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Assessment of physics soil properties, landform and land use for mapping potential areas for groundwater recharge on the Mogi Guaçu river banks

Avaliação das propriedades físicas do solo, relevo e uso do solo para mapeamento de potenciais áreas para recarga de água subterrânea nas margens do Rio Mogi Guaçu

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Abstract

In Brazil, Mogi Guaçu River is inserted in the one of the most important hydrogeological provinces, populous and economically developed. Although essential to freshwater sustainably manage, analysis of water recharge zones is difficult, complex, time-consuming and expensive, because require further information regarding soils and the relationship with the landscape, rainfall and vegetation. This study aims to develop fuzzy logic models for the groundwater recharge zoning in a sub-basin located in the Mogi Guaçu River banks. The spatial variability of soil attributes was determined through ordinary kriging. For the topography, the Topographic Wetness Index (TWI) was considered. The analysis of vegetation cover was represented by the Normalized Difference Vegetation Index (NDVI). Were generated and tested models with 3 different groups of input variables: 1 – soil indexes; 2 – soil indexes + TWI; 3 – soil indexes + TWI + NDVI. The development of fuzzy logic models with input variables representing the soil, landscape and vegetation was the most effective in the complex recharge mapping, characterizing consistently the saturated hydraulic conductivity obtained from field.

Palavras-Chave: Fuzzy logic; Groundwater recharge zoning; Topographical Wetness Index.

Resumo

No Brasil, o Rio Mogi Guaçu está inserido em uma das províncias hidrogeológicas mais importantes, populosas e economicamente desenvolvidas. Embora essencial para a gestão sustentável da água doce, a análise de zonas de recarga de água é difícil, complexa, demorada e dispendiosa, porque

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requer informações adicionais sobre solos e a relação com a paisagem, precipitação e vegetação. Este estudo tem como objetivo desenvolver modelos de lógica fuzzy para zoneamento de áreas de recarga de água subterrânea em uma sub-bacia localizada às margens do Rio Mogi Guaçu. A variabilidade espacial dos atributos do solo foi determinada através da krigagem ordinária. Para a topografia foi considerado o Índice de Umidade Topográfica (TWI). A análise da cobertura vegetal foi representada pelo Índice de Vegetação por Diferença Normalizada (NDVI). Foram gerados e testados modelos com 3 diferentes grupos de variáveis de entrada: 1 – índices de solo; 2 – índices de solo + TWI; 3 – índices de solo + TWI + NDVI. O desenvolvimento de modelos via lógica fuzzy com variáveis de entrada representando o solo, a paisagem e a vegetação foi o mais eficaz no complexo mapeamento da recarga, caracterizando de forma consistente a condutividade hidráulica saturada obtida em campo.

Keywords: Lógica fuzzy; Zoneamento de recarga de água subterrânea; Índice Topográfico de Umidade.

Introduction

Freshwater has a crucial share in groundwater resources. Mogi Guaçu River is inserted in the Paraná River Basin, one of the most important hydrogeological provinces in Brazil, with about 45% of the groundwater reserves in the national territory. Additionally, it is one of the most populated and economically developed regions in the country. Thus, the analysis of potential water recharge zones to sustainably manage this resource is essential, although studies in this field are difficult, complex, time-consuming and expensive (SENER *et al.*, 2018).

Nowadays, a new conception of research linked to the understanding of the hydrological cycle and its interaction with the landscape has become necessary to analyze the environmental processes that involve from the vegetal cover to the aquifer system, called the critical zone (GIARDINO; HOUSER, 2015). This is the zone where all the main processes associated with the hydrological cycle occur, taking as reference the vegetal cover and its relation to the atmosphere, pedosphere, hydrosphere and the lithosphere. While the behavior of water in aquifers is discussed in hydrology and the atmosphere in hydrometeorology, the interaction between the flow of water in the soil profile (vadose zone) to its recharge process and all the consequences of such interaction is subsidies in hydropedology (LIN, 2010).

There is a high degree of uncertainty in determining the groundwater recharge rate because direct measurement is complex and this is partly due to high variation in time and space (JOVIEN *et al*., 2023). The groundwater recharge is the process by which incoming water takes place into the aquifer or even the passage of water from the vadose to the saturated zone of the soil. In this scenario, the downward water flow is the central processes and is controlled mainly by the soil infiltration capacity (LEAP, 1999), which is dependent on the soil texture and the degree of saturation (JOVIEN *et al*., 2023). So, the soil functions as a dynamic reservoir of water and its characteristics directly affecting the process of aquifer recharge. This influence is associated with the soil properties, land use and its position in the landscape, factors that govern your ability to infiltration (SINGH *et al*., 2019; SINGHA; NAVARRE-SITCHLER, 2021). Soil texture and structure, as well as hydraulic conductivity, are attributes that deserve to be highlighted in the process. Texture refers to the size distribution of soil particles such as sand, silt and clay, while structure is the arrangement of primary soil particles into secondary units (SSSA, 2008) and can represented by density and porosity. Yeh *et al*. (2009) show a significant relationship between locations of the groundwater recharge potential zone and soil structure. Saturated hydraulic conductivity is positively related to macroporosity (BEVEN; GERMANN, 1982) and indicates the ease with which the soil transmits water (SSSA, 2008).

Santos and Pereira (2013) record, besides the importance of texture and structure, as determining properties in the movement of water in the soil profile, the relevant role of two other factors: relief, since flat areas tend to absorb the greater part of the water and inclined areas tend to provide greater surface runoff and low infiltration rates; and vegetation, are critical in the process are intercepted and rainwater runoff, this process also based understanding of the dynamics of water in the landscape. The vegetation plays a prominent role in the hydrological process of a hydrographic basin, especially in the interception and evapotranspiration acting indirectly in all phases of the hydrological cycle (CHENG *et al*., 2020). In afforestation areas, soil moisture changes are the most important factor to understand its impact on the hydrological system (CHENG *et al*., 2020). Therefore, soil use can change the quality and quantity of water in the basin as well as influence the underground water storage system and the source and watercourses (SHEKAR; MATHEW, 2023).

