Ciências Agrárias
SEMINA

DOI: 10.5433/1679-0359.2022v43n4p1403

Modeling of soil loss by water erosion in the Tietê River Hydrographic Basin, São Paulo, Brazil

Modelagem da perda de solo por erosão hídrica na Bacia Hidrográfica do Rio Tietê, São Paulo, Brasil

Guilherme Henrique Expedito Lense[1]; Lucas Emanuel Servidoni[1]; Taya Cristo Parreiras[2]; Derielsen Brandão Santana[1]; Talyson de Melo Bolleli[3]; Joaquim Ernesto Bernardes Ayer[4]; Velibor Spalevic[5]; Ronaldo Luiz Mincato[6]*

Highlights

About 18% of the Tietê River Basin presents high soil loss.
Places with steep reliefs and low vegetation have high soil losses.
Conservation practices should be encouraged in the region to minimize soil losses.

Abstract

Since the mid-16th century, the Tietê River has been an important route for the territorial occupation and exploitation of natural resources in the interior of São Paulo and Brazil. Currently, the Tietê River is well known for environmental problems related to water pollution and contamination. However, little attention has been focused on water erosion, which is a serious issue that affects the soils and waters of the hydrographic basin. Thus, this work aimed to estimate soil loss caused by water erosion in this basin, which has an area of approximately 72,000 km², using the Revised Universal Soil Loss Equation (RUSLE). The RUSLE parameter survey and soil loss calculation were performed using geoprocessing techniques. The RUSLE estimated an average soil loss of 8.9 Mg ha^{-1} yr^{-1} and revealed that 18% of the basin's territory presents high erosion rates. These are priority zones for conservation practices to reduce water erosion and ensure long-term soil sustainability. The estimated sediment transport was 1.3 Mg ha^{-1} yr^{-1}, whereas the observed sedimentation, which was calculated based on data from the fluviometric station, was 0.8 Mg ha^{-1} yr^{-1}. Thus, the results were equivalent considering the large size of the study area and can be used to assist in managing the basin. Estimating soil losses can help in the planning of sustainable management of

---

[1] Doctoral Students of the Graduate Program in Environmental Sciences, Universidade Federal de Alfenas, UNIFAL-MG, Alfenas, MG, Brazil. E-mail: guilherme.lense@sou.unifal-mg.edu.br; les.servidoni@gmail.com; derielsen@hotmail.com

[2] Master in Environmental Sciences, UNIFAL-MG, Alfenas, MG, Brazil. E-mail: tayacristo1@gmail.com

[3] Doctoral Student Graduate Program in Environmental Engineering Science, Universidade de São Paulo, USP, São Carlos, SP, Brazil. E-mail: bolleli@usp.br

[4] Prof. Dr., Centro Universitário de Paulínia, UNIFACP, Paulínia, SP, Brazil. E-mail: joaquimeba@gmail.com

[5] Prof. Dr., Faculty of Philosophy, Geography, University of Montenegro, UCG, Niksic, Montenegro. E-mail: velibor.spalevic@gmail.com

[6] Prof. Dr., Institute of Natural Sciences, UNIFAL-MG, Alfenas, MG, Brazil. E-mail: ronaldo.mincato@unifal-mg.edu.br

* Author for correspondence

Received: Sept. 09, 2021 - Approved: Mar. 28, 2022

the Tietê River Hydrographic Basin and highlights the importance of minimizing water erosion, thus helping to prevent additional pollution and contamination with sediments, agrochemicals, and fertilizers.

Key words: RUSLE. Sediment delivery rate. Soil conservation. Soil sustainability.

Resumo

Desde meados do século 16, o rio Tietê tem sido uma importante rota de ocupação territorial e exploração dos recursos naturais do interior de São Paulo e do Brasil. Atualmente, o Rio Tietê é bastante conhecido pelos problemas ambientais relacionados à poluição e contaminação das águas. No entanto, pouca atenção tem sido dada à erosão hídrica, que é um problema sério que afeta os solos e as águas da bacia hidrográfica. Assim, este trabalho teve como objetivo estimar as perdas de solo causadas pela erosão hídrica nesta bacia, que tem uma área de aproximadamente 72.000 km², utilizando a Equação Universal de Perdas de Solo Revisada (RUSLE). O levantamento dos parâmetros RUSLE e o cálculo das perdas de solo foram realizados utilizando técnicas de geoprocessamento. O RUSLE estimou uma perda média de solo de 8,9 Mg ha^{-1} ano^{-1} e revelou que 18% do território da bacia apresenta altas taxas de erosão. Estas são zonas prioritárias para práticas de conservação para reduzir a erosão hídrica e garantir a sustentabilidade do solo a longo prazo. O transporte de sedimentos estimado foi de 1,3 Mg ha^{-1} ano^{-1}, enquanto a sedimentação observada, calculada com base nos dados da estação fluviométrica, foi de 0,8 Mg ha^{-1} ano^{-1}. Assim, os resultados foram equivalentes considerando a grande extensão da área de estudo e podem ser utilizados para auxiliar na gestão da bacia. A estimativa das perdas de solo pode auxiliar no planejamento do manejo sustentável da Bacia Hidrográfica do Rio Tietê e destacar a importância de minimizar a erosão hídrica, auxiliando na prevenção de poluição adicional e contaminação por sedimentos, agroquímicos e fertilizantes.

Palavras-chave: RUSLE. Taxa de entrega de sedimentos. Conservação do solo. Sustentabilidade do solo.

Introduction

The Tietê River is the largest river in the state of São Paulo at 1,136 km long, and it is used for navigation, water supply, and power generation. The river arises in the municipality of Salesópolis in São Paulo and flows in an E-W direction into the Paraná River along the border with the state of Mato Grosso do Sul (Biblioteca Virtual, 2018). At the beginning of Brazil's colonization, this river was a source of transportation, water, and food through fishing and hunting. Therefore, it was fundamental for the emergence of villages in the second half of the 16th century that would become important towns, such as São Miguel, Carapicuíba, Santana de Parnaíba, Barueri, Guarulhos, Itaquaquecetuba, Mogi das Cruzes, and the city of São Paulo, which has been stated capital since 1681 and was established based on the installation of Jesuits near the Tietê in 1554 (Nóbrega, 1978; Bruno, 1991; Zanirato, 2011).

However, despite the historical and economic importance, it plays for the state of São Paulo and for Brazil, the Tietê River has become better known for its environmental problems, which are mainly related to the pollution and contamination of its waters due to the accelerated and disorderly urbanization process in the region (Seabra, 2018). The

Tietê River has become a receptacle for waste, sewage, and industrial waste produced by urban areas built around it (Zanirato, 2011). Along 163 km of the river, between the municipalities of Mogi das Cruzes and Cabreúva, the water quality is classified as poor and unsuitable for use and aquatic life (SOS Mata Atlântica, 2020).

Although pollution is a widely discussed problem, water erosion in the Tietê River Hydrographic Basin is an issue that has received little attention. In addition, the few studies on water erosion found in the region are carried out in sub-basins of the Tietê River Hydrographic Basin, not considering the entire área (Fernandes et al., 2012; F. M. Santos et al., 2020). Water erosion is a serious environmental problem for Brazil because it leads to soil degradation through the loss of fertility, reduction in microbiota, and decreases of soil carbon stocks; thus, it has direct impacts on global warming. In addition, erosion causes siltation and pollution of water bodies through the deposition of sediments, fertilizers, and agrochemicals (Panagos et al., 2018).

