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Papers

Geotechnical and geoenvironmental characterization of the São Pedro stream basin - Uberlândia/MG: a contribution to urban drainage planning

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Abstract
This article presents the results of a research aimed at conducting geotechnical and geoenvironmental characterization the São Pedro stream basin, in Uberlândia/MG, from the physical environment attributes and properties, to use land as a means of rainfall infiltration. The methodology focuses on analytical mapping and generating cartographic documents that are individually elaborated and analyzed. Besides that, the characterization of unconsolidated materials (*in situ* and in the laboratory) and the coefficient of permeability (k) tests (*in situ* with a Guelph permeameter) were performed. With this data at hand, a quali-quantitative analysis of the physical environment features was made through the study of its attributes and their representation in maps. Variables related to infiltration and runoff processes were privileged. For the area of the São Pedro stream basin, values of k varying between 10^{-4} and 10^{-5} cm/s were found. The suitability map for infiltration showed the areas next to the streams and in the stream mouth as non-suitable or slightly suitable. On the other hand, the areas close to the drainage divides of the basin showed to be highly suitable. The center of the basin and the region between the Jataí and the Lagoinha streams are also highly suitable for infiltration. These areas with higher suitability are appropriate to the implementation of structural and non-structural measures that seek to reduce flood risks. Thus, we hope to contribute to urban planning in this study area through these geoenvironmental maps.
Keywords: geoenvironmental mapping. coefficients of permeability. Infiltration. Floods.

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Introduction

An Urban Drainage Planning (UDP) has to be one of the components of a city's Urban Master Plan (TUCCI, 1997, p.9). It must contain the geotechnical and geoenvironmental mapping that results from a detailed process of a quali-quantitative investigation and assessment of the characteristics of the physical environment through the study of its attributes and their representation in maps.

Geotechnical mappings integrated with geoenvironmental maps broaden the components and the goals of the environmental analysis, defining both the potentialities and the limitations of territorial planning. After creating a number of geoenvironmental maps, it is possible to provide data and information on the environment for territorial planning. Therefore, we expect to contribute toward public managers' decisions on adequate land use.

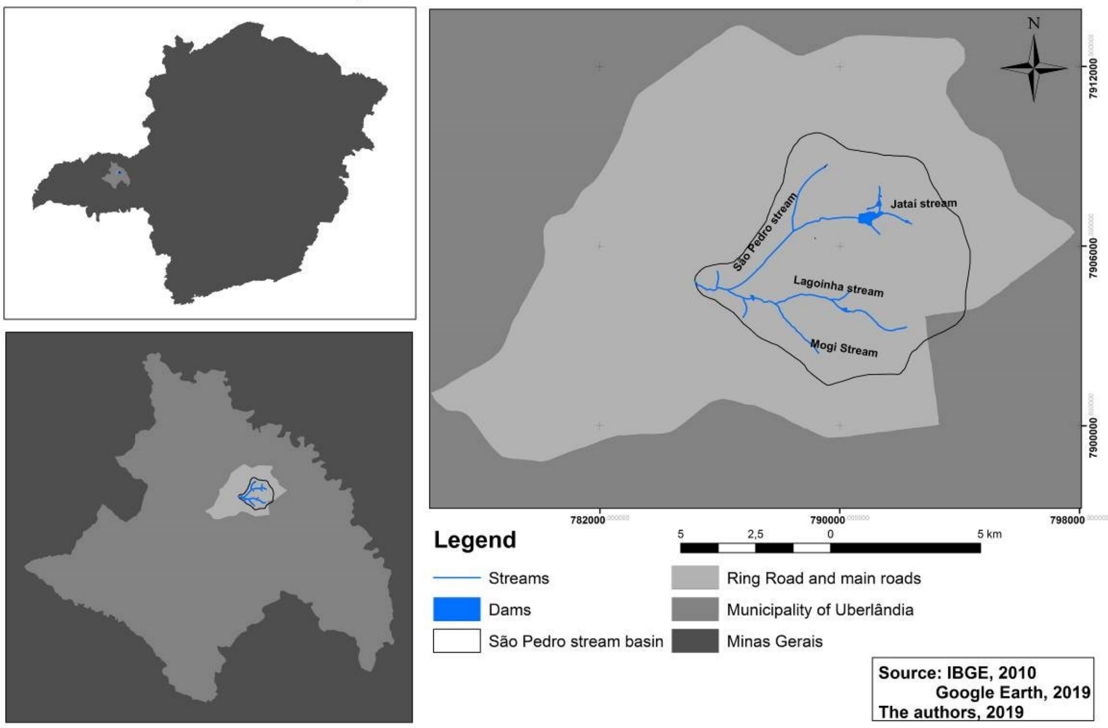
The study area of this paper is the São Pedro stream basin, in the city of Uberlândia-MG, which suffers from recurring flooding. Its main causes lie in intense urban occupation, which leads to the expansion of impermeable surfaces. Moreover, the stream has had its natural configuration modified through the installation of a closed piping system in the 1980s, over which Rondon Pacheco Avenue was built.

This research aimed to perform a geoenvironmental characterization, placing emphasis on the geotechnical aspects of the São Pedro stream basin to use the land as a means of water infiltration. We have prioritized areas with low occupancy density or facing increasing settlement in order to contribute to the urban drainage master plan.

Study Area

The São Pedro stream basin is almost entirely in the urban area of Uberlândia-MG, covering 48,201 km² and draining the São Pedro, the Jataí, the Lagoinha, and the Mogi streams (Figure 1).

Figure 1. Location of the São Pedro stream basin in Uberlândia/MG.



Source: the authors, 2019

Methodology

The primary cartographic base was built through the following 1984 topographic maps of the Ministry of Defense, which are at a scale of 1:25000: Sucupira Waterfall: SE-22-Z-B-VI-4-SO; das Moças Stream: SE-22-Z-B-VI-3-NE; Pau Furado: SE-22-Z-B-VI-4-NO, and Uberlândia: SE-Z-B-VI-3-SE. With the *Arcgis 10®10.2.2 software,* a mosaic was rendered to obtain a single file with the limits of the study area. Following that, it was possible to vectorize the contour lines and the elevated points. As the stream is in an urban area, the vectorization of the drainage system was made on two other basis: the base of geotechnical unities delimitated by Nishiyama (1998) at a scale of 1:100.000, and the QuickBird QBCP satellite image of July/2007, at a scale of 1:2000, checked on Google Earth.

