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Technical Note

A temporal and spatial simulation of the sediment input in an agricultural basin in the municipality of Fernandópolis, São Paulo, Brazil

Simulação temporal e espacial do aporte de sedimentos em bacia agrícola no município de Fernandópolis (SP)

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ABSTRACT

The characterization of sediment input in watersheds is an important tool for projects that support soil conservation and watershed management. A spatial and temporal analysis of the sediment input in an agricultural watershed tributary of Santa Rita River was performed by means of a geoprocessing simulation in the municipality of Fernandópolis, São Paulo, Brazil. In order to accomplish this, there was a simulation of sediment delivery using the Modified Universal Soil Loss Equation (MUSLE) method for basins, from October 2012 to September 2013. There was a total of 433.87 t of sediments contributed in the period evaluated, resulting in an average soil loss of 3,635 t.ha^{-1}.yr^{-1}. The period with the greatest amount of sediment input was from December 2012 to March 2013. 65.1% of all the sediments were produced at that time. In the most critical month of sediment input, February 2013, about 15% of the total basin area showed sediment contributions ranging from 2 to 15 t.ha^{-1}.yr^{-1}. Sugarcane contributed the most sediment, accounting for 92% of the total, and an average of 6,343 t.ha^{-1}.yr^{-1}.

Keywords: slope; diffuse pollution; water resources; land use and occupation.

RESUMO

A caracterização do aporte de sedimentos em bacias hidrográficas representa uma importante ferramenta para subsidiar projetos de conservação do solo e de manejo de bacias hidrográficas. Assim, neste trabalho realizou-se uma análise temporal e espacial do aporte de sedimentos em bacia hidrográfica agrícola afluente do Ribeirão Santa Rita, situada em Fernandópolis, São Paulo, por meio de simulação com o uso de geoprocessamento. Para isto, realizou-se a simulação do aporte de sedimentos pelo método da equação universal de perda de solo modificada para bacias, no período de outubro de 2012 a setembro de 2013. Verificou-se um aporte total de sedimentos de 433,87 t no período avaliado, resultando em uma perda média de solo de 3,635 t.ha^{-1}.ano^{-1}. O período de maior aporte de sedimentos foi de dezembro de 2012 a março de 2013, quando foram produzidos 65,1% do total de sedimentos do período avaliado. No mês mais crítico, fevereiro de 2013, cerca de 15% da área total da bacia apresentou aportes de sedimentos variando de 2 a 15 t.ha^{-1}.ano^{-1}. A cultura da cana-de-açúcar foi a que mais contribuiu com os aportes de sedimentos, sendo responsável por 92% do total e com média de 6,343 t.ha^{-1}.ano^{-1}.

Palavras-chave: declividade; poluição difusa; recursos hídricos; uso e ocupação do solo.

INTRODUCTION

The agricultural occupation of watersheds in the last few decades have caused numerous problems related to the degradation of riparian forests and the precarious conservation of the soil. Consequences of the occupation include the reduction in the availability of water in addition to water quality problems (TUNDISI and TUNDISI, 2010). Among the main factors that cause water degradation is the excessive production of sediment, which is associated with the processes of displacement, transport, deposition and compaction. These processes obey the natural laws of terrain (CARVALHO, 2008, p.73), which are usually strengthened in places with constant modifications in land use and occupation (SCAPIN, 2005).

Vegetative soil covers allows the kinetic energy from rain dropping on surfaces to dissipate, reducing the initial disintegration of the soil particles and, consequently, the sediment concentration in the runoff. Moreover, the soil cover represents a mechanical obstacle to the free

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surface water runoff, causing a decrease in the velocity and the capacity of disintegration, and the transport of sediments (SILVA et al., 2005). Effects such as these were already verified by Donadio, Galbiatti and Paula (2005), who, evaluating the influence of the remaining natural vegetation and agricultural activities on water quality in four springs, concluded that the sampling periods, as well as the soil characteristics and their different uses, influence the water quality of the sub-basins.

Thus, the rational management of watersheds should allow for the minimization of the diffuse transport of sediments, since, besides being composed of minerals and organic matter, they may have nutrients and defenses, which degrade water quality and the environment (MILLER et al., 2013).

In order to evaluate the impacts of human actions and the proposed solutions (MANGO et al., 2011), the characterization of sediment transport in watersheds is of extreme importance for river basin management plans (OYARZÚN et al., 2011). Among the ways of evaluating the potential of sediments that originated from erosion processes, it is worth highlighting the sediment input, which refers to the total soil loss potential of a watershed (SILVA, SCHULZ; CAMARGO, 2003).

Sediment input can be determined by several methods. The Modified Universal Soil Loss Equation (MUSLE) method stands out. It is estimated from variables that relate to type, slope, land use and land occupation, as well as surface runoff and flood discharge (CHAVES, PIAU, 2008). Considering that within a watershed these variables are integrated and have great spatial variability, with the use of geoprocessing, it is possible to map the origins of the sediment inputs that are above a tolerable amount, which then allows for the implementation of proposals that mitigate erosive processes.

Thus, the objective of this work was to evaluate the temporal and spatial variability of the sediment input in an agricultural watershed located in the municipality of Fernandópolis, in the Northwest region of São Paulo. It was carried out by means of a simulation and with the use of geoprocessing.

METHODOLOGY

This work was conducted in an agricultural watershed located in the municipality of Fernandópolis, São Paulo. It has a total area of 1,309 km^2 and is a tributary of Ribeirão Santa Rita, which is located between the coordinates 20°17'30" and 20°18'15" south, and 50°15'58" and 50°16'51" west (Figure 1).

