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A Statistical Approach for the Assessment of Saturated Hydraulic Conductivity Values of Unsaturated Urban Soils Obtained by Field Infiltration Tests

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Abstract: An evaluation and interpretation of the obtained results focusing the hydraulic conductivity of anthropogenic saturated soil, k, has been performed on an urban area vadose zone. Four methods have been used to quantify the hydraulic conductivity: the tube infiltrometer (TI), the double ring infiltrometer (DRI), the minidisk infiltrometer (MDI) and the inversed auger (IA). This study comprises (a) a comparative analysis of the results obtained by each method between several trials performed at the same location and at distinct locations within the plot, (b) a comparative analysis of the results of all methods, and (c) a statistical analysis regarding the correlation between k as a dependent variable and the infiltration area A as the main independent variable. To select the k values close or corresponding to the saturation state for TI and IA methods, a domain of validity was defined. A new parameter, $k^* = k/A$, was introduced which represents the hydraulic conductivity corresponding to an infiltration surface unit (1 cm^2). An increase in this ratio with the increase in the infiltration area, within the same method or between different methods, indicates the heterogeneity of the terrain but especially the fact that the infiltration area no longer represents the main independent variable on which the hydraulic conductivity depends for the saturated state.

Keywords: urban soil; vadose zone; hydraulic conductivity; infiltration area; hydraulic conductivity assessment methods

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1. Introduction

Studies of city-scale urban aquifer water dynamics should be based on accurate urban groundwater balance analysis including natural and human-induced water sources, geological and anthropogenic strata, and the entire set of the urban infrastructure elements. Since the knowledge of deposits located in the shallow urban subsurface is increasingly important for urban planning [1], there is a need for better classification of anthropogenic materials and their hydraulic conductivity. To date, there are very few published hydraulic studies on anthropogenic strata in cities, and most of them are of a pioneering nature. Previous studies developing city-scale urban hydrogeological models [2–5] demonstrated the necessity of correctly quantifying the anthropogenic strata hydraulic conductivity to properly assess aquifer dynamics as well as groundwater recharge from precipitation.

Techniques to quantify accurately the saturated hydraulic conductivity k (LT^{-1}) have yet to be developed [6]. Several studies have highlighted the spatial variability of the saturated hydraulic conductivity in soil characterized by uniform texture, even when applying a single test method. This is due to numerous and variable factors, not all of which are detectable (preferential flow, cracks, roots, structure, and others). When different techniques with different theoretical bases are considered, the topic becomes still more complex, even in homogeneous soil.

Comparative studies show the differences both between the saturated k values achieved when applying the same method while modifying the measurement device infiltration area for the same lithological unit of natural ground, and between k values obtained when applying distinct methods (using different infiltration areas corresponding to the testing device) on the same natural ground [7,8]. Some authors [9,10], applying the DRI method on natural undisturbed ground, obtained insignificant differences between the values of hydraulic conductivity when varying the infiltration area, but the values for increased infiltration area showed an appreciable decrease in the standard deviation.

Other studies [11] show differences of about one order of magnitude between the saturated k values obtained when applying the DRI and the tension disk infiltrometer (TDI) methods on clay. Also, large differences have been obtained when applying the TI and the TDI methods in situ, as well as when laboratory tests are performed [12]. The differences between the results obtained by applying TI and TDI arise mainly due to the water volume able to pass through the macroporous medium. This is much greater in the case of TI, where the water moves vertically, than for TDI, where there is also a horizontal component.

Other authors show that the differences in the estimation of the k value are due to TDI membrane's resistance when it is crossed by air bubbles due to the water flow geometry [13,14], or even due to the spontaneous development of plant roots (grass) during the test run [15]. Very small differences between the k values obtained by TI and IA tests on clayey soils without microstratification were highlighted by van Hoorn [16]. Bagarello et al. [17] highlighted that by using the TI method on sandy silty soils, more accurate results could be obtained than on clayey soils. Most authors point out that some methods applied on so called "homogeneous" natural lands overestimate and others underestimate the hydraulic conductivity value, the process of water infiltration into unsaturated zone being extremely complex. It depends on a multitude of factors such as the presence of macropores (due to the structure and texture of the terrain, plant roots, etc.), terrain heterogeneity, the requirements for preparation and completion of the test, the differences between the algorithms of the methods, the predominant lithological nature of the terrain, and last, but not least, the experience of the operator and of the analyst.

Through time, substantial changes occur in the composition, structure, and texture of the soil, especially in urban areas as a result of the anthropogenic activity. Urban soil is defined as non-agricultural material resulting from anthropogenic activities and emerges through the processes of filling, extraction, and contamination of the natural surface with a minimum thickness of 50 cm [18] or as material that was modified, altered, and transported by human activities in the urban environment [19].

Urban soils are highly heterogeneous and may consist of mixtures of demolition materials, household waste, slag, allochthonous material, and others. These can be captured in an allochthonous or in a native matrix. In relation to the "homogeneity" or "quasi-homogeneity" of the natural terrain, two main groups of urban soils can be distinguished: (a) urban soil made of lithological homogeneous material, for example, allochthonous clayey material coming from a well-defined lithological sequence and used to fill a negative morphological surface; and (b) urban soil consisting of lithological mixtures (e.g., sand, gravel, clay) with materials originating from demolitions and other sources.

In the first group, the urban soil can be considered as a "homogeneous" layer, but different from the native terrain. Even if, from the lithological point of view, its characteristics could be similar, there are differences of porosity, compaction, mechanical properties, and other attributes. These differences can occur both vertically and horizontally, depending on the anthropogenic activity the soil has been exposed to. In this situation, the assessment of the saturated hydraulic conductivity k of the vadose zone can be conducted by methods also used for natural soils; however, the use of the data must take into consideration the allochthonous nature of this strata as well as the lithological nature of the indigenous substrata which may have distinct hydraulic properties. Thus, field tests performed on natural and compacted loess showed that the hydraulic conductivity was reduced by 1–2 orders of magnitude, leading to a low rate of water infiltration [20]. At a small scale, laboratory studies have identified useful methods for simulating water hydrodynamics in the vadose zone for layered soils [21].

In the second group, the lack of homogeneity of urban soil is obvious and no similarity is expected between the results obtained by applying several methods of determining saturated hydraulic conductivity of the vadose zone. The determination of the hydraulic conductivity using usual methods can lead to very dissimilar values, even when using the same method. This is due to the fact that each method provides point-based information. Consequently, interpretation and validation of any results are critical.

Especially for "homogeneous" soils, by using test devices with large infiltration area, values of hydraulic conductivity are obtained for the saturated state much closer to a supposed real value. From a theoretical point of view, in the case of group (b) soils, the best way to determine the hydraulic conductivity for the saturated state would be the flooding of the entire surface, which is completely impractical. The only possibility is to perform tests on distinct points. However, the urban soil being heterogeneous over relatively short distances, the values obtained may differ considerably for the same test method but also between different methods. In this situation, the following questions can be asked: (1) How can the achievement of the saturation or incipient saturation state be judged, for the tests which allow multiple infiltration runs in the same location as TI and IA methods and how can the selection of the results be made corresponding to this state? (2) If, for a relatively small representative elementary volume (REV) comprising two very close test locations where methods with distinct infiltration surfaces are applied, the amplitude of the selected values is smaller for the device with a smaller infiltration area, does this mean that these values better characterize the tested environment? (3) If the hydraulic conductivity for the saturated state is an intrinsic value that characterizes the type of urban soil (heterogeneous) in the test point and it is dependent on the infiltration area, then what is the influence of other factors on the results? (4) Is it possible to obtain a characteristic value of the saturated hydraulic conductivity for a heterogeneous anthropogenic terrain?

In order to obtain the saturation state for homogeneous soils, either the soil in the location of the test device has to be saturated for a time, which may depend on the initial saturation of the material, or more trials have to be performed. When the values for consecutive attempts of estimation of k are sufficiently similar, it can be considered that the saturated state has been reached. In fact, using an infiltration technique in an initially unsaturated soil under ponding conditions, the field saturated soil hydraulic conductivity is obtained due to entrapped air bubbles. Císlerová et al. [22] highlighted that, at higher moisture content, the air entrapment in large pores sealed off by water films will increase drastically and the saturated hydraulic conductivity will accordingly decrease. According with Sakaguchi et al. [23], the saturated hydraulic conductivity measured on a soil that contains entrapped air can be smaller than the unsaturated hydraulic conductivity close to saturation. On the other hand, repeating the same experiment many times at the same point can induce weakening of the particle bonds and migration of small particles [24], leading to the change of hydraulic conductivity. Therefore, air entrapment in the soil is a complex phenomenon that can have effects on "saturated soil hydraulic conductivity" obtained by field test methods, this term being often used for practical purposes instead of field saturated hydraulic conductivity, which is more or less close to the real state of the soil saturation. As will be seen in the following sections, in the case of urban soil, there are often large differences between the values of hydraulic conductivity obtained after consecutive trials in the same location for TI and IA methods. In this sense, a domain of validity of the saturated hydraulic conductivity values has been defined, within which are included the values selected for the calculation of the average value of the hydraulic conductivity when these are close to or reaching the saturation state.

In a homogeneous and isotropic ideal soil, the value of the hydraulic conductivity for the saturated state k, determined by any method, would be the same in any location and the amplitude between observed values would be $A_{pl} = 0$. If two or more distinct test methods are applied, using the same or different infiltration areas A, theoretically, $k_1 \neq k_2 \neq \ldots \neq k_i$ should be obtained (i represents the test method number) and $A_{pl} > 0$. Differences could appear due only to the specific calculation algorithm and/or operator error, and the infiltration area has no influence. In reality, the soil is not homogeneous, the homogeneity representing an idealization and a simplification of the analyzed REV. And so, as we highlighted before, the infiltration area represents an independent variable which can influence *k* values because this surface can comprise other influencing factors (soil heterogeneity, cracks, roots, etc.) that may or may not be dominant. If the same test method uses distinct infiltration areas, then the differences between the *k* values, obtained as a dependent variable, will also include the influence of the area variation as an independent variable and the amplitude $A_{pl} > 0$ between saturated *k* values. Also, between the distinct applied methods, the amplitude will be $A_{pl} > 0$ and will contain the influences induced by the operator, calculation algorithm, and the size of the infiltration area.

