Revista Brasileira de Recursos Hídricos
Brazilian Journal of Water Resources
Versão On-line ISSN 2318-0331
RBRH, Porto Alegre, v. 21, n. 4, p. 728-741, out./dez. 2016
Scientific/Technical Article

http://dx.doi.org/10.1590/2318-0331.011616029

Water erosion vulnerability and sediment delivery rate in upper Iguaçu river basin – Paraná

Vulnerabilidade à erosão hídrica e taxa de aporte de sedimentos na Bacia Hidrográfica do Alto Rio Iguaçu – PR

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Received: February 24, 2016 - Revised: May 19, 2016 - Accepted: June 30, 2016

ABSTRACT

Soil erosion is one of the most striking environmental degradation processes, which its mapping and assessment is an important tool for management activities and natural resource management in river basins, allowing managers to implement policies and sustainable land use occupation. This work aimed to apply the Revised Universal Soil Loss Equation (RUSLE) in a GIS environment in the upper Iguaçu river basin, located at Paraná State, in order to assess the vulnerability to water erosion as well as the concentration of dissolved solids in suspension to estimate the solid discharge and sediment delivery rate, allowing the identification of more susceptible areas to water erosion. The results showed that over 23.52% of the upper Iguaçu river basin presented soil losses below 2.5 t ha^{-1} yr^{-1}, meaning current low potential for erosion. Regarding the solid discharge, the basin has values ranging from low to very high, also leading to high values for sediment delivery rate. The identification of risk areas associated with accelerated erosion, carried out in this study provide important information for measures associated with the management, conservation and planning of land use in the basin, which is highly relevant for predicting development of various scenarios for the state Paraná for its hydroelectric potential.

Keywords: Soils; Geoprocessing; RUSLE.

RESUMO

A erosão do solo é um dos processos de degradação ambiental mais impactantes, no qual seu mapeamento e avaliação consiste em uma importante ferramenta para atividades de manejo e gestão dos recursos naturais em bacias hidrográficas, permitindo aos gestores implementar políticas de uso e ocupação do solo de forma sustentável. O presente trabalho teve por objetivo a aplicação da Equação Universal de Perda de Solo Revisada (RUSLE) em ambiente SIG, na Bacia Hidrográfica do Alto Rio Iguaçu (BHARI), localizada no Estado do Paraná / Brasil, afim de avaliar a vulnerabilidade à erosão hídrica bem como a concentração dos sólidos dissolvidos em suspensão para estimar a descarga solida e a taxa de aporte de sedimentos, permitindo identificar áreas mais suscetíveis à erosão hídrica. Os resultados mostraram que mais de 23,52% da BHARI apresentou perdas de solo abaixo de 2,5 t ha^{-1} ano^{-1}, significando baixo potencial atual de erosão. Em relação a descarga sólida, a bacia apresentou valores variando de baixo a muito alta, levando também a elevados valores para a taxa de aporte de sedimentos. A identificação de áreas de risco associadas à erosão acelerada, realizadas neste estudo, fornecem subsídios importantes para medidas associadas ao manejo, conservação e planejamento do uso do solo nesta bacia, a qual é altamente relevante para predição de desenvolvimento de cenários variados para o Estado do Paraná por seu potencial hidroelétrico.

Palavras-chave: Solos; Geoprocessamento; RUSLE.

INTRODUCTION

Accelerated soil erosion has been widely recognized as an environmental problem related to the use of soil for agricultural and forest-based practices. This affects soil's productive capacity, causing a reduction in its porosity as well as retention capacity and water infiltration, resulting in an increase of surface runoff, from the transportation of sediments and the aggradation of water resources.

As a result, changes in soil coverage, biomass and the hydrological regime in basins tend to occur, affecting the erosion process, as Lee and Lee (2010) and Mello et al. (2015) have suggested, possibly causing alterations in the fluvial geomorphology (GUERRERO et al., 2013).

According to Pandey, Chowdary and Mal (2007), in order to adequately manage a drainage basin, with a goal of natural resource sustainability, it is necessary to have specialized information about the erosion potential of the soil and the production as well as the transportation of sediments. However, modeling the soil erosion process is a complex task due to the diverse interactions that occur among both the active and passive factors influencing the process.

Still, the quantitative evaluation of erosion can contribute to the preparation of possible strategies for drainage basin management in the context of sustainable development. So, in this manner, erosion simulation models, especially distributed models, are useful to evaluate different strategies of soil usage and better the management of soil in drainage basins (BESKOW et al., 2009).

In this context, many efforts have been made to develop and improve models to predict soil loss, which varies from empirical equations like the Universal Soil Loss Equation (USLE) (WISCHMEIER; SMITH, 1978) and its revised version (RUSLE) (RENARD et al., 1991), up to the most sophisticated models, such as the Water Erosion Prediction Project (WEPP) (NEARING; LANE; LOPES, 1994), currently geo-WEPP and SWAT (ARNOLD et al., 1998; GASSMAN et al., 2007). The latter can be physically more efficient than the empirical models but they usually need a high amount of input data, for which, information is frequently not readily available. Furthermore, they are computationally more rigorous, particularly in reference to the soil erosion potential on a medium to large scale, such as in a large drainage basin (WANG et al., 2009).

On the other hand, RUSLE has been extensively used on different scales, principally for the simplicity of its formulation (HUI et al., 2010; WANG et al., 2009). Its evaluation results from many factors that influence the erosive process, which are: rainfall erosivity (R); soil erodibility (K); usage and management of the soil (C); conservational practices (P) and topography (LS), the last-mentioned represented by slope length effects (L) and declivity (S). These characteristics, especially the calculation manner of the LS factor incorporated into the model, allows the application of RUSLE on a large scale (DURÃES; MELLO, 2014).

As all equation factors are able to be specialized, it has been common to use geoprocessing in the evaluation of soil erosion vulnerability. So, in this manner, the tools associated with a Geographical Information System (GIS) can facilitate the the acquisition of topographical factors through derivation of a digital elevation model (DEM), as demonstrated by Wang et al. (2009). With the use of GIS, the complexity of a drainage basin can be understood through its discretization in smaller and more homogenous units, facilitating the understanding of the erosion process.

The Upper Iguaçu River Basin (UIRB) makes up part of a fundamental planning and environmental management unit in the state of Paraná, draining directly to the Itaipu reservoir. In this sense, it is of extreme importance that studies of this nature be developed with the purpose of subsidizing the handling, management, and the use of natural resources due to the strategic importance of this drainage basin for the economy of the state of Paraná and even Brazil, due its hydroelectric potential.

