# Soil physical and hydraulic properties in the Donato stream basin, RS, Brazil. Part 1: Spatial variability

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**ABSTRACT:** The processes of water flow and water storage in the soil are directly associated with its hydraulic properties, which may vary significantly in space. Therefore, this study aimed to perform a spatial analysis of saturated hydraulic conductivity and the parameters of the soil water retention curve in the Donato basin, located in the municipality of Pejuçara, in the northwest region of the state of Rio Grande do Sul, Brazil, with geographic coordinates between 28º 25' 34" S and 53º 40' 30" W, and 28º 24' 50" S and 53º 41' 30" W, 590 m of altitude. Undisturbed soil samples (total of 55) were collected from August to November of 2012. The results have demonstrated larger variability for hydraulic conductivity and for the parameter α of the retention curve, and allowed identifying that the high spatial heterogeneity of the studied variables could be associated with factors such as climate, land use and land cover, sampling errors, sampling grid density and also the level of soil compaction.

**Key words:** saturated hydraulic conductivity, retention curve, soil heterogeneity

## Propriedades físico-hidráulicas do solo na bacia do arroio Donato, RS, Brasil. Parte 1: Variabilidade espacial

**RESUMO:** Os processos de fluxo e armazenamento de água no solo estão diretamente associados às suas propriedades hidráulicas, as quais podem variar significativamente no espaço. Por estas razões, este trabalho objetivou realizar uma análise espacial da condutividade hidráulica saturada e dos parâmetros da curva de retenção de água no solo na bacia do arroio Donato, localizada no município de Pejuçara, na região Noroeste do estado do Rio Grande do Sul, entre coordenadas geográficas 28º 25' 34" S e 53º 40' 30" O, e 28º 24' 50" S e 53º 41' 30" O, 590 m de altitude. Amostras de solo indeformadas (total de 55) foram coletadas de agosto a novembro de 2012. Os resultados revelaram maior variabilidade para a condutividade hidráulica saturada e para o parâmetro α da curva de retenção, e permitiram identificar que a grande heterogeneidade espacial das variáveis analisadas pode estar associada a fatores tais como clima, uso e cobertura do solo, erros de amostragem, adensamento da malha amostral e também ao grau de compactação do solo.

**Palavras-chave:** condutividade hidráulica saturada, curva de retenção, heterogeneidade do solo

# INTRODUCTION

Plant development is strongly related to water availability, which depends on its flow and storage in the soil. However, the flow and storage of water are directly associated with the hydraulic properties of the soil (Hu et al., 2007; Coppola et al., 2009).

These properties can vary significantly in space (Taskinen et al., 2008). Thus, it is crucial that the spatial variability of soil hydraulic properties for being accounted for in agro-hydrological models. Such models can allow different irrigation regimes (if applicable) and different land use managements to be established.

In addition, it is known that hydraulic variables are difficult to obtain in the field, require long time and expensive equipment, skilled labor and, due to their variability, require many samplings that can hardly be extrapolated.

In this context, one of the major challenges in soil water flow modeling is to quantify the spatial variability of physical and hydraulic properties, such as soil water retention curve and hydraulic conductivity, since they are extremely heterogeneous.

Because they are crucial in modeling, these properties have been evaluated by several authors in relation to water movement in the vadose and/or saturated zone (Hu et al., 2007; Taskinen et al., 2008; Coppola et al., 2009; Champo & Zamarrón, 2010; Paleologos & Sarris, 2011; Santos et al., 2012; Furtunato et al., 2013; Fang et al., 2016; Montzka et al., 2017). The understanding of these variables is important, being required in studies on the efficiency of irrigation techniques, drainage and agricultural productivity.

Based on the foregoing, this study aimed to perform a spatial analysis of the saturated hydraulic conductivity ($K_{sat}$) and soil water retention curve parameters (RC) in the Donato stream basin, located in the most important agricultural region of RS, Brazil.

# MATERIAL AND METHODS

The study area is located in the municipality of Pejuçara, in the northwest region of the RS, Brazil, with geographic coordinates between 28º 25' 34'' S and 53º 40' 30'' W, and 28º 24' 50'' S and 53º 41' 30'' W, 590 m altitude and comprises the Donato stream basin, with an area of 1.10 km². This basin is part of a set of sub-basins of the Potiribu river, which is a contributor to the left bank of the Ijuí river, the latter being an affluent of the left bank of the Uruguay river (Figure 1).

