Reduction of sediment yield by riparian vegetation recovery at distinct levels of soil erosion in a tropical watershed

Redução da produção de sedimentos pela recuperação da vegetação ripária em níveis distintos de erosão do solo em uma bacia hidrográfica tropical

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ABSTRACT

Riparian vegetation plays an important role in sediment retention, thus reduces sediment yield in watersheds. The Brazilian Forest Law (Law 12,651/2012) requires maintenance of fixed-width buffers of riparian vegetation but allows the continuity of agriculture, livestock, and forestry farming activities in some parts of the Areas of Permanent Preservation (APP). This paper aimed to evaluate sediment reduction by recovering the APPs with vegetation strips of permitted widths (5, 8, 15, and 30 m), as per the Forest Law. We considered three land use scenarios that present distinct erosion rates – predominance of areas with forest cover, pasture, and agriculture. The Soil and Water Assessment Tool (SWAT) model was used to simulate sediment yield in these scenarios at the Jundiaí-Mirim Watershed in São Paulo, Brazil. The SWAT was calibrated and validated for monthly streamflow. We obtained statistical indices for the processes of calibration and validation, respectively, as: NS = 0.77 and 0.70, PBIAS = -10.2 and -12.5, and RSR = 0.48 and 0.55. The highest reduction in sediment yield (30%) was observed with the total recovery of the APPs (vegetation strips of 30 m) in the current land use scenario. The recovery of the APPs with vegetation strips of 5, 8, and 15 m yielded sediment reduction below 10% in the alternative land use scenarios. The APP strips with reduced recovery maintained high rates of sediment yield. Additionally, even with a total recovery of the APP it is necessary to adopt soil conservation practices throughout the basin's agricultural area to minimize the impacts on water resources.

Index terms: SWAT; APP restoration; Brazilian Forest Law; Land use scenarios.

RESUMO

Considera-se que a vegetação ripária desempenha papel importante na retenção de sedimentos e, portanto, na diminuição da produção de sedimentos em bacias hidrográficas. A Lei Florestal (Lei 12.651/2012) determina a manutenção da vegetação ripária em faixas de largura fixa, mas permite a continuidade das atividades agrossilvipastoris em parte das Áreas de Preservação Permanente (APPs). Buscou-se, por meio deste estudo, avaliar a redução da produção de sedimentos pela recuperação da vegetação das APPs em 5, 8, 15 e 30 m, larguras admitidas pela Lei Florestal, considerando três cenários de uso do solo, que apresentam diferentes taxas de erosão: predomínio de áreas de floresta, pastagem e agricultura. O modelo SWAT (*Soil and Water Assessment Tool*) foi utilizado para simular a produção de sedimentos nesses cenários na bacia hidrográfica do rio Jundiaí-Mirim, localizada no estado de São Paulo, Brasil. O SWAT foi calibrado e validado para a vazão em escala mensal, obtendo-se os seguintes índices estatísticos: NS = 0,77 e 0,70, PBIAS = –10,2 e –12,5, RSR = 0,48 e 0,55 nos processos de calibração e validação, respectivamente. O maior valor de redução da produção sedimentos gerados (30%) foi observado com a recuperação total das APPs (30 m) no uso atual da bacia. Recuperando-se as APPs em 5, 8 e 15 m, a redução da produção de sedimentos ficou abaixo de 10%, nos cenários alternativos. As faixas reduzidas de APPs recuperadas mantêm alta a produção de sedimentos. E, ainda, mesmo com a recuperação total das APPs é necessário adotar práticas de conservação do solo em toda a área agrícola da bacia, a fim de minimizar os impactos nos cursos hídricos.

Termos para indexação: SWAT; recuperação das APPs; Legislação Florestal Brasileira; cenários de mudança do uso do solo.

INTRODUCTION

Land use affects the components of the hydrological cycle and, consequently, sediment flows in watersheds (Ghaffari et al., 2010; Alvarez-Garreton et al., 2019; Kang et al., 2020; Zhang et al., 2020). Since the removal of natural vegetation induces accelerated soil erosion, replacing forests with agricultural land significantly increases erosion rates (Germer et al., 2009). It is estimated that the replacement of forests with cropland increases soil erosion by 52% worldwide (Borrelli et al., 2017).

The sediments generated due to erosion are carried to watercourses, lakes, ponds, and artificial dams, taking nutrients and pesticides adsorbed on their surfaces. This results in silting up of river channels and contamination of water bodies, hence putting them at risk (Hajigholizadeh; Melesse; Fuentes, 2018; Himanshu et al., 2019). Additionally, there are costs resulting from the repair of damages caused by sediment deposition in rivers, lakes, and dams (Batista et al., 2017; Food and Agriculture Organization of the United Nations - FAO, 2019). Riparian vegetation plays a major role in mitigating these impacts, as this strip acts as a natural barrier to the movement of sediments. Hence, the contaminants adsorbed on them are prevented from reaching the watercourses (Santos; Sparovek, 2011; Mekonnen et al., 2014; Sweeney; Newbold, 2014; Mello et al., 2017). On the other hand, alternative uses of the strips surrounding the water bodies result in less ground cover and tend to increase sediment yield since the strips do not retain enough sediments.

