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SPATIAL VARIABILITY OF SEDIMENT GENERATION AND CONNECTIVITY IN HPPS WATERSHEDS

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Abstract

The knowledge of the spatial variability of the generation and transport of sediments allows the identification with considerable precision critical areas regarding the generation and flow of detrital materials in watersheds. This paper aims to relate the spatial variability of soil loss and sediment connectivity in a contribution basin of the Batalha Hydroelectric Power Plant reservoir in the municipality of Cristalina (GO). The methodology comprised the bivariate spatial correlation between production estimates (MUSLE) and the Connectivity Index (CI) applied at a slope scale in the basin's contribution area. The results indicate the configuration of four spatial patterns: low production and low connectivity index in most of the area, comprising the higher and flatter portions; low production and high connectivity index in the vicinity of springs and drainage channels; high production and low connectivity index in the higher, steeper and more distant portions; and high production and high connectivity, predominating in the steepest portions and closest to the channels or even in those portions that are more distant but are connected to the channel, in the latter situation via more intense surface runoff flow lines. In this sense, the importance of this methodology is highlighted in the identification of critical areas, which are priority areas for the implementation of mitigating measures of the impacts resulting from hydric erosive processes.

Keywords: Water Erosion, Sediment Contribution, Critical Areas, Water Reservoirs.

Resumo / Resumen

VARIABILIDADE ESPACIAL DA GERAÇÃO E CONECTIVIDADE DE SEDIMENTOS EM BACIAS DE UHES

O conhecimento da variabilidade espacial de produção e transporte de sedimentos permite identificar com considerável precisão (distintas situações quanto) áreas críticas quanto à geração e fluxo de materiais detríticos em bacias hidrográficas. Este artigo tem como objetivo relacionar a variabilidade espacial da perda de solos e a conectividade de sedimentos em uma bacia de contribuição do reservatório da usina hidrelétrica de Batalha no município de Cristalina (GO). A metodologia compreendeu a correlação espacial bivariada entre as estimativas de produção (MUSLE) e o Índice de Conectividade (IC) aplicados em escala de vertente na área de contribuição da bacia. Os resultados indicam a configuração de quatro padrões espaciais: baixa produção e baixo índice de conectividade na maior parte da área, compreendendo as porções mais elevadas e planas; baixa produção e elevado índice de conectividade nas imediações das nascentes e dos canais de drenagem; alta produção e baixo índice de conectividade nas porções mais elevadas, íngremes e distantes; e alta produção e elevada conectividade, predominando nas porções mais íngremes e próximas dos canais ou mesmo naquelas mais distantes e conectadas ao canal, nesta última situação via linhas de fluxo de escoamento superficial mais intenso. Neste sentido, destaca-se a importância desta metodologia na identificação de áreas críticas e, portanto, prioritárias para implantação de medidas atenuantes dos impactos decorrentes de processos erosivos hídricos.

Palavras-chave: Erosão Hídrica, Aporte de Sedimentos, Áreas Críticas, Reservatórios.

VARIABILIDAD ESPACIAL DE LA GENERACIÓN Y CONECTIVIDAD DE SEDIMENTOS EN CUENCAS DE UHES

El conocimiento de la variabilidad espacial de la producción y el transporte de sedimentos permite identificar con bastante precisión diferentes situaciones de generación y flujo de materiales detríticos en cuencas hidrográficas. Este artículo tiene como objetivo relacionar la variabilidad espacial de la pérdida de suelo y la conectividad de los sedimentos en una cuenca de aportación del embalse de la central hidroeléctrica de Batalha, en el municipio de Cristalina, Goiás, Brasil. La metodología consistió en la correlación espacial bivariada entre las estimaciones de producción (MUSLE) y el Índice de Conectividad (IC), aplicados a escala de ladera en el área de contribución de la cuenca. Los resultados indican la configuración de cuatro patrones espaciales: baja producción y bajo índice de conectividad en la mayor parte del área, que comprende las porciones más altas y planas; baja producción y alto índice de conectividad en las proximidades de los manantiales y canales de drenaje; alta producción y bajo índice de conectividad en las porciones más altas, empinadas y distantes; y alta producción y alta conectividad que prevalecen en las porciones más empinadas y cercanas a los canales o incluso en las más distantes y conectadas al canal, en esta última situación a través de líneas de flujo de escorrentía superficial más intensas. En este sentido, se destaca la importancia de esta metodología en la identificación de áreas críticas y, por lo tanto, prioritarias para la implementación de medidas de mitigación de los impactos resultantes de los procesos hídricos erosivos.

Palabras-clave: Erosión hídrica, Contribución de sedimentos, Áreas críticas, Embalses.

INTRODUCTION

The knowledge about the spatial-temporal variability of soil degradation rates and sediment dynamics in watersheds, especially those with structures intended for multiple use of water, has always been of great importance throughout the history of civilizations (LIU et al., 2017). This is because these large structures, in addition to regulating the flow of rivers, mitigating the effects of climate seasonality and ensuring water in dry periods, began to acquire, throughout their existence, new meanings due to their importance as a source of supply and power generation, among many other activities related to economic dynamism in the area of influence of their facilities (PHUONG; SHRESTHA; CHUONG, 2017; MORRIS, 2020; THOMAS et al., 2020).

Spatio-temporal models result from the need to fill spatial and temporal voids arising from the impossibility (of surveying every single area directly) of working with direct field survey. It is an alternative based on evidence and structured by means of continuous variables and considered most important, being supported by data collected directly and indirectly, and complemented by different modes of verification in the field (COLMAN et al., 2018; CORRÊA; CRUZ, 2010; EZZAOUINI et al., 2020; HARMON et al., 2019; MITASOVA et al., 1996). Although these are predictive models, with eventual discrepancies in relation to the reality that can be observed in the field, when applied to large areas, they become significant because the spatial and temporal coverage implies in efficiency gains. The erosive processes that occur on the earth's surface are extremely complex and still not sufficiently understood, making their quantitative prediction important for area evaluation, especially when large areas are analyzed (MITASOVA et al., 2013).

Among the sedimentological models most widely used in most countries, the Modified Universal Soil Loss Equation (MUSLE) can be highlighted, which after several adaptations, presents wide application and satisfactory performance for the most diverse environmental conditions (AREKHI; SHABANI; ROSTAMIZAD, 2011; BENAVIDEZ et al., 2018; SADEGHI et al., 2014). This is a model designed to estimate soil losses per rainfall event. Its development began in the 1960s by the Soil Conservation Service of the United States Department of Agriculture (SCS - USDA) and since then has been improved, as well as modified for various geographical conditions (KITAHARA et al., 2002). When properly applied, this equation allows the identification of areas that are potentially erodible and, consequently, prone to sediment generation (SILVA, 2004). It helps in the determination of the most adequate management and conservation practices aiming at the reduction of soil loss.

Considering the above, the present work aims to estimate and relate the spatial variability of soil loss with the Connectivity Index (CI) of sediments in the basin's contribution area, as well as to evaluate the result of the interaction of these two important variables in the configuration of possible critical areas regarding the generation and transport of sediments in a hydrographic basin tributary to the São Firmino stream in the municipality of Cristalina - GO.

