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Artigos

INDIRECT METHODOLOGIES FOR MEASURING SOIL ERODIBILITY AND CHARACTERIZING ITS SPATIAL VARIABILITY

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Abstract:

Abstract

The present study analyzed different indirect methodologies for measuring soil erodibility and characterized the spatial variability of soil erodibility in the Pântano River Hydrographic Basin (PRHB), state of Mato Grosso do Sul, Brazil. Nine methodologies/adaptations were tested in 103 soil samples collected covering the main soil types in the hydrographic basin. The data were submitted to a validation proposal and underwent descriptive and correlation statistical analyses. A spatial dependence analysis and mapping by kriging was also carried out. The methodologies that best represented the erodibility estimates at PRHB were those by Sharpley and Williams (Latossolos Vermelho-Escuros [Oxisols] and Planossolos [Alfisols]), Wischmeier and Smith (Latossolos Roxos [Oxisols]), and Renard (Podzólicos Vermelho-Escuros and Podzólicos Vermelho-Amarelos [Ultisols]). The final map indicated erodibility medium (46.4% of PRHB), low (45.1%), very low (0.5%) and very high (7.9%). The findings indicated that the use of a single indirect methodology may underestimate or overestimate the soil erodibility.

Keywords: Pântano River Hydrographic Basin, Soil erosion, Kriging, Soil management and conservation, Mato Grosso do Sul.

Resumo:

Resumo

METODOLOGIAS INDIRETAS DE MENSURAÇÃO DA ERODIBILIDADE DO SOLO E CARACTERIZAÇÃO DA VARIABILIDADE ESPACIAL.

O presente estudo objetivou analisar diferentes metodologias indiretas para mensuração da erodibilidade do solo, bem como caracterizar a sua variabilidade espacial na Bacia Hidrográfica do Rio Pântano (BHRP), Mato Grosso do Sul. Avaliou-se nove metodologias/adaptações aplicadas aos dados de 103 amostras de solo abrangendo os principais tipos existentes na bacia. Os dados passaram por uma proposta de validação e posteriormente por análise estatística descritiva e de correlação. Realizou-se também a análise da dependência espacial e mapeamento por krigagem. As metodologias que melhor representaram a erodibilidade do solo na BHRP foram dadas pelas propostas de Sharpley e Williams (Latossolos Vermelho-Escuros e Planossolos), Wischmeier e Smith (Latossolos Roxos) e, Renard (Podzólicos Vermelho-Escuros e Vermelho-Amarelos). O mapa final, indicou erodibilidade média

(46,4% da BHRP), baixa (45,1%), muito baixa 0,5% e, muito alta 7,9% da área da bacia. Concluiu-se que o uso de uma única metodologia pode subestimar ou superestimar a erodibilidade do solo.

Palavras-chave: Bacia Hidrográfica do Rio Pântano, Erosão do solo, Krigagem, Manejo e conservação do solo, Mato Grosso do Sul.

Resumen:

Resumen

El presente estudio tuvo como objetivo analizar diferentes metodologías indirectas para medir la erosionabilidad del suelo, así como su variabilidad espacial em la Cuenca del Río Pântano (CRP), estado de Mato Grosso do Sul, Brasil. Se probaron nueve metodologías/adaptaciones en103 muestras de suelo cubriendo los tipo principales existentes en la cuenca. Los datos se sometieron a propuesta de validación y a análisis estadístico descriptivo y de correlación. También se realizó un análisis de dependencia espacial y mapeo por krigagem. Las metodologías que mejor representaron la erosionabilidad em la CRP fueron las propuestas de Sharpley y Williams (Latossolos Vermelho-Escuros y Planossolos), Wischmeier y Smith (Latossolos Roxos) y, Renard (Podzólicos Vermelho-Escuros y Podzólicos Vermelho-Amarelos). El mapa final indicó erosionabilidad medio (46,4% de la CRP), bajo (45,1%), muy bajo 0,5% y muy alto 7,9% de la cuenca. Se concluyó que el uso de una única metodología puede subestimar/sobrestimar la erosionabilidad del suelo.

Palabras clave: Cuenca del Río Pântano, Erosión del suelo, Krigagem, Manejo y conservación del suelo, Mato Grosso do Sul.

INTRODUCTION

Knowledge of soil characteristics is of vital importance for conservation planning, mainly due to erosion processes, which represent a serious environmental problem across the planet. According to Bertoni and Lombardi Neto (2008), erosion processes are closely related to the use and inadequate management of soils as indicated by the soil characteristics. Thus, combating erosive processes constitutes a great challenge, and it requires detailed knowledge of the soils and an elaboration of adequate management proposals aimed at environmental sustainability.

Soil erodibility is an important factor for conservation planning because it represents the natural susceptibility of the soil to the action of erosive agents (ARRAES et al., 2010). Numerous studies have been carried out in Brazil with the aim of studying this factor, such as the work by Vieira (2008) in Santa Catarina; Vale Júnior et al. (2009) in Roraima; Chaves et al. (2010) in the Federal District; Castro et al. (2011) in the Cerrado Goiano; and Carvalho and Leite (2015) in Mato Grosso do Sul and Lima et al. (2019) in the state of São Paulo.

At a global level, works on soil erosion include those by Zhang et al. (2008) in China; Albaladejo et al. (2009) in Spain; Parwada and Van Tol (2016) in South Africa; Takal et al. (2017) in Afghanistan; and Al Rammahi and Khassaf (2018) in Iraq.

According to Arraes et al. (2010), soil erodibility can be determined in three ways: a) using natural rain under field conditions; b) using the ratio of soil losses and erosivity under simulated rainfall; and c) using equations that consider soil attributes as influencing variables. Although this last method is less precise than the previous two, it represents a fast and low-cost method. Thus, many researchers have adopted these indirect methods (LIMA et al., 2007; ARRAES et al., 2010; ANACHE et al., 2015; SILVA et al., 2016; Al RAMMAHI; KHASSAF, 2018; LIMA et al., 2019).

Among the numerous proposed methods, a number deserve to be highlighted, such as the method by Wischmeier and Smith (1978), which was based on soil data from the American Midwest. The work by Lima et al. (1990) presents an adaptation of this previous method for application in Brazilian Latossolos [Oxisols]. Denardin (1990) proposed a robust equation for estimating erodibility based on 31 Brazilian soil profiles, and this equation is widely used in Brazil. However, works by Demarchi and Zimback (2014) have adopted a simpler and more practical proposal described by Bouyoucos (1935).

A review of the literature also indicates other proposed methodologies, such as the approach applied in the Water Erosion Prediction Project (WEPP) model (SHARPLEY; WILLIAMS, 1990), the model proposed by Chaves (1996) and the method presented by Renard et al. (1997).

Given this variety of globally recognized methodologies (with each developed in different edaphoclimatic conditions), the application of a single method may not be appropriate for representing an area of interest. Thus, it is essential to evaluate as many methodologies as possible for a better result.

Moreover, the spatial variability of soil erodibility is another important factor to determine, and geostatistics have been widely used for this purpose (GREGO; VIEIRA, 2005; MIQUELONI et al., 2015; LIMA et al., 2019). Geostatistics allow for the interpretation of results based on the structure of the natural variability of the variable itself and the estimation of behavior of nonsampled locations within the same sample area (YAMAMOTO; LANDIM, 2013).

Given the above, the objective was to analyze different indirect methodologies for measuring the soil erodibility factor in the Pântano River Hydrographic Basin and to characterize the spatial variability of soil erosion through the use of geostatistical techniques.

MATERIAL AND METHODS

The present evaluation was conducted based on a field survey (soil samples) performed in the Pântano River Hydrographic Basin (PRHB), east of the state of Mato Grosso do Sul, Brazil. The PRHB has an area of 1,348.6 km^2, which is distributed in the municipalities of Selvíria, Aparecida do Taboado and Inocência, and it stands out as an important tributary of the Paraná River (Figure 1).

