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Cross assessment of erosive processes with methodologies for quantifying soil loss.

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A B S T R A C T

The erosive processes that take place across the globe are the cause and intensifier of several environmental problems. These can occur naturally - shaping the terrestrial structure - as well as in an anthropogenic way through harmful interventions to the environment. There are several methodologies to predict the intensity of soil loss in a region, providing data of local problems regarding the occurrence of erosion. In this study, three different methodologies are evaluated: natural vulnerability to erosion, USLE and AHP together with the support of a geographic information system environment, to determine the efficiency of each of these methods in the Hydrographic Basin of Córrego do Engano, São Paulo, Brazil. For the evaluation of each method, a cross-reference was conducted with real erosive process found in the study area using satellite images. It was found that USLE and AHP had the best results, with the local slope working as an important factor in the calculations.
Keywords**:** GIS, Erosion, Soil Management, Erosion Prediction, USLE

Avaliação cruzada de processos erosivos com metodologias para quantificar a perda de solo

R E S U M O

Os processos erosivos que ocorrem em todo o mundo são a causa e intensificadores de diversos problemas ambientais. Estes podem ocorrer de forma natural - moldando a estrutura terrestre - bem como de forma antropogênica por meio de intervenções prejudiciais ao meio ambiente. Existem diversas metodologias para prever a intensidade da perda de solo em uma região, fornecendo dados de problemas locais quanto à ocorrência de erosão. Neste estudo, três metodologias diferentes são avaliadas: vulnerabilidade natural à erosão, USLE e AHP juntamente com o suporte de um sistema de informação geográfica ambiental, para determinar a eficiência de cada um desses métodos na Bacia Hidrográfica do Córrego do Engano, São Paulo, Brasil. Para a avaliação de cada método, foi realizado um cruzamento com processos erosivos reais encontrados na área de estudo por meio de imagens de satélite. Constatou-se que USLE e AHP tiveram os melhores resultados, sendo a inclinação local um fator importante nos cálculos.
Palavras-chaves**:** SIG, Erosão, Manejo do Solo, Predição de Erosão, USLE

Introduction

The erosion caused by the action of the terrestrial hydrological cycle, according to Beskow et al. (2009), is one of the most significant environmental degradation processes, causing, in places where the process is at an advanced stage, the reduction of soil fertility - due to the removal of the soil's top protective layer or the washing of nutrients by runoff water - and the siltation of water bodies.

Several factors affect the intensity and speed of erosive processes, such as the water cycle (with a focus on rain), the intrinsic characteristics of the soil, such as its erodibility and physicochemical properties, the topography and relief, the vegetation cover of the place, in addition to possible anthropic and natural intensifiers (WUEPPER et al., 2019).

According to Julien (1994) and Reusser et al. (2015), human activities have a profound influence on erosive processes, increasing the intensity of erosive action, in some area, by up to 100 times, compared to natural geological erosion. Moreover, there are indications that the trend for the future is the increasing in erosion process around the globe (BORRELLI et al., 2020).

Nevertheless, the anthropic action is not always negative in relation to triggering erosion, according to Barrow (1991), US Department of Agriculture (2007) and Laloy & Bielders (2010), Ahmad et al. (2020), Alewell et al. (2020), since, when well executed, it is possible to apply preventive (or compensating) measures to try to reduce natural erosive processes. The first step is to identify the problem where conservation practices are needed, then identify the best use for that soil, apply the necessary correction for the type of use identified (either by correcting the structure or even restring the natural local vegetation) and properly maintain the solution adopted.

Some of the main measures to reduce erosion due to water action, for example, are: the reduction of the dispersion effect and the detachment of particles that happens when the raindrop contacts the soil; the reduction of the soil temperature; the enhancement of water infiltration; and improvement of the organic matter present in the soil (BENEAUD et al. 2020).