From the statistical point of view, selecting values with the lowest amplitudes better characterizes the study environment. If the infiltration area changes for different locations when applying the same or distinct methods, the occurrence of extreme values with relatively low frequency can have a disproportionate effect on the amplitude of the selection and consequently lead to a misinterpretation of the value of the dependent variable [25], and comparing only the *k* values, this aspect cannot be highlighted. To minimize this effect, in order to compare results obtained by different test methods, we have defined a new variable, $k^* = k/A$, which represents the saturated hydraulic conductivity corresponding to a unit infiltration surface (equal to 1 cm^2). We assumed this unitary surface to be homogeneous. Therefore, with the increase in the infiltration area, the value of the *k/A* ratio must decrease (hypothesis "0"). The values of the amplitudes determined for the variable k^* better describes the results obtained by the test method, and the infiltration area is the main variable which controls the *k* values. In reality, there are other variables, especially at the surface of the soil, which can influence the *k* values: cracks, roots, and others. In urban soils, in addition to the heterogeneity, undetected underground cavities may also be present. If the *k/A* ratio between the methods increases with an increase in the infiltration area (hypothesis "1"), then other variables have a decisive influence on the *k* value (either as single or cumulative variables). A statistical analysis has been also made for the results obtained from different methods to test whether the infiltration area of the frequently used test devices can be considered the main independent variable, which controls the value of saturated hydraulic conductivity. This should help to determine the cumulative weight of other independent variables, having an influence on the dependent variables *k* and k^*, and establish the significance of the *k/A* ratio.

Answers to questions (1) to (4) are provided by this study through (a) a comparative analysis of the results obtained by each method between several trials performed at the same location and at distinct locations within the same plot and defining the domain of validity and selection of saturated *k* values in the field for TI and IA methods, (b) a comparative analysis of the results obtained by used methods, and (c) a stochastic analysis regarding the correlation between the anthropogenic soil hydraulic conductivity in the saturated state *k* as a dependent variable and the infiltration area *A* as the main independent variable using a qualitative interpretation based on *k/A* ratio significance.

In urban areas with a wide spread of anthropogenic soil, a correct determination of the hydraulic conductivity corresponding to the saturated state of this type of material has multiple applications, such as optimization of the urban drainage systems, analysis of the hydraulic interaction between urban infrastructure elements and green spaces, optimal installation of green infrastructure, and many others. The correct quantification of the water recharge from liquid or solid rainfall (snow), required for urban hydrological and hydrogeological studies, is still a challenge.

2. Materials and Methods

Four methods were used to assess the saturated hydraulic conductivity of the vadose zone of urban soil: the tube infiltrometer method (TI), the double ring infiltrometer method (DRI), the minidisk infiltration method (MDI), and the inversed auger method (IA). The water infiltration through the soil, for the first three methods, takes place only through the area corresponding to the base of the test device. For the IA method, the infiltration occurs both through the area corresponding to the base of the drilling hole as well as through its lateral surface. A comparative analysis of the results was undertaken for the all four methods. The first three (TI, DRI, and MDI) have been separately compared with the IA method, which tested the soil at depths of 30, 60, and 90 cm in order to highlight the possible influence of the surface factors. The details of the devices are shown in Figure 1. The tests were carried out on the same site (urban unsaturated soil) in similar weather conditions during a drought period.

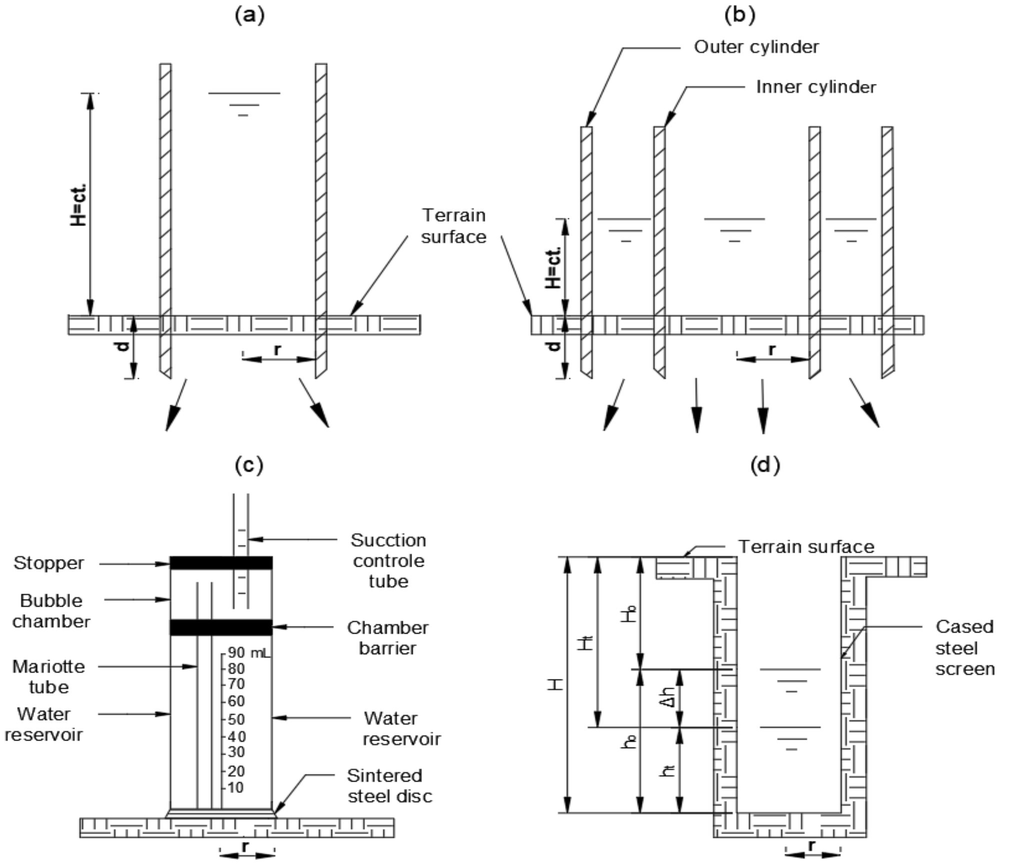

Figure 1. The schemes of the test devices. (**a**) tube infiltrometer, TI: $H = ct.$—poured water column height, d—soil penetration depth, r—infiltration radius; (**b**) double ring infiltrometer, DRI: $H = ct.$—poured water height; (**c**) minidisk infiltrometer, MDI; (**d**) Inversed auger, IA: H-borehole depth, H_o—poured water level depth, H_t—water level depth at time t, h_o—water column height at time $t = 0$, Δh—drawdown between step time t_i and t_{i+1}, h_t—water column height at time t_{i+1}.

2.1. Tube Infiltrometer/Single Ring Infiltrometer Method (TI)

The device consists of a metal ring or a cylinder with a wall thickness of less than 5 mm, sharpened at the bottom to penetrate the unsaturated ground, at a depth d (Figure 1a). When water is poured into the tube, a hydraulic load H is created and maintained constant throughout the duration of the test by means of a reservoir, in which the volume of water is equal to the volume of water poured into the infiltrometer. Then, the water level in the reservoir is measured for certain time steps and the cumulative infiltration I (L) and the infiltration rate $I = dI/dt$ (LT^{-1}) are determined and used to compute the saturated hydraulic conductivity k (LT^{-1}) using the following relation [26,27]:

$$I = A_w \cdot t + B_w \cdot \sqrt{t} \quad (1)$$

where t (T) is time, and A_w (LT^{-1}) and B_w ($LT^{-0.5}$) are coefficients related, respectively, to the hydraulic conductivity and sorptivity. Assuming that, in the last part of the infiltration process, a stationary regime is reached, then $I = A_w \cdot t + c = k \cdot a' \cdot f \cdot t + c$, where A_w represents the slope of the straight line and c the intersection with the y axis, k (LT^{-1}) is the hydraulic conductivity, $a' = 0.9084$ is a constant, and f is a correction factor depending on soil texture α^* [28,29], hydraulic head H (L), and the ring geometry as in Figure 1a.

2.2. Double Ring Infiltrometer Method (DRI)

The infiltrometer is made up of two cylinders, open at both ends, concentrically placed on the surface of the ground: an inner and an outer ring (Figure 1b) which have to penetrate the terrain surface at a recommended depth of $d = 0.05 \ldots 0.10$ m [30]. The test consists of achieving a constant H (L) water level in both cylinders and recording water volumes added at certain time steps to determine the cumulative infiltration I (L) and infiltration velocity, $v = dI/dt$ (LT^{-1}) where t (T) is the time. The saturated state hydraulic conductivity k is calculated using Philip's equation [31,32]:

$$I_{(t)} = S \cdot t^{0.5} + A \cdot t \quad (2)$$

where S ($LT^{-1/2}$) represents the sorptivity and A (LT^{-1}) is a constant that represents the influence of the gravitational component at saturation, $A = m \cdot k$ and $m = 2/3 = ct.$ [33]. Using field data, two graphs are built: $I = f(t)$ and $v = f(t)$.

2.3. Minidisk Infiltrometer Method (MDI)

The infiltrometer is designed to measure the hydraulic conductivity of unsaturated ground at suction values ranging from −0.5 to −7 cm. It is composed of two chambers that are filled with water (Figure 1c). The bubble chamber controls the value of the suction. The water used for the infiltration test is stored in the "water reservoir". At the bottom of the tank, there is a sintered steel disc with a thickness of 0.3 cm and a radius r = 2.25 cm, the total volume of the tank being V = 135 mL. Adjusting the suction (negative pressure) in the upper chamber prevents the water infiltration through macropores such as cracks, wormholes, and others. The infiltration of water through the soil is determined by the hydraulic forces that characterize the soil matrix. The hydraulic conductivity is dependent on pore geometry, soil water content, and capillary effect [34]. The value of hydraulic conductivity for the saturated state is obtained when all pores (including macropores) are full of water and the water flows. Even for close locations, quantification of the water flow through macropores can be challenging. Application of suction prevents the filling of macropores, and the results obtained by this method provide the hydraulic conductivity for the saturated state that characterizes the clay matrix. In this way, we can compare the values obtained for saturated k by applying the other methods (for REV corresponding to each location), which also include the effect of macropores or cracks, with the values obtained only for the clay matrix. In this sense, given the very small infiltration area of the device, the MDI locations chosen has no visible cracks or traces of vegetation, and at the start of tests, it was assumed that the presence of wormholes or underground roots was excluded.

For the calculation of the hydraulic conductivity coefficient, the pairs of values obtained during the test of cumulative infiltration I (L) and time t (T) are required, adjusted with the following relation [35]:

$$I = C_1 \cdot t + C_2 \cdot \sqrt{t} \quad (3)$$

where C_2 ($LT^{-1/2}$) is a sorption-related parameter, C_1 (LT^{-1}) is related to the hydraulic conductivity parameter $C_1 = k \cdot A$, and represents the gradient of the cumulative infiltration curve vs. the square root of time; A is a value that depends on van Genuchten parameters (n and α) corresponding to a particular texture of the soil, ray of infiltration disk, and the suction at the disk surface which were determined for 12 soil texture classes [36]. Starting from these values, the parameters are calculated for the minidisk infiltrometer, with a radius of 2.25 cm and suction between 0.5 and 7 cm, by the manufacturer, Decagon Devices, Inc., Plullman, WA, USA [37].