Changes in land use and land cover in the Tietê River Basin over time have caused deforestation, intensive land use, and overgrazing, which have caused high erosion rates that have compromised agricultural production in vast areas. Thus, evaluating and monitoring water erosion and understanding its extension and magnitude can be implemented in conjunction with more efficient management practices aimed at soil conservation (Prasannakumar et al., 2012; Borrelli et al., 2018).

Therefore, modeling is a relatively simple method of assessing the magnitude of water erosion because it is uncomplicated to implement and interpret. Water erosion models require minimal resources compared to field experiments and can be applied using data available in scientific repositories (Ganasri & Ramesh, 2016; Alewell et al., 2019). The Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997), which is adapted from the USLE (Wischmeier & Smith, 1978), is the most commonly used model for estimating soil losses (Alewell et al., 2019). The RUSLE is a flexible and practical model for areas with low data availability, and its results can assist in the management and conservation of natural resources at the scale of hydrographic basins (Zerihun et al., 2018; Alewell et al., 2019).

Under this scenario, this work aimed to estimate the soil losses due to water erosion in the Tietê River Hydrographic Basin using the RUSLE.

Materials and Methods

Study area

The study was carried out in the Tietê River Hydrographic Basin, which has an area of approximately 72,000 km² and is located in Southeast Brazil at coordinates from 51° 34' 5" to 45° 38' 20" West and 20° 31' 55" to 24° 0' 32” South, Datum SIRGAS 2000 (Figure 1). According to the Köppen classification, a tropical (Aw) climate is predominant in the West, a humid subtropical (Cfa) climate is predominant in the central portion of the basin, and a temperate oceanic (Cfb) climate is found in the East closer to the coast (Alvares et al., 2013). The average annual rainfall varies between 1,202 and 3,085 mm (Marcuzzo, 2020).

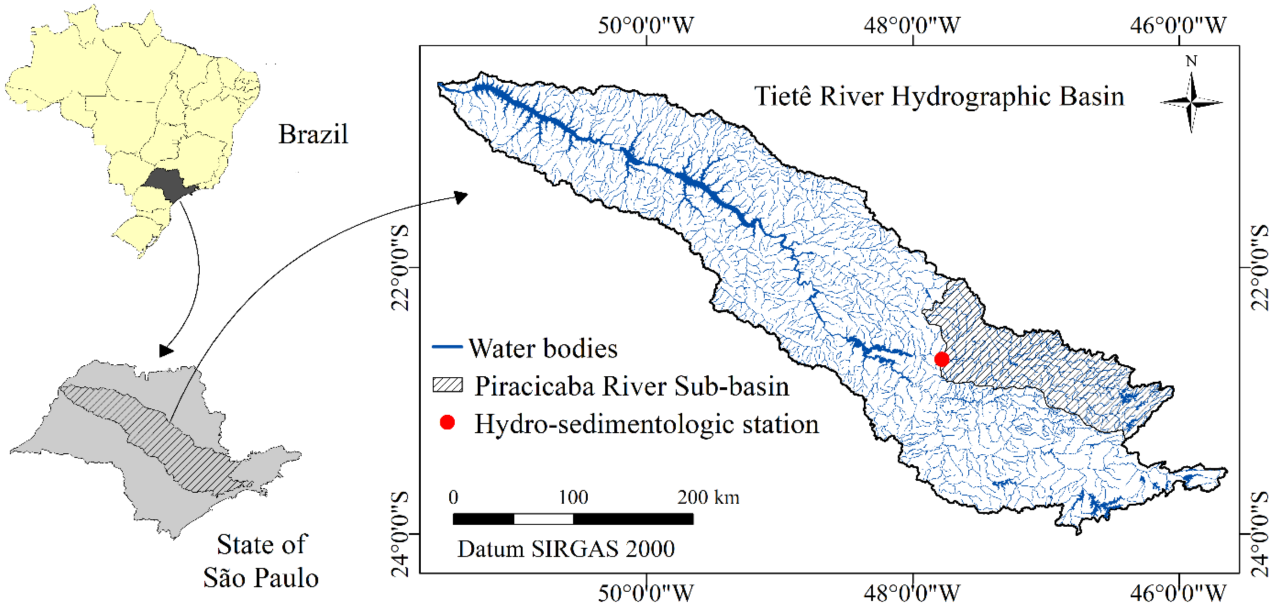

Figure 1. Location of the Tietê River Hydrographic Basin, Brazil.

Regarding the soil types, mostly Argisols (43.96%), Latosols (35.06%), and Neosols (4.78%) are found in the basin. Other less frequent soil classes are Cambisols (3.64%), Gleissoles (1.42%), Nitosoils (0.9%), Organosols (0.37%), Planosols (0.32%), Luvisols (0.07%) and Chernosols (0.02%). The map of Figure 2 was obtained from the soil map of the State of São Paulo, which was revised and enlarged (scale 1:250,000) (Rossi, 2017).

The territory is mainly occupied by pastures (37.90%), sugarcane (30.10%), forest formations (14.40%), urban areas (6.65%), planted forests (3.41%), water bodies (3.20%), temporary crops (2.58%), cerrado (1.20%), perennial crops (0.40%) and non vegetated areas (0.16%). The class “planted forests” consists mainly of eucalyptus plantations. The land use (Figure 3) from 2019 was obtained from the digital platform Mapbiomas Project (2020). The Mapbiomas Project consists of an open access platform that provides data on land use and land cover in the Brazilian territory with a high level of precision and which are prepared involving a collaborative network with experts in biomes, land uses, remote sensing and Geographic Information Systems (Mapbiomas Project, 2020).

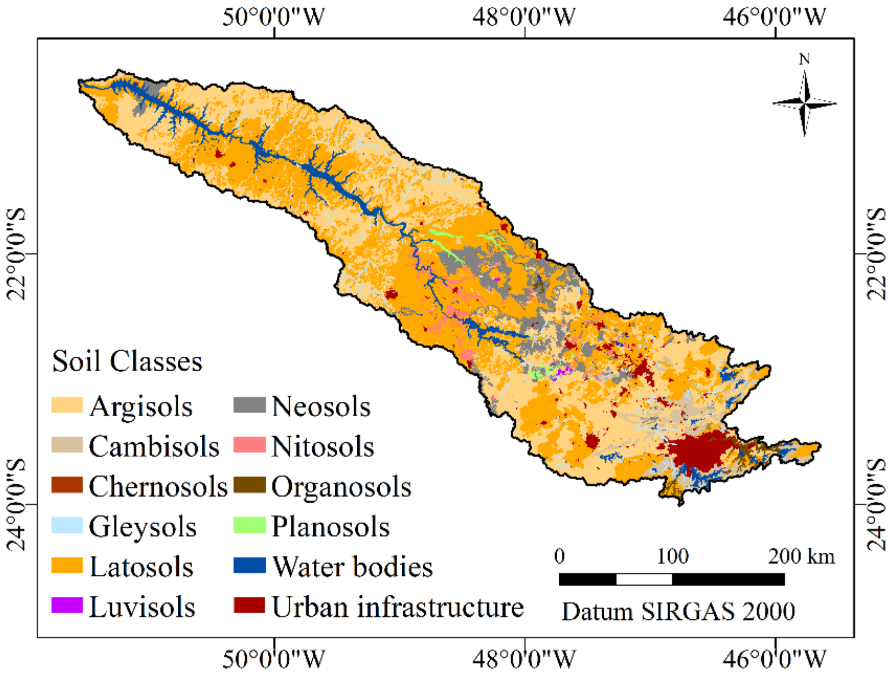

Figure 2. Soil map of the Tietê River Hydrographic Basin, Brazil, based on Rossi (2017).

