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Article

Sediment Yield in a Watershed characterized by expansion of sugarcane

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Abstract: This study presents results of the sediment yield Watershed of Ribeirão do Pinhal, in the city of Limeira, São Paulo, conducted under three different scenarios of the land use: 1 – land use in 2008, 2 – with reforested protection areas, 3 – the increase sugarcane's areas over grassland and citrus areas. The Soil and Water Assessment Tool (SWAT) was used as a hydro-sedimentological modeling tool to simulate these scenarios. This watershed was divided into five sub-watersheds according to the prevalent use, and adjustments were made in soils database parameters and cultures that are in SWAT, to adapt it to the Brazilian reality. Was used climatological data of eight years (2007-2014) for this modeling. Different sediment yield could be noted in the different types of land use, sub-watersheds and scenarios. The uses that presented higher sediment yield, in ascending order, were: natural vegetation, sugarcane, citrus, annual crop e grassland. Sub-watershed number 2 had the highest sediment yield (~10Mg.ha^{-1}), while the sub-watershed 5, the lowest (5.51Mg.ha^{-1}). This remained in the three scenarios. Overall, scenario 2 had the lowest sediment yield (7.74Mg.ha^{-1}). Scenario 1 had 8.37 Mg.ha^{-1} and scenario 3, 8.58Mg.ha^{-1}. SWAT was considered efficient to simulate the sediment yield by scenarios and by use, combining different thematic and tabular data when performing the necessary adjustments on their original database.

Keywords: SWAT; ArcGIS; simulations scenarios; sediment yield

1. INTRODUCTION

Water scarcity has great global importance, since it imposes difficulties in development, increases the incidence of diseases, produces economic and social stress, increases inequalities between regions and countries as well as jeopardizes the maintenance of life on the planet (Bicudo, 2010).

Knowing the hydrologic cycle of a watershed allows us to better understand the interactions between the elements and natural phenomena that compose it, together with anthropogenic actions on it. There is no land on Earth, no matter how small, that does not integrate into a watershed or subbasin (CRUZ, 2003).

Watershed is an area composed of downstream areas and a drainage network that naturally captures rainfall to converge the flowage to a single point of exit. This form of space selection allows the demarcation of the watershed according to the scale of the study and should incorporate the issue of interest, enabling the division of a larger watershed in sub- or micro basins (BIKE & AQUINO, 2001 and PORT M.; PORT R. 2008).

Elements that constitute a watershed directly influence their responses to rainfall events, most notably, according to GOLDENFUM (2001) and RIGHETTO (1998), their pedological units, vegetation cover, geomorfological characteristics (slope, shape, area and drainage network) and also geological features (RESENDE et al., 2007).

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TUNDISI & MATSUMURA-TUNDISI (2008) emphasize the need for a systemic, integrated and predictive approach in water management under the view of a watershed. According to these authors, a database that is consolidated and processed into management tools can be one of the most effective solutions to combat shortage, stress and deterioration of water quality.

When analyzing the quality of forest fragments of the Jundiaí-Mirim-SP River watershed, between 1972 and 2013, FENGLER et al., (2015) highlighted the key role of urbanization and deforestation in the process of amending the environmental quality through indicators of environmental disturbance. The author also point out the importance of creating public policies to manage this problem.

Despite technological advances, natural resources have not been used in an orderly and rational manner, and the indiscriminate use of these resources have been the cause of a quick and intense environmental degradation (OLIVEIRA & SOSA, 1995). This has caused the decrease in the productive capacity of the soil; sedimentation of rivers, lakes and reservoir; imbalance of the hydrological regime; contamination of aquifers and superficial waters; depreciation and extinction of plant and animal species; environment pollution.

The sediment transport is controlled by factors such as the amount and distribution of rainfall, physical and chemical structure of the soil, topographic conditions and vegetation cover. Human activity increases or decreases the amount of water flowing on the surface, influencing the river regime and the sediment transport (CHRISTOFOLETTI, 1981).

Soil erosion is not just an agricultural problem. It is associated with a number of environmental, social and economic issues. It has also been recognized as a major setback for food security and a serious problem for sustainable development (TELLES et al., 2011).

Due to the importance of studies on hydric erosion, there are several mathematical models that consider factors of anthropic and natural order, the estimates of sediment yield, among other hydrological parameters. These models are used for the dimensioning of erosion control structures, evaluation of land management practices and environmental assessment and planning (MACHADO, 2003).

