistemas de Informações Geo-referenciadas: conceitos e fundamentos, Campinas, SP, Editora Unicamp, 2003.

SPÖRL, C. Análise de fragilidade ambiental relevo-solo com aplicação de três modelos alternativos nas altas bacias do Rio Jaguari-Mirim, Ribeirão do Quartel e Ribeirão da Prata, Dissertação (Mestrado em Geografia Física), Universidade de São Paulo, 2001.

SPÖRL, C. Metodologia para elaboração de modelos de fragilidade ambiental utilizando redes neurais, Tese (Doutorado em Geografia), Universidade de São Paulo, 2007.

TARBOTON, D.G., Watershed delineation using TAUDEM, A tutorial for using TauDEM to delineate a single watershed, Utah State University, 2011. Available: https://hydrology.usu.edu/taudem/taudem5/TauDEM5DelineatingASingleWatershed.pdf Accessed: February 04, 2022.TRICART, J. Ecodinâmica. Rio de Janeiro, IBGE, Diretoria Técnica, SUPREN, 1977.

USGS, United States Geological Survey, EarthExplorer. Available: https://earthexplorer.usgs.gov/ . Accessed: March 01, 2019.WALTRICK, P. C.; MACHADO, M.A.M.; DIECKOW, J.; OLIVEIRA, D. Estimativa da erosividade de chuvas no estado do Paraná pelo método da pluviometria: atualização com dados de 1986 a 2008. Revista Brasileira de Ciência do Solo, v.39, p.256-267, 2015. https://doi.org/10.1590/01000683rbcs20150147 WESTERVELT, J., SHAPIRO, M., U.S. Army Construction Engineering Research Laboratory. Available: https://grass.osgeo.org/grass76/manuals/r.reclass.html Accessed: February 04, 2022.

WISCHMEIER, W. H. A rainfall erosion index for a universal soil loss equation. Soil Science Society of America Proceedings, v.23, p.246–249, 1959. https://doi.org/10.2136/sssaj1959.03615995002300030027x

WU, X.Z. Development of fragility functions for slope instability analysis, Technical Note, Landslides, v.11, 2014. https://doi.org/10.1007/s10346-014-0536-3

ZADEH, L.A. Fuzzy Sets. Information and Control, v. 8, p.338—353, 1965. https://doi.org/10.1016/S0019-9958(65)90241-X

AUTHORS' CONTRIBUTION

Karen Carilho da Silva Lira carried out the creation, methodology, data curation, formal analysis of the project, projection, software, the original draft of the writing and the editing of the text. Humberto Rodrigues Francisco carried out the data creation, methodology, curation, formal analysis, visualization, software, supervision, and the review and editing of the writing. Aldi Feiden performed the writing, methodology, formal analysis, review and editing of the writing.