MATERIALS AND METHODS

LOCATION AND CHARACTERIZATION OF THE STUDY AREA

The research area comprises a watershed on the right bank of the São Firmino river, a tributary of the São Marcos river, in the municipality of Cristalina in the State of Goiás - Brazil, as shown in Figure 1. The higher parts, in residual and flat forms, are supported by Ferruginous Detrital-Lateritic Coverings, composed of agglomerates, laterites, sand and clay. The intermediate and steeper segments are associated with the dissection of the Canastra Group - Paracatu Formation with the predominance of rocks such as sericite phyllite and carbonaceous phyllite. These segments transition to the lower, flatter and already concaved parts, with the occurrence of Alluvial Deposits composed of gravel and sand (MOREIRA et al., 2008).

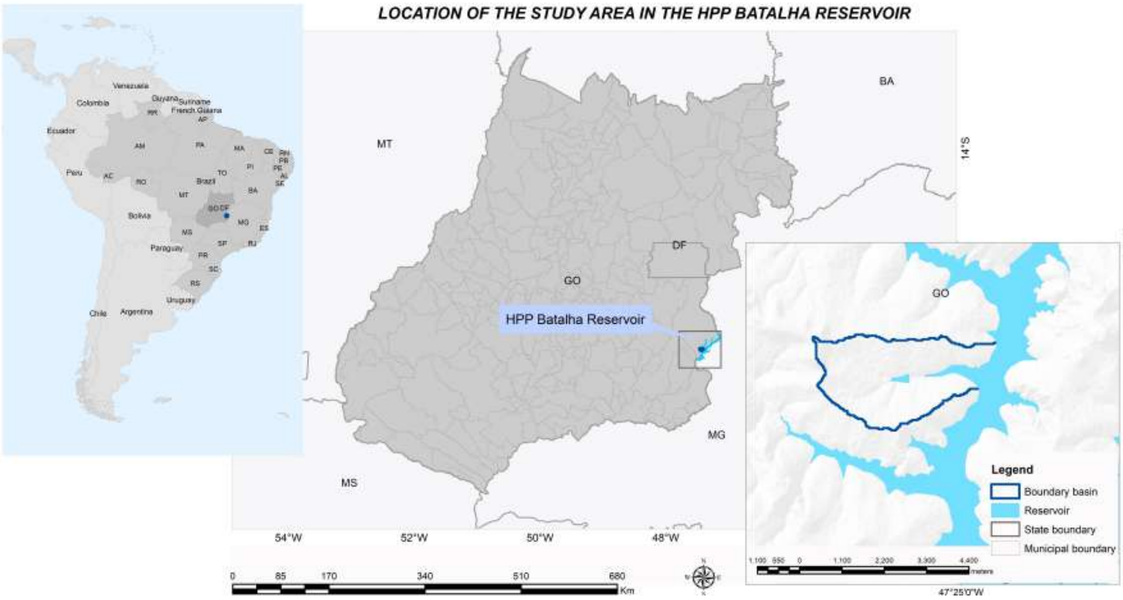

Figure 1 - Location of the research area on the right bank of the São Firmino stream, a tributary of the São Marcos river basin in Cristalina - GO.

Correlating the reading and interpretation of the works of Resende (2016), Rosa et al. (2018) and IBGE (2018), with morphometric and morphographic variables of the terrain, it is noteworthy that in the higher and residual areas there is a predominance of the Plintossol (Concretionary Petric), with a texture varying from clayey to gravelly, followed, sometimes, by steep segments with the occurrence of Leptosol (Dystrophic Lithic) of sandy to gravelly texture. In lower positions, there are flatter areas with the predominance of Ferralsol (Yellow-Red) and, in greater occurrence, Ferralsol (Red), both Dystrophic and with a texture varying from clayey to very clayey. Going to even lower and more dissected levels, there is the predominance of the Cambisol (Dystrophic Haplic) of clayey to medium texture, sometimes substituted, when in steeper segments, by the Leptosol (Dystrophic Lithic), also of sandy to gravelly texture, occurring in more isolated areas. Finally, there is the predominance of Fluvisol (Dystrophic) along the plain with a low altimetric gradient and connected to the reservoir.

This is a basin that, although not very developed, presents a tendency to elongation, whose evolution occurs through indentations in the form of stepped amphitheaters resulting from the association between the lower altimetric gradient in the longitudinal direction and high slopes in the transversal direction. According to Monteiro (1951), the area's climate can be characterized as semi-humid tropical, with a dry winter, rainfall of 5.3 mm to 6.9 mm, from June to July, and an average temperature of 24.6 °C during the same period. The summer is hot and rainy, with temperatures around 30.3 °C in October and accumulated precipitation ranging from 243.1 mm to 275.2 mm in January and December (SILVA; SANTANA; PELEGRINI, 2006). It comprises an important area in which there is intense use by agriculture, especially precision agriculture, with emphasis on the high number of irrigation pivots (PEREIRA JÚNIOR; FERREIRA; MIZIARA, 2017).

METHODOLOGY

The evaluation of the spatial variability of sediment generation and connectivity comprised the bivariate spatial relationship between the estimates of soil loss, resulting from the application of the Modified Universal Soil Loss Equation (MUSLE), and the Connectivity Index (CI) of the slopes with the drainage channel. The first indicates the generation capacity, while the second allows assessing the transport capacity of sediments generated upstream of a point, as well as its continuity downstream, which may present higher probability of movement or deposition. Therefore, the application of both procedures considered the spatial variability of non-cumulative factors, such as land cover and land use conditions and soil erodibility, in addition to the cumulative factors resulting from the effect of variables, such as flow length and contribution area. These imply the behavior of dependent variables, such as flow rate and flow intensity. This adaptation sought to consider the hydrosedimentological contribution of each specific area, the aforementioned cumulative effects, from upstream to downstream, as well as to preserve MUSLE application protocols, at a slope scale, preventing the extension of river channels from influencing the results, in particular by overestimating the final values.

SPATIAL VARIABILITY OF SOIL LOSS ESTIMATES

The estimate of soil loss and sediment generation was determined using the (MUSLE), as proposed by Williams (1975); Williams (1981) and Smith et al. (1984). In the present work, this equation was applied considering the spatial variability of the independent and dependent variables, on a slope scale, based on Equation 1:

$$Y = 11.8(Qqp)^{0.56} \cdot K\ LS\ CP \qquad \textit{Equation 1.}$$

where: Y = estimate of soil loss in the rainfall event, in tons; Q = volume in runoff, in m³; qp = peak discharge of the rainfall event, in m³/s; and K, LS, C and P USLE conventional parameters. With this, it is noted that the estimate of soil loss through the Modified USLE tends to be more detailed in space and time, since it is directly related to momentary hydrological conditions, in particular the spatial variability of the volume converted into surface runoff and peak flow.

SPATIAL VARIABILITY OF RUNOFF (Q) AND PEAK DISCHARGE ESTIMATES - QP

The volume converted into surface runoff (Q) was determined from the product of effective precipitation (Pe) by the specific contribution area. For this purpose, the proposal of the Soil Conservation Service (SCS) was adopted, currently the Natural Resource Conservation Service (NRCS) of the United States Department of Agriculture (USDA) (NRCS, 2004), in determining the effective precipitation or height of the water depth converted into runoff. This proposal consists of the relationship between the precipitation resulting from the pluviometric event and the infiltration capacity of the soil, as shown in Equation 2:

$$Pe = \left[\frac{(P-0.2\,S)^2}{(P+0.8\,S)}\right], \text{ as long as } P >= \text{Ia} = 0.2\,S \qquad \textit{Equation 2.}$$

where: Pe = effective precipitation or height of the resulting water flow, in mm; P = rainfall or pluviometric height resulting from the rainy event, in mm; S = soil infiltration potential, in mm; and Ia => 0.2 S = abstraction or initial loss considered, in mm. As observed in the first part of Equation 2, effective precipitation considers an initial loss corresponding to 20% of the infiltration potential due to interception by vegetation, retentions in micro relief, as well as other forms of wetting of the environment. This implies stating that rainfall events with a total volume of less than 20% of the soil infiltration potential do not provide surface runoff.

