

## Spatial Variability of Saturated Hydraulic Conductivity in a Karstic Environmental Protection Area

*A Variabilidade Espacial da Condutividade Hidráulica Saturada em Área de Proteção Ambiental Cárstica*

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### Abstract

Saturated hydraulic conductivity (Ksat) is a fundamental property to understand water and solute dynamics in saturated and unsaturated soils. The objective of this study is to present and assess the results of a statistical analysis of the data obtained from the determination of the permeability of a variety of soils (Argisols, Latosols, Gleysols, and Cambisols) of the Lagoa Santa Karst Environmental Protection Area (State of Minas Gerais, Brazil). Software R version 4.0.4 was used for the statistical analyses. Argisol, Cambisol, and Gleysol samples yielded normal conductivity distributions at depth, with mean values of  $1.16 \times 10^{-1}$  m/d,  $6.14 \times 10^{-2}$  m/d, and  $1.95 \times 10^{-3}$  m/d, respectively. Regarding the log-normal distributed Latosol samples P48 and P52 and Gleysol sample P54sup, it was concluded that probability, respectively of 85.72%, 96.55%, and 47.37%, exists for hydraulic conductivity values between  $0.1 \times 10^{-1}$  m/d and  $4 \times 10^{-1}$  m/d to occur. Studies or criteria to establish Ksat values that should be really representative of the whole study area have not been found. It was preferable to characterize Ksat in terms of levels of probability of occurrence rather than values, such as the mean or median, in order to represent an area that will be subject to the same water flow control operations (irrigation and drainage practices, leaching and erosion control, etc.). Therefore, it is not appropriate to assume a normal distribution of saturated hydraulic conductivity values for areas with the characteristics of Lagoa Santa.

**Keywords:** Saturated hydraulic conductivity; Ksat; Groundwater

### Resumo

A condutividade hidráulica saturada (Ksat) é uma propriedade fundamental para conhecimento da dinâmica da água em solos saturados ou não saturados. O objetivo deste estudo é apresentar e avaliar os resultados das análises estatísticas dos dados provenientes da determinação da permeabilidade de diferentes solos (argissolos, latossolos, gleissolos e cambissolos) da Área de Proteção Ambiental Carste de Lagoa Santa, em Minas Gerais. Os valores de Ksat foram determinados por intermédio de um permeâmetro de carga constante e para as análises estatísticas foi utilizado o software R em sua versão 4.0.4. O argissolo, cambissolo e gleissolo (em profundidade) apresentaram distribuições normais de condutividade, tendo como média  $1,16 \times 10^{-1}$  m/d,  $6,14 \times 10^{-2}$  m/d e  $1,95 \times 10^{-3}$  m/d, respectivamente. Em relação aos latossolos (P48 e P52) e ao gleissolo (P54sup.), que possuíam distribuição log-normal, pôde-se concluir que existe uma probabilidade de 85,72%, 96,55% e 47,37%, respectivamente, de se encontrar valores de condutividade hidráulica no intervalo de  $0,1 \times 10^{-1}$  m/d a  $4 \times 10^{-1}$  m/d. Não foram encontrados estudos ou critérios para o estabelecimento de valores realmente representativos da Ksat para a área de estudo como um todo. Constatou-se ser preferível caracterizar a Ksat em termos de níveis de probabilidade de ocorrência, ao invés de utilizar um valor, como a média ou a mediana, para representar uma área que estará sujeita às mesmas operações de controle de fluxo de água (práticas de irrigação, de drenagem, de controle de lixiviação, de erosão, etc). Portanto, não é apropriado assumir distribuição normal para os valores de condutividade hidráulica saturada em áreas com as características de Lagoa Santa.

**Palavras-chave:** Condutividade hidráulica saturada; Ksat; Água subterrânea

## 1 Introduction

Saturated hydraulic conductivity ( $K_{sat}$ ), also known as permeability coefficient, is a physical parameter fundamental for the analysis of the intensity at which water flows in soil, being highly relevant in providing essential information on water's capacity to transport solutes and chemical substances in practically all flow mechanisms (Bagarello, Baiamonte & Caia 2019; Bagarello et al. 2014; Gonçalves & Libardi 2013).

Maximum hydraulic conductivity is reached when the soil is totally saturated, and such parameter is therefore named saturated hydraulic conductivity (Alagna et al. 2016; Di Prima et al. 2019; Keller et al. 2012; Mesquita 2001).

$K_{sat}$  values can considerably change for the same soil, because of holes made by animals and plant roots. In this sense, it is not always possible to admit that sample data for a certain soil type are normally distributed, being unpractical to represent them by the mode, the mean, or the median (Lozano-Baez et al. 2018; Reynolds et al. 2009; Zhang et al. 2019).

Provided that saturated hydraulic conductivity ( $K_{sat}$ ) is known and using mathematical models, the unsaturated hydraulic conductivity ( $K$ ) can be determined and information on movement of water and solutes in soils can be obtained (Bagarello et al. 2014; Mesquita 2001).

Determinations in the laboratory and in the field reveal a broad dispersion of data, which indicates that this property is highly variable (Cherubin et al. 2016; Mubarak et al. 2010; Pinheiro, Jong van Lier & Simunek 2019).

The investigation of the water dynamics in soils is fundamental to understand infiltration and other water movements in soils in pedological, hydrogeological, and chemical leaching studies (Alagna et al. 2019; Azam et al. 2009).

Saturated hydraulic conductivity is affected by soil attributes, such as structure, texture, homogeneity, soil density, density of particles, total porosity, macro and micro porosities, and any other factor that can influence pore size and configuration. The characterization and better understanding of these attributes is fundamental to any conclusions on the physical processes that take place in the soil (Abbasi et al. 2013; Khaledian, Shabanpour & Alinia 2016; Kreiselmeier et al. 2020; Kumar et al. 2010).

Several researchers have proposed new methodologies and models to determine hydraulic conductivity and how water flows through the soil. However, saturated hydraulic conductivity has been considered constant throughout the study area. This supposition results from convenience and ease and is totally questionable, because  $K_{sat}$  values

can vary to the point of being asymmetrically distributed (Gonçalves & Libardi 2013; Mubarak et al. 2010).

The movement of water in the soil is a function of the hydraulic conductivity ( $K$ ), which is calculated from the saturated hydraulic conductivity, implying the necessity of the precise determination of  $K_{sat}$  values (Mesquita 2001).

