

Communication

Saturated Hydraulic Conductivity Measurements in a Loam Soil Covered by Native Vegetation: Spatial and Temporal Variability in the Upper Soil Layer

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Abstract: Saturated hydraulic conductivity (K_s) of soil, especially of the upper soil layer, is a basic parameter for modeling water infiltration and solute transport in the soil. In the present study, spatial and temporal variability of K_s in the upper soil layer of a loam soil, which was covered by native vegetation for 20 years and had not undergone any cultivation treatment, is investigated. Saturated hydraulic conductivity of 76 undisturbed soil samples, taken twice a year at the dry (37 soil samples) and rainy periods (39 soil samples), was measured using a constant head method. The study reveals that K_s values exhibit significant spatial variability over the two time periods of measurement and follow a lognormal distribution with a coefficient of variation greater than 70%. On the contrary, there was no statistically significant seasonal variability of K_s between summer (dry period) and winter (rainy period) sampling ($p > 0.05$), and, therefore, there was no significant temporal variability of K_s . The outcome of this study indicated that hydrological models have to include more process understanding in terms of natural variability.

Keywords: saturated hydraulic conductivity; spatial variability; temporal variability



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1. Introduction

Saturated hydraulic conductivity (K_s) expresses the soil's ability to transport water under saturated conditions and is a key parameter in water movement and solute transport models in soil. In addition, the K_s of the upper soil layer plays an important role in the distribution of rainwater infiltration and surface runoff [1].

Usually, in hydrological modeling, the value of K_s is considered constant. However, hydraulic conductivity depends on soil structure, which could vary in both space and time. Any change in the surface soil layer caused by natural factors, such as rainfall, growth and decay of plant roots, shrinking and swelling, or human interventions, such as cultivation treatments, wheel-traffic compaction, etc., can lead to changes in soil porosity. These changes can seriously affect hydraulic conductivity and consequently soil water storage. Especially, efforts to incorporate the temporal variability of soil hydraulic properties in modeling studies are quite rare [2,3].

The various cultivation treatments in the surface soil layer can significantly affect the pore size distribution with a direct effect on its hydraulic properties, mainly in a relatively small water pressure heads range close to saturation [4–8]. Many researchers have reported that the soil cultivation treatment leads to an increase in the hydraulic conductivity [9–11], while others reported that it leads to a decrease [5,12–14]. The type of cultivation treatment plays a crucial role in which trend will prevail in the soil.

For the determination of K_s in the field or the laboratory, various techniques and devices are used. Regardless of the measurement method, the value of K_s is representative

of the specific place and time at which the measurement was carried out. Saturated hydraulic conductivity measurements have been observed to change spatially following lognormal distribution [8,15–18]. However, the relationship between K_s and other soil properties, such as soil texture, soil bulk density, and organic matter, is not strong enough to permit accurate estimations of K_s [19].

With regard to the temporal variability of K_s , many researchers came to the conclusion that, in agricultural soils, K_s has a seasonal variation, meaning that it is expected to decrease as cultivation progresses and soil is compacted and pores are blocked [18,20,21].

Some of the research studies have investigated the seasonal behavior of K_s (temporal variability) based only on one-year measurements [17,18], assuming that K_s follows a constant circular pattern, where influencing factors may change periodically. However, when the measurements of K_s are taken for many years, a periodic behavior occurs only in certain cases [22,23], while more often, a clear and constant periodicity is absent [16,23,24].

Strudley et al. [25] studied 80 papers on the effects of several factors that affect the hydraulic properties of agricultural soils (e.g., cultivation, soil compaction, irrigation, soil texture, soil organic matter, residue management, climate, and topography) and concluded that a general rule cannot be applied, since studies results are too contradictory. Strudley et al. [25] proposed that the data collection should be strengthened in order to clarify spatial and temporal trends, and that seasonal/annual measurements should be performed to clarify short-term changes. In addition, he indicated that other secondary factors may affect K_s measurements. Among those secondary factors, there are some related to soil biological activity, which is relatively unexplored and could partly explain the observed temporal variability of K_s . Indeed, the growth of roots, the decomposition of dead roots, and the earthworms affect the networks of macro-pores, which can significantly change the K_s in space and time [26–28]. Finally, there are indications that soil biochemical activity due to bacteria, roots, and fungi can significantly affect the hydraulic behavior of soil [28–31].