The soils of the Donato stream basin are predominantly Oxisol and Ultisol with high clay content (> 60%), characterized by being well drained and deep (Castro et al., 2000).
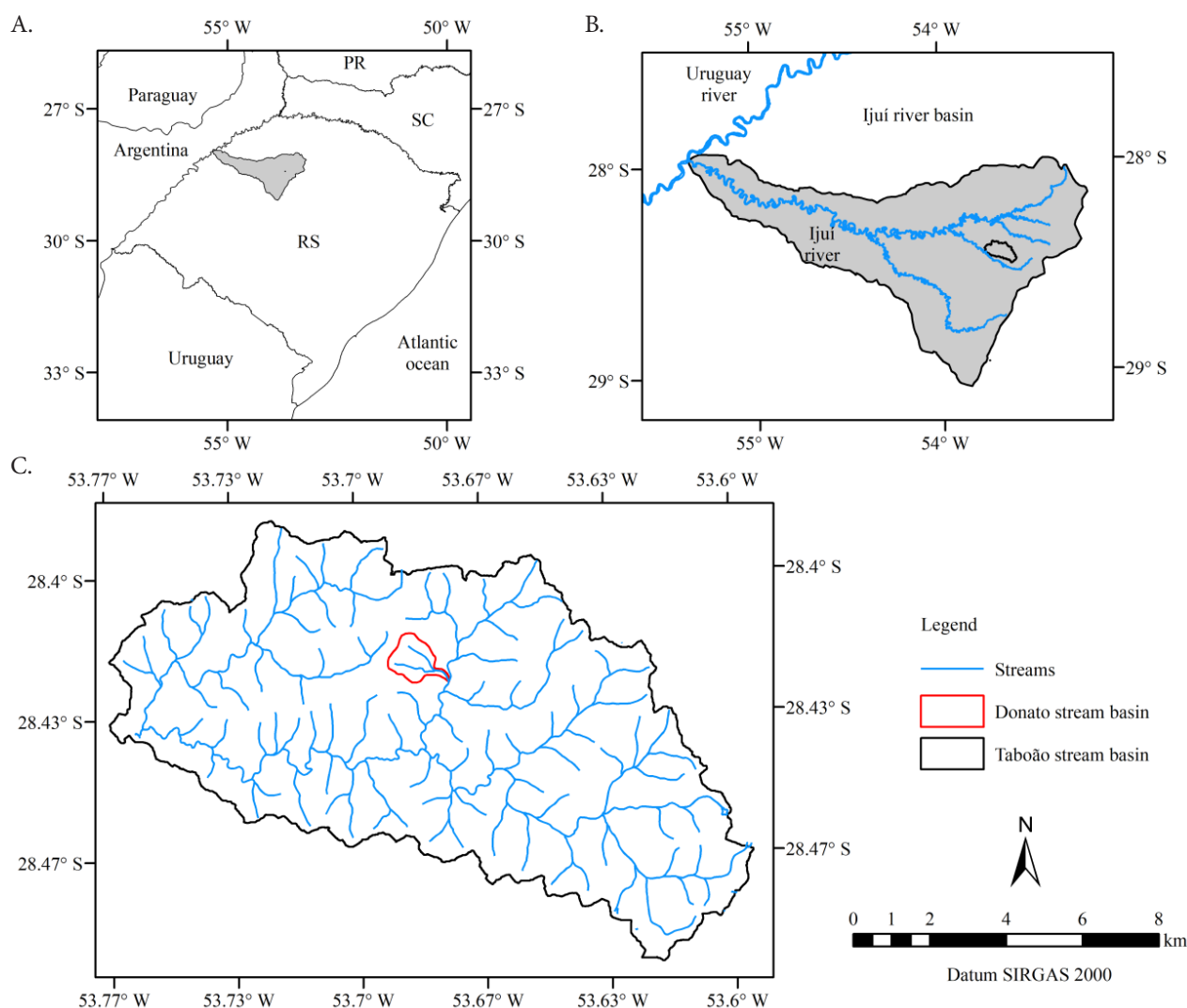


**Figure 1.** Donato stream basin location : Rio Grande do Sul state (A), Ijuí river basin (B) and Taboão and Donato stream basins (C)

The soil use is essentially agricultural with the practice of direct cultivation throughout the basin area, with wheat (*Triticum* spp.), oats (*Avena sativa*) and soybean (*Glycine max*) being the most common crops. All crops are non-irrigated, and soybean is cultivated in the summer, while during the winter the farmers cultivate wheat and oats in the basin.