Figure 1 – Map of the location of the basin being studied.

MUSCLE was the methodology employed for the simulation of sediment input with the use of geoprocessing, as shown in Equation 1.

$$Y = 89{,}6 \cdot \left(Q \cdot q_p\right)^{0{,}56} \cdot K \cdot LS \cdot C \cdot P \qquad (1)$$

So that,
Y is the sediment input in a determined interval of time (t);
Q is the volume of surface runoff in a determined interval of time (m^3);
q_p is the maximum flow ($m^3.s^{-1}$);
K is the soil erodibility factor (MJ mm $ha^{-1}.h^{-1}.year^{-1}$);
LS is the length factor and degree of slope (dimensionless);
C is the management and use factor (dimensionless); and
P is the conservationist practices factor (dimensionless).

The base material used to obtain all of the coefficients and input variables of the model were the climatic data of the city of Fernandópolis (CIIAGRO, 2014), the software PLÚVIO 2.1 (SILVA et al., 1999), the soil map (OLIVEIRA et al., 1999), the slope map, the watershed map, and the land use and land occupation map (Figure 2).

The sediment input calculations were performed individually for the hydrological units (hu) with an area equivalent to the pixels of a geometric resolution of 2.5 m, that is, with an area of 6.25 m^2. These hu are constituted of the combination of type, slope, use and occupation of the land.

Calculating the surface flow volume (step I of the flow chart of Figure 2) was performed by Equation 2.

$$Q = Q' \cdot AP \cdot 10^{-3} \qquad (2)$$

So that:
Q is the volume of the surface runoff of the pixel (m^3);
Q' is the surface runoff (mm); and
AP is the area of the pixel (m^2).

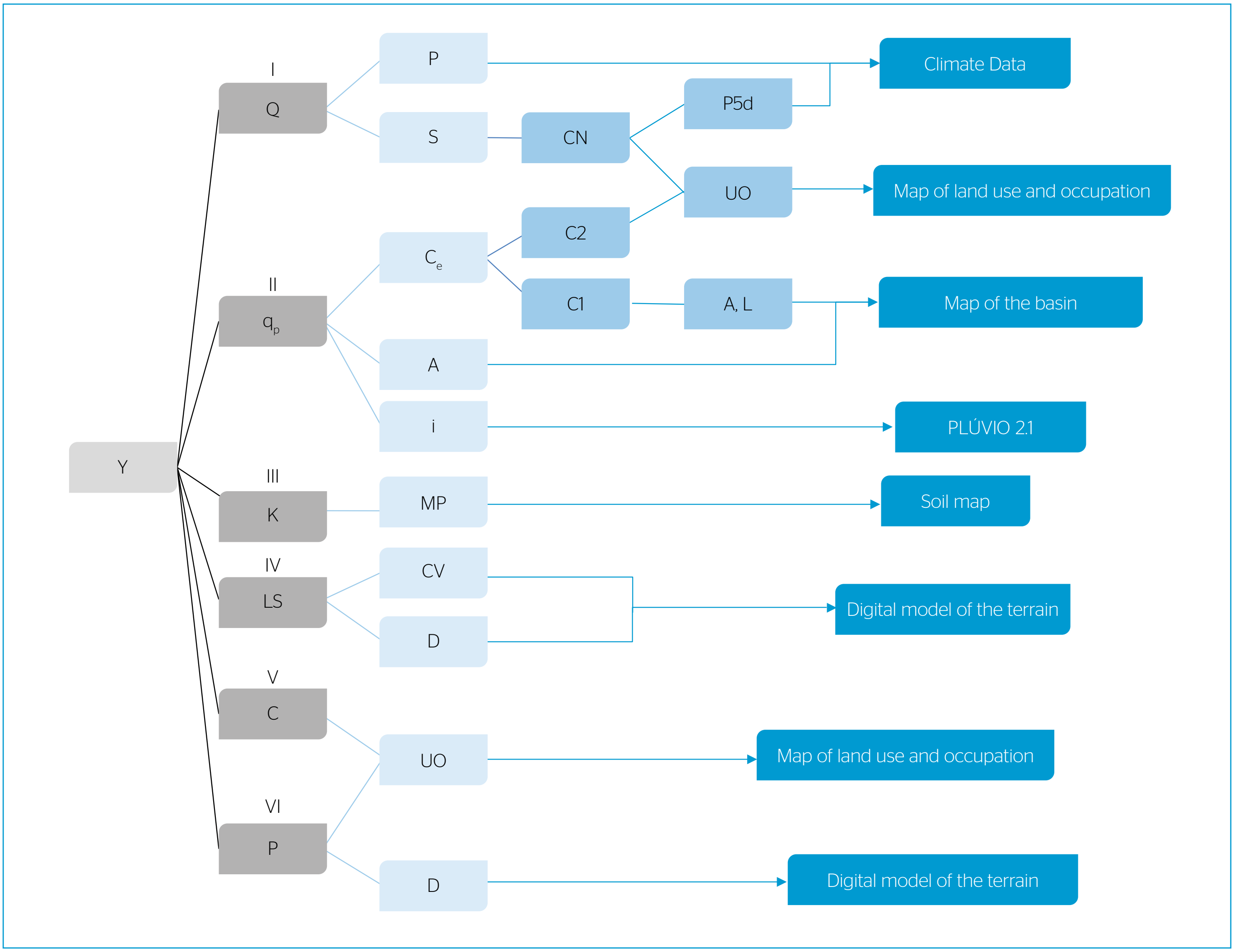

Figure 2 – Flowchart of the methodology used to obtain the input data when determining sediment input (Y) in 6 stages (I, II, III, IV, V and VI).