While many studies have investigated the effect of different types of soil cultivation treatments on the spatial and temporal variability of K_s , the effect of various natural non-anthropogenic factors on K_s in the case of uncultivated agricultural soils has not been investigated in depth.

Fuentes et al. [24] found that K_s values in a natural prairie in the Palouse region of Washington State were much higher than those from soils that had undergone conventional tillage and no-tillage, and the temporal variability of K_s was pronounced. This phenomenon was attributed to the expansion of soil pores caused by wetter soil conditions.

Zhou et al. [32] examined four different land uses in four land series in the USA and found that in the case of woodland treatment, there was no obvious temporal change of K_s compared to the other three uses and attributed this situation to the absence of human intervention and existence of permanent vegetation.

Bormann and Klaassen [17] examined three land uses (grassland, crops, and forest) in two typical Northern German soil types: Podzol and Stagnosol, in relation to their hydraulic and hydrological properties. Among these properties was the saturated hydraulic conductivity. The seasonal variability of the soil hydrological characteristics was estimated using four sampling replications in 2006. The results showed that land use affects the K_s value, and significantly, spatial variability of K_s was observed. Regarding seasonal variability of K_s , this was not statistically significant at the 5% probability level but was significant at the 10% level in 50% of all cases.

From the abovementioned, it seems that the issue of temporal variability of K_s remains open, especially in the cases of agricultural soils covered by local native vegetation, which are met in farmlands left uncultivated.

In the present study, the spatial and temporal variability of K_s of the upper soil layer of a loam soil covered by native vegetation without any cultivation treatment is investigated. The saturated hydraulic conductivity measurements on undisturbed soil samples taken twice a year, during the dry and rainy periods (summer and winter), were conducted in the laboratory using a constant head method.

2. Materials and Methods

2.1. Study Area and Sampling

Experiments were conducted in the experimental field of the Laboratory of Agricultural Hydraulics of Agricultural University of Athens (Greece). The soil was flat and characterized as loam soil with soil texture: 38.8% sand, 39.5% silt, and 21.7% clay. The soil may be classified as a loam of the Typic xerofluvent [8].

During the experiments, the soil was covered by native vegetation. The species encountered were *Malva Sylvestris*, *Tribulus Terrestris*, *Galium Aparine*, *Sinapis Arvensis*, *Convolvulus arvensis*, *Lolium* spp. The soil had been left uncultivated without any treatment (irrigation, fertilization, plowing, cutting) for approximately 20 years, and native vegetation grew freely.

An experimental plot with sampling grid dimensions of 16×35 m, with 4×5 m, was established on the study field, and soil samples from the edges of sampling grids were taken.

Two samplings were performed, 1 during the dry season (summer) on 13 July 2015 and the other during the rainy season (winter) on 11 December 2015. Before sampling, plant residues on the soil surface were taken away. Soil cores of 5.6 cm diameter and 8 cm depth were received with a manual hammer-driven core sampler. Similar sample sizes are widely used for K_s measurement [33–35]. However, the small soil samples may not be representative of the soil examined. Jafari et al. [36] reported that larger sample diameters may provide more representative results by reducing edge effects, soil compaction, and deformation of soil structure. In total, 37 and 39 undisturbed soil samples were taken during the dry and rainy season, respectively.

The mean soil bulk density values during the dry and rainy period samplings were 1.11 g cm^{-3} and 1.16 g cm^{-3} , respectively, and soil porosity was $0.53 \text{ cm}^3 \text{ cm}^{-3}$.

In the following figure (Figure 1), the distribution of monthly precipitation during the sampling year is depicted. The data of precipitation height were recorded by a rain gauge established in the experimental field. As shown, the annual precipitation was 457.6 mm and approximately half of this (204.6 mm) was recorded between samplings (Figure 1).

