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Modeling of soil losses in the Camaquã River Hydrographic Basin, southern Brazil

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ABSTRACT: Water erosion is considered the main form of soil degradation of tropical and subtropical soils, causing the reduction of the productive capacity of the land and the eutrophication and silting of water bodies. However, the modeling of soil erosion is fundamental to design conservation practices of soils and waters. The objective of this work was to estimate soil losses in the Camaquã River Hydrographic Basin, located in southern Brazil, a region where water erosion is one of the main environmental problems. The modeling was performed using the Erosion Potential Method with the aid of geoprocessing techniques. The sediment delivery rate in the area was calculated from total sediment and flow data of the Camaquã River from a hydrosedimentological station. The Camaquã River Hydrographic Basin presented an estimated average soil loss of 7.4 Mg ha^{-1} year^{-1} and in 25% of the region the soil losses were higher than the tolerable limits. In the basin, a sediment delivery rate of 0.41 Mg ha^{-1} year^{-1} was observed, while the estimated value was 1.14 Mg ha^{-1} year^{-1}. The identification of areas with high rates of soil losses due to water erosion, made in the present work, can help in the planning and management of soil conservation practices in the Camaquã River Hydrographic Basin.

Key words: erosion potential method; modeling; soil conservation

Modelagem de perdas de solo na Bacia Hidrográfica do Rio Camaquã, sul do Brasil

RESUMO: A erosão hídrica é considerada a principal forma de degradação dos solos tropicais e subtropicais, causando a redução da capacidade produtiva das terras e a eutrofização e assoreamento de corpos hídricos. Todavia, a modelagem da erosão do solo é fundamental para projetar práticas conservacionistas dos solos e das águas. O objetivo do trabalho foi estimar as perdas de solo na Bacia Hidrográfica do Rio Camaquã, localizada no sul do Brasil, uma região onde a erosão hídrica é um dos principais problemas ambientais. A modelagem foi realizada utilizando o Método de Erosão Potencial com auxílio de técnicas de geoprocessamento. Foi calculada a taxa de entrega de sedimentos na área a partir de dados de sedimentos totais transportados e de vazão do Rio Camaquã, a partir de uma estação hidrossedimentológica. A Bacia Hidrográfica do Rio Camaquã apresentou uma perda de solo média estimada em 7,4 Mg ha^{-1} ano^{-1} e em 25% da região as perdas de solo foram maiores que os limites toleráveis. Na bacia foi observada uma taxa de entrega de sedimentos de 0,41 Mg ha^{-1} ano^{-1}, enquanto o valor estimado foi de 1,14 Mg ha^{-1} ano^{-1}. A identificação das áreas com elevadas taxas de perdas de solo por erosão hídrica, feita no presente trabalho, pode auxiliar no planejamento e gerenciamento de práticas conservacionistas do solo na Bacia Hidrográfica do Rio Camaquã.

Palavras-chave: método de erosão potencial; modelagem; conservação do solo

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Introduction

Water erosion is considered one of the main forms of soil degradation and a challenge to be faced by farmers, technicians and researchers working in the area of soil conservation. Until nowadays, erosion has degraded millions of hectares of arable land by reducing its productive capacity or making them unproductive. In addition, and no less important aspect of soil erosion, is the contamination of the environment caused by the intake of sediments, organic material, plant nutrients, pesticides and other chemical species in surface waters, compromising its quality by eutrophication and siltation, raising the costs of water treatment for human and animal consumption (Bertol et al., 2019).

Soil erosion monitoring is an essential tool for planning the adoption of soil conservation practices. However, the measurement of soil losses by erosion in the field by means of experimental plots is an expensive and time-consuming procedure. Thus, several models were developed and applied to estimate soil erosion worldwide (Mohammed et al., 2020).