For this reason, the objectives of this work were: to determine the current potential of the soil to suffer water erosion, applying the Revised Universal Soil Loss Equation (RUSLE); to estimate the annual average of solid discharge by way of the hydrosedimentological rating curves; and sediment delivery rate based on the relation between gross water erosion and solid discharge for the studied points

MATERIAL AND METHODS

Study area and its description

The UIRB, with a drainage area of 2,740 km^2, is a tributary of the Iguaçu river that flows into the Paraná River. The basin is located between the geographic coordinates 25° 13' 48" and 25° 49' 48" south latitude and 48° 57' 36" and 49° 41' 24" west longitude. The UIRB includes 26 subbasins, with a mainly flat relief, featuring a great area of natural dale on both banks and forming well-defined floodplains (KNAPIK et al., 2011). The climatic classification of the basin according to the Köppen method is the Humid Subtropical Climate type (Cfb), with hot summers and mild winters and no dry season. The UIRB has its meteorological and atmospheric dynamic conditions influenced by the polar and tropical air masses, with annual average precipitation at 1,500 mm according to Silva, Lermen and Nery (2001) and with average temperature varying from 12.9 °C in the coldest month to 22.5 °C in the hottest month, with annual average of 16.4 °C. Figure 1 shows the location of the said drainage basin in the state of Paraná.

According to the basemap from SUDERHSA (2004), the predominant soils in the basin are the Latosols (42.76%), Argisols (23.47%), Cambisols (12.71%), Gleysols (11.28%), Orgonosol (7.29%), Litholic Neosol (2.26%) and Fluvic Neosol (0.23%). The distribution percentage of each class of soil usage on the UIRB, shown on Table 1, was obtained by satellite imaging from LANDSAT 8 in 2012 with a 30 m resolution. The soils map and soil usage and coverage map can be found in Figure 2a and 2b, respectively.

Table 1. Percentage distribution of the soil types in UIRB.

Soil Use	Area (%)	Soil Use	Area (%)
Outcrops	0.43	Forestry	4.71
Water	17.68	Mining	0.47
Wetland	1.45	Bare Soil	1.04
Grassland	22.42	Urbanization	14.24
Perennial Crop	0.16	Annual Crop	8.11
Native Forest	19.94	Shrubby	9.35

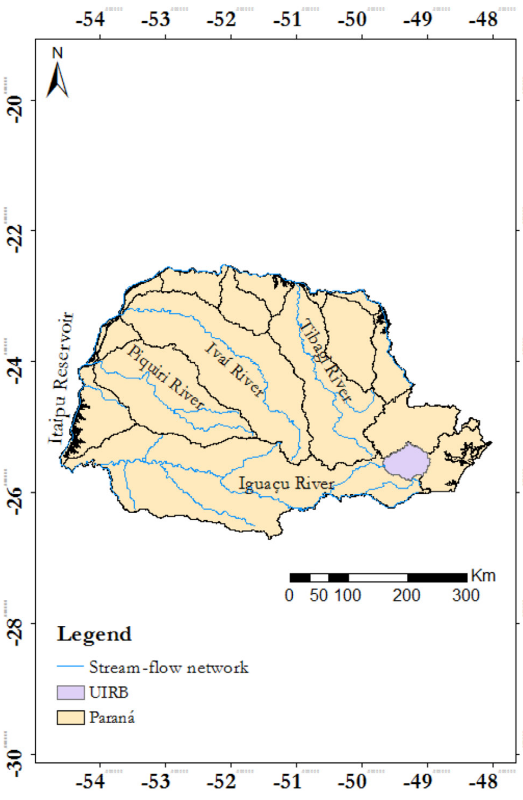

Figure 1. Map of the location of the UIRB in the state of Paraná.

Sediment yield

In order to describe sediment production in the UIRB, monitored sedimentometric data is implemented and made available within the National Water Agency's (Agência Nacional das Águas or ANA) hydrometeorological network. This data allows for the creation of the hydrosedimentological rating curve via the relation between the concentration of solids in suspension and the respective discharge at a given flow measuring section. The daily sediment load, designated as solid discharge (Qss) is, therefore, estimated in relation to the average concentration of solids in suspension and the section's discharge.

The locations used to acquire the rating curve correspond, as well, to the flow measuring and sedimentometric stations, that is to say, for every location there is a history of discharge and solids in suspension. The locations P1, P2, P3, P4, P5, P6 and P7 define the limits of the subbasins sub-1, sub-2, sub-3, sub-4, sub-5, sub-6 and sub-7, respectively. This information is presented in Table 2 and the spatial distribution of the stations is presented in Figure 3.

Application of the RUSLE to the UIRB

In order to characterize the erosion process, it is necessary to analyze the elements of the physical environment that take part in this process. This means that it is essential when working in large areas, to utilize a system in which it is possible to promote a spatial interaction among the data, this process being known