Three sets of samples were collected in August, October and November of 2012. During the first sampling, oats and wheat were being cultivated on the area, in the second sampling the soil was covered by only the remaining straw of these crops and in the third one soybean was already being cultivated, approximately 40 cm tall.

A regular grid was established covering all basin area. The soil was sampled at the crossing points of the grid, with regular spacing of 140 m and the most distant samples were collected in a regular spacing of 200 m, making a total of 55 points (Figure 2). These samples complement the study of Medeiros (2004), which determined the soil water retention curves in 23 of the 55 points of this study. These 23 curves refer to the depth of 30 cm and were also used in this study.

In each of the 23 points where soil samples were already collected by Medeiros (2004) to obtain the retention curve, only one additional sample per point was collected to determine the saturated hydraulic conductivity. In the other points, two samples were collected, one to determine the soil water retention curve and the other to determine the saturated hydraulic conductivity.

The Richards chamber method was applied to determine the water retention curve (RC), considering the matric potentials of -10, -30, -50, -70, -100, -150, -200, -250, -300 and -500 kPa. For the determination of $K_{sat}$, the variable head permeameter was used. Therefore, the variables analyzed were the soil saturated hydraulic conductivity and the soil water retention curve parameters n, α, $\theta_{sat}$ and $\theta_{res}$, fitted according to the model of Genuchten (1980), defined by:

$$\theta(h) = \theta_{res} + (\theta_{sat} - \theta_{res})(1 + |\alpha h|^n)^{-m} \qquad (1)$$

where:

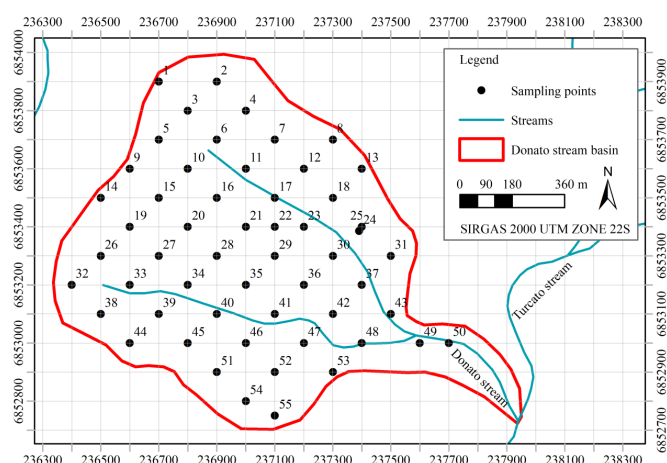$\theta(h)$ - soil moisture associated with a given matric potential ($cm^3\ cm^{-3}$);

h    - matric potential, cm;

$\theta_{sat}$    - saturated soil water content, $cm^3\ cm^{-3}$;

$\theta_{res}$    - residual soil water content, $cm^3\ cm^{-3}$; and,

α, n and m - empirical shape parameters of the soil water retention curve ($cm^{-1}$, dimensionless, dimensionless), where m = 1- (1/n).

The RETC software (Genuchten et al., 1991) was used to fit the retention curve and determine the parameters of Eq. 1.

## RESULTS AND DISCUSSION

The location maps of $K_{sat}$ and the fitted parameters of the Genuchten (1980) soil water retention curve model allow a better visualization of the spatial distribution of the variables analyzed (Figure 3). Some variables were pre-transformed, such as $K_{sat}$ (Figure 3A) and the parameter α (Figure 3B), to facilitate future treatment of these data. Blue points on the $K_{sat}$ map represent the locations for which the saturated hydraulic conductivity value was very low and undetectable during the permeameter test.