After outlining the stream basin, we started the preliminary demarcation of the unities of unconsolidated materials through the integration of the aforementioned basis and the definition of a map key, which were verified in the field. In a summarized version, Table 1 describes the three pillars of the methodology proposed by Zuquette and Gandolfi (2004) adopted in this research, by basing mainly on the characteristics of the unconsolidated materials and on the coefficient of permeability tests (k).

Table 1. Methodological Framework according to ZUQUETTE and GANDOLFI (2004).

Information collection	Previous information	Bibliographical reference
		Flooding historical
		Rainfall and pluviographic data
	Information gathering	Satellite images / topographic map
		Fieldwork
		Sampling
		Laboratory and field tests
Data processing	Information tabulation	Integration of data in several ways
		Data bank
Analysis and interpretation of data for the elaboration of cartographic documents	Preliminary maps	DTM (Digital Terrain Model)
		Declivity
		Determination of the sample collecting sites
		Classification of the satellite images
	Statistical analyses	Descriptive analysis of the sampling sites (Graphs)
	Spatial analyzes	Matrices
		Map of unities of unconsolidated materials in the São Pedro stream basin
Geoenvironmental map	Joint analysis (integrated)	The suggestion of places for the implementation of structural measures to remediate and prevent floods.

Source: Adapted from ZUQUETTE and GANDOLFI, 2004, P.62

To determine the sample sites for laboratory tests, we employed the method of key areas, according to the methodology recommended in the Eastern European countries, described in Zuquette (1987). The selection of the sampling spots was not at random for the unities of unconsolidated materials had already been delimited. Another parameter that influenced the selection of the sampling sites was urban land use, which hindered a uniform sampling. The method of key areas is used for areas of at least 10 km^2, rendering the production of reliable data with a few samples, enabling investments in the fieldwork and laboratory tests.

For the 48,201 km^2 study area and based on the homogeneity of the unities of unconsolidated materials, two points per km^2 were first considered for sampling, summing up to 96 sample collecting points. However, for the cost of collecting, repeatability, and similarity of the samples, only 77 were selected. Despite that, 5 sites could not be sampled because of anthropic occupancies, such as civil construction and buildings. Therefore, there were remaining 72 points distributed in the unities of unconsolidated materials. To standardize the sampling information and organize the data, we applied a field form, which was elaborated by Nossa (2004) in her Master's dissertation.

We used both a 4" manual screw-type auger, which can go over a depth of 100cm and a VULCAN model VPS-520 mechanical auger capable of boring to a depth of 80cm. Nonetheless, the disturbed soil sampling was obtained at a depth of 100cm, using the manual auger to reach the final depth. The mechanical auger was necessary only in situations of very compacted soil. After removing the samples, we applied a preliminary visual and tactile test through the permeation and dilatancy test, according to the procedures indicated by Nogueira (2005).

Soil classification

The soil samples were sent to the Geotechnical Laboratory of the Faculty of Civil Engineering of the Universidade Federal de Uberlândia or determining the grain specific mass, particle-size analysis, and the Atterbeg limits. To perform the particle-size test, the NBR 7181/84, the ABNT NBR 7250/1982, and the ABNT NBR 6508/1984 standards were adopted. The 7181/84 standard suggests a soil analysis using a mix of sieving and sedimentation. The liquidity and plasticity limits were acquired, respectively, through the application of ABNT 6459/84 and NBR 7180/84 standards.

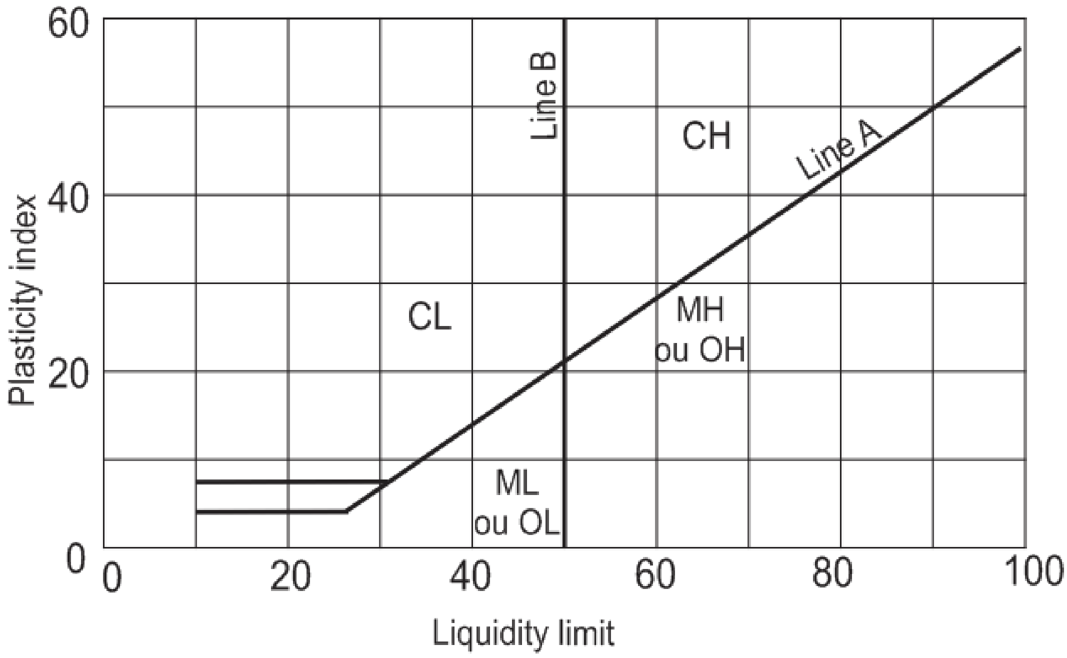
Although it is widely used by geotechnicians who work in dams, we adopted the Unified Soil Classification System (USCS), which was quite useful for understanding the mechanical and behavioral characteristics of the study area. As reported by Pinto (2006), the USCS, proposed by Casagrande, divides soils into three major groups: coarse-grained, fine-grained, and highly organic.

For the USCS, coarse-grained soils are classified into gravel or sand in accordance with their grain size distribution, followed by their secondary features. The first analysis examines if the sample has less than 5% fines passing the #200 sieve. Thus, their gradation has to be verified to aid classification. Gravel soils can be categorized as well-graded, whose diameters of the particles cover a limited range, and as poorly graded, with particles providing a broad array of diameters. In order to quantify these soils, both a uniformity coefficient (Cu) and a curvature coefficient (Cc) are applied (PINTO, 2006).

