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Joaquim Ernesto Bernardes AYER, Ronaldo Luiz MINCATO, Luca LAMMLE, Luis Felipe Pigatto Miranda SILVA, Danilo Francisco Trovo GAROFALO, Lucas Emanuel SERVIDONI, Velibor SPALEVIC, Sueli Yoshinaga PEREIRA[1]

HYDROSEDIMENTOLOGICAL DYNAMICS IN THE GUARANI AQUIFER SYSTEM, RIBEIRÃO PRETO, STATE OF SÃO PAULO, BRAZIL

SUMMARY

This research evaluated the effects of agriculture on hydrosedimentological dynamics in the city of Ribeirão Preto in the State of São Paulo, Brazil. Physical and chemical analyses of the soils of the Ribeirão Preto hydrographic sub-basin were carried out. A water erosion susceptibility map was generated using the Revised Universal Soil Loss Universal Equation as well as water level and potentiometric depth maps of the studied region. Using geophysical data, a local three-dimensional geological model was prepared that clearly differentiates the outcrop regions of the Guarani Aquifer System. The research results indicate that the key reasons for hydrosedimentological changes under intensified erosion processes are conventional management and forest fragmentation, which cause soil losses above the region's average tolerance limit of 8.5 Mg ha^{-1} $year^{-1}$. Apart from soil damage, the calculated soil loss of about 1 million tons per year leads to a high risk of contamination in the Guarani Aquifer System. In regions located north of Ribeirão Preto, where the Guarani Aquifer System is shallowest, the risk of contaminants diffusing through agriculture is very high. In this context, modelling hydrosedimentological dynamics is of great importance as it enables accurate evaluation of the natural susceptibility of the aquifer to diffuse contamination. It also helps to identify sites that exceed the tolerance limit for soil loss, which are critical for conservation. However, there are no safe levels of

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[1]Joaquim Ernesto Bernardes Ayer,(corresponding author: joaquimaeba@gmail.com) Geosciences, State University of Campinas - UNICAMP, BRAZIL; Ronaldo Luiz Mincato, Institute of Natural Sciences, Federal University of Alfenas, Minas Gerais, BRAZIL; Luca Lammle, Geography, State University of Campinas – UNICAMP, BRAZIL; Luis Felipe Pigatto Miranda Silva, Environmental Sciences, Federal University of Alfenas - UNIFAL, Minas Gerais, BRAZIL; Danilo Francisco Trovo Garofalo, Geosciences, State University of Campinas – UNICAMP, BRAZIL; Lucas Emanuel Servidoni, Environmental Sciences, Federal University of Alfenas – UNIFAL, Minas Gerais, BRAZIL; Velibor Spalevic, University of Montenegro, Faculty of Philosophy, Department of Geography, Danila Bojovica bb, 81400 Niksic, Montenegro; Sueli Yoshinaga Pereira, Institute of Geosciences, State University of Campinas - UNICAMP, BRAZIL.
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soil loss, and attention should be paid to all areas that have soil loss values above what is considered natural. Soil losses for areas in forests were calculated as 0.03 Mg ha^{-1} $year^{-1,}$ which is well below the average for land under agricultural use (2.03 Mg ha^{-1} $year^{-1}$). The results of this research reveal critical hydrosedimentological dynamics in the studied area that affect both the quantity and quality of the water of the Guarani Aquifer System..

Keywords: Hydropedology; Soil Management; Aquifer; RUSLE.

INTRODUCTION

The surface and groundwater interaction takes place in different forms and degrees of intensity, with the surface water being the main cause for the groundwater contamination (USGS, 1998). In general, surface water is hydraulically connected to groundwater. However, how these occur and the magnitudes of their interactions are not easy to estimate. Land use changes representing the natural balance between morphogenetic and pedogenetic rates and are influencing erosion processes in the studied basin. This can result in sediment layers being deposited, which based on their composition, can contaminate the hydrogeological resources. In fact, over time, they can become a secondary source of contamination, principally by getting deposited on the floodplains.

Quantifying the susceptibility to soil loss or sediment production by water erosion helps to evaluate and quantify the sediments that can be carried by water in an area (Sakuno et al., 2020; Chalise et al., 2019; Tavares et al., 2019; Khaledi Darvishan et al., 2019; El Mouatassime et al., 2019; Spalevic et al., 2017). Therefore, crossing these data with the piezometric surface of a specific area can provide an overview of the interactions and the material exchange that occurs.

Taking into consideration the mentioned above, the aim of this study was to evaluate, using systemic analysis, the interaction between the exposed areas of the Guarani Aquifer System (GAS) and the surface dynamics and the uses upstream of this region influencing the production and transport of the sediments by water erosion.

MATERIAL AND METHODS

The study of this research was the area of the Municipality of Ribeirão Preto (Figure 1), located in Northwest of the São Paulo state of the south-eastern Brazil. In 2017, the population of this municipality was estimated at around 682,302 inhabitants (IBGE, 2017). Based on the Köppen classification, the climate in Ribeirão Preto is of the mesothermal tropical, subtype - Cwa (Alvares et al., 2014). The study area belongs to the hydrographic basin of Rio Grande, which limits the municipality to the north and it is drained mainly by the Ribeirão Preto subbasin, whose headwaters are found in the centre-south portion and in the north of the subbasin.