The surface runoff was determined in accordance with the method from *Soil Conservation Service* (PRUSKI; BRANDÃO; SILVA, 2003), from Equation 3.

$$Q' = \frac{(P - 0{,}2 \cdot S)^2}{(P + 0{,}8 \cdot S)} \quad (3)$$

So that:

Q' is the surface runoff (mm);

P is the accumulated precipitation in a determined time interval (mm); and

S is the maximum capacity for soil storage (mm).

Equation 3 is valid for the situation where P > 0.2S. For the situations where P ≤ 0.2S, the value of Q was equal to 0. The P values were obtained from the data available in the database from the Agrometeorological Information Center of Fernandópolis' automatic station, which is located 500 m from the studied basin. The value of S was determined by Equation 4.

$$S = \frac{25400}{CN} - 254 \quad (4)$$

So that:

S is the maximum capacity of soil storage (mm); and

CN is the number of the corrected curves with antecedent soil moisture.

The number of the curve was corrected with the antecedent soil moisture, from the equations:

1. $CN = 0.0077\, CN_{II}^2 + 0.1694 CN_{II} + 2.1658$ ($r^2 = 0.9978$), for the accumulated precipitation of the last 5 days (P5d) less than 35.0 mm;
2. $CN = CN_{II}$, for the accumulated precipitation of the last 5 days (P5d) between 35.0 and 52.5 mm;
3. $CN = -0.0067 CN_{II}^2 + 1.596\, CN_{II} + 6.9307$ ($r^2 = 0.9000$), for the accumulated precipitation of the last 5 days (P5d) above 52.5 mm.

The values of CN_{II} adopted by the different land use and land occupations of the hu are showed in Table 1.

The calculation of maximum flow provided by the hu (stage II of the flow chart of Figure 2) was determined by equation 5.

$$q_p = \frac{q_p' \cdot AP}{A} \quad (5)$$

So that:

q_p is the maximum flow of the hu ($m^3\ s^{-1}$);

q_p' is the maximum flow of the watershed ($m^3\ s^{-1}$);

AP is the area of the pixel (m^2); and

A is the drainage area of the basin (m^2).

The calculation of the maximum flow of the watershed (q_p') was determined by the rational method (DAEE, 2005), from Equation 6.

$$q_p' = 0{,}1667 \cdot C \cdot i \cdot A \quad (6)$$

So that:

q_p is the maximum flow ($m^3\ s^{-1}$);

C is the surface runoff coefficient;

i is the maximum rainfall intensity ($mm\ h^{-1}$); and

A is the drainage area of the waershed (ha).

The surface runoff coefficient (C_e) of the basin was determined by Equation 7.

$$C_e = \left(\frac{2}{1+F}\right) \cdot \left(\frac{C2}{C1}\right) \quad (7)$$

So that:

C_e is the surface runoff coefficient of the basin;

F is the shape factor of the basin;

C1 is the shape coefficient of the basin; e

C2 is the volumetric runoff coefficient;

The shape factor (F) was determined by Equation 8.

$$F = \frac{L}{2 \cdot \left(\frac{A}{\pi}\right)^{0{,}5}} \quad (8)$$

So that:

F is the shape factor of the basin;

A is the drainage area of the watershed (km^2); and

L is the length of the main talvegue (km).

The shape coefficient (C1) was determined by Equation 9.

$$C1 = \frac{4}{2+F} \quad (9)$$

Table 1 – Curve number values (CN_{II}) adopted for the different uses and occupations in the hydrological units.

Description	CN_{II}
Pasture	79
Building area	92
Meadows	79
Woods	52
Perennial crops	76
Sugar cane	76
Paved roads	98

The volumetric runoff coefficient (C2) was determined by Equation 10.

$$C2 = \frac{\sum C_i \cdot A_i}{A} \quad (10)$$

So that:

C2 is the volumetric runoff coefficient;

C_i is the volumetric runoff coefficient of the use and occupation "i";

Ai is the total area of use and occupation "i" (km^2); and

A drainage area of the watershed (km^2).

The volumetric runoff coefficient (C_i) was assigned for each land use and occupation according to Table 2.

The maximum rain intensity (i) was determined using the equation of intensity, duration, and frequency of rainfall with the aid of the software PLÚVIO 2.1 (SILVA *et al.*, 1999). The equation for the location of the studied watershed was Equation 11.

Table 2 – Values adopted for the volumetric runoff coefficient (C_i) for each land use and occupation in the basin.

Description	C_i
Pasture	0.25
Building area	0.70
Meadows	0.25
Woods	0.20
Perennial crops	0.30
Sugar cane	0.35
Paved roads	0.70

$$i = \frac{1732.921 \cdot T^{0,118}}{(24,990 + tc)^{0,814}} \quad (11)$$

So that:

i is the maximum rainfall intensity (mm h^{-1});

T is the period of return (years), considered 10 years; and

ct is the concentration time (min).

The soil erodibility factor (K) (stage III of the flowchart of Figure 2), which was adopted for the entire watershed (considering that these are argisols, according to the pedological map of the state of São Paulo) (OLIVEIRA *et al.*, 1999), was 0.04 MJ mm ha^{-1}.year^{-1}.