The topography exerts a strong control on surface runoff and groundwater movement (SILVA *et al*., 2016; OLIVEIRA *et al*., 2022; SHEKAR; MATHEW, 2023), revealing this landscape characteristic as the most important in controlling water flow and, therefore, demonstrating its importance as an element in the hydrological cycle. Temporary or permanent water saturation areas play a central role from a hydrological, ecological and geomorphological point of view (SINGHA; NAVARRE-SITCHLER, 2021; JOVIEN *et al*., 2023). These areas have a strong relationship with the water table dynamics, due to expansion and contraction during rainfall events. Recharge can be conceptualized as deep percolation from soil moisture under saturation excess conditions (MESSERSCHMID; ALIEWI, 2022). The Topographic Wetness Index (TWI) is of great relevance identification of these locations, as they address the relationship between the local slope and the specific upstream contribution area, thus having a significant spatial variation (SHEKAR; MATHEW, 2023). Identification of wetlands, in a landscape, allows the identification of areas of either greater or smaller water recharge potential based on soil infiltration rate (SILVA *et al*., 2016).

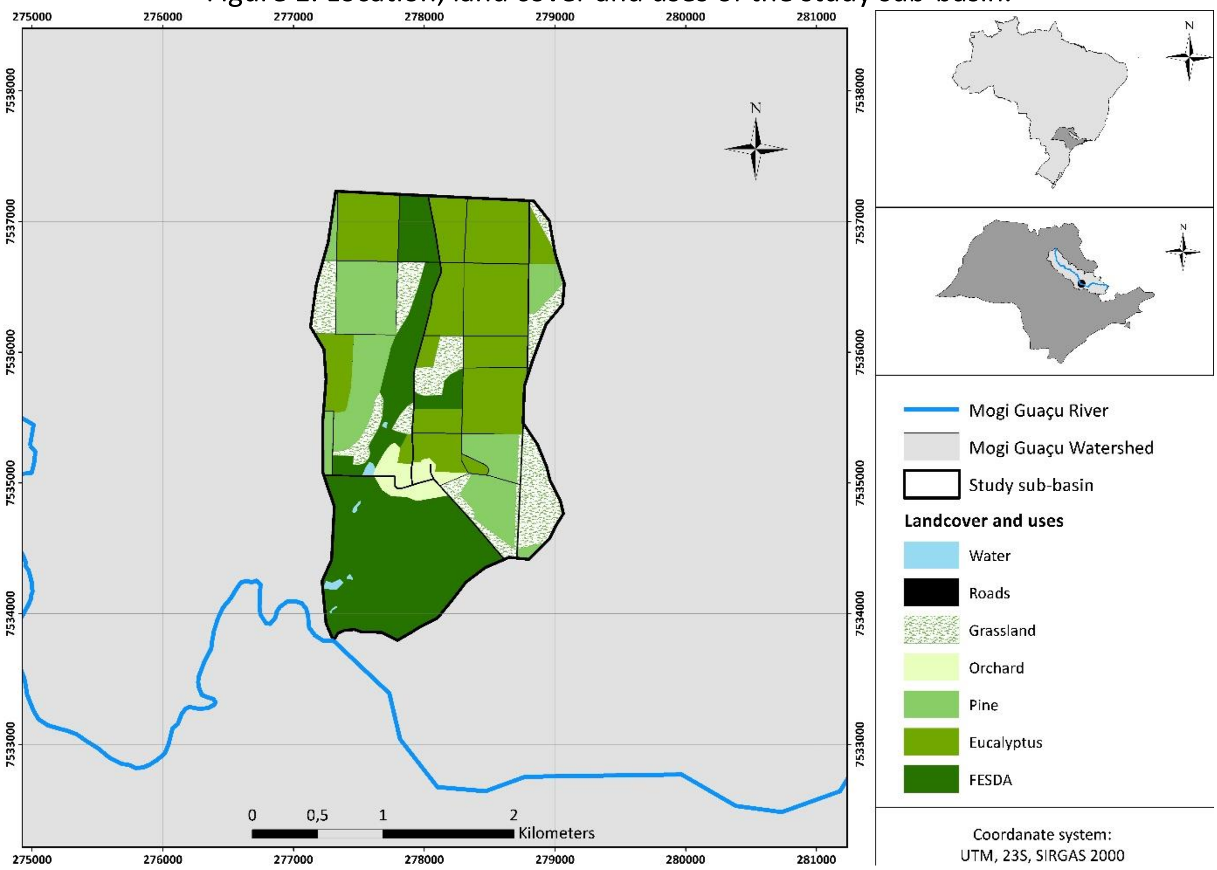
Predicting the spatial distribution of groundwater recharge is challenging. Therefore, although it is basic hydrogeological information and a water conservation tool in basins, it is rarely determined (MESSERSCHMID; ALIEWI, 2022). Statistical methods, commonly used to predict relationships between detailed spatial variations of soil properties and environmental variables, often rely on the assumption of linearity and do not consider spatial correlation of soil observations, although the relationships between soil property variation and the underlying environmental variables can be very complex (ZHU *et al*., 2010). Fuzzy logic allows, however, to integrate these factors in the groundwater recharge analysis (GHAZAVI *et al*., 2018; RAJASEKHAR *et al*., 2019; SINGHA *et al*., 2021; SHEKAR; MATHEW, 2023). The ability to generate maps without abrupt limits establishment is a great advantage of this method, being more suitable for applications where changes occur gradually, as in soils (ZHU *et al*., 2010; SILVA *et al*., 2016).

In this way it is possible, besides understanding the influence of each factor analyzed, to define recharge process favorable areas from the analysis of the joint effect of the factors, incorporating the soil-landscape relationships and the knowledge of soil experts. Thus, the present study aimed to understand the soil, topography and vegetation variables in the groundwater recharge process and to integrate them into fuzzy logic models for the zoning of potential areas to the process in the study sub-basin, located in the Mogi Guaçu River banks, SP, Brazil.