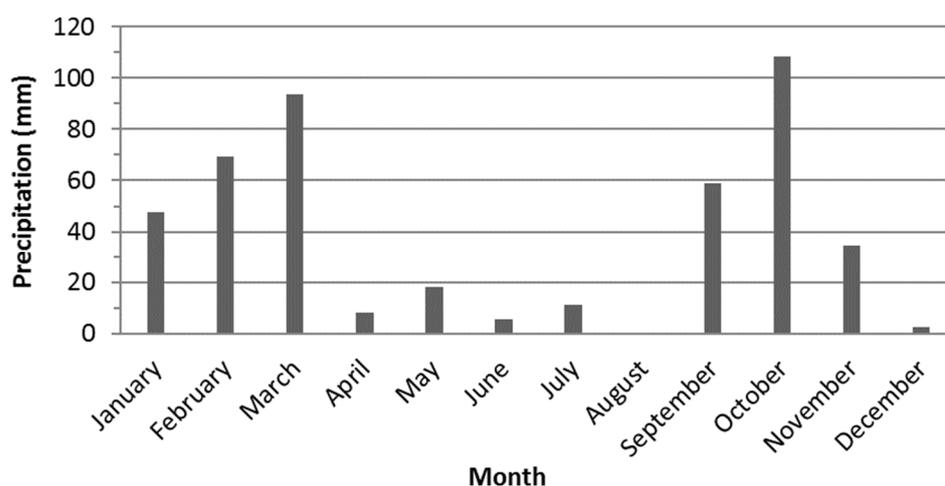


Figure 1. Distribution of monthly precipitation during the sampling year 2015.

The mean antecedent soil water content value during the sampling of the dry and rainy period was $0.02 \text{ cm}^3/\text{cm}^3$ and $0.137 \text{ cm}^3/\text{cm}^3$, respectively. The soil water content values were measured by a dielectric sensor ML2 [37].

2.2. Saturated Hydraulic Conductivity Determination Method

Saturated hydraulic conductivity measurements on undisturbed soil samples were conducted using a constant head method [38]. Before K_s measurement, soil cores were

prepared by saturating from the bottom with a degassed solution of 5 mM CaSO₄ for 48 h [24].

2.3. Statistical Analysis

In order to determine significant differences of K_s between the 2 samplings (at summer and winter) a paired *t*-test was performed. The Shapiro–Wilk *W* test was applied to determine whether measured values were normally distributed. In addition, the Coefficient of Variation (CV) was calculated for assessing the spatial variability of K_s . For all tests, the significance level was set at 0.05. Statistical analysis was performed using the statistical package Statgraphics Centourion (version 16.1).

3. Results and Discussion

The results of statistical analysis of experimental K_s values for the two sampling periods are presented in Table 1. The values of asymmetry, skewness, and kurtosis were used to determine whether the experimental values exhibited normal distributions. Specifically, if these statistical parameters were outside of the range -2 to $+2$, they indicate significant deviations from normality. As shown in Table 1, the skewness values for both dry and rainy period samplings were outside of the abovementioned normal range, while the kurtosis value was outside the normal range only in the case of the rainy period sampling.

Table 1. Statistical parameters of experimental values of saturated hydraulic conductivity (K_s) during the two sampling periods (dry and rainy).

Statistical Parameters	Dry Period	Rainy Period
Number of samples	37	39
Average (cm min ⁻¹)	1.70	1.68
Standard deviation(cm min ⁻¹)	1.22	1.31
Coefficient of variation (%)	72.15	77.65
Minimum value (cm min ⁻¹)	0.25	0.16
Maximum value (cm min ⁻¹)	5.59	5.75
Range (cm min ⁻¹)	5.34	5.59
Standardized skewness	3.08	4.02
Standardized kurtosis	1.78	3.22

In Figure 2, the density functions of dry and rainy period sampling are depicted, and it is clearly shown that they are not symmetrical because the data follow lognormal distributions. In addition, a normality distribution check was carried out using the Shapiro–Wilk *W* test ($p < 0.001$), which also confirmed that the spatial variability of K_s cannot be described by a normal distribution. Similar results have been observed by other researchers who studied the spatial variability of K_s in different cases of soils [39,40]. Then, the assessment of temporal variability was performed by applying the paired *t*-test using the log-transformed values of K_s . The results showed that the K_s values between the two sampling periods did not differ significantly ($p = 0.67$).