From  $K_{sat}$ , it is possible to model water flow in soils and it is applicable to projects focusing on irrigation, drainage, percolation of chemical substances, and the recovery of degraded areas (Leij et al. 2004; Price, Jackson & Parker 2010).

In the study area, which is an environmental protection area as a consequence of its karst relief, the dependence on groundwater is high, not only for urban water supply, but also irrigation, animal watering, and local industry.

Considering the importance to know the saturated hydraulic conductivity behavior in soils, the objective of this study is to statistically assess soil permeability and to know the probabilistic distribution of  $K_{sat}$  values for a better representation of the saturated hydraulic conductivity in an environmentally vulnerable, karstic geological context.

### 1.1 Characterization of the Study Area

The study area is located 30 km north of Belo Horizonte (State of Minas Gerais, Brazil), extending for ca. 500 km<sup>2</sup>. Created by the Federal Government via Decree 98881 dated 25<sup>th</sup> January 1990, the Environmental Protection Area (APA) named Lagoa Santa Karst is 356 km<sup>2</sup> in area and encompasses part of the Lagoa Santa, Pedro Leopoldo, Matozinhos, and Funilândia municipalities. It is located in the Minas Gerais karstic region, where limestone predominates in the formations that compose the Bambuí Group (Pessoa 2005).

The geomorphologic characteristics of the region have promoted the formation many caves, which shelter a variety of archeologic and paleontological sites. The calcareous formations, cliffs, sinkholes, sinks, and springs make of this protection area one of the most important speleological sites of Brazil, of unmeasurable scientific and cultural richness and beauty (Auler 1994; Kohler 1989; Pessoa 2005).

The same rock types and geological structures that constitute such historical, cultural and scenic heritage also respond for the economic resources of the region. The abundant limestone is exploited by the lime and cement industry, which is usually unaware of the environmental impacts. These activities, besides causing damages to the historical and cultural heritage, strongly affect natural vegetation and cause environmental degradation.

The climate in the Lagoa Santa APA is of category Awi (Koppen 1948), that is, hot, with alternating, rainy (summer) and dry (winter) seasons, being annual thermal variations lower than 5 °C (Ribeiro 1995). The mean annual rainfall is 1381 mm (Kohler 1989).

The soil types that predominate in the Lagoa Santa APA are: dark-red alic Latosol and red-yellow dystrophic podzolic in the Lagoa Santa municipality; red-yellow dystrophic podzolic in the Pedro Leopoldo municipality; red-yellow alic podzolic and dark-red alic Latosol in Matozinhos; and, dark-red alic Latosol and alic Cambisol in Funilândia (Kohler 1989).

The Lagoa Santa APA is located in the São Francisco Craton, close to the Araçuaí Belt. Locally, the Lagoa Santa APA is inserted in the domains of the following lithostratigraphic units: Sete Lagoas Formation (Lagoa Santa Member, Pedro Leopoldo Member) and Serra de Santa Helena Formation. The Sete Lagoas Formation is formed by homocline carbonate ramps that characterize the base of the Bambuí Group. It is composed of dolomites, limestones, and pelites (Pessoa 2005). It is divided in the Pedro Leopoldo Member, composed of beige, pink, light gray and greenish, massive, laminated calcilutites and calc-siltites displaying stylolites and load structures, and the Lagoa Santa Member, composed of fine to medium, dark gray to black, laminated to massive calcarenites with levels of beige, gray and yellowish siltites, also displaying stylolites (Pessoa 2005). The Serra de Santa Helena Formation is composed of siltites and argillites with levels of fine to very fine, gray to greenish gray, pink and yellowish sandstones. Plane-parallel lamination, tabular crossed stratification and wavemarks are the predominant textures (Auler 1994).

According to Kohler (1989), karstic reliefs develop on water-soluble rocks (limestones), which undergo corrosion from superficial and underground waters. The Lagoa Santa APA hydrogeological domain is classified as karstic, because of the secondary porosity that results from discontinuities and dissolution structures, originating two – pelite-carbonate and carbonate – aquifer systems.

The carbonate aquifers are limited at the base by rocks belonging to the basal complex (gneisses, migmatites, granitoids). The hydrogeological complexity of the karstic terrains results mainly from the fact that drainage basins are not necessarily limited by the watersheds, extending in subsurface beyond the superficial limits.

## 2 Methodology and Data

Figure 1 is a simplified geological map of the study area, known as the Lagoa Santa Karst Environmental Protection Area (Lagoa Santa APA).

The codes signaled in Figure 1 correspond to soil sampling points. Table 1 lists these points, together with corresponding soil types and lithostratigraphic units.

In order check the variability in the Ksat normal distribution along two horizons, 20 (superficial – depths from 0-5 cm to 20 cm) and six (subsuperficial – depths from 20 to 40 cm) were collected at sampling point P54. Sample collecting and preparation procedures were as follows:

1) The 26 Gleysol samples were collected at depths from 0-5 to 20 cm by inserting a metallic cylinder in the soil; 2) Sample saturation in the laboratory, using a 0.005 M deaerated solution of calcium sulfate ( $\text{CaSO}_4$ ) saturated with thymol ( $\text{C}_{10}\text{H}_{14}\text{O}$ ). The samples were kept soaking for seven days (Figure 2A), until the beginning of the essays. A constant-head permeameter was used to determine the permeability of the soil samples (Figure 2B). The difference in volume measured with a burette is the volume of solution drained through the sample in a chosen time interval. The same laboratorial procedure was applied to the 114 Argisol, Cambisol and Latosol samples.

The permeability values obtained for the 140 soil samples were adjusted to 20 °C, and were the result of the ratio between the viscosity of the solution used in the laboratory and the viscosity of the water at 20 °C.

Ksat of each soil sample (at 20 °C) was determined using Darcy Law – Equation 1:

$$V = K . i . A . t \quad (1)$$

For the probability distribution analysis, the normal distribution was assumed. The normal distribution, also known as normal or Gauss curve, is a function of two parameters: mean and standard deviation (Walpole et al. 2009) – Equation 2:

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{1}{2\sigma^2}(x-\mu)^2} \quad (2)$$

Where:

$\pi = 3,14\dots$ ;

$e = 2,71\dots$ ;

$\sigma$  = standard deviation.