2.4. Inversed Auger Method (IA)

The method consists of drilling a hole at a given depth cased with a steel screen with the same diameter, filling it with water, and measuring the change of the water level at certain time intervals (Figure 1d). The saturated k value is given by the following equation [16]:

$$k = \frac{\log\left(h_o + \frac{r}{2}\right) - \log\left(h_t + \frac{r}{2}\right)}{t} = 1.15 \cdot r \cdot \tan(\alpha) \tag{4}$$

where t is time and other variables are as given in Figure 1d.

2.5. The Urban Area Experimental Site and Measurements Set Up

The test site area was an artificial green area located in Bucharest, Romania. This zone was initially a depression which, about 30 years ago, was filled with material about 1 m thick. Buildings and green areas have since been established. The lithological structure of the site is derived from an investigation borehole located at about 30 m NE of the test perimeter (Figure 2a). Anthropogenic material with a thickness of about 1 m, located near the ground surface, overlays a silty clay stratum. A slightly confined shallow sandy aquifer strata, with a depth of the piezometric level of 3.56 m, is located under the clayey layer.

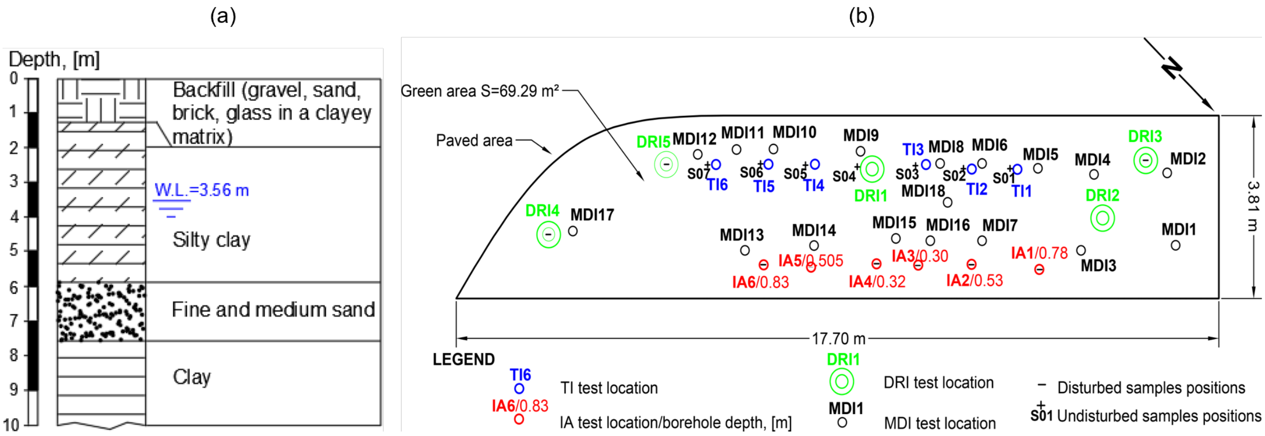

Figure 2. The experimental site: (**a**) the lithological column; (**b**) the distribution of the test locations and the applied methods.

This test site was selected for the following reasons:

- The upper part of the ground is made up of urban soil;
- The area is partially covered by vegetation (trees and grass) and could be considered a human-made "green area";
- The ratio between the perimeter length and width is about 5:1 and the space between different test locations is small, as is shown in Figure 2b, leading to a relatively balanced compensation of the assessed values' variation due to the terrain heterogeneity, because smaller soil volumes are functionally more homogeneous than larger volumes [38];
- The area is not affected by pedestrian traffic and therefore has not been subjected to compaction or other actions. During the tests, only the operator's access, on established routes, was allowed.

2.5.1. Sampling and Laboratory Tests

In the vicinity of the DRI and TI test location (Figure 2b), samples of disturbed and undisturbed soil were collected down to depths of 20 cm. Also, disturbed samples, up to a depth of approximately 90 cm, were collected from the drill holes associated with the IA tests. Samples were collected after performing the infiltration tests to avoid terrain disturbance, with the exception of IA locations where samples were collected during the drilling works. Granulometric analyses were performed on all samples. On undisturbed samples, consistency indices, natural and dry density, porosity, and the degree of saturation were determined. Laboratory determinations revealed a filler material up to 0.90 m depth consisting of sand and gravel, brick debris, glass fragments, and roots, attached to a clayey matrix. The values of the indices and parameters determined in the laboratory, by groups of depth, are presented in Supplementary S1 as electronic Supplementary Material (ESM). The clayey matrix falls between the groups of medium- and high-plasticity ($10 < I_p < 20$), and in terms of consistency, it has a hard state ($0.5 < I_c < 0.75$). An exception is marked by the locations DRI 4/P01, that shows a plastic consistent state ($0.5 < I_c < 0.75$), and by DRI 5, that indicates a strong plastic state ($0.75 < I_c < 1$). The activity index I_A of the clay material, which characterizes the intensity of the water interaction with fine particles (clay fraction), is determined as a ratio between the plasticity index I_p and the percentage of particles smaller than 2 μm. This indicates a terrain with medium activity ($0.75 < I_A < 1.25$), values below 0.75 characterize a low active ground, and those over 1.25 a very active one.

2.5.2. Tube Infiltrometer Set Up

The tests were performed at six locations, as shown in Figure 2b, with the distances between locations varying between 1.1 and 2.5 m. In each location, several trials were carried out. Tubes with different heights and diameters were used. The maximum height of pouring water into the tubes H, the average of the hydraulic heads of the trials performed in each location H_{avg}, the soil penetration depth of the infiltrometer d, and the internal radius of the tube r (see Figure 1a) are given on ESM as Supplementary S2. The different number of trials within each test location is attributed to the different periods of time in which water infiltration occurred, all locations being tested over the same time period. The value of the constant α^* was chosen corresponding to the texture-structure category of the soil and is confirmed by the results of the granulometry tests.

At the same time, to reduce the influence of α^* variation on the values obtained for k, we used tubes with a height over 20 cm, as the influence of the chosen α^* on k decreases with the increase in the H value [39].

For the six tests, multiple trials for each location were performed for the following reasons: (a) the tests were carried out in all locations at the same time; (b) the relatively small diameter of the tubes and the heterogeneity of the soil led to the idea that it is quite unlikely to reach the saturated state of the soil (corresponding to the steady state) after a single attempt. This could happen, in the immediate vicinity of the surface, either due to high hydraulic conductivity, to the access paths being obstructing by the water-driven fine particles and subsequently transported by the water flow, or due to entrapped air; and (c) the physical effect of the soil–water interaction on time intervals can be better emphasized.

For each location, the following parameters were computed:

- The hydraulic conductivity k of each trial T_n (T-trial, n-number of trials in each test location), according to the hydraulic head corresponding to the water height, on the basis of the accumulated S (cumulative drawdown) records of the hydraulic head H_n at certain time intervals (registered in the water reservoir);
- The hydraulic conductivity k_{dcH} for each TI_i location using the average of the hydraulic heads (H_{avg}) measured for n trials at each location i and, where the cumulative infiltration calculation was used, the average of the absolute drawdowns S of the hydraulic head H_n recorded at that location for the same cumulative time values;
- The k_{avg} hydraulic conductivity as the average of the values determined on n trials at each location.

2.5.3. Double Ring Infiltrometer Set Up

Five DRI tests were performed. Rings of 28 and 53.2 cm diameter were placed in the field at a depth of 5 cm, the area of the inner tube base being S = 615.75 cm^2. The height of the water in both rings was H = 7 cm, corresponding to the position of the upper level marker.

The lower marker was positioned 1.6 cm below, this height difference corresponding to a volume of V = 1000 cm^3 of water, needed to be supplemented to maintain a constant level. The duration of the tests varied between 73 and 132 min. By maintaining the constant water level, a steady state flow regime was achieved when two successive additions of water showed no significant differences in volume.

2.5.4. Minidisk Infiltrometer Set Up

A total of 18 MDI tests were performed. The locations were chosen in the vicinity of the performed TI, DRI, and IA tests with a suction of −5 cm (drought conditions, relatively high content of sand and presence of macropores) and parameter A = 8.4.

2.5.5. Inversed Auger Method Set Up

The IA tests (depths between 0.30 and 0.83 m and with a diameter of 10 cm) were performed in six locations, away from the TI tests, on an alignment located at a distance of approximately 1.80 m from the TI test alignment. Because the ground is made up of fillings, stainless steel filters have been introduced in the holes to support them during the tests (avoiding the wall clogging). Several trials were made at each location. Their number, the average hydraulic head on each h_{oavg} location, and the geometric data according to the notations of Figure 1d) are presented on ESM as Supplementary S4. The variable hydraulic head test has been chosen. The following parameters were determined for each location:

– The hydraulic conductivity k of each test, according to the hydraulic head given by the initial height of the water column in the drilling h_o at $t_o = 0$, and the hydraulic head values h_i based on the cumulative drawdown Δh and corresponding to different times t_i;
– The hydraulic conductivity k_{dch} for each location AI_i using the average of the hydraulic heads measured for n tests at each location i; for the calculation of the dynamic level h_i the mean of the absolute drawdown h of the hydraulic head H_n recorded during the n tests on the location for the same cumulative time values was used;
– The hydraulic conductivity k_{avg} as the average of the values obtained for n tests at each location.

3. Results

3.1. Tube Infiltrometer (TI)

The k values for each location and each trial are shown in Table 1. The results of the experimental records for each trial and test location, as well as the cumulative graphs of infiltration by time $I = f(t)$ and infiltration rate by time $I = f(t)$, are given on ESM as Supplementary S2. Saturated hydraulic conductivity was computed using Equation (1).

Table 1. The k values obtained by the TI method.