In Figures 3 and 4, the Box and Whisker plots of measured K_s values (Figure 3) and log-transformed K_s values (Figure 4) are presented. The red crosses are the average values, and the vertical blue lines within the rectangular shapes are the medians values. As shown, there were no statistically significant differences between the dry and rainy periods (summer and winter, respectively).

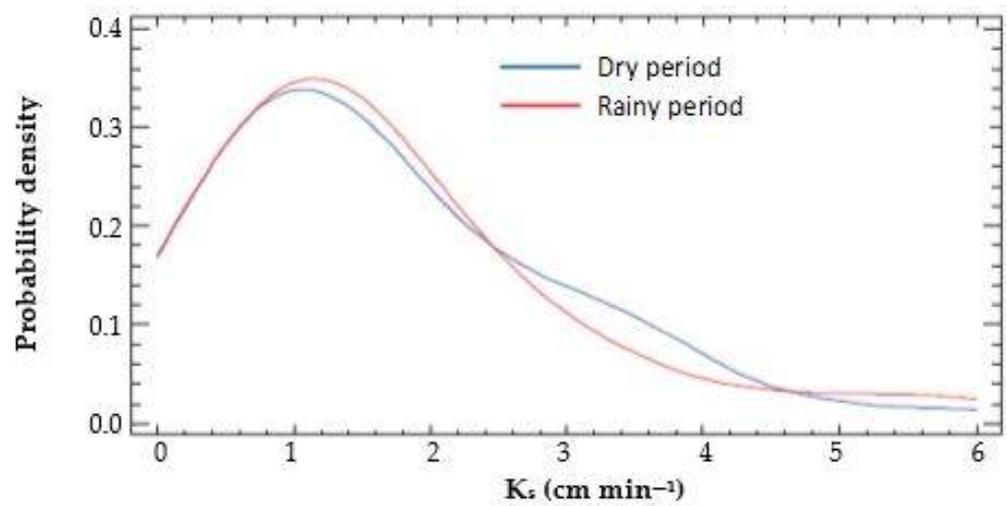


Figure 2. Probability density function of the saturated hydraulic conductivity measurements (K_s) during the dry and rainy period.

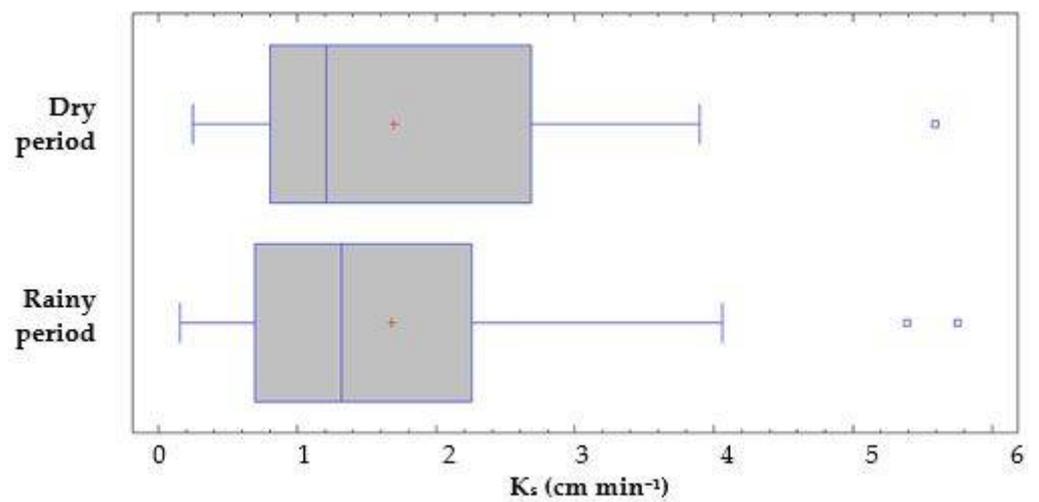


Figure 3. Box and Whisker plot of measured saturated hydraulic conductivity values (K_s) during the dry and rainy period. Values presented by the square symbol are outliers.