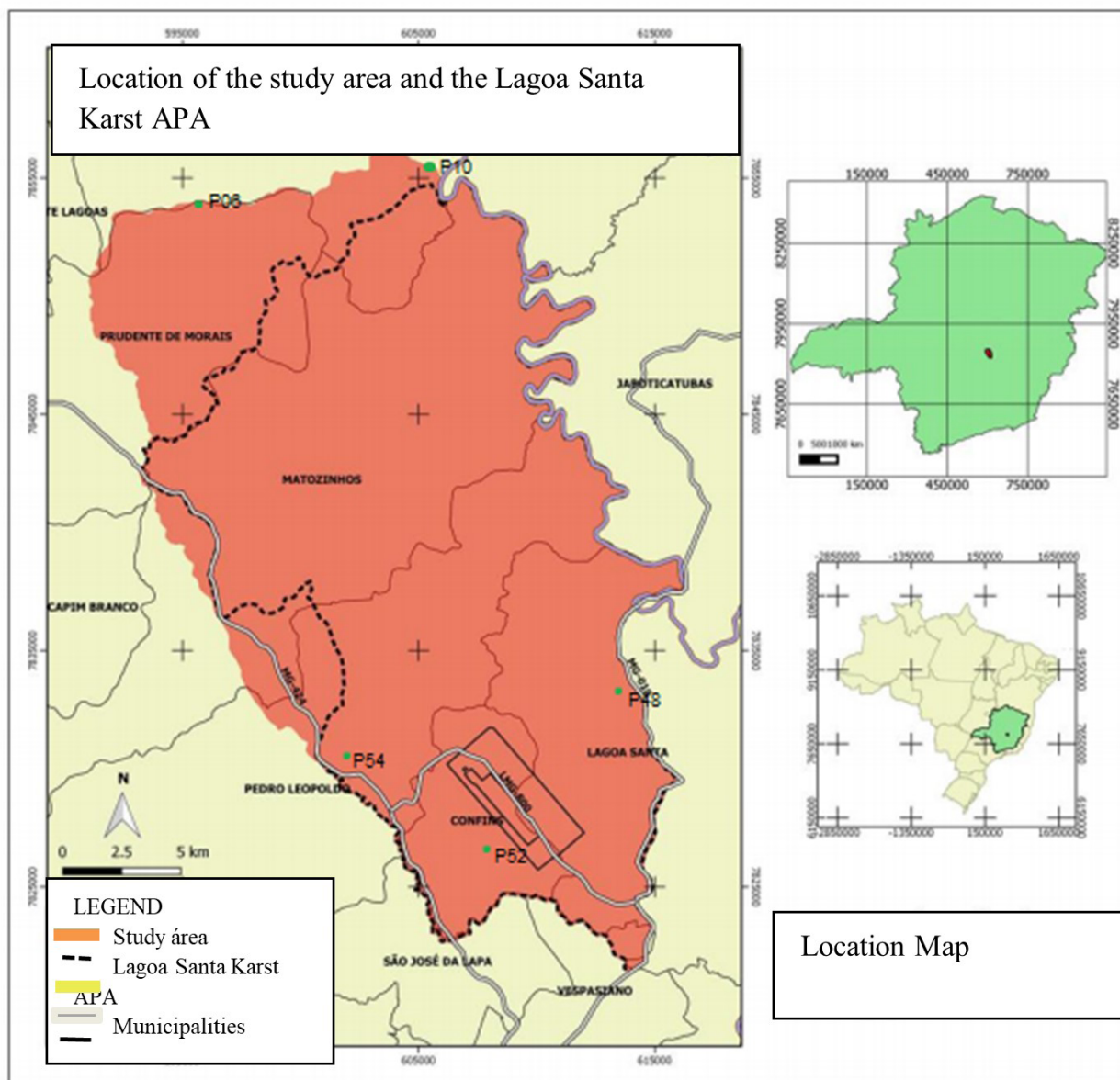


Figure 1 Map of the study area and location of soil sampling points (modified from Vieira 2018).

Table 1 Pedo-geological characteristics of the sampled points.

Code	Soil type / number of samples	Lithostratigraphic Units
P06	Argisol / 22	Serra de Santa Helena Formation
P10	Cambisol / 34	Alluvial Covers
P48	Latosol / 28	Serra de Santa Helena Formation
P52	Latosol / 30	Lagoa Santa Formation
P54	Gleysol / 26	Pedro Leopoldo Member

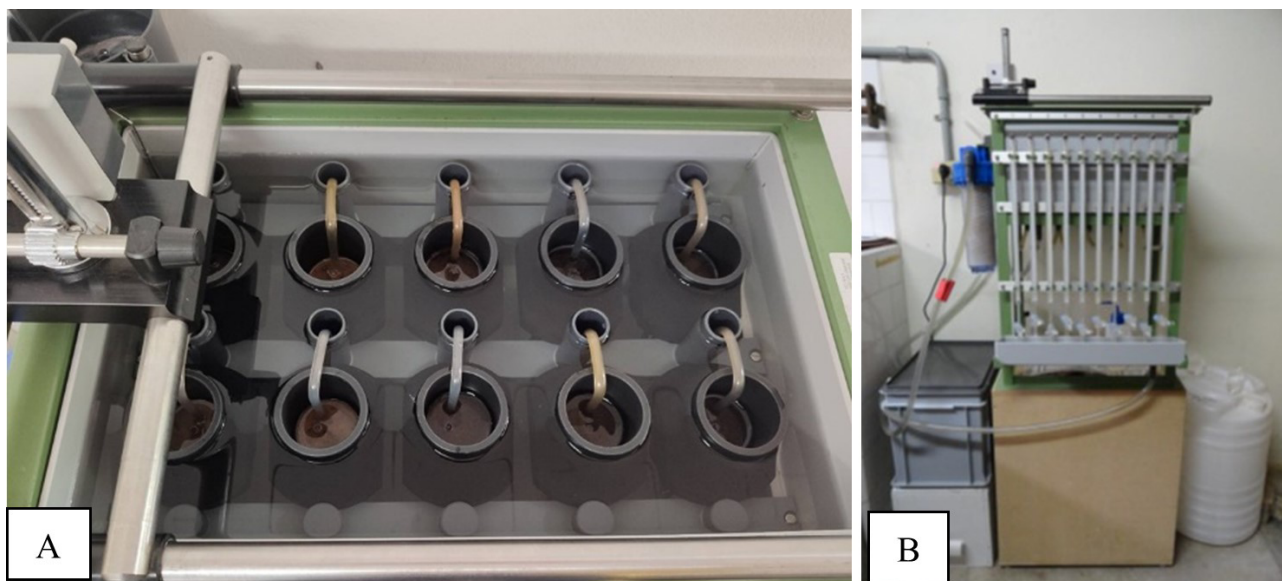


Figure 2 View of A. sample preparation; B. the constant-head permeameter.

