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Erosive Potential in Sub-basins of the Lower Itapecuru River in the State of Maranhão, Northeastern Brazil

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ABSTRACT

The aim of the present study was to estimate the loss of soil due to sheet erosion in ten sub-basins (SWDs) located in the lower course of the Itapecuru River based on different scenarios of land use and coverage in the years 2005, 2010 and 2015. For such, the Universal Soil Loss Equation (USLE), including the following factors: rainfall erosivity (R), soil erodibility (K), topographic factor (LS), soil use and conservation factor (CP). Annual R amounts were 11314.5 MJ mm ha⁻¹ yr⁻¹, with the greatest effects found in March and April. K values were related to soil types in the sub-basins, dominated by Plinthosols and Argilosols, with estimated contributions of 0.0429 and 0.030 t ha MJ⁻¹ mm⁻¹, respectively. The LS factor demonstrated a flat, smooth topography with slopes ranging between 0 and 5° over 93% of the study area. The standard CP indicated that green areas were prevalent in all years analyzed and that the main changes in the ten-year period occurred in sub-basins 1, 2 and 10. Regarding the USLE, the "very low" class was the most representative throughout the time series. However, changes in the CP factor, especially in sub-basins 1 and 2, evidenced the expansion of areas susceptible to sheet erosion, with the increase in the occurrence of "moderate" and "moderate to strong" classes triggered by changes in landscape patterns. The present findings are important to environmental management and the prioritization of environmental conservation actions in the SWDs.

Keywords: erosivity, erodibility, relief, soil conservation, USLE.

Potencial erosivo das sub-bacias hidrográficas do Baixo Curso do Rio Itapecuru, Estado do Maranhão, Nordeste do Brasil

RESUMO

O objetivo desta pesquisa foi estimar a perda de solo por erosão laminar em dez sub-bacias hidrográficas (SBHs) localizadas no Baixo Curso do Rio Itapecuru, com base em diferentes cenários de uso e cobertura da terra nos anos de 2005, 2010 e 2015. Com este propósito optou-se pela utilização da Equação Universal de Perda de Solos – EUPS, que integra os seguintes fatores: erosividade da chuva (R), erodibilidade do solo (K), fator topográfico (LS) e fator de uso e conservação do solo (CP). Os resultados evidenciaram que R anual equivale a 11.314,5 MJ mm ha⁻¹ ano⁻¹, com maiores efeitos nos meses de março e abril. Os valores de K estão relacionados com as tipologias de solos das SBHs, onde predominam Plintossolos e Argilossolos, respectivamente com contribuições estimadas de 0,0429 e 0,030 t ha MJ⁻¹ mm⁻¹. O fator LS revelou que predomina relevo plano e suave, com declividades variando entre 0° e 5°, estendendo-se por 93% da área de estudo. O padrão de CP indicou que as áreas verdes foram predominantes nos anos de 2005, 2010 e 2015, e que, entre os 10 anos, as principais alterações foram constatadas para as SBHs 1, 2 e 10. Quanto a EUPS, a classe “Muito Baixa” foi a mais representativa em toda série temporal. No entanto, devido as mudanças no Fator CP, principalmente nas SBHs 1 e 2, evidenciou-se a ampliação das áreas susceptíveis à erosão laminar, devido ao aumento das classes “Moderada” e “Moderada a forte”, desencadeada pelas alterações nos padrões da paisagem. Os resultado obtidos são significativo para gerenciamento ambiental e priorização das ações de conservação ambiental das SBHs.

Palavras-chave: erosividade, erodibilidade, relevo, conservação do solo, EUPS.

Introduction

The management and conservation of soil and water in a river basin requires the understanding of the dynamics of erosive processes to which this planning unit is subjected. Erosion is “the process of the detachment and accelerated dragging of soil particles caused by the action of water and wind” (Bertoni and Lombardi Neto, 2012, p. 68) and is considered one of the greatest problems of land degradation throughout the world (Devatha et al., 2015). Erosion constitutes a huge risk to the extensive territory of Brazil (Guerra et al., 2014). According to Vitte and Mello (2007, p. 130-131) “erosion problems in Brazil are the result of the combination of a rapid process of land occupation and technification, fragile soils and a climatic regimen that is propitious to the intense occurrence of this phenomenon.” Erosive processes have diverse impacts on environmental components, with negative effects on soil fertility (Prasannakumar et al., 2012), the silting of rivers (Demarchi and Zimback, 2014), floods and gullies (Vieira, 2008), overflows (Zhou et al., 2008), changes in the landscape pattern (Shi et al., 2013), changes in water quality (Santos and Hernandez, 2013) and socioeconomic problems (Guerra et al., 2014).