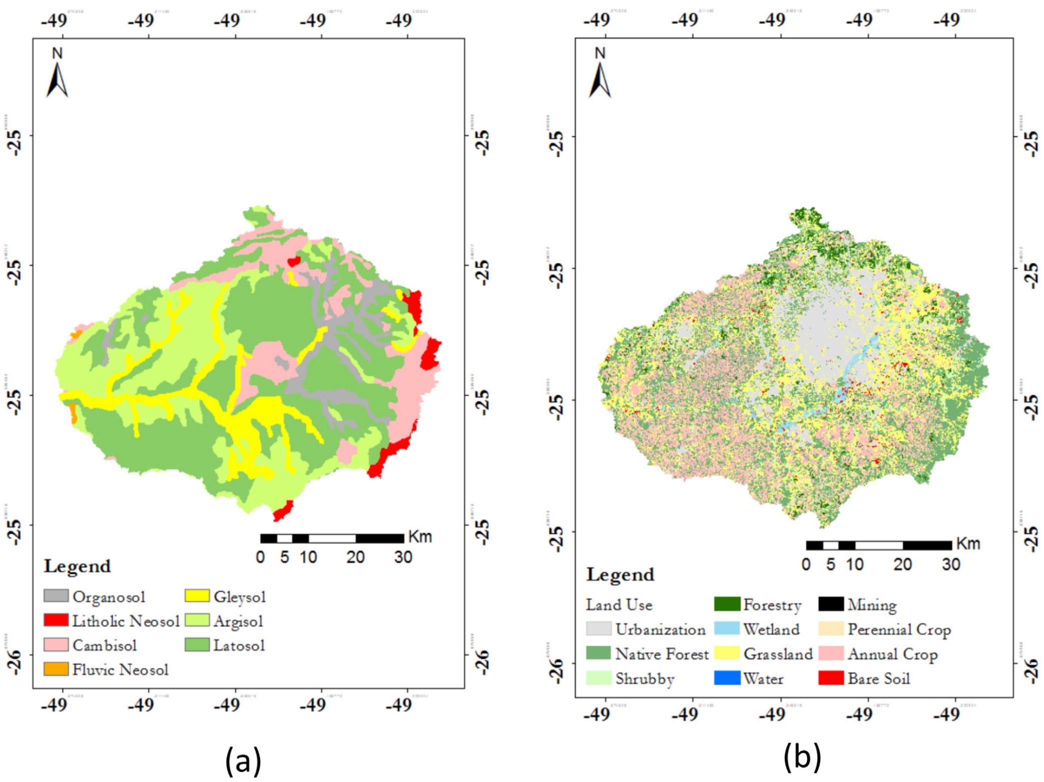

Figure 2. UIRB soil map (a) and soil usage and coverage map (b).

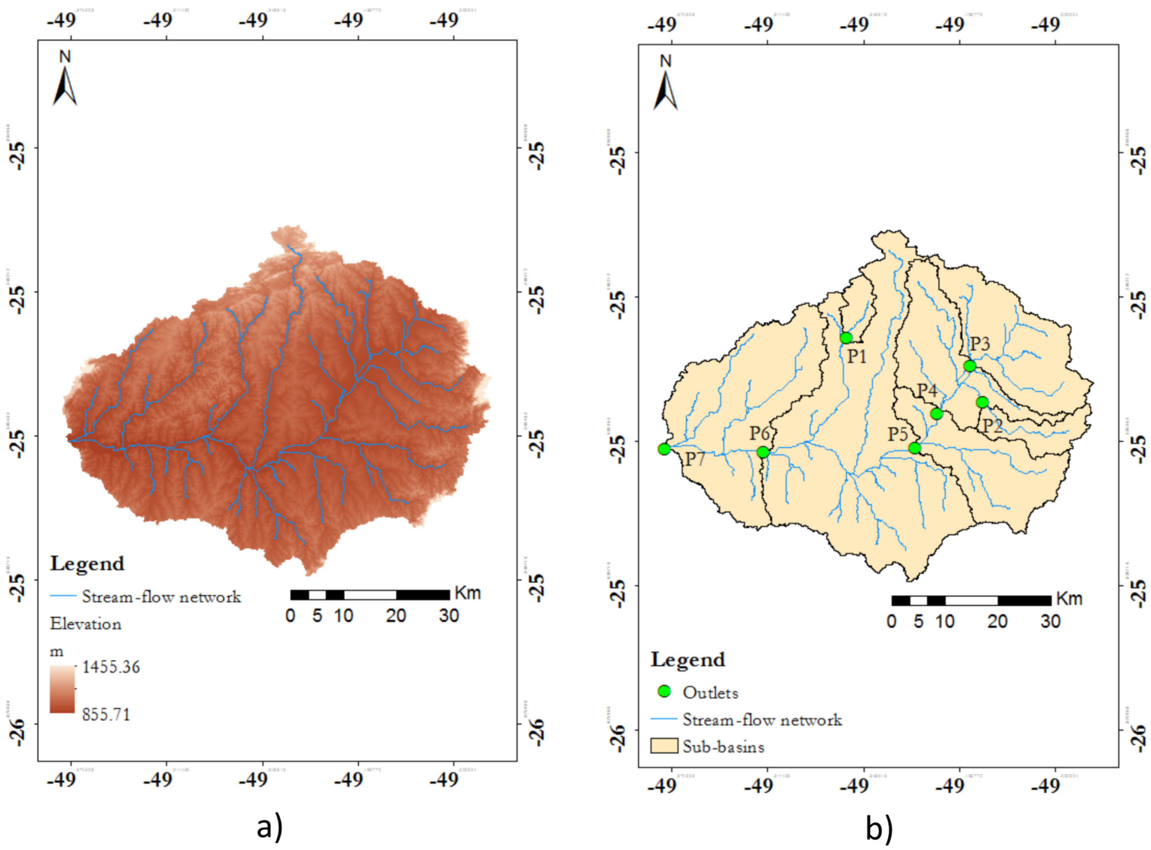

Figure 3. Digital Elevation Model (a) and flow measuring/sedimentometric location (b).

Table 2. Main data for the utilized stations.

Outlet	ANA Code	South Latitude	West Latitude	Series
P1	65021000	25.3547	49.3547	2001-09
P2	65010000	25.5191	49.1466	2002-05
P3	65006075	25.4538	49.1714	2001-10
P4	65013005	25.5280	49.2188	1984-10
P5	65017006	25.5986	49.2592	1993-10
P6	65025000	25.6003	49.5133	1994-10
P7	65028000	25.5886	49.6319	2002-08

as Map Algebra. This study has chosen the RUSLE model and applied it with support of SIG ArcMap® (ESRI, 2004). This model is part of the refinement of the USLE developed by Renard et al. (1991) envisioning its application to scale on drainage basins, stemming from an adjustment of the topographical LS-factor, represented in Equation 1.

$$A = R \cdot K \cdot L \cdot S \cdot C \cdot P \quad (1)$$

where: A represents the annual amount of soil loss (t ha^{-1} yr^{-1}); R is the rainfall erosivity variable (MJ mm ha^{-1} ha^{-1} yr^{-1}); K is the erodibility variable of the soils (t h MJ^{-1} mm^{-1}); L is the length of the slope; S is the declivity variable; C is the the soil coverage variable and P is the conservational practices variable.

R-factor represents the potential of natural rain to cause soil erosion, whose physical definition consists of the kinetic energy of rain with an intensity of up to 30 consecutive minutes (WISCHMEIER; SMITH, 1978). For an estimation of annual average erosivity based on spatial distribution, with an aim to arrange the Map Algebra more precisely, this study has utilized a geographical and statistical model developed by Mello et al. (2013).

The K-factor represents the intrinsic vulnerability to erosion, that is to say, the ease with which soil particles are displaced by the impact of raindrops. The values of K utilized and the respective citations are presented in Table 3.

In light of the existing limitations of the conception of the topographical variable, Moore and Burch (1986) proposed a theoretical basis for determining this variable, which is based on Yang's (1984) unit stream power theory. This theory demonstrates that water on the surface of soil presents a certain amount of energy which is capable of disaggregating and transporting the solid particles, moving them in the direction of the slope and, in turn, representing the LS-factor in complex relief areas, such as is the case with drainage basins, once the model of the specific contribution area has been considered.