Soil erosion modeling allows the investigation of the process remotely and the representation of the current erosion rate of a given area. In addition, it also allows the evaluation of past scenarios and simulation of possible future scenarios (Luetzenburg et al., 2020). Therefore, erosion modeling can be interpreted as a valuable technique in the identification of areas with high soil losses, in the management of watersheds and in the evaluation of different soil management practices. Furthermore, modeling can help in the proposition of public policies aimed at reducing soil losses due to erosion (Lense et al., 2020).

Among the models, the Universal Equation of Soil Loss (USLE) (Wischmeier & Smith, 1978) and its revised version (RUSLE) (Renard et al., 1997), deserve to be highlighted, which have wide application worldwide (Alewell et al., 2019). Another model, not as famous as the above, however, which deserves to be mentioned, due to the simplicity of application, which results from the ease of determination of its parameters, is the Erosion Potential Method (EPM) (Gavrilovic, 1962). The choice of which model to use involves the selection of the existence of a method developed or adapted to the edaphoclimatic conditions of the area to be studied. On the other hand, this criterion is often not met, which leads to the selection of models that mainly meet the criterion of low data requirement and that are able to provide a rapid diagnosis and accurately considered satisfactory by the researchers (Efthimiou et al., 2017). The use of easily obtainable information is the main advantage of EPM, since it is based on tabulated values, which can be easily determined in field surveys or with the aid of geoprocessing.

Considering that an estimate of soil loss rates is important to design and direct effective soil and water conservation measures, the objective of this study was to estimate the rates of soil losses in the Camaquã River Hydrographic Basin, located in southern Brazil, a region where water erosion is one of the main environmental problems (SEMA, 2015).

Materials and Methods

Water erosion modeling was performed using the EPM (Gavrilovic, 1962). EPM was developed by Slobodan Gavrilovic based on field water erosion assessment research conducted in the Morava River basin area of Serbia in the 1960 (Dragičević et al., 2016). The model has been widely used worldwide and recently the application of EPM has been adapted to Brazilian edaphoclimatic conditions by Sakuno et al. (2020). Since then, the application of the model in the country has increased with precise results (Lense et al., 2020; 2021). The EPM estimates soil loss according to Equation 1.

$$W_{yr} = \left(\sqrt{\frac{t_0}{10}+0.1}\right)\cdot H_{yr}\cdot\pi\cdot\sqrt{\left[Y\cdot X_a\cdot\left(\varphi+\sqrt{I_{sr}}\right)\right]^3}\cdot Bd \qquad (1)$$

where: W_{yr} - total soil loss, in Mg ha^{-1} year^{-1}; t_0 - average air temperature, in °C; H_{yr} - annual rainfall, in mm; Y - soil resistance to water erosion, dimensionless; X_a - coefficient of land use and management, dimensionless; ϕ - coefficient of the degree of erosive features, dimensionless; I_{sr} - average slope of area, in %; and, Bd - average density of soils, in kg dm^{-3}.

The EPM was developed for application in watersheds. Thus, based on the delimitation of the brazilian hydrographic basins carried out by the "Agência Nacional de Águas e Saneamento Básico", the Camaquã River Hydrographic Basin was selected as the study area. The Camaquã River Hydrographic Basin is located in southern Brazil, in the State of Rio Grande do Sul, between the parallels 30°15' to 31°35' South, limiting to the West by the meridian 54°15' and to the East by the meridian 51°00' (Figure 1). The watershed has an area of about 24,000 km^2 and a total population estimated at 356,133 habitants, distributed in 28 municipalities (SEMA, 2015).