Erosive potential can be measured with different methods, such as the Universal Soil Loss Equation (USLE) proposed by Wischmeier and Smith (1978). This equation is the most widely used model throughout the world and provides useful information for the adequate planning of soil and water conservation. The application of the USLE on the scale of a river basin is facilitated by the use of a geographic information system (Oliveira et al., 2012). The equation has been employed in the international literature addressing erosive potential in river basins in order to suggest strategies for soil management and conservation (Irvem et al., 2007; Shi et al., 2012), environmental recovery (Stipp et al., 2011) and the management of natural resources (Beskow et al., 2009; Bezerra and Silva, 2014). According to Bezerra and Silva (2014, p. 195), “the study of the risk of soil loss constitutes one of the elements that can serve as the basis for the planning of river basins and defining goals, objectives and actions to be developed in studies and environmental plans addressing water resources”.

Information generated in the modeling of soil loss due to sheet erosion is fundamental to the environmental management of a river basin and assists in the understanding of interactions triggered by erosive processes. The results allow

the mapping of areas that are more susceptible to erosion and should be prioritized in control and conservation measures aimed at ensuring the sustainability of a given unit of analysis. However, there are no publications with information on the estimate of soil loss due to sheet erosion in the Itapecuru River basin in the state of Maranhão in Brazil.

The area selected for the present study consists of ten sub-basins located in the municipalities of Bacabeira, Rosário and Santa Rita that make up part of the industrial and port expansion of the state capital, São Luís. Increasing pressure on natural resources is projected for upcoming years, especially if environmental planning strategies are not drafted and implemented with the aim of maintaining the landscape as well as conserving vegetation, soil and water.

The purpose of the present study was to estimate soil loss due to sheet erosion in ten sub-basins located in the lower course of the Itapecuru River based on different land use and coverage scenarios in the years 2005, 2010 and 2015 in order to contribute information to the process of environmental planning in the region.

Methodology

Study area: Itapecuru River basin

The Itapecuru River basin covers 53,216.84 km², which corresponds to 16% of the area of the state of Maranhão (NUGEO, 2011). The basin is surrounded to the south and east by the Parnaíba River basin over the Itapecuru Hills, Azeitão Mesa and other small rises, to the west and southwest by the Mearim River basin and to the northeast by the Munim River basin (IBGE, 1998). According to Alcântara (2004), the different altitudes allow the classification of the Itapecuru River into upper, middle and lower courses (Figure 1).

The present study was focused on ten sub-basins (SWDs) located in the lower course of the Itapecuru River, covering an area of 421.6 km² and situated in the municipalities of Rosário, Bacabeira and Santa Rita in the state of Maranhão, Brazil. The estimated population in the three municipalities is 93,227 inhabitants: 16,553 in Bacabeira, 41,694 in Rosário and 35,980 in Santa Rita (IBGE, 2015). Geographically, the sub-basins are located in the microregion denominated Itapecuru Mirim in the northern portion of the state approximately 50 km from the state capital São Luís and limited by the

following coordinates: UTM 598658/574822 East and 9678715/9653145 North (Figure 2). The main accesses are through roadways BR-135 and BR-

402, which interlink the municipalities to the state capital.

Figure 1. Location of Itapecuru River basin and altitudinal division into upper, middle and lower courses.

Figure 2. Location of sub-basins of lower Itapecuru River.

Production in the region is mainly related to industrial agriculture, civil engineering, the

mechanical metal industry and the service industry (FSADU, 2013). Among these enterprises, only some agricultural, livestock and extraction activities are historically linked to the economic base of the municipalities of Bacabeira, Rosário and Santa Rita (IMESC, 2014). With the implantation of the work site for a large petrochemical enterprise and the creation of the industrial district of Bacabeira in 2008, the basis of the economy was altered and new economic activities emerged in the region.

According to the Thornthwaite moisture index, the climate is humid (LABGEO, 2002). Mean annual rainfall (1975-2015) in the region is 1998.8 mm. Two well-defined seasons occur. The rainy season spans from January to July and the dry season spans from August to December (INMET, 2015).

The soils in the area under the influence of the sub-basins are dystrophic argilluvico plinthosol, concretionary petric plinthosol, dystrophic red-yellow argisol and dystrophic yellow latosol (IBGE, 2007). The topography is characterized as flat to mildly undulating, corresponding to a dry flat surface on which plateaus, low hills with somewhat convex tops (sometimes nearly mesas molded in sedimentary rock) and shallow valleys are located (FSADU, 2008).

Universal Soil Loess Erosion (USLE)

The USLE was used for the estimation of soil loss due to sheet erosion. This equation was developed by Wischmeier and Smith (1978), modified by Bertoni and Lombardi Neto (2012) and is generically expressed by the following equation:

$$A = R.K.(L.S).(C.P)$$

in which:

(A) = Accumulated soil loss per unit of area in $t\ ha^{-1}\ year^{-1}$;

(R) = Rainfall erosivity in $MJ\ mm\ ha^{-1}\ year^{-1}$;

(K) = Soil erodibility in $t\ ha\ MJ^{-1}\ mm^{-1}$;

(L) = Slope length in meters;

(S) = Slope steepness in degrees;

(C) = Management (dimensionless);

(P) = Conservation practice (dimensionless).