The degree factor and slope length (SL) (stage IV of the flow chart from Figure 2) was obtained for the hydrological units, according to Bertoni and Lombardi Neto (1999), using Equation 12.

$$LS = 0,00984 \cdot CV^{0,63} \cdot D^{1,18} \quad (12)$$

So that:

SL is the factor of the length and degree of the slope (m);

FL is the flow path length (m); and

D is the declivity (%).

The flow path length (IL) was considered as the runoff obtained from the terrain digital model (TDM) of the ASTER satellite (NASA, 2010), which uses the *flowlength* tool from the ArcGIS 10.1 software. The declivity was determined from the declivity map generated from the same TDM, using the slope tool of the ArcGIS 10.1 software (Figure 3).

The land use and management factor (C) (step V of the flowchart of Figure 2) was assigned to the hu, according to the use and occupation

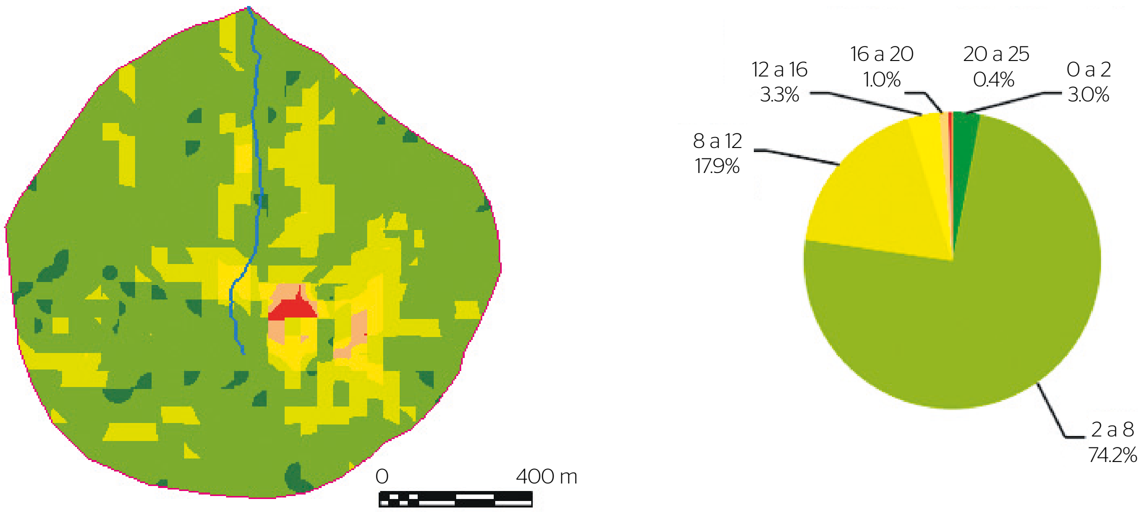

Figure 3 – Declivity map of the watershed.

of the land (Figure 4), following the recommendations of Silva, Schulz and Camargo (2003), according to Table 3.

The land use and occupation map was digitized manually, and a visual interpretation of the classes was made, using a Google Earth image (GOOGLE INC., 2013), dated September 12, 2011 and having a geometric resolution of 1 m.

The conservationist practices factor (P) (step VI of the flowchart of Figure 2) was attributed to the hu, according to the type of soil conservation practice adopted and the terrain declivity, following the recommendations of Silva, Schulz and Camargo (2003), according to Table 4.

After calculating the sediment input for the hu, the totals for each basin were determined in all of the evaluated periods, by means of the sum of the inputs of all hu of the basin. In all, the sediment inputs of the period from October 27, 2012 to September 30, 2013 were simulated at approximate intervals of 30 days. Then, where necessary, data were converted from tonnes per year (t.year-1) to tonnes per hectare per year (t.ha-1.year-1). The classification of the risk of erosion followed the guidelines used by Lagrotti (2000), which were: <1 (very low), 1 to 2 (low), 2 to 5 (moderate), 5 to 10 (high) and > 10 (very high).

RESULTS AND DISCUSSION

The total sediment input of the river basin in the studied year was 433.87 t, which corresponded to 3,635 t ha^{-1}-year^{-1}, and was considered a moderate erosion risk value (between 2 and 5 t ha $^{-1}$.year^{-1}). These results are similar to those obtained by Cambazoglu and Gogus (2004), who, using modified MUSLE to predict sediment production in different basin in the Black Sea region of Turkey, obtained values varying from 1.35 to 3.67 t .ha^{-1}.year^{-1}.

Table 3 – Factor C values assigned to uses and occupations.

Description	C Factor
Pasture	0.070
Building areas	0.000
Meadows	0.010
Woods	0.001
Perennial crops	0.200
Sugar cane	0.300
Paved roads	0.000

Table 4 – P values assigned due to conservation practices and terrain declivity.

Description	Average declivity (%)	P Factor
Pasture (terracing)	1	0.12
	5	0.12
	10	0.12
Building areas (hill below)	1	0.45
	5	0.45
	10	0.45
Meadows (permanent vegetation)	1	0.30
	5	0.25
	10	0.30
	14	0.35
Woods	5	0.10
(permanent vegetation)	10	0.12
Perrenial crops	5	0.10
(terracing)	10	0.12
Sugar cane (terracing)	1	0.12
	5	0.10
	10	0.12
	14	0.14
Paved roads (hill below)	1	0.45
	5	0.45
	10	0.45