Watercourses that cross agricultural areas have high sediment concentrations, especially when the riparian vegetation is narrow or absent (Allan et al., 1997; Broadmeadow; Nisbet, 2004). Restoration of riparian vegetation reduces the sediment, nitrogen, and phosphorus loads that reach the watercourses (Mello et al., 2017), providing benefits, such as prevention of soil contamination and protection of biodiversity (Sweeney et al., 2004; Sparovek et al., 2012).

The Brazilian Forest Law states that fixed-width buffers surrounding watercourses, springs, lakes, and ponds should be protected through the preservation or recovery of natural vegetation. These areas are called "Areas of Permanent Preservation" (APP) (Brasil, 2012). However, the Forest Law allows the continuation of agriculture, livestock, and forestry farming activities initiated before July 2008. In these circumstances, riparian vegetation is maintained only in a small portion of the APPs.

The APP strips without recovered vegetation can act as sources of sediment; additionally, they are less efficient in retaining sediments from the upper catchment area (Guidotti et al., 2020). There are a few studies on the effects of riparian vegetation on sediment yield in river basins, mainly for widths as narrow as those allowed by the Brazilian Forest Law.

Studies like this can be performed through hydrological modeling, a tool that allows predicting and evaluating the impacts of changes in land use on the dynamics of water and sediments in watersheds (Bressiani et al., 2015). The Soil and Water Assessment Tool (SWAT) hydrological model (Arnold et al., 2012) is a semi-distributed, time-continuous, and process-based river watershed model that allows assessment of the impact of land use and management on soil and streams in small to large watersheds. SWAT has been applied in several studies worldwide for watershed planning and management (Betrie et al., 2011; Gassman; Sadeghi; Srinivasan, 2014; Bressiani et al., 2015; Vigiak et al., 2016; Khelifa et al., 2017; Kaffas; Hrissanthou; Sevastas, 2018; Gharibdousti; Kharel; Stoecker, 2019; Qiu et al., 2019; Rafee et al., 2019).

Several studies around the world have utilized SWAT as a tool to evaluate the reduction of sediment yield in riparian forests. Shan et al. (2014) determined the optimal width of the vegetation strip that assured clean water in reservoirs that varied with the type of soil and topography. Zhang et al. (2017) assessed the effect of the size of sub-basin partition on modeling and identified a reduction in sedimentation rate from 74.07% to 29.4%, due to riparian buffers, among the eight sub-watersheds they studied. Moriasi, Steiner and Arnold, (2011) found that applying a riparian forest buffer only and a combination of a riparian forest buffer and filter strip buffer simultaneously resulted in a reduction in suspended sediment concentration by 68% and 72%, respectively. Vigiak et al. (2016) evaluated the effect of current riparian land in reducing sediment fluxes in a stream network. They concluded that the impact of riparian filtering on reducing sediment fluxes in stream networks at hillslopes was always positive, with a median efficiency of 50%. Monteiro et al. (2016) used the SWAT model to estimate the effects of recovery of riparian vegetation strips of 5, 30, and 60 m width on river discharges and sediment exports. They concluded that the riparian forest reduces the sediment yield by 23.8%, 29.4%, and 31.4% in vegetation strips of 5, 30, and 60 m width, respectively.

However, some questions remain unanswered. First, how do different widths of recovered riparian

forests reduce sediment yield at upstream regions with different erosion rates? And second, is the reduction in sediment yield associated with the increase in the width of the recovered APP? These questions led to the formulation of this study.

This work stems from the hypothesis that there is a proportional decrease in sediment yield with an increase in the recovered APP width, even in areas with high soil erosion rates. Our objective was to evaluate the reduction of sediment yield at different widths of recovered APPs along watercourses, around springs, and at water bodies. We studied the effect of current land use, and alternative land uses (with higher rates of soil erosion) at the river basin.

MATERIAL AND METHODS

Study area

The study was performed at the Jundiaí-Mirim Watershed (JMW), which is a part of the "Water Resources Management Unit 5" (UGRHI 5; acronym in Portuguese) in São Paulo, Brazil. It is located between 23° 05'S and 23° 11'S, and 46° 44'W and 46° 51'W (Figure 1). The JMW covers an area of 11,750 ha, but this study was performed in an area of 9,545 ha located upstream of the flow control point. The climate of this region is in a transition band between Cfa and Cfb, according to the Köppen climate classification (Alvares et al., 2013). The region has rainy summers and dry winters, an annual mean temperature of 21 °C (min: 14.5 °C, max: 27.4 °C), and annual mean rainfall of 1,450 mm. The mean elevation of the study region is 794 m above sea level and ranges from 712 to 952 m. The soil types according to the World Reference Base for Soil Resources (WRB) are - Dystric Cambisol (Clayic) (64%), Dystric Leptosol (Loamic, Ochric) (10%), Rhodic Ferralsol (Clayic, Dystric, Ochric) (10%), Haplic Ferralsol (Clayic, Dystric, Ochric) (9%), Dystric Gleyic Cambisol (Clayic) (5%), Haplic Acrisol (Loamic and Clayic) (1%), and Dystric Gleysol (Loamic) (1%). The landform comprises hills and high hills with convex tops and valleys of medium carving and medium interflow dimensions. Land uses comprise native forests (32%), planted pastures (19%), rangelands (8%), and plantations of *Eucalyptus* spp. (9%). Crops such as grains, fruits, and vegetables together account for 18% of additional land use. Urbanized areas represent 9% of land use, and bare soil areas occupy 3% of the total land. Finally, other uses such as roads, lawns, wetlands, and water bodies represent 2% of the JMW area (Moraes; Carvalho; Peche Filho, 2016). The predominant soil type and topology (slope class) of JMW