In the case of RUSLE, the LS-factor incorporates an important concept associated with the contribution of runoff from upstream cells to downstream ones, embodying a physical significance that is more appropriate to the erosion process than the formulation proposed by Wischmeier and Smith (1978). In this study, the LS-factor calculation procedure proposed by Moore and Burch (1986) was used and applied via the *Raster Calculator Tool* from the program ArcGIS, being represented by the equation below (ZHANG et al., 2013):

$$LS = \left(FA \times \left(CS/22{,}13\right)\right)^{0,4} \times \left(\text{sen}\left(S\right)/0{,}0896\right)^{1,3} \quad (2)$$

where: FA is the flow accumulation from the contribution área; CS is the DEM cell size, corresponding to 30 m of spatial resolution and S is the declivity in radians calculated for each DEM.

In accordance with Wischmeier and Smith (1978), the P variable represents cultural practices that can contribute to soil erosion management. As monitoring soil management and conservational practices are difficult to achieve via satellite imaging, since they represent a small portion of the basin, this variable was considered to be 1. It must be highlighted that this same thought was used in various works, such as those of Pradhan et al. (2012), Vemu and Pinnamaneni (2011), Silva, Montenegro and Santos (2012), Oliveira et al. (2014) and Durães, Mello and Beskow (2016). The values of C used in this study were obtained from the literature presented in Table 4.

Sediment Delivery Rate (SDR)

In order to determine the SDR in the UIRB, the concept presented by Walling (1983) was first used. It defines SDR as the relation between the transported sediment in the basin control section (average value calculated from a history of discharges) and the average potential erosion considering the entire basin area, being configured as dimensionless and expressed in the following manner:

$$SDR = Y / E \quad (3)$$

in which: Y represents sediment transportation, also called average sediment production (t ha^{-1} yr^{-1}), determined in the control section of the water basin; and E is the average potential water erosion (t ha^{-1} yr^{-1}).

To estimate the sediment production in the basin and consequently its delivery rate, it is necessary to first determine the rating curve of discharge based on the data monitored at the UIRB (Table 2), enabling the calculation of the sediment transported through the rating curve. Equations 4, 5, 6, 7, 8, 9 and 10, for the locations P1, P2, P3, P4, P5, P6 and P7, respectively, enable the calculation of the sediment transported through the rating curve (Figure 4).

$$\hat{y} = 15.91x^{1.0792} \qquad R^2 = 0.79 \quad (4)$$

$$\hat{y} = 5.0529x^{0.999} \qquad R^2 = 0.81 \quad (5)$$

$$\hat{y} = 8.1869x^{0.9848} \qquad R^2 = 0.77 \quad (6)$$

$$\hat{y} = 17.006x^{0.9704} \qquad R^2 = 0.87 \quad (7)$$

$$\hat{y} = 18.312x^{0.8866} \qquad R^2 = 0.77 \quad (8)$$

$$\hat{y} = 23.483x^{0.8014} \qquad R^2 = 0.63 \quad (9)$$

$$\hat{y} = 4.0183x^{1.0841} \qquad R^2 = 0.87 \quad (10)$$

Table 3. Soil Erodibility classes occuring in the UIRB.

Soil	K (t h MJ^{-1} mm^{-1})	Source
Argisol	0.033	Sá et al. (2004)
Fluvic Neosol	0.042	Ribeiro and Alves (2008)
Cambisol	0.0508	Araújo, Salviano and Holanda Neto (2011)
Latosol	0.0191	Mannigel et al. (2002)
Litholic Neosol	0.0569	Castro et al. (2011)
Organosol	0.061	Silva and Alvares (2005)
Gleysol	0.0362	Batalha (2006)

Table 4. CP-Factor for soil coverage and usage conditions.

Land Cover	CP-Factor	Source
Outcrops	0	-
Water	0	-
Wetland	0.01	Borges et al. (2012)
Grassland	0.025	Silva (2004)
Perennial Crop	0.25	Bertoni and Lombardi Neto (2005)
Native Forest	0.00013	Martins et al. (2010)
Forestry	0.0026	Martins et al. (2010)
Mining	1	-
Bare Soil	1	-
Urbanization	0	-
Annual Crop	0.29	Ruhoff et al. (2006)
Shrubby	0.0015	Xavier, Silva and Silva (2013)

RESULTS AND DISCUSSION

Figure 5 presents the annual average rain erosivity (R-factor) at the UIRB. It can be observed on the figure that the values range from 5,243 to 6,735 MJ mm ha^{-1} yr^{-1}, the lowest values being found at the highest altitude areas of the basin. This pattern reaffirms the results found by Mello et al. (2013), in which erosivity presents a pattern inversely proportional to the altitude in some parts of the southern region of Brazil. Furthermore, studies developed by Hoyos, Waylen and Jaramillo (2005) in the Colombian Andes region and Nel, Reynhardt and Summer (2010), in South Africa, showed the same pattern seen in the present study.

According to the authors mentioned above, this pattern can be explained by the formation of convective rains, which causes high intensity and short duration precipitation before the clouds reach elevated altitudes, preventing the formation of orographic rains. However, this situation differs from those found by Durães and Mello (2014) and Oliveira et al. (2014), who used the same technique for estimating erosivity, observing that the greatest values