Location	Parameter	Trials																			k_{dcH}, m/d	k_{avg}, m/d
		T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14	T15	T16	T17	T18	T19		
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
TI1	H_n, cm	30.4	42.6	--	47.3	46.4	42.5	47.3	46.7	45.8	45.7	44.4	45.9	45.6	47.8	46.1	--	--	--	--	44.6	--
	k, m/d	4.63	1.53	--	3.18	3.51	2.56	2.79	2.04	1.57	1.77	1.6	1.47	1.18	0.96	0.88	--	--	--	--	0.996	2.119
TI2	H_n, cm	55.4	59	57.6	56.5	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	57.1	--
	k, m/d	0.38	0.24	0.16	0.17	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	0.16	0.238
TI3	H_n, cm	26.3	30.1	35	29.8	21.2	32.1	33	32.7	29.6	26.7	31.1	--	--	--	--	--	--	--	--	29.7	--
	k, m/d	0.35	0.34	0.37	0.82	0.71	1.20	0.94	0.98	1.89	1.29	1.25	--	--	--	--	--	--	--	--	0.395	0.923
TI4	H_n, cm	23.8	25.4	28.9	27.9	30.7	30.2	27.1	30.2	32.4	30.1	30.1	31.8	31.9	30.7	--	--	--	--	--	29.4	--
	k, m/d	17.6	10.3	2.53	1.48	0.97	0.60	0.39	0.22	0.19	0.46	0.47	0.18	0.14	0.12	--	--	--	--	--	0.049	2.546
TI5	H_n, cm	49.9	50.3	56.1	54	52.5	54.4	53.4	52.4	--	--	--	--	--	--	--	--	--	--	--	52.9	--
	k, m/d	0.69	0.61	0.46	0.98	0.77	0.65	0.42	0.23	--	--	--	--	--	--	--	--	--	--	--	0.237	0.600
TI6	H_n, cm	44.6	20.5	45.6	49.5	45.2	45.2	49.6	48.4	46.5	42	49.2	48.8	48.4	45.8	48.8	50.6	48.4	48.5	42.8	45.7	--
	k, m/d	1.38	4.76	2.44	2.81	3.53	3.73	2.39	3.27	1.83	6.81	0.47	5.6	3.3	7.14	4.03	6.59	6.14	5.96	2.99	0.54	3.946

Theoretically, in a REV, with homogeneous soils, the hydraulic conductivity is minimum when the soil moisture is minimum and reaches a maximum value when the soil reaches the saturation state, the two parameters being directly correlated. In this experiment, the absolute values of the hydraulic conductivity obtained for the unsaturated and saturated state of the urban soil were not compared, but the relative values obtained for the hypothetical saturation or incipient saturation states for consecutive trials in the same location were compared. Moisture measurements could not be performed between successive attempts to avoid disturbing the ground. Thus, between two hypothetical saturation states corresponding to the $i-1$ and i trials, the infiltration velocity tends to become constant and the corresponding REV hydraulic gradient decreases by decreasing the pathway taken by the water particle as a result of the pore saturation. Consequently, the hydraulic conductivity, corresponding to the two hypothetical saturation states, decreases as the soil saturation increases until it becomes constant. To avoid any confusion, note that, in the following, the decrease in the hydraulic conductivity value with the increase in the soil saturation refers to the hydraulic conductivity values corresponding to the hypothetical saturation state between successive trials. It should be noted that the values of k_{dcH} hydraulic conductivity (column 20—Table 1) determined using the average of the hydraulic head tests and the mean of the water level oscillations differ greatly from the arithmetic mean k_{avg} (column 21—Table 1) and they are close to the measured hydraulic conductivity k values for the previous tests in each location. This is interpreted as meaning that the terrain was saturated due to water infiltration or that it was in the early stage of saturation. This is not valid for the TI6 location where, though there was a higher number of tests, there is no clear decrease in the hydraulic conductivity value as the number of tests increases (increasing the saturation state).

The variation of hydraulic conductivity could be due either to the ground heterogeneity or to a lower cohesion compared to the natural soil (through processes of entrainment of the soil particles by the infiltration water, which can clog different pathways and which are subsequently released). This phenomenon is more pronounced with the presence of anthropogenic elements such as brick, concrete, and glass fragments (identified in this location) which contribute to the hydraulic instability of the clayey matrix and of the permeable porous medium.

Hydraulic conductivity shows relatively low values for the TI2 location, which tend to stabilize due to the fact that the field is predominantly made up of fine material (clayey and silty, 82%) (Supplementary S1 on ESM—S02/P01). The questions, especially for heterogeneous areas containing anthropogenic products, are by which criterion can the correct value of the hydraulic conductivity be determined and how many trials/tests would be needed for a location to determine the final saturated value of k. In the case of TI5, as the values decrease for the first tests, the land tends to saturation, and then they increase, probably due to water movement following new pathways, and finally decrease again as the saturation increases (Figure 3).

At the TI2 and TI4 locations, the hydraulic conductivity decreases as the number of tests increases and the water infiltration becomes stable due to the ground saturation. In TI1 and TI5, the k values first decrease, then rise, and finally again decrease as the water movement tends to a stationary regime. The decrease in k values followed by an increase can be attributed to the obstruction of pores and superficial fissures, to the presence of air, and to the soil heterogeneity, the water pathways being subsequently unlocked.

In TI3 and TI6 in particular, the scatter of values is much higher between consecutive trials, indicating a general increase in k values as the number of trials increases. This means that reaching the steady state regime is more difficult as the water infiltration pathways close and re-open by mobilizing and further removing fine particles. The first trials highlight smaller k values, probably due to the entrapped air. Finally, both curves indicate a decrease in hydraulic conductivity and possibly a tendency towards stabilization of the flow. Due to the relatively small surface of the studied area and the short distance between the test points, it can be argued that the heterogeneity of the urban soils leads to large variations of hydraulic conductivity.

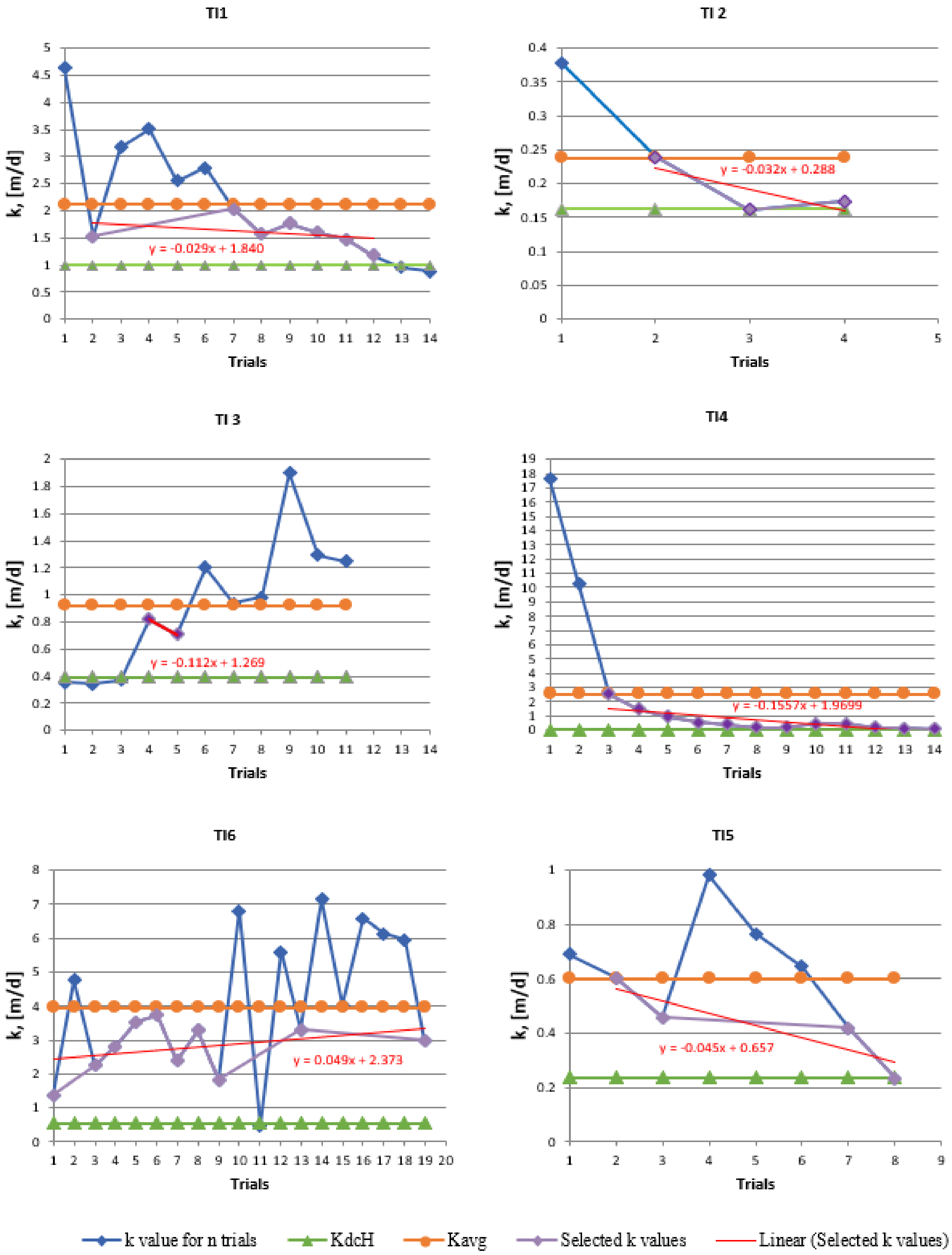

Figure 3. The variation of hydraulic conductivity value vs. the number of trials at each TI test location.

Figure 3 shows an area delineated by two horizontal lines. The upper one represents the arithmetic average of the hypothetical saturation state of k_i values obtained for each test (k_{avg}, column 21 of Table 1) and the lower represents the value of the hydraulic conductivity obtained by the mean of the hydraulic head values and of the mean level oscillation values (k_{dcH}, column 20 of Table 1). This interval was defined as "*the saturated hydraulic conductivity validity domain*".

If we accept that all k values above the upper line are overvalued and those below the bottom line are underestimated, it means that the value that could be considered for each location would be in the range delimited by the two parallel lines, being the average of the k_{avg} and k_{dcH} values. Since, in the boundary range, there are usually more values whose distribution is not central, the value of hydraulic conductivity was calculated using a linear regression for the selected values: $y = ax + b$, where a represents the slope, b the intersection with the ordinate, y the value of k, and x the number of the selected tests. The equations of the regression curves for selected values within the validity domain, as it was defined, are given in Figure 3.

The value of k_{ss} hydraulic conductivity determined at each TI location represents the average of the values determined by the regression curve for the selected trials (within the interval bordered by the two parallel lines).

The number of trials at each location is important. For example, if, at the TI1 and TI4 locations, where the values obtained for k between the first and the last trials show very large differences, 5–6 attempts would have been performed, then the error of the calculated k_{ss} values should have been quite high. The required number of trials to reach the steady state flow cannot be known at the beginning of the tests. This can be estimated only after performing the tests, computing k values and determining the validity domain.

As the k value decreases when the number of trials (and consequently the ground saturation) increases, there should be an inverse correlation between the values obtained for k and the number of trials. This correlation can be seen in Figure 3 for all the locations with the exception of TI3 and TI6. For these two, a direct correlation can be observed (the k values increase with the increase in the tests number). From the physical point of view, these data sets should be considered as not being complete and a larger number of trials should be made. Also, for TI3, the regression curve for the selected and simulated values (used to compute the k_{ss}) shows an inverse slope, indicating an inverse correlation. Due to the small number of available values, the k_{ss} value is expected to change if more tests are performed. For TI6, the regression line indicates a direct correlation, but its position is very close to the horizontal. A horizontal line should probably have been obtained with a few more attempts. From a strict statistical point of view, this shows a lack of correlation, but the physical interpretation indicates the achievement of incipient steady state for the infiltrated water. This is also valid for TI1 and TI4 locations, where the regression lines are close to the horizontal.

3.2. Inversed Auger (IA)

The hydraulic conductivity values were computed using Equation (4) and the results are shown in Table 2. The field recorded data and the corresponding graphs are presented in Supplementary S5 on ESM.