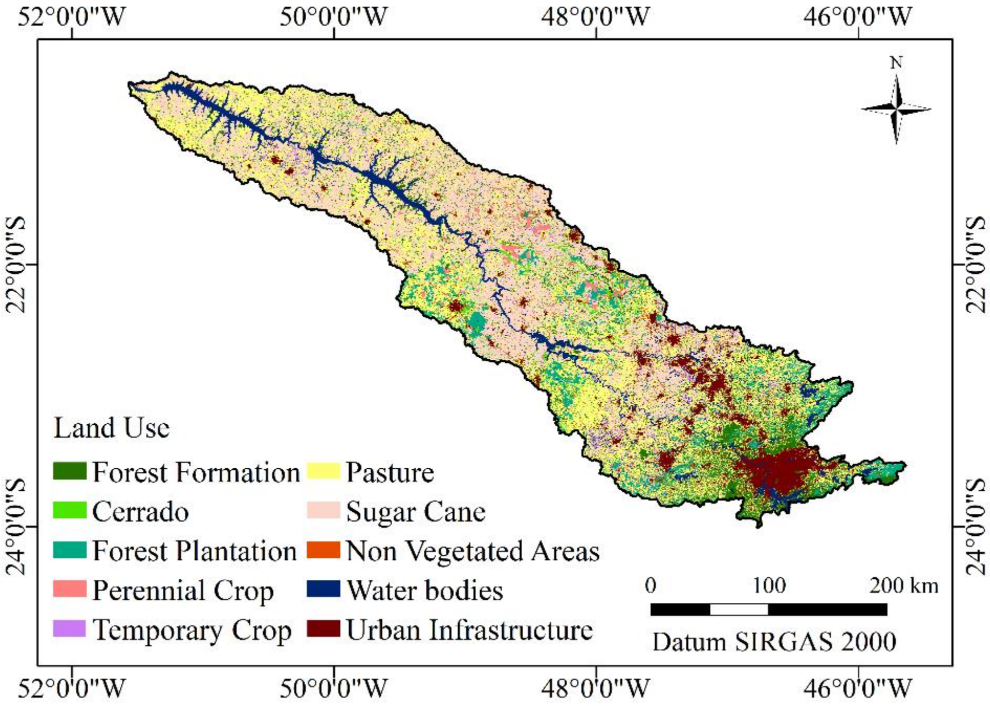

Figure 3. Land use and land cover map (2019) of the Tietê River Hydrographic Basin, Brazil, obtained from the Mapbiomas Project (2020).

The basin has altitudes between 248 and 2,030 m, with an average of 580 m (Figure 4A). The Digital Elevation Model (DEM), with a spatial resolution of 30 m, was extracted from the digital platform "Brasil em Relevo" (Miranda, 2005). From the DEM, the slope map was generated (Figure 4b) with the Slope tool on ArcMap 10.5 (Environmental Systems Research Institute [ESRI], 2016). The relief predominantly presents slopes between 3 and 8%.

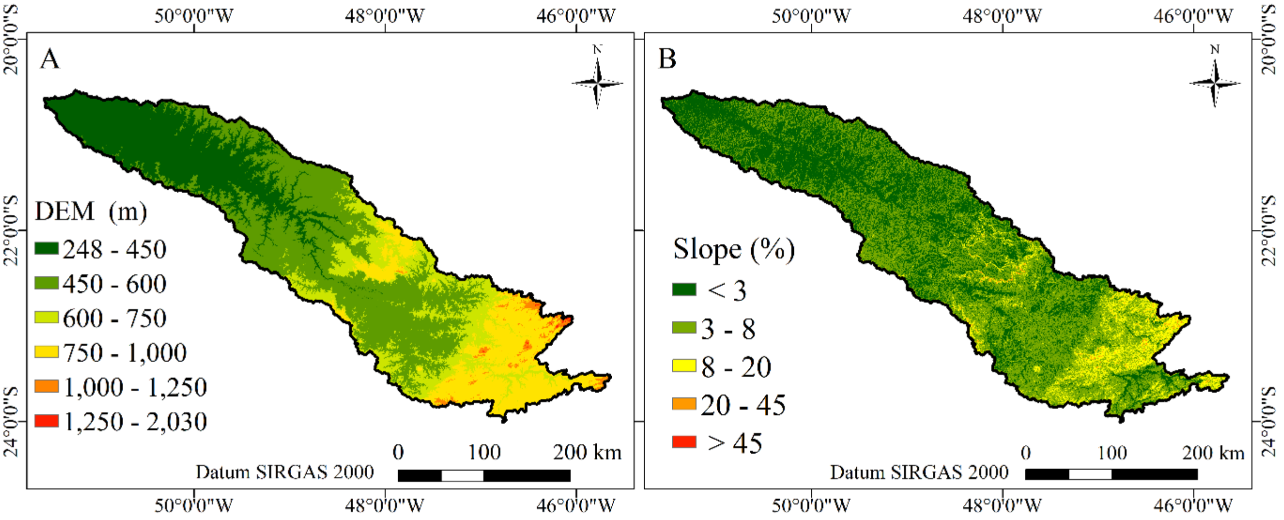

Figure 4. Digital elevation model (DEM) (A) and slope map (B) of the Tietê River Hydrographic Basin, Brazil. DEM extracted from Miranda (2005).

Revised Universal Soil Loss Equation – RUSLE

The RUSLE model estimates soil losses in a given area according to Equation 1:

$$A=R \cdot K \cdot LS \cdot C \cdot P \qquad (1)$$

where A is the mean annual soil loss, Mg ha^{-1} yr^{-1}; R is the rainfall erosivity factor, MJ mm ha^{-1} h^{-1} yr^{-1}; K is the soil erodibility factor, Mg ha^{-1} MJ^{-1} mm^{-1}; LS is the dimensionless topographic factor; C is the dimensionless land use and management factor; and P is the dimensionless conservation practices factor.

The R factor represents the ability of rainfall and associated runoff to cause soil erosion, and it is given by the product of the kinetic energy of rain by its maximum intensity in 30 minutes (Wischmeier & Smith, 1978; Bertol et al., 2019). In the Tietê River Basin, detailed rainfall records are lacking; thus, the R factor was generated according to the multivariate geographic model for the southeast region of Brazil, as proposed by Mello et al. (2013). With this model, it is possible to estimate the R factor using latitude, longitude, and altitude data, as applied in Equation 2 in each pixel of the DEM, which was performed using the Raster Calculator tool (ESRI, 2016).

$$R = -399433 + 420.49 \cdot A - 78296 \cdot LA - 0.01784 \cdot A^2 - 1594.04 \cdot LA^2 + 195.84 \cdot LO^2 + 17.77 \cdot LA \cdot LO - 1716.27 \cdot LA \cdot LO + 0.1851 \cdot LO^2 \cdot A + 0.00001002 \cdot LO^2 \cdot A^2 + 1.389 \cdot LA^2 \cdot LO^2 + 0.01364 \cdot LA^2 \cdot LO^3 \qquad (2)$$

where R is the rainfall erosivity factor in MJ mm ha^{-1} h^{-1} yr^{-1}, A is the altitude in meters, and LA and LO are the latitude and longitude, respectively, both in negative decimal degrees.

The K factor represents the soil's natural susceptibility to erosion, which in turn is influenced by its physical, chemical, and mineralogical attributes (Wischmeier & Smith, 1978). Determining this factor in situ is an onerous process that requires at least 22 years of data collection in an experimental plot under natural rain conditions (Bertol et al., 2019). Due to these limitations, its determination was based on the soil erodibility values for the state of São Paulo reported in the specialized literature (Table 1).

