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SIMULATING THE EFFECT OF PERMANENT PRESERVATION AREAS ON SOIL EROSION RATES

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HIGHLIGHTS

The watershed does not have riparian forests around most of the watercourses.

The watershed has areas with soil losses above tolerable limits.

Areas with higher vegetation cover had lower soil losses.

Permanent preservation areas could reduce the soil loss in the watershed soil by 10%.

ABSTRACT

Water erosion is one of the main problems faced by the Furnas Lake Surrounding Watershed, located in southeast Brazil. The erosive process is intensified by inadequate land occupation of the lake margins where should be riparian forests, or permanent preservation areas (APP), in order to protect water resources. In this context, our work aimed to estimate the soil losses of this watershed using the Revised Universal Soil Loss Equation (RUSLE) in two different scenarios: I - considering the actual occupation of the area, and II - building an alternative scenario where permanent preservation areas were present. Therefore, we considered physical, edaphoclimatic, and land use and management factors. To simulate the presence of preservation areas, we based it on the Brazilian Forest Code (Bill no. 12.651/2012). In the real scenario (I), the total soil loss estimated was 31,580,907.47 Mg.year^{-1} (32% over the Soil Loss Tolerance) with an average loss of 19.00 Mg·ha^{-1}.year^{-1}, while in the conservationist scenario (II), there was 10% decrease, which means the mitigation of the erosion process as well as of the negative environmental impacts that can be generated by soil degradation.

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INTRODUCTION

Water erosion is one of the most important forms of soil degradation in Brazilian agriculture, and this problem can be aggravated by inadequate land-use and occupation, and by the lack of environmental management practices to soil conservation (Dechen et al., 2015; Cunha et al., 2017). High erosion rates can reduce agricultural productivity, cause siltation of watercourses, and decreasing water quality due to the transportation of sediments, nutrients and agrochemicals (Beskow et al., 2009).

Empirical models of prediction are useful tools to evaluate erosion rates and establish plans to reduce soil losses (Cunha et al., 2017). These models require easily obtainable and low-cost information, moreover, large scale water erosion evaluate is only possible with modeling techniques (Alewell et al., 2019). The Revised Universal Soil Loss Equation (RUSLE), developed by Renard et al. (1997), is a widely used model to estimate annual soil loss in watersheds (Ganasri and Ramesh, 2016) that requires low data input and overcome climatic and geographic restrictions (Bhandari et al., 2015). Associating the RUSLE with Geographic Information Systems (SIG), it is possible to produce maps to identify areas with an elevated risk of erosion and estimate the impacts of the different scenarios of land occupation, as well as the conservation practices effects on agricultural lands (Galdino et al., 2016).

Water erosion is one of the main issues faced by the Furnas Lake Surrounding Watershed, located in southeast Brazil. This watershed has a high capacity to produce water and a national strategic role in electricity production. The erosive process is intensified by the inappropriate land occupation of the lake margins with crops and pasture, eliminating the riparian forests or permanent preservation areas (APP), removing the protection of water resources (IGAM, 2013). According to the Brazilian Forest Code, the watercourses margins should be designated to Permanent Preservation Areas (APP) and, being covered or not with native vegetation, have the function of preserve water resources and biodiversity, protect the soil and ensure the well being of the communities (Brasil, 2012).

The identification of critical areas is fundamental to implement erosion mitigation practices and achieve an effective soil conservation program (Ganasri and Ramesh, 2016). Moreover, public policies concerning agriculture and the environment can generate effects on the erosion rates, reducing or amplifying them (Devátý et al., 2019). Therefore, our work aimed to estimate soil losses by water erosion over the Furnas Lake Surrounding Watershed using the Revised Universal Soil Loss Equation (RUSLE) in two different scenarios: I - considering the actual land occupation, and II - building an alternative scenario where permanent preservation areas were present around the lake.