The mean and standard deviation were calculated via Equations 3 and 4:

$$\mu = \frac{\sum_{i=1}^n x_i}{n} \tag{3}$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^n (x_i - x_m)^2}{n}} \tag{4}$$

Where:

- $x_i$  = sample values;
- $n$  = number of elements in the sample;
- $x_m$  = mean value.

The log-normal distribution was used to describe soil properties that are positively asymmetric. Positively asymmetric distributions are a consequence of the fact that many environmental variables cannot assume negative values, thus starting from zero (Parkin & Robinson 1993). It can also be applied in situations where the log-natural transformation generates a normal distribution, that is, variable X (continuous) will have a log-normal distribution when  $Y = \ln(X)$  (Walpole et al. 2009).

The Shapiro and Wilk test (1965) was applied to check whether the distribution of the samples is normal. Two hypotheses must be formulated for the test to be performed: in  $H_0$ , the sample comes from a normal distribution; in  $H_1$  the sample does not come from a normal distribution. Then, the significance level is determined (it can vary from 0 to 1) and the test statistic ( $W$  – Equation 5) is calculated. By

means of an interpolation or with the aid of a software, it is checked whether  $p$  (probability obtained by interpolation) is greater than the significance level defined initially; if yes, the null hypothesis is accepted (Shapiro & Wilk, 1965).

$$W = \frac{b^2}{\sum_{i=1}^n (x_i - (x_m))^2} \tag{5}$$

$b$  can be calculated by:

$$\sum_{i=1}^{n/2} a_{n-i+1} \cdot (x_{n-i+1} - x_{(i)}) \text{ if } n \text{ is even;}$$

$$\sum_{i=1}^{(n+1)/2} a_{n-i+1} \cdot (x_{n-i+1} - x_{(i)}) \text{ if } n \text{ is odd.}$$

For the statistical analyses, software R version 4.0.4 was used. The first step was to insert the  $K_{sat}$  data in the program, attributing a variable for the record of column  $K_{sat}$ .

The Shapiro-Wilk test was applied for each soil class. Then, for soil classes that were normally distributed, graphs of the Boxplot type were drawn, in order to compare sample quartiles with those of the normal distribution. For the samples that were not normally distributed, the natural logarithm was applied to each  $K_{sat}$  value. Boxplot graphs were used in the study of the variability of the measurements.

### 3 Results

In Table 2 can see a summary of the results of the Ksat data exploratory analysis.

The high differences between mean and median values, interquartile range, total range, standard deviation, variation coefficient, kurtosis coefficient, and asymmetry coefficient show that the probability distribution of Ksat is not normal, even if the analyses were made with a small number of samples. The total range for the soil groups is approximately three times higher than the interquartile range, which indicates the existence of values very distant among themselves, despite being less frequent. The analysis of quartiles shows that the results are closer to the lowest values, because the upper quartile is much lower than the maximum value and the lower quartile is much higher than the minimum value and 50% of the data fall between these quartiles. The statistical distribution is normal for some groups of soil samples; however, considering all the samples of the study area, the statistical distribution of the data is not normal. Therefore, more appropriate statistical tests are the non-parametric, because they do not depend on the data statistical distribution.

The variability of results can be explained by the fact that Ksat is highly influenced by chemical and specially physical aspects of the soil, such as aggregation, macro- and micro-porosity, texture, morpho-structures, spatial variations in depth and in the horizontal direction (Castellini et al. 2019; Fernández-Gálvez et al. 2019; Guellouz et al. 2020; Hosseini, Ganijan & Pishch 2011; Mesquita 2001; Zhou, Gomez-Hernandez & Li 2014). Several studies show the variation range of the Ksat data, independently of the methodology adopted for the measurements, the geographic location, soil use and occupation, and soil type (Baiamonte et al. 2017; Papanicolaou et al. 2015). Picciafuoco et al. (2019) showed that ample Ksat variations can result from many soil characteristics and not exclusively soil structure. For soils plowed for agriculture, minimum and maximum Ksat values were more than 50% greater than those obtained for soils used for pasture (Picciafuoco et al. 2019). According to Viola et al. (2013), soils from native forests yield in average Ksat circa 1.8 and 2.1 times greater than the values obtained for soils of annual cultures and pastures, respectively.

As stated before, two hypotheses were formulated for the soil types:  $H_0$ : the sample comes from a normal

**Table 2** Summary of the results of the statistical analysis of the saturated hydraulic conductivity (Ksat) data for each soil type.

Soil types	Ksat (m/d)					
	P06 Argisol	P10 Cambisol	P48 Latosol	P52 Latosol	P54 (sup.) Gleysol	P54 (subsup.) Gleysol
Minimum	1.65E-03	2.93E-03	1.25E-02	1.25E-02	1.14E-02	1.10E-03
First Quartile	5.73E-02	4.34E-02	1.18E-01	1.06E-01	3.47E-02	1.36E-03
Second Quartile	9.73E-02	6.52E-02	1.93E-01	1.38E-01	8.31E-02	1.72E-03
Third Quartile	1.66E-01	8.25E-02	2.63E-01	2.31E-01	2.85E-01	2.17E-03
Maximum	3.02E-01	1.22E-01	6.28E-01	6.28E-01	7.39E-01	3.76E-03
Mean	1.16E-01	6.14E-02	2.28E-01	1.82E-01	1.91E-01	1.95E-03
Median	9.73E-02	6.52E-02	1.93E-01	1.38E-01	8.31E-02	1.72E-03
Variance	7.60E-03	9.05E-04	2.68E-02	1.67E-02	4.99E-02	8.21E-07
Standard Deviation	8.72E-02	3.01E-02	1.64E-01	1.29E-01	2.23E-01	9.06E-04
Asymmetry Coefficient	6.92E-01	-6.66E-02	1.22E-00	1.90E-00	1.39E+00	1.57E+00
Kurtosis Coefficient	-4.14E-01	-3.92E-01	9.40E+00	4.45E-00	8.38E-01	2.66E+00
Variation Coefficient	7.53E-01	4.90E-01	7.17E-01	7.10E-01	1.17E+00	4.65E-01
Lower Quartile	-1.05E-01	-1.52E-02	-9.90E-02	-8.15E-02	-3.41E-01	-1.40E-04
Upper Quartile	3.28E-01	1.41E-01	4.80E-01	4.19E-01	6.61E-01	3.19E-03
Total Range	3.00E-01	1.19E-01	6.15E-01	6.15E-01	7.27E-01	2.66E-03
Interquartile range	1.09E-01	3.91E-02	1.45E-01	1.24E-01	2.50E-01	8.10E-04
			4.90E-01	4.90E-01	7.39E-01	3.76E-03
Outliers			5.52E-01	6.28E-01		
			6.01E-01			

distribution;  $H_1$ : the sample does not come from a normal distribution. Applying the Shapiro-Wilk test to a significance level of 5%, W values were obtained as shown in Table 3.