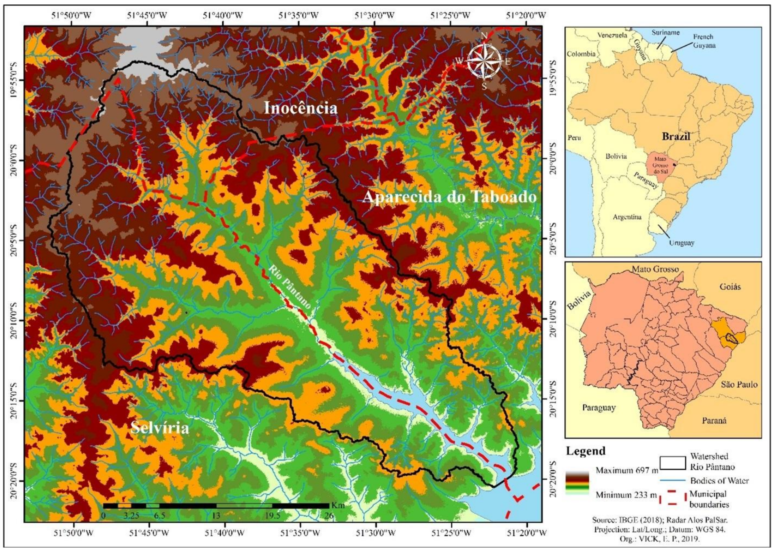

FIGURE 1
Location of the study area, PRHB.

In total, 103 samples from individual collections (at a depth of 0 - 0.20 m) distributed in 54 locations in the PRHB were analyzed, as shown in Figure 2. In each location highlighted on the map, two samples were collected (separated by a minimum distance of 100 m). Eventually, only one sample was collected.

The spatialization of the sampling points was carried out based on the different types of soils present in the soil map of the state of Mato Grosso do Sul (MATO GROSSO DO SUL, 1989), which is available at a scale of 1:250,000 (SISLA, 2020). This map was chosen because it presents an appreciable spatial detail of the distribution of soils in the study area and because it is still widely used in environmental studies of a regional nature. However, certain nomenclature is inconsistent with the most recent Brazilian system of soil classification (EMBRAPA, 2018).

Therefore, despite making use of the official configuration of the Soil Map of Mato Grosso do Sul (soil spacing and nomenclature), the updated nomenclature for the studied soils (EMBRAPA, 2018; IBGE, 2021) is concomitantly presented in Table 1.

In this way, the results presented in this work can be easily adapted to the more current SiBCS classification nomenclature.

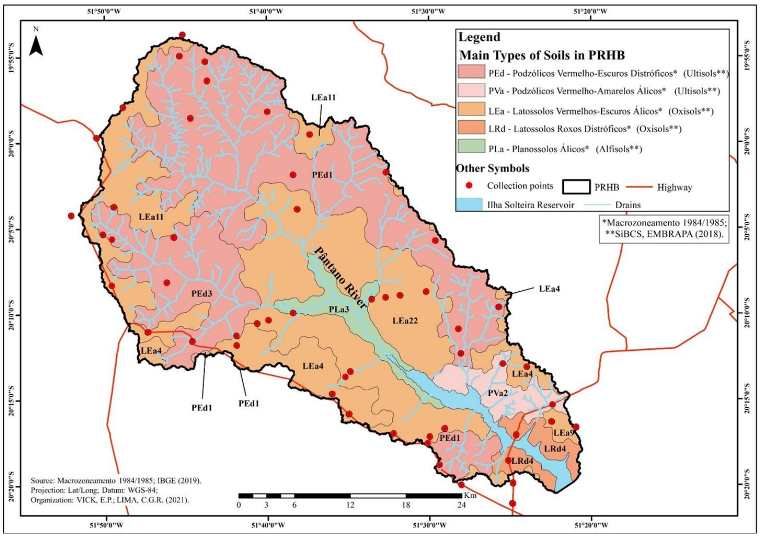

FIGURE 2
Map of soils and sampling sites in the PRHB.

Thus, the collection consisted of the following soils: Podzólicos, currently named Argissolos [Ultisols]; Latossolos [Oxisols] and Planosolos (Alfisols). Five main types were differentiated according to the distribution presented in Figure 2: Podzólico Vermelho-Escuro Distrófico (PEd1 and PEd3), Podzólico Vermelho-Amarelo Álico (PVa2), Latossolo Roxo Distrófico (LRd4), Latossolo Vermelho-Escuro Álico (LEa11, LEa22, LEa4 and LEa9) and Planossolo Álico (PLa3).

To maintain an adequate proportion, the sample distribution considered the representativeness of the different subtypes of soils observed in the state soils map (Table 1).

TABLE 1
Representativeness of the samples collected in the PRHB.

Main Soils Types	Subtypes[1] (+associations)	Area (km^2)	Area (%)	n. samples
***LEa - Latossolos Vermelho-Escuros Álicos*[1]** *Latossolos Vermelhos Distrófico*[2], *(OXISOLS*[3]*)*	LEa11	152.25	11.29	14
	LEa22	334.85	24.83	23
	LEa4	86.98	6.45	8
	LEa9	8.76	0.65	4
***LRd - Latossolos Roxos Distróficos*[1]** *Latossolos Vermelhos Distroférricos*[2], *(OXISOLS*[3]*)*	LRd4	37.22	2.76	6
***PEd - Podzólicos Vermelho-Escuros Distróficos*[1]** *Argissolos Vermelhos Distróficos*[2], *(ULTISOLS*[3]*)*	PEd1	470.79	34.91	28
	PEd3	158.86	11.78	12
***PVa - Podzólicos Vermelho-Amarelos Álicos*[1]** *Argissolos Vermelho-Amarelos Distróficos*[2], *(ULTISOLS*[3]*)*	PVa2	49.81	3.69	4
***PLa - Planossolos Álicos*[1]** *Planossolos Háplicos Distróficos*[2], *(ALFISOLS*[3]*)*	PLa3	49.08	3.64	4
Total		1348.6	100	103

Source: [1]Soil Types and Subtypes according to State Soils Map (MATO GROSSO DO SUL, 1989; SISLA, 2020); [2]Soil name updated according to Map of Natural Resources and SiBCS (IBGE, 2018; EMBRAPA, 2018); [3]Soil Types adapted according to SiBCS (EMBRAPA, 2018).

After collection, the samples were identified, prepared and analyzed according to Embrapa

As a physical attribute of the soil, the granulometry (total sand, very coarse sand, coarse sand, medium sand, fine sand, very fine sand, silt and clay) was determined by the pipette method (NaOH 1 mol L-1) and analyzed.

A particle size analysis was also carried out without the use of dispersant. For soil chemistry, the organic matter (OM) content obtained indirectly from organic carbon (OC) was analyzed.

The soil erodibility factor (k) was indirectly determined according to the following methodologies:

a) Bouyoucos (1935):

$$k = \left[\frac{\%Sand + \%Silt}{\%Clay}\right] / 100 \qquad (1)$$ [1]

where k = soil erodibility (Mg ha h ha-1 MJ-1 mm-1).

b)Denardin (1990):

$$k = [0,00000748 * M] + [0,00448059 * P] + [0,0631175 * DMP] + [0,01039567 * R] \qquad (2)$$ [2]

with

$$M\ (\%) = [(\text{“New” Silt} + \text{“New” Sand}) * \text{“New” Silt}] \qquad (3)$$ [3]

where “New” silt = (silt + very fine sand) and “New” sand = (very coarse sand + coarse sand + medium sand + fine sand).

where P is the soil permeability, as coded in Wischmeier et al. (1971). The permeability class assignments were performed by observing the soil texture, as described in Demarchi and Zimback (2014), (Table 2).

TABLE 2
Soil permeability classes.

Textural Class[1]	Permeability	Permeability Class[2]
clay (very clayey, clay) and silty clay	Very slow	6
silty clay loam and sandy clay	Slow	5
sandy clay loam and clay loam	Slow to moderate	4
loam, silt loam and silt	Moderate	3
loamy sand and sandy loam	Moderate fast	2
sand	Fast	1

Source: [1]Textural Triangle, United States Depatment of Agriculture (USDA, 1983); [2] Wischmeier et al. (1971). Adapted from Demarchi and Zimbach (2014).