Table 1
Soil erodibility factor (K)

Soil Classes *	K** Mg ha^{-1} MJ^{-1} mm^{-1}	Soil Classes *	K** Mg ha^{-1} MJ^{-1} mm^{-1}
Argisols	0.0425	Luvisols	0.0312
Cambisols	0.0508	Neosols	0.0510
Chernosols	0.0309	Nitosols	0.0237
Gleysols	0.0361	Organosols	0.0610
Latosols	0.0162	Planosols	0.0097

*Brazilian Soil Classification System (H. G. Santos et al., 2018). ** Values from Mannigel et al. (2002), A. M. Silva and Alvares (2005).

To assign the K factor values according to the existing soil classes, the soil map (Figure 2), which was clipped for the study area, was converted into a 30 m spatial resolution raster, where the values of each grid cell represented the soil erodibility.

The RUSLE includes the single topographic factor LS, which represents both the influence of slope length (L) and terrain slope (S) on soil erosion once they occur together within a terrain area because they are interdependent (Bertol et al., 2019). The LS factor was calculated using a Geographic Information System according to Mitasova et al. (1999) methodology, which is represented by Equation 3.

$$LS = (m+1) \cdot \left(\frac{FA \cdot 30}{22.13}\right)^m \cdot \left(\frac{\sin(S)}{0.0896}\right)^n \qquad (3)$$

where LS is the topography, dimensionless; FA is the flux accumulation expressed as the number of cells in the DEM grid; S is the slope of the basin in degrees; m and n are empirical parameters ranging from 0.4 - 0.6 and 1.0 - 1.4, respectively, according to the predominant type of erosion in the area (laminar or furrows); and 30 is the spatial resolution of the DEM, m.

The FA parameter was calculated from the DEM (Figure 4A) using the Flow Accumulation tool in ArcMap 10.5 (ESRI, 2016). The parameters m and n were defined as 0.4 and 1.0, respectively, assuming the prevalence of laminar erosion in the basin because sugarcane, pastures, and forest formations are the main land use classes in the region.

Among the RUSLE factors, the C factor is the most important because it represents the effect of all variables of soil management, vegetation cover, and residual plant biomass on soil erosion. As the K factor, this parameter can be used in the field in long-term experiments (Bertol et al., 2019). Considering the application of erosion modeling at a basin scale, the C factor values can be extracted from the scientific literature considering the land use classes (Panagos et al., 2015; Batista et al., 2017). Thus, the values of C for the Tiete River Hydrographic Basin are represented in Table 2.

Table 2
Land use and management factor (C)

Land use	C*	Land use	C*
	dimensionless		dimensionless
Forest formation	0.0004	Pasture	0.0500
Cerrado	0.0020	Sugarcane	0.1124
Forest plantation	0.0470	Not vegetated areas	1.0000
Perennial crop	0.1350	Water bodies**	-
Temporary crop	0.2060	Urbanization**	-

*Values of F. G. B. Silva et al. (2010); Cunha et al. (2017); Nachtigall et al. (2020). **Areas not considered in the calculation of soil loss.

The land use map, a 30 m spatial resolution raster, was employed to determine the C factor, in which each grid cell value represents its values.

The P factor expresses the ratio of soil losses under a given supportive conservation practice compared to the losses in a standard plot condition, that is, without such practice (Wischmeier & Smith, 1978). The RUSLE considers three types of supportive conservation practices: contour cultivation, strip cultivation, and terracing. These practices generate subfactors that when multiplied together, result in P values ranging from 0 to 1, with values closer to 0 indicating a higher efficiency of soil erosion reduction (Renard et al., 1997).

In the state of São Paulo, although agriculture is assumed to be largely mechanized at all stages of production, conservation practices cannot be spatially determined (Medeiros et al., 2016). Thus, based on the work of F. G. B. Silva et al. (2010) and Medeiros et al. (2016), the slope (α) was used as a key property for the adoption of conservation practices. For this purpose, the slope map was used (Figure 4b) as follows: for gradients of inclination lower than 5%, a value of P = 0.6 was assumed; and for gradients higher than 20%, a value of P = 1 was assumed. For gradients between 5 and 20%, the P factor can be defined using Equation 4.

$$\mathrm{P} = 0.69947 - 0.08911 \cdot \alpha + 0.01184 \cdot \alpha^2 - 0.000335 \cdot \alpha^3 \quad (4)$$

where P is a dimensionless conservation practice factor and α is the slope in %.

All parameters and the spatialization of the soil loss results were calculated in ArcMap 10.5 software using the Raster Calculator tool (ESRI, 2016).

Validation

Since the RUSLE does not specify the sediment delivery rate (SDR), it is necessary to separately calculate this parameter, which represents the ratio between gross erosion in a given area and the amount of sediment that reached water bodies; thus, sediment deposited on the relief is excluded. The SDR was determined using Equation 5, as proposed by Vanoni (1975).

$$SDR = 0.472 \cdot \mathrm{A}^{-0.125} \quad (5)$$

where SDR is the sediment delivery rate in % and A is the hydrographic basin area in km².

Sediment production can be measured in situ (usually at fluviometric stations) and used to validate the estimates of soil losses caused by water erosion. Therefore, after combining the RUSLE and SDR outcomes, it was possible to validate the model using data on the total sediments transported with water discharge and daily runoff, as proposed by Beskow et al. (2009) and Batista et al. (2017).

Initially, a curve relating the total sediments transported in the hydrographic basin and the water discharge was built (Figure 5). Data monitored between 2007 and 2020 at a hydrosedimentological station located in the Piracicaba River Hydrographic Sub-basin were used (Figure 1). These data are provided by the “Agência Nacional de Águas e Saneamento Básico” (ANA), which has several stations in the Tietê River Hydrographic Basin area. However, certain stations present discontinuous and sparse measurements, while others are inoperative.

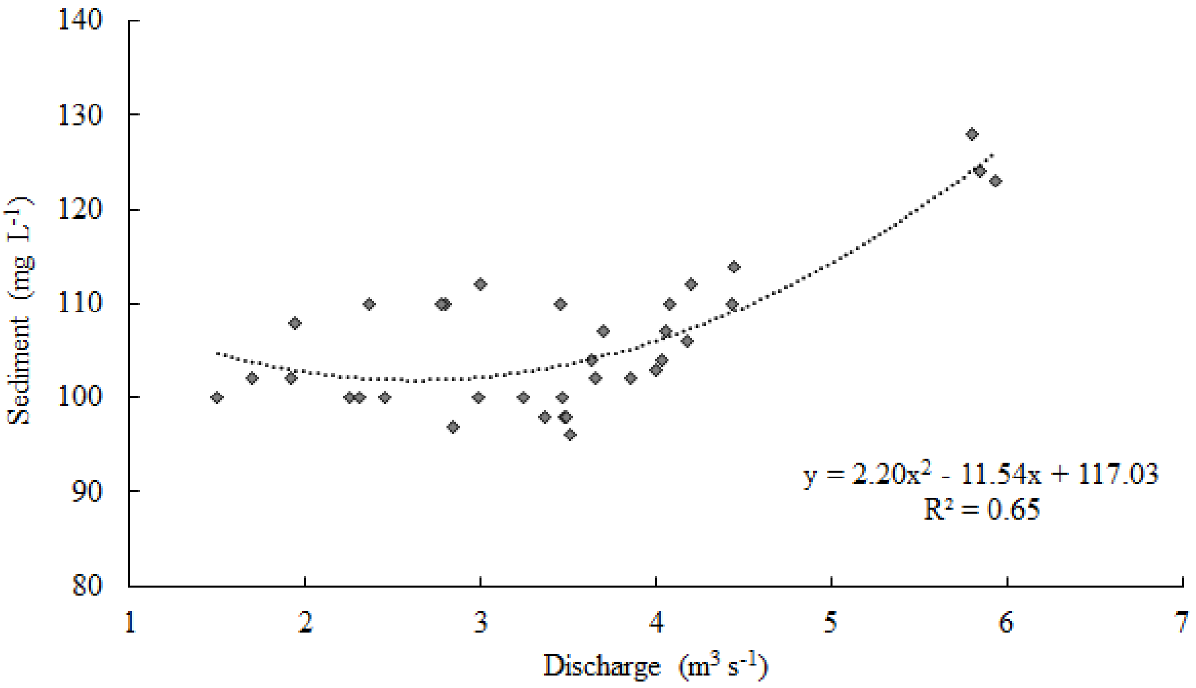

Figure 5. Water discharge curve (sediment transported × water discharge) in the Piracicaba River Hydrographic Sub-basin, Brazil.