Thereby, it is understood, working as an hypothesis, the importance of studying methods of assessing erosive processes and identifying the susceptibility of an area to their occurrence. Thus, when identifying which places are most susceptible, the level of its fragility and the cause, measures can be taken to prevent the appearance of further erosions, contain or mitigate the existing ones, being possible to define places that are most suitable for the development of some type of culture, develop environmental policies aimed at encouraging conservationist practices, among others (AMERICAN SOCIETY OF AGRONOMY, 2014; BORRELLI et al., 2017; EVANS et al., 2020; HUANG et al., 2020).

Several methods and models have been developed to analyze and evaluate erosive processes, being mainly divided into two categories: qualitative and quantitative assessments. The qualitative assessment takes into account the shape and degree of erosion through measurements of size. Meanwhile, the quantitative evaluation allows a numerical modeling and representation of the process based on predefined parameters obtained through tests or estimations obtained through physical, statistical and parametric models (ALMOROX et al., 2010).

Many methodologies are expensive, requiring a large amount of data, time and a great deal of study (MOSAVI et al., 2020). Thus, the Universal Soil Loss Equation (USLE) method, developed by Wischmeier and Smith (1978), for being considered the simplest and easiest implementation model for the prediction of erosion processes (BESKOW et al., 2009), is one of the best known and most used.

In USLE and its various adaptations (CHUENCHUM et al., 2020), soil loss is estimated through six factors, namely the erosivity (R) - index based on precipitation and runoff values -, soil erodibility (K), the ramp length (L), the slope in relation to the terrain (S), the use and occupation of the soil (C), and the conservationist practices (P).

Another widely used method is multicriteria analysis, especially the Analytical Hierarchical Process (AHP), developed by Saaty (1977). This process is based on pairwise comparison between variables, and can serve both for ranking preferences within the context of the same attribute, as to define the relative importance of the attributes analyzed (Ehrlich, 2004). AHP is a tool developed to compare variables of any nature, adapting very well to the analysis of susceptibility to soil erosion from the parameters previously established, being used in several studies, such as Martini et al. (2006), Silva et al. (2016), Wei et al. (2020), Sadhasivam et al. (2020), Das et al. (2020).

In the Brazilian context, another very popular methodology is the Natural Vulnerability to Erosion (VNE), proposed by Crepani et al. (2001). According to this method, the vulnerability of a place is evaluated based on five variables, called themes, namely geology, geomorphology, soils, vegetation and climate. Based on a predefined distribution of values for each attribute class within each theme, ranging from 1.0 to 3.0, the vulnerability of the location is defined. Within this vulnerability scale, the closest values 1.0 are the ones with the greatest stability, while the values close to 3.0 are the most vulnerable areas. This method is widely used in geographical studies due to the data needed being vastly available for many different regions and can be easily exported in Geographical Information Systems (SOARES JUNIOR, 2020; MATULE & MACARRINGUE, 2020).

Therefore, the objective of this work is to compare and evaluate the efficiency of the above mentioned erosion susceptibility study methods by comparing their results with real erosion processes identified in the study basin from satellite images.

Materials and methods

Study area attributes:

The hydrographic basin chosen for this study is the Córrego do Engano basin, a mostly rural basin located in the northwest region of the State of São Paulo, within the municipality of Nova Canaã Paulista.

The local climate is Aw, tropical, with rains concentrated during the summer. The average annual temperature is 22.6 ˚C with an average annual rainfall of 1227 mm. (IBGE, 2018)

According to Rossi (2017), the main types of soils found in the area are the Red Argisols (PV4), the Red-Yellow Argisols (PVA1) and the High Gleisols (GX5), as shown in Figure 1b.

The area is predominantly composed of pastures and croplands. The existing native vegetation consists of portions of permanent preservation area, legal reserve and riparian vegetation, almost all of which are very close to the stream bed. Details can be seen in the land use and occupation map in Figure 1c. (GIOVANINI, 2019)

The relief of the area is predominantly smooth to wavy, with slopes varying from 2% to 45%, with more than 87% of the area with slopes between 2% and 10%, according to the sloppiness chart created based on the TOPODATA SRTM images (INPE, 2008), seen in Figure 1d.