DMP is defined as follows:

$$DMP\ (mm) = \Sigma(\mathbf{Ci} * \mathbf{Pi}) \qquad (4)$$ [4]

where Ci = center of textural class i, expressed in mm; and Pi = proportion of occurrence of textural class i, expressed in %. In the present study, this calculation was defined as follows (based on the classification of sieves of the Brazilian Association of Technical Standards):

$$DMP\ (mm) = [(1.5 * \text{Very Coarse Sand}) + (0.75 * \text{Coarse Sand}) + (0.355 * \text{Meduim Sand}) + (0.1575 * \text{Fine Sand}) + (0.825 * \text{Very Fine Sand}) + (0.031 * \text{Silt}) + (0.00376 * \text{Clay})]/100 \qquad (5)$$ [5]

with

$$\mathbf{R} = (\mathbf{OM} * \text{“New” Sand})/100 \qquad (6)$$ [6]

where OM = organic matter (%). c) Wischmeier and Smith (1978):

$$\mathbf{K} = \left\{\frac{[2.1(10^{-4})(12 - \mathrm{OM})\mathrm{M}^{1.14} + 3.25\,(\mathrm{EST}-2) + 2.5\,(\mathrm{PER}-3)]}{100}\right\} 0.1317 \qquad (7)$$ [7]

with

$$\mathbf{M} = (\%\,\text{Silt} + \%\,\text{Very Fine Sand})\ \mathbf{x}\ (100 - \%\,\text{Clay}) \qquad (8)$$ [8]

where OM = soil organic matter content (%); PER = permeability, given indirectly as a function of texture (Table 2); and EST = soil structure.

For EST, due to technical difficulty, an adaptation was performed depending on the textural class of the soil.

According to Donagemma et al. (2016), soils with a sandy texture (sand, loam sand or sandy loam) are predominantly characterized by a weak small granular structure, which provides great friability. Thus, considering that in very sandy soils, the low amount of clay provides little physical structure (RIBEIRO, 1999), there is a consequent reduction in the aggregation of soil particles.

Therefore, soils with fine and granular structures are produced. On the other hand, in soils with higher clay contents, the cohesion between the grains is greater, which leads to the formation of better structured soils (CAMPOS et al., 1995). Therefore, the assignment of EST classes for this study was performed based on the predominance of sandy soils and only a small portion with higher clay contents in the PRHB, as shown in Table 3.

TABLE 3
Soil structure factor for different textural classes.

Structure[1]	Structure class[1]	Adaptation classified[2]
very fine granular	1	sand $^{(n = 13)}$
fine granular	2	loamy sand, sandy loam $^{(n = 80)}$
medium to coarse granular	3	sandy clay loam $^{(n = 6)}$
blocks, laminar or solid	4	clay $^{(n = 4)}$

Source: [1]Wischmeier et al. (1971); [2]Organized and adapted by the Author; n = number of classified samples.

d) According to Wischmeier and Smith (1978) adapted by Lima et al. (1990):

In this case, the only difference in relation to the method described above is that the granulometric analysis data were obtained without using a dispersing agent.

e)According to the following expressions by Renard et al. (1997):

$$K = 0.0034 + 0.0405\ x \exp\left[-0.5\left(\frac{\log DG + 1.659}{0.7101}\right)^2\right] \qquad (9)$$ [9]

with

$$K = 0.0034 + 0.0405\ x \exp\left[-0.5\left(\frac{\log DG + 1.657}{0.6986}\right)^2\right] \qquad (10)$$ [10]

where DG is the geometric average diameter of the soil particles (mm); fi is the fraction corresponding to the particle size (%); and mi is the arithmetic average of the particle size limits (mm).

f) According to the method proposed by Chaves (1996) and presented in Chaves (2010):

$$k = \frac{-0.00043\ (FS + SIL)}{OC + 0.000437\ TS + 0.000863\ SIL} \qquad (11)$$ [11]

where FS = % fine sand on the soil A horizon; SIL = % silt from the soil A horizon; OC = % organic carbon from the soil A horizon; and TS = % total soil sand.

g)According to an expression proposed by Sharpley and Williams (1990) that was presented in the works of Anache et al. (2015) and Al Rammahi and Khassaf (2018), who presented this methodology with punctual variations produced different results, the equation is initially the same:

$$k = A\ x\ B\ x\ C\ x\ D\ x\ 0,1317 \qquad (12)$$ [12]

with

$$A = [0.2 + 0.3\exp(-0.0256\,SAN\left(1 - \frac{SIL}{100}\right))] \quad (13)$$ [13]

$$B = [\frac{SIL}{CLA+SIL}]^{0.3} \quad (14)$$ [14]

$$C = [1.0 - \frac{0.25\,C}{C+\exp[(3.72-2.95\,C)]}] \quad (15)$$ [15]

$$D = [1.0 - \frac{0.70\,SN1}{SN1+\exp(-5.51+22.9\,SN1)}] \quad (16)$$ [16]

where SAN = sand (%); SIL = silt (%); CLA = clay (%); C = content (%) of soil organic carbon; and SN1 = (1 minus sand content (%) divided by 100).

The difference between the references is that the formula applied by Al Rammahi and Khassaf (2018) uses nominal percentages (example: 10% = 10) while Anache et al. (2015) apply percentages in fractional amounts (example: 10% = 0.1).

Thus, erodibility was determined in 9 different ways defined as follows: K(Bouyoucos), K(Denadin); K(Wischmeier); K(Lima); K(Renard_a); K(Renard_b); K(Chaves); K(Sharpley_a) (as presented by Anache et al. (2015)) and K(Sharpley_b) (as presented by Al Rammahi and Khassaf (2018)).

A descriptive statistical analysis was performed on the generated data using an Excel spreadsheet. This step aimed to help validate the different methods. On the other hand, the Pearson correlation matrix was set up to assess the interaction between the attributes studied.

Posteriorly, the spatial dependence was analyzed using Gamma Design Software GS+ 7.0 (ROBERTSON, 2004). Thus, for each erodibility factor, the experimental semivariogram was calculated based on the presupposition of intrinsic hypothesis stationarity according to the following expression (YAMAMOTO; LANDIM, 2013):

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i=1}^{N(h)} [Z(X_i) - Z(X_i + h)]^2 \quad (17)$$ [17]

where N(h) is the number of experimental pairs of observations Z(xi) and Z(xi + h) separated by a distance h.

For the semivariographic adjustments, the following were observed: a) the smallest sum of squares of the deviations (SSD); b) the highest coefficient of spatial determination (R^2); and c) the highest spatial dependence evaluator (SDE).

The final adjustment model and the number of interpolating neighbors for kriging were defined using the highest correlation coefficient (r) between the observed vs. estimated cross-validation (CV) values.

After this step, interpolation by kriging was performed, with the integration of data and editing of the final maps performed in ArcGIS 10.6® software (ESRI 2019).

RESULTS AND DISCUSSION

Table 4 shows the results for the granulometry and organic matter of the soil in the PRHB, and they that although sandy soils were predominant, appreciable levels of organic matter were also observed. The following textural classes were also observed: LEa11 (sand, loamy sand and sandy loam); LEa22 (loamy sand, sandy loam and sandy clay loam); LEa4 (sand, loamy sand and sandy loam), LEa9 (sandy loam and sandy clay loam), LRd4 (clay, loamy sand and sandy loam), PEd1 (sand, loamy sand, sandy loam, sandy clay loam), PEd3 (sand, loamy sand, sandy loam), PLa3 (sand and loamy sand) and PVa (loamy sand and sandy loam).

TABLE 4
Particle size and soil organic matter characteristics in the PRHB.