The calculation of the USLE was based on a database developed for the present study in a geographic information system. The modeling of the database of such a system consists mainly of the definition of information planes, which are also denominated levels or layers. Information planes vary in number, type of format and theme in

accordance with the needs of each task or study (Câmara et al., 2001). For annual soil loss (A), information planes were generated for each variable in the equation. Rainfall erosivity (R) expresses the capacity of rainfall in a given location to cause erosion in an unprotected area. This factor was determined by the sum of monthly erosivity indices, which were determined based on the recommendations proposed by Lombardi Neto and Moldenhauer (1992), to give the annual R value.

$$EI = 68.730\left(\frac{r^2}{P}\right)^{0.841}$$

in which:

(EI) = mean monthly erosivity index in $MJ.mm/(ha.h.year)$;

(r) = mean monthly precipitation in millimeters;

(P) = mean annual precipitation in millimeters.

For the calculation of R, mean total monthly and annual precipitation data from a 40-year historical set (1975 to 2015) were used. These data were acquired from the meteorological station of the Brazilian National Meteorology Institute (INMET, 2015) located in the city of São Luís.

Soil erodibility (K) is the property of the soil that represents its susceptibility to erosion and is defined as the amount of material removed per unit of area when other determinant factors are constant. K is a quantitative value determined experimentally on plots of land and is expressed as soil loss per unit of rainfall erosivity index (Bertoni and Lombardi Neto, 2012). The information plane for K was created based on a pedological map of the state of Maranhão (IBGE, 2007), on which soil classes were correlated with erodibility values found in the scientific literature (Table 1).

The recommendation proposed by Bertoni and Lombardi Neto (2012) was used for C and P (management and conservation practices), with the combination of the two factors on a single information plane, denominated CP. The CP values were the only information planes of the USLE to vary among the years 2005, 2010 and 2015, enabling the evaluation of erosive processes in the sub-basins of the Itapecuru River in a ten-year period. For such, images from the Landsat-5 Thematic Mapper satellite from 2005, 2010 and 2015 were acquired from the Brazilian National Space Research Institute (INPE, 2015) and analyzed.

The following land use/coverage classes were used for the mapping: human occupation (high, medium and low), vegetation (high, medium and low), exposed soil and agriculture. The CP values were attributed based on adaptations of studies by Stein et al. (1987), Brito et al. (1998),

Tomazoni et al. (2005) and Ribeiro and Alves (2007) (Table 2).

Table 1. Soil typologies in lower Itapecuru River basin, erodibility values and source of data.

Soil groups	Erodibility t ha MJ ⁻¹ mm ⁻¹	Source
Ultisols	0.030	Baptista, 1997
Gleysols	0.036	Crestana, 2006
Latosols	0.020	Baptista, 1997
Neosols	0.027	Baptista, 1997
Plinthosols	0.0429	Chaves, 2010

Table 2. Classes of land use and coverage, CP values and source of data.

Classes of land use/coverage	CP factor	Source
High density occupation	0	Stein <i>et al.</i> (1987); Brito <i>et al.</i> (1998)
Medium and low density occupation	0.3	Brito <i>et al.</i> (1998)
High vegetation	0.00004	Stein <i>et al.</i> (1987)
Medium vegetation	0.0007	Stein <i>et al.</i> (1987)
Low vegetation	0.01	Tomazoni <i>et al.</i> (2005)
Agriculture	0.2	Brito <i>et al.</i> (1998)
Exposed soil	0.8	Ribeiro and Alves (2007)

The information planes of slope length (L) and steepness (S) were obtained separately, but subsequently combined to facilitate the application in the USLE, thereby composing a topographic information plane (LS) using the equation proposed by Bertoni and Lombardi Neto (2012):

$$LS = 0.00984^{L0.63} \chi S^{1.18}$$

in which:

(LS) = topographic factor;

(L) = slope length in meters;

(S) = steepness in degrees.

LS is an important factor in the equation, as greater slope length and steepness leads to the carrying of soil particles at a greater velocity and with greater force (Baptista, 1997). The percentages of the steepness classes were obtained through the creation of a clinographic map of the sub-basins. The values used for LS in the different steepness classes were attributed based on the study by Kok *et al.* (1995) (Table 3).

Table 3. Mean LS values per steepness class.

Steepness class	LS factor
0 – 5°	0.5
5 – 15°	3.5
15 – 30°	9
> 30°	16

Source: Kok *et al.* (1995)

After the determination of the information planes for rainfall erosivity (R), soil erodibility (K), management and conservation practices (CP) and the topographic factor (LS), all components of the

USLE were converted into Raster files with the description of each pixel in cells dimensioned in quadrants measuring 20 x 20 meters. For each quadrant, soil loss (A) was estimated by multiplying the factors that compose the equation using the Raster Calculator tool of the ArcGis program, version 10, of the Environmental Systems Research Institute.

The results of the USLE were categorized on different levels of susceptibility to erosive processes, following the recommendation proposed by Ribeiro and Alves (2007) (Table 4). The results of the mapping were converted into percentage values to facilitate the identification of changes having occurred in the sub-basins of the lower Itapecuru River between 2005 and 2015.

Table 4. Classes of soil loss due to sheet erosion.