For this purpose, the total accumulated precipitation resulting from the pluviometric event considered in the present work was determined using the Intensity - Duration - Frequency (IDF) relationship, proposed by Villela and Mattos (1975), through the equation obtained by Oliveira et al. (2005) for the municipality of Cristalina, through Equation 3:

$$i = \frac{k \times TR^{a}}{(tc+b)^{c}} \Rightarrow i = \frac{878.213 \times TR^{0.2088}}{(t+12)^{0.7600}} \qquad \textit{Equation 3.}$$

where: i = average of maximum precipitation intensities, in mm/h; TR = return time, in years; t = surface runoff concentration time, in min; k, a, b and c are adjustment coefficients specific to the weather station. For this purpose, we considered a return time of 25 years, and a rain time equal to the concentration time of the surface runoff of the referred basin, which was calculated based on the proposal by Watt and Chow (1985) through Equation 4.

$$Tc = 7.68\,(L/Sw^{0.5})^{0.79} \qquad \text{Equation 4.}$$

where: Tc = surface runoff concentration time, in min; L = length of the basin's main flow line, in km; and Sw = average slope gradient of the basin in m/m.

The values of S were estimated based on the values of CN (Curve Number) or Flow Number, as proposed by the NRCS - USDA (2004), as shown in Equation 5.

$$S = \frac{25{,}400}{CN} - 254 \qquad \text{Equation 5.}$$

where: S = soil infiltration potential, in mm; CN = Curve Number, dimensionless; and 25400 and 254 are constants originating from the model. The relationship between cover types and soil use conditions, soil types (Hydrological Groups) and their correspondence in CN values is presented in Tables 1 and 2.

The peak flow (qp) was determined based on the product resulting from the effective precipitation by the contribution area, distributed by the peak time of the hydrograph, which corresponds to the interval between the rainfall and flow peaks, according to Schwab's proposal. et al. (1981), based on Equation 6:

$$qp = 0.0021xPexA/Tp \qquad \text{Equation 6.}$$

where: qp = peak flow of the event, in m³/s; Pe = effective precipitation or portion of precipitation available for surface runoff, in mm; A = contribution area, in ha; and Tp = hydrograph peak time, in hours. In applying this equation, a peak time corresponding to 0.6 of the concentration time for each basin was considered through Equation 7.

$$Tp = 0.6\;x\;Tc \qquad \text{Equation 7.}$$

DETERMINATION OF HYDROLOGICAL GROUPS (GH) AND SOIL ERODIBILITY (K FACTOR)

The Hydrological Groups, as well as the erodibility values of the soils were determined based on the evaluation of soil types, in particular texture and depth.

Table 1 - Soil classes, textures and their correspondence in Hydrological Groups and their Erodibility. * Adapted from, Tucci (2008); Tucci and Marques (2001). **Adapted from Mannigel et al. (2008); Nunes et al. (2022).

Classe de Solo	Texture	Hydrological Group*	K Factor **
Cambisol (Dystrophic Haplic)	Clayey to Mean	C	0.0441
Ferralsol (Dystrophic Red)	Clayey to Very Clayey	B	0.0061
Ferralsol (Dystrophic Yellow-Red)	Clayey	B	0.0081
Fluvisol (Dystrophic)	Mean to Sandy	A	0.0290
Plintossol (Concretionary Petric)	Clayey to Gravel	C	0.0438
Leptsol (Dystrophic)	Sandy to Gravel	D	0.0570

The soil map was prepared from the compilation and review of existing mappings for the area (RESENDE, 2016; ROSA et al., 2018; IBGE, 2018), followed by cartographic adjustment, based on relief morphometry and morphography, as well as additional field surveys. Soil types, their correspondence in hydrological groups and their erodibility are presented in Table 1.

PREPARATION OF THE DIGITAL ELEVATION MODEL AND CALCULATION OF THE TOPOGRAPHIC FACTOR - LS FACTOR

The calculation of the LS factor was performed based on the methodological proposal by McCool et al. (1987). This is an adaptation of the classic proposal of the LS factor derived from MUSLE for land with steeper slopes, thus avoiding overestimation of the results due to higher slopes. Thus, the LS factor was calculated based on Equation 8.

$$LS = (L/22.13)^m (16.8\, sen\, \theta - 0.5) \qquad \textit{Equation 8.}$$

where: L = ramp length, in m; m = dimensionless exponent, which was calculated using Equation 9:

$$m = \frac{sen\theta}{sen\theta + 0.269(sen\theta)^{0.8} + 0.05} \qquad \textit{Equation 9.}$$

where: θ = slope angle, in degrees, i.e. θ = tangent (s/100), where s = slope in %. Thus, Factor S = 3.0 (sin θ) 0.8 + 0.56 (for ramp length less than 4 m); S = 10.8 sin θ + 0.53 (for ramp length greater than 4 m and slope less than 9%); S = 16.8 sin θ - 0.5 (for ramp length greater than 4 m and slope greater than 9%). The calculation of the LS factor was applied only along the slopes, so that the river lineaments would not influence the resulting values.

DETERMINATION OF THE LAND USE/LAND COVER AND MANAGEMENT FACTOR (CP), AND CURVE NUMBER (CN)

The mapping of land use and land cover conditions sought to meet the phytophysiognomic patterns of the Cerrado (RIBEIRO; WALTER, 2008), and its correspondence in CP factor values, as adapted from Stein et al. (1987). Oliveira (2012), also tried to contemplate the effects arising from the relationship between precipitation and soil behavior, as proposed by Tucci (2008) and Tucci and Marques (2001), resulting in Curve Number (CN) values. In this method, the CN values vary from 0 (low runoff capacity) to 100 (high runoff capacity). It is noteworthy that the calculation considered the soil in the antecedent moisture condition III (AMC III), which considers a rainfall volume greater than 53 mm in the previous 5 days. For this, the land use and land cover classes were defined based on the interpretation and supervised classification of the MSI (MultiSpectral Instrument) sensor image from the Sentinel-2 satellite, color, 10 m spatial resolution, RGB 483 composition, referring to June 8th, 2020. The association of hydrological groups (Table 1) with land use and land cover conditions and their correspondence in Curve Number as well as CP factor values is presented in Table 2.

Table 2 - Land use and land cover conditions and their respective values, Curve Number and CP factor.
* Adapted from, Tucci (2008); Tucci e Marques (2001). ** Stein et al. (1987); Oliveira (2012).