The absence of these data hinders the sustainable planning of the entire basin; moreover, identifying sites of sediment deposition into water bodies is difficult. Therefore, environmental problems, such as siltation and water quality reductions, are caused by erosion processes. The validation was based on data from a sub-basin of the study area, as performed by Beskow et al. (2009) and Batista et al. (2017).

The observed sediment was determined based on the sediment x flow curve of the daily runoff of the Piracicaba River sub-basin (9,769 km²), which was obtained from the ANA database. Then, it was compared to the sediment estimated by the model (RUSLE/SDR).

Results and Discussion

The R factor ranged from 7,090 to 12,464 MJ mm ha^{-1} h^{-1} yr^{-1}, with an average of 7,734 MJ mm ha^{-1} h^{-1} yr^{-1} (Figure 6A). These findings corroborate Mello et al. (2013), who classified the region as being of “strong erosivity” based on the high rainfall rate.

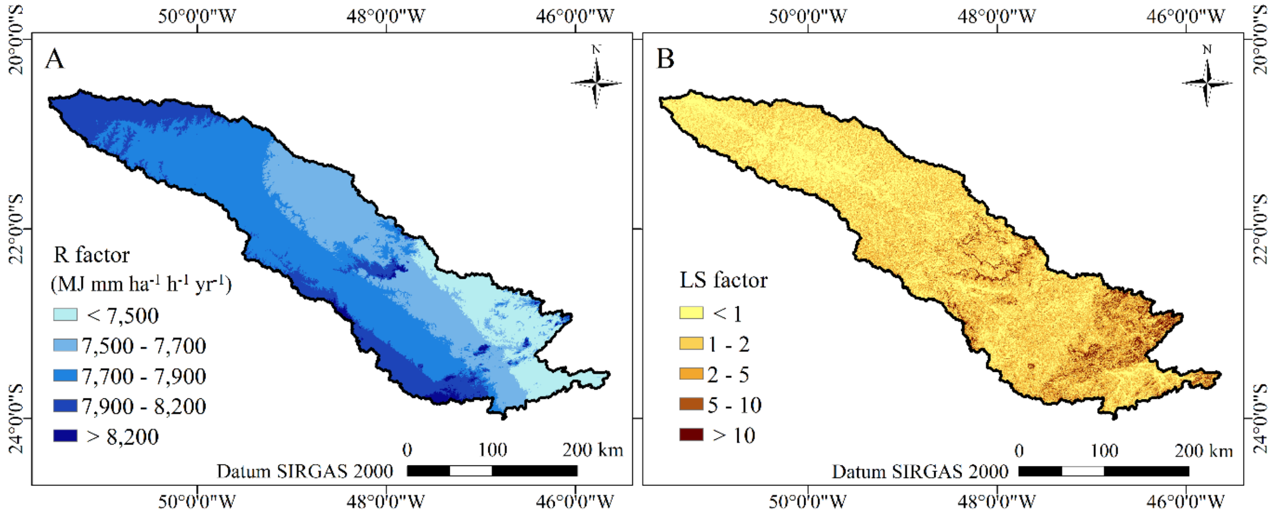

Figure 6. Spatial distribution of rainfall erosivity (A) and topographic (B) factors.

The LS factor (Figure 6B) had an average value of 1.98, indicating that much of the relief of the Tietê River Basin has low vulnerability to erosion. However, approximately 4% of the region presented LS values greater than 10, which can be considered zones of high vulnerability due to the higher speed of runoff (Beskow et al., 2009). These locations are concentrated mainly in the eastern portion of the basin, near the Serra do Mar. This result highlights the need to align agriculture practices with the implementation of conservation measures to reduce the speed of surface runoff and, consequently, water erosion in these regions.

Regarding the soil types, the Tietê River Basin presents an average K factor of 0.029 Mg ha^{-1} MJ^{-1} mm^{-1}. According to Mannigel et al. (2002), it can be classified as having medium erodibility (between 0.015 and 0.030 Mg ha^{-1} MJ^{-1} mm^{-1}). This outcome can be explained by the high occurrence of Latosols (35.06%), which are soils with low susceptibility to erosion, mainly due to their well-developed structure and good natural permeability (Bertol & Almeida, 2000).

In turn, Argisols are predominant in the area (43.96%), and this soil type has a high K score (0.0425 Mg ha^{-1} MJ^{-1} mm^{-1}). These soils have an eluvial A horizon with a coarse and often sandy texture and are prone to water erosion due to their fragile structure and poor aggregation. In addition, during longer rainfall events, runoff could reach the textural B horizon, which has a high clay content and is less permeable, thus leading to greater soil losses (Medeiros et al., 2016; H. G. Santos et al., 2018). It is noteworthy that when soils with low and high K scores are subjected to management that does not include conservation practices, high soil losses can occur (Lense et al., 2021).

The RUSLE estimated an average soil loss for the area of 8.9 Mg ha^{-1} yr^{-1}, which corresponds to a total annual loss of approximately 63 million tons of soil. The spatial distribution of these losses was qualitatively classified according to Avanzi et al. (2013) and is illustrated in Figure 7.

In 18% of the Tietê River Basin, soil losses were classified as high and very high (above 15.0 Mg ha^{-1} yr^{-1}). These areas are mainly concentrated in places with steep reliefs and low vegetation cover and therefore should be a priority for the adoption of conservation practices aimed at mitigating the harmful impacts caused by water erosion. Mainly in these areas with high soil losses, the land use planning for the Tietê River Hydrographic Basin must respect agricultural suitability and soil type vulnerability. As an example of the application of this practice, we can highlight the technical guidelines for licensing the sugar-alcohol sector in São Paulo, which are based on the State Agro-environmental Zoning of the Sugar-Alcohol Sector, which classifies the regions of São Paulo into suitability categories for sugarcane cultivation. Thus, since 2008, in areas classified as unsuitable, environmental licenses have not been granted for the installation or expansion of activities in the sugar-energy sector (São Paulo, 2008; Medeiros et al., 2016). According to Medeiros et al. (2016), respecting land use capacity is a primary factor for the sustainable use of natural resources and should be considered an essential condition for defining public policies aimed at soil conservation.