For TUCCI (2005), "a model is the representation of some object or system, in a language or form of easy access and use, which aims at understanding it and getting answers for different entries."

The SWAT (Soil and Water Assessment Tool) is a mathematical model of public domain, developed in the early 90s, by the United States Department of the Agricultural Research Service (USDA-ARS) and the Soil and Water Research Laboratory – Temple – Texas A&M University. It is the result of the merger and upgrading of components of predecessor models such as CREAMS, GLEAMS, EPIC, SWRRB and QUAL2E, in such a way that in only one model it allows to generate results with new refinements and better computational efficiency (GASSMAN et al., 2007).

The model was developed to predict the effect of different management scenarios on water quality, sediment yield and pollutant loads in agricultural watersheds (SRINIVASAN & ARNOLD, 1994). It divides the total watershed in subbasins based on its terrain, preserving their spatially distributed parameters, such as soil type and land use. In addition, the SWAT has an interface called ArcSWAT, developed to integrate the ArcGIS® (a GIS – geographical information system) toolbox, which facilitates the processing of spatial data and the geographic database.

The area of study is located in a region historically known as the cradle of Brazilian citrus production, but like other traditional cultures, it has lost space for the expansion of sugarcane. The chosen watershed is also a source of water supply to about 1/3 of the population of Limeira-SP, Brazil.

Therefore, this study aimed to simulate sediment yield in three different scenarios of land use in a watershed and evaluate how these combinations, between the elements that compose it, impacted the process of soil loss by water erosion.

2. Material and Method

The area of study is the subbasin of Ribeirão do Pinhal (Figure 1), located between the coordinates 22°26′25,03′′S/47°24′38,17′′O and 22°40′00,73′′S/47°11′00,51′′O (Datum SIRGAS2000).

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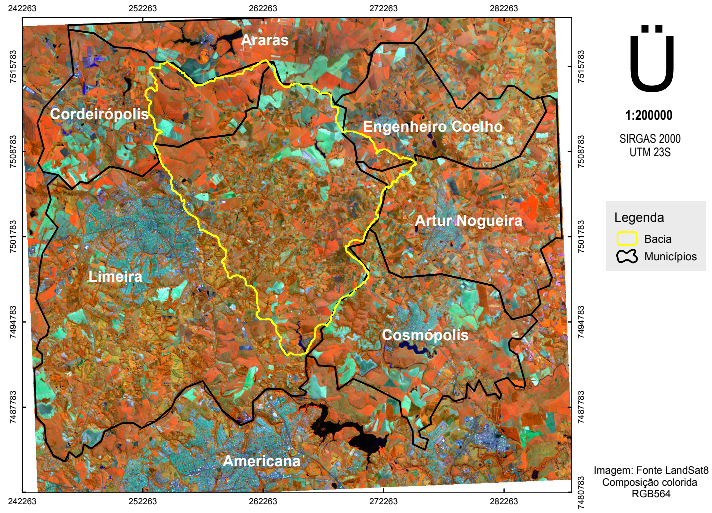

Figure 1. Ribeirão do Pinhal-SP watershed location.

The Ribeirão do Pinhal-SP watershed has an area of 289 km ² being most inserted in the city of Limeira. It also covers the cities of Cordeirópolis, Engenheiro Coelho and Artur Nogueira, therefore an intermunicipal watershed. It is integrated into the UGRHI5-Water Resource Management Unit, in a traditionally industrial region. The UGRHI5 consists of the Watershed Committee of the Piracicaba, Capivari and Jundiaí rivers (CBH-PCJ), created by the São Paulo State Law no. 7.663/91.

Regarding geomorphology, the Ribeirão do Pinhal Watershed is located in the Depression of the Middle Tietê, which is contained in the São Paulo Peripheral Depression, which is part of the Paraná Sedimentary Watershed.

The predominant climate is categorized as **Aw**, rainy tropical type, according to the Köppen classification. It is a warm region, with dry winter and with its coldest month with an average temperature higher than 18°C.

The original vegetation was composed basically by bushland, further in the South and Southeast, and the rest by tropical broadleaf forest, which was almost completely suppressed by agricultural expansion (initially by citriculture and currently by the sugar-alcohol sector) and the growth of urban areas.

The thematic basis for entry in the SWAT model was obtained from the project undertaken by the Agronomic Institute of Campinas (IAC), in 2008, in the region formed by the Ribeirão do Pinhal Watershed.