It is possible to accept hypothesis  $H_0$  only for (subsuperficial) soils P06, P10 and P54. This is explained by the fact that in these cases calculated p was greater than 5%. Figures 3, 4, 5, 6, 7, and 8 show the graphs for normal distribution fits and the variability of the measurements.

The Boxplot graphs show the concentration and trend of the results close to the lowest values, because the rectangle limited by the upper and lower quartiles is located closed to the minimum value, highlighting the asymmetry and therefore differing from what would be a normal distribution.

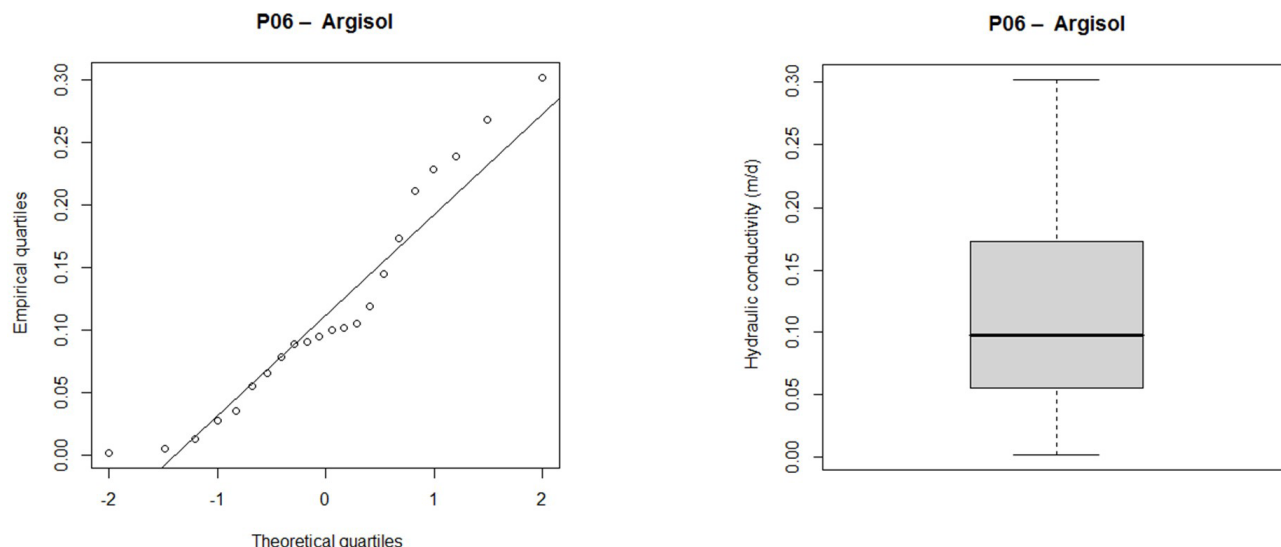
In Figures 3, 4 and 5, the confidence intervals for the medians overlap, indicating that the differences are not statistically significant.

It is observed in Figures 7 and 8 an amount of anomalous values for samples collected at depths up to 20 cm. This can be explained by the higher density of roots and biotic activity closer to the surface, resulting in a higher quantity of macropores and fissures, influencing the measurements of  $K_{sat}$ . For samples collected at depths between 20 and 40 cm, the distribution of  $K_{sat}$  values is more homogeneous. According to Cadima, Libardi and Reichardt (1980), soils are more homogeneous in deeper layers, consequently reducing the spatial variability, making it possible to obtain representative mean values from a normal distribution.

The graphs relative to samples P06, P10, and P54 show that  $K_{sat}$  values fall on a straight line (Henry’s law), validating the Shapiro-Wilk test. Table 4 presents the statistical parameters for these normally-distributed soil types.

**Table 3** Results from the Shapiro-Wilk Test.

Soil type	Number of samples	Calculated W	Tabulated W	p
P06 (Argisol)	22	0.926	0.911	0.104
P10 (Cambisol)	34	0.983	0.933	0.872
P48 (Latosol)	28	0.871	0.924	0.003
P52 (Latosol)	29	0.801	0.926	0
P54 (Gleysol/sup.)	19	0.778	0.901	0
P54 (Gleysol/subsup.)	7	0.857	0.818	0.144



**Figure 3** Normal probability plots and Boxplot for variable  $K_{sat}$ .

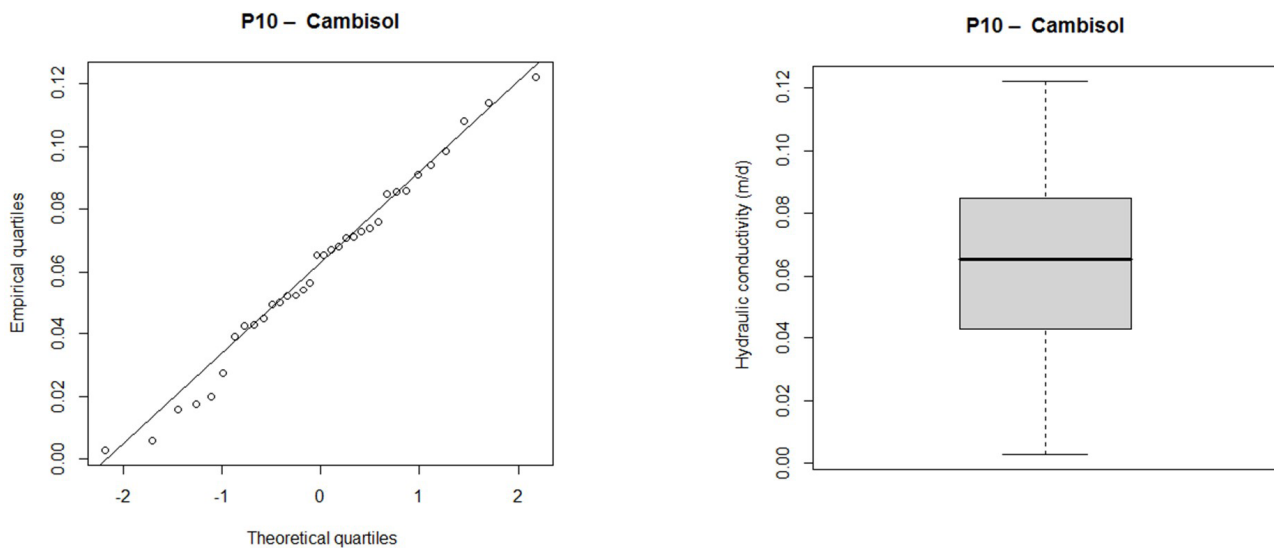


Figure 4 Normal probability plots and Boxplot for variable Ksat.