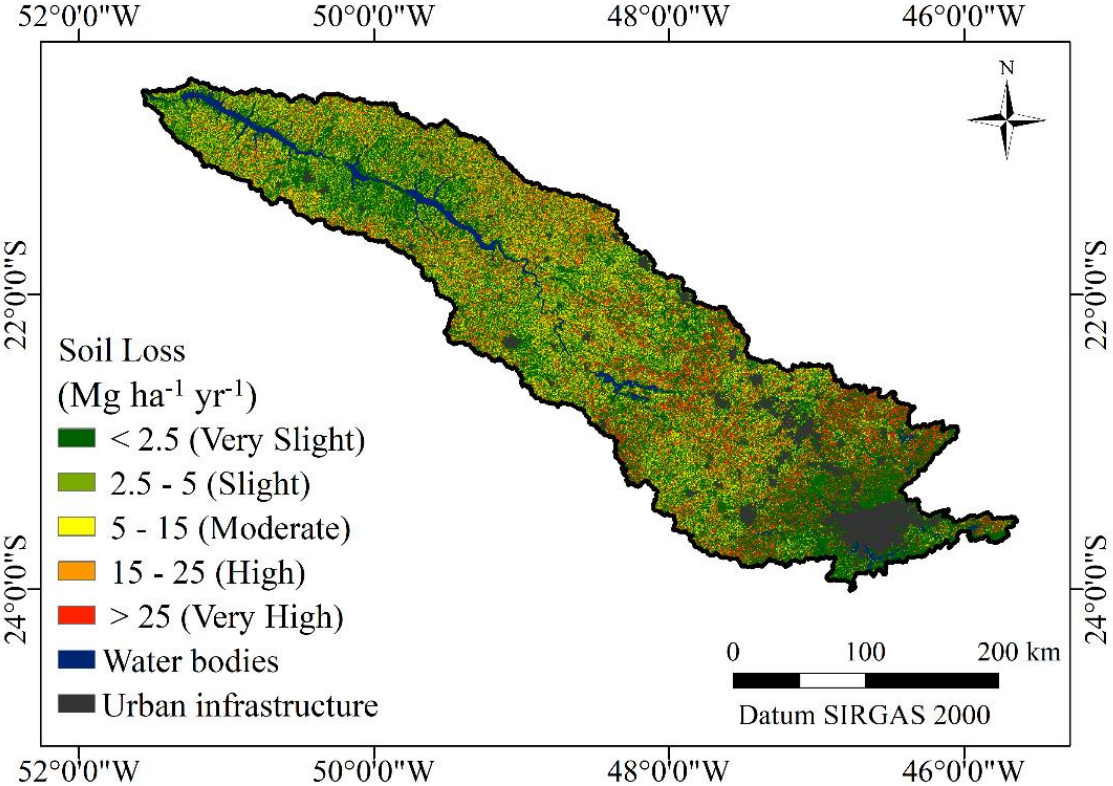

Figure 7. Spatial distribution of soil losses. Qualitative soil loss classes adapted from Avanzi et al. (2013).

The Brazilian Forest Code (Lei nº 12.651 de 25 de maio de 2012, 2012) itself offers some interesting resources to combat soil loss in areas with a high rate of water erosion. The protection of riparian vegetation and the implementation of legal reserve areas, requirements provided for in the Forest Code, when applied to rural properties, contribute to reducing the problem of water erosion. For example, it is planned to implement a legal reserve in areas with steeper relief (slopes or parts thereof, with a slope greater than 45°). In this way, the Forest Code is an important instrument for erosion control in Brazil, but there is a need for greater inspection in order to ensure that the requirements laid down by law are met. In addition, this legislation is not enough to combat erosion, farmers need technical guidance to plan and implement conservation practices and also financial assistance to encourage them to adopt these practices (Merten, 2013).

Considering the land use classes, the highest erosion rates were observed in non-vegetated areas (exposed soils) (32.4 Mg ha^{-1} yr^{-1}), followed by temporary crops (17.4 Mg ha^{-1} yr^{-1}), planted forest (13.6 Mg ha^{-1} yr^{-1}), pasture (11.5 Mg ha^{-1} yr^{-1}), sugarcane (10.5 Mg ha^{-1} yr^{-1}) and perennial crop (10.3 Mg ha^{-1} yr^{-1}) areas. In areas with forest formation and cerrado, soil losses were 2.5 and 1.6 Mg ha^{-1} yr^{-1}, respectively.

In areas with perennial and temporary crops, soil conservation techniques can be used, such as direct planting, land leveling through terrace construction and level planting, and reconstitution and maintenance of permanent preservation areas and legal reserves, to reduce soil losses and ensure the sustainability of agricultural production systems. In addition, due to the high presence of sugarcane crops in many regions, in the off-season period, when the soil is highly devoid of vegetation cover, coincides with periods of higher rainfall (Corrêa et al., 2018).

In this scenario, water erosion mitigation practices can be done from the implementation of policies to finance agricultural production and agricultural insurance conditioned to the adoption and implementation of soil conservation practices, which promote the sustainability of agricultural systems in the long term. The effectiveness of such practices can also be promoted by permanent rural extension programs, regulatory policies for the certification of sustainable agricultural production and, in addition to strengthening regulatory and inspection agencies, by rigorous inspection of the implementation of these conservationist practices.

Thus, management practices aimed at maintaining soil cover and reducing soil exposure time are essential, which is also valid for areas of planted forest (eucalyptus) and perennial and temporary crops, where soil losses are concentrated in the period of soil exposure during planting/seeding. In this context, adopting crop rotation and intercropping and reducing residue incorporation into the soil by plowing, direct planting, green manure, and spontaneous vegetation management would be good alternatives for maintaining soil cover/protection. Conservation practices aimed at increasing soil protection through vegetation directly interfere with the C factor of RUSLE, contributing to the reduction of estimates of soil losses, since among the parameters of RUSLE, the C factor is the main influencing factor human about the erosive process (Ouyang et al., 2010; Devátý et al., 2019). In addition, the C factor is one of the most sensitive to variations in space and time, since this parameter follows the growth of vegetation that varies according to the dynamics of rainfall (Nearing et al., 2005).

The sustainable use of soils allows for the maintenance of organic matter, improves the structure and water infiltration, and reduces surface runoff. Indirectly, it reduces the need to add fertilizers and agrochemicals and mitigates impacts related to contamination, eutrophication, and siltation of water bodies. Moreover, the reduction of water erosion has the potential to decrease agricultural production expenses. According to Dechen et al. (2015), the losses of P, K^+, Ca^{2+}, and Mg^{2+} in Brazilian temporary crops can represent additional expenses on the order of US$ 1.3 billion each year.

The SDR in the Piracicaba River sub-basin, which is calculated at 0.149, indicates that 14.9% of soil losses reach water bodies. This fraction of soil can cause siltation and contains nutrients and contaminants, thus leading to the depreciation of water quality and aggravating the water pollution of the Tietê River. The estimated sediment transport, which was calculated based on integrating the RUSLE/SDR, was 1.3 Mg ha^{-1} yr^{-1}, whereas the observed sedimentation, which was calculated based on data from the fluviometric station, was 0.8 Mg ha^{-1} yr^{-1}. Thus, the results were equivalent considering the large size of the study area and can be used to assist in making planning decisions and managing the basin.

It is noteworthy that water erosion modeling performed over large areas, especially when used for practical purposes, is considered accurate if the estimation errors do not exceed the observed erosion by a factor of two or three times (Bagarello et al., 2012). Furthermore, as observed in this study, the RUSLE tends to overestimate soil losses, as indicated by Amorim et al. (2010), but generates tolerable errors and shows greater precision in areas with high rates of water erosion. According to Beskow et al. (2009), modeling errors are associated with the difficulty of accurately determining the RUSLE factors, especially the LS parameter, which requires a DEM with better spatial resolution (such DEMs are often found only in small subbasins), as well as the C factor, because of the uncertainties associated with determining land use over large areas.

Regardless of the errors, the estimation of soil losses in large areas, such as the Tietê River Basin, should be interpreted as a tool to assess the dimensions of the erosive process and assist in the proposition and adoption of environmental and agricultural policies to minimize adverse impacts (Alewell et al., 2019).