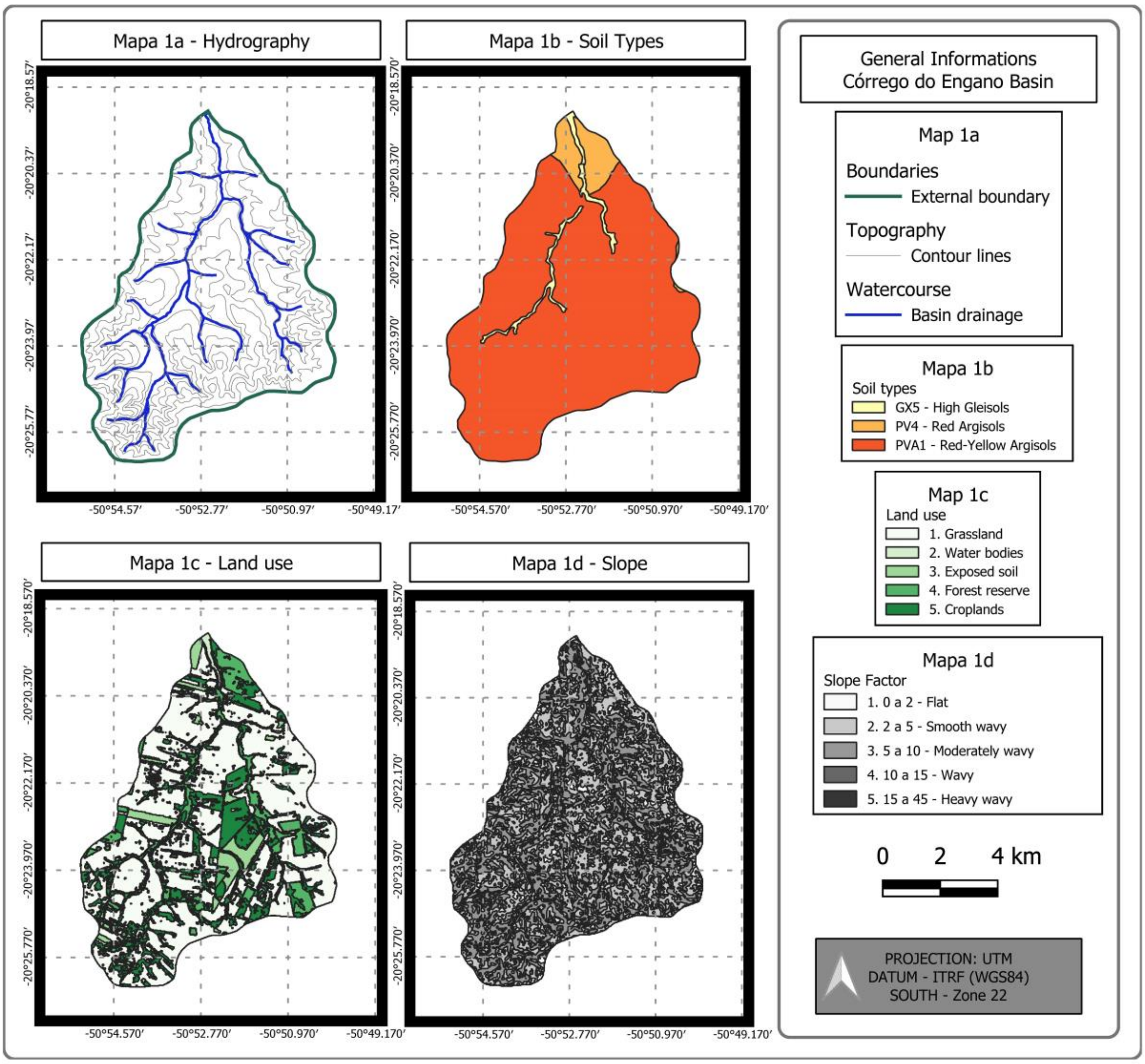

FIGURE 1 – Maps related to the watershed main characteristics

Adopted Methods Application:

The entire methodology was applied in a GIS environment, with frequent use of the LEGAL tool, using the software SPRING 5.5.2 (1996) and QGIS (2009).