favor erosion. Therefore, sedimentation of water bodies tends to be a relevant problem in this basin.
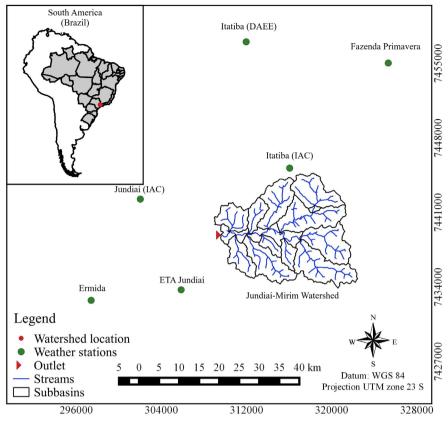
The SWAT model

The SWAT model simulates spatial soil water content, runoff, soil erosion, nutrient cycles, plant growth, and crop management practices for each Hydrological Response Unit (HRU). An HRU consists of homogeneous land use, management, soil, and topographical characteristics. The hydrological processes of a watershed are modeled on a daily time-step, predicting the impact of land use and management on water, sediment, and agricultural chemical yields. It uses the water balance equation to simulate hydrological processes. Sediment yield is estimated using the "Modified Universal Soil Loss Equation" (MUSLE), where the model calculates the flow of sediments to rivers; thus, simulating the stages of transport and deposition (Neitsch et al., 2011; Arnold et al., 2012).

Climate data and river discharge

Daily rainfall data were obtained from six meteorological stations (Figure 1). The data on solar radiation, wind velocity, relative humidity, and maximum and minimum air temperatures were obtained from one of them (Jundiaí (IAC)). The monthly streamflow data were obtained from the fluviometric station of the Department of Water and Sewage of Jundiaí (Ponte do Fava) located in the JMW outlet. All data presented here are from 2004 to 2017.

Digital elevation model (DEM), land use, and soil data

The digital elevation model (DEM) was generated from interpolating 2 m digital contour maps and the drainage network of the basin. The land use map (scaled at 1:25,000) was generated for 2013 from digital orthophoto and images from the GeoEye-1 satellite. The soil map (scaled at 1:20,000) was obtained from Moraes, Carvalho and Peche Filho, (2016) (Figure 2). These maps originally had a spatial resolution of 30 x 30 m; however, to simulate the APP strips of 5, 8, and 15 m width, the data was standardized with a spatial resolution of 5 m x 5 m. In this study, six slope classes (0–5%, 5–10%, 10–15%, 15–20%, 20–25%, and >25%) were defined, and 3869 HRUs were generated from the soil and land use map. The HRUs were generated using the DEM, slope classes, the current use map of the JMW, and 13 sub-basins were created. To adjust the conditions of the JMW, values for the C- and P- factors of the Universal Soil Loss Equation (USLE_C and USLE_P) and the Curve-Number (CN) were inserted in the SWAT model database (Table 1, 2, and 3).

Figure 1: Location, boundaries, and drainage network of the Jundiaí-Mirim Watershed (JMW), and observations stations (six weather stations and one fluviometric gauge station).

SWAT calibration and validation

Data from 2004 to 2017 was used for the simulation of the scenarios, with data for the first four years used for the warm-up of the SWAT model. Thus, the results are from 2008 to 2017. Average monthly streamflow data from 2011 to 2014 were used for calibration, and the data for the years 2015 and 2017 were used for the validation procedure. The SWAT Calibration and Uncertainty Programs (SWAT-CUP), and the Sequential Uncertainty Fitting algorithm (SUFI2) were used to investigate sensitivity and uncertainty in predictions of streamflow. The SUFI2 was chosen because of its speed, robustness, and versatility. Additionally, it provides the use of broader ranges of parameters in the uncertainty intervals and enables fewer iterations to achieve flow calibration compared to other methods. We selected the Nash-Sutcliffe coefficient (NS) (Moriasi et al., 2007) as the objective function to compare the performance of simulations using the observations as reference. To perform sensitivity analysis, 19 parameters related to
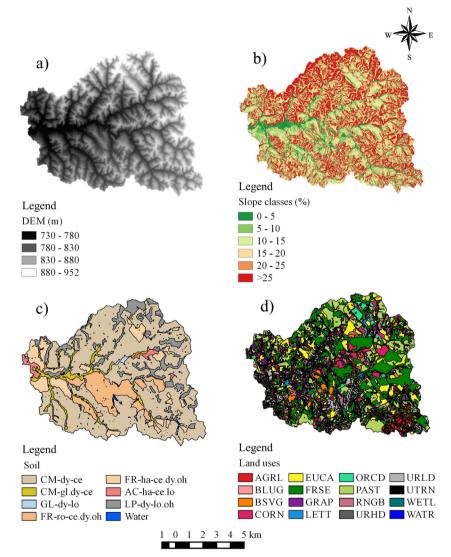
hydrological processes in watersheds were selected, and their initial ranges were determined (Table 4). The t-stat indicators and p-values were used to identify the most sensitive parameters of JMW in the sensitivity analysis (Abbaspour; Vagnefi; Srinivasan, 2018; Premanand et al., 2018). To assess the uncertainties of calibration and validation, the p- and r- factors were used.