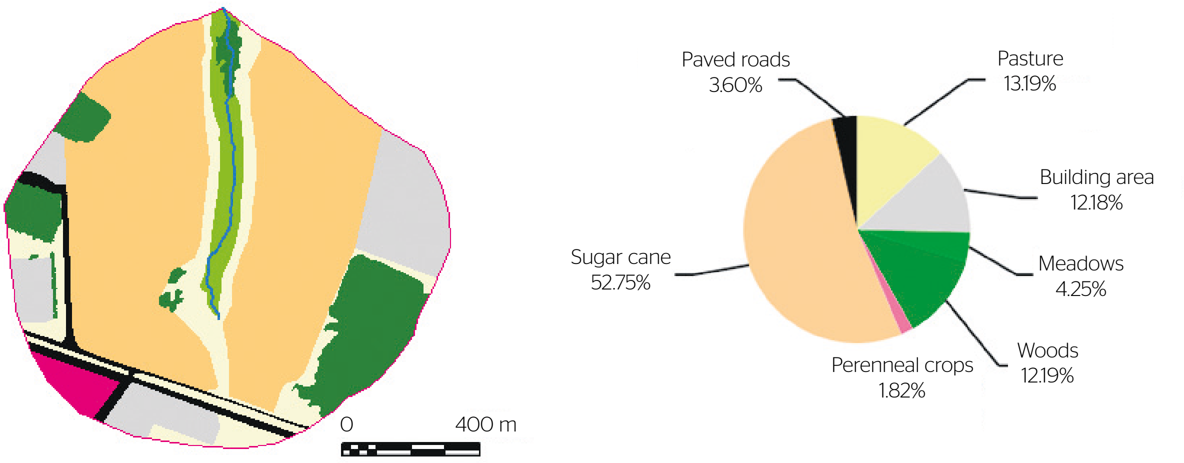

Figure 4 – Map of land use and occupation.

However, when analyzing the monthly totals, it can be observed that some values exceed the limits of moderate erosion risk (above 5 t.ha^{-1}.year^{-1}), reaching a high erosion rate, as observed in Figure 5.

Results such as those obtained by several authors in different Brazilian watersheds, under different conditions, showed mean values varying from 2.0 to 50 t.ha^{-1}.year^{-1} (AVANZI et al., 2013; SILVA et al., 2008; SILVA *et al*., 2011; VALLE JUNIOR *et al*., 2010; TEN CATEN; MINELLA; MADRUGA, 2012). However, in most cases, the method used in the simulation was MUSLE.

The most critical period in the sediment input for the year evaluated was between December and March, with values ranging from 47.15 to 104.81 t (4.664 to 11.083 t.ha^{-1}.year^{-1}). The total contribution in this period corresponded to 65.1% of the total of the year evaluated for the basin. This fact can be explained by the higher concentration of surface runoff, which in the same period corresponded to 76.0% of a total of 420.1 mm in the same year.

Regarding the spatial-temporal distribution of sediment input, it was observed that in the most critical period of sediment input (February 28, 2013), 15% of the total area of the basin had sediment

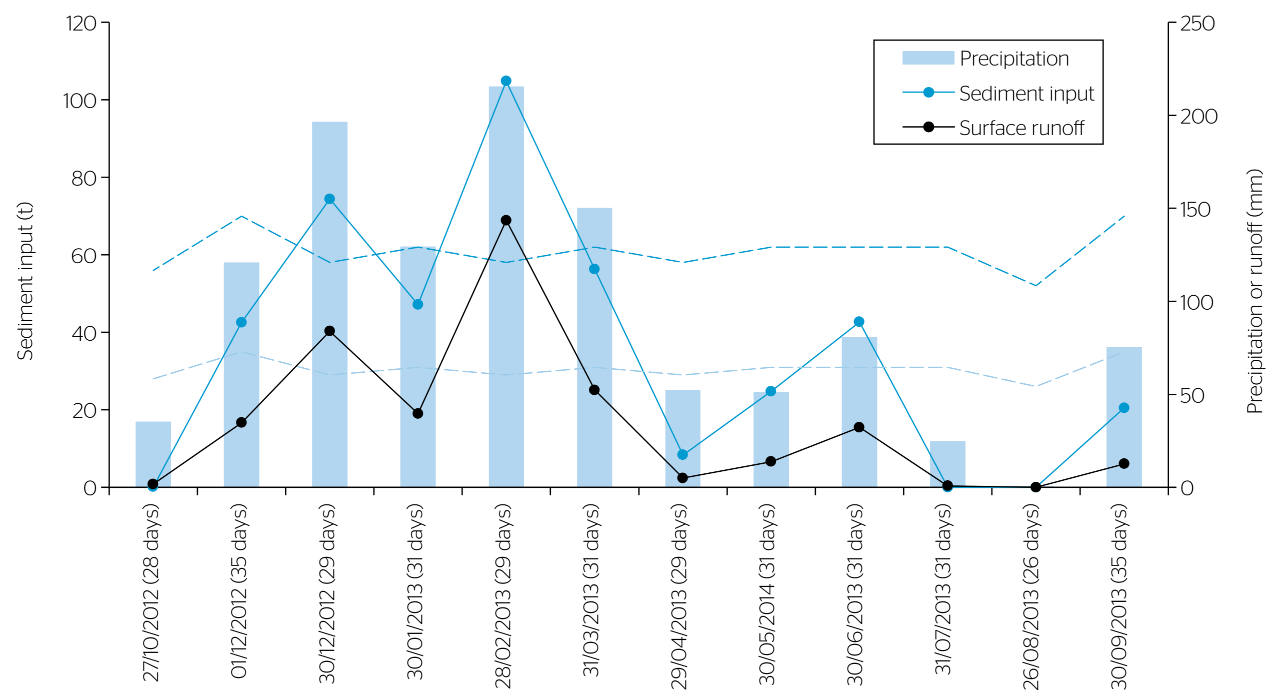

Figure 5 – Precipitation variation (P), of the sediment input (Y), of the surface runoff (Q), and of the low (green dotted line) and moderate (red dotted line) erosion risk limits of the considered intervals.