The soils of the region are mostly neosols, argisols and planosols, with smaller areas of luvisols and chernosols (Table 1). The soil map (Figure 1) was obtained from the Soil Map of Brazil in the scale 1:5,000,000 (Santos et al., 2011). From the survey of soil classes, soil resistance to water erosion (Y) was determined for each soil type of the area, according to Sakuno et al. (2020) (Table 1). The Y parameter is based on tabulated values ranging from 0.20 to 2 and expressing the effect of soil

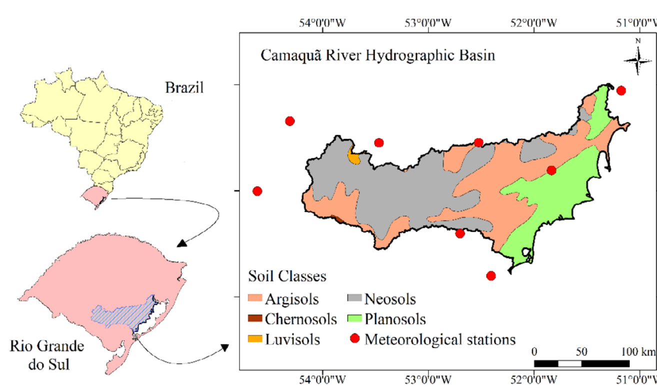

Figure 1. Location and Soil Map of the Camaquã River Hydrographic Basin, Rio Grande do Sul, Brazil.

Table 1. Soil classes and soil resistance coefficient values to water erosion (Y), soil density (Bd) and soil loss tolerance (T) in the Camaquã River Hydrographic Basin, Rio Grande do Sul, Brazil.

Land use	Area (%)	Y (dimensionless)	Bd (kg dm^{-3})	T (Mg ha^{-1} year^{-1})
Neosols	41.3	1.5	1.38	7.60
Argisols	36.9	0.8	1.35	5.40
Planosols	21.1	0.5	1.51	12.08
Luvisols	0.5	0.9	1.37	5.38
Chernols	0.2	0.6	1.48	11.32

characteristics and their source material on resistance to the erosive process. Soils with higher Y values are less resistant to water erosion. Soil density values (Bd) (Table 1) were obtained based on the information available for soils of the region present in the "Sistema de Informação dos Solos Brasileiros (SISolos)", a database with several soil attributes collected and analyzed in all regions of Brazil.

According to the Köppen climatic classification, the climate in the Camaquã River Hydrographic Basin is subtropical, with hot summer (Cfa) (Alvares et al., 2013). The region has an average annual rainfall of 1,475 mm and average temperatures of 12.8 and 22.7 °C in the winter and summer months, respectively (SEMA, 2015). The climatic factors considered by the EPM (H_{yr} and t_0) were obtained for the year 2020 based on the network of meteorological stations of the "Instituto Nacional de Meteorologia". The stations are distributed in the interior and in areas adjacent to the watershed and are represented in Figure 1. The climatic variables were interpolated by the ordinary Kriging method, with adjustment of the spherical model, using the Geostatistical Wizard tool of the ArcGIS 10.5 software (ESRI, 2016). The spatial distribution maps of H_{yr} and t_0 are illustrated in Figure 2.

The coefficient of soil use and management (X_a) represents the action of vegetation cover in soil protection against water erosion. The values range from 0.05, in areas with good vegetation index, to 1.00, for areas with exposed soil. To classify the parameter X_a, the land use map of the Camaquã River Hydrographic Basin in 2019 was used, illustrated in Figure 3. The land use map was obtained based on the 2019 Collection 5 of the MapBiomas Project, which gathered and information on land use and occupation of the entire Brazilian territory. In the hydrographic basin, areas with rural formation and temporary crops predominate (Table 2), which consist mainly of the cultivation of irrigated rice, tobacco and watermelon (SEMA, 2015). The parameter X_a was determined for each land use class (Table 2) using tabulated values adapted to Brazilian edaphoclimatic conditions by Sakuno et al. (2020).

The factor ϕ is a way of representing which erosive features predominate in a given region. This parameter is classified based on tabled values ranging from 0.10 in areas without signs of erosion occurrence, to 1.00 in areas with severe erosive features. The parameter ϕ was classified according to Gavrilovic (1962) for each land use class and is represented in Table 2. Due to the predominance of rural areas, temporary crops and forest formation, the prevalence of laminar erosion in the hydrographic basin was defined.