Were used:

a. Pedological map (Figure 2), generated from the interpretation of analytical data of physical and chemical soil samples collected in the field, with the aid of photointerpretation, to define the mapping units. (SiBCS, 2006);

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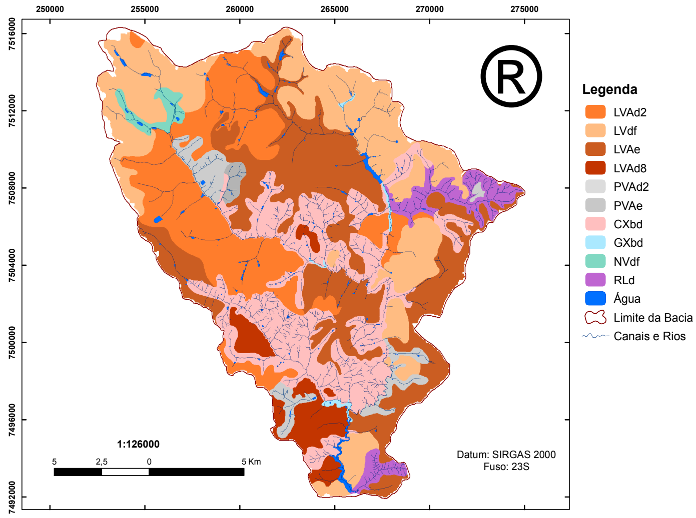

Figure 2: Map of the Ribeirão do Pinhal watershed soils. Source: IAC/2008.

b. Map of land use (Figure 3) for the year 2008, generated from the interpretation of images from the IRS-P6 satellite (panchromatic sensor with 5m of spatial resolution) plus the merger of IRS-P6 with a color composition of bands from the American LandSat7 satellite. Initially the map had 32 units of use mapped and later, after the merger of uses with similar characteristics, the map of land use for this study was generated.

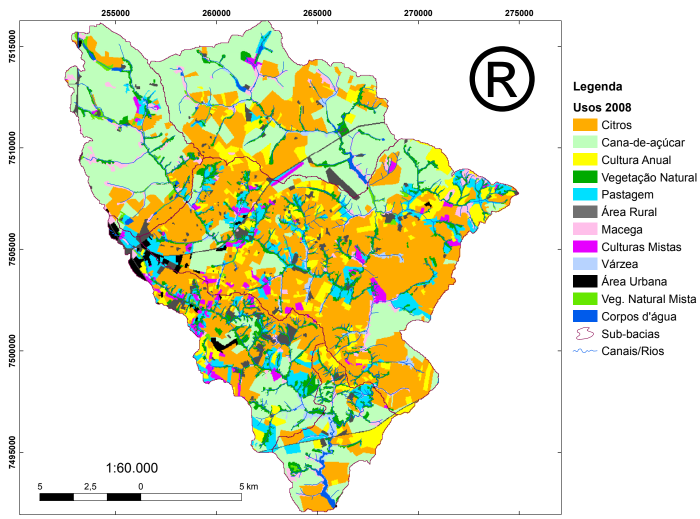

Figure 3: Map of the Ribeirão do Pinhal-SP watershed land use.

c. The Digital Elevation Model (DEM) – basis for generation of topographic variables such as: delimitation of the watershed, calculation of LS factors to the equation of the Universal Soil Loss Equation (USLE), map of slope, drainage network, among others – was generated via interpolation level curves, obtained from planialtimetric maps on a 1:10000 scale in the region. The spatial resolution adopted was 30x30m.

Other input data generated was the map of land use containing the Areas of Permanent Preservation (APP), properly legalized according to the Brazilian Forest Law in force ("Forest Code of 1965," with a final declaratory act in May 2012, under No. 12651 and regulation sanctioned on May 5, 2014). These protection areas were generated in the vicinity of water bodies (30m away), then they were inserted in the map of use from 2008, replacing the usages found in these areas, by using Natural Vegetation, thus composing scenario 2.

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For weather data, a historical series of records collected by the meteorological station of Cordeirópolis, neighboring city of Limeira, was used. Daily data regarding rainfall (mm), maximum and minimum temperature (°C), solar radiation (MJ/m ^{2}), wind speed (m/s) and relative air humidity (%) were selected from a period of eight years. Eventually, some missing records were supplied by modeled data through the Global Weather Data for SWAT, a climate modeler available at the SWAT electronic address.