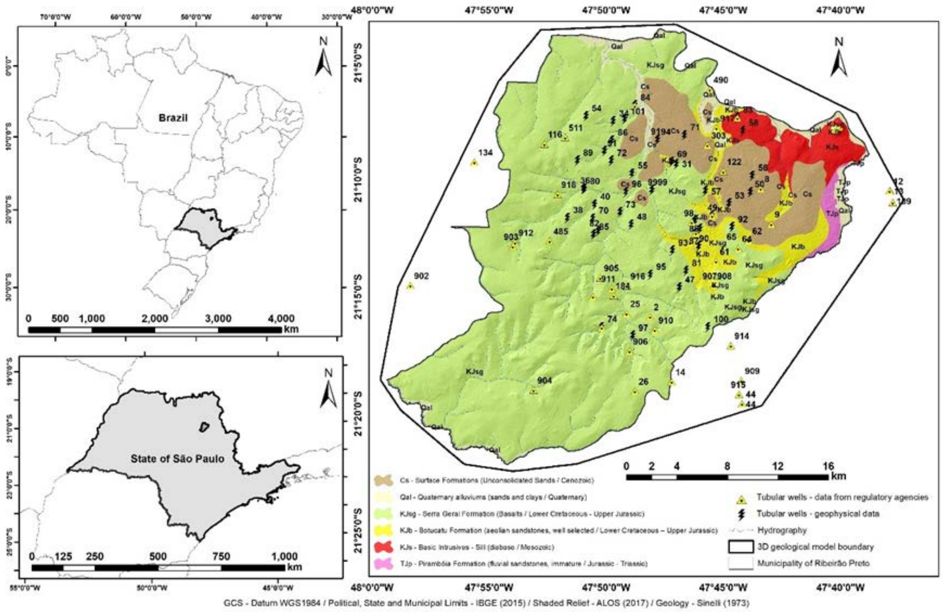

Figure 1. Study area: The locations, geological, geophysical data collection and sites of the tubular wells.

The region constitutes part of the Paraná Sedimentary Basin and is composed of Cretaceous basaltic rocks from the Serra Geral Formation, as well as the Jura-Cretaceous sedimentary rocks from the Botucatu and Piramboia Formations. These formations together constitute the São Bento Group. However, some portions are covered by Cenozoic sandstones (Figure 1). In the study area, the Botucatu Formation is basically composed of sandstones having cross-stratifications, typical of the desert environments, with the characteristic fine to medium grain and well-selected grains, having high hydraulic conductivity and specific storage. The Piramboia Formation, on the other hand, consists of fluvio-lacustrine sandstones with plane-parallel stratifications and fine to medium granulation and, often, with wave and current marks. In these sedimentary rocks, thick successions of flood basalts and diabase intrusions from fissural magmatism were placed (Soares et al., 1973; Sinelli et al., 1980). Finally, thick soil profiles cover almost the whole municipality (Figure 2) (São Paulo, 2017).

The data from 128 tubular wells (Figure 1) drawn from the public agencies DAERP and SIAGAS, were interpolated by kriging in the ArcGIS 10.0 Geographic Information System (GIS) were used to obtain the depth of the static water level and the GAS potentiometric surface in the region.

To identify the outcropping areas of the Botucatu Sandstone, geophysical data from 45 tubular wells from Empresa Perfil Master and construction profile data from 38 tubular wells (Figure 1) from the Department of Water and Sewage of Ribeirão Preto - DAERP were used.

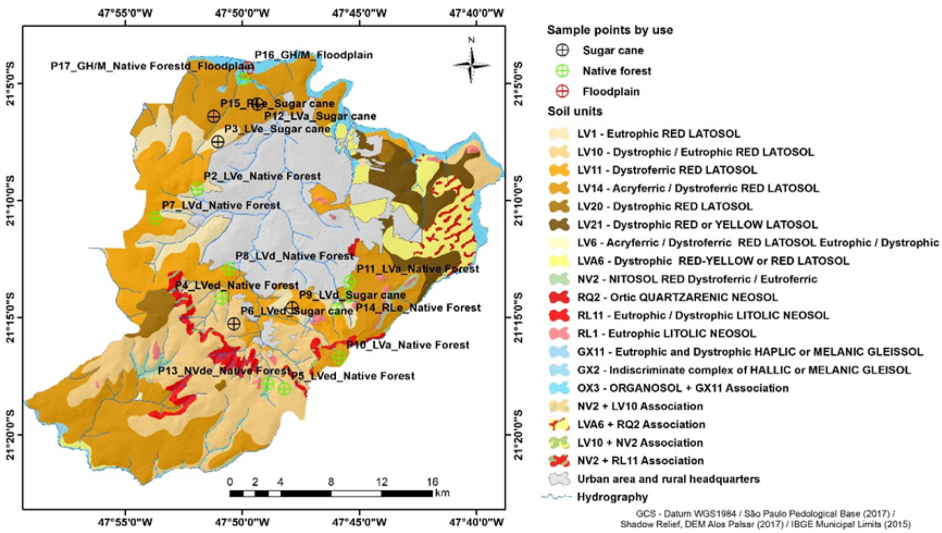

Figure 2. Map showing the pedological units second Brazilian Soil Classification System (EMBRAPA, 2018) in the Ribeirão Preto Municipality (Source: São Paulo, 2017) and sample points of the soils.

These data enabled the interpretation of the geophysical profiles using the software 'Display 6, Century Geophysical'. In the interpretations, four basaltic lava flows from the Serra Geral formation, were identified, just as demonstrated by of Fernandes et al. (2010). As well as the dry and wet phases in the formation of Piramboia (Sinelli, 1973).