The 3-main methodologies adopted are, as follow: Universal Equation of Soil Loss (USLE), Analytical Hierarchical Process (AHP) and Natural Vulnerability to Erosion (VNE).

Universal Equation of Soil Loss (USLE)

USLE and its coefficients were used according to Equation 1 below:

A=R.K.LS.C.P (Equation 1)

being:

A = soil loss calculated per unit area (ton.ha-1.year-1);

R = rain erosivity (MJ.mm.ha-1.h-1.year-1);

K = soil erodibility (ton.h.MJ-1.mm-1);

LS = topographic factor (dimensionless);

C = land use and cover (dimensionless);

P = conservationist practices (dimensionless).

The erosivity factor (R) was calculated following the methodology of Lombardi Neto and Moldenhauer (1992) where for each month the average monthly erosion index can be obtained according to the following Equation 2:

$EIm = 68,730.(p^2/P).0,841$ (Equation 2)

Where p is the average monthly precipitation (mm) and P is the average annual precipitation (mm). The R factor is then calculated as the sum of the EI for each month, consequently for the region under study the value used will be 6,556.00 (MJ.mm/ha.h.year) according to the climate monitoring station closest to the County.

The erodibility factor was obtained from the results observed by Mannigel et al. (2002) who used an indirect method of determination (BOYOUCOS, 1935) from a study of erodibility and loss tolerance for soils in the state of São Paulo. Thus, based on Figure 1b, there are three erodibility values (t.ha.h / ha.MJ.mm) for the region, being: soil PVA1 - Red Argisols where K = 0.0466; soil PVA4 - Red-Yellow Argisols where K = 0.0228 and soil GX5 – Haplic Gleisols where K = 0.0044.

According to Bertoni and Lombardi Neto (2008) the Equation 3 is used to calculate topographic factors (L and S):

LS = 0,00984* C*0,63* D*1,18(Equation 3)

Where C refers to the ramp length in meters and D the degree of slope in degrees.

To calculate these factors, the map in Figure 1d was used, which shows the slope values in degrees based on the landscape relief obtained through the TopoData Digital Elevation Model (VALERIANO, 2004). The methodology proposed by Ruthes et al. (2012) uses maps from numerical terrain models, hypsometric curves and the local drainage system to create an image with the values referring to the ramp length (GIOVANINI, 2019).

For land use, occupation and management factors (C and P), the land cover map (Figure 1c) is adopted, and the values attributed to each class were based on averages obtained through other studies, as shows Table 1.

Table 1 - Land use C factor values adopted to calculate the soil loss rate

Land Use - Classes	**C Factor**
Water Bodies	0,0
Grassland	0,042
Exposed Soil	1,0
Forest and riparian vegetation	0,012
Croplands	0,05
Urban area	0,0

Sources: Tomazoni & Guimarães (2005); Ruhoff *et al*. (2006); Oliveira *et al*. (2007)

After determining the soil loss for the entire study area, was performed a segmentation of the region with the results, generating a susceptibility map with the classification according to the proposal by Berskow et al. (2009).

Analytical Hierarchical Process (AHP):

For the method that uses the analytical process, four main environmental factors were initially ranked, based on their interdependencies and correlations, which influence the susceptibility to erosion, ranking them in values from highest to lowest in relation to their importance. This technique uses objective data, from other works in the area, as well as considers the subjectivity based on the researcher's expertise to define the importance of each attribute (BOUFELDJA, S. at al. 2020).