These points represent the most critical areas for agricultural management, since they are associated with soil compaction processes. The basin area is predominantly of low hydraulic conductivity, with few dispersed samples of high values. As mentioned by Santos et al. (2012), the soil textural class and the agricultural cultivation conditions also contribute to high soil heterogeneity.

Higher variability was observed for saturated water content (Figure 3D) along the entire basin, while residual water content (Figure 3E) does not change much because the RETC model sets it equal to zero in most cases to continue fitting the other parameters. The spatial distribution of $\theta_{sat}$ values may also be related to the types of soils located in the basin, all Oxisols, which are characterized by being porous, but susceptible to compaction (Bergamin et al., 2010). Additionally, the authors cite that compaction in Oxisols diminishes the total porosity and macroporosity. This explains why higher $\theta_{sat}$ values were obtained along the springs, where the soil is less compacted.

Due to the fact that they are clayey soils, it is possible that this fact explains why, in general, at points where $K_{sat}$ is smaller, $\theta_{sat}$ is higher. This is because clay particles do not facilitate infiltration near saturation, reducing hydraulic conductivity and causing the soil to lose water through evaporation. Moreover, according to Hu et al. (2008), soil water flow is more affected by clay content when the soil becomes dry, which happened during the first soil sampling. All samples of lower $\theta_{sat}$ values located in the northwestern portion of the basin (Figure 3D) were obtained when the soil was very dry, during the drought that began in November 2011 and continued until August 2012.

Regions of high and low α values were also observed along the area (Figure 3B). This parameter directly influences the air-entry pressure and its value may be greater than this pressure (Arraes, 2014). Its influence on the water retention curve is a translation, indicating that the lower the value of α, the greater the matric potential associated with a specific soil moisture. Thus, the highest values of this parameter in Figure 3B
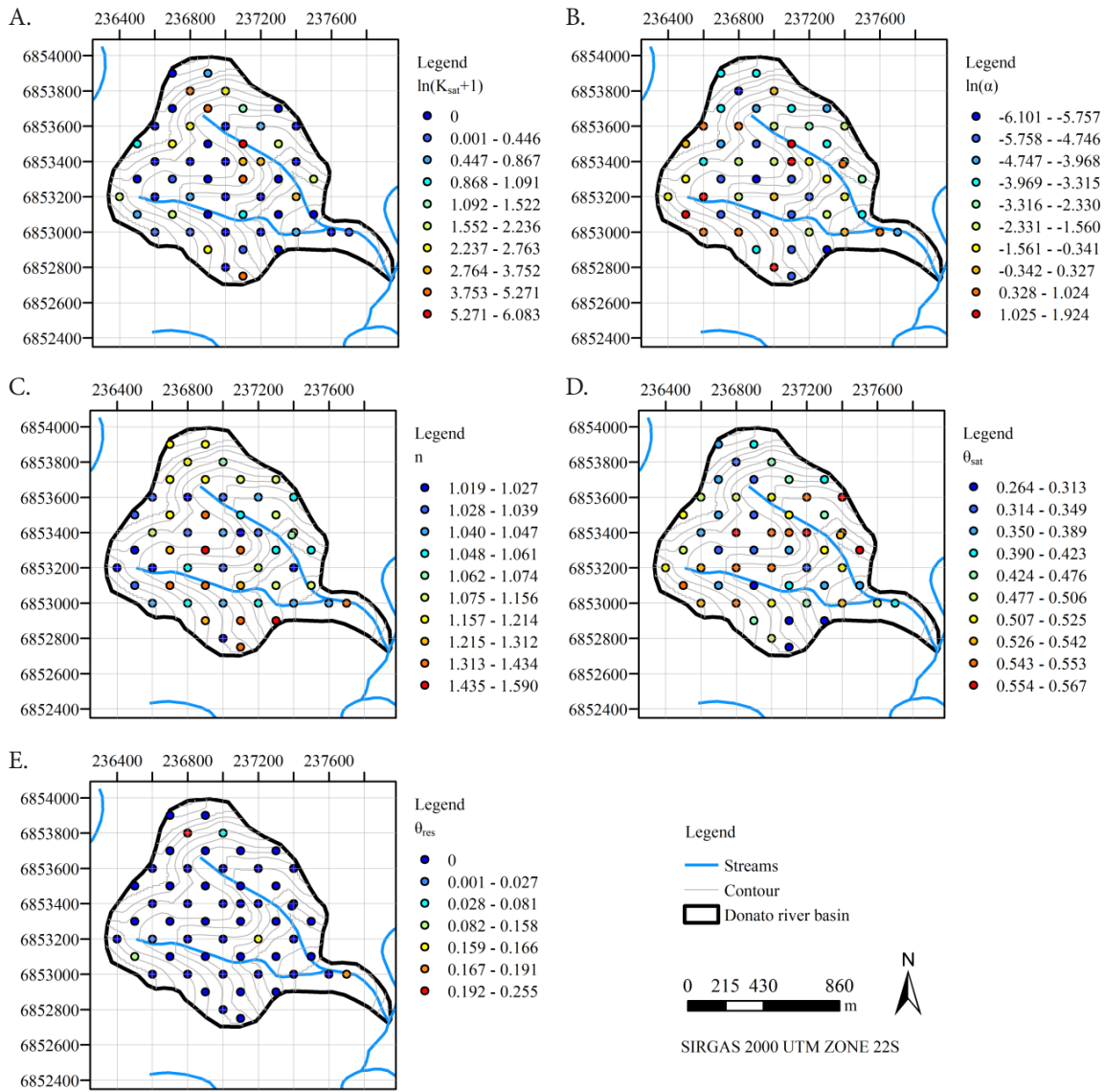