Methodology

The study area is inserted into the Mogi Guaçu River banks (Figure 1), more precisely in the Mogi Guaçu Conservation Units Complex.

Figure 1. Location, land cover and uses of the study sub-basin.



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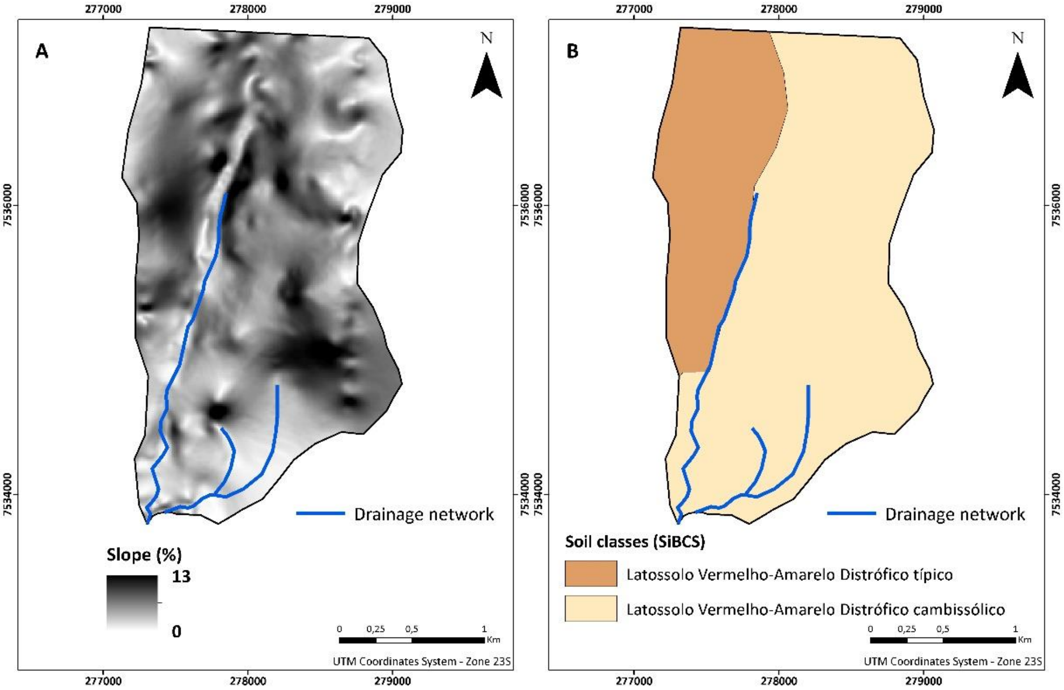
The land cover and uses in the area are Pinus and Eucalyptus planted forests, grassland not managed for about 20 years, the native forest Alluvial Semideciduous Seasonal Forest (FESDA) and orchard (Figure 1). The climate defined for the area varies according to the Koppen classification, between Aw climate (tropical climate with dry winter season and rainy season in summer) and Cwa climate (humid temperate climate with dry winter and hot summer). In the Mogi Guaçu Basin, average annual temperatures range from 20.5 ° C to 22.5 ° C and mean annual rainfall ranges from 1,400 to 1,600 mm (SPAROVEK *et al*., 2007).

The studied sub-basin has an area of 4.8 km^2, a perimeter of about 10 km and predominance of smooth undulating relief with an average slope of 5% (Figure 2A). The relief information used in the analyzes (Figure 2A) comes from a planialtimetric survey (1:10,000 scale) conducted throughout the sub-basin and performed through a cloud of 5,000 points collected for the detailed description of the relief. Instrument used was a Topcon Geodetic GNSS Receiver Hiper L1/L2, with 40 universal channels capable of tracking GPS and GLONASS satellite signals, horizontal accuracy of 3 mm + 0.5 PPM and vertical accuracy of 5mm + 0.5 PPM. The collected data were transferred to the ArcGIS 10.2 (Esri Inc., 2014) software, where the construction of the Digital Elevation Model (DEM) built with a resolution of 10 meters was carried out with the aid of the tool Topo to Raster.

According to the soil map at 1:30,000 scale (UCRBEEc, 2010), grid of Araras (SF-23-YA-II), refined from the semi-detailed soil survey of the State of São Paulo 1981 (OLIVEIRA *et al*., 1982), the predominant soil type in the study area classified according to the Brazilian Soil Classification System (SiBCS) (EMBRAPA SOLOS, 2018) is the Latossolo Vermelho-Amarelo (LVA) (Figure 2B). The LVA Distrófico cambissólico occupies most of the area (75%) and the LVA Distrófico típico occupies the remaining portion. In this area, the soils are formed from sandstone rocks of the Aquidauana Formation and Alluvial Reservoir.

Figure 2. Sub-basin maps: (A) slope; and (B) soil classes.



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<u>Variables used in the modeling groundwater recharge potential areas</u>