From the profiles, the depth and type of lithology of the layers were obtained. Then, a 'dropdown' style table, '.txt' format was created, with the coordinates X (longitude), Y (latitude) and Z (depth) of the layers. The table was then transferred to the GMS 10.1 software by producing a well-shaped file (Figure 3A). Next, a set of blank cross-sections was generated connecting the tubular wells (Figure 3B) using the finite element method (Figure 3C) (GMS, 2015). Finally, a shapefile of the geological boundary of the model (Figure 3E) was created. This was interpolated in three-dimensions in an irregular triangular network (TIN) with 50 m spacing between the triangle edges (Figure 3D). This enabled the creation of a three-dimensional model of the geology of the municipality to accurately identify the outcrop regions of the Botucatu Sandstone.

The hydrosedimentological dynamics was evaluated and the sediment produced was quantified by applying the Revised Soil Loss Universal Equation (RUSLE) (Equation 1), by Renard et al., (1997) with support for SIG ArcGIS 10.0.

$$A = R \times K \times L \times S \times C \times P \quad (1)$$

where: 'A' is the soil loss (Mg ha^{-1} year^{-1}); 'R' is the erosivity through rain (MJ mm^{-1} ha^{-1} h^{-1} year^{-1}); 'K' is the soil erodibility (Mg ha^{-1} MJ^{-1} mm^{-1}); 'L' and 'S' represent the topographic factors, calculated by the relationship between the slope and the ramp length (dimensionless) and ‘C’ and ‘P’, respectively, soil cover factors and as practices of management and conservation

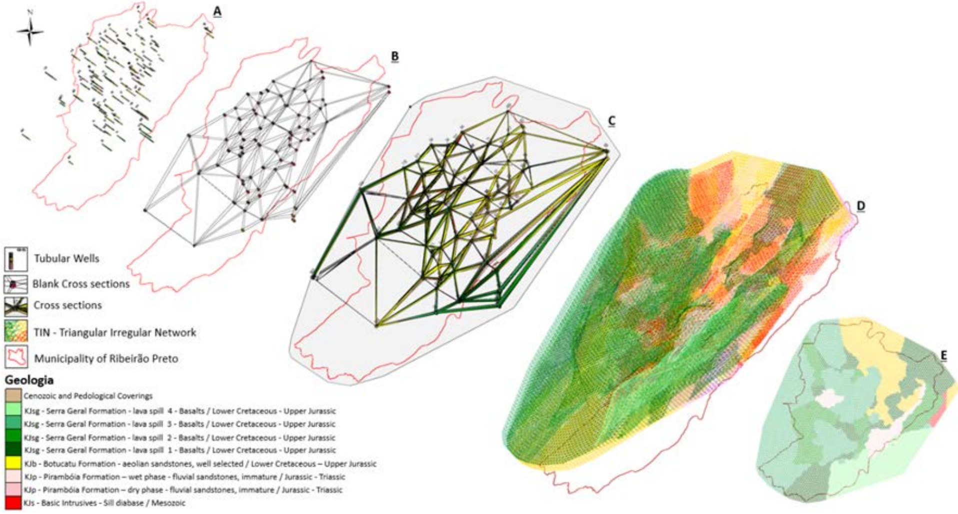

Figure 3. Methodological procedures for the elaboration of the geological model: Stage A - plot of the tubular wells; Stage B - connection between the wells (blank cross-sections); Stage C - attribution of the lithology to the sections created (cross-sections); Stages D and E - creation of the Irregular Triangular Network (TIN) and three-dimensional geological model.

To accomplish this, 17 sample points were chosen, distributed within the main pedological units of the municipality (Figure 3) and inside the Ribeirão Preto hydrographic subbasin. Among these, 11 points were under native forest, which shows the soil pattern without anthropic alterations, 5 were under temporary use of raising sugarcane, a clear indication of the main anthropic dynamics and 1 in the lowland floodplain at the mouth of the Ribeirão Preto river, in a the area of deposition of sediments. Regarding the soil types sampled, two (2) points were under forest and one (1) under sugarcane for the following soil units: Acriferric Red Latosol (LVa); Eutrophic Red Latosol (LVe); Dystrophic Red Latosol (LVd) and Eutrophic / Dystrophic Red Latosol (LVed). In the Dystrophic / Eutrophic Red Nitosol (NVde) and Eutrophic Litolic Neossolo (RLe), occupying restricted areas; one (1) sample was drawn from the native forest and one (1) from agricultural use. To complement the evaluation of the hydrosedimentological dynamics, two (2) points were collected from the floodplain region, one (1) under forest and one (1) under sugarcane, all being taken at the mouth of the Ribeirão Preto River, where the Gleisols and / or Melanic (GH / M) are dominant. The protocols and procedures of Lemos and Santos (2011) were adopted for soil collection. Among the soil classes, the Latosols are the most highly significant economically, as well as the most abundant in the municipality.

In order to calculate the RUSLE K factor, samples were collected in May 2018, from each soil unit described, with and without deformed structure, at 0 to 0.30 and from 0.30 to 0.60 m depths. From the soil samples, several physical, chemical and morphological attributes of the soils were obtained: particle size and clay dispersed in water, and the flocculation index (EMBRAPA, 1998); soil permeability to water using field infiltrometers and with triplicate (Zhang, 1997; Dane and Topp, 2002); aggregate stability from the soil sieving method in water (Kemper and Rosenau, 1986), which enabled the geometric weighted average diameter (DMG) to be calculated (Kemper and Chepil, 1965). An analysis of soil fertility was also done (EMBRAPA, 1998).