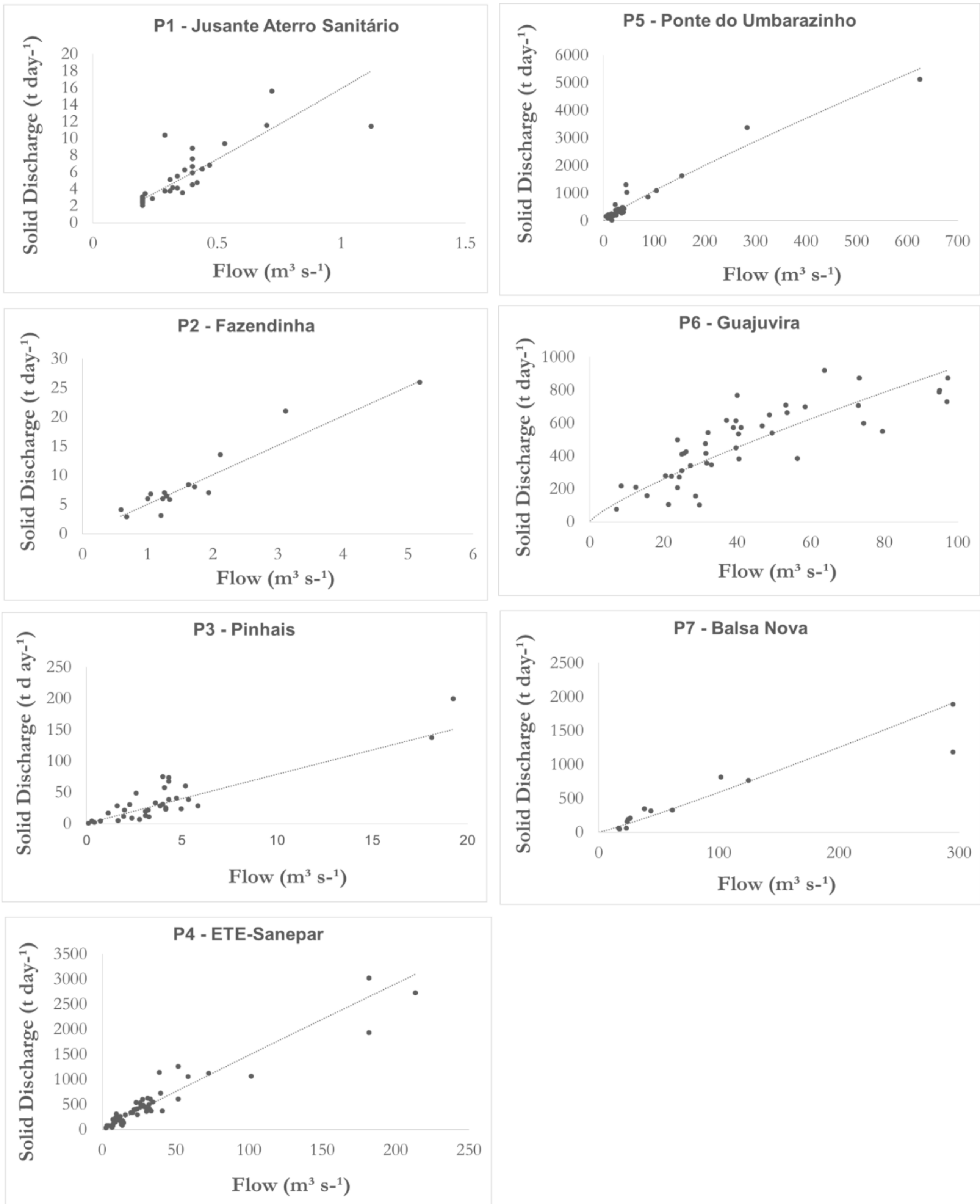

Figure 4. Analyses of the stations' sedimentological rating curves.

were concentrated at the head of the studied basins, showing that the orographical effect is fundamental to the erosive rains pattern. According to the authors, such features can be attributed to the different characteristics and phenomena inherent to the process of rain formation in each region (south and southeast).

Figure 5b shows the map of K-factor. It should be noted in the figure that K is a reflection of the predominant pedological unit in the basin (Latosols), with more than 40% occurrence in the area, showing smaller values of erodibility, which has varied in studies from 0.0088 to 0.0149 MJ mm ha^{-1} yr^{-1}, such as the studies

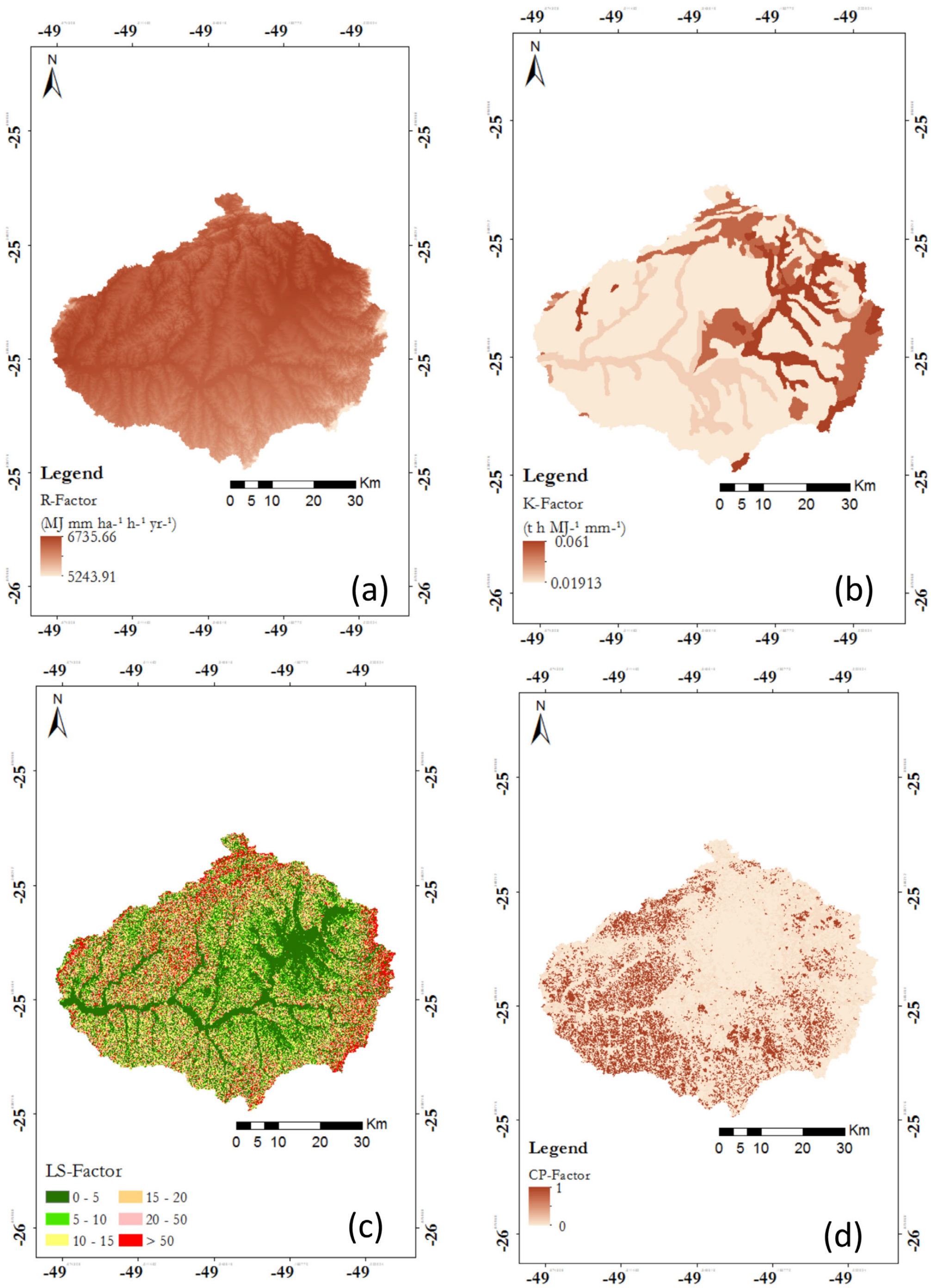

Figure 5. RUSLE variables map: (a) R-factor; (b) K-factor; (c) LS-factor and (d) CP-factor.

of Marques et al. (1997), Mannigel et al. (2002) and Silva et al. (2009). This variation in the results of erodibility in one single soil type demonstrates that this variable represents diverse meanings within the same class, which, in some ways, makes its acquisition not viable via field sampling for areas as extensive as the basin that was analyzed. Likewise, the adoption of values from the literature, to represent erodibility of the predominant soil classes in large basins, becomes viable and applicable.