After the preparation of the input data, the import of this data was performed in SWAT, via ArcSWAT. In this step, first of all, the total watershed limit area based is automatically generated based on the DEM and in its final outlet point. Then, five subbasins were generated, through the ArcSWAT interactive mode (Figure 4). The criteria adopted for the location of the outlet point for each subbasin were: the proximity of these points to the streamflow measurement locations provided by the city of Limeira and the predominant land use, for the analysis of the influence of such use on the sediment yield.

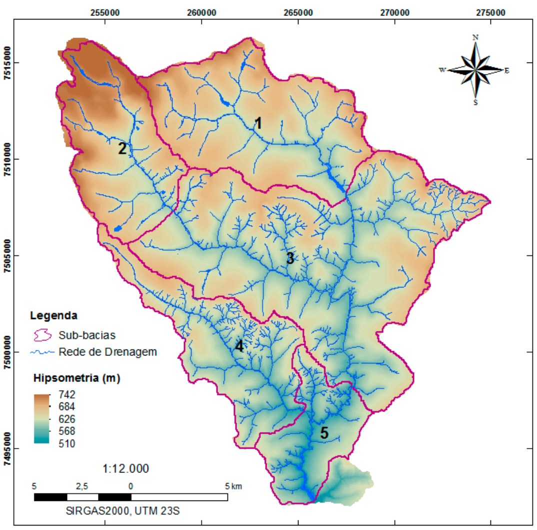

Figure 4: Map of the five subbasin generated by the SWAT still containing the drainage network and the hypsometry of the watershed.

The next step is the import of maps of land use and soils, associating each mapped unit to its corresponding in the crops and soils table, native to the SWAT database. These native SWAT tables contain specific parameters of various crops and soils which, used in conjunction with the other input parameters, enables the execution of simulations. Because it is a model designed at first to meet the specificities of American crops and soils, with a predominantly temperate climate, this native database has some parameters different from those associated with regions of tropical climate, such as Brazil. These differences could be noted after the first simulation. After evaluation of these preliminary results, some SWAT crop table parameters were adjusted based on the local literature, as shown in Table 1 and, for the soil map, all the analytical information was generated from the chemical and physical field data generated by the Center for Soils and Environmental Resources of IAC.

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Table 1. Values used for adjustments in parameters of the most influential uses, in the database of uses of SWAT, identified as relevant for the adaptation to the conditions of agricultural management of Brazil.

Uses	HVSTI	WSYF	BLAI	UsleC
Grassland	0.4	0.3	6	0.0075
Annual Crop	0.5	0.3	6	0.1069
Citrus	0.3	0.09	2	0.05
Sugarcane	0.8	0.2	5	0.0754
Forest	0.02	0.01	6	0.001

Parameters that have had their original values (*default*) changed were: *HVSTI, BLAI, WSYF* and *USLE_C*.

The parameters *HVSTI* and *WSYF* represent respectively the harvest index in ideal conditions of growth and the harvest index in high-stress conditions for plant growth. These parameters are linked to the crop harvesting process and are indices of the surface biomass fraction that is removed during the harvesting operation (ARNOLD, 2012).

The leaf area index (LAI), named by WATSON (1947) as the ratio between the leaf area of the canopy and the projected surface unit in the soil (m2/m2), is a physical variable that is directly related to transpiration and the productivity of plants. The BLAI parameter represents the maximum leaf area index achieved by culture.

The *C factor* of USLE had its value adjusted to conditions consistent with the reality of the Brazilian agricultural system, which is different from the American system. Estimates of the *C factor* for various crops in Brazil are described in MARIA & LOMBARDI NETO (1997), BERTONI & LOMBARDI NETO (1990) and BERTOL (2002).

Based on soils and crops, the slope map of the watershed was generated (Figure 5), guided by the following slope intervals: 0-3%, 3-9%, 9-12%, 12-25% and greater than 25% (LEPSCH & BELLINAZZI, 1983).