Classes	Soil loss due to sheet erosion (t ha ⁻¹ y ⁻¹)
Very low	0 – 1
Low	1 – 10
Low - moderate	10 – 50
Moderate	50 – 100
Moderate - strong	100 – 500
Strong	500 – 1000
Very strong	1000 – 5000
Extreme	> 5000

Source: Ribeiro and Alves (2007).

Results and Discussion

Rainfall erosivity (R)

R values ranged from 0.0057708 MJ mm ha⁻¹ year⁻¹ in October to 3161.046 MJ mm ha⁻¹ year⁻¹ in April. Mean annual R was 11,314.5 MJ mm ha⁻¹

¹ year⁻¹, which was the value incorporated into the raster for the estimation of the USLE. As the R potential is related to the incidence of precipitation, this component of the erosive process exerts greater influence in rainier months and its effects are abruptly attenuated in dry months (Figure 3).

Figure 3. Mean precipitation (mm) and erosivity (mm ha⁻¹ year⁻¹) in sub-basins of lower Itapecuru River (1975-2015).

According to Oliveira et al. (2012), R values in Brazil range from 1672 to 22,452 MJ mm ha⁻¹ year⁻¹. In the mapping conducted by these authors, the zone corresponding to the lower Itapecuru River basin had R values between 10,000 and 12,000 mm ha⁻¹ year⁻¹, which is in agreement with the finding in the present investigation. Soares (2010) reports a similar trend in the Bacanga River basin, which is located 40 km from the study area, in which the annual R value was 10,714.05 mm ha⁻¹ year⁻¹, with the highest potential in April (3,613.59 MJ mm ha⁻¹ year⁻¹) and the lowest in October (0.007335 MJ mm ha⁻¹ year⁻¹).

According to Machado et al. (2014), high annual precipitation does not necessarily lead to greater erosivity, as the capacity of water to cause erosion is linked to the concentration of rains in a given period of the year. Rain occurs in a concentrated manner at specific times of the year in tropical regions (Guerra, 2012), which aggravates erosive processes in these periods. The rainfall data for the lower Itapecuru River basin indicate that greater concentrations of rain occur in March, April and May (Figure 3) and the potential for erosivity to result in higher A values is therefore greater in this period.

According to Hoyos, Waylen and Jaramillo (2005), high R values are expected in the tropics due to kinetic energy and the intensity of convective rains. Thus, it is important to understand precipitation dynamics, since rainfall is the driving force of erosion (Oliveira et al., 2012). In the lower Itapecuru River basin, the Intertropical Convergence Zone is the main climatic factor responsible for the incidence of rainfall. Thus,

understanding the behavior of this meteorological system in detail is fundamental to the precise modeling of erosive processes in the region.

Soil erodibility (K)

The spatialization of soil erodibility (K) is directly related to the pedological mapping of the lower Itapecuru River basin, since this variable is an intrinsic property of each class of soil. According to the Brazilian Institute of Statistics and Geography (IBGE, 2007), the main groups of soils in the sub-basins are Plinthosols, Ultisols, Latosols and Gleysols (Figure 4).

The predominant soil types are Plinthosols and Ultisols, which jointly cover an area of 330.48 km², totaling 79% of the surface of the sub-basins of the lower Itapecuru River. Latosols and Neossolos respectively represent 14% and 7% of the mapped areas (Table 5). Following the pedological survey, K was calculated by crossing soil type in the sub-basins with K values extracted from the literature. Figure 5 displays the information plane for erodibility.

As different soil types have different degrees of proneness to erosive processes, understanding the K factor is fundamental. According to Bertoni and Lombardi Neto (2012, p. 61), “erosion is not the same in all soils. Physical properties, especially structure, texture, permeability and density, as well as chemical and biological characteristics exert different influences on erosion”.

Plinthosol has the greatest erodibility and covers the largest portion of the sub-basins of the lower Itapecuru River (57%). Hence, such areas undergo greater effects of erosive processes under adverse conditions (Table 5). SWD 1 and SWD 2 have greater natural resistance to erosion due to the predominance of Latosols, which have a low K value in the study area. Another important aspect is the need to calibrate K factors for the lower Itapecuru River basin. Although the use of estimates in the composition of the USLE is valid and widely described in the literature, the identification of K values on a local scale enables a more detailed understanding of erosive processes.

Figure 4. Pedological mapping of sub-basins of lower Itapecuru River.

Table 5. Distribution of soil classes in each sub-basin (SWD) of lower Itapecuru River.