Main Soil Types[1]	Subtypes[1] (+associations)	Descriptive Measures						
		n. samples	Attribute	Value			Standard Deviation	Variation Coeff. (%)
				Average	Min.	Max.		
LEa - Latossolo Vermelho-Escuro Álico	LEa11 (Area = 11.29%)	14	Sand	86.2	82.3	90.3	2.4	2.8
			Silt	4.2	0.2	6.4	1.6	39.0
			Clay	9.5	7.6	11.5	1.3	13.6
			O.M.	1.3	0.8	1.7	0.2	17.6
	LEa22 (Area = 24.83%)	23	Sand	81.6	62.8	87.8	6.5	8.0
			Silt	5.5	1.4	15.2	3.4	61.4
			Clay	12.8	8.3	26.3	4.3	34.0
			O.M.	1.6	1.1	2.4	0.3	20.6
	LEa4 (Area = 6.45%)	8	Sand	85.2	78.4	92.0	4.1	4.8
			Silt	3.7	0.5	6.7	1.9	53.5
			Clay	10.9	5.7	14.7	2.8	26.3
			O.M.	1.4	1.1	1.9	0.2	17.1
	LEa9 (Area = 0.65%)	4	Sand	67.3	63.8	75.0	5.1	7.6
			Silt	7.0	4.1	9.4	2.2	31.8
			Clay	25.6	17.0	31.0	6.2	24.5
			O.M.	2.0	1.7	2.5	0.3	17.5
LRd - Latossolo Roxo Distrófico	LRd4 (Area = 2.76%)	6	Sand	48.2	23.1	86.6	29.1	60.3
			Silt	11.6	1.9	20.4	7.7	66.6
			Clay	40.0	10.8	56.8	21.6	53.9
			O.M.	2.1	1.1	3.6	0.9	45.2
PEd – Podzólico Vermelho-Escuro Distrófico	PEd1 (Area = 34.91%)	28	Sand	83.1	70.0	92.2	5.4	6.5
			Silt	5.4	1.4	9.9	2.3	42.2
			Clay	11.4	4.3	22.0	3.9	34.8
			O.M.	1.4	0.8	2.3	0.3	25.7
	PEd3 (Area = 11.78%)	12	Sand	85.8	77.6	93.0	5.0	5.8
			Silt	4.7	1.5	11.4	2.8	59.9
			Clay	9.3	5.3	13.7	2.5	27.5
			O.M.	1.3	0.8	1.8	0.2	22.3
PVa – Podzólico Vermelho-Amarelo Álico	PVa2 (Area = 3.69%)	4	Sand	82.9	77.2	86.6	4.5	5.4
			Silt	5.6	2.5	8.5	2.8	51.1
			Clay	11.4	9.6	15.2	2.5	22.2
			O.M.	1.5	1.0	2.0	0.4	64.5
PLa - Planossolo Álico	PLa3 (Area = 3.64%)	4	Sand	90.4	88.4	92.6	1.8	2.0
			Silt	1.7	0.9	2.2	0.5	33.2
			Clay	7.8	6.3	9.2	1.3	17.0
			O.M.	1.1	1.1	1.2	0.1	5.5

Source: [1]Soil types and subtypes according to State Soils Map (MATO GROSSO DO SUL, 1989; SISLA, 2020).

Table 5 shows the results of the review on the erodibility of Brazilian soils (field work with natural and/or simulated rainfall). Although only few references were found, the organization of these data allowed us to collate information to help validate the applied methodologies.

It should be noted that soil erodibility can be classified according to its potential. Thus, according to Castro et al. (2011), $K < 0.0090$ is equivalent to very low erodibility, $0.0090 < K \leq 0.0150$ is equivalent to low erodibility, $0.0150 < K \leq 0.0300$ is equivalent to medium erodibility, $0.0300 < K \leq 0.0450$ is equivalent to high erodibility, $0.0450 < K \leq 0.0600$ is equivalent to very high erodibility, and $K > 0.0600$ is equivalent to extremely high erodibility.

TABLE 5
Table 5 - Soil

*Main Soil Types**	K factor references(n) (observed values)		Subtypes** (+Association)	K factor references(n) (observed values)
LEa - Latossolo Vermelho-Escuro Álico	**Latossolo Vermelho-Escuro Álico**(5) *K = 0.002; K = 0.008; K = 0.013* **Latossolo Vermelho-Escuro Distrófico**(5) K = 0.004; K = 0.009; K = 0.009; K = 0.021; K = 0.022; K = 0.026 ---------------------------- **Latossolo Vermelho-Escuro, fase arenosa**(1) K= 0.017 **Latossolo Vermelho-Escuro, orto**(1) K = 0.015 ---------------------------- **Latossolo Vermelho-Escuro**(2) K = 0.015 ---------------------------- **Latossolo Vermelho-Escuro**(4) K= 0.016	*K Average = 0.014* *Low Erodibility* *Extremes classes: very low to medium*	**LEa11** - Latossolo Vermelho-Escuro Álico, medium texture + **Areias Quartzosas** Álicas.	**Areias Quartzosas**(2) K = 0.046; **Areias Quartzosas**(4) K = 0.045 ---------------------------- *Extremes classes: very low to very high*
			LEa22 - Latossolo Vermelho-Escuro álico, medium texture + **Podzólicos Vermelho-Escuro Álico e Distrófico**, sandy/medium texture + **Podzólico Vermelho-Amarelo Álico**, medium sandy texture.	**Podzólicos Vermelho-Escuro Álico e Distrófico**(3) K = 0.024; K = 0.032; K = 0.034 **Podzólico Vermelho-Amarelo Álico**(3) K = 0.031 ---------------------------- *Extremes: very low to high*
			LEa4 - Latossolo Vermelho-Escuro Álico, medium texture, and Distrófico, medium texture.	*Extremes: very low to medium*
			LEa9 - Latossolo Vermelho-Escuro Álico, medium texture + LEa clayey texture.	*Extremes: very low to medium*
LRd - Latossolo Roxo Distrófico	**Latossolo Roxo Distrófico**(5) *K = 0.009; K = 0.012; K = 0.016* **Latossolo Roxo Eutrófico**(5) *K = 0.004; K = 0.025* ---------------------------- **Latossolo Roxo**(2) K = 0.019 ---------------------------- **Latossolo Roxo**(4) K = 0.012	*K Average = 0.016* *Medium Erodibility* *Extremes: very low to medium*	**LRd4** - Latossolo Roxo Distrófico, Eutrófico. very clayey and clayey texture + **Terra Roxa Estruturada** Eutrófica, very clayey texture + **Terra Roxa Estruturada** Eutrófica, very clayey texture.	**Terra Roxa Estruturada**(1) K = 0.018 **Terra Roxa Estruturada/Latossólica**(4) K = 0.018 ---------------------------- *Extremes: very low to medium*
PEd - Podzólico Vermelho-Escuro Distrófico	**Podzólico Vermelho-Escuro Distrófico**(3) *K = 0.024; K = 0.034* **Podzólico Vermelho-Escuro Álico e Distrófico**(3) K = 0.024; K = 0.032; K = 0.034	*K Average = 0.029* *Médium Erodibility* *Extremes: medium to high*	**PEd1** - Podzólico Vermelho-Escuro Distrófico. and Eutrófico, medium texture.	*Extremes: médium to high*
			PEd3 - Podzólico Vermelho-Escuro Distrófico, sandy/medium texture + **Podzólico Vermelho-Amarelo Distrófico**, medium texture + **Latossolo Vermelho Escuro Álico**, medium texture.	**Podzólico Vermelho-Amarelo Distrófico**(3) K = 0.027 **Latossolo Vermelho-Escuro Álico**(5) K = 0.008; K = 0.002; K = 0.013 ---------------------------- *Extremes: very low to high*
PVa - Podzólico Vermelho-Amarelo Álico	**Podzólico Vermelho-Amarelo Álico**(3) *K = 0.031* **Podzólico Vermelho-Amarelo Distrófico**(3) K = 0.027 ---------------------------- **Podzólico Vermelho-Amarelo. var. laras**(1) K = 0.043 **Podzólico Vermelho-Amarelo. orto**(1) K = 0.034 **Podzólico Vermelho-Amarelo. v.piracicada**(1) K = 0.028 ---------------------------- **Podzólico Vermelho-Amarelo**(2) K = 0.029 ---------------------------- **Podzólico Vermelho-Amarelo**(4) K = 0.032	*K Average = 0.032* *High Erodibility* *Extremes: medium to high*	**PVa2** - Podzólico Vermelho-Amarelo Álico, and Distrófico. sandy/medium and medium texture + **Solos Litólicos** Distróficos, medium texture, very gravel.	Areias Quartzosas(2) K = 0.046; Areias Quartzosas Hidromórficas(2) K = 0.048 Solos Litólicos(4) K = 0.050 Areias Quartzosas Hidromórficas(4) K = 0.047 Areias Quartzosas(4) K = 0.045 Regossolos(4) K = 0.043 ---------------------------- *Extremes: médium to very high*
PLa - Planossolo Álico	**Planossolo (Solonetz-solodizado)**(3) K = 0.012 ---------------------------- **Planossolo Solódico**(4) K = 0.002 **Planossolo**(4) K = 0.002 **Solonetz Solodizado**(4) K = 0.005	*K Average = 0.005* *Very Low Erodibility* *Extremes: very low to low*	**PLa3** - Planossolo Álico, sandy/medium and sandy/clay texture + **Glei pouco Húmico** Álico, indiscriminate texture + **Areias Quartzosas Hidromórficas** Distróficas and Álicas.	**Glei pouco húmico**(4) K = 0.001 ---------------------------- **Areias Quartzosas Hidromórficas**(2) K = 0.048 **Areias Quartzosas Hidromórficas**(4) K = 0.047 ---------------------------- *Extremes: very low to very high*