Similar to the TI tests, the hydraulic conductivity values k_{dch} (column 19 in Table 2) differ from the arithmetic mean k_{avg} (column 20, Table 2) and they are closer to the k values determined for the last trials at each location. This leads to the interpretation that the terrain was saturated or is in the early stage of so-called saturation. On the other hand, the last determinations of k values in the row corresponding to each location (especially for locations with a greater number of trials) show oscillating values when compared to the neighboring ones. The variation of the values may be due to the change in the structure of the ground, either due to its heterogeneity or due to lower cohesion than of the natural terrains, and the entrainment of the soil particles that can clog different access paths which are subsequently released.

Table 2. The k values obtained by the IA method.

Location	**Parameter**	**Trials**																		k_{dch} **m/d**	k_{avg}**, m/d**
		T1	**T2**	**T3**	**T4**	**T5**	**T6**	**T7**	**T8**	**T9**	**T10**	**T11**	**T12**	**T13**	**T14**	**T15**	**T16**	**T17**	**T18**		
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**
IA1	h_0, cm	50.2	72.7	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	k, m/d	0.145	0.094	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--	0.108	0.120
IA2	h_0, cm	43.9	44.6	48.1	45.4	50.2	--	--	--	--	--	--	--	--	--	--	--	--	--	--	--
	k, m/d	1.31	1.12	0.83	0.42	0.36	--	--	--	--	--	--	--	--	--	--	--	--	--	0.392	0.808
IA3	h_0, cm	27.8	29.8	29.9	29.9	27.4	29.9	19.4	29.9	29.9	27.6	14.2	28.9	29.8	29.7	28.7	29.9	29.9	29.9	--	--
	k, m/d	8.58	3.32	3.92	3.36	3.35	2.32	4.15	2.65	1.78	8.41	22.7	2.37	2.76	1.56	1.64	1.47	1.12	3.37	2.371	4.382
IA4	h_0, cm	17.1	21	31.9	27.1	28.6	27.1	27.2	30.6	27.5	31.1	31.3	31.7	31.9	31.3	30.7	31.8	31.9	--	--	--
	k, m/d	12.24	4.60	4.81	3.12	4.10	3.76	3.91	2.87	13.47	4.87	2.21	2.85	1.60	2.40	1.30	1.68	0.89	--	1.643	4.156
IA5	h_0, cm	26	36.4	50.5	48.8	50.1	37.8	47.9	39.4	38.6	--	--	--	--	--	--	--	--	--	--	--
	k, m/d	1.92	1.54	1.59	1.34	0.70	1.06	0.89	1.01	0.61	--	--	--	--	--	--	--	--	--	0.948	1.184
IA6	h_0, cm	75.4	62.8	68.5	73.3	74.8	70.1	72.6	69.1	--	--	--	--	--	--	--	--	--	--	--	--
	k, m/d	3.44	2.02	2.04	1.37	1.60	1.43	1.19	1.36	--	--	--	--	--	--	--	--	--	--	1.466	1.805

It should also be considered that the water also infiltrates through the lateral surface of the drilling hole, and this differs from one location to the other: the deeper boreholes open places with a different makeup of the clay matrix. Consequently, the hydraulic conductivity corresponds to the tested depth range for each location. Figure 4 illustrates the changes of hydraulic conductivity as a function of the number of tests for each location.

As with the TI tests, in Figure 4, a validity domain is shown of the hydraulic conductivity values determined between k_{dch} and k_{avg} (the lowest and highest values). An exception is the location IA1, where only two trials were performed (whose values are outside the limits of the validity domain). We point out that tests at all locations were made in the same period of time, and the cumulative durations of the two IA1 trials exceed the cumulative duration of the tests in other locations. Therefore, in the case of IA1, the calculation value can be chosen as the average of the two values that delineate the validity domain. Generally, an inverse correlation is found between the hydraulic conductivity and the number of tests (a decrease in the hydraulic conductivity values with the number of tests).

In the locations IA3 and IA4, for T11 and T9 trials, respectively, there is a sudden increase in the k value of more than one order of magnitude. The hydraulic head applied in T11 of IA3 (Table 2) represents approximately 50% of the hydraulic head applied to other trials. In the case of T9 of the IA4 location, the hydraulic head is very close to the hydraulic head applied to the other tests. A high hydraulic conductivity variation could be the result of the infiltration process progression due to the action of the water on the heterogeneous media by mobilization/demobilization of the fine particles (the depths of the drill holes are 30 cm and 29 cm, Figure 2b). Also, the lithological constitution of the clayey matrix has to be considered with the presence of brick debris, splinters, or thickening elements along the walls of the borehole. According to Supplementary S1, the samples taken around the depth of 30 cm indicate a matrix made up of silty clay, but the interpretation based on the macroscopic description of the excavated ground corroborated the granulometry of the adjacent locations, indicating the presence of a sandy clay on the surface with the silty clay located at the bottom. To lower the hydraulic head by 50%, the hydraulic conductivity should be characteristic of the lower horizon, but its variation is far too large, so the lithological differences are not so important.

The value of hydraulic conductivity k_{ss} corresponding to each IA location (Table 3) represents the average of the values determined by the regression line for the selected trials (trials within the boundary bounded by the two parallel lines) except for IA1, where the calculated value k_{ss} was determined as the mean of k_{avg} and k_{dch} values, k_{ss} = 0.114 m/day.

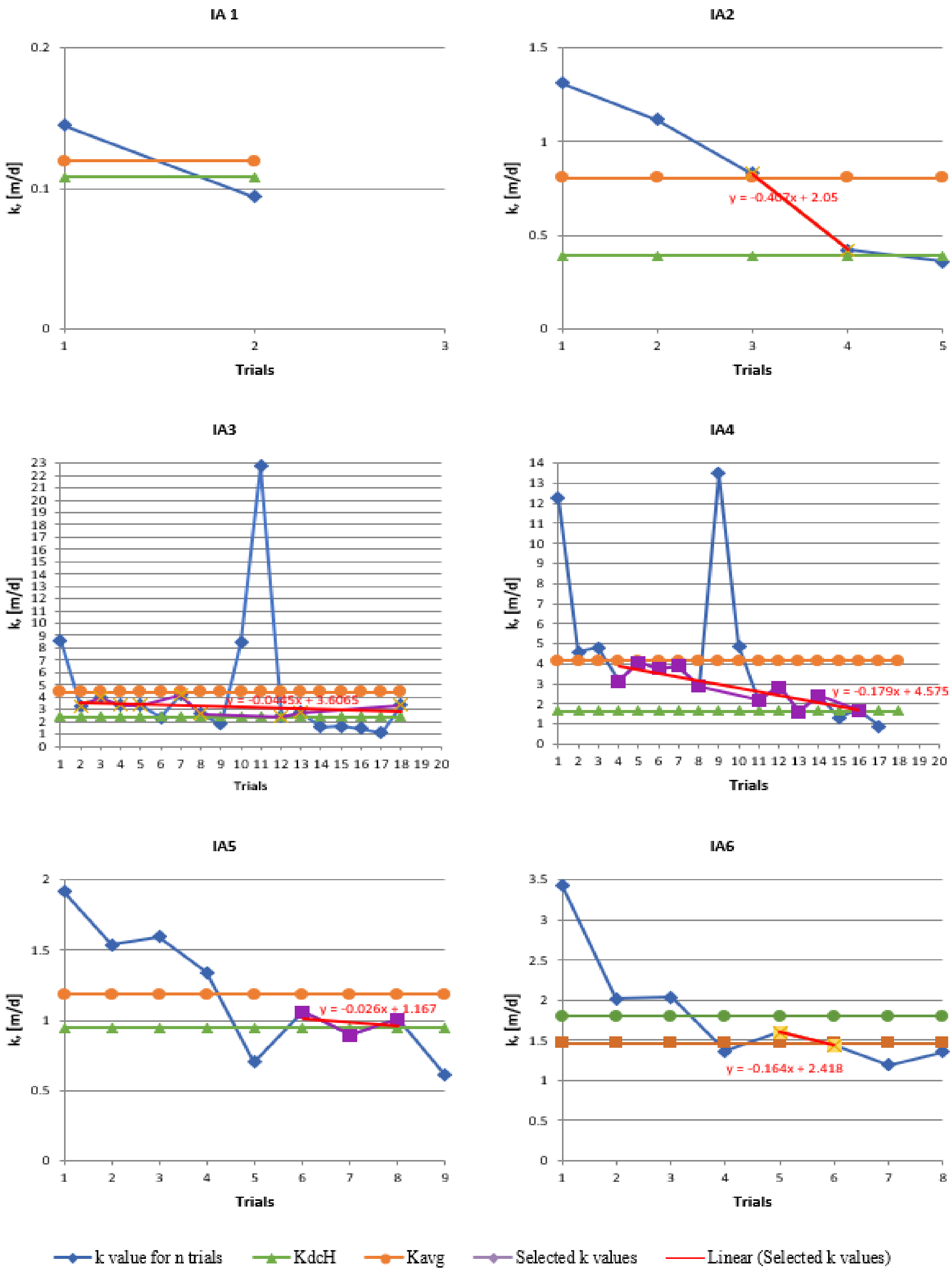

Figure 4. The variation of the hydraulic conductivity value in relationship to the number of trials on each IA location.

Table 3. The statistical parameters values of k variable for the TI and IA test locations.

Test Type	Location	Obtained/Observed Values				Validity Domain						
						Selected Values				Simulated/Calculated Selected Values		
		No. of Trials	k_{avg}, m/d	s_o	V_o	No. of Trials	k_s, m/d	s_{so}	V_{so}	k_{ss}, m/d	s_{ss}	V_{ss}
TI	TI1	14	2.119	1.084	0.512	7	1.594	0.262	0.165	**1.596**	0.096	0.060
	TI2	4	0.238	0.099	0.419	3	0.191	0.042	0.218	**0.192**	0.032	0.167
	TI3	11	0.923	0.479	0.519	2	0.765	0.079	0.104	**0.765**	0.079	0.104
	TI4	14	2.546	5.08	1.997	12	0.646	0.715	1.106	**0.646**	0.561	0.868
	TI5	8	0.600	0.230	0.383	4	0.429	0.152	0.355	**0.432**	0.132	0.307
	TI6	19	3.946	1.965	0.498	10	2.747	0.770	0.280	**2.740**	0.257	0.094
IA	IA1	2	0.120	0.036	0.302	--	--	--	--	**0.114**	--	--
	IA2	5	0.808	0.419	0.519	2	0.625	0.288	0.460	**0.625**	0.288	0.460
	IA3	18	4.382	5.035	1.149	9	3.250	0.579	0.178	**3.254**	0.235	0.072
	IA4	17	4.156	3.503	0.843	10	2.848	0.885	0.311	**2.857**	0.741	0.260
	IA5	9	1.184	0.440	0.372	3	0.985	0.085	0.086	**0.985**	0.026	0.026
	IA6	8	1.805	0.729	0.404	2	1.516	0.116	0.076	**1.516**	0.116	0.076

Figure 4 shows that some values (especially those related to the final IA trials) are below the lower limit of the validity domain (below k_{dch} value), with a downward but oscillating trend. Apparently, the elimination of these values would lead to an erroneous evaluation of k_{ss}, but it should be considered that the k_{dch} value depends on the number of trials and averages of the hydraulic head changes. Therefore, its position in the graph changes with the number of trials, and the values between the two limits of the range indicate the tendency toward the beginning of a steady state regime. A clear example is represented by IA3, where the value obtained at the last trial rises within the domain, while the previous four are below the lower limit of the validity domain with a partially downward trend. The regression line of the selected values is very close to the horizontal, indicating the entry into the steady state. In locations IA2, IA4, and IA6, the large angle between the regression line and the horizontal indicates that the steady state has not been reached. However, for IA6, the close and slightly oscillating values of the last trials indicate the approach of early stage of steady state flow.