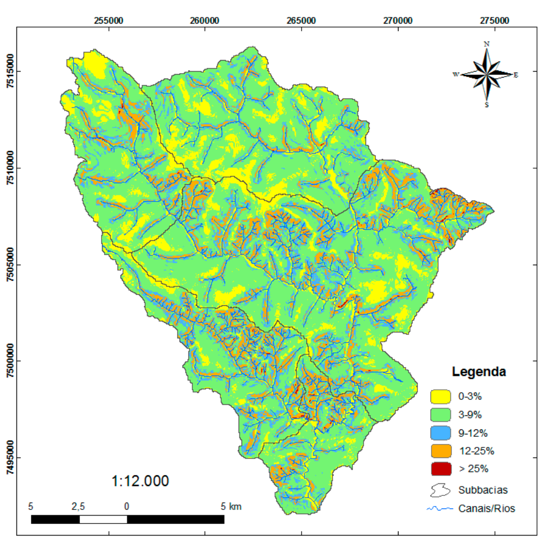

Figure 5: Map of slope of the Ribeirão do Pinhal-SP Watershed

After incorporating thematic data into the SWAT database and the anticipated adjustments, cross-referencing was performed, generating the HRU's (Hydrological Response Units). The purpose of the division of the basin by HRU's is the grouping of areas with common physical characteristics, to reduce the processing time of the model and to allow a more specific analysis of a given location of the watershed (NEITSH et al., 2010; NEITSH et al., 2011; WINCHELL et al., 2008).

The last step was the importation of the climate data. The climate series used corresponds to the period of January 1st, 2007, to August 26th, 2014, for a total of eight years. The data present daily values

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and are separately imported. More details on the input pattern can be found in the manual data input and outputs of the SWAT (ARNOLD et al., 2012).

At the end of this data entry phase, the simulation is performed again and the results are verified. To do so, the first year of climate data was defined as system training and the following years for the final results. Based on these preliminary results, the identified sediment yield values were not consistent with those normally found for Brazil.

These values were closer to the Brazilian conditions when the parameters in the SWAT crop table were adjusted according to the values described in Table 1.

Then, simulations were performed for the three proposed scenarios:

1. 2008 land uses;
2. Lands uses with the regularized APP areas and;
3. Increase of 30% of sugarcane area over citrus and grassland areas.

3. Results and Discussion

The results were achieved by the simulation of the three originally proposed scenarios, by basically altering the thematic information on land use. All the information generated by the cross-referencing of the themes and calculations related to the hydrological phenomena of the watershed was individually stored in each HRU's, generating several output reports in a file format read in any spreadsheet or text editor.

For the analysis of the results, only the uses that presented sediment yield more relevant to the total watershed were considered.

Table 2 shows the uses that most influenced sediment yield in the watershed.

Table 2: Distribution of the areas of the most representative uses in the Ribeirão do Pinhal Watershed, in the three scenarios evaluated.

	Scenario 1		**Scenario 2**		**Scenario 3**	
Uses	*ha*	%	*ha*	%	*ha*	%
Grassland	678.45	2.34	603.66	2.08	499.76	1.73
Annual Crop	2162.14	7.47	1817.92	6.28	2121.46	7.32
Citrus	13658.17	47.16	12092.04	41.75	9553.63	32.99
Sugarcane	-11741.30	40.54	11172.50	38.58	15756.91	54.40
Forest	722.72	2.50	3276.39	11.31	1030.75	3.56

In scenario, 2 we can note the increase in the APP area (represented in Table 2 by *Forest*) due to its regularization, jumping from 2.5% to 11.31% increase in relation to the total area of the watershed. On the other hand, *Citrus* was the use that had highest loss in percentage points: 5.41%, therefore, the use with larger areas in disagreement with what is prescribed in the forestry law currently in force.

In scenario 3, when 30% of the grassland area is replaced by sugarcane area, little difference can be noted. However, as for the citrus, there is a significant change, even with the alternation of the prevailing use over the total watershed area, becoming the sugarcane, the use of greater coverage.

In relation to the distribution of uses by subbasins, by the map of land uses we see a greater predominance of the use of sugarcane over subbasins 1 and 2. In the subbasin 3, the prevalence is the citrus use. The subbasins 4 and 5 have a more varied use, with emphasis on natural and grassland vegetation.

Information on the soils of the Ribeirão do Pinhal Watershed were fundamental to the development of this study, due to the level of detail in which the soil map was generated and the quality of the physical and chemical data of the samples, both made available by the Soils and Environmental Resources Center of IAC, in 2008 (http://www.iac.sp.gov.br/areasdepesquisa/solos/listapublicacao.php).

As for the soil types in each subbasin, we can note the predominance of the Ferralsol, representing more than 40% of the subbasin areas 1 and 2, where the predominant slope varies from 3 to 9%. Another important observation is the predominance of Cambisol in the subbasins 4 and 5. The presence of Cambisol (SiBCS, 2006) in subbasin 3 is also of importance, where the predominant use is citrus.