The spatial distribution of the LS-factor is presented in Figure 5c. Note that 69.49% of the basin shows values of less than 10, representing a low vulnerability associated with the topographical effect. Conversely, 30.51% of areas show high erosion potential, especially in the areas at the head, which represent greater slopes. Additionally, it is important to consider that the lower values are distributed among areas of lower altitude, while the higher values are found in areas of higher altitude. Such results, utilizing the methodology proposed for the calculation of the LS variable, based on Moore and Burch (1986), are more significant when compared to other methods, since it allows the determination of the existing breakage among basin relief units, providing this variable along the slopes.

The spatial distribution of water erosion vulnerability as estimated using RUSLE, is presented in Figure 6, was adapted to conform to the classification proposed by Beskow et al. (2009), and was also applied in the works performed by Durães and Mello (2014) and Oliveira et al. (2014). This type of classification allows a qualitative grouping of water erosion vulnerability into classifications that range from Light to Extremely High. Table 5 shows the distribution of soil erosion classes in the UIRB according to the classification proposal of Beskow et al. (2009).

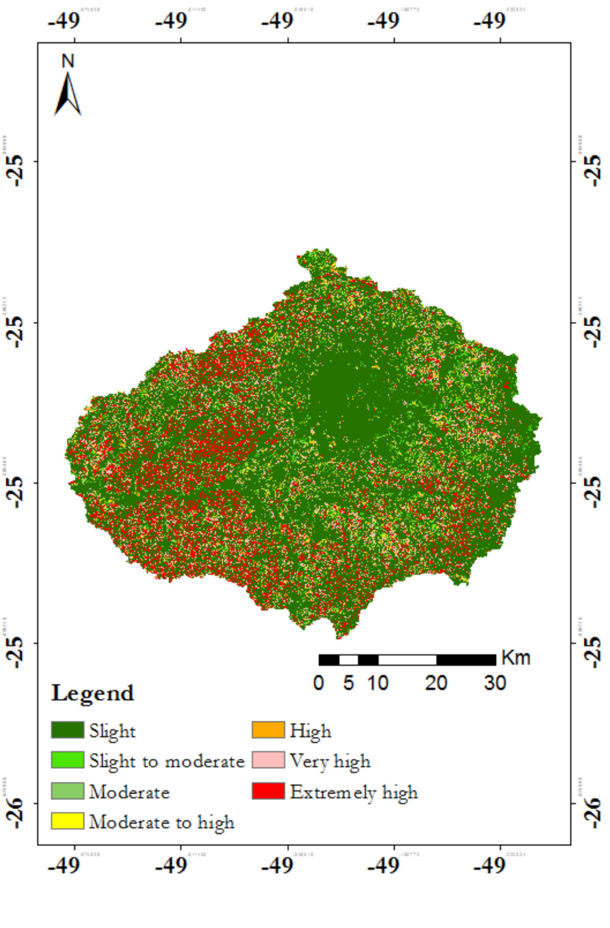

Figure 6. Map of potential water erosion in the UIRB.

It is important to mention that the previous interaction of the variables described in RUSLE concerning the type of vegetation is important, due to the fact that it helps in the understanding of areas that are more vulnerable to water erosion.

The stratification of potential soil loss using Map Algebra via SIG, allows the analysis of impact an activity may have on soil erosion behavior in a determined area of a drainage basin. In agricultural areas, this technique results in a more refined application of erosion management techniques, thereby reducing the pressure on management systems that have been adopted.

The innovation presented in this study, supported by techniques that have already been conceptualized, consists of the application of the multivariate model for estimating the -factor, which was spatially distributed across a resolution of 30 meters. It bears mentioning that the model developed by Mello et al. (2013), showed high accuracy once it was adjusted and tested with a robust set of rainfall erosivity data.

It can be observed that areas with a sharp slope, higher altitudes and forest cover have shown soils with lower vulnerability, demonstrating the importance of vegetational cover for soil protection against the effects of erosion agents.

In this sense, Avanzi et al. (2013), who analyzed the process of water erosion in an afforested basin, noticed that in areas intended for planting eucalyptus there is evidence of greater levels of soil loss than in areas with Atlantic Forest vegetation, which reinforces the role of native cover in soil conservation.

The results presented in Table 6 refer to the variation in soil loss for each tolerance classification in the subbasins (Figure 3 and Table 2) and also show the respective pedological unit.

It can be noticed in the figure that the higher rates of soil loss can be associated with the combination of Argisols covered by annual crops. The losses of soil within the Cambisol and Gleysol classifications can mostly be traced to the presence of exposed soil, fields and perennial crops. It is also important to observe that the Litholic Neosol unit showed lower soil loss rates in relation to its cover being made up of natural forests in preserved areas located at the UIRB head.

For the Latosol classification, losses of less than 10 t ha^{-1} yr^{-1} can be seen in approximately 50% of its area of occurrence, as a result of its low erodibility, showing the intrinsic importance of

Table 5. Simulated soil loss intervals for current soil use in the UIRB.

Soil loss intervals (t ha^{-1} yr^{-1})	Classification	Area (%)
0 to 2.5	Slight	23.52
2.5 to 5	Slight to moderate	8.19
5 to 10	Moderate	8.70
10 to 15	Moderate to high	5.43
15 to 25	High	7.55
25 to 100	Very high	20.01
>100	Extremely high	26.60

Table 6. Water erosion classification sorting as proposed by Beskow et al. (2009) and its distribution percentage by subbasin and soil type.