Source: *, ** Soil types/subtypes according to State Soils Map (MATO GROSSO DO SUL, 1989; SISLA, 2020).
(n) = Sources, where: (1)Bertoni e Lombardi Neto (2008); (2)Galdino et al. (2003); (3)Marques et al. (1997); (4)BRASIL (1997); (5)Silva et al. (2000)

The data in Table 5 allow for two analyses. In the first case (first column), the data are broadly grouped, with references to the main soil types (LEa, LRd, PEd, PLa, and PVa) being presented without considering the associations. Thus, for LEa, the average value of 0.014 Mg ha h ha-1 MJ-1 mm-1 was observed, which corresponded to low erodibility. LRd, on the other hand, presented medium erodibility (0.016 Mg ha h ha-1 MJ-1 mm-1), which was similar to PEd (0.029 Mg ha h ha-1 MJ-1 mm-1); however, the average value of the latter was much higher because it is a Podzólico [Ultisol]. PLa indicated low erodibility (0.005 Mg ha h ha-1 MJ-1 mm-1) and PVa indicated high erodibility (0.032 Mg ha h ha-1 MJ-1 mm-1), which is the most critical among those studied.

Silva and Alvares (2005) organized a database on soil erodibility and pointed out that Latossolos [Oxisols] (0.016 Mg ha h ha-1 MJ-1 mm-1) and Planossolos [Alfisols] (0.009 Mg ha h ha-1 MJ-1 mm-1) had close medium class values and highlighted Podzólicos [Ultisols] as one of the highest medium erodibility soils (0.042 Mg ha h ha-1 MJ-1 mm-1).

With regard to the studied soils, Sousa and Lobato (2020) indicated that Latossolos [Oxisols] that present medium texture and/or high sand contents may present a similar behavior as Areias Quatzosas [Quartzipsamments], which is more susceptible to erosion. However, the most clayey Latossolos have lower erodibility. According to Santos et al. (2020), Latossolos are generally deep, well-drained and friable. Such conditions impart good resistance to laminar erosion under natural conditions or when well managed.

Planossolos [Alfisols] usually have a textural B horizon with clay increments and may have low permeabilities (SANTOS et al., 2020). However, according to Almeida et al. (2020), it is highlighted that under conditions of densification, they can be very susceptible to erosion, especially with high sand contents.

Podzólicos [Ultisols] (PEd and PVa) have a natural tendency to be more susceptible to erosion (ZARONI; SANTOS, 2020), mainly due to their textural relationship (EMBRAPA, 2018). However, when they have medium textures and lower textural ratios, good infiltration conditions can reduce erodibility problems. In the specific case of PVa, Santos et al. (2020) pointed out that these soils are very susceptible to erosion. Thus, such information is broadly in line with that in Table 5.

On the other hand, the data in Table 5 also enabled more specific verifications when including data for the occurrence of associations. These data can be seen in the second column of the table "(+associations)". For some cases of LEa, such as LEa11 and LEa22, the amplitude increased since there are occurrences of Areias Quartzosas [Quartzipsamments] and Podzólicos [Ultisols]. Likewise, the amplitude increased for PEd3 (due to Latossolos [Oxisols]), PLa (due to Gleissolos [Entisols] and Areias Quartzosas [Quartzipsamments]), and PVa (with the presence of very sandy soils).

The data in the second column (Table 5), however, show limited support for the validation of the methodologies since they expand the scale of values. It is also noteworthy that the associations occur on a reduced scale in the study area, and there is no certainty that the field data in this study correspond exactly to one of these reported associations. Thus, the validation process was carried out considering only the erodibility of the main types of soils (LEa, LRd, PEd, PLa, and PVa).

Therefore, in Table 6, the erodibility values for different methodologies and soil types are presented. This table highlights the cases considered most suitable when compared to the data in the previous table (1st column of Table 5). Therefore, these cases met the following rules:

a)Framing of average values;

b)Framing of extreme values (between minimum and maximum).

An initial highlight in Table 6 is that despite the methodological differences, Bouyoucos' proposal was the only one to distance itself far from the others, and the very high values (reaching 0.2221 Mg ha h ha-1 MJ-1 mm-1) were the least adequate in this study. Such behavior is due to the high levels of sand for most of the soils of PRHB, which in some cases reached more than 90% (Table 4). As this methodology is strictly based on granulometric relationships, it is inadequate when there is the presence of high levels of sand or clay. Mannigel et al. (2002) also observed this type of behavior for this methodology, which produced values on the order of 0.4278 Mg ha h ha-1 MJ-1 mm-1 (extremely high class) for a Podzólico [Ultisol].

TABLE 6
Descriptive statistics of soil erodibility for the different methodologies in the PRHB

Main Soil Types[1]	Descriptive Measures						
	Methodology	Value				Std. Deviation	K Factor Variation (extremes values)
		Average	Class to K factor (K Average)	Min.	Max.		
LEa - Latossolo Vermelho-Escuro Álico	$K_{(Bouyoucos)}$	0.0797	extreme high	0.0222	0.1653	0.027	medium <k> extrem. high
	$K_{(Denardin)}$	0.0385	high	0.0311	0.0474	0.003	high <k> very high
	$K_{(Wischmeier)}$	0.0104	low	>0.0001	0.0244	0.005	very low <k> medium
	$K_{(Lima)}$	0.0149	low	0.0055	0.0361	0.007	very low <k> high
	$K_{(Chaves)}$	0.0156	medium	0.0007	0.0255	0.005	very low <k> medium
	$K_{(Renard\_a)}$	0.0290	medium	0.0236	0.0394	0.004	medium <k> high
	$K_{(Renard\_b)}$	0.0318	high	0.0251	0.0450	0.005	medium <k> high
	$K_{(Sharpley\_a)}$	0.0348	high	0.0181	0.0406	0.005	medium <k> high
	$K_{(Sharpley\_b)}$	0.0136	low	0.0046	0.0239	0.003	very low <k> medium
LRd - Latossolo Roxo Distrófico	$K_{(Bouyoucos)}$	0.0292	medium	0.0076	0.0825	0.032	very low <k> extrem. high
	$K_{(Denardin)}$	0.0275	medium	0.0208	0.0348	0.006	medium <k> high
	$K_{(Wischmeier)}$	0.0186	medium	0.0038	0.0270	0.011	very low <k> medium
	$K_{(Lima)}$	0.0314	high	0.0095	0.0454	0.015	low <k> high
	$K_{(Chaves)}$	0.0167	medium	0.0146	0.0198	0.002	low <k> medium
	$K_{(Renard\_a)}$	0.0374	high	0.0247	0.0436	0.008	medium <k> high
	$K_{(Renard\_b)}$	0.0428	high	0.0264	0.0506	0.011	medium <k> very high
	$K_{(Sharpley\_a)}$	0.0265	medium	0.0237	0.0328	0.003	medium <k> high
	$K_{(Sharpley\_b)}$	0.0234	medium	0.0105	0.0409	0.011	low <k> high
PEd - Podzólico Vermelho-Escuro Distrófico	$K_{(Bouyoucos)}$	0.0946	extrem. high	0.0353	0.2221	0.040	high <k> extrem. high
	$K_{(Denardin)}$	0.0395	high	0.0351	0.0496	0.003	high <k> very high
	$K_{(Wischmeier)}$	0.0111	low	0.0010	0.0291	0.006	very low <k> medium
	$K_{(Lima)}$	0.0159	medium	0.0039	0.0354	0.007	very low <k> high
	$K_{(Chaves)}$	0.0152	medium	>0.0001	0.0284	0.007	very low <k> medium
	$K_{(Renard\_a)}$	0.0280	medium	0.0196	0.0358	0.004	medium <k> high
	$K_{(Renard\_b)}$	0.0306	high	0.0203	0.0404	0.005	medium <k> high
	$K_{(Sharpley\_a)}$	0.0371	high	0.0302	0.0461	0.003	high <k> very high
	$K_{(Sharpley\_b)}$	0.0144	low	0.0083	0.0437	0.005	very low <k> high
PVa - Podzólico Vermelho-Amarelo Álico	$K_{(Bouyoucos)}$	0.0801	extrem. high	0.0558	0.0940	0.016	very high <k> extrem. high
	$K_{(Denardin)}$	0.0409	high	0.0334	0.0478	0.005	high <k> very high
	$K_{(Wischmeier)}$	0.0160	medium	0.0083	0.0221	0.006	very low <k> medium
	$K_{(Lima)}$	0.0225	medium	0.0105	0.0335	0.010	low <k> high
	$K_{(Chaves)}$	0.0116	low	>0.0001	0.0222	0.010	very low <k> medium
	$K_{(Renard\_a)}$	0.0307	high	0.0282	0.0346	0.002	medium <k> high
	$K_{(Renard\_b)}$	0.0339	high	0.0308	0.0387	0.003	high
	$K_{(Sharpley\_a)}$	0.0364	high	0.0328	0.0403	0.003	high
	$K_{(Sharpley\_b)}$	0.0143	low	0.0106	0.0189	0.004	low <k> medium
PLa - Planossolo Álico	$K_{(Bouyoucos)}$	0.1208	extrem. high	0.0975	0.1475	0.022	extrem. high
	$K_{(Denardin)}$	0.0353	high	0.0341	0.0369	0.001	high
	$K_{(Wischmeier)}$	0.0029	very low	0.0004	0.0056	0.002	very low
	$K_{(Lima)}$	0.0059	very low	0.0032	0.0115	0.003	very low <k> low
	$K_{(Chaves)}$	0.0135	low	0.0103	0.0151	0.002	low
	$K_{(Renard\_a)}$	0.0231	medium	0.0215	0.0244	0.001	medium
	$K_{(Renard\_b)}$	0.0245	medium	0.0225	0.0260	0.001	medium
	$K_{(Sharpley\_a)}$	0.0334	high	0.0316	0.0343	0.001	high
	$K_{(Sharpley\_b)}$	0.0087	very low	0.0073	0.0097	0.001	very low <k> low