The RUSLE was calculated following the procedures listed: K Factor obtained by the indirect method of evaluating soil erodibility of Denardin (1990), from the data sampled in each soil unit; R Factor obtained from Trindade et al. (2016) and the study area shows an erosivity of 6500 MJ mm ha^{-1} h^{-1} $year^{-1}$; LS Factor (Figure 3A) was calculated employing the method of Hickey (2000), with the data derived from the Digital Elevation Model (DEM) SRTM 2, and corrected by the ArcGIS Fill function which eliminates anomalous pixels. In order to apply the Hichey (2000) algorithm, altimetry and slope were used as input data, from which the flow direction was obtained. From this to the area of contribution and accumulation of flow, by $D\infty$ method of Tarboton (1997); C Factor (Figure 4B) was obtained from the Earth Explorer image / multispectral bands repository of the Landsat-8 OLI satellite (Operational Land Imager), from 05/09/2015, with atmospheric and geometric treatment, georeferenced to the World Geodetic System - WGS 1984. Then, the 8 classes of land use and cover were defined: urban area, roads and rural headquarters; floodplain hygrophilous fields; water bodies; temporary crops; permanent crops; pasture; native forest and mining. The image produced by stacking all the multispectral bands, in a false-colour composition (R5G4B6), using a 2% linear contrast, was segmented in the ENVI 5.3 software.

From the segmentation, the digital image classification was performed, by applying the non-parametric statistical algorithm, Support Vector Machines (SVM) (Huang et al., 2002) available in EnviFX. This classifies each segment based on the spectral attributes of the shape and texture of each use and ground cover, based on the training data and multispectral bands. The image was cropped, according to the shapefile of the municipality limits (IBGE, 2013). The values of the factors of land use ‘C’ and conservation practices ‘P’ (Figure 4B) were taken from the specialized literature.

In ArcGIS 10.6, by map algebra, the product of the natural factors' R ',' K 'and' LS 'and the anthropic factors' C' and P 'were obtained, the water erosion susceptibility map was generated and the soil loss rates were quantified for the entire area. To assess areas with unsustainable water erosion rates, the Soil Loss Tolerance limit was also calculated, based on the method of Bertol and Almeida

(2000). Then, the map of the soil units (Figure 2) was related to the erosion susceptibility map, with the TPS broken down for each soil unit.

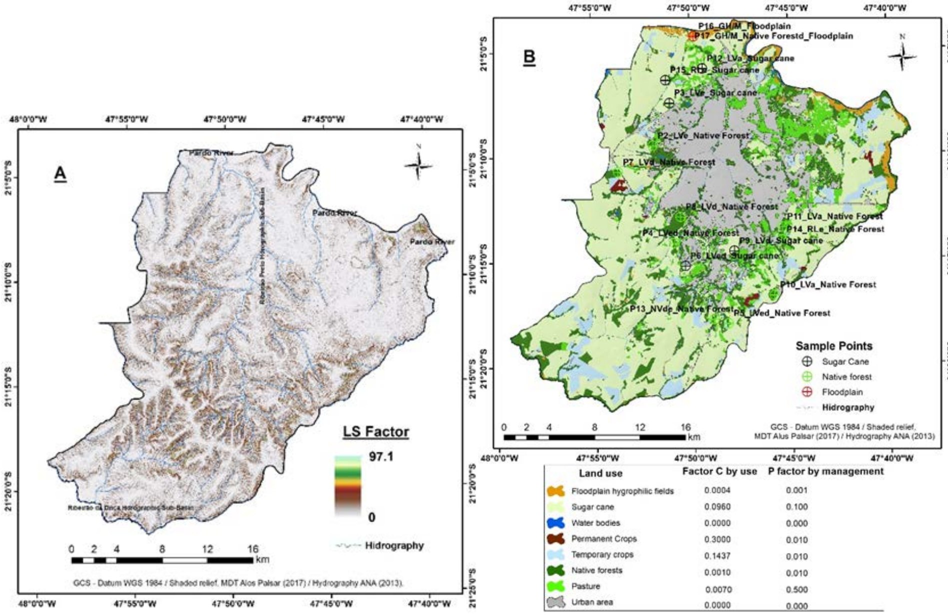

Figure 4. A - Topographic factor ‘LS’; B - Use and management map with values of the factor of use, and coverage factor ‘C’, as well as conservationist practices factor ‘P’.Sources: Eucalyptus under no-tillage and native forest (Martins et al., 2010); Soy under no-tillage (Bertol et al., 2001); Sugarcane without burning at harvest and with terracing (Andrade et al., 2011); Conserved pasture and degraded pasture (Roose, 1977) and Flood plain area (Oliveira et al., 2007).

RESULTS AND DISCUSSION

According to the geological model (Figure 5), of Botucatu Sandstones outcrops are located in the north of the municipality, near the Rio Grande floodplain. The yellow portions shown in Figure 5, indicate the Botucatu Sandstone outcrops, and are recharge areas of the GAS, and are therefore, influenced by the runoff of practically of the whole Ribeirão Preto subbasin, (Figure 5A). Even in the areas the Botucatu Sandstones (Figures 1 and 5), are cover by the soils and by the Cenozoic Sandstones, the runoff waters are able to penetrate through these layers and recharge the aquifer.

According to the particle size of the soils (Figure 6A), when these are formed in the areas of the outcrop of the Botucatu Sandstone, the sand content is highest, reaching at the 400 g kg^{-1} at point 16, which is covered with indiscriminate floodplain soils, and 380 g kg^{-1} in the point 12, at the areas of Acriferric Red Latosol.