Then the pairwise comparison is made using a data matrix assigning numerical weights accordingly to each parameter depending on its influence in the amount of soil loss. The definition of relative importance was adopted according to studies already carried out as in Bertoni and Neto (2008), Fushita et al. (2011) and Freitas et al. (2012) following Silva et al. (2016), as shown in Table 2

Table 2 - Pairwise comparison matrix of the factors analyzed and the relative weights for each factor

Factors	Precipitation	Pedology	Land Use	Slope	Weighted Importance
Precipitation	1	1/3	1/5	1/7	0.055022
Pedology	3	1	1/3	1/5	0.117786
Land Use	5	5	1	1/3	0.263378
Slope	7	5	3	1	0.563813

The erosion susceptibility map is then generated by multiplying the weight of importance of each factor by the score for the respective class of factor, which varies from 1 to 5, indicating degrees of very low to very high susceptibility, respectively (ASLAM et al., 2020). Equation 4 expresses this procedure in detail.

x*xi + y*yi + z*zi + t*ti (Equation 4)

Where:
x – Weight importance of rainfall factor;
xi – Precipitation class grade (in relation to Table 2);
y – Pedology factor importance weight;
yi – Pedology class grade;
z – Weight importance of land use factor;
zi – Land use factor grade;
t – Slope factor importance weight;
ti – Slope class grade.

For the precipitation map, the middle class value of 3 was adopted, due to the presence of only one pluviometric station close to the location, which does not provide as much data as the all other factor, being this the reason why the precipitation factor is less important among all. For the other factors, the marks adopted for each class are shown in Table 3. (HAIDARA et al., 2019; TAIRI et al., 2019; AL-RAHBI et al., 2020).

Table 3 - Classes Division and their respective grades for the factors of slope, land use and pedology

Intensity	Class Mark/Grade	Slope (%)	Land use	Pedology
Very low	1	< 2	Water Bodies; Forest and riparian vegetation; Urban	
Low	2	2 – 5	Pasture	PVA1
Average	3	5 – 10	Cropland	
High	4	10 – 15	Exposed Soil	PV4
Very high	5	15 – 45		GX5

Finally, the values were verified based on the Consistency Ratio (Rc) (Eastman, 2005), and the area was sliced into five degrees of susceptibility, ranging from very low to very high.

Natural Vulnerability to Erosion (VNE):

According to the method developed by Crepani et al. (2001), the natural vulnerability to erosion is determined through the average of vulnerabilities attributed to its five themes, namely: geology, geomorphology, soils, vegetation and climate.

The vulnerability ranges from 1.0 to 3.0, with the values of each class for each theme previously defined by Crepani's original work. Thus, in this study, the existing classes in the drainage basin were identified based on each of the factors contained in the method and the calculation was performed with their respective values (FERREIRA & SILVA, 2020).

For the geology theme, an excerpt from the Geological Map of the State of São Paulo (2006) was used, where there is a predominance of dacites (1.62 km²), arenites (44.22 km²) and arenites/sandy clay (26.62 km²).

For the geomorphology theme, were used: the slope map (Figure 1d); the altimetric amplitude map, obtained based on the TOPODATA images (VALERIANO MM, 2005), which were interpolated creating a rectangular grid and then sliced; and the interfluvial amplitude map, obtained by calculating the distance between drainage channels within each of the main geomorphological units of the drainage basin.

The classes of the soil theme were obtained from the pedological map shown in Figure 1b.

For the Vegetation theme was adopted a modification of the methodology proposed by Crepani et al. (2001) made by Ribeiro & Campos (2007) due to similarities with the region under study. Consequently, it was possible to attribute the vulnerabilities according to the class of land use and occupation, as shown in Figure 1c.

Regarding the climate theme, the only annual precipitation value was used, dividing it by 12 months, obtaining a monthly average of 102.16 mm/month. (CIIAGRO, 2018)

Finally, a general vulnerability map was produced and sliced with the values found in order to better visualize the results and compare them with the other methods studied.

Comparison with existing erosive processes:

A research was carried out using satellite images from the Google Earth© program with 2020 recent photographs — which are made available by the DigitalGlobe platform —, in order to locate erosion processes in progress in the studied watershed.

The erosive processes found in the area were further classified according to the type and degree of erosion identified. The classes used and examples of points where each can be observed are shown in Figure 2.

Several analyzes were then carried out crossing the location of the erosive processes with the results of the methods of estimating susceptibility to erosion, as well as with other specific factors that make up these methods.