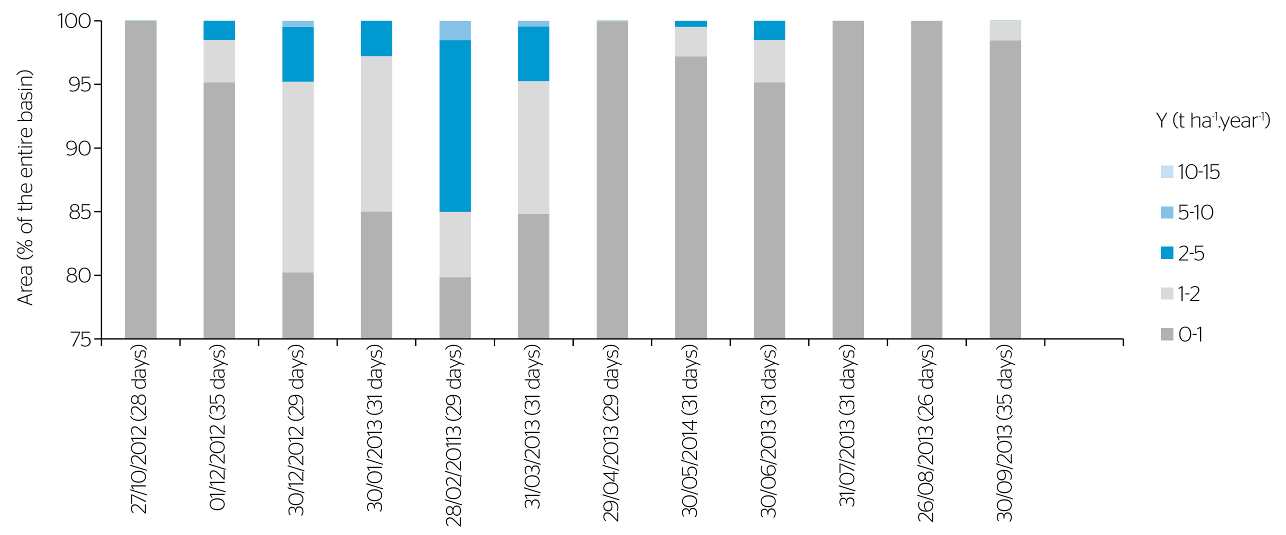

Figure 6 – Space-time distribution of the sediment input of the watershed in the classes of risk erosion from the agricultural basin of the tributary of the Ribeirão Santa Rita in Fernandópolis, São Paulo.

inputs varying from 2 to 15 t. ha^{-1}.ano^{-1} (Figure 6), with 1.52% of the basin showing inputs ranging from high to very high risk of erosion (above 5 t.ha^{-1}.year^{-1}).

The period with the lowest input of sediments was from July 1, 2013 to August 26, 2013, when the inputs remained below 1 t.ha^{-1}.year^{-1}, that is, there was a very low risk of erosion. Figure 7 shows the spatial variability of sediment inputs within erosion risk classes in the evaluated periods.

It is observed that the most critical area, with the highest concentration of high sediment inputs, is located in the southeast region of the basin, where the soil is exploited with sugarcane on declivities between 20 and 50%. It is observed that, from the total sediment input in the period, 19.83% of the total area (23.63 ha) had inputs classified as high to very high risk of erosion (above 5 t.ha^{-1} year $^{-1}$) (Figure 8).

Avanzi et al. (2013), who evaluated the soil losses of a basin forested by MUSLE in the coastal plain of the Brazilian coast, obtained a risk varying from high to very high in 8.7% of the total area of the basin. Comparing these with the results obtained in this work, it is observed that the tributary basin of the Ribeirão Santa Rita had higher sediment inputs, which was already expected, since native forests occupy only 12.19% of the area.

The occupation that provided the greatest input of sediments was the cultivation of sugarcane, which contributed with 92.12% of the total sediment input in the basin. Of the 62.8 ha of sugarcane that occupy the basin, 36.7% resulted in sediment inputs higher than 5 t.ha^{-1}.year^{-1} (Figure 9), producing an average of 6,343 t.ha $^{-1}$.year^{-1}.

Weill and Sparovek (2008), who studied the soil life of the Ceveiro microbasin in Piracicaba, São Paulo, observed that in the areas of sugarcane cultivation, the loss rates were greater than soil