Sub-basin	Distribution (%) of the soil loss classifications ($t\ ha^{-1}\ yr^{-1}$)						
	0 to 2.5	2.5 to 5	5 to 10	10 to 15	15 to 25	25 to 100	>100
sub-1	67.59	2.39	3.53	2.48	3.20	8.35	12.47
sub-2	75.82	2.47	2.49	1.53	2.43	8.23	7.03
sub-3	20.40	12.35	12.26	7.19	9.75	22.89	15.16
sub-4	26.71	11.57	11.49	6.59	8.74	20.79	14.11
sub-5	24.36	10.07	10.42	6.10	8.16	20.81	20.08
sub-6	20.20	7.99	8.80	5.63	7.86	20.46	29.06
sub-7	18.49	7.28	7.84	5.09	7.29	20.53	33.48
Soil	**Distribution (%) of the soil loss classifications ($t\ ha^{-1}\ yr^{-1}$)**						
	0 to 2.5	**2.5 to 5**	**5 to 10**	**10 to 15**	**15 to 25**	**25 to 100**	**>100**
Arg.	24.39	8.56	7.94	5.79	9.10	35.79	8.43
Fluv. Neos.	61.37	3.26	3.76	2.74	3.51	11.91	13.45
Camb.	22.63	4.77	8.33	5.71	8.42	26.05	24.10
Latos.	25.48	11.52	12.73	8.41	11.57	26.35	3.94
Lit. Neos.	83.05	4.98	1.03	0.78	1.05	2.93	6.17
Organ.	21.60	10.01	12.56	5.40	6.79	20.82	22.82
Gleys.	21.15	7.93	7.43	4.69	7.36	20.50	30.94

the physical attributes of this soil in relation to natural erosion vulnerability, as discussed by Oliveira et al. (2014). The other half can be found in the lowest areas of the basin and, therefore, in regions where there has been an accelerated occupation process and an alteration of the native cover, especially depending on the type of annual and perennial crops in this region, favoring the water erosion processes when not properly managed.

In relation to soil loss in the subbasins, it can be observed that subbasins 1 and 2, represented by locations P1 and P2, showed lower levels of water erosion since they are located in better preserved areas, characterized as being riverhead regions.

The values referring to sediment production, estimated in Equations 4, 5, 6, 7, 8, 9 and 10, are presented in Table 7 in terms of average annual value and in accordance with the classification proposed by Carvalho et al. (2000) and the sedimentometric rating curves that enable the calculation of sediment transportation, are presented in Figure 4.

The use of the sediment rating curve stems from the fact that the daily collection and analysis of samples is economically unviable, assuming that the discharge is a good predictor of the concentration of sediments, however, in certain cases, this technique has been seen to be imprecise with the degree of dispersion quite sharp (HICKS; GOMEZ; TRUSTRUM, 2004) and this is due to the fact that variables that influence the sediment transport process vary greatly in space and time. Nevertheless, as shown by Córdova and González (1997), the use of this technique is employed in larger basins since the variations between the daily average outflow maximums and minimums are not very significant.

On the other hand, Duvert et al. (2012) argue that the use of a rating curve for smaller basins is not recommended since it can lead to erroneous interpretations concerning the non-linearity and high dispersion among discharge and the concentration of sediments in suspension. In this context, Li et al. (2004) proposed the use of an erosion runoff index over the use of a rainfall erosivity index in order to estimate the solid discharge in basins of

Table 7. Sediment yield at the evaluated sedimentometric stations.

Point	Area (km^2)	Name	Solid Discharge ($t\ ha^{-1}\ year^{-1}$)	Class
P1	27	Jusante Aterro Sanitário	0.765	Moderate
P2	106	Fazendinha	0.469	Low
P3	385	Pinhais	0.413	Low
P4	808	ETE-Sanepar	5.124	Very High
P5	1160	Ponte do Umbarazinho	2.584	High
P6	2330	Guajuvira	0.923	Moderate
P7	2740	Balsa Nova	1.126	Moderate

up to 200 km^2, whileas for Duvert et al. (2010), the peak outflow represents a better answer for the estimation of this variable due to the fact that runoff characteristics translate the basin's behavior in a more efficient manner.

Thus, an alternative to circumvent these limitations is through the use of multivariable models that combine the physical and climatic characteristics, which may represent a better adjustment and understanding of the phenomenon, since the regression method traditionally used only broaches the topic of geographical relief physically described by the β parameter.

Chella et al. (2005) evaluated sediment transportation in the Barigui River, which is a subbasin of the Upper Iguaçu River and found solid discharge values varying from 10 to 350 t day^{-1} in five monitored locations, classifying it as Moderate and High.

Knapik (2009) evaluated a water quality model using field data for the UIRB and found sediment concentration values varying from 100 a 176 mg L^{-1} at locations P5, P6 and P7, reaffirming that the values measured are inferior to the 500 mg L^{-1} limit in the CONAMA 375/05 classification. Likewise in this study, the observed values of sediment concentration varied from

69.4 to 175.4 mg L^{-1} for the analyzed locations, indicating that although there exists a relative amount of anthropic occupation, the values are still within tolerable limits.

In this sense, the sediments are considered of great importance in the evaluation of water contamination levels, thanks not only to their capacity to accumulate metals, but also for transporting possible sources of contamination, which can release contaminant species (FROEHNER; MARTINS, 2008).

The suspended solid discharge yields of the UIRB varied from 0.47 to 5.124 t ha^{-1} yr^{-1}, at the inspected stations, and in accordance with the classification proposed by Carvalho et al. (2000), the basin presents sediment production varying from Low to High. Still, for the state of Paraná, Bollmann and Marques (2001) obtained solid discharge values for the Cachoeiras River Basin of the order of 3,6 t ha^{-1} yr^{-1}. Silva Júnior et al. (2011) evaluated the sediment production in the Mimoso River Basin in the state of Pernambuco, and found values varying from 0.91 to 10.91 t ha^{-1} yr^{-1} in an area of 194.82 km^2. Lima Neto, Wiegand and Araújo (2011) evaluated the total sediment production at 1.48 t ha^{-1} yr^{-1} in a semi-arid Brazilian basin that has an area of 20,000 km^2.

Considering the influence of the vegetational cover and the soil use, especially in locations where there is a strong presence of urbanization, it was observed that station 65013005 (ETE-SANEPAR), located downstream of the metropolitan region of Curitiba (MRC), showed an average value of 5.124 t ha^{-1} yr^{-1}, constituting the highest concentrated value for the UIRB. This value is similar to those found in the study performed by Chella et al. (2005), where values such as 0.6 t ha^{-1} yr^{-1} were apparent in areas with lower degrees of anthropization and in areas where the urban nucleus belonging to the MRC exerted greater influence. These values were up to 4.57 t ha^{-1} yr^{-1}. In the referenced study, it can be seen that the highest sediment production rates occurred in sections where there exists a greater urban presence (subbasins 4 and 5), reaffirming the preponderant role of large urban centers in strengthening pollution loads.