Pinto (2006) forwards that well-graded soils occur when the Cc value lies between 1 and 3. On the one hand, when this value is below 1, there is a discontinuity in the gradation curve. On the other hand, when it is higher than 3, the curve tends to be uniform in its central portion. If the sample has between 5 and 12% fines in its coarse range, the system will present two secondary characteristics (granulometric constancy and fines properties), thereby resulting in an intermediate classification. Lastly, when a coarse-grained has over 12% fines, it is necessary to identify the properties of the fines by the plasticity chart (PINTO, 2006).

The fine granulation is represented by silt (M), clay (C), and organic soil (O), which are grouped by their grain-size distribution (silt and clay). Nevertheless, the behavior of clay is analyzed by its content and its activity with the consistency indexes (PINTO, 2006). Figure 2 shows the plasticity index (PI) according to the classification of Casagrande *apud* Pinto (2006). Clayey soils plot above "A-line", whereas silty soils are under "A-line".

Figure 2. Plasticity Diagram.

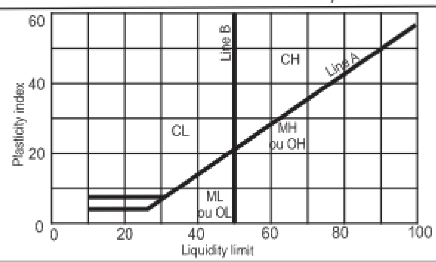


Source: PINTO, 2006, p. 68

Compressibility is a complementary feature of fine soils as the greater the Liquidity Limit is, the more compressible soil is. If this value is above 50, compressibility (H) is high and low (L) if it is under 50. Figure 2 also represents this property in “B-line” (PINTO, 2006). When the index is close to lines “A” and “B” or the PI ranges from 4 to 7, both classifications are considered. Consequently, the categorization is as complete as possible. Figure 3 illustrates The Unified System’s classification scheme as seen in Pinto (2006).

Figure 3 – The Unified System’s classification scheme

% P#200<50	G>S : G	% P#200 < 5	GW CNU > 4 e 1 < CC < 3
			GP CNU < 4 ou 1 > CC > 3
		% P#200 > 12	GC
			GM
		5 <#200 < 12	GW - GC, GP - GM, etc.
	S> G : S	% P#200 < 5	SW CNU > 6 e 1 < CC < 3
			SP CNU < 6 ou 1 > CC > 3
		% P#200 > 12	SC
			SM
		5 <#200 < 12	SW - SC, SP - SC, etc.
% P#200<50	C	CL	
		CH	
	M	ML	
		MH	
	O	OL	
		OH	



Source: PINTO, 2006, p. 69

b) *In situ* test with a Guelph permeameter

The delimitation of the homogeneous unities preceded the tests of water infiltration using a Guelph permeameter. Moreover, we highlight that this test was not run in the Organic/Hydromorphic unity as the soil was saturated or with significant saturation. Such saturation condition would imply the use of a pumping test, which is adequate for situations where the tested site is below the water level. In this research, forty places were selected in the study area to perform the test with the Guelph permeameter.

As stated by Soto (1999), this tool was developed by Reynolds and Elrick at the University of Guelph, in Canada, in 1985. It is a simple tool used in the field, which requires only auger boreholes with a permanent water supply regime and constant piezometric load. It generates accurate data for the determination of the unsaturated soil hydraulic conductivity and can be used both on the soil surface and in the soil profile as long as there is some water supply and the hydraulic charging is constant and known.

After running the tests, the results were interpreted based on the theoretical model developed by Reynolds and Elrick (1983), with adequations to Richard's equation (1931) for permanent flow in a cylindrical borehole. The method of one-ponded H-level is used to calculate the parameters of soil infiltration (COSTA; NISHIYAMA, 2007 *apud* ELRICK et al., 1989). This method consists of applying a constant height of water (H) in the well and, when a steady-state is reached, the flow rate Q and the field hydraulic conductivity (Kfs) are determined. However, when reclassifying the key, *natural breaks* are used whenever the intervals are grouped according to the samples, because of their heterogeneity.

c) Data analysis and mapping

The thematic maps were elaborated according to the assessed parameters of the physical environment. To make these maps, three stages were followed: (i) the pre-processing, (ii) the processing *sensu strictu*, and (iii) the mapping generation. During the (i) pre-processing, a complex survey of cartographic data took place by adjusting the study area, selecting areas of unconsolidated material, selecting field test areas, and data collection.

In (ii) processing, an interpolation of the field and laboratory data was applied with the use of the Ordinary Kriging method (no trends in the data) with the spherical semivariogram model, which was the pattern that obtained the higher heterogeneity in the data. Furthermore, secondary data from Nishiyama (1998) and Beicher (2001) studies were incorporated as well. With this processing, it could be rendered the spatialization of the concentrations of clay, SCG (silt, clay, and gravel), and the coefficients of permeability for depths from 10cm to 40cm, among others.

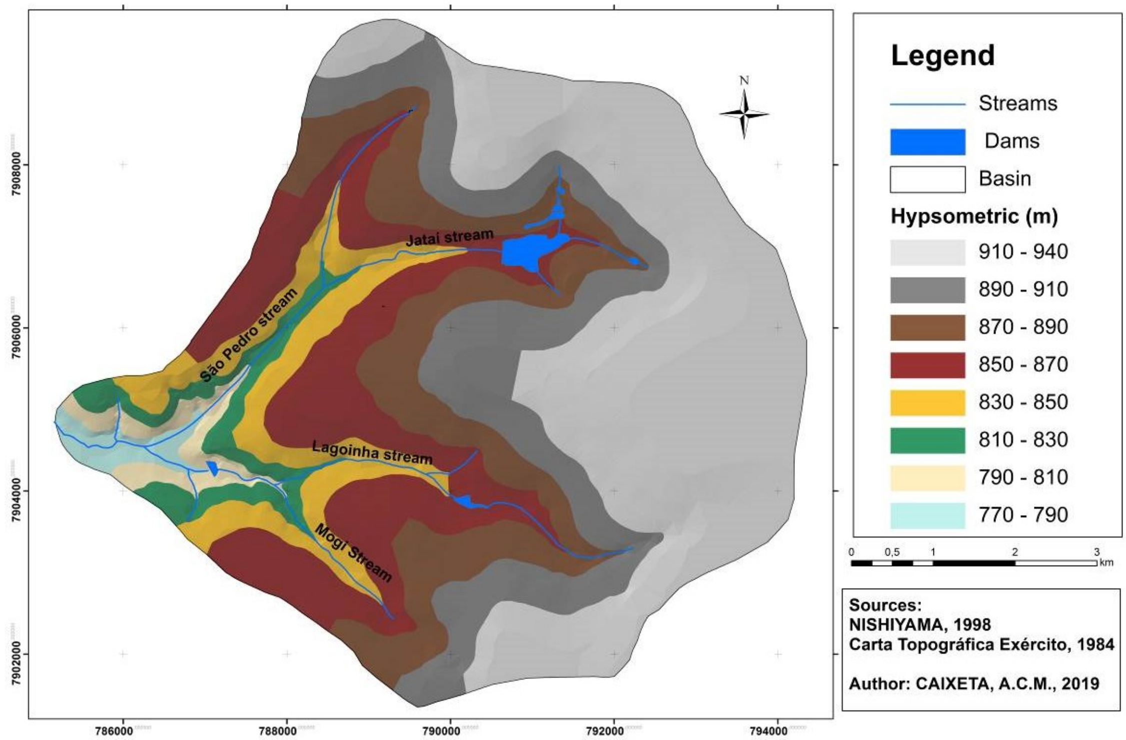
We also applied algebra maps to elaborate the geoenvironmental map of the potential of infiltration, which uses the bedrock, water level depth (NA) (NISHIYAMA, 1988), and the unities of unconsolidated materials map and from their results, another map overlapped was done for the depth of 40 cm in order to create the suitability infiltration map.