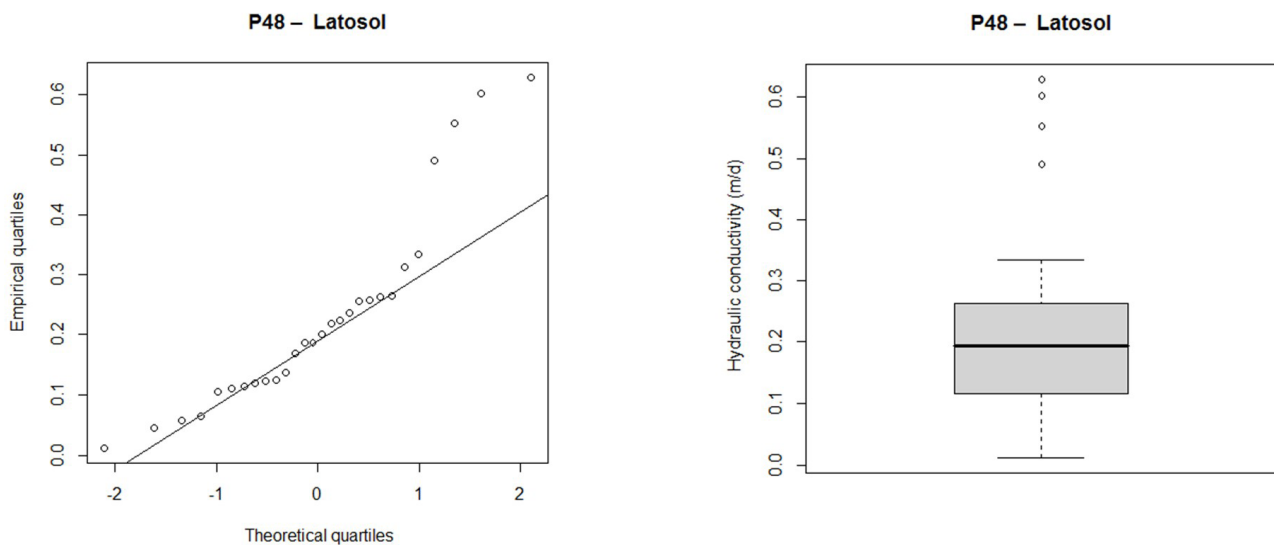


Figure 5 Normal probability plots and Boxplot for variable Ksat.

The Shapiro-Wilk test was applied to the non-normally distributed samples to check whether the distribution is log-normal. The natural logarithm was applied to all Ksat values, resulting in the parameters listed in Table 5.

Considering that  $p$  is  $>5\%$ , the soil samples define a log-normal distribution. Figure 9 shows that the data tend to plot on a straight line, after Ksat values are converted to natural logarithms.

The probability of occurrence was estimated, assuming a log-normal distribution of Ksat values, as shown in Table 6.

The values listed in Table 6 show that for Latosols samples P48 and P52 there is the probability of 85.72% and 96.55%, respectively, to obtain Ksat values in the interval of  $0.1 \times 10^{-1}$  m/d and  $4 \times 10^{-1}$  m/d. For Gleysol samples P54, Ksat values fall in the  $1 \times 10^{-2}$  m/d to  $80 \times 10^{-2}$  m/d interval.

Several studies consider Ksat constant, assumed to be the arithmetic mean of a normal distribution of Ksat values. However, Ksat usually differs from the mean, showing that mean values do not always represent the actual permeability of the soil.



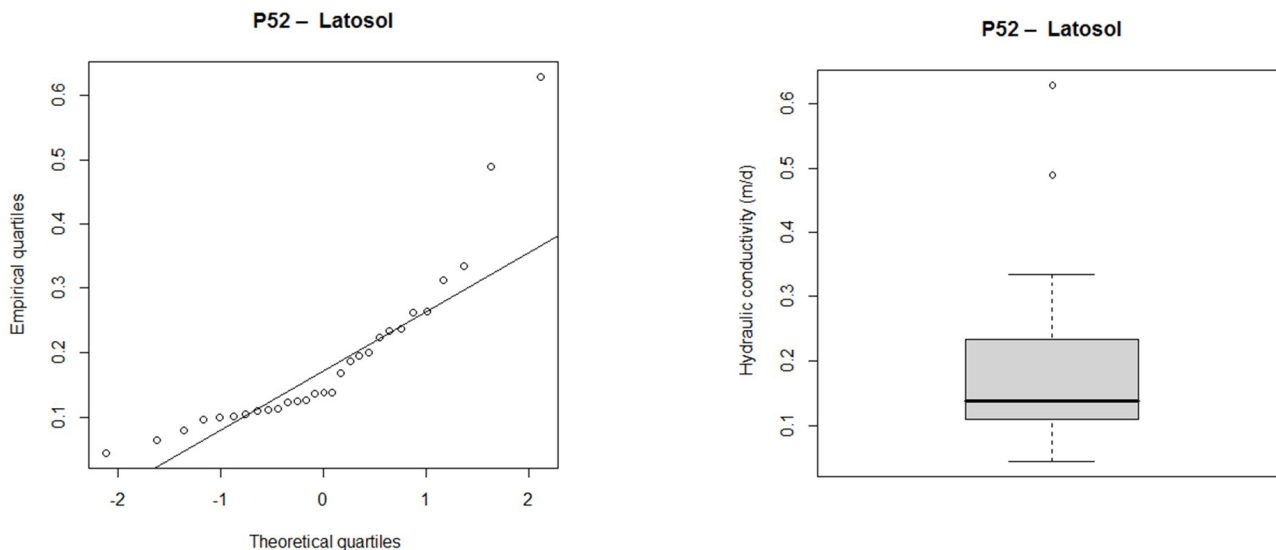


Figure 6 Normal probability plots and Boxplot for variable Ksat.