Finally, modeling large-scale soil losses is a method of highlighting the importance of soil conservation and drawing attention to this topic, which is often not considered in national and international discussions. Soil is a resource considered nonrenewable within the human time scale; therefore, stimulating and ensuring its conservation is essential for the sustainability and survival of current and future generations (Medeiros et al., 2016; Bertol et al., 2019; Lense et al., 2020).

Conclusions

In the Tietê River Hydrographic Basin, 18% of the area has soil losses above 15.0 Mg ha^{-1} yr^{-1}, which were classified as areas with high rates of water erosion. These areas are mainly concentrated in places with steep reliefs and low vegetation cover. These areas should be a priority in the mitigation of water erosion, and conservation practices should be encouraged across the region to minimize soil losses as much as possible and ensure long-term soil sustainability.

Estimating soil losses can help in the planning of sustainable management of the Tietê River Hydrographic Basin and highlights the importance of minimizing water erosion, thus helping to prevent additional pollution and contamination with sediments, agrochemicals, and fertilizers.

Acknowledgments

The authors thank the "Fundação de Amparo à Pesquisa do Estado de Minas Gerais - Brasil" (FAPEMIG) for the scholarship offered to the first author. This study was funded in part by the "Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil" (CAPES) - Finance Code 001.

References

Alewell, C., Borrelli, P., Meusburger, K., & Panagos, P. (2019). Using the USLE: chances, challenges and limitations of soil erosion modelling. *International Soil and Water Conservation Research, 7*(3), 203-225. doi: 10.1016/j.iswcr.2019.05.004

Alvares, C. A., Stape, J. L., Sentelhas, P. C., Gonçalves, J. L. M., & Sparovek, G. (2013). Köppen's climate classification map for Brazil. *Meteorologische Zeitschrift, 22*(6), 711-728. doi: 10.1127/0941-2948/2013/0507

Amorim, R. S. S., Silva, D. D., Pruski, F. F., & Matos, A. T. (2010). Avaliação do desempenho dos modelos de predição da erosão hídrica USLE, RUSLE e WEPP para diferentes condições edafoclimáticas do Brasil. *Engenharia Agrícola, 30*(6), 1046-1049. doi: 10.1590/S0100-69162010000600006

Avanzi, J. C., Silva, M. L. N., Curi, N., Norton, L. D., Beskow, S., & Martins, S. G. (2013). Spatial distribution of water erosion risk in a watershed with eucalyptus and Atlantic Forest. *Ciência e Agrotecnologia, 37*(5), 427-434. doi: 10.1590/S1413-70542013000500006

Bagarello, V., Di Stefano, V., Ferro, V., Giordano, G., Iovino, M., & Pampalone, V. (2012). Estimating the USLE soil erodibility factor in Sicily, South Italy. *Applied Engineering in Agriculture, 28*(2), 199-206. doi: 10.13031/2013.41347

Batista, P. V. G., Silva, M. L. N., Silva, B. P. C., Curi, N., Bueni, I. T., Acérbi, F. W., Jr., Davies, J., & Quinton, J. (2017). Modelling spatially distributed soil losses and sediment yield in the upper Grande River Basin - Brazil. *Catena, 157*, 139-150. doi: 10.1016/j.catena.2017.05.025

Bertol, I., & Almeida, J. A. (2000). Tolerância de perda de solo por erosão para os principais solos do estado de Santa Catarina. *Revista Brasileira de Ciência do Solo, 24*(2), 657-668. doi: 10.1590/S0100-06832000000300018

Bertol, I., Cassol, E. A., & Merten, G. H. (2019). Modelagem e modelos utilizados para estimar a erosão do solo. In I. Bertol, I. C. de Maria, & L. S. Souza (Eds.), *Manejo e conservação do solo e da água* (pp. 462-497). Viçosa, MG: SBCS.

Beskow, S., Mello, C. R., Norton, L. D., Curi, N., Viola, M. R., & Avanzi, J. C. (2009). Soil erosion prediction in the Grande River Basin, Brazil using distributed modeling. *Catena, 79*(1), 49-59. doi: 10.1016/j.catena.2009.05.010

Biblioteca Virtual (2018). *São Paulo: hidrografia.* Governo do Estado de São Paulo. https://www.saopaulo.sp.gov.br/spnoticias/orgaos-governamentais/biblioteca-virtual/

Borrelli, P., Oost, V. K., Meusburger, K., Alewell, C., Lugato, E., & Panagos, P. (2018). A step towards a holistic assessment of soil degradation in Europe: coupling on-site erosion with sediment transfer and carbon fluxes. *Environmental Research, 161*, 291-298. doi: 10.1016/j.envres.2017.11.009

Bruno, E. S. (1991). *História e tradições da cidade de São Paulo.* Hucitec.

Corrêa, E. A., Moraes, I. C., Cunha, C. M. L., & Pinto, S. A. F. (2018). Influência do cultivo de cana-de-açúcar nas perdas de solo por erosão hídrica em Cambissolos no Estado de São Paulo. *Revista Brasileira de Geomorfologia, 19*(2), 231-243. doi: 10.20502/rbg.v19i2.1303

Cunha, E. R., Bacani, V. M., & Panachuki, E. (2017). Modeling soil erosion using RUSLE and GIS in a watershed occupied by rural settlement in the Brazilian Cerrado. *Natural Hazards, 85*, 851-868. doi: 10.1007/s11069-016-2607-3

Dechen, S. C. F., Telles, T. S., Guimarães, M. F., & Maria, I. C. (2015). Perdas e custos associados à erosão hídrica em função de taxas de cobertura do solo. *Bragantia, 74*(2), 224-233. doi: 10.1590/1678-4499.0363

Devátý, J., Dostál, T., Hösl, R., Krása, J., & Strauss, P. (2019). Effects of historical land use and land pattern changes on soil erosion - Case studies from Lower Austria and Central Bohemia. *Land Use Policy, 82*(1), 674-685. doi: 10.1016/j.landusepol.2018.11.058

Environmental Systems Research Institute (2016) *ARCGIS Professional GIS for the desktop version 10.5.* Redlands, Software. ESRI. Retrieved from https://desktop.arcgis.com/en/arcmap/10.5/get-started/setup/ arcgis-desktop-quick-start-guide.htm

Fernandes, A. M., Nolasco, M. B., Hissler, C., & Mortatti, J. (2012). Mechanical erosion in a tropical river basin in southeastern Brazil: chemical characteristics and annual fluvial transport mechanisms. *Journal of Geological Research, 2012,* 127109. doi: 10.1155/2012/127109

Ganasri, B. P., & Ramesh, H. (2016). Assessment of soil erosion by RUSLE model using remote sensing and GIS - a case study of Nethravathi Basin. *Geoscience Frontiers, 7*(6), 953-961. doi: 10.1016/j.gsf.2015.10.007

Lei Nº 12.651, de 25 de maio de 2012 (2012). *Código Florestal Brasileiro, DF.* http://www.planalto.gov.br/ccivil_03/_ato2011-2014/2012/lei/l12651.htm

Lense, G. H. E., Avanzi, J. C., Parreiras, T. C., & Mincato, R. L. (2020). Effects of deforestation on water erosion rates in the Amazon region. *Revista Brasileira de Ciências Agrárias, 15*(4), e8500. doi: 10.5039/agraria.v15i4a8500

Lense, G. H. E., Parreiras, T. C., Spalevic, V., Avanzi, J. C., & Mincato, R. L. (2021). Soil losses in the State of Rondônia, Brazil. *Ciência Rural, 51*(5), e20200460, 2021. doi: 10.1590/0103-8478cr20200460