For both test methods (TI and IA), using the values of Tables 1 and 2, the following were computed for each location: the standard deviations s_o of the values obtained for k for all tests, the standard deviations s_{so} for the k values selected within the validity domain, and the standard deviations s_{ss} for the k values computed/simulated with the regression curve equation for the selected trials together with the corresponding coefficients of variation V_o, V_{so}, V_{ss}. These parameters, together with the values of the hydraulic conductivity, are presented in Table 3 as a simple average of the selected values k_s and as an average of the values simulated by the k_{ss} curve in the validity domain.

It can be observed that for each location, the standard deviation and the variation coefficient values decrease from the obtained group of values to the selected ones. The smallest values are for the simulated group of values and signify that the magnitude, as well as the uncertainty, associated with the attempts to determine the k value, decrease if the values defined on the validity domain are considered.

The decrease in the variation coefficient suggests that the simulated k values are closer to real values as an expression of geological environment variability. By comparing the statistical parameters s and V, we see a large variation from one location to another. This mainly indicates a different behavior of infiltrated water related to the heterogeneity of the ground (lithological differences, clogging/opening of access ways, air presence with implication on the saturation degree, etc.).

This is also emphasized by the fact that for the selected group of values, the statistical parameters are much closer, showing a decrease in the variability of the geological factors as the infiltration process approaches the "steady state". The situation found in the TI4 location is significant, where the calculated statistical parameters have values greater than one and the differences between the k values (obtained for each of the 14 trials) are between one and two orders of magnitude. TI graph 4 of Figure 3 shows a normal evolution as the number of tests increases, indicating a gradual decrease in the k value with an increase in saturation. It can be considered that the excessively high values of k obtained for the first attempts are related to the flow of water through a dry soil with cracks with larger openings as well to vegetation. As voids fill and water interacts with the clay fraction, which can lead to swelling, the infiltration velocity is attenuated, leading to a decrease in k. In locations IA3 and IA4, the coefficients of variation for the group of the observed values are very high due to the results obtained in the T11 and T9 trials for the respective locations. By selecting the k values from the validity domain, in the cases of IA2 and IA6, the values of k_s and k_{ss} are equal because only two values have been identified in this field with which the regression line was built.

Structural and lithological heterogeneity can influence the seepage process through the unsaturated zone, but this process is also related to the relatively short time of the contact between the water and the lithological/mineralogical environment. As consequence, it is not appropriate to check if the data (in this case, the k values determined by n trials on each location) come from the same geological set on the basis of their variance, as the urban soil is a mixture of natural and anthropogenic materials, chaotically mixed.

For comparison, shown in Table 4 are the values of hydraulic conductivity that define the validity domain (k_{dcH} and k_{avg}) for each location, the average of these values k_m (as the central value of the domain), and the hydraulic conductivity value obtained on the basis of the selected values k_{ss} according to the regression line. The k_{ss} hydraulic conductivity value is considered as the closest to the real saturated value and is used below as k.

Table 4. The k mean values determined by the TI and IA tests.

Test Type	Location	k, [m/d]			
		k_{dcH}	k_{avg}	$k_m = (k_{dcH} - k_{avg})/2$	k_{ss}
TI	TI1	0.996	2.119	1.557	**1.596**
	TI2	0.16	0.238	0.199	**0.192**
	TI3	0.395	0.923	0.659	**0.765**
	TI4	0.049	2.546	1.297	**0.646**
	TI5	0.237	0.600	0.418	**0.432**
	TI6	0.54	3.946	2.243	**2.740**
IA	IA1	0.108	0.120	0.114	**0.114**
	IA2	0.392	0.808	0.600	**0.625**
	IA3	2.371	4.382	3.376	**3.254**
	IA4	1.643	4.156	2.899	**2.857**
	IA5	0.948	1.184	1.066	**0.985**
	IA6	1.466	1.805	1.660	**1.516**

With the exception of TI4 and TI6, all the k_m values are quite close to k_{ss} values determined by linear regression. It is obvious that by applying a polynomial regression curve of second degree or even higher, with a better degree of approximation, these differences would change. Therefore, a rapid evaluation can be made by calculating the value of k_m. However, it is more correct to determine the k_{ss} values by applying the appropriate regression curve.

3.3. Double Ring Infiltrometer (DRI)

To assess the hydraulic conductivity from field records of cumulative infiltration I and infiltration rate v, Equation (2) was used. The field data and the corresponding graphs $I = f\ (t)$ and $v = f\ (t)$ are shown in Supplementary S3 on ESM. The saturated hydraulic conductivity values are shown in Table 5. These can be considered as average values of the locations since the tests performed with a constant level were completed at steady state, so that at each location marked in Figure 2b, a single test was performed.

Table 5. The *k*, *A*, and *k/A* values for each type of test in ascending order of the infiltration area values.

Test Type	*k*, (m/d)	A_area, (cm^2)	*k/A*, (m/d/cm^2)	*k* Amplitude, (m/d)	*k/A* Amplitude, (m/d/cm^2)	*A* Amplitude, (cm^2)
TI3	0.765	41.854	0.01828	2.548	0.03343	33.268
TI4	0.646	41.854	0.01543			
TI5	0.432	57.012	0.00758			
TI2	0.192	61.584	0.00312			
TI6	2.74	74.969	0.03655			
TI1	1.596	75.122	0.02125			
IA3	3.254	507.870	0.00641	3.315	0.00632	795.230
IA4	2.857	531.080	0.00538			
IA5	0.985	733.500	0.00134			
IA2	0.626	807.300	0.00078			
IA6	1.516	1188.800	0.00128			
IA1	0.119	1303.100	0.00009			
DRI3	2.226	615.752	0.00362	4.094	0.00665	0
DRI2	1.945	615.752	0.00316			
DRI1	2.711	615.752	0.00440			
DRI5	5.512	615.752	0.00895			
DRI4	6.039	615.752	0.00981			
MDI1	0.178	15.900	0.01119	0.467	0.02937	0
MDI2	0.115	15.900	0.00723			
MDI4	0.241	15.900	0.01516			
MDI3	0.136	15.900	0.00855			
MDI5	0.105	15.900	0.00660			
MDI6	0.241	15.900	0.01516			
MDI7	0.178	15.900	0.01119			
MDI18	0.063	15.900	0.00396			
MDI8	0.262	15.900	0.01648			
MDI16	0.209	15.900	0.01314			
MDI15	0.105	15.900	0.00660			
MDI9	0.471	15.900	0.02962			
MDI14	0.084	15.900	0.00528			
MDI10	0.126	15.900	0.00792			
MDI13	0.262	15.900	0.01648			
MDI11	0.042	15.900	0.00264			
MDI12	0.004	15.900	0.00025			
MDI17	0.052	15.900	0.00327			
Average	**1.058**	**251.114**	**0.00938**	--	--	--
TI average	**1.062**	**58.733**	**0.01703**	--	--	--
IA average	**1.560**	**845.275**	**0.00255**	--	--	--
DRI average	**3.687**	**615.752**	**0.00599**	--	--	--
MDI average	**0.160**	**15.900**	**0.01004**	--	--	--

The *k* values obtained by this method are greater than 1 (m/d) and have a relatively large variation from one location to another.

3.4. Minidisk Infiltrometer (MDI)

The hydraulic conductivity value *k* was determined by applying Equation (3) and using the field data. The graphs $I = f\left(\sqrt{t}\right)$ and the corresponding regression curves are shown in Supplementary S4 on ESM. The values obtained for the hydraulic conductivity *k* are shown by Table 5. Compared to those obtained by the above-mentioned methods (TI and DRI), the values differ by up to three orders of magnitude.

An explanation of the very low values obtained for hydraulic conductivity would be that the infiltration area, being very small (device feature), largely overlaps the clay matrix of the filler material. An analysis of the values in relation to infiltration area is presented in the following sections.

4. Discussion

4.1. Comparative Analysis of the Results Obtained by the Four Testing Methods

Figure 2b shows a diagrammatic map of the test area with locations of the different types of tests. Positions of these locations can be measured as distance along an axis from the lower left to lower right, with the origin on the left. A plot of these distances against k values of each test location is shown in Figure 5a.