**Figure 2.** Grid of soil sample collection points in the Donato stream basin

**Figure 3.** Location maps of the soil physical and hydraulic properties: $\ln(K_{sat}+1)$ (A), $\ln(\alpha)$ (B), parameter n (C), saturated soil water content $\theta_{sat}$ (D), residual soil water content $\theta_{res}$ (E)

indicate areas where the soil is probably less compacted and also generally coincide with the highest $K_{sat}$ values (Figure 3A).

On the other hand, the fitted values of the parameter n (Figure 3C) indicated intermediate spatial variability, due to the small amplitude of the data, between 1.0 and 1.2. This parameter controls the slope of the water retention curve and the higher the value of n, the steeper the water retention curve will be. It is also influenced by the level of soil compaction. Furthermore, as shown by Arraes (2014), soil water flow is more sensitive to this parameter than to $\alpha$ and, therefore, must be obtained with greater precision, which is justified, considering its spatial variability.

These maps highlight that the spatial variability of the variables in the basin area is important and should not be disregarded, since $K_{sat}$ and water retention curve are hydraulic properties that affect the soil water flow. Table 1 shows the statistical summary of the 55 samples of $K_{sat}$ and the water retention curve parameters, without data transformations.

The sample variance for $\alpha$ and $K_{sat}$ parameters are highest, due to the presence of some very high values in certain regions. This result is in agreement with the work of Coppola et al. (2009), who

**Table 1.** Statistical summary of the 55 samples of $K_{sat}$ and the water retention curve parameters

| Statistics | α (cm⁻¹) | n | θ_sat (cm³ cm⁻³) | θ_res (cm³ cm⁻³) | K_sat (cm d⁻¹) |
|---|---|---|---|---|---|
| Mean | 0.921 | 1.145 | 0.455 | 0.016 | 25.455 |
| Minimum | 0.002 | 1.019 | 0.264 | 0.000 | 0.000 |
| Maximum | 6.849 | 1.590 | 0.567 | 0.255 | 437.414 |
| Median | 0.128 | 1.065 | 0.494 | 0.000 | 0.300 |
| Quartile 1 | 0.017 | 1.040 | 0.373 | 0.000 | 0.000 |
| Quartile 3 | 1.237 | 1.194 | 0.535 | 0.000 | 6.897 |
| Variance | 2.588 | 0.020 | 0.008 | 0.003 | 5530.436 |
| Standard deviation | 1.594 | 0.141 | 0.089 | 0.052 | 74.367 |
| Interquartile distance | 1.219 | 0.154 | 0.162 | 0.000 | 6.897 |
| Coefficient of variation (%) | 173.2 | 12.3 | 19.5 | 324.1 | 292.2 |

also found higher coefficients of variation for $K_{sat}$ and $\alpha$. Moreover, the results of these authors indicate that the RC parameters have a great impact on the prediction of uncertainties and can not be ignored in stochastic simulations of variables important to groundwater flow.