Source: [1]Soil types according to State Soils Map (MATO GROSSO DO SUL, 1989; SISLA, 2020).

In Table 6, the methods that fit LEa were those of Wischmeier and Sharpley_b, while the one by Chaves only coincided with the class of extreme values. Although the two methods completely fit the criteria adopted, the Wischmeier methodology (which indicated a medium value in line with that found by Correchel (2003)) had an extremely low minimum value. Some works identified similar behavior, such as Marques (2013), and negative values in some cases, as observed by Oliveira and Bahia (1984). Thus, the Sharpley_b methodology was a better fit for LEa in the PRHB.

For LRd (Table 6), the best methodology was that of Wischmeier. The Chaves methodology was partially met but only coincided with the medium value.

Some studies (AMORIM et al., 2009; EDUARDO et al., 2013) indicated that the Wischmeier methodology may be inadequate for some very weathered soils. However, based on the adopted criteria, at least for the most clayey soils of the PRHB (LRd), the methodology presented an appreciable result.

In the case of PEd (Table 6), only the Renard_a methodology met the adopted criteria. This methodology is strongly influenced by the variation in the geometric average diameter of the soil particles, and it seemed to best represent the sandy soils of the PRHB. It was also the standout methodology for PVa.

For PLa, the methodologies that fit were that of Lima and Sharpley_b. In this case, the fact that both methodologies met the adopted criteria suggests the possibility of using both. However, as a final choice criterion, the spatial behavior of each methodology will also be evaluated.

Before the geostatistical analysis, the interactions between the tested methodologies and the soil attributes were analyzed. Thus, in Tables 7 and 8, the Pearson correlation matrices between the methodologies for determining soil erodibility and the correlation matrix between the methodologies and soil attributes are presented.

In Table 7, the correlations between Bouyoucos vs Denardin (r = 0.27), Bouyoucos vs Sharpley_a (r = 0.63) and Denardin vs Sharpley_a (r = 0.62) are highlighted. The highlight for this set of methodologies is the positive relationship between them, which is in contrast to other pairs with negative relationships, such as Bouyoucos vs Wischmeier (r = -0.61), Bouyoucos vs Lima (r = -0.72), Bouyoucos vs Renard_a and b (r = -0.84) and Bouyoucos vs Sharpley_b (r = -0.62). This finding indicates two groups that assume opposite behaviors in their results. In the first case (positive correlations), the Bouyuocos methodology is extremely influenced by the sand and clay content (whose erodibility increases with the increase in sand and decreases with the increase in clay) (Table 8). In Denardin's methodology, despite being much better developed, the same influence of particle size is also observed, although in this case, it does not have an extreme weight as in Bouyoucos' methodology. Similarly, the calculation method presented in Sharpley_a's methodology also shows this influence of sand and clay contents.

TABLE 7
Correlation matrix between methodologies for determining soil erodibility.

Methodologies	Correlation Coefficient							
	$K_{(Bouyoucos)}$	$K_{(Denardin)}$	$K_{(Wischmeier)}$	$K_{(Lima)}$	$K_{(Chaves)}$	$K_{(Renard\_a)}$	$K_{(Renard\_b)}$	$K_{(Sharpley\_a)}$
$K_{(Denardin)}$	0.27							
$K_{(Wischmeier)}$	-0.61	0.09						
$K_{(Lima)}$	-0.72	-0.11	0.92					
$K_{(Chaves)}$	-0.06	0.38	0.05	0.08				
$K_{(Renard\_a)}$	-0.84	-0.23	0.86	0.90	0.01			
$K_{(Renard\_b)}$	-0.84	-0.25	0.85	0.90	0.01	1.00		
$K_{(Sharpley\_a)}$	0.63	0.62	-0.09	-0.31	0.01	-0.45	-0.46	
$K_{(Sharpley\_b)}$	-0.62	-0.21	0.74	0.72	0.09	0.78	0.78	-0.18

Thus, these methodologies (Bouycous, Denardin and Sharpley_a) will indicate greater erodibility due to the increase in the coarser material (sand) contents and vice versa (Table 8).

TABLE 8
Correlation matrix between methodologies for determining soil erodibility and physical/chemical soil attributes.

Methodology/ Attribute	Correlation Coefficient								
	$K_{(Bouyoucos)}$	$K_{(Denardin)}$	$K_{(Wischmeier)}$	$K_{(Lima)}$	$K_{(Chaves)}$	$K_{(Renard\_a)}$	$K_{(Renard\_b)}$	$K_{(Sharpley\_a)}$	$K_{(Sharpley\_b)}$
Sand	0.73	0.52	-0.70	-0.79	-0.13	-0.86	-0.87	0.51	-0.79
Silt	-0.56	-0.13	0.80	0.76	0.19	0.77	0.78	-0.07	0.83
Clay	-0.73	-0.62	0.61	0.75	0.09	0.83	0.84	-0.63	0.71
Organic M.	-0.53	0.04	0.56	0.62	0.59	0.66	0.67	-0.30	0.52

This pattern regarding Brazilian soil erodibility seems to be a common understanding among researchers from Brazil. The increase in soil erodibility is linked to the greater presence of sand, and consequently, due to the characteristics of sand (more friable and less structured soils); thus, they aremore prone to erosion despite occasionally presenting good infiltration capacity.

On the other hand, the other methodologies (Wischmeier, Lima, Renard_a and b, and Sharpley_b) seem to have behavior indicating that higher erodibility would be related to lower soil drainage capacity. Thus, more sandy soils would have lower erodibility than more clayey soils (Table 8).

Therefore, to reinforce the ideas discussed, Figures 3 and 4 show the graphs of the trend lines observed for the positive and negative correlations between the methodologies and the sand content of the PRHB soils.