Lastly, the final maps (iii) resulted from an analysis of both the geoenvironmental map of the potential of infiltration and the suitability infiltration map. Thus, it was possible to obtain areas that are favorable to infiltration and therefore meant for the application of structures for rainfall infiltration.

Results

The hypsometric map shown in Figure 4 indicates that in the boundary area of the São Pedro stream basin the relief has a smooth decay as observed by the amplitude between the contours of 940 and 910 m. Due to the low descent of the relief next to the drainage divide, it is noted that water infiltration increases and hence there is a decrease of runoff surface. Next to the mouth of the basin, the relief has a stark amplitude, going from the contour of 810 to that of 770 m, which allows an opposite topographic behavior to the basin head area.

Figure 4 – Hypsometric map.

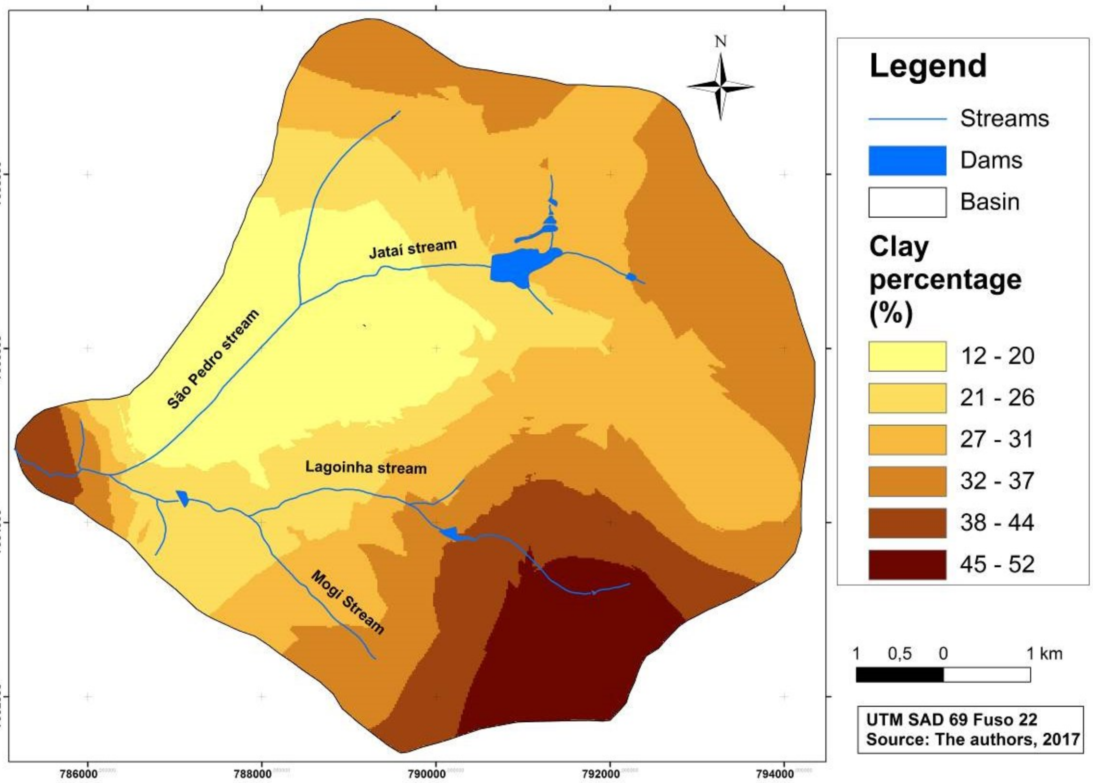


Source: the authors, 2019

Figure 5 displays the interpolation of the clay percentages in the basin. From the grain-size analyses, it was found that the clay rates vary between 12 and 53%. The locations with the highest concentration are close to the drainage divide, near the mouth of the mainstream and also in the Lagoinha stream spring area.

The largest concentration of clay fractions is at the head portion of the Lagoinha stream (above 40%). With approximately 8 km² (16, 5% of the area), this could be considered the least permeable spot in the São Pedro stream basin. However, to assure it, it is necessary to integrate the percentages of clay with the permeability data gathered in the field. Therefore, it was possible to relate water infiltration with surface runoff.

Figure 5 – Map of concentration of clay fraction in the unconsolidated materials.