Classes de cobertura e condições de uso do solo	Hydrological Group				**CP Factor****
	A	B	C	D	
	Curve Number*				
Agriculture - level terracing	60	71	79	82	0.005775
Bare ground - with Conservation	62	71	78	81	0.051365
Bare ground - without Conservation	72	81	88	91	1.000000
Pasture - medium and low transpiration	47	67	81	88	0.005000
Reforestation - medium transpiration	36	60	70	76	0.016350
Forests - dense and high transpiration	26	52	62	69	0.000040
Savannas - medium transpiration	36	60	73	79	0.000700
Permanent grasslands - mean transpiration	36	60	73	79	0.000000
Water	0	0	0	0	0.000000

FLOW AND SEDIMENT CONNECTIVITY INDEXES - IC

The Index of Connectivity – IC (flow and sediment connectivity indexes) was based on the probability of flow between cells, whose gradient allows the formation of lineaments in the data matrix. To this end, it was calculated based on the proposal of Borselli, Cassi, and Torri (2008), who correlated data observed in the field with estimates obtained via georeferenced spatial data modeling, which was also analyzed and implemented in a GIS environment by Cavalli et al. (2013) and also applied by Mishra et al. (2019), through Equation 10:

$$IC = log_{10}\left(\frac{Dup}{Ddn}\right) = log_{10}\left(\frac{\bar{W}\,\bar{S}\,\sqrt{A}}{\sum_{i=0}^{i=n}\frac{dn}{Wn\,Sn}}\right) \qquad \textit{Equation 10.}$$

where: Dup corresponds to the potential for sediment carriage produced by the slope above the nth cell of the data matrix, and Ddn corresponds to the potential for slope arrest and/or retention below cell n. The relationship between the two defines the connectivity index (IC). From the components upstream of cell n we have W = average of the roughness index, dimensionless (in this case the USLE CP factor was used); S = average of the gradients, in m/m, both from the contribution area (A in m²) upstream of cell n. From the downstream components we have dn = flow length, in m; Wn = roughness index; and Sn = slope gradient, both referring to cell n of the data matrix. As for the minimum contribution area, this resulted from the cell size or from the spatial resolution of the matrix set used (900 m²). The relationship between the square root of the contribution area and the upstream flow length makes the IC dimensionless. Thus, according to Borselli, Cassi and Torri (2008), the connectivity index can vary from -∞ to +∞, having its increase conditioned by successive values of IC +.

RESULTS AND DISCUSSION

MORPHOMETRIC CONDITIONING CHARACTERISTICS AND THEIR RELATIONSHIP TO SOIL TYPES AND SEDIMENT DYNAMICS

The morphometric configuration of the basin under study indicates a more pronounced evolution in the longitudinal direction, in view of the greater elongation provided by the retreat of the headwaters, where the greater gradient was in the transverse direction to the drainage channel. The gradient map (Figure 2a) shows the influence of the three geological units on the slope inclination pattern.

The transition from the lithologies of the Detrital-Lateritic Covers (upper portion) and the Canastra Group - Paracatu Formation (intermediate portion) to the Alluvial Deposits is marked by steeper slopes. This transition indicates differences in the behavior of the materials that make up each unit due to different weathering processes.

Consequently, less developed soils occur in these environments Leptsol (Dystrophic) and Cambisol (Haplic), while a specific unit tends to result in less steep slopes and thicker soils such as Ferralsol (Dystrophic) and Ferralsol (Yellow-Red).

One of the main differences consists of younger soils coming from natural erosion, while those more developed, and therefore thicker, imply greater sediment generation when poorly managed. In this sense, the steep areas (Figure 2a), associated with shorter flow lengths (Figure 2b), are more favorable to flow connectivity, considering the shorter time it takes for runoff (Figure 2c) to reach the drainage channel. On the other hand, the steep and more distant portions, despite the longer runoff concentration time, can also contribute with the transfer of sediments through flow lineaments, which can be enhanced by the increasing specific contribution area (Figure 2d).

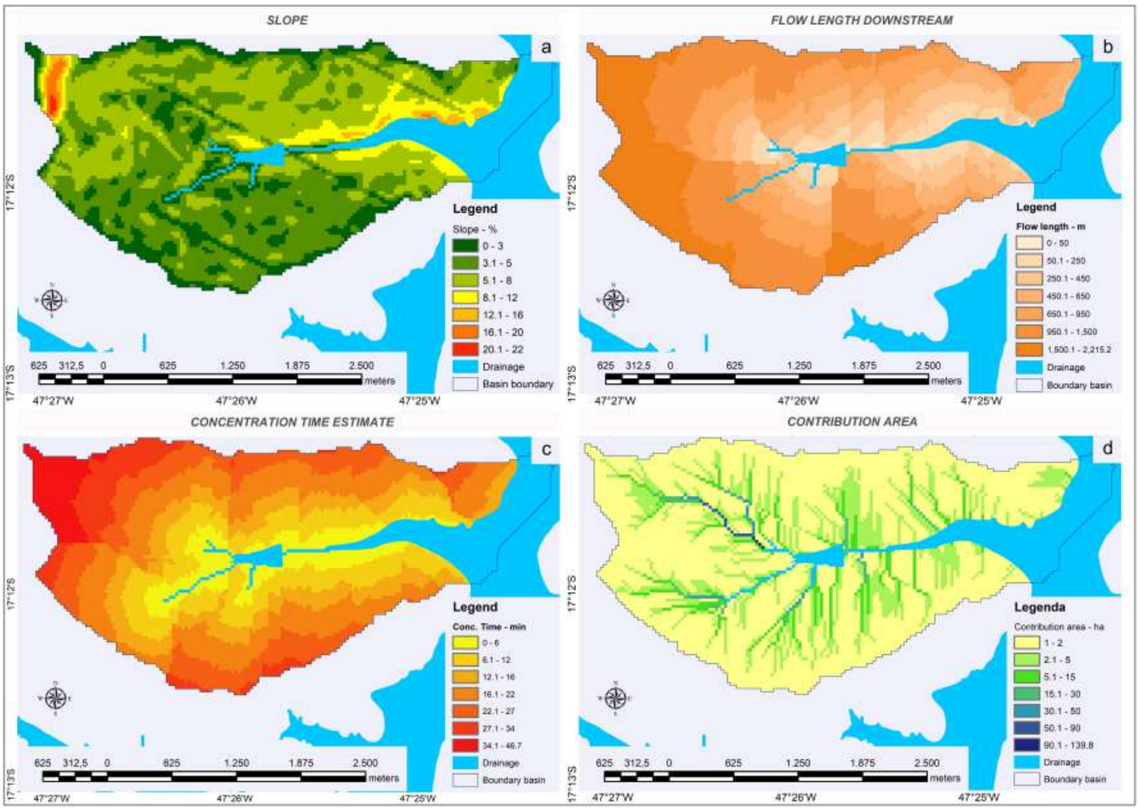

Figure 2 - gradient (part a); downstream flow length (part b); concentration time estimate (part c); and contribution area (part d) maps.

Regarding hydrological dynamics, the association of transition areas, with higher gradients, as well as younger soils (Figure 3b), tends to result in environments with higher CN (Figure 3c), and therefore with lower infiltration potential (Figure 3d).