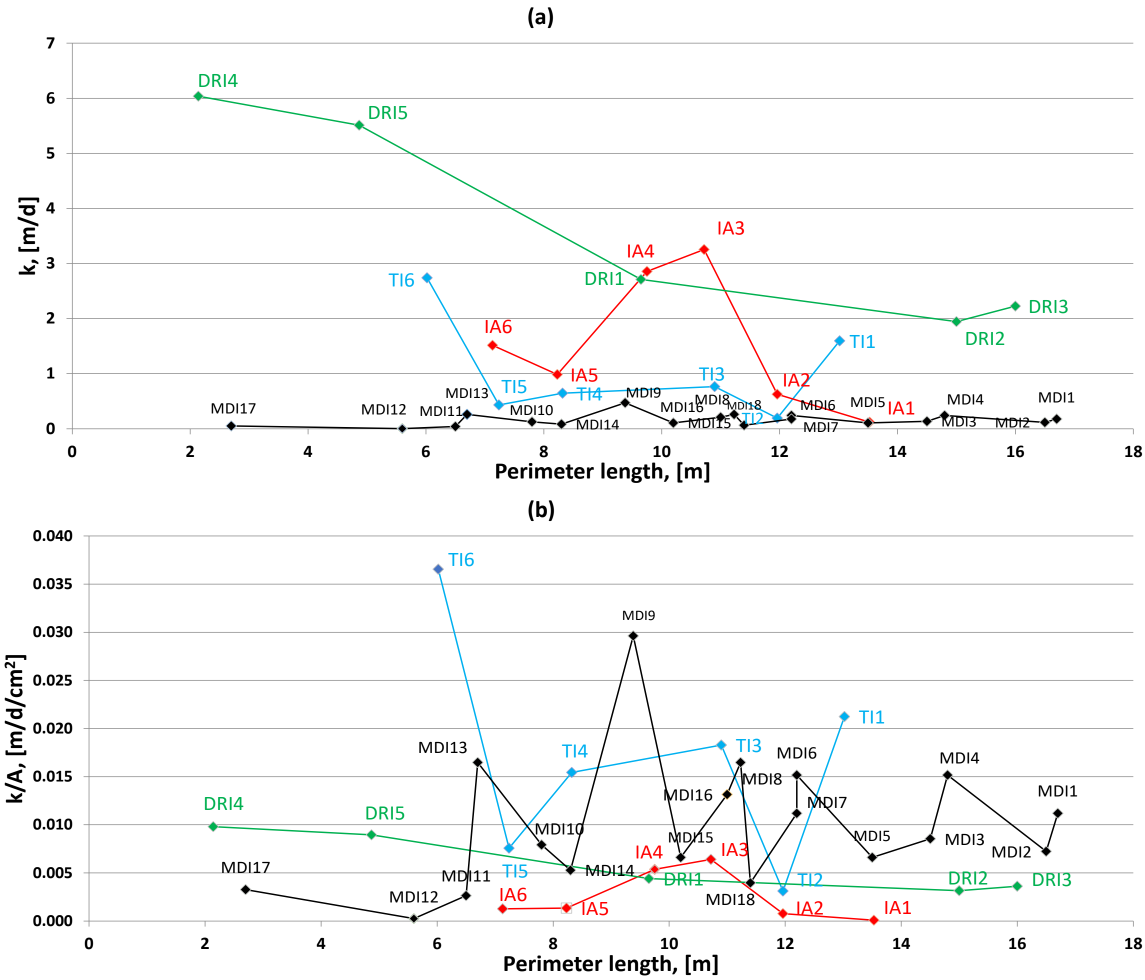

Figure 5. The analyzed parameters distribution along the test area length: (**a**)—distribution of k values, (**b**)—distribution of k/A values.

It can be observed that the hydraulic conductivity values assessed by applying the DRI and IA methods have the largest amplitude between the test locations. The values determined by the MDI method have very small amplitude and its average can be considered as the characteristic value of the studied area.

When the measured values are represented in ascending order of the infiltration areas corresponding to each test method (Table 5), the k amplitude increases with the increase in the infiltration area, which supports the conclusion that the values obtained by the MDI method are the appropriate ones. However, from the physical point of view, an experiment performed on wider surfaces should lead to results that characterize the investigated zone better. If, apart from the geological variable *k*, we define the variable $k^* = k/A$ which represents the hydraulic conductivity corresponding to a unitary infiltration surface (equal to 1 cm^2) and reconstruct the graph of Figure 5a with the k/A values of Table 5, the distribution in Figure 5b is obtained.

Comparing the distributions shown by Figure 5a,b, the pattern of values is inverted in the last figure. The hydraulic conductivity corresponding to the surface infiltration unit shows the smallest amplitudes in the case of the IA and DRI methods. The maximum amplitudes of *k/A* were obtained for the MDI and TI methods. This can be explained as due to the fact that by applying the DRI and IA methods, the water infiltrates through a much larger surface area compared to the other two methods, so the obtained values for the saturated hydraulic conductivity by the DRI and IA methods characterize the tested locations better by increasing the estimation confidence. This is particularly important in assessing the hydraulic conductivity for urban soils, as they are most often made of heterogeneous material. The small values of the saturated hydraulic conductivity obtained by the MDI method (where the infiltration surface is the smallest and the tests were carried out with a negative pressure) would rather characterize the clay matrix of the material that forms the urban soil and not the urban soil in its entirety.

If the terrain had been ideally "homogeneous" (hypothesis "0" stated above), the hydraulic conductivity for the saturated state, determined by any of the methods, should have been the same and the *k/A* ratio should have decreased with increasing infiltration surface area. The amplitude of this ratio should be the smallest for the methods with the largest infiltration surface, and the graphical representation of these values (according to Figure 5b) should be represented by parallel horizontal lines for equal infiltration surfaces for the same method. In the present case (heterogeneous soil), the *k* values differ significantly from one location to another within the same test method (Figure 5a) given that the respective locations are very close; the compared values of the amplitudes of the *k/A* ratios (Figure 5b) seem to confirm the hypothesis that their value decreases with increasing infiltration area. However, in particular, the variations of *k/A* values between close locations, determined by the method with large and equal infiltration areas (DRI), indicate the presence of other variables independent of the infiltration area that can influence the saturated *k* value. Moreover, in the case of MDI tests from close locations (MDI14 and MDI9), where the determined *k* value is a characteristic of the clay matrix, the amplitude between the *k/A* values (A = ct.) is very high. This indicates either a lithological/granulometric variation or the existence of other variables (roots, macropores below the ground surface, etc.), or even the cumulative effect of these variables that could not have been highlighted at the beginning of the tests. Therefore, in the case of performing several tests, considering that *k* is dependent on the size of the infiltration area, the *k/A* ratio provides qualitative information on the influence of other variables on the *k* values determined by the magnitude of the amplitudes of the *k/A* ratios. The influence of the infiltration area on the determined saturated *k* values, as well as of other cumulated variables, is presented in the following sections.

4.2. Considerations Regarding the Average Values Obtained for k and k/A Ratio as Geological Variables Related to Each Test Method for Both Data Selection Categories

The arithmetic average of the hydraulic conductivity values for the entire tested area, considering the values obtained by applying all the four methods on all the locations (not grouped by selection intervals), is k = 1.058 m/day (Table 5). This value is very close to the one obtained by applying the TI method (1.062 m/day). The one corresponding to the DRI method (3.687 m/day) is the highest value, and the one determined by the MDI method (0.160 m/day) shows the lowest value (almost seven times smaller as general average). The amplitude values confirm the situations presented by Figure 5. Significant differences between the averages obtained by each method are observed. Apparently, according to the values of the obtained averages, the simple arithmetic average of all the *k* values selected for the four methods or the average obtained by applying the TI method would best characterize the studied site. The smallest amplitude of the *k* values was obtained by the MDI method (0.467 m/day), with the one obtained by the DRI (4.094 m/day) being the highest. The amplitude resulting from the TI method (2.548 m/day) occupies an intermediate position, which means that the lowest spread of values is obtained by the MDI method.

Figure 6 shows the relationships between the calculated *k* and *k/A* averages and the variation coefficients for the grouped and non-grouped selection intervals and for each testing method, respectively.

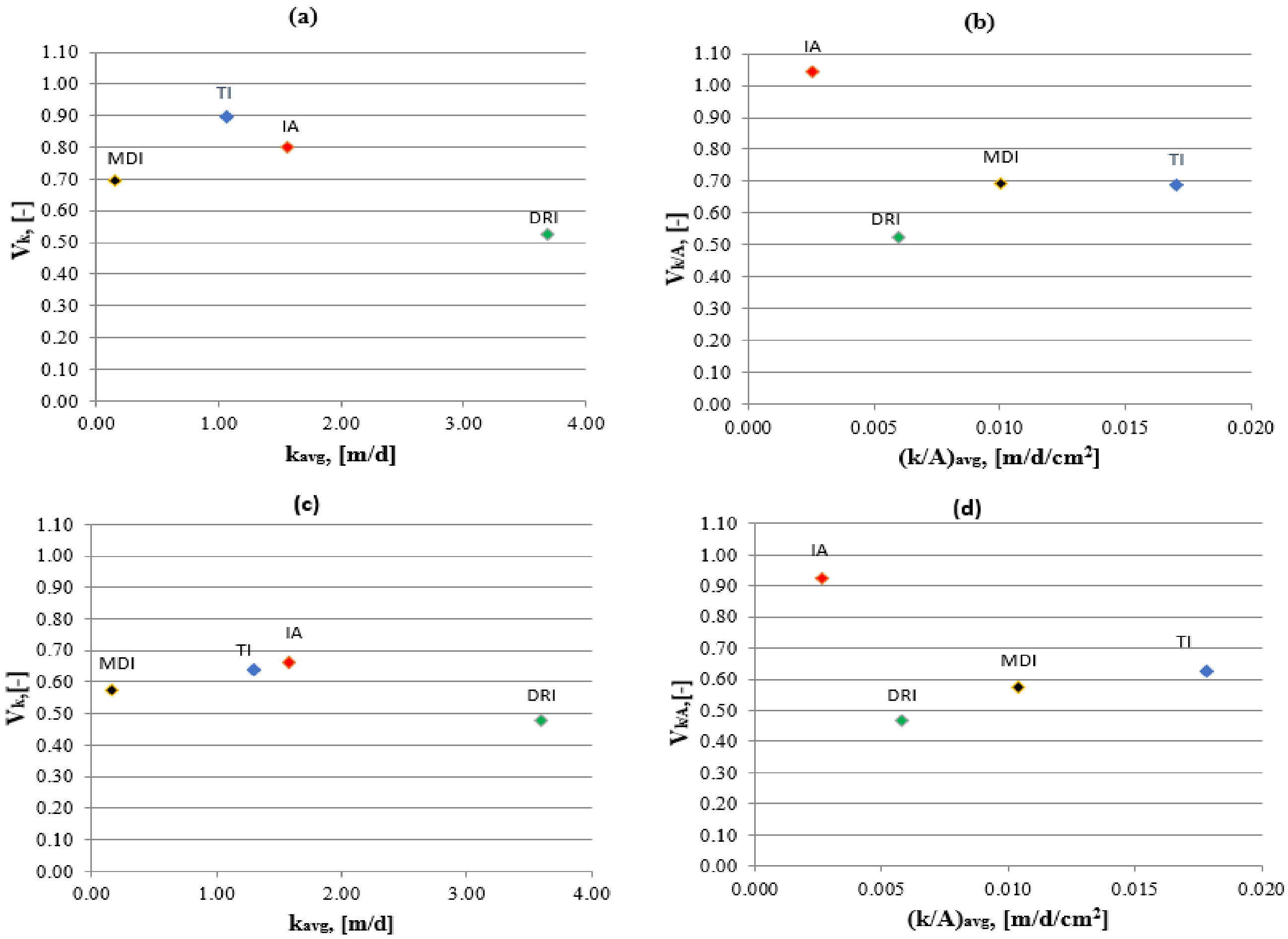

Figure 6. The relationship between the calculated means of *k* and *k/A* vs. variation coefficients for ungrouped (**a**,**b**) and grouped selections (**c**,**d**).

The lowest variation coefficient was obtained for the DRI method, both for the selection mean of the hydraulic conductivity value k_{DRI} and for the hydraulic conductivity value corresponding to an infiltration surface unit $k^* = k_{DRI}/A_{DRI}$. At the same time, in the case of ungrouped elements, the variation coefficient exceeds the value of 0.5 by very little, considered statistically a maximum value for a normal variation of the analyzed parameter. In the case of grouped elements, the value of the variation coefficient decreases below this limit. The variation coefficient determined on the basis of the data provided by the MDI method is located in an intermediary position between those obtained for TI, IA (highest values), and DRI (lowest value). These values show that the comparative analysis of the results made only on the basis of the magnitude of the amplitude between the maximum and minimum values can lead to erroneous conclusions.