In relation to sediment yield simulation, in Table 3 it can be observed the contribution of each subbasin within each of the 3 scenarios.

Table 3: Sediment yield by subbasin within each scenario. Average of eigth years evaluated, expressed in *Mg. ha*$^{-1}$.

	Subbasin 1	**Subbasin 2**	**Subbasin3**	**Subbasin 4**	**Subbasin 5**	**Average 8 years**
Scenario 1	6.22	10.71	8.69	9.69	6.53	8.37
Scenario 2	6.19	10.67	8.20	8.13	5.51	7.74
Scenario 3	8.04	11.22	9.23	8.75	5.66	8.58

In a first analysis, it is noted that in the 3 scenarios, subbasin 2 is the largest sediment yielder. The subbasin 2 is located in the most upstream region of the Ribeirão do Pinhal watershed, therefore, at its head. FREITAS et al. (2013) points out, in their study conducted in the Jundiaí-Mirim/SP river watershed, the environmental indicators for the prioritization of the recovery of APP's, among which the headwater areas of the watershed, where the outcropping of the aquifer and the birth of the river is located, and which are more susceptible to erosion processes. Thus, this study supports the rationale that, in a possible environmental action aimed at reducing sediment yield, the recovery of subbasin 2 should be initially prioritized.

However, subbasin 1 was the one that suffered the greatest impact in changes. This is explained by the great part of its area being covered by an Ferralsol LVAe, which, even though it does not possess the greatest erodibility factor (Usle *K* factor), it had a great final weight in the calculation of sediment yield.

Scenario 2, which refers to the use with preserved APP's, was the one that presented lower sediment yield, as expected.

As for scenario 3, where a greater sediment yield relative to scenario 2 was expected, there was a slight difference. However, it has proved the fact that, with the expansion of the sugarcane crop, the superficial sediment yield is also increased.

The rates of sediment yield decreased in the subbasins 4 and 5. This is explained by the fact that in these subbasins, a greater substitution of grassland by sugarcane took place. And, according to the results obtained in this study, the grassland use presented a greater potential of sediment yield.

The following maps show the spatial distribution of sediment yield by HRU's in each scenario.

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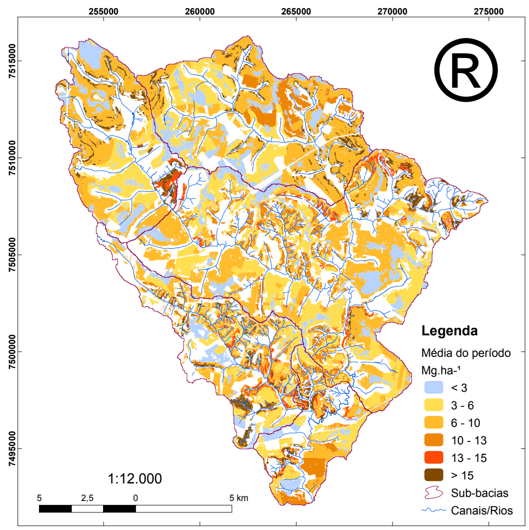

Figure 6: Average sediment yield of the period by HRU, for scenario 1.

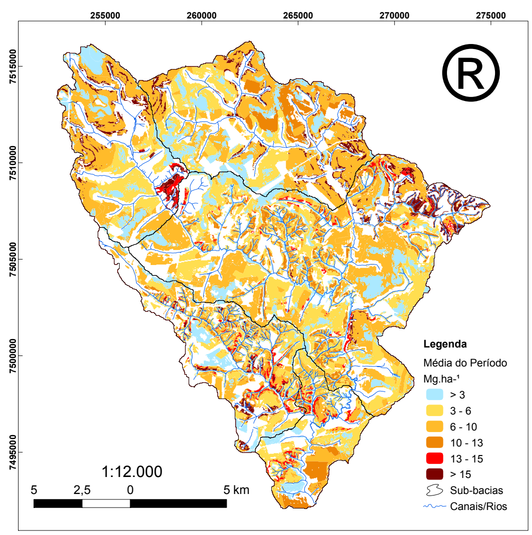

Figure 7: Average sediment yield of the period by HRU, for scenario 2.