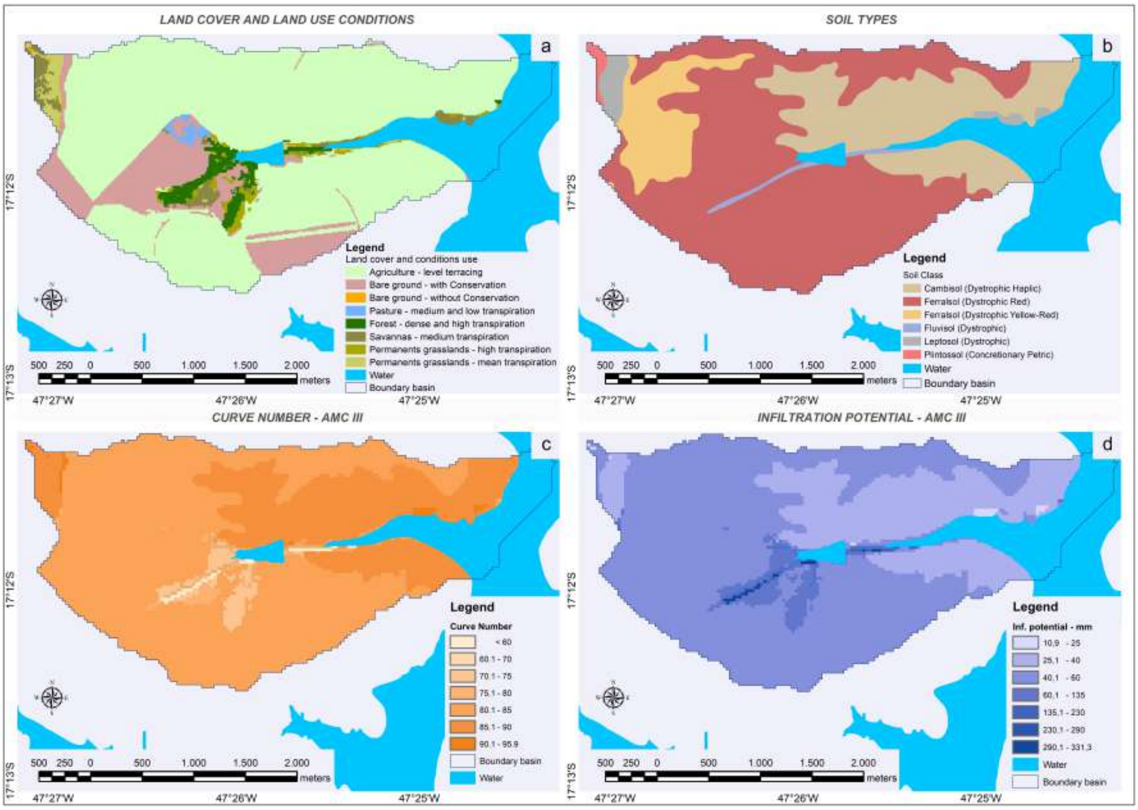

Figure 3 - Land use/land cover (part a); soil types (part b); spatial variability of CN (c); and infiltration potential (d) maps.

These environments, besides the thin soils, have a high potential for acceleration and intensification of flows, which converge laterally and deepen linearly, increasing the likelihood of erosion processes in segments characterized as a colluvial ramps, which show little resistance to the kinetic energy arising from the intensification of surface runoff upstream.

The environments with lower values of CN and higher infiltration potential are located in the lower portions. They are part of the same lithological unit (alluvial deposits), with low gradients, thicker soils due to the larger volumes of detrital materials deposited and, mainly, remnants of vegetation. Although these environments are favorable to infiltration processes and sediment deposition, the absence of vegetation can allow the transfer directly to the fluvial channel or reservoir.

RAINFALL-RUNOFF RATIO, SOIL ERODIBILITY, TOPOGRAPHIC FACTOR, LAND COVER, AND CONSERVATION PRACTICES IN SEDIMENT INPUT ESTIMATES

Considering the relationship between flow lengths and average basin slope gradient and its resulting runoff concentration time (WATT; CHOW, 1985), we arrived at an estimate of 46.7 minutes for the entire basin area which could contribute to the outflow, resulting in a maximum flow convergence. Considering this time in the Intensity-Duration-Frequency relationship, a maximum precipitation intensity of 77.56 mm/h was reached, which resulted in an estimated pluviometric height of 60.36 mm. This scenario, given the variability of the infiltration potential of the soils, resulted in an effective precipitation ranging from 40.1 mm to 49.4 mm in areas with a greater gradient and less developed soils. In areas of lower gradients, with more developed soils, Ferralsol (Dystrophic Red and Yellow-Red), values ranged from 5 mm to 40 mm. Adjacently, there are environments with lower gradients, with deeper soils, resulting from alluvial processes, which condition Effective Precipitation to below 5 mm, as illustrated in Figure 4a.

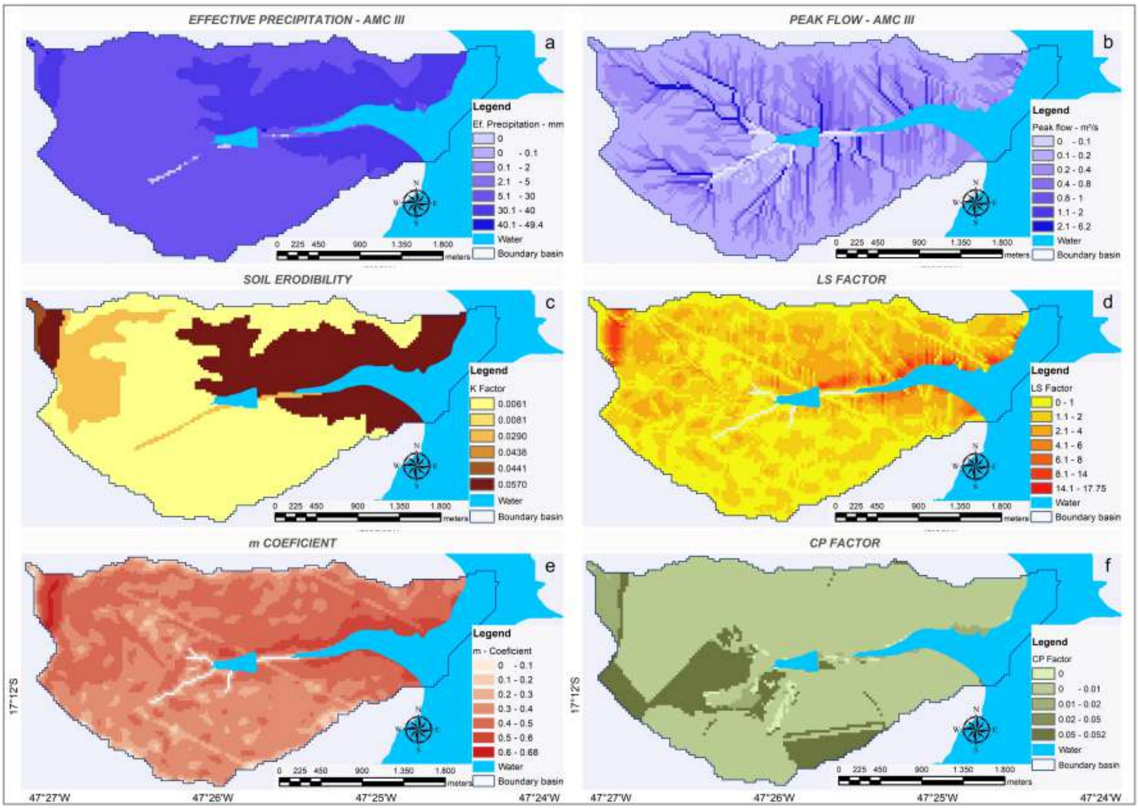

Figure 4 - Spatial variability of MUSLE factors: effective precipitation (a); peak flow (b); soil erodibility (c); m coefficient (d); LS factor (e); and CP factor (f) maps.