Although the focus of this study was the analysis of sediment yield, it was not possible to perform calibration for this variable. The absence of the recorded data was a limiting factor for sediment calibration. However, we argue that most of the parameters used in the hydrologic calibration process strongly influenced the sediment yield.

Scenarios assessed

To obtain different soil erosion rates in the JMW, three scenarios of land use were created. These scenarios do not necessarily represent the trend of the land use dynamics of the watershed. Hypothetical scenarios of

land use change have been used previously to assess the impacts of those changes on hydrological components and sediment flows (Ghaffari et al., 2010; Can et al., 2015). The scenarios of land use were based on the conversion of native forests in the current use scenario to pasture and agricultural areas (conventionally growing corn), resulting in three land use scenarios, viz., current land use (LUC), land use changed to pasture (LUP), and land use changed to agriculture (LUA). The pasture and agricultural areas at JMW increased by 31.8% in the LUP and LUA scenarios, relative to the areas of native forests in LUC (Table 5).

Figure 2: Digital elevation model (DEM) (a), map of slope classes (b), soil types (c), and land uses (d) of JMW. Dystric Cambisol (Clayic), Dystric Gleyic Cambisol (Clayic), Dystric Gleysol (Loamic), Rhodic Ferralsol (Clayic, Dystric, Ochric), Haplic Ferralsol (Clayic, Dystric, Ochric), Haplic Acrisol (Clayic and Loamic), Dystric Leptosol (Loamic, Ochric). AGRL: cropland; BLUG: grassland; BSVG: bare soil; CORN: corn; EUCA: *Eucalyptus* spp.; FRSE: native forest; GRAP: vineyard; LETT: vegetable garden; ORCD: orchard; PAST: pasture; RNGB: rangeland; URHD: urban high density; URLD: urban low density; UTRN: roads; WETL: wetland; WATR: water.

Table 1: C factor values inserted in the SWAT model.

Land use[*]	Description	C factor
AGRL	Cropland[**]	0.1345[1]
BLUG	Grassland	0.0030[1]
BSVG	Bare soil	1.0000[1]
CORN	Corn	0.1100[2]
EUCA	*Eucalyptus* spp.	0.0491[5]
FRSE	Native forest	0.0004[3]
GRAP	Vineyard	0.0875[1]
LETT	Vegetable garden	0.1350[1]
ORCD	Orchard	0.0875[1]
PAST	Pasture	0.0080[4]
RNGB	Rangeland	0.0010[3]
URHD	Urban high density	0.0075[1]
URLD	Urban low density	0.0075[1]
UTRN	Roads	0.0100[1]
WATR	Water	0.0000[1]
WETL	Wetland	0.0004[1]

[*]Code used in SWAT. [**]Non conservationist conventional agriculture. Source: [1]Adapted from Bertoni and Lombardi Neto (2017); [2]De Maria and Lombardi Neto (1997); [3]Silva et al. (2010); [4]Weill and Sparovek (2008); [5]adapted from Silva et al. (2010).

Table 2: P factor values inserted in the SWAT model.

Slope classes (%)	P factor[*]
0 - 5	0.5
5 - 10	0.6
10 - 15	0.7
15 - 20	0.8
20 - 25	0.8
> 25	0.9

[*]P factor of the Universal Soil Loss Equation (USLE_P). Source: Adapted from Bertoni and Lombardi Neto (2017).

Four APP vegetation recovery scenarios of 5, 8, 15, and 30 m widths (Table 6), taking into account that all watercourses in the watershed are up to 10 m wide, were created. The buffers were inserted along with drainage networks through QGIS 2.6.1 Brighton. The vegetation recovery scenarios in the APPs (0, 5, 8, 15, and 30 m wide) were associated with the three land use scenarios (LUC, LUP, and LUA), resulting in a total of 15 scenarios.

Table 3: CN values for soil moisture condition II inserted in the SWAT model.