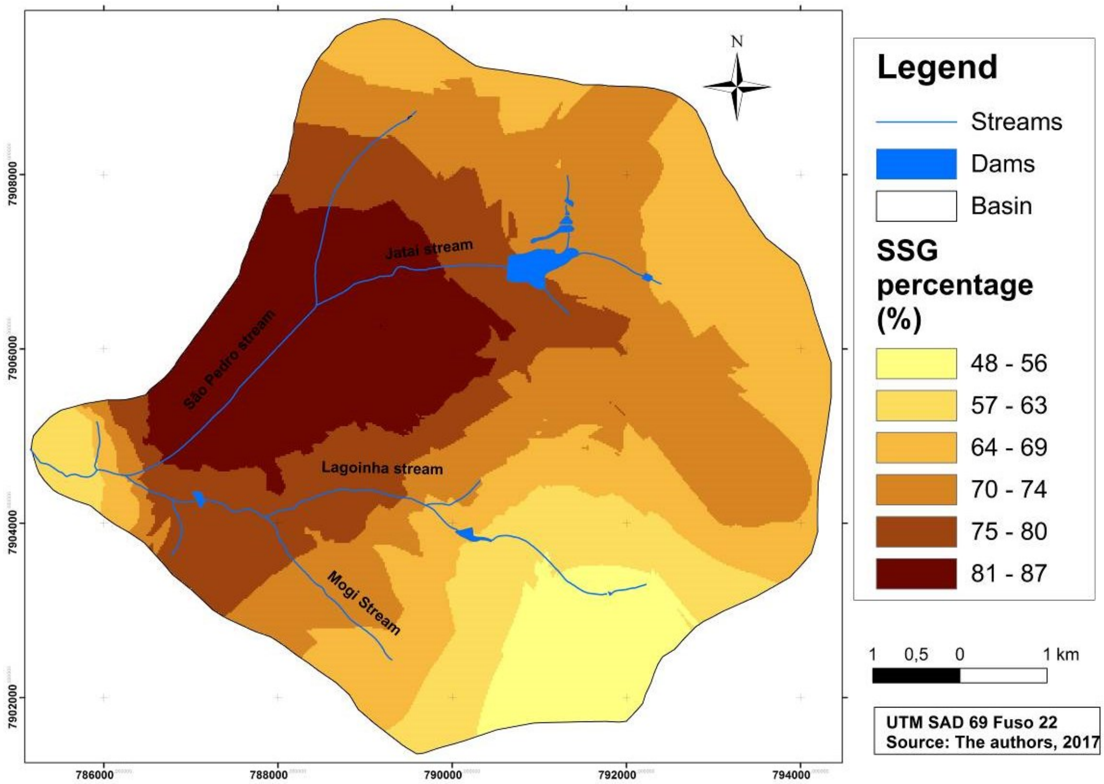


Source: the authors, 2017

It is known that silt, sand, and gravel present good characteristics for water infiltration, with growth rates from the finest to the coarsest fraction. Due to that, this paper tried to integrate the three size fractions to the behavioral analysis of the soil for water infiltration adopting the SSG (Silt/Sand/Gravel) denomination. Figure 6 depicts the resulting map from the interpolation of the sum of the values for silt, sand, and gravel particle-size percentages.

Moreover, Figure 6 indicates that the adjacent area to the São Pedro stream has around 80% of SSG. At the mouth of the São Pedro stream, these values move to around 50%. Despite that, the greatest fraction of the particle-size distribution is clay, which does not favor infiltration and consequently, it increases surface runoff.

Figure 6. Map of the SSG percentages found in the unconsolidated materials.



Source: the authors, 2017

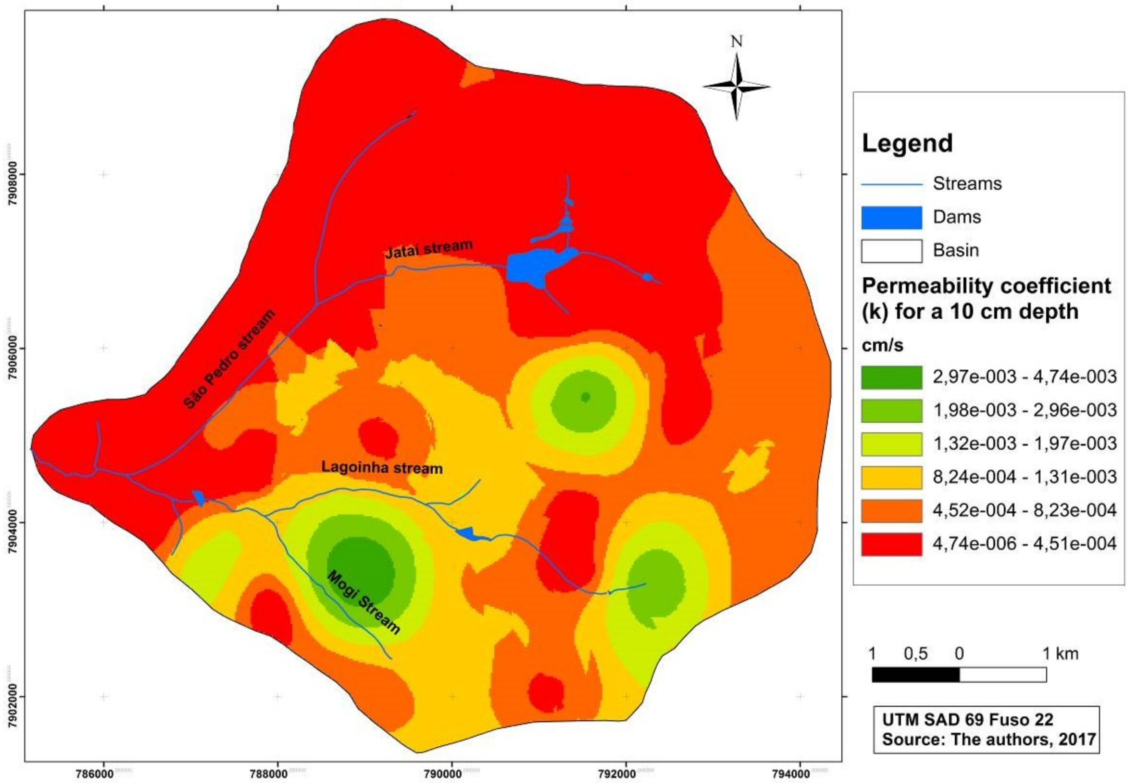
The areas in the spring of the São Pedro and the Jataí streams have 70% of SSG. The Mogi stream has 65% and the Lagoinha stream 55%. Thus, the SSG is higher in the center-west portion of the basin.

Coefficient of permeability (k)

Another fundamental parameter to understanding water infiltration in the soil is permeability. Figure 7 presents the coefficient of permeability map for a 10 cm depth. Apparently, this soil depth has considerable difficulty in allowing water infiltration when compared to those at a 40 cm depth (Figure 8). In the North, near the mouth and on the left side of the São Pedro stream, it is noticed a low permeability that hits values of

4,74x10^{-6} cm/s. High permeabilities can be found between the Lagoinha and the Mogi streams, reaching 3,62x10^{-3} cm/s. The center of the basin and the Lagoinha stream spring are two other prominent places with high permeability coefficients.