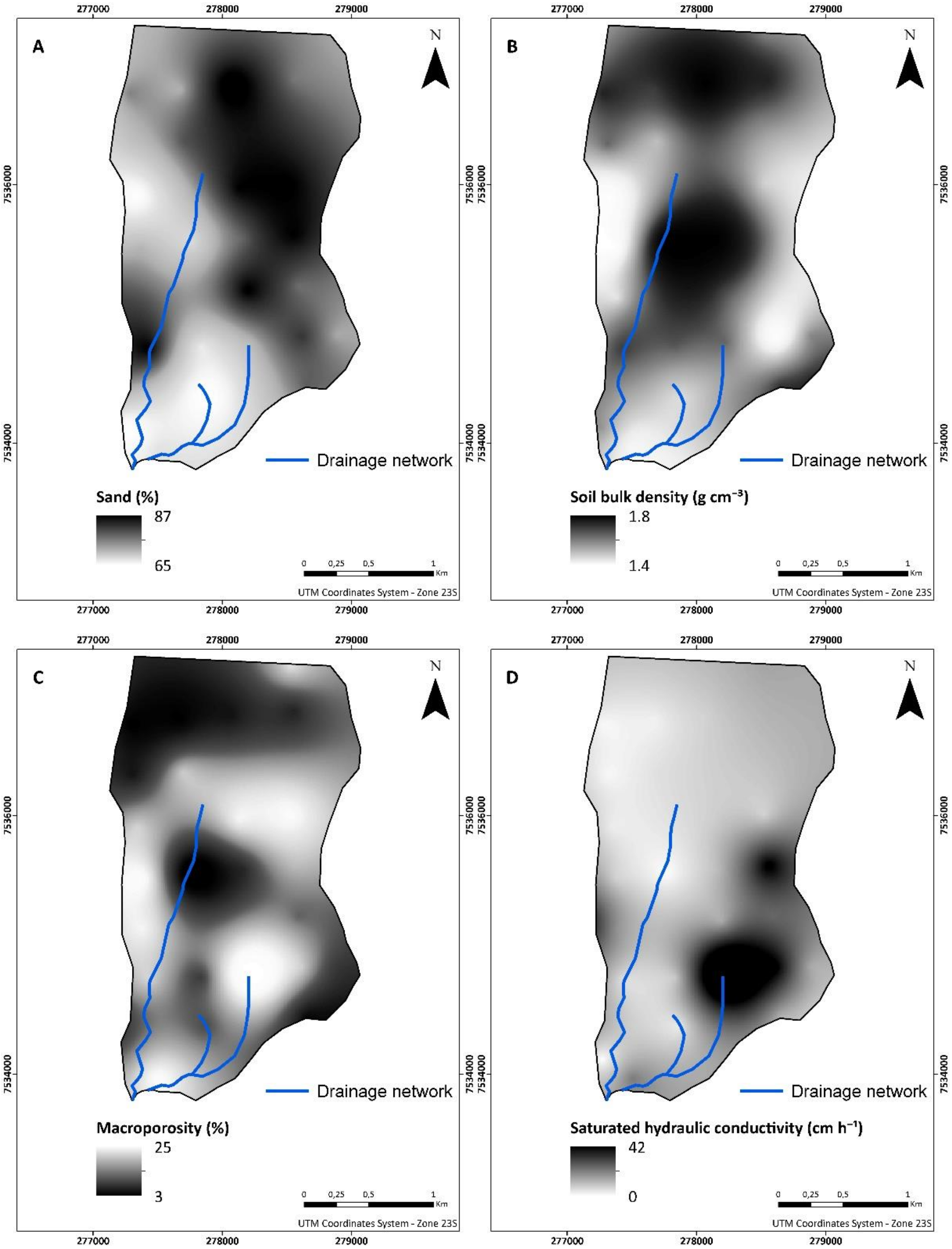
In the development of the models zoning favorable areas to the groundwater recharge process, the choice of the following input variables was considered: soil, topographic and land cover. For the soil variable, texture (% sand), soil density and macroporosity attributes were used; for topography, the Topographic Wetness Index (TWI); and for vegetation, the Normalized Difference Vegetation Index (NDVI). The generated models were compared to the saturated hydraulic conductivity spatial variability in the basin. In addition, we sought to meet the following basic premises: simple model; weighted model; model with the lowest possible number of variables; model with simple sampling variables; model with economically feasible sampling variables; model with chronologically viable sampling variables; and model with physical and theoretical meaning about the phenomenon analyzed.

These aspects were aimed at generating results that could represent the areas favorable to the process of groundwater recharge in a practical and optimized way, in order to facilitate the prediction of scenarios and behaviors of surface and groundwater, thus contributing as a useful tool for the management resources. In the present study, the choice of the input variables was performed based on the criteria presented in the considerations for the development of the models, all of which occur continuously in the landscape.

Moreover, it deserves highlight three points relevant to modeling the favorable areas to the groundwater recharge process and peculiar to this study sub-basin. First, the rainfall and lithology factor, due to the microscale of the analysis (4.8 km^2), can be considered homogeneous throughout the study area and little relevant for the differentiation of the favorable zones or not the infiltration, being outside the elaboration of the tested models. Second, regarding the depth of the soil, the area of study consists of the class of Latossolo Vermelho Amarelo (LVA). The LVA are very deep, associated with plan reliefs, smooth wavy or wavy and, in depth, are uniform in color characteristics, texture and structure (EMBRAPA SOLOS, 2018). This fact, theoretically, besides conferring a good homogeneity in relation to the depth of the soils in the sub-basin, makes this factor little influential in the differentiation between areas favorable or not to the groundwater recharge process, especially in the scale of applied analysis. Third, based on the concepts presented, was adopted that sampled layer (20-40 cm depth) represents, in these conditions, the main structural and textural soil characteristics active in water infiltration process into the vadose zone.

This work is based on soil attribute results from field data as published in Klinke Neto *et al*. (2017), referred to in this study as soil indexes. The soil attributes data spatialized (Figure 3) were obtained using a systematic survey (400 × 400 meters) conducted across sub-basin. At each point, soil samples were collected in the layer of 20 to 40 cm and analyzed: sand fraction (%) by sieving, soil bulk density (g cm^{-3}) (BLAKE, 1965), macropores (%) (GROHMANN, 1960) and saturated hydraulic conductivity (cm h^{-1}) (KLUTE, 1965). The application of the geostatistical methodology followed the classic procedures described by Matheron (1965) and the Oliver and Webster (2014) considerations.

Figure 3. Soil physical attributes distribution maps: (A) sand fraction (%), (B) soil bulk density (g cm^{-3}), (C) macroporosity (%) and (D) saturated hydraulic conductivity (cm h^{-1}).



Source: Adapted from Klinke Neto et al. (2017).

The topographic attributes obtained from the DEM and used to generate the Topographic Wetness Index (TWI) were: elevation, slope, flow direction, accumulated flow or contribution area. The direction distribution and consequent accumulation of surface flow were processed using the SAGA (Automated System for Geoscientific Analyzes) software (CONRAD *et al*., 2015), using the flow direction algorithm D∞ (TARBOTON, 1997). The contribution area is calculated from the product of the accumulated flow by the area of each cell (100 m^2). By presenting the distribution of surface water saturation zones and soil water content the TWI estimates, based on the DEM, a balance between water accumulation and drainage conditions on a local scale. Numerically, the TWI is represented by Equation 1 (BEVEN; KIRBY, 1979):

$$TWI = \ln a/\tan b \qquad (1)$$

where, a is the catchment area grid size in m^2; and b is the slope expressed in radians.