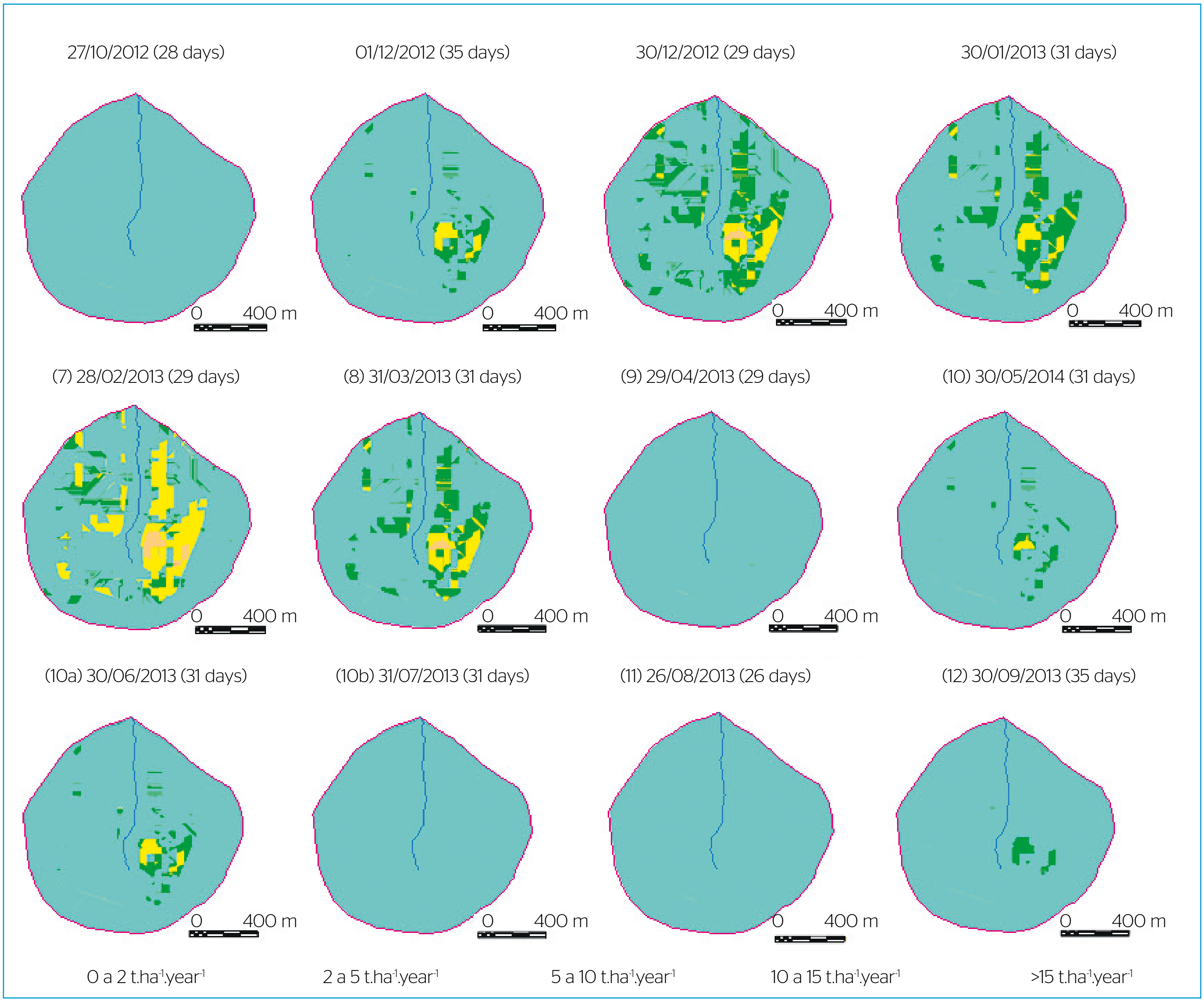

Figure 7 – Spatial distribution of the sediment input of the watershed in erosion risk classes.

renovation rates and there was a loss of the superficial horizon, which is usually the most fertile and rich in organic matter. These areas, due to the high flow of machinery and people, usually have excessive soil compaction and degradation of its physical properties, favoring the potential for water to act as an erosive agent (FERNANDES et al., 2013).

The second agricultural occupation with the highest total sediment input in the period was pastures, which, occupying a 13.2% area of the basin, were responsible for 5.02% of the total sediment input of the basin in the period evaluated. The mean sediment input was 1.384 t.ha^{-1}.year^{-1}. However, even perennial crops that provided 1.46% of the total sediment input in 1.82% of the basin area had a soil loss of 2,920 t.ha^{-1}.year^{-1}, demonstrating its significant potential in producing sediments.

These results are similar to those obtained by Silva *et al.* (2008), for the sub-watershed of Ribeirão Marcela in southern Minas Gerais, which obtained maximum soil losses of 0.945 t.ha^{-1}.year^{-1} for pasture and 3,943 t.ha^{-1}.year^{-1} for eucalyptus. Erdogan, Erpul and Bayramin (2007) also used MUSLE to assess the risk of erosion in the Kazan watershed in Turkey. They obtained results of up to 1 t.ha^{-1}.year^{-1} in 96.3% of the fruit areas and in 80% of the pasture areas.

According to these results, the input of sediments originating from the agriculturally affected areas of the Ribeirão Santa Rita tributary basin are well above the soil losses provided by the native forests. These were 0.132 t.ha^{-1}.year^{-1}, which are in agreement with the results obtained by Martins *et al.* (2003). In different soil types, they obtained values ranging from 0.06 to 0.13 t.ha^{-1}.year^{-1}.