MATERIAL AND METHODS

Study site

The state of Minas Gerais is separated into 36 Water Resources Planning and Management Units (WRPMU), which are characterized by physical, socio-cultural, economic, and political aspects (IGAM, 2013). The Furnas Lake Surrounding Watershed belongs to the Rio Grande hydrographic Basin and is one of the WRPMU called GD3. Furnas Hydroelectric Plant is located in the GD3 (Figure 1), which presents an area of 16,643.00 km^2 and covers 48 municipalities with an estimated population of 842,260.00 inhabitants (IBGE, 2011). The predominant climates on the area are, according to Köppen classification, subtropical highland (Cwb) and humid subtropical (Cwa) (Alvares et al., 2013). The average annual temperature range between 21 and 23°C, and the average annual precipitation, between 1300 and 1600 millimeters (IGAM, 2013).

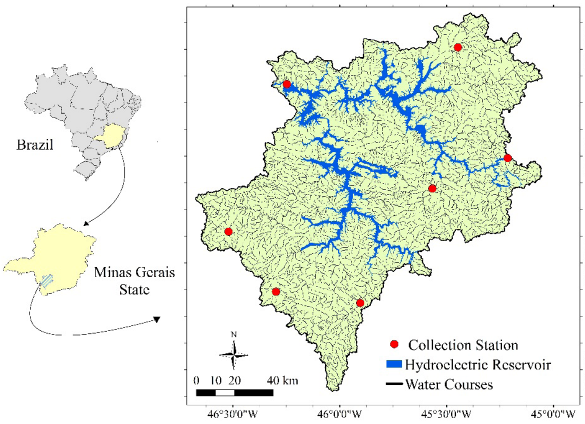

FIGURE 1 Location of the Furnas Lake Surrounding Watershed and the sediment collection stations of the Instituto Mineiro de Gestão das Águas, Minas Gerais, Brazil.

Revised Universal Soil Loss Equation (RUSLE)

The Revised Universal Soil Loss Equation (RUSLE) estimates the average soil loss of a given area according to Equation 1 (Renard et al., 1997). The parameters, data processing, and the modeling itself were developed on ArcMap 10.3 (ESRI, 2015), using the Spatial Analyst extension, where, A= average annual soil loss (Mg ha^{-1} year^{-1}); R= rainfall erosivity factor (MJ mm ha^{-1} h^{-1} year^{-1}); K= soil erodibility factor (Mg.ha^{-1} MJ^{-1} mm^{-1}); LS =

topographic factor, given by the relation between the relief length (L) and declivity (S) (dimensionless); C = cover and management factor (dimensionless); P = conservation practices factor (dimensionless).

$$A = R \cdot K \cdot LS \cdot C \cdot P \qquad [1]$$

Rainfall erosivity (R)

The R-factor represents the potential of a pluviometric precipitation to disaggregate particles of an unprotected soil. This factor takes into consideration the total precipitation and the kinetic energy of rainfall drops on the soil (Beskow et al., 2019). Due to the lack of detailed registers about the basin rainfalls, we generated a geographic and multivariate model to the southeast region of Brazil, as proposed by Mello et al. (2013) (Equation 2), which allows to estimate the average annual rainfall erosivity using the latitude, longitude, and altitude from the study watershed. The calculation was executed on the Raster Calculator tool (ESRI, 2015) through each cell of the Digital Elevation Model (DEM), where, R = rainfall erosivity factor (MJ mm ha^{-1} h^{-1} $year^{-1}$); A= average annual soil loss (Mg ha-1 year-1); LA = latitude and LO = longitude, both in decimal negative degree.

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

The R-factor values for the watershed ranged from 6.140 to 12.320 MJ mm ha^{-1} h^{-1} $year^{-1}$ (Figure 2).

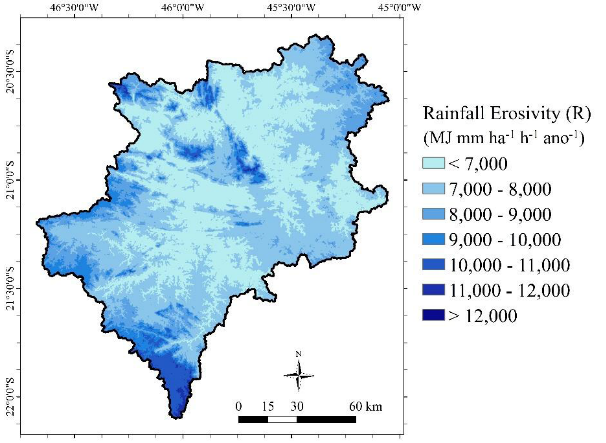

FIGURE 2 Rainfall erosivity factor (R) for the Furnas Lake Surrounding Watershed, Minas Gerais, Brazil.