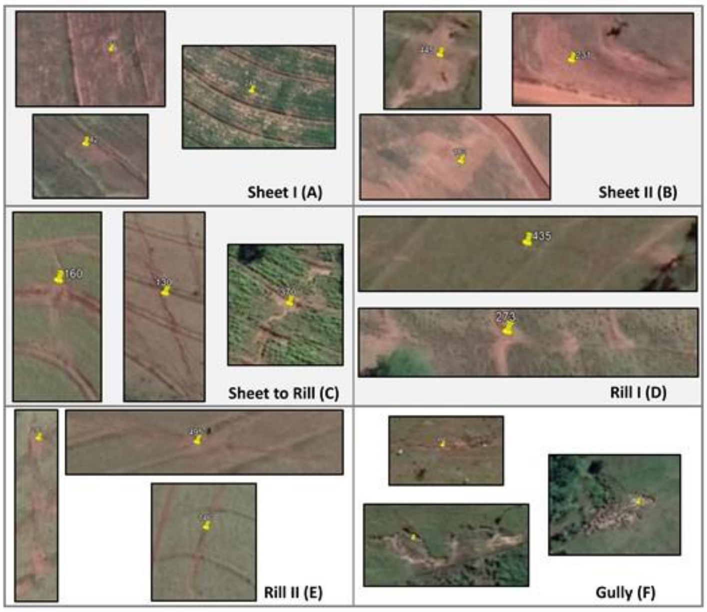

Figure 2 – Types of erosive processes located on the drainage basin area

Results

The resulting maps from applying the USLE, AHP and VNE methods are shown, respectively, in maps 2a, 2b and 2c, in Figure 3, as well as the more than 600 erosion points in the watershed located after observation of satellite images

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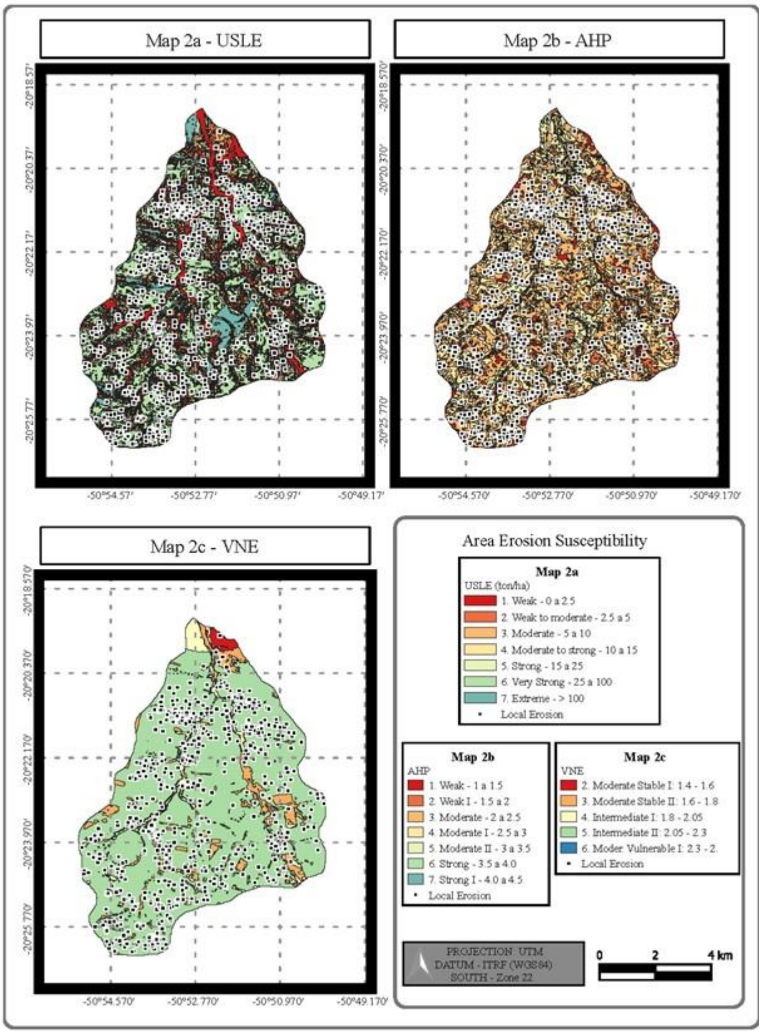

Figure 3 – Erosion susceptibility for the three different methods adopted to determine the erosion susceptibility

It is possible to observe that there are several differences between the maps for the three methods studied. Note that Map 2c is the most homogeneous among them. The Intermediate II class occupies most of the drainage basin, and it is possible to observe some well-defined regions occupied by the moderately stable class II, and a small region in the watershed exutory where the Moderately stable I and Intermediate I classes are presented.