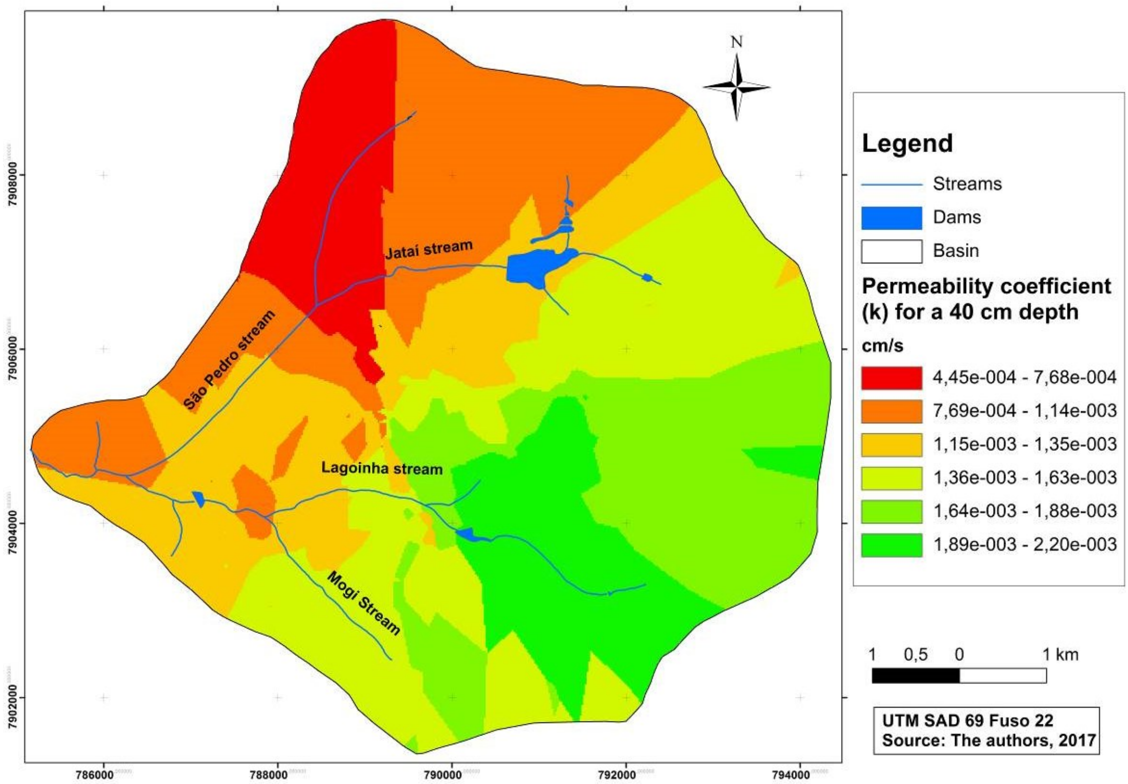
Figure 7. Interpolation through the spherical Kriging method of the coefficients of permeability at a 10 cm depth.



Source: the authors, 2017

The permeability at a 40 cm depth (Figure 8) shows higher values in the eastern region of the basin, near the Lagoinha stream spring. In both the Lagoinha stream and in the Jataí stream springs, permeability ranging from 1,36x10^{-3} cm/s to 1,5x10^{-3} cm/s is observed. Eventually, the São Pedro stream spring has a lower permeability than the other springs.

Figure 8. Interpolation through the spherical Kriging method of the coefficients of permeability at a 40 cm depth.

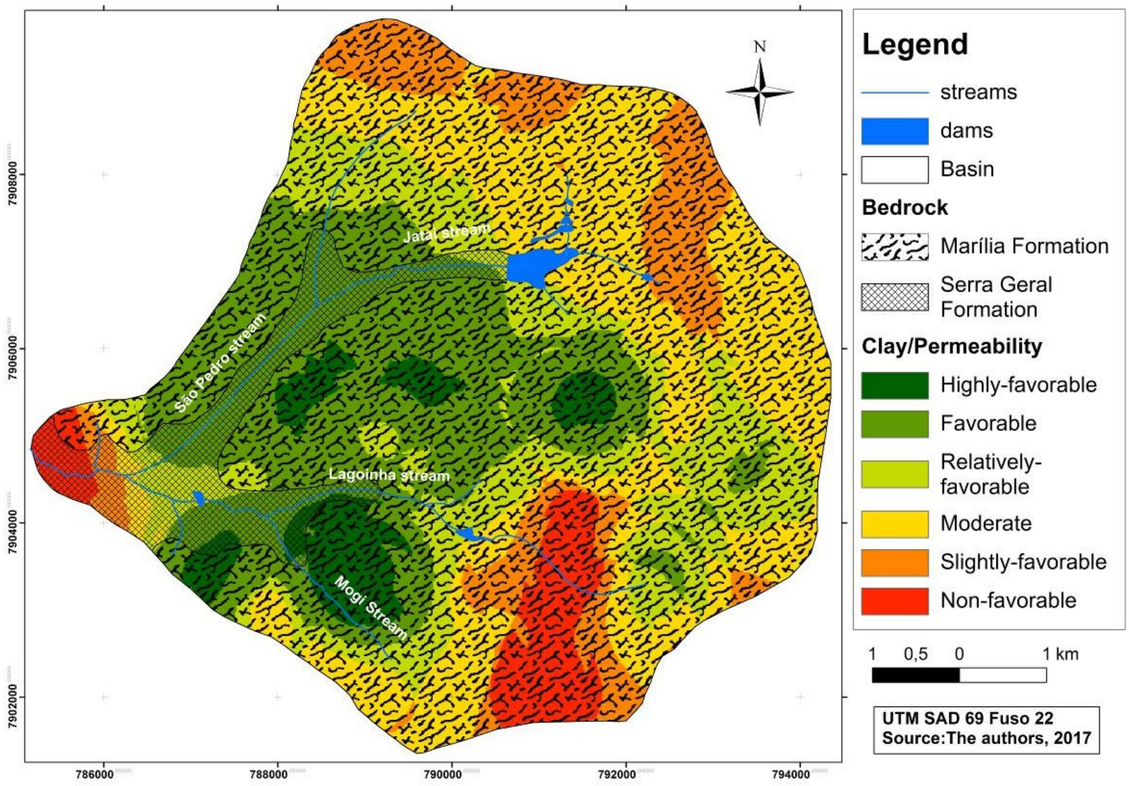


Source: the authors, 2017

Infiltration and infiltration suitability

The data integration percentages of clay and permeability allowed the estimation of the infiltration process. In the center of the São Pedro stream basin, there is a highly favorable area to infiltration, especially between the Lagoinha and the Mogi streams and between the Jataí and the Lagoinha streams (Figure 9). The areas close to the drainage divide present a moderate infiltration capacity. The portion near the São Pedro stream mouth has low infiltration values for it has a high clay concentration and low permeability.