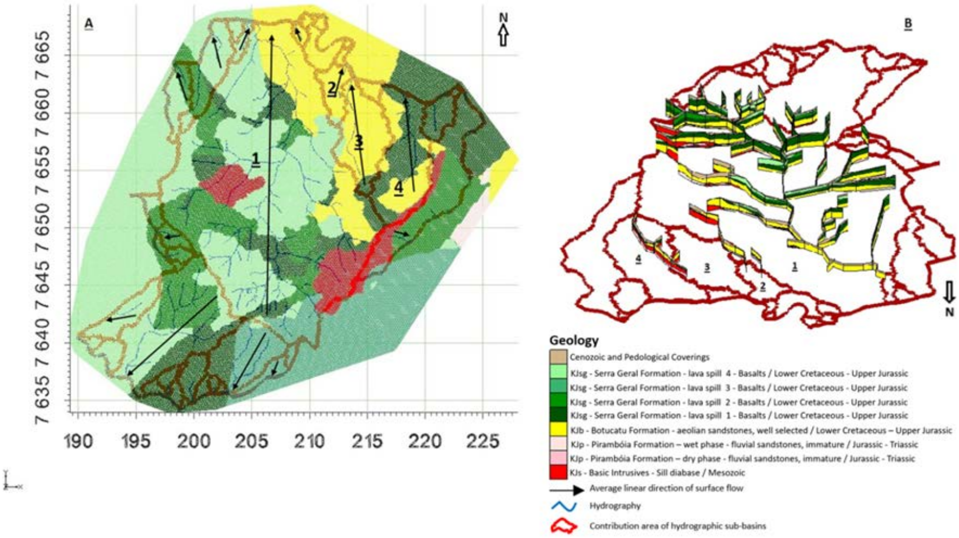

Figure 5. A - São Bento Group's geological model, hydrography and areas of contribution to the hydrographic sub-basins of the Municipality of Ribeirão Preto; B - Geological profiles drawn over the hydrography that flow to the outcrop areas of the Botucatu Sandstone.

In these latter soil type, when formed on the basaltic rocks of the Serra Geral Formation, it reached a maximum of 120 g kg^{-1}, what reflected in the permeability of the Latossols over the region of the outcrop of the GAS, with 99 mm h^{-1} permeability and 24 cm s^{-1} infiltrability at point 12 (Figure 6B). However, in the regions upstream of the Ribeirão Preto Subbasin, above the basalts, the soils show less permeability and thus the runoff increases, transporting the sediment to the lower and flat areas, precisely in the free GAS areas, where the higher infiltration rate is achieved.

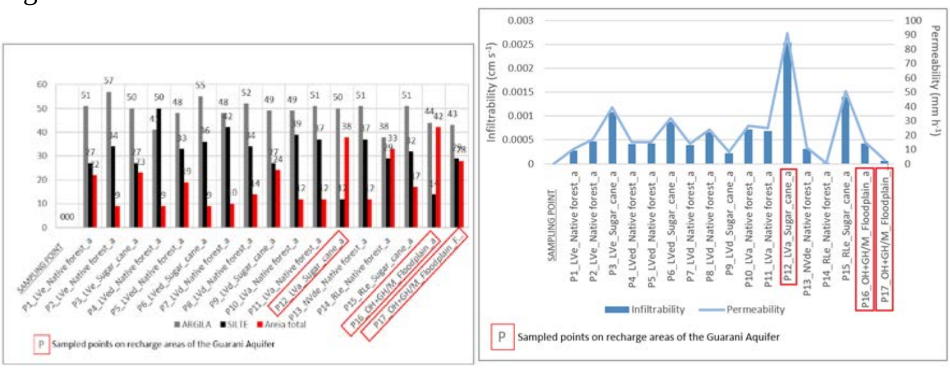

Figure 6. A – Histogram illustrating soil granulometrical composition; B - Histogram illustrating soil infiltration and permeability.

The soils formed over the Free GAS, also show higher levels of acidity and aluminum and lower Cation Exchange Capacity - CTC, indicative of lower fertility, In the Ribeirão Preto Municipality these regions are located in the areas with lowest altitudes. The soils on the Serra Geral Formation rocks, however, are more clayey with greater agricultural workability because of their higher CTC, moisture retention, lower acidity and better fertility. As the iron content is high, these soils have the characteristic red colour and therefore are generally classified as Latossols and Argisols. They occur i regions higher than 525 m altitude, located in the north region of the municipality.

The Latosols sampled under the native forest (MN) and agricultural use (UA), generally presented, on average, organic matter (OM) content, of 54.4 g kg-1, and 28 g kg-1 respectively. For soils under agricultural use, this value was lower and indicative of the degradation of this soil attribute, caused perhaps by the conventional management methods used. This condition is aggravated by deforestation and burning the sugarcane harvest in some cases, which decreases the deposition of plant debris and reduces the base exchange capacity of these soils. Low levels of OM, along with mechanization management techniques, can also be linked to the lower average values in the DMG of the Latosols surface horizon at the sites with sugarcane, of 4.7 mm as against the 4.85 mm with native forest.

In Latosols, in basaltic and diabase areas (Figures 1 and 2), management can produce structures that are harmful to the growth of seedlings and roots, due to less aeration, infiltration and water movement in the soil profile and therefore favouring erosive processes. Thus, inadequate management practices and the lack of conservation methods favour the disintegration of soil structures and cause latosols to have low permeability, of the order of 26 mm h-1, on average, for soil under agricultural use, and 26.6 mm h-1, for soil under native forest. The resulting low permeability arises mainly from the clayed texture, although the compaction caused by mechanization also has influence. This characteristic of low permeability together with the clayey texture and the average geometric diameter of the soil aggregates under agricultural use, suggest a possible change in the hydrosedimentological dynamics, including the likelihood of an increase in the surface runoff and concomitant rise in the transport of the sediments and potential contaminants employed in the agricultural production and in urban centres, which can contaminate the GAS groundwater.