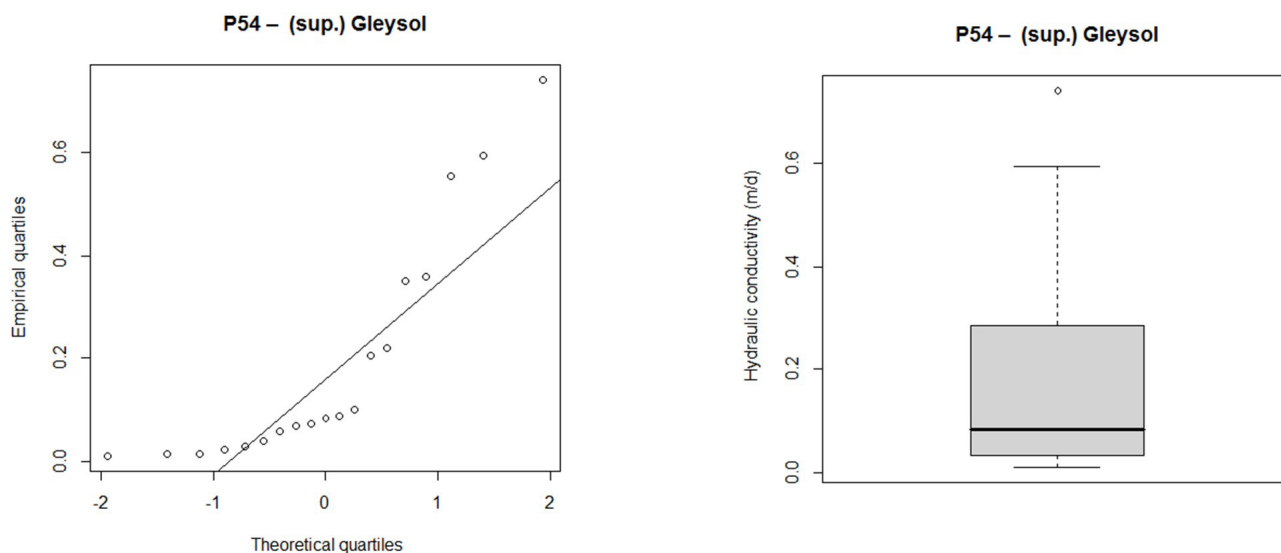


Figure 7 Normal probability plots and Boxplot for variable Ksat.

### 3.1 Relationship between Ksat and Groundwater

Groundwater storage and circulation in rock formations underlying the soil types of the study area can be correlated to them, mainly when it comes to well production.

According to Pessoa (2005), the calcareous rocks of the study area have developed a secondary porosity and constitute the main aquifer of the region, as groundwater flow takes place preferentially along the intersections

between foliation planes, lithological contacts, and fractures. The Sete Lagoas Formation encompasses free karstic-fissural aquifers limited at the base by impervious gneissic rocks of the crystalline basement (Auler 1994).

Groundwater flows inside dissolved karstic features of the Lagoa Santa Member, thanks to its purer calcitic mineralogical composition. However, in the Pedro Leopoldo Member, consisting of an assemblage of carbonate minerals with siliciclastic contribution, groundwater flows through brittle structures (Auler 1994; Silva, Moreira & Auler 1987).

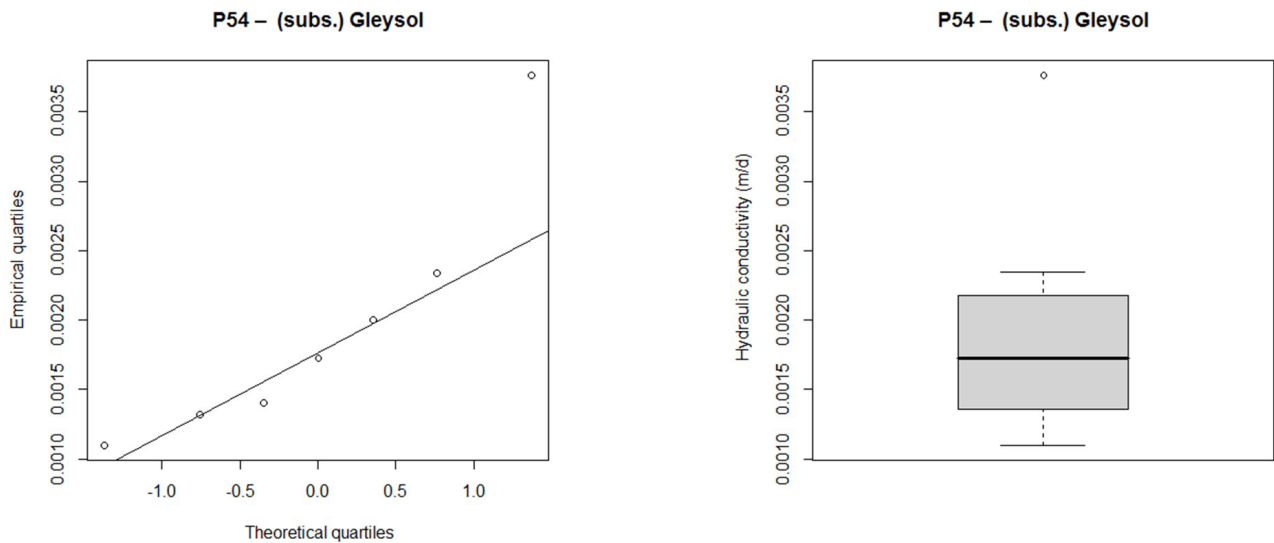


Figure 8 Normal probability plots and Boxplot for variable Ksat.

Table 4 Statistical summary for samples P06, P10, and P54.