The spatial variability of the effective precipitation associated with the increasing specific contribution area resulted in a predominant peak flow of 0.26 m³/s, which can exceptionally reach 6.2 m³/s at the point of higher flow concentration (Figure 4b), located in the segment under the effect of the maximum specific contribution area (139.8 ha). When related to the soil erodibility map (Figure 4c), it is worth mentioning the incidence of flows with a rate up to 0.8 m³/s on soils with high K factor, such as Cambisol (Dystrophic Haplic) with a medium-texture, and Leptsol (Dystrophic) with textures varying from sandy to gravelly. The high potential for soil loss is confirmed in areas marked by high peak flows, as well as high LS factors, whose highest values are concentrated near the fluvial plain or the drainage channel. Situations such as these configure a high potential for soil loss, especially in segments that mark the transition from areas with agricultural use to environments with little vegetation remaining and without conservationist practices, therefore, with a high CP factor, as can be observed both near the channel and the reservoir (Figure 4f).

BIVARIATE RELATIONSHIP BETWEEN ESTIMATED SEDIMENT INPUT AND CONNECTIVITY INDEX

The result of the spatial variability, in particular the cumulative effect of the MUSLE conditioning variables as well as the CI along the slopes can be seen in Figure 5.It can be seen that the estimates of soil loss are more accentuated from the intermediate segments of the slopes, intensifying as a result of the increase in the LS factor, which reaches its maximum values near the drainage channel or the reservoir. The maximum estimate of sediment contribution reaches, exceptionally, 25.54 tons in the segment with the largest specific contribution area, which provides maximum concentration of runoff volume and peak flow, associated with the predominance of high CP factor values. Besides this situation, it is also worth mentioning the higher occurrence of areas with soil loss estimates between 1 and 10 tons.

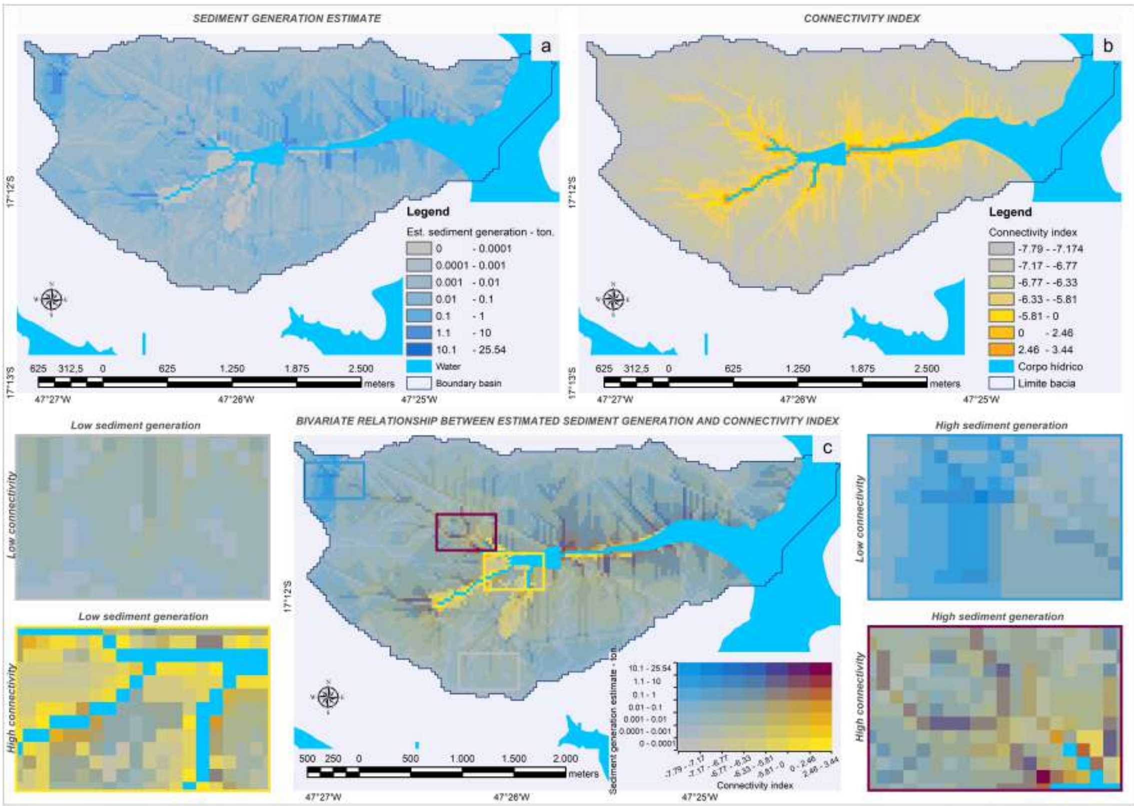

Figure 5 - estimated sediment generation (part a); connectivity index (part b); and bivariate relationship (part c) maps.

This loss starts in the intermediate segments and goes to the vicinity of the plain. This loss is also associated with more intense flow lineaments. These situations, even though they are eventually followed by segments with low soil loss estimates, indicate critical areas in terms of sediment generation and input. This is because these segments are spatially correlated to those with maximum connectivity index of the slopes with the drainage channels, as illustrated in Figure 5b, which implies the cumulative effect and, consequently, sediment transfer from upstream to downstream.

Based on the same figure it is possible to see that these environments are eventually succeeded by segments with low soil loss estimates. These environments correspond to the fluvial plain, which is characterized be a reduction in gradient, forming concave segments and, consequently, a lower LS factor. However, it is noteworthy that these same environments are under the effect of intense upstream surface runoff, which implies a high connectivity index. This suggests that these intense flows end up mobilizing the sediments naturally deposited along the plains, moving them along the drainage channel or reservoir.

In this sense, it is understood that the potential for soil loss and sediment input in hydrographic systems should be interpreted under a dynamic perspective, considering the specific character of each model used. One is intended to estimate disaggregation and, consequently, soil loss, while the other indicates the greater or lesser ease of mobilization of the sediments generated. Considering the above, it is understood that the areas marked in brown, as well as those marked in yellow and immediately preceded by segments in blue are considered critical areas as to the generation and contribution of sediments to the drainage channel or reservoir.