Mannigel, A. R., Carvalho, M. P., Moreti, D., & Medeiros, L. R. (2002). Fator erodibilidade e tolerância de perda dos solos do Estado de São Paulo. *Acta Scientiarum, 24*(5), 1335-1340. doi: 10.4025/actasciagron.v24i0.2374

Mapbiomas Project (2020). *Coleção 5 da série anual de mapas de cobertura e uso de solo do Brasil.* Recuperado de https://mapbiomas.org/

Marcuzzo, F. F. N. (2020). Bacia hidrográfica do Rio Tietê: precipitação pluviométrica especializada. *Geographia Meridionalis, 5*(3), 243-266. doi: 10.15210/GM.V5I3.16926

Medeiros, G. O. R., Giarolla, A., Sampaio, G., & Marinho, M. A. (2016). Estimates of annual soil loss rates in the state of São Paulo, Brazil. *Revista Brasileira de Ciência do Solo, 40,* e0150497. doi: 10.1590/18069657rbcs20150497

Mello, C. R., Viola, M. R., Beskow, S., & Norton, L. D. (2013). Multivariate models for annual rainfall erosivity in Brazil. *Geoderma, 203,* 88-102. doi: 10.1016/j.geoderma.2013.03.009

Merten, G. H. (2013). A visão norte-americana da conservação do solo e da água. *Agroecologia e Desenvolvimento Rural Sustentável, 6*(2), 56-66. http://www.emater.tche.br/site/arquivos_pdf/teses/Rev-Agroeco_2013_Art-Merten.pdf

Miranda, E. E. (2005). *Brasil em relevo.* EMBRAPA Monitoramento por Satélite. Recuperado de http://www.relevobr.cnpm.embrapa.br

Mitasova, H., Mitas, L., Brown, W. M., & Johnston, D. M. (1999). *Terrain modeling and soil erosion simulations for fort hood and fort Polk test areas.* Geographic Modeling and Systems Laboratory, University of Illinois. http://fatra.cnr.ncsu.edu/~hmitaso/gmslab/reports/cerl99/rep99.html

Nachtigall, S. D., Nunes, M. C. M., Moura-Bueno, J. M., Lima, C. L. R., Miguel, P., Beskow, S., & Silva, T. P. (2020). Modelagem espacial da erosão hídrica do solo associada à sazonalidade agroclimática na região sul do Rio Grande do Sul, Brasil. *Engenharia Sanitaria e Ambiental, 25*(6), 933-946. doi: 10.1590/S1413-4152202020190136

Nearing, M. A., Jetten, V., Baffaut, C., Cerdan, O., Couturier, A., Hernandez, M., Le Bissonnais, Y., Nichols, M. H., Nunes, J. P., Renschler, C. S., Souchère, V., & Van Oost, K. (2005). Modeling response of soil erosion and runoff to changes in precipitation and cover. *Catena, 61*(3), 131-154. doi: 10.1016/j.catena.2005.03.007

Nóbrega, H. M. (1978). *História do rio Tietê.* Governo do Estado de São Paulo.

Ouyang, W., Skidmore, A. K., Hao, F., & Wang, T. (2010). Soil erosion dynamics response to landscape pattern. *Science of the Total Environment, 408*(6), 1358-1366. doi: 10.1016/j.scitotenv.2009.10.062

Panagos, P., Borrelli, P., Meusburger, K., Alewell, C., Lugato, E., & Montanarella, L. (2015). Estimating the soil erosion cover-management factor at the European scale. *Land Use Policy, 48,* 38-50. doi: 10.1016/j.landusepol.2015.05.021

Panagos, P., Standardi, G., Borrelli, P., Lugato, E., Montanarella, L., & Bosello, F. (2018). Cost of agricultural productivity loss due to soil erosion in the European Union: From direct cost evaluation approaches to the use of macroeconomic models. *Land Degradation & Development, 29*(3), 471-484. doi: 10.1002/ldr.2879

Prasannakumar, V., Vijith, H., Abinod, S., & Geetha, N. (2012). Estimation of soil erosion risk within a small mountainous sub watershed in Kerala, India, using Revised Universal Soil Loss Equation (RUSLE) and geo information technology. *Geoscience Frontiers, 3*(2), 209-215. doi: 10.1016/j.gsf.2011.11.003

Renard, K. G., Foster, G. R., Weesier, G. A., Mccool, D. K., & Yoder, D. C. (1997). *Predicting soil erosion by water: a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE).* United States Department of Agriculture.

Rossi, M. (2017). *Mapa pedológico do Estado de São Paulo: revisado e ampliado.* Instituto Florestal.

Santos, F. M., Oliveira, R. P., & Mauad, F. F. (2020). Evaluating a parsimonious watershed model versus SWAT to estimate streamflow, soil loss and river contamination in two case studies in Tietê river basin, São Paulo, Brazil. *Journal of Hydrology: Regional Studies, 29,* 100685. doi: 10.1016/j.ejrh.2020.100685

Santos, H. G., Jacomine, P. K. T., Anjos, L. H. C., Oliveira, V. A., Lumbreras, J. F., Coelho, M. R., Almeida, J. A., Araujo, J. C., Oliveira, J. B., & Cunha, T. J. F. (2018). *Sistema brasileiro de classificação de solos* (5a ed. rev. ampl.). EMBRAPA.

São Paulo (2008). Resolução SMA Nº 88, de 19 de dezembro de 2008. Secretaria Estadual de Meio Ambiente. Diário Oficial do Estado de São Paulo, São Paulo. https://www.infraestruturameio ambiente.sp.gov.br/ legislacao/2008/12/resolucao-sma-88-2008/

Seabra, O. C. L. (2018). Bacia do Alto Tietê: a montagem do sistema hidrelétrico de São Paulo e sua problemática. *Boletim Paulista de Geografia, 100,* 56-84. https://publicacoes.agb.org.br/index.php/boletim-paulista/article/view/1499

Silva, A. M., & Alvares, C. A. (2005). Levantamento de informações e estruturação de um banco de dados sobre a erodibilidade de classes de solos no Estado de São Paulo. *Geociências, 24*(1), 33-42. http://www.ppegeo.igc.usp.br/index.php/GEOSP/article/view/9738

Silva, F. G. B., Minotti, R. T., Lombardi, F., Neto, Primavesi, O., & Crestana, S. (2010). Previsão da perda de solo na Fazenda Canchim - SP (EMBRAPA) utilizando geoprocessamento e o USLE 2D. *Engenharia Sanitaria e Ambiental, 15*(2), 141-148. doi: 10.1590/S1413-41522010000200005

SOS Mata Atlântica (2020). *Observando o Tietê 2020: o retrato da qualidade da água e a evolução dos indicadores de impacto do Projeto Tietê.* SOS Mata Atlântica.

Vanoni, V. A. (1975). *Sediment deposition engineering.* American Society of Civil Engineers.

Wischmeier, W. H., & Smith, D. D. (1978). *Predicting rainfall erosion losses. A guide to conservation planning.* Supersedes Agriculture Handbook. United States Department of Agriculture.

Zanirato, S. H. (2011). História da ocupação e das intervenções na várzea do Rio Tietê. *Revista Crítica Histórica, 2*(4), 117-129. doi: 10.28998/rchvl2n04.2011.0007

Zerihun, M., Mohammedyasin, M. S., Sewnet, D., Adem, A. A., & Lakew, M. (2018). Assessment of soil erosion using RUSLE, GIS and remote sensing in NW Ethiopia. *Geoderma Regional, 12,* 83-90. doi: 10.1016/j.geodrs.2018.01.002