The factor I_{sr} represents the influence of relief on water erosion. To represent this parameter, the Digital Elevation Model

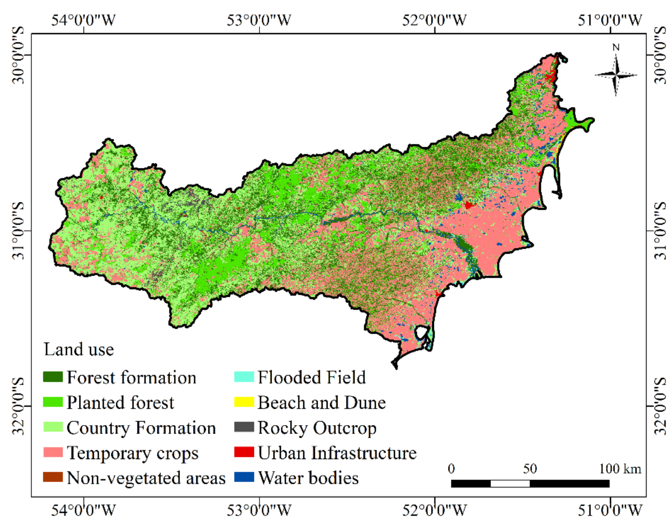

Figure 3. Land use of the Camaquã River Hydrographic Basin, Rio Grande do Sul, Brazil.

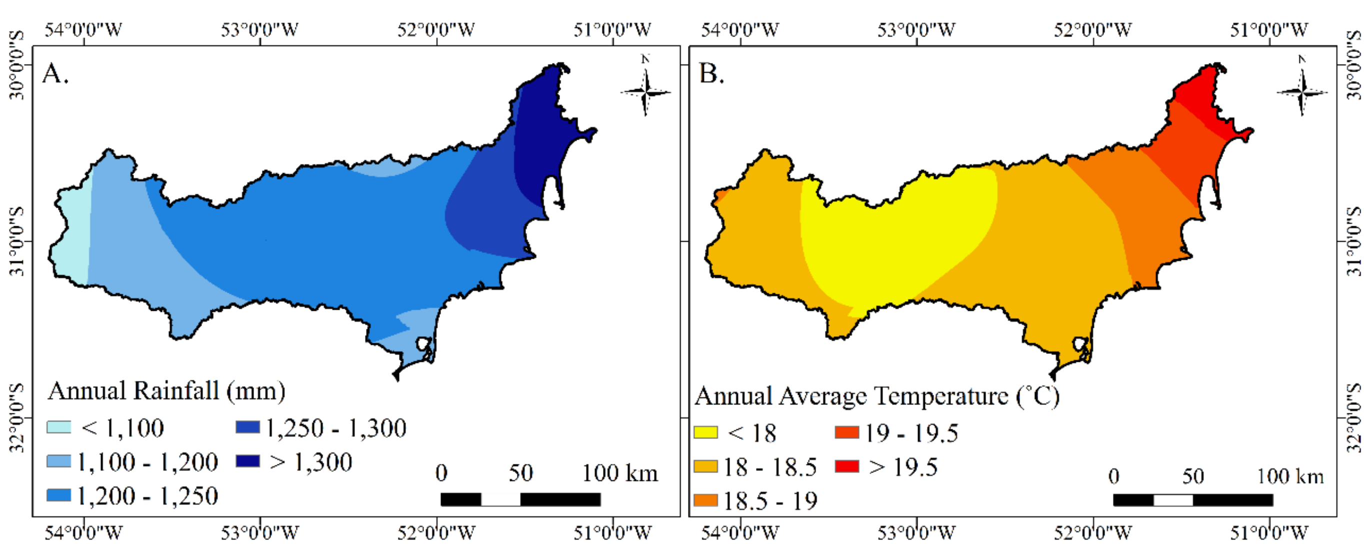

Figure 2. Annual rainfall and annual average temperature for 2020 in the Camaquã River Hydrographic Basin, Rio Grande do Sul, Brazil.