The evaluation of the vegetation cover in the study area was carried out through the Normalized Difference Vegetation Index (NDVI), which properly represents the differences between the various vegetation cover present in the landscape. For this, the image of the CBERS-4 sensor, with a spatial resolution of 10 meters, was made available on the INPE (National Institute for Space Research) website. The images were pre-treated (equalization), a composition of the bands of interest was made and then the scene recording was performed by the map-to-map technique with the aid of the topographic survey previously performed. NDVI was estimated by applying the visible infrared bands according to (Equation 2):

$$NDVI = (band\ 5\ (NIR) - band\ 4\ (R)) / (band\ 5\ (NIR) + band\ 4\ (R)) \qquad (2)$$

where, NIR is near infrared; and R is red.

Model generation via fuzzy logic

Each variable adopted in the present study had the form of the fuzzy function, adjusted as a function of the parameters: mean point, which means the value of 0.5 of fuzzy pertinence, and/or scattering, which indicates how fast fuzzy relevance decreases from 1 to 0 (CARRINO *et al*., 2011). The fuzzy methodology allows making predictions about the scenarios susceptibility to a given phenomenon, through several operators. For the combination of thematic maps using fuzzy logic, the GAMMA operator was applied in this study. This operator allows a good variety of scenarios by manipulating the Gama index (γ) (DOU *et al*., 1999), that was chosen 0.7 according with Carrino *et al*. (2011) and Bonham-Carter (1994), considered one of the most balanced.

Thus, fuzzy logic models with the cited operator were generated with three different groups of input variables: soil indexes (sand, macroporosity and soil bulk density); soil indexes + TWI; soil indexes + TWI + NDVI. The saturated hydraulic conductivity mapping (Figure 3D) performed with field samples was used as the reference for the qualitative evaluation of the models generated, since this attribute represents the water transport capacity in the soil and thus provides important information about the water movement in this medium and, consequently, in the landscape. In addition, the final maps of the generated models were classified into four relevance classes in terms of being recharge process potential (possibility of occurrence of the situation of interest): 1 – very low (0 - 0.25); 2 – low (0.25 - 0.50); 3 – mean (0.50 - 0.75); and 4 – high (0.75 - 1).

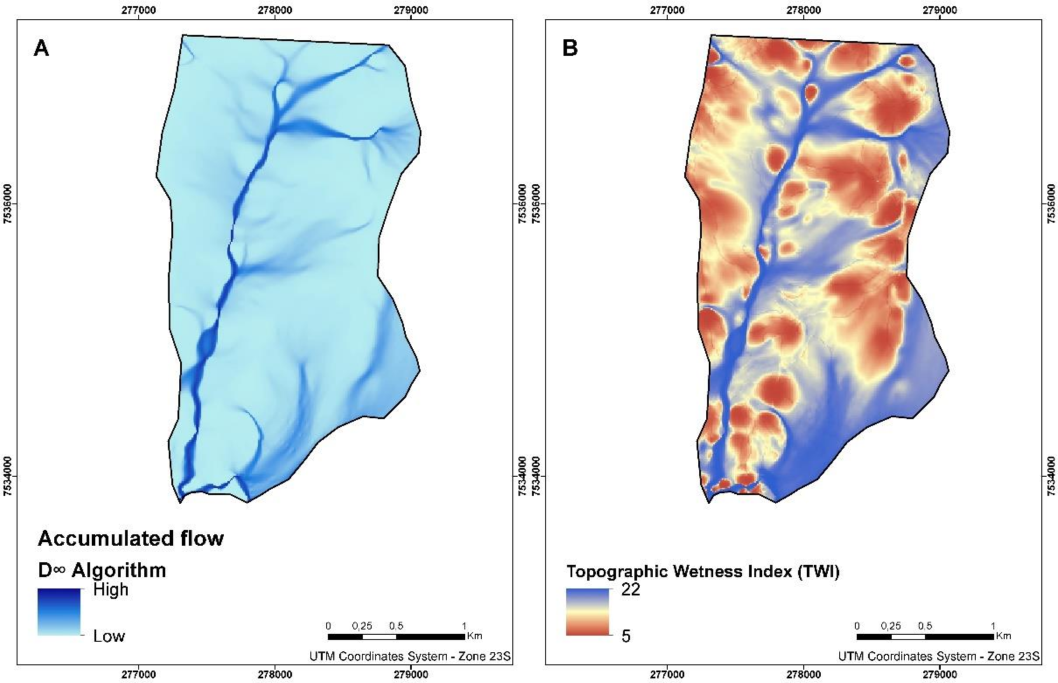
Results and Discussion

Topographic Wetness Index (TWI)

The technique used to generate the FD map is one of criteria cannot be neglected in the process of obtaining the TWI, because will dictate the actual hydrological quality of the generated surface. In direct comparison with the drainage network obtained in the field topographic survey (Figure 2A), the algorithm D∞ was precise and therefore suitable for hydrological analysis on the scale as this research (Figure 4A). As verified in other studies (OLIVEIRA *et al*., 2012; SILVA *et al*., 2016), the algorithm D∞ considers the divergent surface shape, that is, the flow can also be divergent (BOGAART; TROCH, 2006). Accordingly, this method tends to provider high detail and definition of preferential flow paths forming the drainage network of the sub-basin.

The generated TWI model (Figure 4B) revealed in detail the rainwater drainage system in the basin and the flow paths preference during a pluviometric event. Besides himself water course in the area, clearly, it is observed the presence of two principals drains in the northern part of the sub-basin as well, the concentration of flow in areas south of the map. The southern part has flat relief (Figure 2A) and areas occupied by native forests (Figure 1), accentuating thus protecting the vegetation from the soil, which in this case gains importance due to the high surface flow accumulated and present at the site.