Maps 2a and 2b demonstrates a large division of the classes into small areas, which is an indication of the importance of the slope, since it is the factor that most segments the watershed. Map 2a shows a predominance of light green color, referring to the very high soil loss class, while some well-defined regions of the extreme soil loss class can be observed in places where exposed soil has been identified. There is also a significant presence of the weak class in the stream bed, which probably also occurs due to the use and occupation factor, since this is zeroed for water bodies.

On the other hand, in Map 2b, referring to the AHP method, there is a predominance of the Medium I and Medium II classes, while it was not possible to visible identify an area with high or higher susceptibility, while small areas of low susceptibility are noted throughout the drainage basin, differing from the other methods.

As for the erosive processes identified by satellite images, it would not be possible to make a strictly visual analysis off their location in relation to the maps of the methods studied. Thus, the points were crossed with the susceptibility classes for each method, being analyzed the distribution of the points by class and the erosion density for each one.

The classes division for erosive susceptibility was adopted in order to enable the visualization of the results. The number of points identified in each of the classes and the density of erosions for the three methods studied are shown in Tables 4, 5 and 6.

Table 4 - Erosive features detected and density, by classes, using USLE

Classes Erosion rate (ton/ha)	Occupied Area (km²)	Total Local Erosion	Erosion Distribution per class (%)	Erosion per km²
Weak - 0 a 2.5	6,75	28	4,58%	4,148
Weak to moderate - 2.5 a 5	6,03	32	5,24%	5,310
Moderate - 5 a 10	10,50	52	8,51%	4,955
Moderate to strong - 10 a 15	8,27	70	11,46%	8,468
Strong - 15 a 25	13,25	130	21,28%	9,814
Very strong - 25 a 100	23,82	278	45,50%	11,670
Extreme - > 100	3,86	21	3,44%	5,443

Table 5 - Erosive features detected and density, by classes, using AHP

Classes Erosion rate (ton/ha)	Occupied Area (km²)	Total Local Erosion	Erosion Distribution per class (%)	Erosion per km²
2. Weak - 1 a 1.5	4,83	27	4,41%	5,592
3. Weak I - 1.5 a 2	4,34	11	1,80%	2,535
4. Moderate - 2 a 2.5	32,50	248	40,52%	7,631
5. Moderate I - 2.5 a 3	27,53	291	47,55%	10,571
6. Moderate II - 3 a 3.5	3,13	33	5,39%	10,557
7. Strong - 3.5 a 4.0	0,12	2	0,33%	17,135
8. Strong I - 4.0 a 4.5	0,03	0	0	0,000

Table 6 – Erosive features detected and density, by classes, using VNE (Natural Vulnerability to Erosion)

Class	Occupied Area (km²)	Total Local Erosion	Erosion Distribution per class (%)	Erosion per km²
2. Moderate Stable I: 1.4 - 1.6	0,55	0	0	0,000
3. Moderate Stable II: 1.6 - 1.8	5,42	13	2,12%	2,399
4. Intermediate I: 1.8 - 2.05	2,88	8	1,30%	2,776
5. Intermediate II: 2.05 - 2.3	62,96	593	96,58%	9,419
6. Moderate Vulnerable I: 2.3 - 2.	0,30	0	0	0,000

In the USLE result, we can observe that the distribution of the points followed the desired pattern, with the amount of erosive processes increasing with the increment in soil loss, except for the last class with the highest soil loss, which may be due to the small area covered by that class.