When comparing samples taken from Latosols at depths of 0 to 30 cm and 30 to 60 cm, the surface horizons contain about 22.2% of the total sand in agricultural use and 13.4% in native forest; however, the 30-60 cm layer contains 20.6% of total sand in agricultural use and 14% in native forest. This implies a probable concentration of the largest grains in the superficial horizons, because fine particles are carried by the superficial flow, confirming the proposition that the anthropic use has altered the characteristics of these soils. At Ribeirão Preto Municipality, the GAS both in free and confined areas near Free GAS are the most utilized for public supply, because of the low levels of mineralization and silica. However, the GAS displays an unconfined behaviour and has acquired its chemical characteristics from the unsaturated aquifer zone (Gallo and Sinelli, 1980). The stable isotopes of the oxygen-18 and deuterium reveal homogeneous values for the aquifer, suggesting that recharge in the urban area occurs only due to local precipitation. The radioactive isotopes tritium and carbon 14 indicate an identical dynamic and reveal that the waters are recent and do not contain artificial tritium, which implies infiltration after 1950 (Gallo and Sinelli, 1980). In this context, the flow of surface water can diffuse agrochemical contaminants in outcrops of GAS. Latosols over GAS Livre have good permeability, due to the high sand content and, in depth; the water has relatively fast circulation and has a recent origin, which favours the exchange of water with the surface. Besides this, the underground water level depth (Figure 7A) that in the northern region of the Ribeirão Preto reaches the surface of terrain in the north area of the municipality in the Pardo River Plain, which increases susceptibility to contamination by diffuse contaminants in the GAS.

The piezometric surface (Figure 7B) flows from northeast to southwest, which implies that part of the flow of sub-basins 1, 2, 3 and 4 (Figure 5) flows over the Free GAS. These flows can be returned to the southwest in depth, due to the GAS piezometric surface (Figure 7B), reaching urban tubular wells with surface contaminants. This increases the vulnerability of GAS in the region where a large part of the local population is concentrated. The piezometric surface reveals drawdown induced by the large concentration of wells and high pumping rates, mainly in the central region of the city (Montenegro et al., 1988; São Paulo, 2008; Conceição et al., 2009). In addition, in the outcrop region of the SAG, the level of groundwater has the lowest depths (Figure 7A), which coincides with the lowest altitudes. Due to this hydrosedimentological configuration, the SAG in the outcrop areas is vulnerable to all contaminants from runoff.

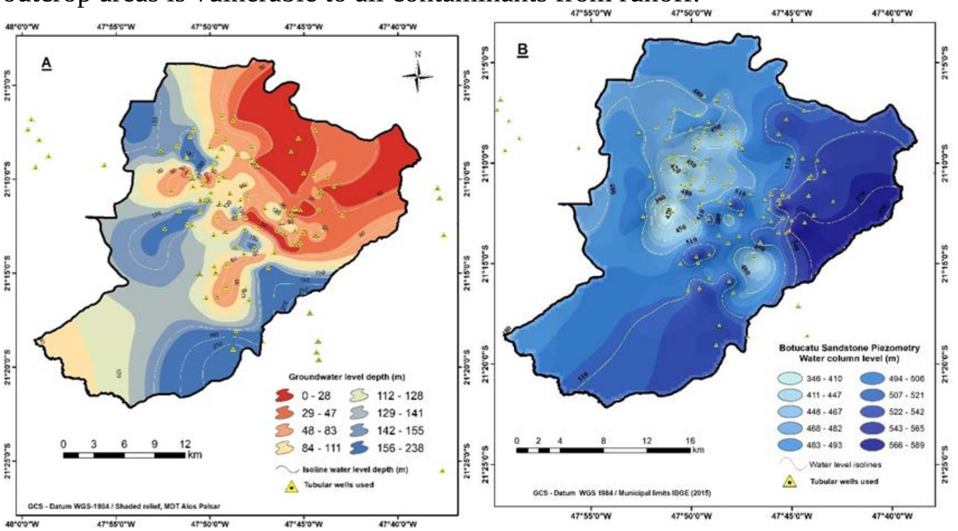

Figure 7. A. Map showing water level depth; B. Map showing the potentiometric surface of the underground water in Ribeirão Preto – SP.

Soil use and management can introduce a series of new alien substances to the natural environment due to the application of agrochemicals, as well as dragging and agitating the soil particles, as shown by London (2011). As a result, free aquifers can be negatively affected by the improper use of agrochemicals and the acceleration of the dynamics and surface hydrosedimentological flows. Thus, the geological units that comprise the GAS would have experienced a series of changes from the time it was formed, which includes the oxidation of grain surfaces and the translocation of groundwater clays. These geological units are also affected by the alteration of clay minerals, such as the change of kaolinite to smectites, and the establishment of secondary porosity, due to the dissolution of the unstable minerals (feldspars and ferromagnesian silicates) and carbonate-induced cementation (Araújo et al., 1999; França et al., 2003). By way of example, the rate of water erosion on average in the area under study is 1.42 Mg ha^{-1} year^{-1} (Figure 8A). Around 5% of the municipality is above the TPS limit; however, when we remove the urban areas from the floodplain and water bodies, it extends to around 7% of the municipal agricultural area, 3,155 ha of the 48,527 ha were demarcated for agriculture and livestock in 2017.It is vital to note that no safe rate of soil loss can be set (Figure 8A). The TPS varied between 8.5 and 9.7 Mg ha^{-1} year^{-1} for the Latosols, 8.5 Mg ha^{-1} year^{-1} for the Nitosols and 6.5 Mg ha^{-1} year^{-1} for the Neosols (Figure 8B).