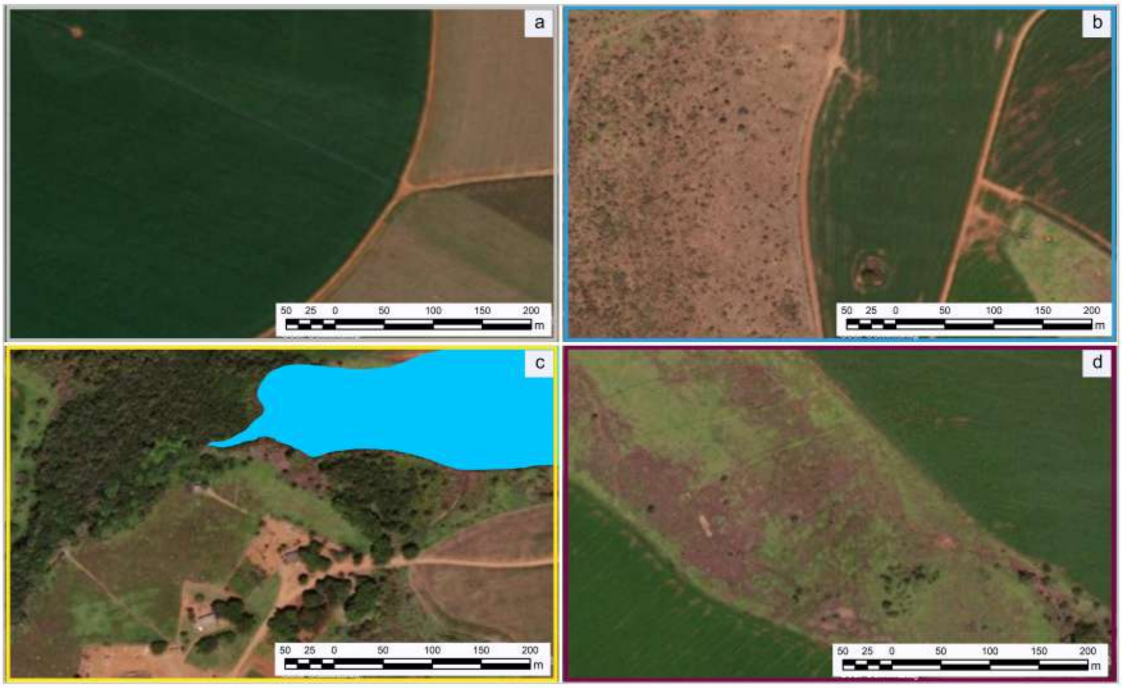

Figure 6 - representative images of the four main situations in the basin under study: low sediment generation and low connectivity (part a); high sediment generation and low connectivity (part b); low sediment generation and high connectivity (part c); and high sediment generation and high connectivity (part d).

Figure 6 presents the situation of each environment in greater detail in terms of cover, management practices and evidence of erosive processes. The rectangle indicated with low soil loss and low sediment connectivity index is characterized by low flow concentration, clayey soils, low LS factor, considerable distance, and therefore longer travel time to the channels or reservoir, and its use is by agriculture and good management practices (Figure 6a). The environment representative of high soil loss and low connectivity index is marked by a steeper flow, poorly developed soils, high LS factor, high distance and travel time to the channel and reservoir, with the condition of exposed soil (Figure 6b). As for the environment with low soil loss and high connectivity index, it is marked by a reduced flow as a result of the plain with remnants of vegetation, deeper soils as a result of accumulation of materials, low LS factor, and immediately near the drainage channel as well as the reservoir (Figure 6c). The segment marked by both high soil loss and high connectivity index is characterized by having a large contributing area and, consequently, high flow intensity, soils with erodibility ranging from medium to high, LS factor ranging from medium to high, being near the drainage channel or the reservoir, and having degraded vegetation or in pasture condition (Figure 6d).

CONCLUSION

The relationship between the spatial variability of the estimates of soil loss and the connectivity index points out, with considerable precision, the occurrence of areas with distinct levels of criticality in terms of sediment production and contribution. In dealing with a bivariate relation that represents two aspects of great importance in the production and contribution of sediments, the same must be interpreted under a dynamic perspective of each area with its segments, both upstream and downstream, which condition the disaggregation and displacement of sediments. The results reinforce the need for monitoring of management practices in the areas of greatest estimated sediment production, as well as the replenishment of vegetation in the nearest plains, or the installation of green belts in the vicinity of the edge of the maximum quota of the reservoirs, with the purpose of minimizing the arrival of sediments generated upstream.

The evaluation of the spatial variability of the estimates of sediment production and connectivity allows the representation of two very important processes in a single plane of information. In this way, it provides a more complete, detailed, dynamic and, therefore, more propitious understanding for decision making. This is true even in the case of large contribution basins, allowing for the planning and application of resources in priority areas and, consequently, the increase in the possibility of more efficient interventions.

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REFERENCES

AREKHI, S.; SHABANI, A.; ROSTAMIZAD, G. Application of the modified universal soil loss equation (MUSLE) in prediction of sediment yield (Case study: Kengir Watershed, Iran). Arabian Journal of Geosciences. v. 5. n. 6. p. 1259 - 1267. 2011. https://doi.org/10.1007/s12517-010-0271-6.

BENAVIDEZ, R. et al. A review of the (Revised) Universal Soil Loss Equation (RUSLE): with a view to increasing its global applicability and improving soil loss estimates. Hydrology and Earth System Sciences, v. 22, p. 6059 - 6086, 2018. https://doi.org/10.5194/hess-22-6059-2018.

BORSELLI, L.; CASSI, P.; TORRI, D. Prolegomena to sediment and flow connectivity in the landscape: A GIS and field numerical assessment. Catena, v. 75, p. 268 - 277, 2008. https://doi.org/10.1016/j.catena.2008.07.006.

CAVALLI. M. et al. Geomorphometric assessment of spatial sediment connectivity in small Alpine catchments. Geomorphology, v. 188, p. 31 - 41, 2013. https://doi.org/10.1016/j.geomorph.2012.05.007.

COLMAN, C. B. et al. Diferentes abordagens para estimar a produção de sedimentos em uma bacia hidrográfica tropical. Revista Brasileira de Recursos Hídricos, v. 23, e. 47, p. 1 - 9, 2018. https://doi.org/10.1590/2318-0331.231820170178.

CORRÊA, C. M. C.; CRUZ, J. Erosão real e estimada através da RUSLE em estradas florestais, em relevo ondulado a fortemente ondulado. Revista Árvore. v. 34, n. 4, p. 587 - 595, 2010. https://doi.org/10.1590/S0100-67622010000400003.

EZZAOUINI, M. A. et al. Comparison of the MUSLE model and two years of solid transport measurement, in the Bouregreg Basin, and impact on the sedimentation in the Sidi Mohamed Ben Abdellah Reservoir, Morocco. Water, v. 12, n. 1882, p. 1-27, 2020. https://doi.org/10.3390/w12071882.

HARMON, B. A.et al. s.sim.terrain 1.0: a landscapes evolution model with dynamic Hidrology. Geoscientific Model Development. v. 12, p. 2837-2854. 2019. https://doi.org/10.5194/gmd-12-2837-2019.

IBGE - Instituto Brasileiro de Geografia e Estatística. Mapeamento de recursos naturais do Brasil escala 1:250.000. Documentação técnica geral, 2018, 8 p. Disponível em . Acesso em 10 fevereiro 2021.

PEREIRA JÚNIOR, L. C.; FERREIRA, N. C.; MIZIARA, F. A expansão da irrigação por pivôs centrais no estado de Goiás (1984 - 2015). Boletim Goiano de Geografia, v. 37, n. 2, p. 323 - 341, 2017. https://doi.org/10.5216/bgg.v37i2.49158.

KITAHARA, H. et al. Application of Universal Soil Loss Equation (USLE) to Mountainous Forests in Japan. Journal of Forest Research, v. 5, p. 231 - 236, 2002. https://doi.org/10.1007/BF02767115.

KUMAR, P. S.; PRAVEEN, T. V.; PRASAD, M. A. Simulation of sediment Yeld over Un-gauged stations using MUSLE and Fuzzy Model. Aquatic Procedia, v. 4, p. 1291 - 1298. 2015.

https://doi.org/10.1016/j.aqpro.2015.02.168.