Table 2. Land use classes and values of soil use and management coefficient (X_a) and coefficient of the degree of erosive features (ϕ) in the Camaquã River Hydrographic Basin, Rio Grande do Sul, Brazil.

Land use	Area (%)	X_a** (dimensionless)	ϕ**
Forest formation	27.0	0.05	0.1
Planted forest	6.1	0.60	0.5
Country formation	32.3	0.30	0.2
Temporary crops	31.7	0.70	0.5
Non-vegetated areas	0.2	1.00	0.6
Flooded field*	0.6	-	-
Beach and dune*	0.1	-	-
Rocky outcrop*	0.2	-	-
Urban infrastructure*	0.3	-	-
Water bodies*	1.5	-	-

*Areas not considered in the calculation of estimated soil loss. **Values classified according to Sakuno et al. (2020) and Gavrilovic (1962).

- DEM (Figure 4A), with spatial resolution of 30 m, was obtained, available on the digital platform "Brasil em Relevo". From the DEM, the slope map was elaborated (Figure 4B), with the Slope tool of ArcMap 10.5 (ESRI, 2016). In the hydrographic basin, the maximum and average altitude correspond respectively to 597 and 186 m with predominant slope between 3 and 8%.

The spatialization of the data, the calculation of soil losses, as well as the preparation of the maps of use and soil classes, DEM and slope, were performed in the software ArcMap 10.5 (ESRI, 2016).

The soil loss results were compared with the soil loss tolerance limits (T) represented in Table 1. The T was determined for each soil class according to the methodology proposed by Bertol & Almeida (2000) using the information available for the soils of the Camaquã River Hydrographic Basin in SISolos.

In addition to estimating water erosion, it is possible to calculate the sediment delivery rate in the Camaquã River Hydrographic Basin by integrating the result of the EPM model by sediment delivery rate (SDR). The SDR represents the fraction of eroded soil that reaches water bodies causing siltation and depreciation of water quality. The SDR was determined using Equation 2 proposed by Vanoni (1975).

$$SDR = 0.472 \cdot A^{-0.125} \quad (2)$$

where: SDR is the rate of delivery of sediments, in %; and, A is the area of the watershed, in km^2.

The SDR can be directly observed and measured in the field (SDR observed), usually through hydro-sedimentological stations. Thus, the estimated SDR can be compared with the actual SDR for the validation of soil loss estimates.

The SDR observed in the Camaquã River Hydrographic Basin was obtained based on the methodology adopted by Batista et al. (2017). First, data on total transported sediments and flow collected between 2016 and 2020 were obtained, from a hydrosedimentological station locates in Santana da Boa Vista at latitude -30° 58′ 12″ and longitude -53° 3′ 0″ and regulated by the "Agência Nacional de Águas e Saneamento Básico", with information available in the database of "Portal HidroWeb". From the information, a curve was made relating the total sediments transported and the water discharge (Figure 5).

The SDR observed was obtained considering the sediment x flow curve and the set of daily flow data referring to the

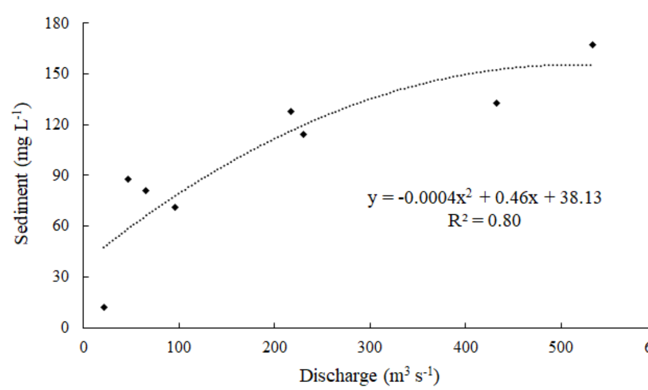

Figure 5. Water discharge curve (sediment transported × water discharge) in the Camaquã River Hydrographic Basin, Brazil.