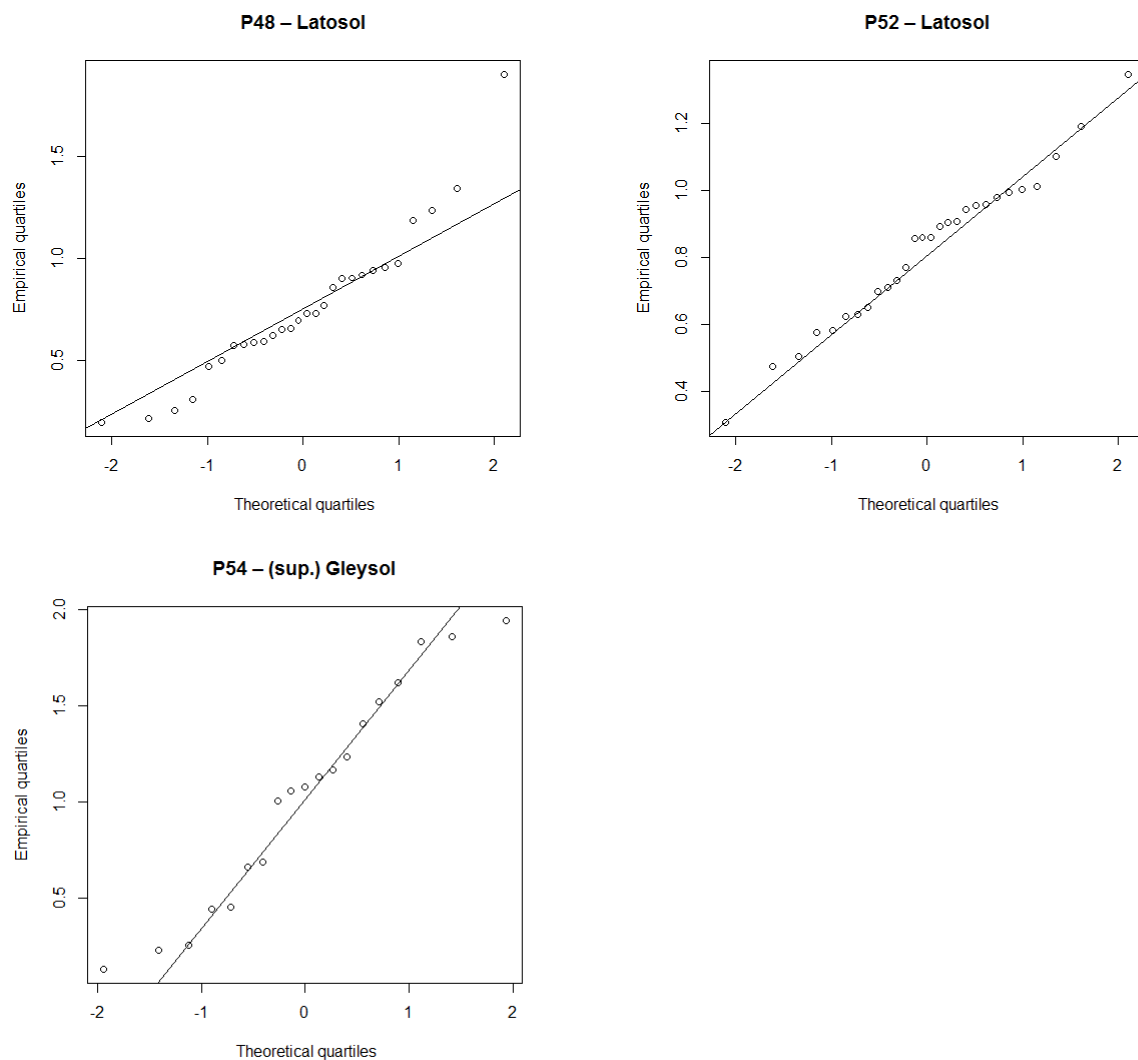
Parameter	P06 (m/d)	P10 (m/d)	P54 (subsup.) (m/d)
Mean	1.16E-01	6.14E-02	1.95E-03
Median	9.73E-02	6.52E-02	1.72E-03
Minimum	1.65E-03	2.93E-02	1.10E-03
Maximum	3.02E-0.	1.22E-02	3.76E-03

Table 5 Results obtained from the Shapiro-Wilk test for a significance level of 5%.

Soil type	Number of samples	Calculated W	Tabulated W	p
P48 (Latosol)	28	0.931	0.924	0.066
P52 (Latosol)	29	0.984	0.926	0.935
P54 (Gleysol-sub.)	19	0.949	0.901	0.396

According to Viana, Kohler and Tavares (1998), specific capacity values of tubular wells located in the Lagoa Santa Formation and Pedro Leopoldo Member are 14.42 m<sup>3</sup>/h/m and 2.78 m<sup>3</sup>/h/m, respectively.

The permeability of the underlying Serra de Santa Helena Formation, composed of metapelites, is low, configuring an aquiclude. Tubular wells tested by por Viana et al. (1998) yielded specific capacity values lower than 2.78 m<sup>3</sup>/h/m.



**Figure 9** Normal probability plots, after converting Ksat values to natural logarithms.

## 4 Conclusions

Saturated hydraulic conductivity can vary in the same area. Ksat values are not normally distributed, and therefore the mean Ksat value cannot always be considered the best representation of such parameter.

For the application of management techniques or even for a detailed study of aquifer vulnerability, it is suggested that the analysis of the probability of occurrence be performed for non-normally distributed soils. The

hypothesis tests made in this study proved to be an important tool for the coherent description of the samples.

A previous statistical analysis showed us that the Ksat frequency distributions are distinct, implying variability and the necessity of a varied number of samples in order to obtain reliable conclusions.

The assessed Ksat values revealed a varied probabilistic distribution, resulting in a ample total range and high variation coefficients, attesting the Ksat spatial variation in the study area.

Table 6 Probability of occurrence.

Latosol (P48)		Latosol (P52)		(Sup.) Gleysol P54	
Interval (10 <sup>-1</sup> m.d <sup>-1</sup> )	Probability	Interval (10 <sup>-1</sup> m.d <sup>-1</sup> )	Probability	Interval (10 <sup>-2</sup> m.d <sup>-1</sup> )	Probability
[0.1-1]	14.29%	[0.1-1]	20.00%	[1-2]	15.79%
[1-2]	39.29%	[1-2]	50.00%	[2-4]	15.79%
[2-3]	25.00%	[2-3]	16.66%	[4-6]	5.26%
[3-4]	7.14%	[3-4]	6.66%	[6-8]	10.53%
[4-5]	3.57%	[4-5]	3.34%	[8-10]	15.79%
[5-6]	3.57%	[5-6]	0	[10-50]	21.05%
[6-7]	7.14%	[6-7]	3.34%	[50-80]	15.79%

Researchers and managers should analyze the risks of estimating parameters that dependent on Ksat and values to be adopted for the soil properties, before taking decisions on the management of water resources at a hydrographic basin scale.

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**Emerson Vinicius Valadares:** methodology; validation; formal analysis. **José Augusto Costa Gonçalves:** conceptualization; writing-original draft; writing-review and editing; visualization. **Marina Souza Matos:** methodology; validation; formal analysis. **Peter Marshall Fleming:** methodology; validation; supervision.

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