Land use	A[*]	B[*]	C[*]	D[*]
AGRL	62	71	78	81
BLUG	31	59	72	79
BSVG	77	80	91	94
CORN	62	71	78	81
EUCA	30	51	70	77
FRSE	20	40	49	52
GRAP	43	65	76	82
LETT	58	72	81	85
ORCD	43	65	76	82
PAST	39	61	74	80
RNGB	30	48	65	73

[*]Soil hydrologic group. AGRL: cropland; BLUG: grassland; BSVG: bare soil; CORN: corn; EUCA: *Eucalyptus* spp.; FRSE: native forest; GRAP: vineyard; LETT: vegetable garden; ORCD: orchard; PAST: pasture; RNGB: rangeland; URHD: urban high density; URLD: urban low density; UTRN: roads; WETL: wetland; WATR: water. Source: Adapted from Neitsch et al. (2011).

Calculation of reduction in sediment yield

Reduction in sediment yield by the APPs was determined according to the Equation 1:

$$R_{syld} = \frac{(SYLD_{withoutAPP} - SYLD_{withAPP})}{SYLD_{withoutAPP}} \times 100 \qquad (1)$$

Here, R_{syld} is the reduction in sediment yield (%); $SYLD_{withoutAPP}$ is sediment yield (Mg ha^{-1}) for scenarios (LUC, LUP, and LUA) at unrecovered APPs; $SYLD_{withAPP}$ is sediment yield (Mg ha^{-1}) for scenarios at recovered APPs after accounting for the width of the strips (5, 8, 15, and 30 m) for each of the land use scenarios. To calculate the R_{syld}, sediment yield of the LUC, LUP, and LUA scenarios at unrecovered APPs were subtracted from the sediment yield of the respective scenarios at recovered APPs.

Statistical analysis

To determine the normality and difference between the scenarios, the data was organized by monthly averages of the sediment yield (Mg ha^{-1}) for the study period (10 years) of each scenario. We performed the Shapiro-Wilk normality test for all scenarios ($\alpha < 0.05$). We compared the land use scenarios using the two-sample Kolmogorov-Smirnov test ($\alpha < 0.10$) (Vlček; Huth, 2009). The two-sample Kolmogorov-Smirnov test is a non-parametric

and distribution-free test that compares the cumulative distributions of the datasets. The null hypothesis of this test considers that two independent samples come from the same distribution (Heumann; Shomaker; Shalabh, 2016).

The *p*-value indicates significant differences between the evaluated scenarios (here: $\alpha < 0.10$), and the *D* value indicates the distance between the probabilistic curves of the evaluated scenarios.

Table 4: Parameters used in the sensitivity analysis of the model, methods (r or v), description, units, and their initial value ranges.

Parameter	Description	Initial range
r_CN2.mgt*	Curve-number in condition II of moisture **	-0.2 to 0.2
r_SLSUBSN.hru	Average slope length [1]	-0.25 to 0.25
r_USLE_P.mgt	P factor of USLE **	-0.25 to 0.25
v_BIOMIX.mgt	Biological mixing efficiency **	0 to 1
r_SOL_Z.sol	Depth from soil surface to bottom of layer [2]	-0.25 to 0.25
r_SOL_AWC.sol	Available water capacity of the soil layer [3]	-0.25 to 0.25
r_SOL_K.sol	Saturated hydraulic conductivity [4]	-0.25 to 0.25
r_SOL_ALB.sol	Moist soil albedo **	-0.25 to 0.25
v_SURLAG.bsn	Surface runoff lag coefficient **	0 to 24
v_ALPHA_BF.gw	Baseflow alpha factor [5]	0 to 1
v_GW_DELAY.gw	Groundwater delay time [5]	30 to 450
v_GWQMN.gw	Threshold depth of water in the shallow aquifer required for return flow to occur [2]	0 to 2
v_GW_REVAPMN.gw	Groundwater "revap" coefficient **	0.02 to 0.2
v_RCHRG_DP.gw	Deep aquifer percolation fraction **	0 to 1
v_REVAPMN.gw	Threshold depth of water in the shallow aquifer required for "revap" or percolation to the deep aquifer to occur [2]	0 to 1000
v_ESCO.hru	Soil evaporation compensation factor **	0 to 1
v_EPCO.hru	Plant uptake compensation factor**	0 to 1
v_CH_K2.rte	Effective hydraulic conductivity in main channel alluvium [4]	-0.1 to 0.1
v_CH_N2.rte	Manning's "n" value for the main channel **	-0.01 to 0.3

*The extension (e.g., .mgt) refers to the input file of the SWAT model in which the parameter is inserted. **Dimensionless. [1]: m; [2]: mm; [3]: mm H_2O/mm soil; [4]: mm h^{-1}; [5]: days.
Source: adapted from Paz et al. (2018) and Martins et al. (2020).

Table 5: Percentage of JMW area with agriculture, forest, and pastures in each of the land use scenarios.

Land uses classes	Land use scenarios		
	LUC[1]	LUP[2]	LUA[3]
Agriculture	6.7	6.7	38.5
Forest	31.8	0	0
Pasture	19.2	50.9	19.2

[1]LUC: current land use; [2]LUP: land use changed to pasture; [3]LUA: land use changed to agriculture.

Table 6: Percentage of the JMW area with riparian forests as a result of APP recovery.

APP* width	Riparian forest area (%)
5 m APP	3.1
8 m APP	4.7
15 m APP	8.5
30 m APP	20.4

*Areas of Permanent Preservation.