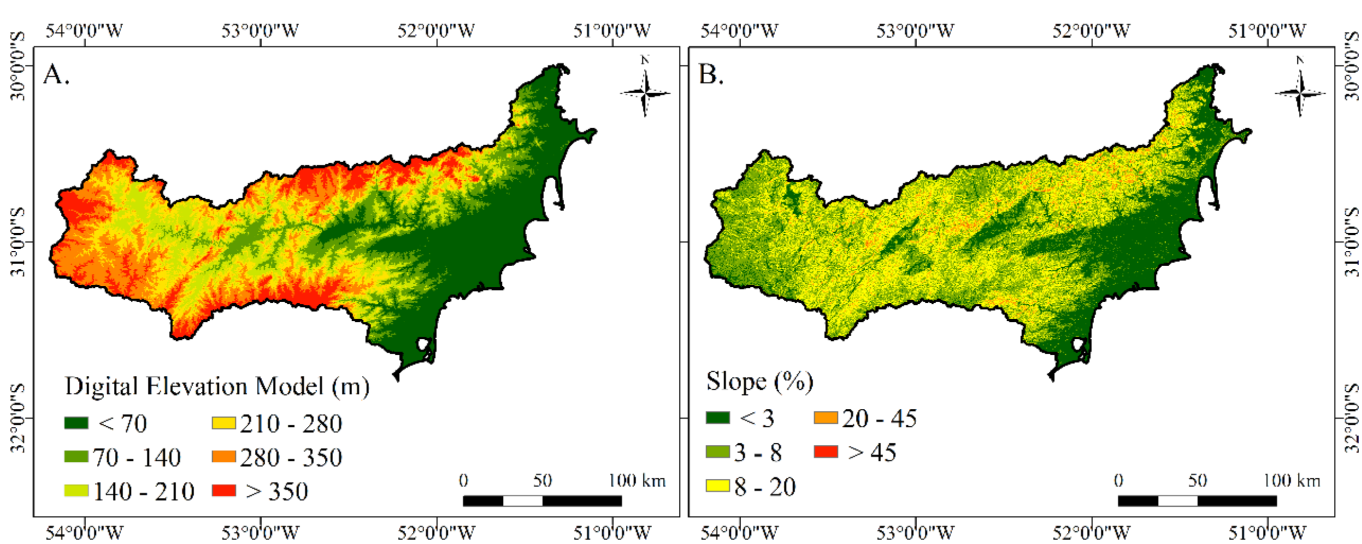

Figure 4. Digital Elevation Model (A) and Slope Map (B) of the Camaquã River Hydrographic Basin, Rio Grande do Sul, Brazil.

drainage area of the hydrosedimentological station of Santana da Boa Vista (7,567 km^2). The observed SDR was compared with the estimated SDR.

Results and Discussion

The Camaquã River Hydrographic Basin watershed showed an estimated average soil loss of 7.4 Mg ha^{-1} year^{-1}. Considering the land use classes, the average soil loss was higher for non-vegetated areas (28.2 Mg ha^{-1} year^{-1}), planted forest (21.3 Mg ha^{-1} year^{-1}) and temporary crops (16.7 Mg ha^{-1} year^{-1}), while for country formation and forest formation the results were 3.6 and 1.3 Mg ha^{-1} year^{-1}, respectively.

The water erosion rates of the area were qualitatively classified according to Avanzi et al. (2013) and are represented in Figure 6. In 57.1% of the hydrographic basin soil losses were classified as “very light” and “light”, while in 11.8 and 10% of the region the erosive rates were “high” and “very high”, respectively. These areas with high soil losses were mainly concentrated in places with steep relief (> 20%) and soils with little vegetation cover. Steinmetz et al. (2018) evaluating soil loss using RUSLE in southern Brazil, observed similar results with erosion rates predominantly ranging from 0 to 2.5 Mg ha^{-1} year^{-1} (35.3% of the assessed area). Nachtigall et al. (2020) evaluating soil losses by RUSLE in the Arroio Fragata Hydrographic Basin in southern Brazil, observed soil losses between 5 and 50 Mg ha^{-1} year^{-1} in 24% of the area. As in our work, these higher soil losses in the region were associated with higher rainfall, steeper areas, and low vegetation cover.