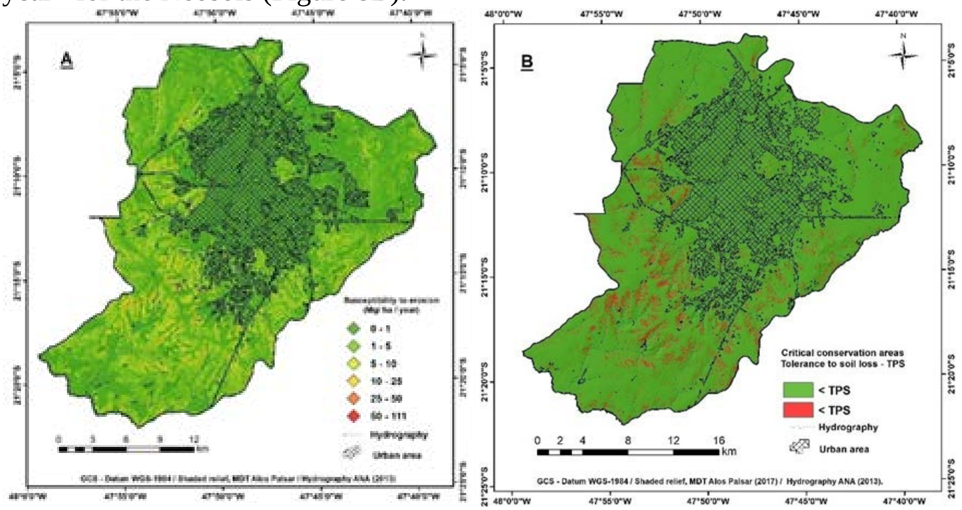

Figure 8A. - Map showing the erosion susceptibility classes; B –soil loss above and below the Tolerance to Loss of Soil limit in Ribeirão Preto Municipality – SP.

However, it is important to recognize that no safe levels of soil loss can be prescribed, mainly because the rates of pedogenesis are not known and also due to the synergistic effects on other environments including rivers and the atmosphere. With TPS values like these, areas with soil losses less than the TPS cannot be assumed to be sustainable. They will necessitate measures to mitigate the soil loss rates to levels closer to those recorded for the native forests.

Considering the average soil losses by land-use class (Table 1), sugarcane, which occupies the largest relative area, has the highest susceptibility to water erosion, with an average loss estimated at 2.83 Mg ha^{-1} $year^{-1}$. Then, the land-use classes with higher erosion susceptibility are silviculture and soybean, with average losses estimated at 1.23 Mg ha^{-1} $year^{-1}$ and 0.35 Mg ha^{-1} $year^{-1}$, respectively. The forests present the lowest erosion rate with 0.03 Mg ha^{-1}, $year^{-1}$ of soil loss. It is noteworthy that the lowland and urban areas have been excluded from the RUSLE calculation, first because it is a sediment receiving area and not a loss area and second because of the waterproofing of the soils.

Table 1. Susceptibility to soil loss for the different classes of uses and management in Ribeirao Preto.

	Area	Average rate of soil loss	Maximum Erosion	Total by class	Contribution to total erosion
Use	ha	Mg ha^{-1} $year^{-1}$	Mgha^{-1} $year^{-1}$	Mgha^{-1} $year^{-1}$	%
Urban area	14446.1	0.00	0.0	0.0	0.0
Hygrophilic fields	1257.9	0.02	4.5	4.5	0.0
Sugarcane	31030.0	110.11	959090.0	959090.0	93.2
Water bodies	223.8	0.00	0.0	0.0	0.0
Temporary culture	4286.7	28.37	15700.3	15700.3	1.5
Permanent culture	254.0	38.99	3419.8	3419.8	0.3
Native forest	8817.8	7.30	2574.1	2574.1	0.3
Pasture	5115.0	27.32	47741.6	47741.6	4.6
Total	65431.2	1.4	110.1	1028530.4	100.0

Losses which exceed the TPS limit (Figure 8B) are mostly between 10 and 25 Mg ha^{-1} $year^{-1}$ and are observed in regions practicing conventional management methods, mainly sugarcane and the permanent and temporary crops. Losses in the range of 25 to 100 Mg ha^{-1} $year^{-1}$ are noted, particularly, in the areas of conventional sugarcane management. These losses are due to the combined effect of the slope, the management employed (Figure 4B) and soil erodibility. Concentrated losses are found in the Eutrophic Latosols unit, one of the most widely utilized in agriculture because of the high fertility and extensive area occupied (Figure 2). Such losses are also found in the Neosols, which is a shallow and sandy soil founded in regions characterized by the highest slopes and erodibility. Neosols present low value of DMG, OM, and CEC, which accentuated the soil particle transport.

The practices of agricultural mining and the accidental burning of sugar cane worsen this situation in all soil classes, as in the State of São Paulo it is prohibited to burn sugar cane for harvest. It must be highlighted that in the tropical regions because the kaolinite soils are naturally flocculated due to the aggregation between the clay, silt and sand particles, they exhibit a more porous and permeable behaviour, an essential attribute for their formation and maintenance of such soils. If this is neglected, with the water hydric regime being shorter than three dry months on average per year, the rates of water erosion can escalate. However, in agriculture, the conventional management practices used cause the break-down of soil structure thus minimizing the natural porosity and negatively influencing the infiltration rates, thereby enhancing the transport of these particles and the OM via the runoff waters.

In the regions of the permanent crops, namely silviculture and/or coffee, soil losses are mostly linked to the low soil cover due to the early years of plant development. Thus, the soil protection by the dossel is lower, which exposed the soil to the rainfall mechanic impact (Martins et al., 2010).