RESULTS AND DISCUSSION

SWAT model calibration, validation, and uncertainty analysis

To determine the sensitivity of the model, we evaluated 19 parameters. We found that the most sensitive parameters for the JMW streamflow, in the descending order of importance, were: soil evaporation compensation factor (ESCO), curve number for moisture condition II (CN2), depth to the bottom of the soil layer (SOL_Z), and available water capacity of soil layer (SOL_AWC). Notably, when the method of the parameter was changed to "replace", the value of the parameter was replaced by the value obtained in the calibration process. In the "relative" method, the value of the parameter changed proportionately with the value of the calibration. Thus, the observed value represented an increase or decrease in the original value of the respective parameter (Table 7).

The sensitive parameters in the JMW calibration process were related to the hydrological processes in the soil. Parameters related to the soil water dynamics exerted the greatest influence on SWAT. Parameters that affect the movement of water in the soil are commonly reported in calibration studies of SWAT as the most sensitive for streamflow; these parameters, however, differ across watersheds (Fukunaga et al., 2015; Andrade et al., 2017; Blainski et al., 2017; Paz et al., 2018).

Monthly river discharge calibration for JMW showed acceptable results. On the outlet, the 95 PPU (95% Prediction Uncertainty) interval captured 60% and 50% of the observed data (p-*factor*) for calibration and validation, respectively. However, the r-*factor* value was 0.95 for calibration and 1.49 for validation. Thus, the value for calibration was not sufficiently large. The calibration and validation of streamflow data (Figure 3) produced satisfactory NS, PBIAS (percent bias), and RSR (ratio of the root mean square error) values (Table 8). Similar values of these indices for the calibration of the SWAT

model have been reported in several studies in Brazilian watersheds (Pereira et al., 2014; Fukunaga et al., 2015; Brighenti; Bonumá; Chaffe, 2016; Blainski et al., 2017; Paz et al., 2018; Martins et al., 2020).

The optimization of the SWAT model by calibration and validation resulted in little difference between the simulated and observed streamflow data from 2011 to 2017 (Figure 3).

Sediment yield across different land use scenarios

The sediment yield and surface runoff were associated with the rainfall pattern over the years (Figure 4), and the scenarios of land use impacted sediment yield in JMW differently. Pairwise comparisons between land use types showed that the LUC and LUP scenarios were statistically similar to each other, but both were significantly different from the LUA scenario (Table 9).

For all years, the current and pasture use scenarios (LUC and LUP) provided the lowest sediment yield. The LUA scenario had sediment yield values about twice as high as the LUC and LUP scenarios. Additionally, the LUA scenario, on average, had higher runoff rates for all years relative to the other scenarios (Figure 4).

Agricultural land use considerably increases soil erosion and, consequently, increases pollution of water sources by sediments generated upstream (Borrelli et al., 2017; Abdulkareem et al., 2018; Phinzi; Ngetar, 2019). In this way, various land uses, and occupations cause different amounts of runoff (Ghaffari et al., 2010; Pereira et al., 2016; Himanshu et al., 2019; Zhang et al., 2020), sediment yield, and sediment load (Batista et al., 2017; Blainski et al., 2017; Mello et al., 2017).

The pasture scenario (LUP) was created to obtain an intermediate sediment yield between current use (LUC; with a higher proportion of forest) and agricultural use (LUA). For the LUP scenario, we used default parameters of the SWAT model and other parameters, such as the USLE/MUSLE C factor (from literature), which represent a pasture with good grass cover. From

Table 7: Parameters used for calibration of JMW streamflow along with the respective method of calibration (r = relative and v = replace), sensitivity analysis (t-stat and p-value), and calibrated value.
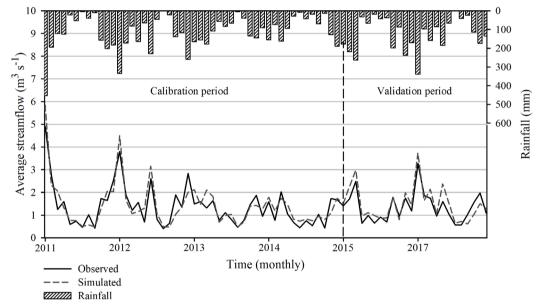
Parameter	Ranking	Method	Sensitivity (t-stat)	Sensitivity (p-value)	Calibrated value
ESCO[1]	1	v	-36.595410820	0.000000000	0.046000
CN2[2]	2	r	-14.667376071	0.000000000	0.002267
SOL_Z[3]	3	r	5.673523230	0.000000020	0.133917
SOL_AWC[4]	4	r	5.203878380	0.000000254	0.268451

[1]ESCO: soil evaporation compensation factor; [2]CN2: SCS runoff curve number for moisture condition II; [3]SOL_Z: depth to the bottom of the soil layer; [4]SOL_AWC: available water capacity of soil layer.

land use maps, we identified two types of pastures: managed pasture (PAST) and degraded pasture (RNGB). Degraded pastures are those that are used extensively with little investment and low productivity but with some coverage of the soil surface. Parts of the pasture areas in Brazil are in some stage of degradation, with low coverage, compaction, and the presence of erosion channels. Our results obtained for LUP, however, do not represent this condition.