Figure 9. Areas with the possibility of infiltration. Rendered by integrating the clay fraction percentages with the coefficient of permeability at a 10cm depth, both superimposed to the bedrock.

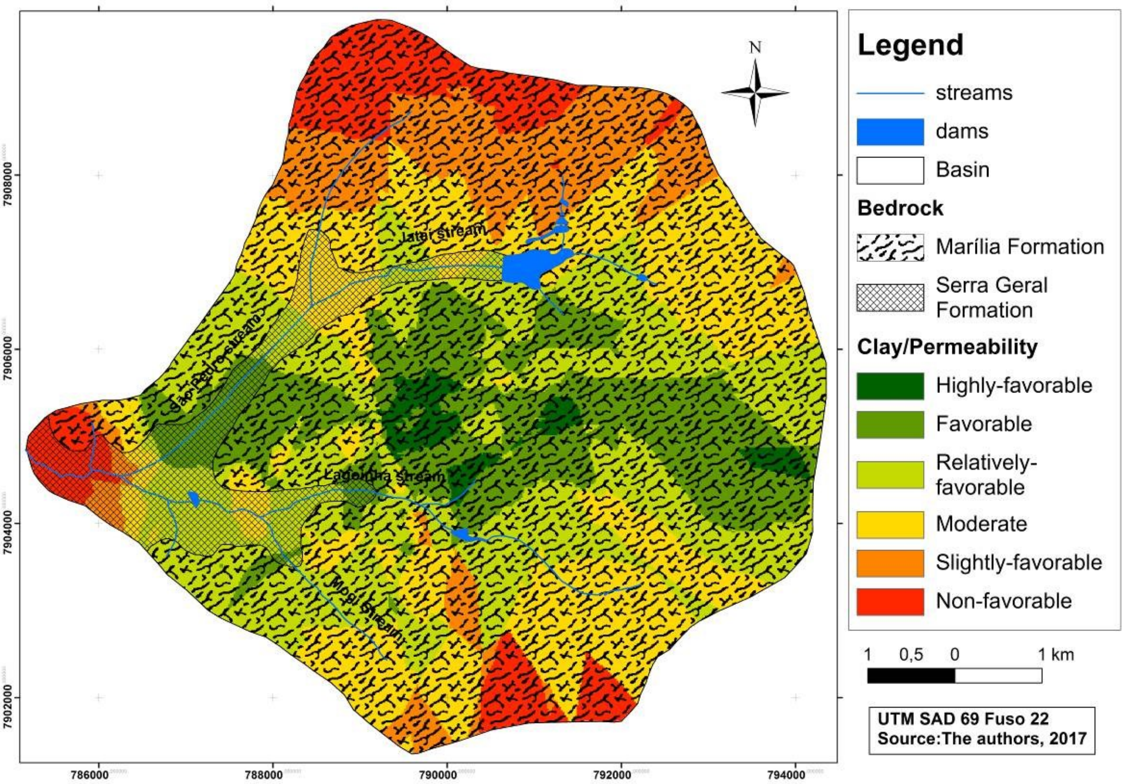


Source: the authors, 2017

Figure 9 reveals the area of the Serra Geral Formation, showing classes that indicate favoring infiltration. This formation is characterized by Nishiyama (1998) as composed by vesicular-amygdaloidal (bottom and top in flows) basalts that have a solid structure and several diaclasis, which may prevent infiltration in some spots. According to Nishiyama (1998), in the head and in the center of the basin, the bedrock corresponds to the Marília Formation, which is formed by immature, conglomeratic, and conglomerated sandstones. It is noted that the integration of the percentages to the depth of 10 cm results in non-favorable areas to infiltration. Noteworthy is the central region of the basin which is classified as being highly favorable and favorable to infiltration.

The reduction of the favorable areas to infiltration in the portion where the Serra Geral bedrock occurs is confirmed by the overlapping the bedrock with the clay percentages and permeability at a 40 cm depth (Figure 10). The most favorable areas to infiltration are between the Lagoinha and the Mogi streams.

Figure 10. Areas with the possibility of infiltration. Rendered by the integration of the clay fraction percentages with the coefficient of permeability at a 40cm depth, both overlapping the bedrock.

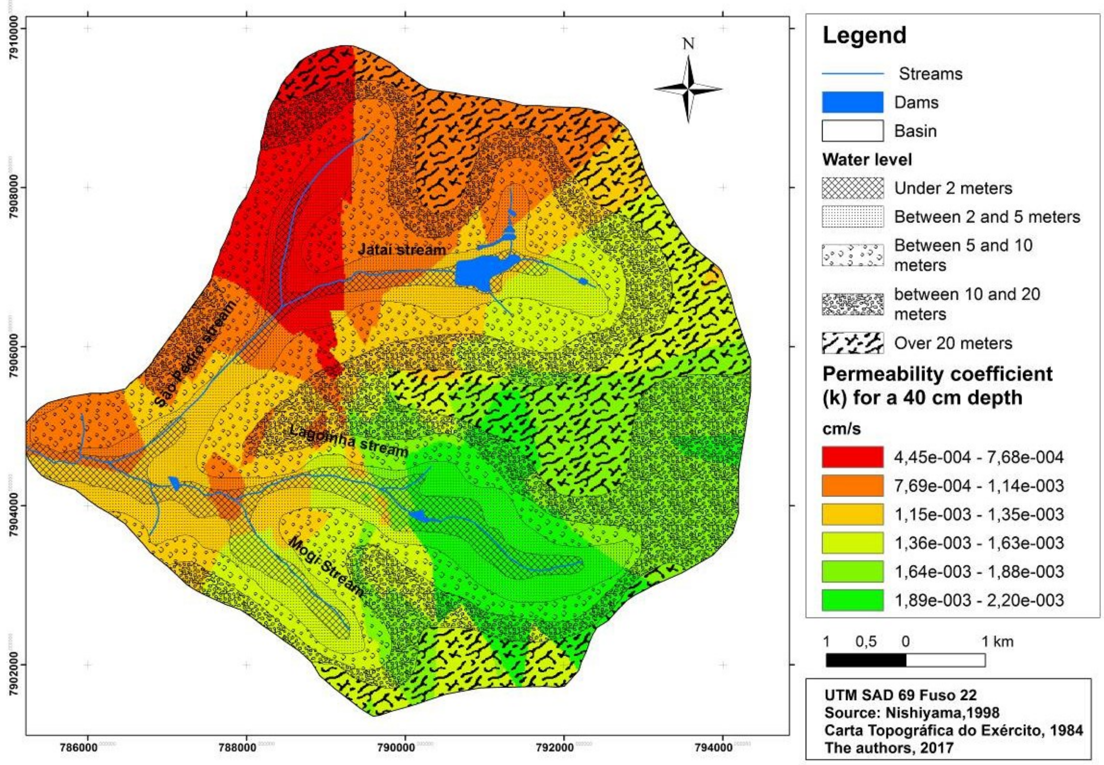


Source: the authors, 2017

The evaluation of the water table depth allows the determination of the thickness of the unsaturated zone for water infiltration. The level of groundwater mapped by Nishiyama (1998) and Beicher (2001) was overlapped to the elevation dimensions to determine the thickness of the unsaturated zone in the study area.