Sub-basins	Ultisols		Gleysols		Latosols		Neossolos		Plinthosols	
	km ²	%	km ²	%	km ²	%	km ²	%	km ²	%
SWD 1	-	-	-	-	36.76	95%	1.15	3%	0.72	2%
SWD 2	-	-	0.61	1%	22.04	41%	5.93	11%	24.90	46%
SWD 3	-	-	-	-	-	-	0.29	5%	5.20	95%
SWD 4	-	-	-	-	-	-	3.41	30%	7.81	70%
SWD 5	-	-	-	-	-	-	1.57	5%	33.02	95%
SWD 6	40.06	36%	-	-	-	-	6.45	6%	64.29	58%
SWD 7	12.22	34%	-	-	-	-	-	-	23.83	66%
SWD 8	0.85	2%	-	-	-	-	7.28	19%	31.07	79%
SWD 9	24.62	69%	-	-	-	-	0.63	2%	10.52	29%
SWD 10	14.23	25%	-	-	-	-	4.70	8%	37.17	66%
TOTAL	91.98	22%	0.61	0.1%	58.81	14%	31.40	7%	238.5	57%

Topographic factor (LS)

According to Minella et al. (2010), with the techniques available in the geographic information system and the ease of obtaining numerical elevation models, it is possible to estimate the LS factor in a less labor-intensive manner, taking into account geo-morphological features, which are determinants with regard to hydrological processes. The determination of the LS factor in the present study was based on Kok et al. (1995), who report mean steepness values per class as a function of established relationships between watershed length and gradient.

A flat, smooth relief predominates, with slopes ranging from 0 to 5° extending over 93% of the sub-basins (329.3 km²). However, SWD 6, SWD 7, SWD 9 and SWD 10 have higher percentages of slopes between 5 and 15° (Table 6 and Figure 6) and therefore have the potential to exhibit a greater influence of the relief on the intensity of erosion. According to Coutinho et al. (2014, p. 6), “areas with steeper slopes can generate a greater outflow velocity, thereby reducing the volume of water stored in the soil and subjecting the basin to degradation processes due to erosion”. Thus, areas with steeper slopes should be prioritized in soil conservation actions aimed at preserving vegetation. Figure 7 displays the

information plane for the topographic factor of the USLE.

Figure 5. Information plan of soil erodibility ($t\ ha\ MJ^{-1}\ mm^{-1}$) for calculation of USLE in sub-basins of lower Itapecuru River.

Table 6. Distribution of steepness classes in each sub-basin (SB) of lower Itapecuru River.

Sub-basin	Unit	Steepness class			
		0°-5°	5°-15°	15°-30°	>30°
SWD 1	km ²	37.78	1.01	-	-
	%	97.40	2.60	-	-
SWD 2	km ²	52.09	1.52	0.01	-
	%	97.1	2.83	0.02	-
SWD 3	km ²	5.44	0.06	-	-
	%	98.98	1.02	-	-
SWD 4	km ²	11.01	0.22	-	-
	%	98.08	1.92	-	-
SWD 5	km ²	34.35	0.24	-	-
	%	99.30	0.70	-	-
SWD 6	km ²	95.06	15.64	0.10	-
	%	85.80	14.12	0.09	-
SWD 7	km ²	33.66	2.38	-	-
	%	93.38	6.62	-	-
SWD 8	km ²	38.58	0.62	-	-
	%	98.42	1.58	-	-
SWD 9	km ²	30.64	5.12	-	-
	%	85.66	14.32	-	-
SWD 10	km ²	53.69	2.41	-	-
	%	95.70	4.30	-	-
TOTAL	km ²	329.3	29.22	0.11	-
	%	93	6.93	0.027	-

Based on Kok et al. (1995)

Figure 6. Clinographic map of sub-basins of Itapecuru River.

Figure 7. Information plane of topographic factor (LS) for calculation of USLE in sub-basins of lower Itapecuru River.

Soil use and conservation factor (CP)

CP values were attributed to each class mapped in the sub-basins based land use/coverage patterns in the area investigated (Figure 8). These

values served as the basis for the information plane of the CP factor (Figure 9). Tables 7, 8 and 9 display the percentages of land use/coverage classes for 2005, 2010 and 2015, respectively.

Figure 8. Map of land use/coverage in sub-basins of lower Itapecuru River in 2005, 2010 and 2015.

Figure 9. Information plane of CP factor for calculation of USLE of sub-basins of lower Itapecuru River in 2005, 2010 and 2015.

Table 7. Quantitative percentage (%) of land use/coverage classes in sub-basins of lower Itapecuru River for 2005.

Classes of land use/coverage	SWD 1	SWD 2	SWD 3	SWD 4	SWD 5	SWD 6	SWD 7	SWD 8	SWD 9	SWD 10	TOTAL
Agriculture	0.36	-	0.07	-	0.18	0.82	0.03	1.15	0.24	0.08	0.41
High occupation	8.64	-	-	-	-	-	-	-	-	-	0.79
Low occupation	2.45	0.24	0.91	0.62	0.90	0.23	1.66	0.59	0.99	2.20	0.99
Medium occupation	1.16	-	-	-	0.35	-	-	0.38	-	1.91	0.43
Exposed soil	14.26	20.05	19.11	12.03	15.87	11.68	9.99	8.70	6.41	15.99	13.14
High vegetation	45.19	64.67	74.26	79.68	69.67	81.75	84.89	81.38	86.13	67.89	73.84
Low vegetation	17.61	7.89	1.46	4.01	10.49	1.30	3.36	1.89	2.79	3.65	4.85
Medium vegetation	7.40	5.75	4.19	-	2.32	1.62	0.06	2.33	3.27	7.97	3.92

Table 8. Quantitative percentage (%) of land use/coverage classes in sub-basins of lower Itapecuru River for 2010.