Soil erodibility (K)

The K-factor represents the intrinsic soil susceptibility to water erosion according to its physical and chemical attributes. The values of this factor can be calculated by experimental plots, but field tests can be expensive and consume time (Beskow et al., 2009). Therefore, we resort to the specialized literature to determinate how resistant the basin soils are, using reported values (Sá et al., 2004; Silva and Alvares, 2005; Silva et al., 2009; Martins et al., 2011). The Map of the soils of Minas Gerais state (UFV et al., 2010) was employed as reference to define the spatial distribution of the K-factor (Figure 3).

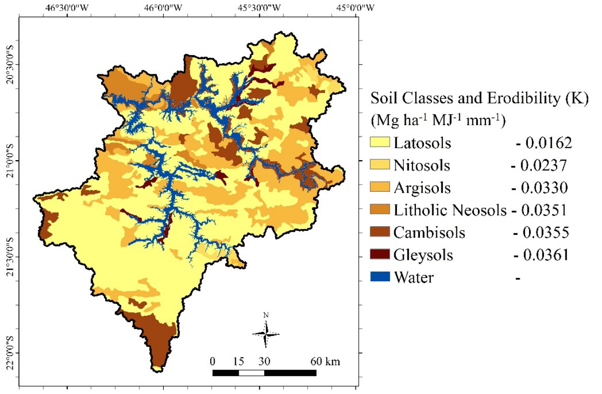

FIGURE 3 Digital map of the Soils and K-factor values for the Furnas Lake Surrounding Watershed, Minas Gerais, Brazil. K-factor was adapted from Sá et al. (2004), Silva and Alvares (2005), and Martins et al. (2011).

The watershed soils were main classified as Latosols (56.69%), followed by Argisols (22.45%), Cambisols (10.53%), Litholic Neosols (3.54%), Nitosols (1.34%) and Gleysols (1.50%).

Topographic factor (LS)

The LS factor expresses the topographic influence on soil erosion (Renard et al., 1997). We calculate this factor using Equation 3, proposed by Moore and Burch (1986), and the average obtained was 3.29 (Figure 4C), where, LS = topographic factor (dimensionless); FA = accumulation flow in the watershed, calculated from the DEM using the ArcMap 10.3 Flow accumulation tool (ESRI, 2015); S = the basin declivity (degrees), where 30 is the spatial resolution of the DEM cells, in meters. FA represents the redirection of runoff flows in the watershed.

$$LS = \left(\frac{FA \cdot 30}{22.13}\right)^{0.4} \cdot \left(\frac{\sin(S)}{0.0896}\right)^{1.3} \qquad [3]$$

The Digital Elevation Model (Figure 4A) was elaborated using the level curves obtained in the Spatial Data Infrastructure of the Sistema Estadual de Meio Ambiente e Recursos Hídricos (SISEMA, 2019). Then, we produce the declivity map (Figure 4) through the Slope tool (ESRI, 2015). The altitude in the watershed range from 717 to 1470 meters and the predominant relief is moderately undulating with an average inclination of 7.70%.