In the areas of the temporary crops, however, the continuous changes in coverage result in several instances when the soil is exposed, opening it up to the erosive action of rainfall. The use of level cultivation techniques, no-till and terracing, for instance, can remedy this situation. Soil losses in the pasture areas are mostly caused by common burning during dry periods, overgrazing and the absence of management techniques, which can be reduced by implementing rotated grazing, reducing the number of cattle per area and correcting the soil.

In such a scenario, the susceptibility to erosion has been estimated to exceed one million tons per year for the municipality of Ribeirão Preto, which can exert disastrous and long-term consequences for the economy of this municipality, due to the natural resources of soil and water getting deteriorated, which historically have ensured economic support.

Thus, assessing the hydrosedimentological dynamics of region provides an overview of the energy and matter flow patterns between the various environmental systems, like the surface and groundwater, facilitating inferences to be drawn regarding the possible interactions. This enables the adoption of measures to reduce the levels of potential contamination, based on precautionary and preventive concepts. Erosion raises the susceptibility level of the aquifer to diffuse the contamination because it ravages the surface soil layers, thus raising the permeability and lowering the water depth level (water table). These erosions encourage runoff which can transport the soil with the agrochemicals in the water courses. Particularly for the Ribeirão Preto, the GAS outcrop area is close to the Ribeirão Preto subbasin, in the Rio Pardo alluvial plains, causing the danger levels of contamination to escalate because of the proximity of the water level, land use and type of occupation. Besides, it must be recognized that CONAMA Resolution No. 430 (CONAMA, 2011) mainly investigates contaminants present in lethal doses, normally from the point sources, neglecting the chronic contaminations, like those arising from diffuse contamination by agrochemicals, which pose greater challenges to study.

Therefore, in the north-eastern region, where the GAS begins and extends into some areas of the urban area, the aquifer faces higher contamination risks, caused by the potentially existing activities of contamination. Besides, the water demand has steadily escalated, which induces extensive lowering cones of groundwater level of the aquifer in the urban area, and which locally alter the direction of the flows by attracting and increasing or decreasing the flows from the areas close to these locations in the urban portion. Besides, the presence of highly deteriorated deactivated wells, which need to be, sealed off by the government or via legal requirement, which, through surface runoff, are indicative of still one, more threat to the protection of quality of the groundwater.

With reference to expanding the use of the lowering cone (Conceição et al., 2009) it is suggested the tubular wells be constructed far away from the areas of highest exploitation, using alternate pumping methodologies to enhance the supply; another way is to regularize the water collection in the Rio Pardo subbasin, and set up environmental preservation areas and a vulnerability to pollution zone; one more method would be to improve agricultural management and control the types of fertilizers and pesticides applied and establish maximum permitted limits, in synchrony with intensive environmental education. Therefore, the hydrosedimentological dynamics in the specific area requires assessment to discover the water erosion hot spots, as revealed by the regions that exceed the established TPS limit (Figure 8B). This data can contribute towards defining the natural susceptibility of the aquifer to diffuse contamination.

Unsatisfactory use of land and poor management directly affect the soil loss rates (Figure 8A), by raising the agricultural production expenditure and lowering the productivity. However, while these harmful and indirect impacts must be considered, it is noteworthy, as examples, that the eutrophication of the water bodies, trophic chain contamination with the pesticides and heavy metals applied heightened quantities of greenhouse gas emissions and loss of environmental and ecosystem services are some other effects (Carvalho, 2008). Such environmental degradation of the resources in turn produces negative effects on all the physical and biological resources in the ecosphere (Morgan and Nearing, 2011). These deleterious effects can be reduced in regions characterized by anthropic actions by implementing simple conservation management practices, including no-till, planting along the counter lines, terracing, rotated grazing, as well as the protection of permanent preservation areas, like the riparian forests. These reparative actions are of paramount importance because of the surface flows in the drainage networks and which can negatively affect the GAS.

Although empirical data to validate the model are lacking, it is crucial to note that because of the paucity of environmental data in Brazil, this work offers a panoramic view of the areas that release and receive the hydrosedimentological flows, thus indicating the regions susceptible to erosion in this landscape, the water to be eroded and sediment deposition. Thus, the combination of the anthropic factors, as well as the uses and management of the specific soils enables the critical areas to be demarcated for the preservation and maintenance of the natural resources, which must be the focus of the sustainable management alternatives.

CONCLUSIONS

Based on the investigation conducted in this study, the following conclusions were drawn:

1 - To identify the hot spots of water erosion, the hydrosedimentological dynamics can be used to define the natural susceptibility of the aquifer to diffuse contamination.

2 – Further studies are required to investigate the effect of agricultural practices on groundwater and aquifers. However, according to local characteristics such as soil porosity, types of rocks, and water level depth, these water resources may be contaminated.

3 – The superficial hydrosedimentological dynamics of the Ribeirão Preto hydrographic sub-basin and adjacent areas can carry particles to the Botucatu Sandstone outcrops, which depending on its composition; can contaminate the Guarani Aquifer System in this point and many others with a similar configuration.

4 - No safe levels have been prescribed for soil loss, as all areas deserve equal attention, especially those having soil loss values exceeding values considered natural. In this case, the soil loss in the native forest for the municipality was 0.03 Mg ha-1 year-1, which is well below the average for agricultural use, which is 2.03 Mg ha-1 year-1. This situation can be considered critical and cause serious problems to the hydrosedimentological dynamics of the area, negatively influencing the water quantity and quality of the Guarani Aquifer System.

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