Figure 4. Accumulated flow map (A) and Topographic Wetness Index (TWI) (B).



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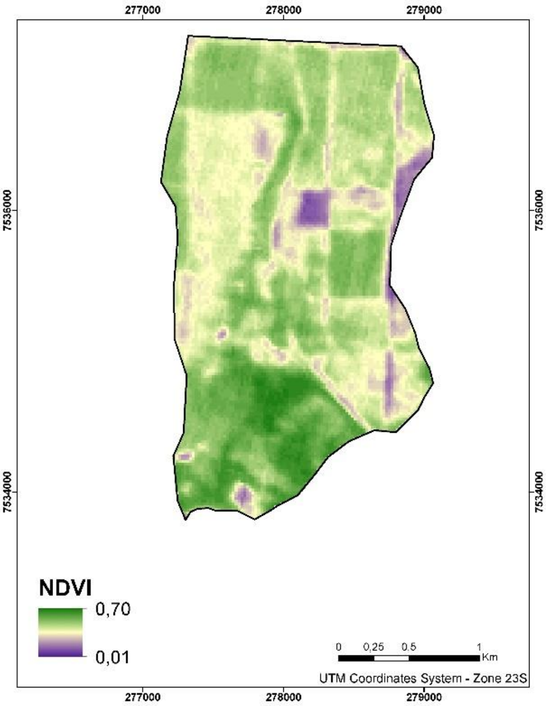
The highest index in the main drainage network (Figure 4B), with emphasis on the south area of the basin where the drainage line meets the Mogi Guaçu River, denotes the importance of preserving these areas not only because they have a high flow volume, but also to act as elements of hydrological connectivity between the landscape and the water bodies, corroborating the observations of Oliveira *et al*. (2020).

The southern part of the sub-basin has a seasonally flooded floodplain area with very flat relief (Figure 2A) and a very diffuse drainage network (Figure 4A). In this case, the peat soil and low soil bulk density directly favors water infiltration into the profile, acting also as sediment retention area and consequent silting inhibitor caused by disturbances in land use in the upper basin parts (SILVA *et al*., 2016).

Normalized Difference Vegetation Index (NDVI)

The NDVI represents vegetation cover and density in an interval ranging from -1 to 1, with 1 being the best cover. In the NDVI analysis, the vegetation with the highest amount of biomass, identified by the darker shades of green (Figure 5), is related to the southern part of the sub-basin, a section of lower elevation and slope, where the Alluvial Semideciduous Seasonal Forest (FESDA) is well structured and a closed canopy (Figure 1). There is also an elongated stretch of dense native vegetation in the central region of the area, referring to the riparian forest of the stream present in the place. The remainder of the basin is mostly occupied by a medium-density vegetation cover (lighter shades of green) (Figure 5). These areas represent primarily old pine or eucalyptus reforestation which, in relation to the hydrological cycle, act to protect the soil, favoring infiltration and increasing the time the water remains in the system.

Figure 5. Normalized Difference Vegetation Index (NDVI).



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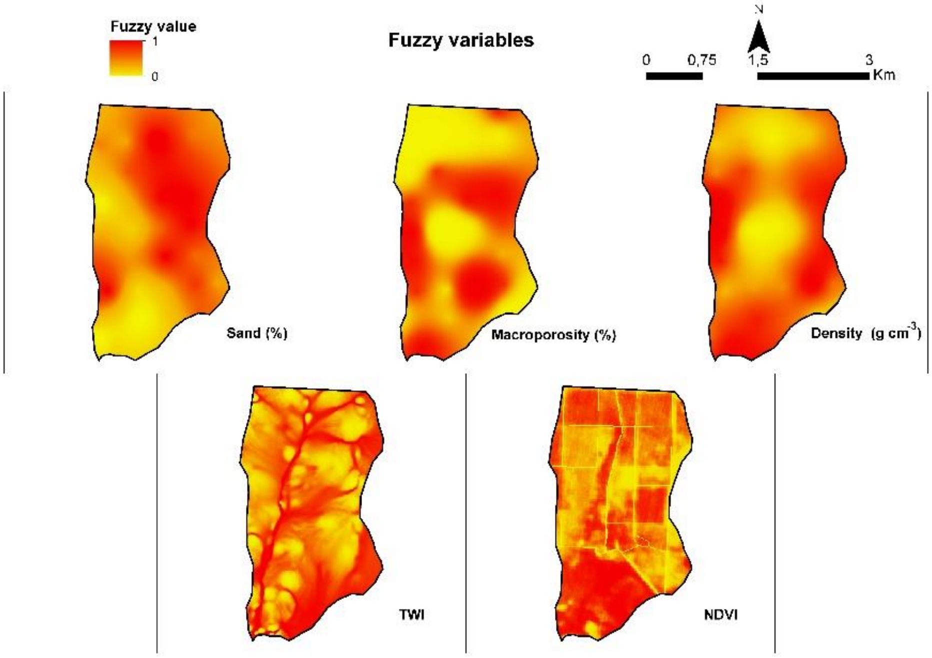
Low NDVI values in the sub-basin (yellowish and reddish) characterize exposed soil regions relating to small degradations, small areas in recovery and to some degraded pastures, and therefore, spatially defined local and prone to erosion (LIMA *et al*., 2013; OLIVEIRA *et al*., 2022). There are also areas without vegetation referring to roads, water bodies and floodplains, which have the lowest values of mapped NDVI. Due to study sub-basin in general present a good vegetation cover, the unpaved roads that cut across the area (Figure 1) and are currently in bad conservation status presenting intense erosion and lack of maintenance, represent the main source of erosion and silting.