Figure 11 presents the integration between the level of groundwater and the coefficient of permeability (k) for the 40 cm depth. The south region of the basin has a deep level, above 20 m and between 10 and 20 m for a coefficient of permeability of 10^{-3}.

Figure 11. Groundwater level integrated to the coefficient of permeability (k) for the 40 cm depth.

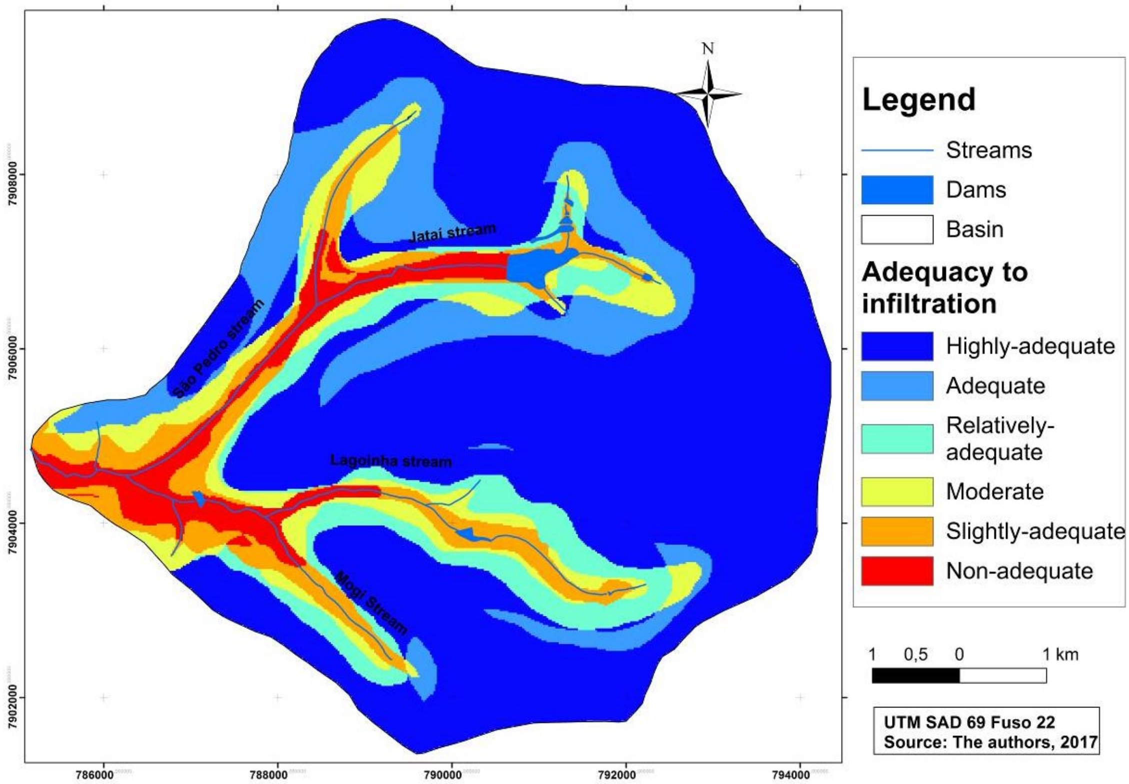


Source: the authors, 2017

Figure 12 displays the suitability infiltration map. As observed, the streams and the mouth of the São Pedro stream are not suitable for infiltration, hence they cause the formation of floods. Thus, it is seen that there is a growth of floods not only due to natural features but also because of anthropic occupancy what shows the necessity of a means to contain the water. The areas next to the drainage divide had the highest favorable values for infiltration.

We emphasized that the northern region of the basin, next to the São Pedro stream, is densely urbanized, which reduces the possibility of implementation of structural and non-structural measures. Despite that, its inclusion in the Urban Drainage Plan is essential; as, for instance, by determining percentages of green areas or by the deployment of rainfall catchment areas on rooftops or by implementing green roofs.

Figure 12. Adequacy and adequate para suitability and suitable.



Source: the authors, 2017

Some sites without urbanization could be used to implement structural measures for rainwater retention, such as sumps, permeable pavements, and parks. Another suggestion is to specify an occupancy zone with a larger percentage than that previewed in Uberlandia's Master Plan. For instance, there are extensive areas which have not been occupied yet between the Mogi and the Lagoinha streams.

Final Considerations

A set of maps has been presented in a way to enable the integrated analysis of important information from a geotechnical and geoenvironmental perspective, involved in the processes of infiltration and surface runoff. It has been observed that the south region of the basin has high clay concentrations and lower silt fractions. In the adjacent areas to the São Pedro stream, there are about 80% of the SSG (Silt/Sand/Gravel) values.

In the central region, in the drainage divides of the basin's main streams, there are the most favorable areas to infiltration. Another important area for infiltration is the southern region of the basin which has a deep water table level of approximately 20 meters and a coefficient of permeability (k) of 10^{-3}. For the basin as a whole, the values of k ranged from 10^{-4} to 10^{-5} cm/s.

The research has broadened the level of knowledge about the hydrological behavior of the basin, indicating its higher infiltration potential next to the drainage divides and its restriction to infiltration next to the streams and in the mainstream mouth. We hope this set of information can be used by the different areas of knowledge that work with such a matter. In addition, we hope that the data rendered by the paper provide subsidies to the planning of the land use and occupation and the choice of areas where studies have to be run in more detail with the aim of controlling floods with a lower cost of management.

The adjacent flood episodes to the São Pedro stream are determined by both geotechnical and geoenvironmental characteristics and anthropic occupancy. They must be taken into account and included in Uberlandia's Urban Drainage Plan. Urban occupancy is still expanding, mainly southwards, where there are still significant green areas to be occupied.

Thus, the research can serve as a reminder of an analysis of the São Pedro stream basin to urban managers.

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