Classes of land use/coverage	SWD 1	SWD 2	SWD 3	SWD 4	SWD 5	SWD 6	SWD 7	SWD 8	SWD 9	SWD 10	TOTAL
Agriculture	0.93	0.00	0.07	1.29	0.18	0.24	1.17	1.32	0.45	0.17	0.48
High occupation	11.45	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.35	1.10
Low occupation	3.49	0.51	0.69	1.18	0.26	0.23	0.69	0.75	0.40	1.65	0.89
Medium occupation	1.05	0.03	0.68	0.00	0.80	0.00	0.00	0.56	0.00	3.67	0.72
Exposed soil	12.01	29.33	10.99	6.26	11.68	4.41	1.50	4.11	2.38	10.17	9.33
High vegetation	34.19	47.16	63.37	32.62	69.15	83.64	92.00	62.88	90.15	76.21	69.99
Low vegetation	14.83	10.53	2.72	6.78	12.37	3.10	0.42	2.89	2.53	4.06	5.81
Medium vegetation	19.42	11.52	21.48	47.94	5.01	6.72	4.21	25.56	3.89	3.24	10.48

Table 9. Quantitative percentage (%) of land use/coverage classes in sub-basins of lower Itapecuru River for 2015.

Classes of land use/coverage	SWD 1	SWD 2	SWD 3	SWD 4	SWD 5	SWD 6	SWD 7	SWD 8	SWD 9	SWD 10	TOTAL
Agriculture	0.56	-	-	0.04	0.15	0.06	1.17	0.54	0.20	0.30	0.29
High occupation	11.80	-	-	-	-	-	-	-	-	0.38	1.14
Low occupation	4.07	0.64	0.76	1.30	1.01	0.30	0.80	0.92	0.53	2.09	1.14
Medium occupation	1.15	0.07	0.73	-	1.09	-	-	0.67	0.00	2.94	0.67
Exposed soil	18.8	27.52	8.58	8.28	10.11	4.01	-	3.99	2.39	9.75	9.31
High vegetation	18.22	27.96	44.42	27.90	60.21	80.49	67.45	58.67	87.77	70.24	60.67
Low vegetation	20.86	13.44	6.51	6.37	14.57	3.00	1.00	5.29	2.39	7.28	7.62
Medium vegetation	22.05	29.35	38.81	52.36	12.17	10.37	28.53	28.23	6.52	6.58	17.88

The high and medium vegetation classes were predominant, covering 77.76% of the surfaces of the sub-basins in 2005, increasing to 80.5% in 2010 and dropping to 78.6% in 2015. Low vegetation accounted for 4.85% of the land coverage in 2005, increasing to 5.81% in 2010 and 7.62% in 2015. The largest changes in vegetation occurred in SWD 1 and SWD 2.

Exposed soil accounted for 13.14% of the study area in 2005. The largest areas were found in SWD 6, SWD 2 and SWD 10. In 2010, the total area of exposed soil diminished to 9.33%, but the inverse occurred for SWD 2, in which the area increased from 9.27% to 29.33%. In 2015, the main changes occurred in SWD 1 and SWD 4, with an increase in exposed soil accompanied by a reduction in areas of vegetation.

Low occupation percentages were found for the three years of reference, totaling 2.20% of

the surface of the sub-basins in 2005, 2.71% in 2010 and 2.94% in 2015. The largest proportions in the three years were found in SWD 1 and SWD 10 due to connections with the main expansion areas of the municipalities of Bacabeira and Rosário.

The percentages for agriculture were the lowest among the land use/coverage classes, corresponding to 0.41% in 2005, 0.48% in 2010 and 0.29% in 2015. The pattern evidenced for agriculture was characterized by small polygons associated with areas of high and medium vegetation and distributed randomly throughout the surfaces of the sub-basins, suggesting that that activity was developed merely as a form of subsistence.

As the land use/coverage pattern, which represents the CP factor, is one of the main agents that can lead to the short-term increase or reduction in erosive processes, it is evident from the

standpoint of the conservation of soil and water resources that the maintenance of native vegetation constitutes a priority action in the environmental management of the sub-basins of the lower Itapecuru River.

According to Mohammad and Adam (2010), studies under different environmental conditions have demonstrated the positive effect of vegetal coverage on the reduction of erosion, as forests diminish the risk of surface runoff and the loss of soil, whereas land cultivation and deforestation create conditions that are favorable to

erosion. Pacheco et al. (2014) postulated this same notion after conducting an experimental study in a small river basin located in northern Portugal, where the adequate use of land reduced soil loss by as much as 86% in comparison to areas in which inadequate land use occurred.

Soil loss due to sheet erosion (A)

Tables 10, 11 and 12 display the percentages of susceptibility classes regarding soil loss due to sheet erosion in 2005, 2010 and 2015.

Table 10. Classes of soil loss due to sheet erosion (%) in sub-basins of lower Itapecuru River in 2005.