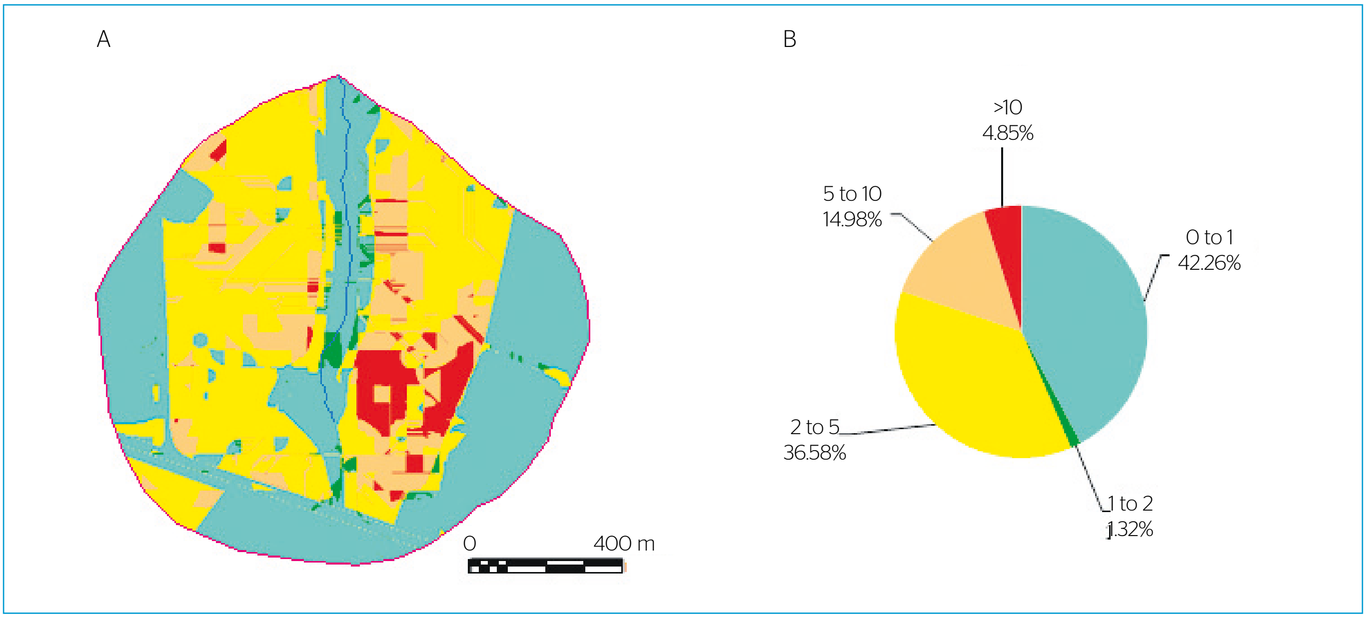

Figure 8 – Spatial distribution of the total sediment input of the period in the watershed area (A) and the percentage of area of the watershed within each erosion risk class (B).

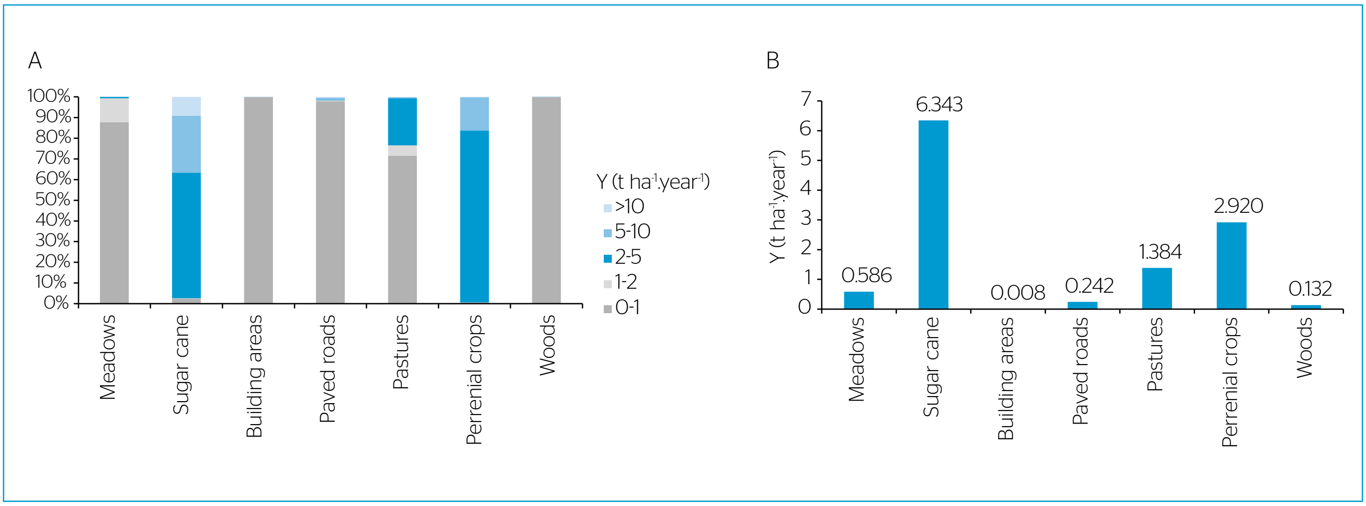

Figure 9 – Percentage distribution of the area of each crop within the erosion risk classes (A) and average loss of soil per crop in the basin (B) in the period evaluated.

CONCLUSIONS

According to the results obtained, it can be concluded that, in the time interval analyzed, the watershed provided 433.87 t of total sediment load, resulting in an average soil loss of 3,635 t.ha^{-1}.year^{-1}, with a moderate risk of erosion. The period of greatest sediment input was from December 30, 2012 to March 31, 2013, when 65.1% of the total sediment of the period evaluated was produced.

In the most critical period of sediment input, in February of 2013, 15% of the total area of the basin had sediment inputs varying from 2 to 15 t.ha^{-1}.year^{-1}, with 1.5% of the basin showing inputs ranging from high to very high risk of erosion (above 5 t.ha^{-1}.year^{-1}). The most critical area is the southeastern region of the basin, where the soil is occupied by sugarcane in declivities ranging from 20 to 50%. The sugarcane crop contributed the most to the sediment inputs, accounting for 92.1% of the total and average of 6,343 t.ha^{-1}.year^{-1}.

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