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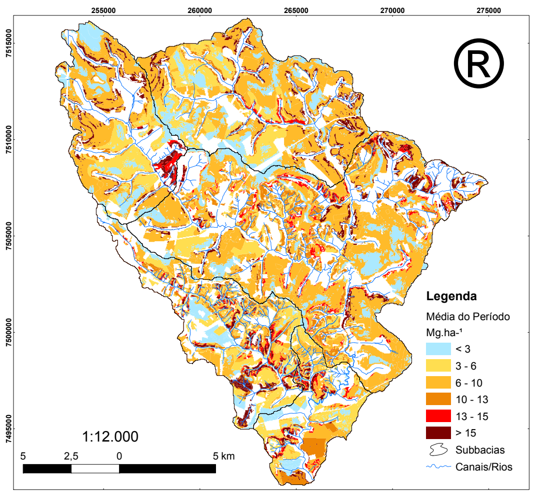

Figure 8: Average sediment yield of the period by HRU, for scenario 3.

In a visual analysis of the maps from Figures 6, 7 and 8, such notable changes in the spatialization of erosive processes are not noticed. An important aspect of these maps is the possibility of visualization of areas with major problems of erosion, as a result of the combination of the various phenomena in the process, offering us better conditions to understand the systematic of these regions to plan and deploy conservation works.

As for the sediment yield per use, considering only the most representative, table 4 summarizes some important information regarding each scenario.

Table 4: Sediment yield by use and by scenario. *Area* in km ², *LS* factor of Usle and *Sed th,* annual average production of the eight years under consideration in tonnes per hectare.

	Scenario 1			Scenario 2			Scenario 3		
Uses	*Area in km²*	*Usle_LS*	*Sed th*	*Area in km²*	*Usle_LS*	*Sed th*	*Area in km²*	*Usle_LS*	*Sed th*
Grassland	6.79	1.48	9.47	6.04	1.45	9.07	5	1.47	9.38
Annual Crop	21.62	1.23	8.75	18.18	1.21	8.52	21.21	1.25	8.79
Citrus	136.62	1.02	7.38	120.93	0.99	7.29	95.54	1.10	7.85
Sugarcane	117.43	1.03	7.35	111.70	1.01	7.20	157.59	1.06	7.66
Forest	7.23	1.88	6.74	32.77	1.71	5.39	10.31	1.84	5.96

In all three scenarios, the ordering of the uses for amount of sediments yield did not vary. In relation to the citrus and sugarcane uses, there is little difference, proving that, for the proposed scenarios, in the climatic, soils and slopes conditions found for the Ribeirão do Pinhal watershed, these two uses have similar behavior regarding sediment yield.

The grassland, when in poor conservation status due to the lack of use of conservation management practices, tends to have a higher sediment yield.

In this study, *USLE* factor *C* values were used for pasture and sugarcane of 0.0075 and 0.7540, respectively. And even with a relatively low value, grassland yielded more sediment in relation to sugarcane, because of the more unfavorable conditions of soils and slopes, the areas in which this use is most concentrated, notably in subbasins 4 and 5.

As mentioned in the methodology, some parameters in the crop database were adjusted to the Brazilian reality. However, the *LS factor* of *USLE*, which has a direct influence on the final calculation of the soil loss equation, is a physical parameter inherent to the watershed terrain conditions, which can not be manipulated or adjusted. In Table 4, it can be observed that the *LS* factor values found for each use are very different, and the highest values are related to the grassland and natural vegetation

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uses. This explains why the natural and grassland vegetation sediment yield have reached values relatively high in relation to the initial expectation of the project.

4. Conclusion

Considering the conditions under which this work was performed and according to the results obtained, it can be concluded that:

- SWAT proved to be adequate for the hydrosedimentological modeling of Ribeirão do Pinhal, allowing a better understanding of the hydrological phenomena of this watershed, in particular, the question of sediment yield;
- The increase of sediment yield in sugarcane expansion areas over citrus and grassland areas was relatively lower than expected. In this study, these uses have had a similar behavior regarding the sediment yield, which explains this little expressive increase.
- Subbasins located in headland areas and/or with predominance of soil more susceptible to erosion, such as argisols and cambisols, presented higher sediment yields.
- Finally, it was found that the SWAT interface with GIS allowed not only the simulation of scenarios of land use and occupation, but also the spatialization of the results, identifying the subbasins and the classes of use and management of soil with higher sediment yield, which is a great tool of territorial management.

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