The small variance of $\theta_{sat}$ does not mean that this parameter does not have a large spatial variability, which can be confirmed by its sampling map (Figure 3D). In this case, it is observed

that, although $\theta_{sat}$ has little sample amplitude, this parameter varies considerably in space. Likewise, the parameter n presents low sample variance and a more uniform spatial distribution than the previous parameters.

Some reasons can be mentioned for the spatial variability of these variables. Firstly, the different soil covers during sampling. In the first sampling the soil was covered with the winter crop (oats and wheat), in the second the soil was covered by the remaining straw of these crops and in the third sampling the summer crop (soybean) was already being grown. In addition, between one crop and the other there was also the transit of machines.

Soil management also influences natural soil heterogeneity (Camargo et al., 2010), promoting variations in organic material accumulation, water movement, compaction and water erosion (Novaes Filho et al., 2007). This is in agreement with the work of Deb & Shukla (2012), who pointed out that the value of $K_{sat}$ varies according to the use of the soil as follows: forested areas > no-tillage > conventional tillage. These authors also comment that samplings over time have the greatest impact on $K_{sat}$ variability, followed by land use. This fact explains why the $K_{sat}$ values are so different, since the samples were collected in different periods, because the number of samples precludes the occurrence of only one set of samples.

Second, samples at 30 cm, close to the soil surface, are more heterogeneous and this increases the variability found for most of the analyzed variables, mainly $K_{sat}$. The same was confirmed by Hu et al. (2007), who verified that the influence of the variability of $K_{sat}$ obtained at the soil surface on water flow is much greater than that of $K_{sat}$ sampled at greater depths. Therefore, it is more appropriate to consider the spatial variability of $K_{sat}$ in the surface.

It is possible that the large $K_{sat}$ variability is also due to the size of the undisturbed samples collected. Bagarello & Provenzano (1996) estimated the hydraulic conductivity in the laboratory using a variable head permeameter (method of this study) and verified that, in general, larger samples produced estimates with smaller values and lower variability than the samples obtained with smaller cylinders (as was the case in the present study). The authors explain that the reason for this difference is that in the small samples the preferential flow increases significantly.

In addition, the lowest values of $K_{sat}$ were obtained in the lower parts of the terrain (concave areas), where the soil was more compacted (as verified during samplings). This is because soil compaction destroys the macropores, reducing the variability of the hydraulic conductivity. According to Souza et al. (2003), these areas are less influenced by the effects of erosion when compared to the convex or flat areas. The authors also add that, in general, the spatial variability of soil properties behaves according to an arrangement defined by factors such as management, erosion and landscape, and not only randomly (randomness of the phenomenon).

Based on these results, it can be expected that the heterogeneity of the aforementioned soil physical and hydraulic properties may result in significant differences in the estimates of other hydraulic or hydrological variables that depend on these properties, such as surface runoff, drains for agricultural drainage, availability of water for irrigation, irrigation water demands, etc. For example, as mentioned by Reichardt et al. (2001), considering soil heterogeneity remains a challenge for the management of agricultural practices, such as irrigation. Since the determination of the irrigation water depths depends on the soil moisture before application, retention and storage capacity, soil density, among other factors, it is obvious that the spatial variability of these properties is of extreme relevance for areas to be irrigated.

## Conclusions

1. There is great variability of the hydraulic properties, represented by the saturated hydraulic conductivity and the parameters of the water retention curve in the soil.

2. The soil heterogeneity found in the study is probably much more influenced by temporal than spatial variability of the phenomenon itself, since the samples were not obtained simultaneously.

3. The soil types in the Donato stream basin are susceptible to compaction, which influences the heterogeneity of saturated hydraulic conductivity and the water retention curve in the soil, demonstrated by the spatial distribution of these parameters according to the regions where the soil was more compacted during the samplings.

## Acknowledgments

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