Soil loss classes (t ha ⁻¹ year ⁻¹)	SWD 1	SWD 2	SWD 3	SWD 4	SWD 5	SWD 6	SWD 7	SWD 8	SWD 9	SWD 10	TOTAL
Very low	65.31	72.58	78.86	83.78	72.75	86.18	90.07	87.26	89.72	76.57	80.73
Low	17.24	7.68	1.49	3.87	9.98	1.26	0.09	1.91	2.45	3.54	4.69
Low to moderate	3.81	0.26	0.07	0.45	0.15	0.65	0.03	1.84	0.55	1.41	0.99
Moderate	12.12	7.85	1.01	0.19	1.20	0.23	0.13	0.30	0.83	2.59	2.75
Moderate to strong	1.16	11.43	18.25	11.72	15.87	10.49	9.08	8.60	5.79	15.14	10.24
Strong	0.34	0.11	0.31	-	-	0.91	0.50	0.03	0.63	0.38	0.44
Very strong	0.02	0.09	-	-	0.06	0.28	1.73	0.06	0.04	0.36	0.16

Table 11. Classes of soil loss due to sheet erosion (%) in sub-basins of lower Itapecuru River in 2010.

Soil loss classes (t ha ⁻¹ year ⁻¹)	SWD 1	SWD 2	SWD 3	SWD 4	SWD 5	SWD 6	SWD 7	SWD 8	SWD 9	SWD 10	TOTAL
Very low	60.55	60.37	85.37	84.74	75.56	92.06	96.33	90.48	94.32	80.68	82.39
Low	22.76	10.20	2.72	6.82	11.57	2.93	0.38	2.87	2.25	3.86	6.33
Low to moderate	5.03	0.56	0.07	1.72	0.39	0.45	1.06	1.92	0.61	1.32	1.23
Moderate	10.62	15.62	1.43	0.71	1.00	0.23	0.64	0.63	0.24	3.97	3.81
Moderate to strong	0.73	13.01	10.42	6.01	11.44	3.91	1.54	4.03	2.28	9.86	6.00
Strong	0.26	0.18	-	-	-	0.27	-	-	0.29	0.17	0.17
Very strong	0.04	0.06	-	-	0.04	0.15	0.05	0.08	-	0.14	0.08

Table 12. Classes of soil loss due to sheet erosion (%) in sub-basins of lower Itapecuru River in 2015.

Soil loss classes (t ha ⁻¹ year ⁻¹)	SWD 1	SWD 2	SWD 3	SWD 4	SWD 5	SWD 6	SWD 7	SWD 8	SWD 9	SWD 10	TOTAL
Very low	56.18	59.01	83.92	84.27	74.10	92.58	96.26	94.41	94.41	78.08	81.29
Low	20.32	13.11	6.44	6.58	13.88	3.03	1.24	2.19	2.19	6.99	7.43
Low to moderate	5.07	0.65	0.00	0.45	0.47	0.16	0.16	0.61	0.61	1.58	1.05
Moderate	17.23	0.03	1.57	0.83	1.78	0.30	0.71	0.29	0.29	3.56	2.49
Moderate to strong	0.84	26.96	8.07	7.79	9.69	3.75	1.54	2.11	2.11	9.47	7.53
Strong	0.29	0.19	-	0.08	0.02	0.16	0.05	0.39	0.39	0.17	0.16
Very strong	0.06	0.04	-	-	0.06	0.04	0.05	-	-	0.15	0.05

Figure 10 show the final maps on the erosive potential of the sub-basins in 2005, 2010 and 2015, respectively, which were created based on the interpolation of the information planes for rainfall erosivity, soil erodibility, the topographic factor and soil use/conservation.

The very low category was the predominant class based on the USLE, with soil loss up to 1 t ha⁻¹ year⁻¹ due to sheet erosion. This

class accounted for 80.73% (339.02 km²) of the surface of the sub-basins in 2005, 82.39% (347.39 km²) in 2010 and 81.29% (342.76 km²) in 2015. These results may be attributed to the predominance of areas with gentle slopes and the significant presence of arboreal vegetation in the sub-basins.

Figure 10. Mapping of erosive potential of sub-basins of lower Itapecuru River in 2005, 2010 and 2015

The low ($1-10\ t\ ha^{-1}\ year^{-1}$) and moderate to strong ($100-500\ t\ ha^{-1}\ classes^{-1}$) were also dominant. The low class accounted for 4.69% of the surface in 2005, 6.33% in 2010 and 7.43% in 2015. Areas with moderate to strong soil loss totaled 10.24% in 2005, 6.0% in 2010 and 7.53% in 2015. The moderate class ($50-100\ t\ ha^{-1}\ year^{-1}$) accounted for 2.75% of the total study area in 2005,

3.81% in 2010 and 2.49% in 2015. The strong and very strong classes corresponded to the smallest areas of the sub-basins.

In the study by Soares (2010), in which USLE values were estimated for two sub-basins located in the rural zone of the city of São Luís, which is 35 km from the lower Itapecuru River, the main soil loss classes were very low and low.