The results of the LUP scenario indicate that with adequate soil cover, even in the absence of riparian forests, there is a negative effect on sediment yield. Different from the results of Moriasi, Steiner and Arnold, (2011), that created a scenario with a 10-m Bermuda grass filter strip buffer in SWAT and obtained a 72% reduction in sediment delivery to the stream in a 342-km^2 watershed.

The average sediment yield varied across the JMW sub-basins and land use scenarios (Figure 5). Sediment yield was always high in the sub-basins with the LUA scenario (ranging from 2.5 to 17 Mg ha^{-1}) and was always low in the sub-basins with the LUC scenario (ranging from 0.7 to 7.0 Mg ha^{-1}). In all scenarios (LUC, LUP, and LUA), the highest sediment yield occurred in sub-basins with the steepest slopes, soils with greater erodibility (Dystric Cambisol (Clayic), Dystric Gleyic Cambisol (Clayic), and Dystric Leptosol (Loamic, Ochric)), and land use with high erosion potential (conventional agriculture).
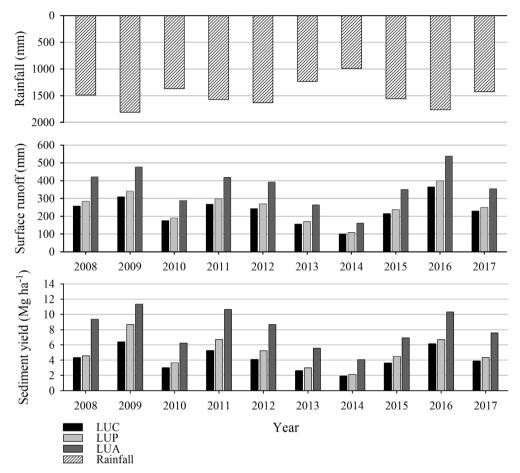

Figure 3: Hydrograph of the observed and simulated monthly streamflow for the calibration period (from 2011 to 2014) and the validation period (2015 and 2017) for the JMW outlet. The monthly rainfall of the period is also shown.

Table 8: Monthly streamflow calibration statistics for the JMW model.

Index	Calibration	Performance rating*	Validation	Performance rating*
NS[1]	0.77	Very good	0.70	Good
RSR[2]	0.48	Very good	0.55	Good
PBIAS[3] (%)	-10.2	Good	-12.5	Good

[1]NS: Nash-Sutcliffe efficiency; [2]RSR: ratio of the root mean square error; [3]PBIAS: percent bias. *According to Moriasi et al. (2007).

Figure 4: Average annual sediment yield (Mg ha⁻¹) and surface runoff (mm) simulated by the SWAT model and total annual rainfall (mm) in the JMW from 2008 to 2017 for LUC, LUP, and LUA scenarios.

Table 9: Pairwise comparisons of land use scenarios (LUC, LUP, and LUA). Reported are d values and associated p-values. Significant difference in responses at p < 0.10.

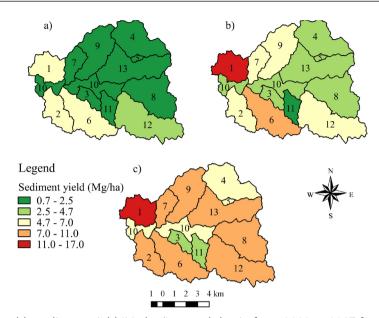| Land use scenarios	p-value	d
LUC x LUP	0.888[ns]	0.075
LUC x LUA	0.035[*]	0.183
LUP x LUA	0.098[*]	0.158

[ns] non-significant difference; [*] significant difference.

Effectiveness of riparian vegetation in reducing sediment yield across scenarios

Sediment yield decreased with an increase in the recovery of riparian vegetation in the APPs. Recovering APPs of 30 m width reduced the sediment yield in January from 1.1 Mg ha⁻¹ to 0.8 Mg ha⁻¹, from 1.2 Mg ha⁻¹ to 0.9 Mg ha⁻¹, and from 3.1 Mg ha⁻¹ to 2.3 Mg ha⁻¹ for the LUC, LUP,

and LUA scenarios, respectively (Figure 6). There was an increase in sediment yield by 21% from the LUC to LUP scenario, but the increase was not significant. The increase in sediment yield from LUC to LUA was approximately 96% (on average) for the entire period. Moreover, in rainy months like January, November, and December this increase was up to 133% from LUC to LUA.

The greatest reduction in sediment yield (30.2%) was observed for the LUC scenario at the recovered APP strips of 30 m width (Figure 7). In this scenario, recovering the APPs in 5, 8, and 15 m wide strips reduced the sediment yield by 19.9%, 20.5%, and 22.2%, respectively. There was only a 10% improvement in the reduction of sediment yield between the most drastic scenario (LUC+5) and the best scenario (LUC+30). Monteiro et al. (2016) also observed little difference in the reduction of sediment yield between the worst-case scenario (5 m wide strips) and the scenarios for APPs with the widest strips (30 and 60 m).