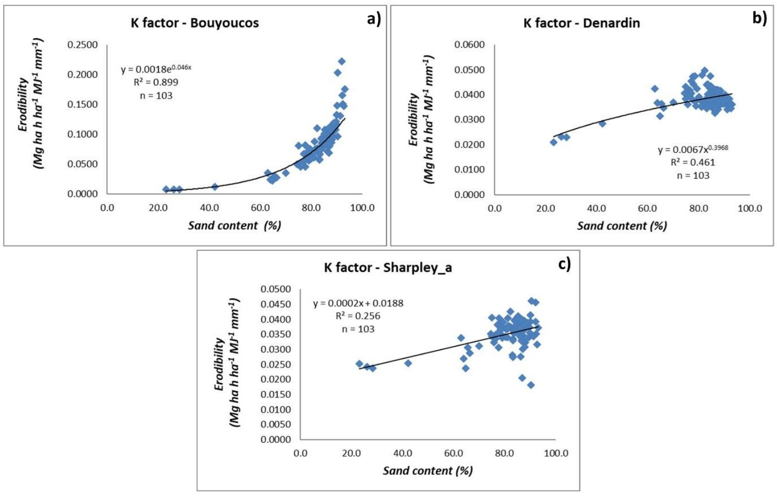

FIGURE 3
Trend lines between the main (positive) interactions of erodibility with the sand content of PRHB soils.

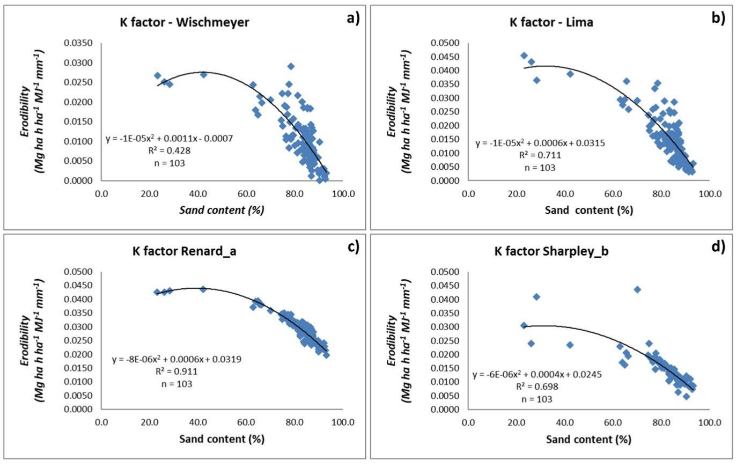

FIGURE 4
Trend line between the main (negative) interactions of erodibility with the sand content of PRHB soils.

Table 9 presents the descriptive analysis of the values determined for each methodology of soil erodibility that will be used in the geostatistical analysis.

TABLE 9
Descriptive statistical analysis of soil erodibility in the PRHB.

Methodology	*Descriptive Statistics Measures*							
	Average	*Median*	*Value*		*Standard Deviation*	*Coefficient*		
			Min.	*Max.*		*Variation (%)*	*Kurtosis*	*Asymmetry*
	Soil Erodibility (Mg ha h ha^{-1} MJ^{-1} mm^{-1})							
$K_{(Bouyoucos)}$	0.0841	0.0828	0.0076	0.2221	0.0365	43.4	2.437	0.772
$K_{(Denardin)}$	0.0382	0.0382	0.0208	0.0496	0.0045	11.7	3.528	-0.836
$K_{(Wischmeier)}$	0.0111	0.0104	>0.0001	0.0291	0.0068	61.2	-0.275	0.621
$K_{(Lima)}$	0.0162	0.0149	0.0031	0.0454	0.0090	55.5	0.817	0.982
$K_{(Chaves)}$	0.0152	0.0160	>0.0001	0.0284	0.0063	41.4	1.574	-0.980
$K_{(Renard\_a)}$	0.0289	0.0278	0.0196	0.0436	0.0050	17.3	0.699	0.902
$K_{(Renard\_b)}$	0.0317	0.0303	0.0203	0.0505	0.0064	20.1	0.960	0.992
$K_{(Sharpley\_a)}$	0.0352	0.0364	0.0181	0.0461	0.0048	13.6	1.788	-1.071
$K_{(Sharpley\_b)}$	0.0143	0.0127	0.0046	0.0436	0.0057	39.8	9.673	2.505

According to Pimentel-Gomes and Garcia (2002), the variability of the data was presented as follows:

According to Pimentel-Gomes and Garcia (2002), the variability of the data was presented as follows: medium variability (Sharpley_a, Renard_a, Denardin); high variability (Renard_b); and very high variability (Bouyoucos, Wischmeier, Lima, Chaves, Sharpley_b). Since the variability of the data is an essential requirement for the geostatistical analysis, it appears that the data are not restricted (Table 9).

The most important approach for geostatistical treatment is the analysis of data asymmetry. Thus, in Table 9, with the exception of the Wischmeier methodology, all others presented positive asymmetries. According to Yamamoto and Landim (2013), when this behavior is observed, the use of data transformation is recommended, although this is not a restrictive condition (CRESSIE, 1991). Therefore, the geostatistical analysis in this study was initially performed on the original data, and data conversion was only performed in cases when adequate semivariographic performance was not observed or when the intrinsic hypothesis was not met (YAMAMOTO; LANDIM, 2013).

Thus, Table 10 presents the semivariographic adjustment parameters for the different methodologies for determining soil erodibility.

TABLE 10
Adjustment parameters of experimental semivariograms for soil erodibility by different determination methodologies.

Methodology	Semivariogram Adjustment Measures									
	Model[(a)]	C_0	C_0+C	R(m)	R^2	*SSR*[(b)]	*SDE*[(c)]	*Cross Validation*		
							%	a	B	r
Soil Erodibility										
$K_{(Bouyoucos)}$	sph	$3.31x10^{-4}$	$1.19x10^{-3}$	26970	0.591	$9.39x10^{-7}$	72.2	0.000	1.039	0.777
$K_{(Denardin)}$*	exp	$1.27x10^{-5}$	$1.49x10^{-4}$	4290	0.410	$1.20x10^{-8}$	91.5	0.006	0.850	0.686
$K_{(Wischmeier)}$*	exp	$1.83x10^{-4}$	$1.06x10^{-3}$	7440	0.594	$3.04x10^{-7}$	82.8	0.000	1.013	0.849
$K_{(Lima)}$*	exp	$1.98x10^{-4}$	$8.86x10^{-4}$	7890	0.713	$1.01x10^{-7}$	77.7	-0.001	1.073	0.883
$K_{(Chaves)}$*	exp	$1.56x10^{-4}$	$5.93x10^{-4}$	25530	0.636	$1.32x10^{-7}$	73.7	0.004	0.754	0.529
$K_{(Renard\_a)}$*	sph	$1.68x10^{-5}$	$1.25x10^{-4}$	6070	0.846	$1.42x10^{-9}$	86.6	0.000	1.015	0.924
$K_{(Renard\_b)}$*	sph	$2.12x10^{-5}$	$1.80x10^{-4}$	5900	0.837	$3.21x10^{-9}$	88.2	0.000	1.009	0.926
$K_{(Sharpley\_a)}$*	exp	$4.95x10^{-5}$	$1.37x10^{-4}$	7230	0.697	$1.97x10^{-9}$	63.9	0.004	0.881	0.583
$K_{(Sharpley\_b)}$*	exp	$1.83x10^{-5}$	$2.74x10^{-4}$	5040	0.596	$1.86x10^{-8}$	93.3	0.001	0.931	0.762

[(a)]Fitted models, where: exp = exponential, sph = spherical; [(b)] SSR = sum of squares of the residuals; [(c)] SDE = spatial dependence evaluator; *transformation of original data used (square root).

(a)Fitted models, where: exp = exponential, sph = spherical; (b) SSR = sum of squares of the residuals; (c) SDE = spatial dependence evaluator; *transformation of original data used (square root).

In Table 10, the best performance fits were spherical (Bouyoucos, Renard_a, Renard_b) and exponential (Denardin, Chaves, Wischmeier, Lima, Sharpley_a and Sharpley_b), with coefficients of spatial determination (R2) ranging between 0.410 (Denardin) and 0.846 (Renard_a) and value ranges that indicated two groups of distinct magnitudes of (4,290 m - 7,890 m) and (25,530 m - 26,970 m).

In general, the methodologies presented appreciable semivariograms with SDE varying between moderate and high (ZIMBACK, 2001). On the other hand, the cross validations indicated that kriging will provide good estimation maps since the correlation between the observed and estimated values had r values ranging from 0.583 (Sharpley_a) to 0.926 (Renard_b).