In this sense, Scapin, Paiva and Beling (2007) characterize urbanized basins and apply various calculation methods in order to evaluate the transport of sediments in the city Santa Maria in the state of Rio Grande do Sul, finding an average value of 0.54 t ha^{-1} yr^{-1}. Although these values may be inferior to those found in this study for the MRC, it is important to consider that the urbanized area in the cited study is considerably smaller. This increase in the transportation of sediments in urban areas is due to the fact that there is an acceleration of runoff in the drainage networks that pass through cities, many of which, have been reground and had the roughness of the channel changed by the replacement of their banks and bottoms with concrete. Therefore, metropolitan regions do not produce erosion themselves but rather they increase the level of pollution in water courses, necessitating the need for mitigating actions to attenuate this process, especially during periods of extreme precipitation because, as demonstrated by Walling and Webb (1987), a very significant portion of sediment transportation occurs in sporadic periods.

Although the data used to construct the rating curve is derived from the ANA database and, thereby, presents a level of uncertainty, it can be seen that the data used had a good fit, principally for location P4, where the average estimated value was close to the average value observed in previous studies that had monitored the region's water currents.

These results have made it possible to estimate the SDR that was utilized to explain the spatial and temporal heterogeneity of the sediment transportation process and its interaction with precipitation as well as with the morphological characteristics of subbasins, in a similar manner in terms of methodology to the study performed by Wang, Yao and Liu (2008). By its own definition, the SDR is a scale factor used to accommodate average differences in sediment yield, having a value between 0 and 1 due to the deposition of sediments caused by changes in the discharge regime and storage tanks (WU et al., 2012).

With sediment production results and average basin erosion estimated through RUSLE, the average SDR was calculated for each subbasin (Figure 3 and Table 2), with the values being shown in Table 8. It should be noted that the average value for the basin was 0.284, meaning that 28.4% of the generated soil loss was transported to the control section, resulting in similarities to the findings of Chaves (2010) who studies the Pipiripau River Basin and found an average value of 0.24. Nevertheless, this same author noted a significant variation in the values found as a result of the methodology adopted in order to estimate the SRD, as well as a result of the rating curves. This reaffirms that, in this context, a continuous surveillance program allows the acquisition of a larger universe of data, resulting in more precise adjustments due to the quality of the data collected.

The values calculated for the UIRB vary in dimension between subbasins of 6.6 to 88.3% (Table 8). This spatial variability has been observed in other studies, like that of De Vente et al. (2008), who obtained a SDR that varied from 0.03 to 55% for in 61 subbasins in Spain. Likewise, Van Rompaey, Krasa and Dostal (2007) calculated the SDR of a basin of 1.960 km^2 in the Czech Republic, acquiring a value of 28%; Verstraeten, Prosser and Fogarty (2007) reported SDR values of 20 to 39% for basins from 167 to 2,173 km^2 in Australia; Fryirs and Brierley (2001) estimated a SDR of nearly 70% in the Bega River Basin in the Australian state of New South Wales, which caused dramatic changes in the fluvial geomorphology and Alatorre et al. (2012) determined a SDR of approximately 5% for an experimental basin of 2.84 km^2 in Spain.

In terms of the sediment delivery rate in Brazil, Silva and Schulz (2007) evaluated the hydrosedimentological dynamic in the Água Fria River Basin in the city Palmas in the state of Tocantins from the period of February 1998 until January 1999 and acquired the average SDR value of 6.2%. Silva, Santos and Silva (2014) found a SDR of 8% for the Tapacurá River Basin in the state of Pernambuco with an area of 470 km^2. On the other

Table 8. Sediment delivery rate calculated for the UIRB by subbasin.

Subbasin	Y (t ha^{-1} $year^{-1}$)	E (t ha^{-1} $year^{-1}$)	SDR
sub-1	0.765	3.47	0.220
sub-2	0.469	2.63	0.178
sub-3	0.413	6.29	0.066
sub-4	5.124	5.80	0.883
sub-5	2.584	6.60	0.392
sub-6	0.923	7.77	0.119
sub-7	1.126	8.36	0.135

hand, Beskow et al. (2009), examining the Rio Grande River Basin in the state of Minas Gerais, found an average value of 1.62% for a drainage area greater than 6,000 km², whereas Durães, Mello and Beskow (2016), upon inspection of the Paraopeba River Basin's SDR, discovered values varying from 8.6% to 66% for an area of 8,659 km².

In accordance with Brown et al. (2005), the impacts of alterations in the use of soil in drainage basins concerning superficial runoff can, in general, be evaluated in terms of maximum and minimum outflow. However, these effects are associated with processes caused by water erosion, since within the hydroseimentological cycle context, water erosion leads to soil volume diminution, which results in a lower water holding capacity.

The results found here show that alterations in soil coverage and usage can significantly affect the hydrological dynamic of drainage basins in terms of surface runoff. This alteration of the runoff can lead to a higher rate of sediment transportation as a result of the upstream erosion process with consequences in the diminution of humidity variability in deep soil layers and the replenishment of aquifers, which results in a reduction of discharge during periods of drought and an increase during rainy periods as a result of the alterations in the water infiltration rates of the soil.

CONCLUSION

The use of the RUSLE model associated with GIS through Map Algebra proved to be an effective tool in determining the water erosion vulnerability of drainage basin soil, allowing for the identification of more vulnerable areas.

The Gleysol classification showed the highest potential rates of water erosion above 25 t ha^{-1} yr^{-1}, corresponding to 51.44% of all occurrences, followed by Cambisol (50.15%), Argisol (44.22%) and Organosol (43.64%).

Subbasins 4 and 5, located downstream from the Curitiba metropolitan region, presented greater rates of sediment production and sediment transportation, showing the preponderant role of large urban centers in strengthening pollution loads in river courses.

The SDR varies spatially in the UIRB as a result of soil coverage, just like topographical features, which tend to prefer sedimentation processes in areas with lower slopes, since they favor this phenomenon.

Considering the spatial and temporal variation of the suspended solids data, the methodology used has proven an important tool in terms of practices, despite inherent limitations, and makes continued research of the UIRB necessary, which would enable a greater and more representative studies.

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Vinícius Augusto de Oliveira: contributed on paper revision, literature review and paper formatting.