Figure 5: Average monthly sediment yield (Mg ha⁻¹) per sub-basin from 2008 to 2017 for (a) LUC, (b) LUP, and (c) LUA scenarios.

The scenarios of LUP and LUA showed a reduction in sediment yield (i.e., progressive recovery) with an increase in the width of the strips. The LUP and LUA scenarios with 5 m wide strips showed a reduction of 4% and 1.8%, respectively. Similarly, the LUP and LUA scenarios with 8 m wide strips showed a reduction of 5.1% and 3.5%, respectively. The 15 m wide strips showed a reduction of 8% for both scenarios. Finally, the LUP and LUA scenarios with 30 m wide strips showed a reduction of 20.6% and 24.0%, respectively (Figure 7).
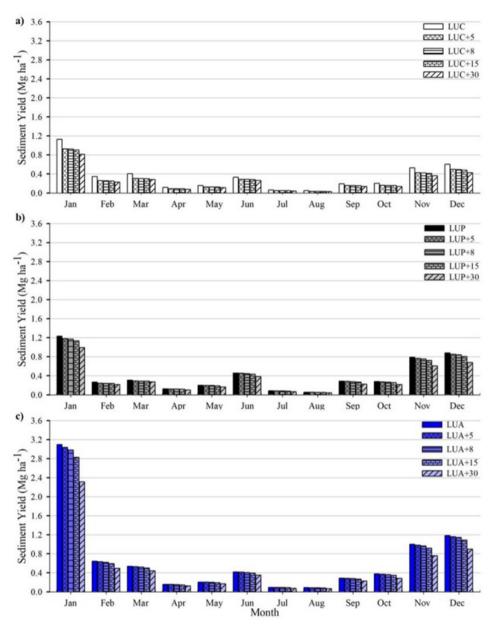
The reduction in sediment yield increased with the progressive increase in the width of the recovered APPs. This indicates that riparian vegetation produced lower amounts of sediments compared to pasture and agriculture. Sediment reduction was relatively lower (< 10%) at recovered APPs (5, 8, and 15 m wide strips) for the alternative uses (LUP and LUA) compared to the reduction in current use.

These results agree with those presented in Guidotti et al. (2020), where they had found that riparian buffers smaller than 8 m can act as a source of sediments to streams. In fact, any area of the APP not covered by riparian forest or not used with conservation management contributes to sediment yield. Even a 15 m wide strip of recovered APP does not reduce satisfactorily the sediment yield.
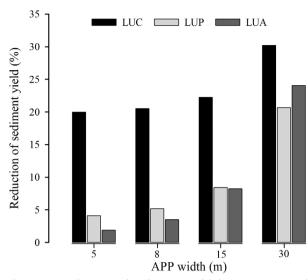
The narrow strip of recovered APPs permitted by the Brazilian Forest Law (Law 12,651/2012) provides low protection to water sources. Therefore, we emphasize that to obtain satisfactory protection of water sources in watersheds, APPs should have the recovered vegetation for the entire width (30 m), and agricultural areas must adopt soil conservation practices to reduce sediment loads that reach riparian zones.

The recovery of the riparian forest in the whole area of the APPs in JMW (20% of the basin area) reduced the sediment yield by 30% in the LUC scenario. In the alternative scenarios, the reduction in sediment yield was lower. Vigiak et al. (2016) observed an 8% reduction in sediment yield in the Danube River basin, where only 2% of the area was occupied by riparian vegetation. We emphasize that the reduction in sediment yield is dependent on edaphoclimatic characteristics and agricultural management of the river basin. Adopting conservation practices in agricultural lands for the preservation and recovery of APPs, and agri-environmental planning on a watershed-scale are very important for the preservation of water sources.

Using the SWAT model, it is possible to evaluate several scenarios of interest to society, authorities, river basin managers, and support environmental recovery programs. The SWAT, post-calibration, is useful for predicting possible impacts of land use changes on water sources in preservation areas, pristine sites, aquifer rechargers, springs, and erosion-prone areas, among others. Thus, we strongly recommend the use of this model by river basin managers while making decisions regarding the conservation of natural resources, especially scarce ones, such as water.

Figure 6: Average monthly sediment yield (Mg ha⁻¹) in the JMW from 2008 to 2017, for (a) current land use scenario (LUC), (b) land use changed to pasture (LUP), and (c) land use changed to agriculture (LUA). Bar plots represent recovery strips of 0, 5, 8, 15, and 30 m width.

Figure 7: Reduction of sediment yield due to recovered vegetation in 5, 8, 15, and 30 m wide APPs of distinct land use (LUC, LUP, and LUA).

CONCLUSIONS

The reduction in the width of recovering riparian vegetation in APP, as permitted by forestry legislation, results in an increase in sediment delivered to watercourses due to the sediment generated in APP zones. In scenarios with high sediment yield, practicing conventional agriculture without conservation management and with partial recovery of riparian forest reduces the sediments that reach watercourses by only 10%. Alternative uses in APP must keep the soil covered and no tilled, as in well-managed pastures, to maintain sediment yield similar to that in riparian forests.

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