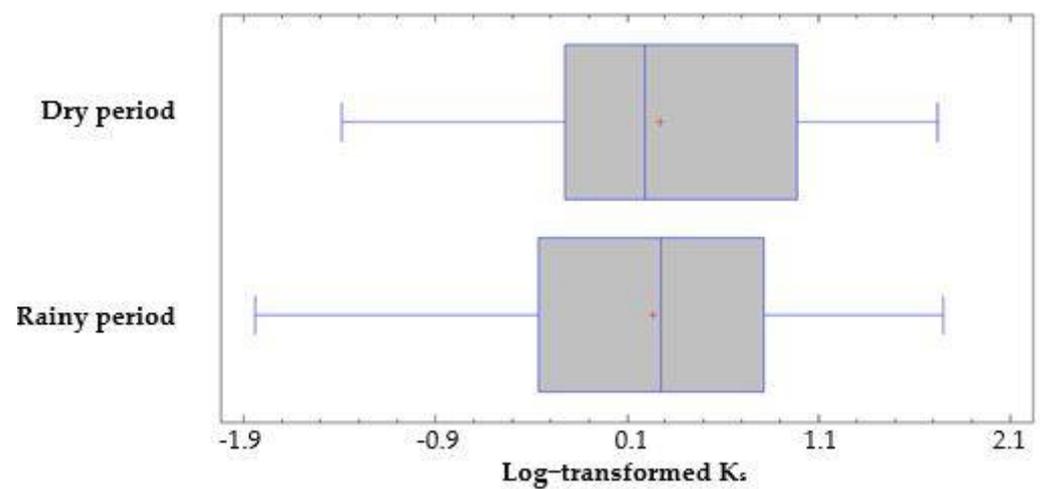


Figure 4. Box and Whisker plot of log-transformed saturated hydraulic conductivity values (K_s) during the dry and rainy period. K_s was measured in cm min^{-1} .

Overall, it appears that experimental K_s values showed high spatial variability in both dry and rainy periods with CV values of 72.15% and 77.65%, respectively, following lognormal distributions, while there was no significant temporal variability of K_s ($p > 0.05$). These CV values indicate a high spatial variability since they are greater than 50% [41,42].

From experiments carried out in both field, e.g., [17,32] and laboratory [39] in soils covered by native vegetation without any cultivation treatment, significant spatial variability of K_s has been recorded, regardless of the device and measurement method, and no significant temporal variability has been recorded in some case studies [32]. It is worth noting that in the case of forest land use, where there is no human intervention, and the soil is covered by the same vegetation almost all throughout the year, no significant temporal variability of K_s has been observed as opposed to other land uses in which there is human intervention [17,32]. The case of forest land use may be considered similar to the case of farmlands left uncultivated, as in our case study.

Probably, in the aforementioned case, the non-significant temporal variability of K_s could be attributed to the existence of permanent natural vegetation, which on the one hand, prevents the destruction of soil aggregates by heavy rainfall, and, on the other hand, its root system maintains a relatively stable macropore system. The root system of permanent natural vegetation may create some relatively stable sequences of macro-pores with high hydraulic conductivity, significantly affecting the soil permeability and "hiding" any temporal variability of small and medium soil pores. The temporal variability of soil porosity in these cases can only be revealed when the unsaturated hydraulic conductivity is measured. We acknowledge that we conducted only two experimental tests, which may not completely represent the dynamic soil hydraulic properties in these two periods. For safer conclusions, the study should be extended over a longer time period and conducted several times within a year. It is also necessary to study cases with other types of natural vegetation, which creates another type of root system.

4. Conclusions

The spatial and temporal variability of saturated hydraulic conductivity of the upper soil layer of a loam soil of 560 m², covered by native vegetation without any cultivation treatment, was investigated.

Statistical analysis of the experimental K_s values measured using a constant head method in undisturbed soil samples taken during the dry and rainy periods showed a high spatial variability of K_s in both sampling periods since the coefficient of variation (CV) was greater than 70%, while there was no significant temporal variability ($p > 0.05$).

Overall, it can be said that in the case of soils covered by natural vegetation without any cultivation treatment and human intervention, the role of both the shoots and the root system of vegetation is crucial in the variability of soil hydraulic conductivity. Thus, it is important to investigate further the interactions between natural soil vegetation and the soil hydraulic properties.

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