However, the author found an increase in the erosive potential between 1976 and 2008, associating the main changes to disorderly land occupation and a reduction in areas with vegetal coverage, which led to silting and changes in the quality of bodies of water. Lopes et al. (2011) found a similar pattern in the sub-basin of Varjota Creek in the state of Ceará, Brazil (70.73 km²), in which 74% of the area had soil loss less than 11 t ha⁻¹ year⁻¹, which corresponded to flatter and/or more vegetated areas. The authors found that areas with greater erosive potential were along the drainage lines of the creeks and in degraded regions.

The main changes between 2005 and 2015 occurred in SWD 1 and SWD 2 due to the increase in areas of greater erosive potential. Zones with soil loss less than 1 t ha⁻¹ year⁻¹ diminished from 65.31% to 56.18% in SWD 1 and 72.58% to 59% in SWD 2, representing losses of 9.14 km² and 13.57 km², respectively, of areas with lower erosive potential. The reduction in green areas in these sub-basins, accompanied by the increase in areas of exposed soil in the rainy season, contributed to the increase in soil loss due to sheet erosion.

Another aspect that merits attention regards the increase in areas of the moderate class in SWD 1 and the moderate to strong class in SWD 2. In SWD 1, areas with soil loss between 50 and 100 t ha⁻¹ year⁻¹ increased from 12.12% in 2005 to 17.23% in 2015. In SWD 2, the increase in erosive processes went from 11.43% in 2005 to 26.96% in 2015. Such increases corresponded to 2.0 km² and 8.33 km² in SWD 1 and SWD 2, respectively. In contrast, no substantial changes in erosion patterns were found in the other sub-basins within the study period.

Changes in the CP factor were related to changes in the landscape pattern of the sub-basins, especially excavating activities in SWD 1 and SWD 2 for the implantation of a petrochemical enterprise. The effects of environmental tensors on the erosive potential of soils are reaffirmed by Ruthes et al. (2014, p. 1100):

“Erosion is the result of the action of diverse phenomena that alter the normal conditions of a river basin. The uncontrolled artificialization of the environment is the major factor that accelerates this process, as the removal of vegetal coverage for the establishment of croplands, road construction, excavation activities, waterway constructions, etc. contributes decisively to the greater disaggregation and, consequently, greater transport of solid particles.”

A reduction in the water quality of creeks is another consequence of the potentiation of soil loss in SWD 1 and SWD 2. According to the FSADU (2014), the excavation activities of the petrochemical enterprise caused changes in the turbidity, total suspended solids, dissolved suspended solids, true color and transparency of bodies of water in these sub-basins, especially in the rainy season. Such changes are indicators of an increase in particulate and dissolved matter due to sheet erosion of the soil. The increase in this process is directly related to changes in the landscape pattern (CP factor).

The use of the USLE as an environmental diagnostic and predictive tool for areas with greater erosive potential in sub-basins is of fundamental importance to the conservation of soil and water resources. The implementation of management measures for areas of risk can help avoid erosive processes as well as minimize costs related to environmental recovery. The present findings underscore the need for actions directed at maintaining green areas, establishing orderly development, reforesting degraded areas and protecting areas in which the steepness of the slopes is greater than 15 degrees.

Conclusion

The mean erosivity observed (11,314.5 MJ mm ha⁻¹year⁻¹) demonstrates that the study area has high erosive potential due to the effects of rainfall. March and April are the months that contribute most to annual erosivity, whereas September and October contribute least. The variability between the rainy and dry seasons demonstrates the need to determine existing relationships between rainfall patterns (volume and intensity) and erosivity in the region. A more detailed R model requires the installation of meteorological stations in the lower lower Itapecuru River basin to perform a diagnosis on a finer scale.

The pedological survey indicated the presence of Plinthosols, Ultisols, Latosols and Neossolos in the sub-basins. Areas deprived of vegetation over the soil that have greater erodibility (K factor) should be prioritized in conservation measures, as such areas are more susceptible to the effects of sheet erosion.

The topographic characteristics demonstrate the predominance of slopes between 0 and 5°, which minimizes the susceptibility of soil loss due to sheet erosion, as demonstrated by the low LS values. However, this aspect does not reduce the need to preserve green areas, as erosive processes are triggered by the combination of other factors of the Universal Soil Loss Equation.

Green areas were predominant in all three years of reference (2005, 2010 and 2015). However, these areas were replaced by exposed soil and occupied areas in sub-basins 1 and 2, thereby potentiating soil loss. Areas with vegetal coverage had lower CP values, indicating that vegetal coverage is the best way to control erosion, especially in areas at risk of degradation.

The “very low” sheet erosion class predominated in the period investigated, with an annual loss of less than 1 t ha⁻¹ year⁻¹. However, sub-basins 1 and 2 exhibited increases in areas of moderate and moderate to strong risks of sheet erosion (losses between 50 and 500 t ha⁻¹ year⁻¹) caused by changes in landscape patterns, as demonstrated by the CP values.

The present findings are significant to environmental planning and the prioritization of environmental conservation actions in sub-basins. The diagnosis of the erosive potential with the aid of the Universal Soil Loss Equation generated important data to be applied in measures directed at the sustainability of environmental resources in the lower Itapecuru River basin.

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