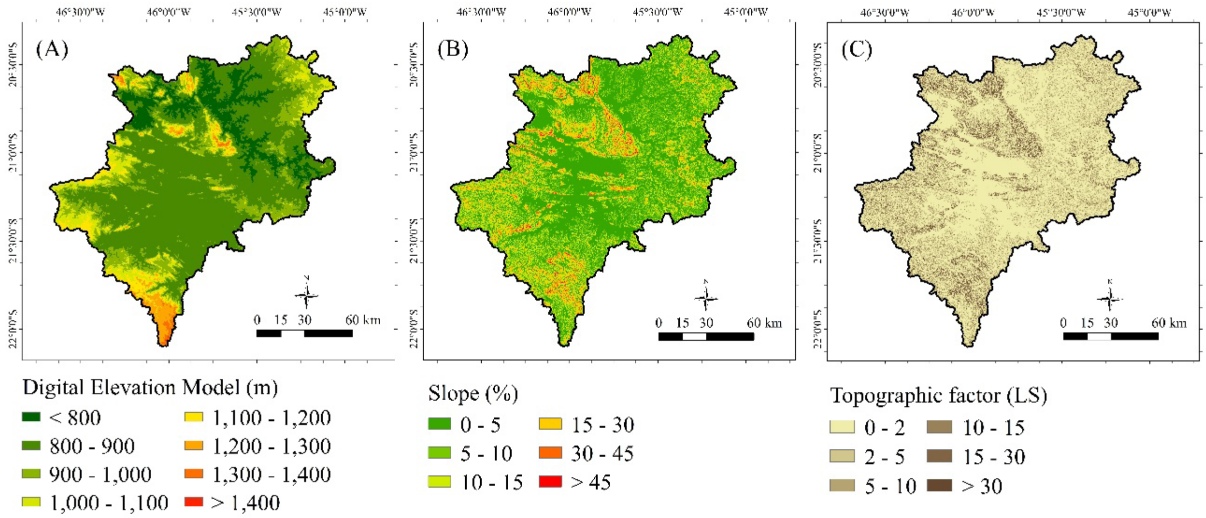

FIGURE 4 Digital Elevation Model (A); Declivity map (B) and LS- Factor (C) for the Furnas Lake Surrounding Watershed, Minas Gerais, Brazil.

Cover management factor (C)

The C-factor refers to the effect of the soil cover against erosion, it ranges from 0 to 1, according to the vegetation density, and higher values represent lower soil protection, due to the impact of the rainfall drops on the soil particles causing it degradation and an intensified surface runoff (Oliveira et al., 2014).

Using the Map of land use of Minas Gerais state of 2018 (Projeto MapBiomas, 2018) as a reference, we elaborated the C-factor map. The watershed area is mainly occupied by pastures (38%) and crops (37.1%), followed by Atlantic Forest (10.19%), Cerrado (4.41%), urbanization (0.62%), bare soils (0.08%) and water bodies (8.05%) (Figure 5).

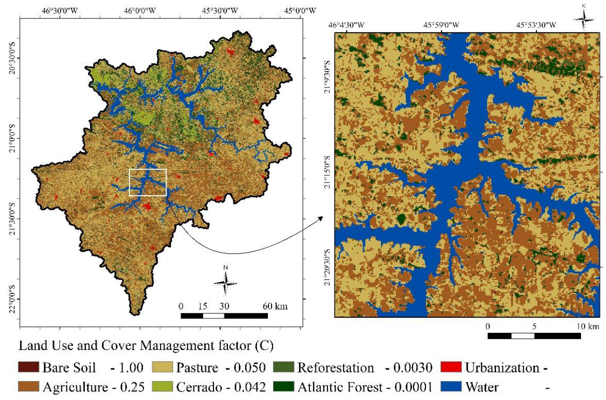

FIGURE 5 Land use map (adapted from the Projeto MapBiomas (2018)) and C-factor (according to Farinasso et al. (2006), Silva et al. (2010) and Bertoni and Lombardi Neto (2012)).

The C-factor values, for each land-use class (Figure 5), were adapted according to Farinasso et al. (2006), Silva et al. (2010), and Bertoni and Lombardi Neto (2012). Bare soils received the maximum value (1), while urban zones and water bodies were not considered on the soil loss equation.

Conservation practices factor (P)

The P-factor ranges from 0 to 1 which express the effect of management practices on soil loss reduction (Oliveira et al., 2014). Due to the wide extent of the watershed, it was not possible to determine the conservation practices of the area. Thus, factor P was calculated with slope as the key property for soil conservation practices (Silva et al., 2010; Medeiros et al., 2016). In slopes lower than 0.5%, the value of P = 0.6 was assumed, and in slopes higher than 20%, we assumed P = 1. For slopes between 0.5 to 20%, the P values of was defined according to Equation 4, Where, P is the factor of conservationist practices (dimensionless), and s is the slope (%).

$$P = 0.69947 - 0.08911 \cdot s + 0.01184 \cdot s^2 - 0.000335 \cdot s^3 \quad [4]$$

Conservationist scenario simulation

To evaluate the impact of the APP presence over water erosion on the Furnas Lake Surrounding Watershed, we built an alternative scenario as if the entire basin was partially adequate with sections I and II of the article 4th of the Brazilian Forest Code (Brasil, 2012).