Zoning of groundwater recharge process favorable areas

The generation of the models for the zoning of the areas favorable to the groundwater recharge process in the study sub-basin, performed through the fuzzy logic, and the choice of the input variables was based on the basic premises presented previously for the development of the models. Thus, the selected variables represent the main factors known to be associated with the groundwater recharge process and act in a selective manner, that is, the texture and structure of the soil, the topography and the vegetation cover. To represent the texture, due to the sandy character of the soils of the area, the sand content (%) was chosen (Figure 3A), to represent the structure, the attributes soil bulk density (g cm^{-3}) (Figure 3B) and macroporosity (%) (Figure 3C) were selected, for the topography TWI (Figure 4B) and to cover the NDVI (Figure 5). Therefore, the models tested associate the areas favorable to the groundwater recharge process with the following characteristics: a higher percentage of sand; a higher percentage of macroporosity; lower soil bulk density; higher value of TWI; and higher NDVI value.

For the transformation of the input variables into fuzzy variables (Figure 6), the following functions were used: to sand (%), macroporosity (%), TWI and NDVI was used Large function mid-point 76, 14, 13, 0.4 and spreading 10, 15, 15 and 5, respectively. In this option, the greater the value of the original pixel closer to 1 will be the value of the fuzzy pixel. For the variable soil bulk density (g cm^{-3}) (Midpoint 1.5 spreading and 15) was used in Small option, which assigns values fuzzified high (close to 1) the smaller original values, the opposite function option Large.

Figure 6. Input variables transformed into fuzzy variables.



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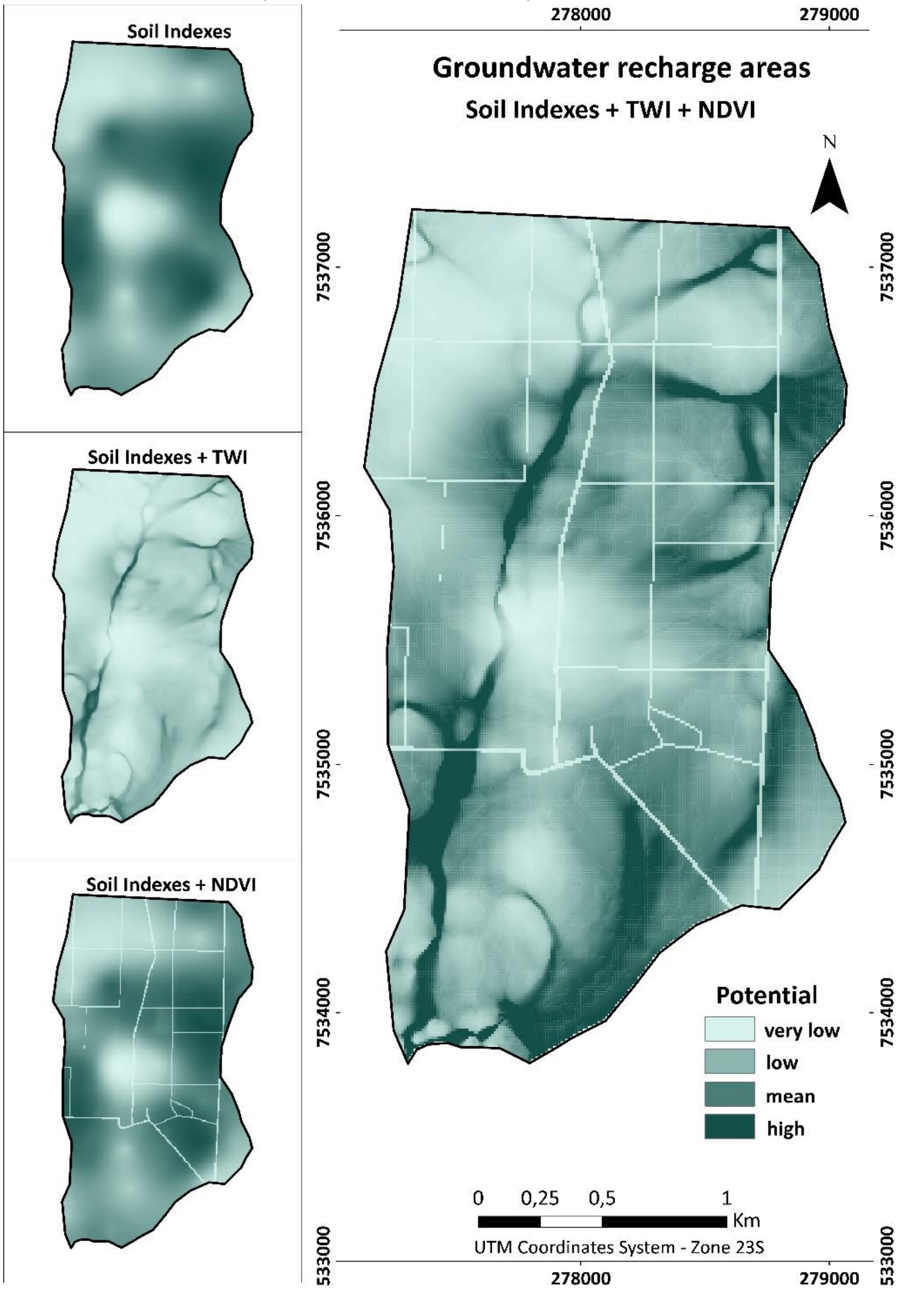
For the Gamma Index 0.7, considered a intermediate optimistic scenario, it was predicted as favorable (Figure 7). In this perspective, the pertinence classes above 0.5 (medium and high pertinence classes) presented an area varying between 17 and 39%, depending on the number of input variables.

The first models generated were based only on physical indexes, and have as the theoretical basis the direct relationship between infiltration capacity and texture, soil bulk density and porosity. In this sense Alvarenga *et al*. (2011) highlight potential soil hydrological indicators as the representative for the assessment of groundwater recharge. In the models generated only with the soil indexes (Figure 7), it is observed that except for a small stretch in the northwest end of the basin, the other areas classified as less favorable to the infiltration are directly related to the drainage lines present in the landscape (Figure 2A), revealing a smaller possibility of infiltration at these sites.

Figure 7. Fuzzy models generated for groundwater recharge areas mapping: soil indexes; soil indexes + TWI; soil indexes + NDVI; soil indexes + TWI + NDVI.