LIU, C. et al. Sediment Problems and Strategies for their Management - Experience from several large river basins. International Hydrological Programme - UNESCO. Paris: UNESCO, 2017. 16 p.

MANNIGEL, A. et al. Fator erodibilidade e tolerância de perda dos solos do Estado de São Paulo. Acta Scientiarum Agronomy, v. 24, n. 5, p. 1335 - 1340. 2002. https://doi.org/10.4025/actasciagron.v24i0.2374

MCCOOL, D. K. et al. Revised slope steepness factor for the Universal Soil Loss Equation. Transactions of the American Society of Agricultural and Biological Engineers - ASAE. v. 30, n. 5, p. 1387–1396. 1987. https://doi.org/10.13031/2013.30576.

MISHRA, K. et al. Towards the assessment of sediment connectivity in a large Himalayan river basin. Science of the Total Environment. v. 661. p. 251 - 265. 2019. https://doi.org/10.1016/j.scitotenv.2019.01.118.

MITASOVA, H. et al. Modelling topographic potential for erosion and deposition using GIS. International Journal of Geographical Information Systems, v. 10, n. 5, p. 629 - 641, 1996. http://dx.doi.org/10.1080/02693799608902101.

MITASOVA, H. et al. GIS-Based Soil Erosion modeling. In: John F. Shrorder (Ed). Treatise on Geomorfology, v. 3, p. 228-258. San Diego: Academic Press. 2013. http://dx.doi.org/10.1016/B978-0-12-374739-6.00052-X.

MONTEIRO, C. A. F. Notas para o estudo do clima do Centro-Oeste Brasileiro. Revista Brasileira de Geografia, p. 22 - 45, jan - mar, 1951.

MOREIRA, M. L. O. et al. (Orgs.). Geologia do estado de Goiás e Distrito Federal: texto explicativo do mapa geológico do estado de Goiás e Distrito Federal. Goiânia: CPRM; SIC - FUNMINERAL, 2008. 143 p.

MORRIS, G. L. Classification of management alternatives to combat reservoir sedimentation. Water, v. 12, n. 861, p. 1 - 24, 2020. https://doi.org/10.3390/w12030861.

NRCS - National Resources Conservation Service. Estimation of direct Runoff from Storm Rainfall. National Engineering Handbook, chapter 10. Washington D. C: Department of Agriculture, USDA, 2004. 79 p.

NUNES, E. D. et al. Methodological Contribution to the Assessment of Generation and Sediment Transport in Tropical Hydrographic Systems. Water, v. 14, n. 4091, p. 1-15, 2022. https://doi.org/10.3390/w14244091

OLIVEIRA, L. F. C. et al. Intensidade-duração-frequência de chuvas intensas para localidades no estado de Goiás e Distrito Federal. Pesquisa Agropecuária Tropical, Goiânia, v. 35, n. 1, p. 13-18, 2005.

OLIVEIRA, J. S. Avaliação de modelos de elevação na estimativa de perda de solos em ambiente SIG. 2012. 103 p. Dissertação (Mestrado em Agronomia) - Escola Superior de Agricultura Luiz de Queiroz - Universidade de São Paulo, Piracicaba, 2012.

PHUONG. T. T.; SHRESTHA, R. P.; CHUONG, H. V. Simulation of soil erosion risk in the upstream area of Bo River watershed - Chapter 6. In: SHIVAKOTI, G. P. et al. (Ed.). Re-defining diversity and dynamism of natural resource management in Asia. Amsterdam: Elsevier, 2017. p. 87 - 100. https://doi.org/10.1016/B978-0-12-805452-9.00006-0.

RESENDE, M. J. G. Classes de solos dos municípios goianos - 2016. Goiânia: Emater - Agência Goiana de Assistência Técnica, Extensão Rural e Pesquisa Agropecuária, 2016. 57 p.

RIBEIRO, J. F.; WALTER, B. M. T. As principais fitofisionomias do bioma Cerrado. In: SANO, S. M.; ALMEIDA, S. P.; RIBEIRO, J. F. (Edit.). Cerrado: ecologia e flora. Brasília: Embrapa Informação Tecnológica, 2008. Cap. 6, p.151-212.

ROSA, L. E. et al. Atributos para mapeamento digital de solos: o estudo de caso na bacia do ribeirão Arrojado, município de Cristalina - Goiás. In: OLIVEIRA, A. C. (Ed.). Elementos da natureza e propriedades do solo. Ponta Grossa: Atena Editora. 2018. p. 69 - 82. https://doi.org/10.22533/at.ed.653182002.

SADEGHI, S. H. R. et al. A review of the application of the MUSLE model worldwide. Hydrological Sciences Journal. v. 59. n. 2. p. 365 - 375. 2014. https://doi.org/10.1080/02626667.2013.866239.

SCHWAB, G. O. et al. Soil and water conservation engineering. New York: Wiley, 1981. 525p.

STEIN, D. P. et al. Potencial de erosão laminar natural e antrópica na bacia do Peixe-Paranapanema. In: Simpósio Nacional de Controle de Erosão, 4, Marília, 1987. Anais, Marília, p. 105-135.

SILVA, V. C. Estimativa da erosão atual da bacia do rio Paracatu (MG/GO/DF). Pesquisa Agropecuária Tropical, v. 34, n. 3, p. 147 - 159, 2004. https://doi.org/10.5216/pat.v34i3.2308

SILVA, S. C.; SANTANA, N. M. P.; PELEGRINI, J. C. Caracterização climática do estado de Goiás. Goiânia: Secretaria de Indústria e Comércio, Superintendência de Geologia e Mineração, 2006. 133 p.

SMITH, S. J. et al. Prediction of sediment yield from Southern Plains Grasslands with the Modified Universal Soil Loss Equation. Rangeland Ecology & Management Journal. v. 37. n. 4, p. 294-297. 1984.

THOMAS, K. et al. Evaluation of the SEdiment Delivery Distributed (SEDD) model in the Shihmen Reservoir Watershed. Journal Sustainability, n. 12, v. 6221, p. 1 - 22, 2020. https://doi.org/10.3390/su12156221.

TUCCI, C. E. M.; MARQUES, D. M. L. da M. Avaliação e controle da drenagem urbana. Porto Alegre: Ed. UFRGS, 2001. 558 p.

TUCCI, C. E. M. Águas urbanas. Estudos avançados, São Paulo, v. 22, n. 63, p. 97-112, 2008.

VILLELA, S. M.; MATTOS, A. Hidrologia Aplicada. São Paulo: McGrawHill do Brasil. 1975. 245 p.

WATT, W. E.; CHOW, K. C. A. A general expression for basin lag time. Canadian Journal of Civil Engineering. v. 12, n. 2, p. 294-300.1985. https://doi.org/10.1139/l85-031

WILLIAMS, J. R. Sediment-yield prediction with universal equation using runoff energy factor. In: USDA-ARS, ed. Present and prospective technology for predicting sediment yield and sources. Washington, 1975. p. 244 - 252.

WILLIAMS, J. R. Testing the modified Universal Soil Loss Equation. In: Proceedings of the Workshop on Estimating Erosion and Sediment Yield on Rangelands. Agricultural Reviews and Manuals - W-26. Arizona: USDA, 1981. p. 157-164.