APPs with vegetation strips of 30 m were simulated for watercourses with less than 10 meters wide; 50 m for watercourses between 10 and 50 m wide; 100 m for watercourses above 50 meters. In the areas surrounding natural lakes and lagoons, the APPs were simulated with 100 m wide in rural areas and 30 m in urban areas.

The APP delimitation around the Furnas Reservoir follows the provisions of the 62th article of the Brazilian Forest Code (Brazil, 2012), that bounds the margins of artificial lakes, intended to generate electricity or public water supply, with concession or authorization previous the Provisory Measure (MP) no. 2.166-67, from august 24th of 2001, as a difference between the maximum normal operative level and the maximum operating quota for which the dam was designed.

The APP delimitation around the Furnas Reservoir followed the provisions of the 62nd article of the Brazilian Forest Code (Brazil, 2012). The bill establishes that artificial lakes whose function is to generate electricity or to supply water, with concession or authorization previous the Provisory Measure (MP) 2.166-67, from August 24th, 2001, must have its margins transformed into preservation areas observing the difference between the maximum normal operating level and the maximum operating quota for which the dam was designed.

Considering that the maximum operative level of the lake is 768 m above sea level, and the maximum operating quota is 769.3 m, the preservation areas would be short and distant from the ideal (Teixeira et al., 2017). Therefore, we built the scenario as if the implementation of the reservoir had occurred after the MP, and we designated 30 m of APP, as established by the code to artificial lakes located in urban zones, and 100 m of APP, for those located in rural areas (Brasil, 2012).

The permanent preservation areas were simulated according to the width of the water courses, and to do so, we use the Buffer tool from ArcMap 10.3 (ESRI, 2015). We obtained the hydrography data from the Sistema Estadual de Meio Ambiente e Recursos Hídricos (SISEMA, 2019), reclassifying latter the land-use map inserting this simulated vegetation margins (Figure 6).

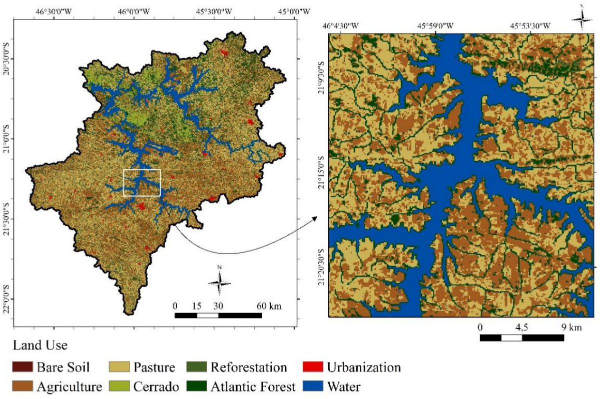

FIGURE 6 Simulation of the conservationist land use scenario in the Furnas Lake Surrounding Watershed, Minas Gerais, Brazil. Adapted from the Projeto MapBiomas (2018).

RUSLE Validation

The sediment production, or net erosion, is the eroded soil fraction transported to the water bodies, and it can be directly observed and measured in the field (which is usually done by the hydro sedimentologic stations), therefore, used to validate soil loss estimates. However, it is worth the mention that, the RUSLE estimates the total of soil erosion (gross erosion), which makes it necessary the integration of the model with the Sediment Delivery Rate (SDR) (Ebrahimzadeh et al., 2018), that represents a relationship between the gross and the net erosion. The SDR was then determined by employing Equation 5 proposed by Varoni (1975), Where, SDR = sediment delivery rate (%); A= watershed area (km^2).

$$SDR = 0.472 \cdot A^{-0.125} \qquad [4]$$

The net erosion observed in the field was acquired using data of the total of transported sediment in the water discharge and of the daily flow, as proposed by Beskow et al. (2009). Initially, we built a curve relating the total of transported sediment and the water discharge of the watershed (Figure 6) with data from hydro-sedimentologic stations operated by the Instituto Mineiro de Gestão das Águas (IGAM), monitored from 2001 to 2018 (Figure 7).