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Due to the input of only the soil indexes, the general appearance of the generated models corresponds directly to the appearance of the variations that occur in them, presenting homogeneous and uniform gradients (Figure 7). Thus, these models do not present a great detail of the areas of interest, being, therefore, only a more comprehensive indicator of the region of interest. However, the results showed a good relationship with the map of saturated hydraulic conductivity (Figure 3D), which is a direct indicator of areas favorable to the infiltration and groundwater recharge process. Shekar and Mathew (2023), to verify the accuracy of the Analytic Hierarchy Process (AHP) and Fuzzy-AHP technics to delineate groundwater potential zones, determined high performance for Fuzzy-AHP, of 77.6%.

In order to increase the detail of the areas and to improve theoretical foundations, models with soil indexes plus TWI (relief) and/or NDVI (vegetal cover) were generated (Figure 7), enabling an interactive analysis of the main factors that influence the behavior of the water in the landscape. Upon analyzing the results are the increase of NDVI and TWI factors separately clearly is a greater influence of the variable intake TWI opposite the entrance of the NDVI variable. This behavior can be attributed preferentially to the two factors given below.

The land cover and use types have a substantial impact on the permeability, evapotranspiration, and runoff (LI *et al.*, 2023). Studies have shown that areas with vegetation and high NDVI values are most likely to have groundwater potential (AMANO *et al.*, 2021; KIM *et al*., 2023; LI *et al*., 2023). In the study sub-basin, the present vegetation cover, although not homogeneous, is sufficiently dense to effectively protect the soil in the great majority of the area (Figure 5), thus softening the effect of this factor in the distinction of zones favorable to recharge (Figure 7). However, in small areas where soil exposure is significant, such as on roads, the reflection in the models is considerable, showing once again the ability of fuzzy logic and the GAMMA operator to obtain weighted and reliable results. Using Fuzzy technique, Li, Abdelkareem and Al-Arifi (2023) also detected an increase in groundwater recharge and surface infiltration with the increase of vegetation. As described by Bertoni and Lombardi Neto (2005) the benefits of vegetation cover (NDVI factor) on soil quality and water are many, among which we highlight the role of vegetation in the air redistribution of rainwater, and working as obstacle to surface runoff, increasing the retention time of water in the landscape and consequently infiltration.

Regarding the landform (TWI factor), there was direct control over the amount of water that infiltrates the profiles. Sites with high TWI values have greater groundwater recharge capacity (Figure 4B and Figure 7), also reported by Singh *et al*. (2019) and Shekar and Mathew (2023). The flat/smooth relief present throughout the basin (Figure 2A) causes small movements in local topography to influence considerably in the models generated, since they directly alter the response of the water movement on the surface. Aspects such as continuity of flow, distribution of water in the landscape and formations of intermittent or perennial drainage networks should be carefully observed for the careful evaluation of a DEM. Thus, in the case of flat/smooth relief basins, commonly found in alluvial areas, topographic detailing will directly influence the response and quality of the derived models. Being derived from the flow direction map, which is directly derived from the DEM, the quality of the DEM will reflect the quality of the TWI. In this study the topographic map used, generated in the 1:10,000 scale from field data, was effective in generating maps with the high degree of detail and good capacity of differentiation of favorable and unfavorable areas to infiltration.

The models with the variables soil indexes + TWI spatial distribution (Figure 7) presented as a good interaction between the slope (Figure 2A), accumulated flow (Figure 4A) and soil bulk density (Figure 3B) maps. The areas with higher humidity concentrate not only along the drainage lines as expected, but, preferably, in the connections of flow concentrations with flat regions and moderate soil bulk density. These areas favor the spreading of the water on the surface of the relief and, consequently, increase the flow time and the groundwater contact area, thus allowing a greater infiltration of the water in the soil profile. Sener *et al.* (2018) using Fuzzy-AHP also verified the best potential groundwater zones concentrated in alluvial areas with lake shores.

The areas to the northwest of the sub-basin represented the sites with the lowest groundwater potential, a fact associated with greater slope and the lower presence of drainage lines, which consequently generate a higher flow velocity, rendering the conditions conducive to the infiltration process unfeasible. Thus, it is important to conserve vegetation and adopt soil conservation practices in these areas of busier relief, in order to reduce erosive potential and increase the potential for infiltration.

The models generated with the input of the three variables considered (soil indexes + TWI + NDVI) (Figure 7) are conceptually more complete, since, they begin to gather the main variables that directly influence the process of infiltration and groundwater recharge of the area, represented here by the characteristics of the soil through of the soil physical attributes, the characteristics of the relief with the TWI and the characteristics of the soil cover with the NDVI. The models resulting from the joint analysis of the three variables were able to reach a great detail and differentiation between the stretches more or less favorable to the groundwater recharge process.

It is noted that the interaction between the soil, topography and vegetation factors considerably restricts the areas considered adequate and/or favorable to the infiltration and groundwater recharge process, denoting to these stretches a significant importance in the management of groundwater resources. In accordance with the generated models, the areas now considered capable to legally use and management should receive treatment to be preserved since these sites are the principal connections between the surface and the water stored in depth. Thus, the model that included the largest number of variables (soil indexes + TWI + NDVI) was considered the most satisfactory to represent the groundwater recharge potential the landscape, besides differentiating sites that match presently map of the saturated hydraulic conductivity property represented with different characteristics of the soil, the relief and vegetation present in the sub-basin.

Final Considerations

The Topographic Wetness Index (TWI) was effective in revealing the main paths of surface drainage during a pluviometric event and showed a good relationship with the flat areas and high accumulation of flow.

The vegetative cover of the area contributes to the protection of the soil and is considered as an important factor of water retention in the sub-basin, however, exposed soil roads contribute to the "channeling" of the flows and to the decrease infiltration in the area.

The construction of groundwater recharge potential models through fuzzy logic, with the input of variables representing soil, relief (TWI) and vegetation (NDVI), proved to be very efficient in the elaboration of complex mappings and different scenarios, consistently representing the hydraulic conductivity obtained from field samples.

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