The erosion density was also satisfactory, but in addition to the discrepancy of the result in the last class, there was also a decrease in density in the moderate class. In general, it can be said that the method has met the expectations, performing close to ideal, since there was a high correlation between the location of more erosion points in areas with a higher soil loss.

The AHP was almost as satisfying as the USLE, with, however, some details from which it can be seen that the points are not distributed exactly as expected. There was a decrease in the number of points from the Weak to Weak I class, despite the areas occupied by both being similar, which causes a decrease in the density of points between them. There is also a similar erosion density between the Moderate and Moderate I classes, being slightly higher in the class with the least susceptibility, which can also be considered a subtle dissonance in relation to what was expected. Finally, no erosive processes were identified in the class with the highest susceptibility - Strong I -, which may be due to the small size of the area occupied by this class.

In the VNE method, higher erosion densities areas are observed as the vulnerability classes increases, which could be an indication of the good method performance, however it is noted that more than 87% of the drainage basin area is in a same class, and the concentration of points in that class exceeds 96%. In addition, erosions were found in only two other classes in addition to the previous one, which totals only three results for the entire analysis of this method. Therefore, due to this imbalance between the areas and the small amount of results to be analyzed, it is not possible to confirm a significant correlation between the method and the actual erosive processes present in the watershed.

In addition, for the methods that performed best - USLE and AHP - each type of erosion process was crossed individually with the methods, in order to verify whether there would also be a correlation between them.

It was found that for the AHP method there was a considerable correlation between each type of erosion and the method, especially for Sheet Erosion II, Rill I and Gully erosions. As for the USLE method, the correlation between the method and the types of erosion individually was considerably less, which may be noted only for Rill I and Ravines.

Given the importance of slope factors and land use for all methods, the crossing of the points with each factor was also carried out, as shown in tables 7 and 8.

Table 7 – Slope factor

Class	Occupied Area (km²)	Total Local Erosion	Erosion Distribution per class (%)	Erosion per km²
1. 0 a 2 - Flat	6,53	38	6,20%	5,819
2. 2 a 5 – Smooth Wavy	36,05	246	40,13%	6,824
3. 5 a 10 – Moderate Wavy	28,40	309	50,41%	10,880
4. 10 a 15 - Wavy	1,57	20	3,26%	12,739
5. 15 a 45 – Strong Wavy	0,07			0,000

Table 8 - Land use factor

Class - AHP / USLE	Occupied Area (km²)	Total Local Erosion	Erosion Distribution per class (%)	Erosion per km²
Water bodies	0,32	0	0,00%	0,000
Forest reserves	7,93	16	2,64%	2,018
Grasslands	44,37	477	78,71%	10,751
Cropland	16,03	90	14,85%	5,614
Exposed soil	4,05	23	3,80%	5,679

It is noted that the distribution of erosive processes increases with the increase of the slope, as expected, which confirms the relevance of this factor for the results of the methods. As for land use, almost 80% of the identified points were in the grassland, which is, mainly, pasture. This class had the highest density of erosion processes, almost the double of that observed for both exposed soil and crops, classes that were considered more susceptible to erosion in all methods.

Conclusions

According to the analyzes carried out regarding the three methods, it was possible to observe several differences between them. It was observed that for the VNE method more than 87% of the watershed area is in the same class, which concentrates 96% of the erosive processes found in the region, while the other two methods have classifications more distributed throughout the study area.

From the comparison carried out using the erosion susceptibility results — calculated via the studied methods — with the erosion processes existing in the watershed — found one-by-one via satellite images — it was found that only the USLE and the AHP could be evaluated in more detail. There was a great correlation between locally found erosions and the places most susceptible to them according to these two methods, and for AHP there was also a correlation with each type of erosion individually.

As for the evaluation of the factors considered in the studied methodologies, the slope factor was consistent with what was expected and had a strong correlation with the erosive processes identified. In addition, even though in all methods the classes "cropland" and "exposed soil" tend to have the highest soil loss rate, thus the highest susceptibility to erosion, most of the erosive processes identified were in pasture areas.

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