Thus, in Figure 5, the kriging maps generated for soil erodibility in the PRHB area for different methodologies are presented.

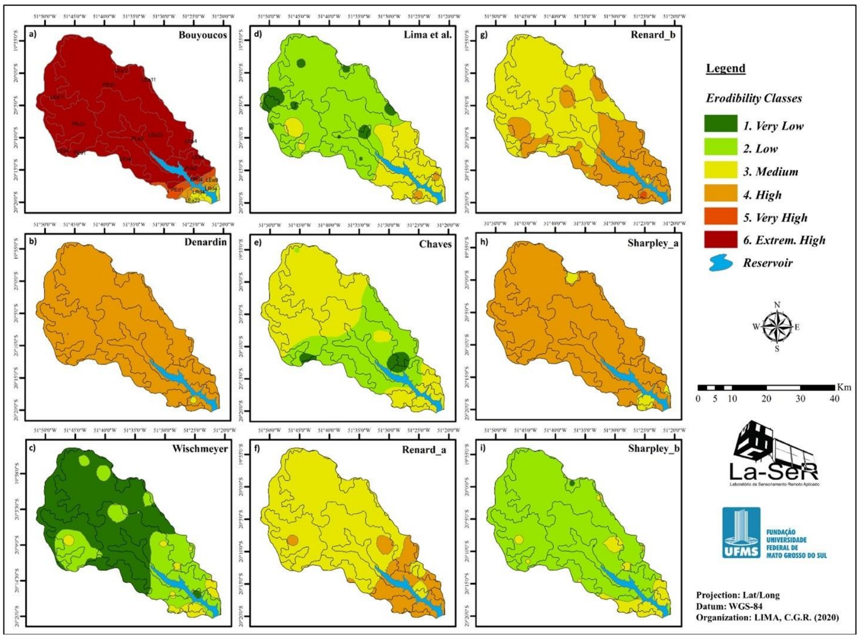

FIGURE 5
Kriging maps of soil erodibility in the PRHB for different determination methodologies.

Figure 5 shows some distinct maps and similar ones. The map that most distinguishes itself from the others is the one proposed by Bouyoucos, which indicated the greatest erodibility for the entire PRHB. On the other hand, there are similarities between the Denardim and Sharpley_a maps (whose high erodibility homogeneously predominated in almost all PRHB) and the proposals by Renard_a and Renard_b (which have the same methodological origin). Renard's proposals, in turn, demonstrated greater spatial variability, with the medium erodibility class predominating in the upper course (more sandy) and high erodibility predominating in the lower course of the basin (less sandy).

The Wischmeier and Lima proposals presented similar characteristics, with differences only in magnitudes since the methodologies are similar (Figure 5). These maps also have some similarities to the Chaves and Sharpley_b maps. It is noteworthy that this last group of maps had the lowest erodibility values for the PRHB.

Based on the analysis performed in Table 6, some methodologies were more adequate than others. Thus, for the LEa areas, the Sharpley_b methodology was adopted; for LRd, that of Wischmeier was adopted; for PEd and PVa, that of Renard_a was adopted; and for PLa, that of Sharpley_b was also adopted since the Lima methodology in geostatistical mapping produced values that were classified as medium erodibility when the extreme values observed in the literature did not exceed the lower class (Table 6).

Thus, considering the integration of these data, Figure 6 shows the final result of the soil erodibility mapping for the PRHB area. These maps (of continuous and classified variability) present the erodibility estimates that are closest to the values observed in the national literature.

In Figure 6, the classification of continuous values, according to Castro et al. (2011), showed that 46.6% of the PRHB area has medium erodibility (predominantly composed of Podzólicos Vermelho-Escuros [Ultisols]), 45.1% of the area has low erodibility (predominantly composed of Latossolos [Oxisols]), while the very low class presented 0.5%, and the very high class presented 7.9% of the basin area (this one predominantly in the Podzólicos Vermelho-Amarelos [Ultisols]).

The results presented by the final map (Figure 6) are technical information of essential utility for environmental planning in the PRHB, mainly because the middle and high erodibility classes account for more than 50% of the basin. These areas have experienced intense changes in land use and coverage due to socioeconomic changes in the eastern region of MS in the last decade, mainly in the municipalities of Selvíria, which mostly cover this hydrographic basin.

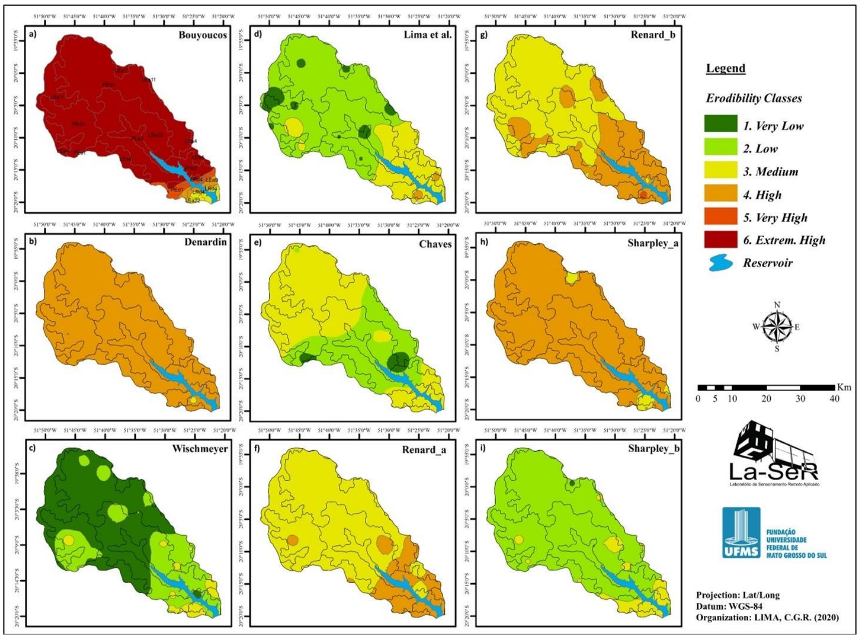

FIGURE 6
Soil erodibility map for the PRHB area.

CONCLUSION

The nine methodologies analyzed represent a portion of the numerous existing indirect methods of measuring soil erodibility. However, they use a group of physical/chemical attributes that are more accessible and less expensive for researchers, such as soil granulometry and organic matter.

Although the analyzed methodologies make general use of the same initial attributes, they sometimes derive antagonistic responses when correlated with particle size. For example, in the case of the Bouyoucos, Denardin and Sharpley_a methodologies, the erodibility increased with the sand content; while for the Wischmeier, Lima, Renard_a, and Sharpley_b methods, the erodibility decreased with increasing sand content. These divergent responses between methodologies indicates that the adoption of a single methodology may result in inadequate estimates for a study area, especially when faced with a wide variety of soils.

Faced with this challenge, the validation and selection of the best methodologies for the study area proved to be consistent and indicated that for the Pântano River Hydrographic Basin, the best estimates were given by the proposals by Sharpley and Williams (LEa and PLa [Oxisols and Alfisols, respectively]), Wischmeier and Smith (LRd [Oxisols]), and Renard (PEd and PVa [both Ultisols]).

From a geostatistical point of view, the different methodologies for measuring soil erodibility showed spatial dependence and appreciable parameters of semivariographic adjustments, which provided good kriging maps. This fact expands the possibilities of using these indirect methodologies since their estimates supported the application of geostatistics, thus allowing for a glimpse of the differences in the spatial behavior of erodibility in the PRHB for all methodological proposals.

The final map of soil erodibility for the Rio Pântano Hydrographic Basin was composed of a mosaic of methodologies that best represented each class of soil, and the following erodibility classes were observed in the basin: medium (46.4% of the basin area, predominantly in Podzólicos Vermelho-Escuros [Ultisols]); low

(45.1%, predominantly in the Latossolos [Oxisols]); while the very low class occupied 0.5%, and the very high class 7.9% of the basin area (this last one predominantly in the PVa [Ultisols]).

Finally, based on the different classes of soils and their physical/chemical characteristics, the use of a single and exclusive methodology can underestimate or overestimate the values of soil erodibility, which will produce results that are unsuitable for use, especially with regard to conservation management.

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