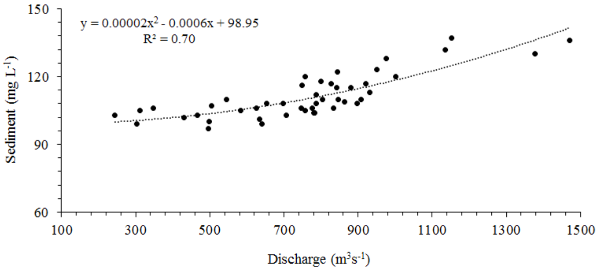

FIGURE 7 Water discharge curve (sediment transported × water discharge) in the Furnas Lake Surrounding Watershed, Minas Gerais, Brazil.

The annual transportation of sediments was calculated considering the flow versus sediment curve and the dataset of daily flow obtained from the Agência Nacional de Águas (ANA, 2019). The observed net erosion was then compared with the soil loss estimate provided by RUSLE.

RESULTS AND DISCUSSION

Gross Erosion

Gross water erosion in the watershed was estimated at 31,580,907.47 Mg year-1. Areas with high slope are those with higher values for the LS-factor and, therefore, presented an intensified erosion process (Figure 8). According to Beskow et al. (2009) and Avanzi et al. (2013), rates below 2.50 Mg ha^{-1} year^{-1}, in the brazilian edaphoclimatic conditions, can be considered as low-intensity erosion, while losses above 15.00 Mg ha^{-1} year^{-1}, represent high risks.

Despite the predominance of water erosion of weak intensity (60% of the basin), about 30% of the area demonstrated being suffering with severe soil loss, reaching values higher than 100 Mg ha^{-1} year^{-1}. Higher rates locations bias the average soil loss of the watershed, pushing it to 19.00 Mg ha^{-1} year^{-1}, and the severe erosion is distributed all over the area, reinforcing the need to plan conservationist measures and to manage the mitigation of the process.

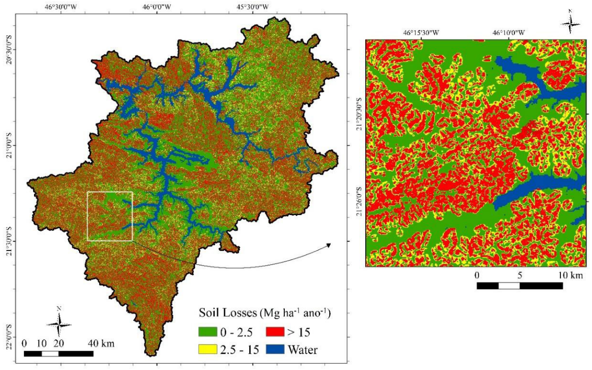

FIGURE 8 Soil Loss Rates in the Surrounding Basin of Furnas Lake, Minas Gerais, Brazil.

Considering the land use and occupation classes, the higher soil losses were detected in bare soil areas (40.70 Mg ha^{-1} year^{-1}), followed by agriculture (36.17 Mg h^{a-1} year^{-1}), cerrado (31.18 Mg ha^{-1} year^{-1}), pastures (12.20 Mg ha^{-1} year^{-1}), reforesting (0.62 Mg ha^{-1} year^{-1}) and Atlantic Forest (0.07 Mg ha^{-1} year^{-1}).

The variation of these rates is related to the C-factor, once high-density vegetation cover (lower C-factor) led to lower losses. A significative portion of the watershed has elevated R-factor (rainfall erosivity), steep relief, and high vulnerability to water erosion, so the soil cover, as well as management practices, can help to attenuate the degradation process. Beskow et al. (2009) also obtained similar results in a watershed located in the same region.

Bare soil areas are concentrated mostly around the hydroelectric reservoir once there was a decrease in its storage volume. Therefore, it is necessary to reforest these spaces, seeking to increase soil protection against the negative effects of the rainfalls, to reduce erosion and the lake siltation.

Agricultural lands also need the adoption of conservationist practices, such adoption of the no-till system, management of plant residues, terracing and level planting, and this task is a responsibility of the farmers, once erosion causes loss of nutrients, organic matter, and agrochemicals, which can harm the agricultural production (Avanzi et al. 2013).