In regions with high erosion rates should be encouraged the adoption of conservation practices of the soil, since according to Didoné et al. (2014), the absence of conservation practices in agricultural cultivation areas in the State of Rio Grande do Sul is the main cause of the accelerated erosive process and high sediment production. Among the conservation practices that can be adopted in the region, we can mainly mention practices that avoid turning over and exposing the soil, such as no-tillage and maintenance of spontaneous vegetation and plant residues on the soil (Dai et al., 2018; Chen et al., 2019; Abdulkareem et al., 2019).

In about 25% of the region, soil losses were above the limits of T (Figure 7). The T can be defined as soil loss that still allows an economically sustainable productivity of agricultural crops (Wischmeier & Smith, 1978). Areas with soil losses above T should be prioritized in the adoption of erosion minimization practices. In addition, it should be emphasized that T is an index that assesses soil degradation in the short term and ideally, that long-term soil losses, even in areas below this limit, are reduced to the maximum possible to ensure soil conservation (Mendes Júnior et al., 2018).

Another important aspect, for the reduction of water erosion in the hydrographic basin, is the need for a wide dissemination of conservation management practices in the soils of the area, since the region has mostly Neosols and Argisols (Figure 1), which are soils with high vulnerability to water erosion. In addition, public policies can be defined in the region considering the land use capacity or agricultural aptitude of each land as an essential factor to determine the sustainable agricultural use of natural resources (Medeiros et al., 2016).

According to the diagnosis of Camaquã River Hydrographic Basin (SEMA, 2015), in the region, the main cause of the intensification of soil erosion and siltation of water bodies, is the deforestation of the riparian forest associated with soil vulnerability to erosion. Thus, greater supervision in the region by the responsible agencies is necessary, in order to combat deforestation and respect the maintenance of permanent preservation areas around water courses and the adoption of legal reserve areas in rural properties, according to the Brazilian Forest Code.

The SDR was calculated in 0.154 indicating that about 15.4% of the soil losses of the region reach the water bodies, while the other 84.6% are retained in the relief of the area. By the integration of the EPM/SDR, a sediment generation of 1.14 Mg ha^{-1} year^{-1}. On the other hand, the SDR value observed was

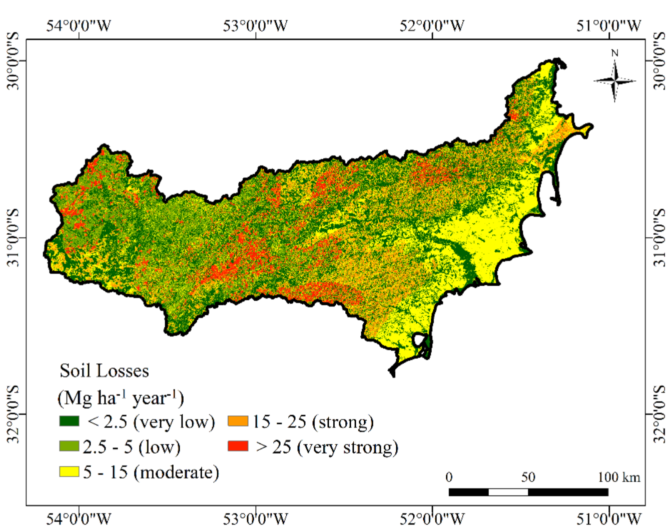

Figure 6. Spatial distribution of soil losses in the Camaquã River Hydrographic Basin, Rio Grande do Sul, Brazil.