The watershed estimated soil losses were compared to the limits of the Soil Loss Tolerance (T). We adopt the following limits: 5.21 Mg ha^{-1} year^{-1} for Litholic Neosols; 5.82 Mg ha^{-1} year^{-1} for Gleysols; 9.49 Mg ha^{-1} year^{-1} for Cambisols; 9.78 Mg ha^{-1} year^{-1} for Nitosols; 10.50 Mg ha^{-1} year^{-1} for Argisols; and 12.50 Mg ha^{-1} year^{-1} for Latosols (Mannigel et al., 2002; Oliveira et al., 2008).

About 32% of the basin presented losses above the T limits, which turn them into priority areas to adopt mitigation actions. The areas with soil losses above T (5,325.80 km2) are located mainly under Latosols (49%), followed by Argisols (29%), Cambisols (13%), and Litolic Neosols (6%). Moreover, these areas are mostly occupied by agricultural (48%) and pasture (41%). This result strengthens the need for the adequacy of land use and occupation planning in the hydrographic basin according to agricultural suitability of soils, mainly the Neosols and Cambisols, which present high susceptibility to erosion and low T limits. Moreover, is essential to recover the degraded pastures and adopt conservation practices in the subbasin area to avoid soil losses. It is worth the mention that Soil Loss Tolerance sets the limits where the soil losses are manageable in the short term. However, practices to reduce erosion and ensure long-term soil sustainability must still be pursued.

Net Erosion

The sediment delivery rate (SDR) calculated was 14.0% indicating a net erosion of 4,421,327.05 Mg year-1, which shows how much sediments achieve the watershed water bodies. Along with the lake siltation, these residues transport nutrients, especially nitrogen (N) and phosphorus (P), leading into eutrophication and deterioration of the water quality (Chen et al., 2016). The net erosion observed in the field, used as validation, was 2.17 Mg ha^{-1} year-1, which means that RUSLE overestimated the losses by 0.81 Mg ha^{-1} year^{-1}, with an absolute error of 37%. However, considering the large work scale (16,222.06 km^2), it is tolerable.

Erosion modeling is a representation of reality, not the reality itself, therefore, subject to errors (Alewell et al., 2019).Thus, despite the difference between model and validation, the application of RUSLE provided satisfactory results and accomplished its objective of being an accessible predictive tool, capable of providing a reliable diagnosis of the water erosion process.

Conservationist scenario

By simulating a conservationist scenario, we noticed a 50% (57.85 km^2) increase of forests in the watershed area. The simulated permanent preserved areas afforded a 10% decrease of the net erosion, representing 438,300.00 Mg year-1 of soil that is no longer deposited in watercourses. That reduction can be higher than the observed, once these areas act like a physical barrier that retains the eroded soil into the basin, which is not taking into consideration by the RUSLE.

Over 60% of the basin presented gross erosion of weak intensity in the actual scenario, while in the conservationist scenario, 65%. Introducing the APP, the proportion of high-intensity erosion was reduced to 27%, and sites with soil losses above the T limits decreased from 32.0% to 29.0%, which is equivalent to a reduction of 486.65 km^2.

APPs also can improve water quality by decreasing the direct transfer of nutrients and contaminants to watercourses (Bispo et al., 2017). Also, vegetation in the margins could increase the reservoir lifetime by reducing siltation.

It is worth the mention that the present study simulated the implementation of permanent preservation areas and their effects, without considering the social and economic aspects involved in the implementation of such areas. However, the possibility of implementing long-term measures that favor the growth of marginal vegetation should be considered in the river basin management planning, once the reduction of water erosion is one of the many ecosystem benefits and services that APP can provide to the environment. In addition to the recovery of APPs, the Government should increase the inspection of illegal deforestation, to ensure that the current APP conservation scenario is closer to that provided in the Brazilian Forest Code (Brasil, 2012).

CONCLUSIONS

The Revised Universal Soil Loss Equation (RUSLE) satisfactorily simulated the erosion process and pointed to higher soil loss rates in areas of steep relief, especially when occupied with crops or bare soil. The model allowed to determine areas with losses above the T limits (32.0%), and those are a priority to the adoption of actions to control water erosion. The simulation of the permanent preservation areas led into a 10% decrease of the soil losses, and given that, the implementation of permanent preservation areas could be an alternative to reduce water erosion and the reservoir siltation on the Furnas Lake Surrounding Watershed.

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