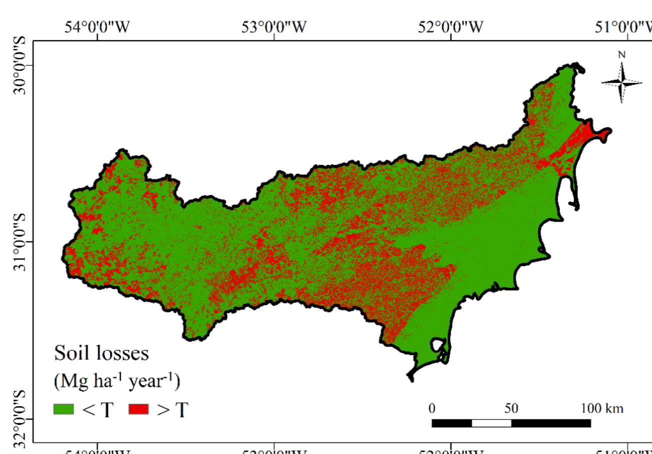

Figure 7. Areas with soil losses below and above the limits of Soil Loss Tolerance (T) in the Camaquã River Hydrographic Basin, Rio Grande do Sul, Brazil.

0.41 Mg ha^{-1} year^{-1} and thus an error of 0.73 Mg ha^{-1} year^{-1} was obtained. It is worth mentioning that according to Amorim et al. (2010), when considering the spatialization of the results, the error associated with water erosion modeling is lower in areas with high soil losses, that is, the models are more efficient in pointing out areas with critical erosive rates.

A possible cause of the observed error is the determination of factor X_a, which presents high sensitivity of variation, decisively interfering in the results provided by EPM (Dragičević et al., 2017). As previously seen, this factor is determined from the land use map and the elaboration of these maps in large areas presents some uncertainties associated with the identification process of each land use class. In addition, the EPM was developed in a region with distinct edafloclimatic characteristics of the Camaquã River Hydrographic Basin, and recently its tabled values underwent a theoretical adaptation to the edaphoclimatic conditions of southeastern Brazil (Sakuno et al., 2020). Thus, it is the first time that the model is applied in southern Brazil, and the observed error indicates the need for an improvement in the calibration of the parameters of the model in this region, so that they represent with greater fidelity the edaphoclimatic conditions of the south of the country.

On the other hand, if we consider the application of modeling in large areas for more practical purposes, it can be considered accurate if the errors of the forecasts do not exceed the rate of soil loss observed by a factor of two or three (Bagarello et al., 2012). According to this criterion, the result of the validation process presents an acceptable error. In addition, estimates of soil losses consist of a representation of reality and not reality itself and, therefore, are prone to uncertainty (Alewell et al., 2019).

Despite errors, modeling should be understood as a diagnostic tool for water erosion levels, a way to test hypotheses, to evaluate relative differences between management systems or trends of long-term soil losses, and estimates should be critically interpreted by managers of the evaluated areas (Alewell et al., 2019; Lense et al., 2021).

Conclusion

In 25% of the Camaquã River Hydrographic Basin, estimates of soil losses are above tolerable limits. The identification of these areas through the spatialization of the modeling results can help in decision making, aiming at the reduction of water erosion, and in the management of soil conservation practices in the Camaquã River Hydrographic Basin. In addition, this study may favor the dissemination of the application of EPM in southern Brazil, due to its simplicity and ease of application, favoring the adaptation of the model in different Brazilian regions.

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Compliance with Ethical Standards

Author contributions: Conceptualization: GHEL; Data curation: GHEL; Formal analysis: GHEL; Investigation: GHEL; Methodology: Project administration: RLM; Resources: RLM; GHEL; Software: GHEL; Supervision: RLM; Validation: GHEL; Visualization: GHEL; Writing - original draft: GHEL; Writing - review & editing: RB; RLM.

Conflict of interest: The authors declare that there is no conflict of interest.

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