As a general observation, the graphs from Figures 5 and 6 indicate a large variation of the values of *k* and *k/A* parameters obtained by different methods.

4.3. The Correlation Analysis between the Hydraulic Conductivity and the Infiltration Area

The influence of infiltration area A as independent variable on the dependent variables D (k and k/A ratio) was examined. Using the results of Table, 5 the general variances $s^2{}_D$ and the conditioned variances $s^2{}_{D(A)}$ of the dependent variables were calculated and are shown in Table 6. As a measure of the variation of the dependent variables under the influence of other factors, the residual variance $s^2{}_{Do}$ was determined. The statistical parameters which indicate the strength and type of correlations, the correlation ratio $\eta_{D(A)}$ and correlation coefficient r, were also calculated. The estimation of the certainty of the linear or non-linear regression was evaluated by the parabolic regression coefficient C_{rp}, defined by the dispersion of theoretical mean values (simulated) $D'_{avg(A)}$ (Table 6) compared to the mean of the observed values D_{avg} (Table 5). The parabolic regression is sufficiently certain if $C_{rp} \geq \eta_{D(A)} \neq \eta_{A(D)} \neq |r|$. In this work, only $\eta_{D(A)}$ and r were computed due to the fact that it should be incorrect to consider that the infiltration area of the device depends on the hydraulic conductivity.

Table 6. The correlation parameters between dependent and independent variables.

D	Types of Analyzed Methods	Rank	Area Interval Limits, cm^2		A_i Interval Center, cm^2	f_{Di} Frequency	$D_{avg(A)}$	$s^2{}_D$	$s^2{}_{D(A)}$	$s^2{}_{Do}$	$\eta_{D(A)}$	r	Calculated $D'_{avg(A)}$	C_{rp}
k, m/d	(a) All	1	10	60	35	21	0.225	2.298	1.717	0.581	0.864	0.470	0.845	0.856
		2	60	160	110	3	1.509						1.279	
		3	160	660	410	7	3.506						2.419	
		4	660	1160	910	2	0.806						2.200	
		5	1160	1260	1210	1	1.516						0.796	
		6	1260	1310	1285	1	0.119						0.296	
			Σ=			35	1.058	--	--	--	--	--	--	--
	(b) All without IA	1	10	40	25	18	0.160	2.445	1.742	0.704	0.844	0.831	0.176	0.991
		2	40	600	320	6	1.062						1.289	
		3	600	630	615	5	3.687						4.125	
			Σ=			29	0.954	--	--	--	--	--	--	--
k/A, m/d/cm^2	(c) All	1	10	60	35	21	0.01057	0.000067	0.000022	0.000045	0.577	−0.445	0.015584	0.839
		2	60	160	110	3	0.02030						0.013731	
		3	160	660	410	7	0.00596						0.007560	
		4	660	1160	910	2	0.00106						0.001675	
		5	1160	1260	1210	1	0.00128						0.000784	
		6	1260	1310	1285	1	0.00009						0.000871	
			Σ=			35	0.00938	--	--	--	--	--	--	--
	(d) All without IA	1	10	40	25	18	0.01004	0.000068	0.000013	0.000055	0.434	−0.237	0.010042	1.000
		2	40	600	320	6	0.01703						0.016995	
		3	600	630	615	5	0.00599						0.005846	
			Σ=			29	0.01079	--	--	--	--	--	--	--

For each dependent variable, the analysis was performed for two situations: for all four applied methods and only for methods that tested the terrain surface (without IA method). Related to the type of analyzed method and according to the values highlighted in Table 6, the following are noted:

Case (*a*)—The correlation coefficient and the correlation ratio indicate a direct and quite strong correlation between k and A. The residual variance $s^2{}_{ko}$ represents about 25% of the general variance $s^2{}_k$. The fact that the conditioned variance represents 75% of the general variance indicates the weight attributed to the independent variable (infiltration area) in determining the fluctuations of the dependent variable (saturated hydraulic conductivity). The scatter diagram of Figure 7a suggests a parabolic correlation.

Although the above mentioned condition regarding the C_{rp} test value is not respected, due to the very small difference between the compared values (C_{rp} = 0.856 < $\eta_{D(A)}$ = 0.864), the parabolic correlation can be accepted, taking in consideration that the residual dispersion represents 25% of the general dispersion and $\eta_{D(A)} = 0.864 \neq |r| = 0.470$. The conditioned means values of the dependent variable and of the selection interval centers for the independent variable were used to draw the graph of Figure 7b (for the grouped observed values). By using the coefficients of the regression curve (parabolic form), the theoretical (simulated) average values of the dependent variable $k'_{avg(A)}$ were obtained (against the observed average values k_{avg}). The curve of the simulated values was constructed, keeping the same values for the infiltration area as in the first curve.

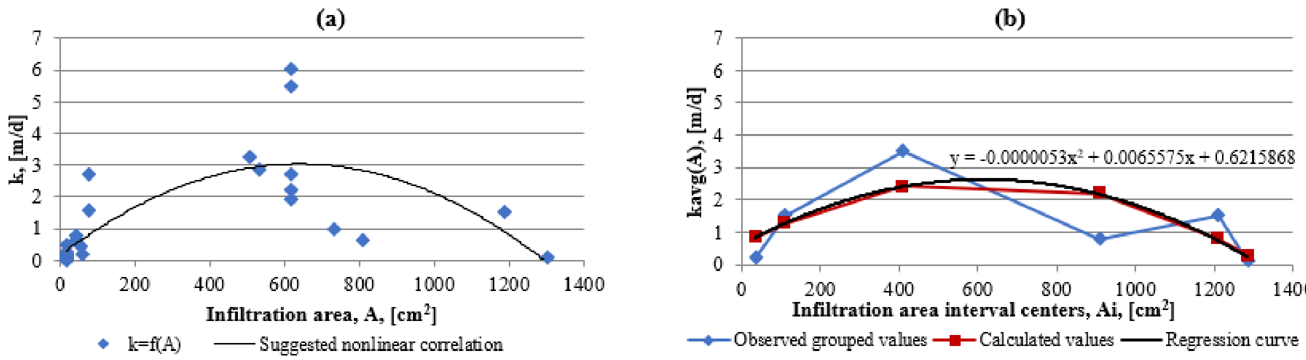

Figure 7. The correlation between k and A values for all methods: (**a**)—ungrouped observed mean values; (**b**)—grouped observed and simulated mean values.

It can be seen that the regression curve equation of Figure 7b has a maximum. If we set to zero the first derivative of the respective equation, we obtain the pair of values of the maximum, namely A = 636.364 cm^2 and k = 2.627 m/day. Therefore, the value of the hydraulic conductivity increases to a maximum that corresponds to an infiltration area slightly larger than that used by the DRI method. Then, it decreases with the increase in the infiltration area, suggesting an inverse correlation. Confirmation of this can be made by analyzing the test procedures corresponding to the test methods. In the MDI, TI, and DRI methods, the water infiltration takes place through the base area of the respective devices. In the case of the IA method, infiltration is also taking place through the lateral surface and the measured values characterize the urban soil at a greater depth in contrast to the other three methods where the measured values characterize only the superficial zone. In this respect, the correlation between the hydraulic conductivity and the infiltration area will be analyzed in Case (b) only for the MDI, TI, and DRI methods.

Case (*b*)—By eliminating IA values, the scatter diagram of Figure 8a could suggest a nonlinear correlation as well as a linear one. The linearity or non-linearity of the correlation was estimated with the values of the statistical parameters (Table 6).

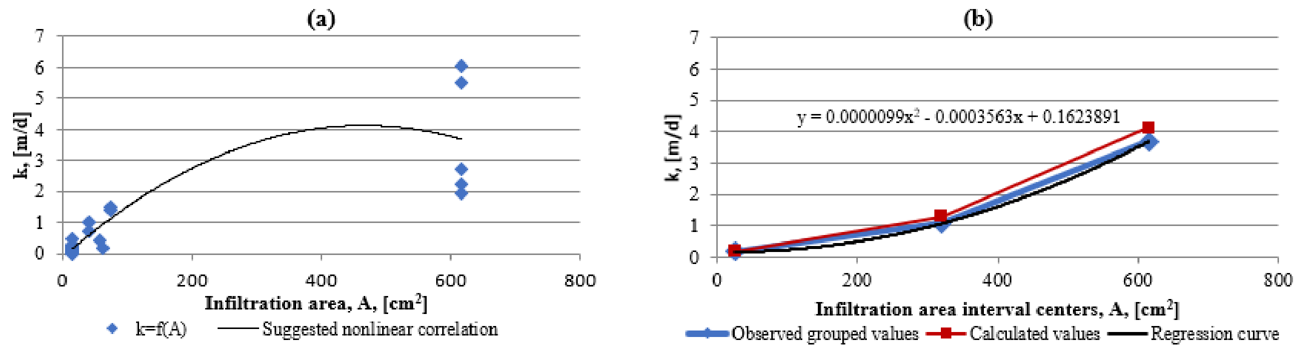

Figure 8. The correlation between k and A values for TI, DRI, and MDI methods: (**a**)—ungrouped observed mean values; (**b**)—grouped observed and simulated mean values.

The results indicate a strong and direct correlation between hydraulic conductivity and infiltration area. The correlation coefficient r = 0.831 has twice the magnitude of the previous case, which indicates the strength of the direct correlation. The tiny difference between the correlation ratio and the correlation coefficient shows that it could be also considered as a linear correlation. However, the value of the parabolic regression coefficient being greater than the correlation ratio $C_{rp} = 0.991 \geq \eta_{D(A)} = 0.844$ shows that the parabolic interpretation approximates much better the regression curve of Figure 8b, where the graphs were prepared according to the methodology previously presented.

The nonlinear dependencies between variables appear when the change of the values of the independent variable determines the non-uniform modification ("accelerated" or "slowed down") of the dependent variable. In situations where the coefficients r and η have equal or very close values (the distinction between linear and parabolic correlation being made on the basis of $C_{rp} \geq \eta$ inequality as in the present case), adjusting the observation data (a parabola instead of a regression line) does not provide informational advantages. In the analyzed situation, the significance of the parabolic correlation should not be interpreted in a geological sense, as the infiltration area is not a geological variable. The parabolic correlation is due to the large variation of the infiltration areas of the three test methods (TI, DRI, and MDI) as well as to the variation of these areas within the TI method, combined with the relatively small number of DRI tests.

The regression curve of Figure 8 indicates that in the study situation, the hydraulic conductivity increases without a limit as the infiltration area increases. It should be kept in mind that the graph of Figure 8 depicts only this experiment and the results depend on the number of tests performed by each method and consequently by the variation of the infiltration area. In the case of the DRI method, only five tests with the constant infiltration area were performed. If more tests had been performed with variable infiltration areas, a decrease in the slope of the regression curve should have been expected (tending towards the horizontal) as the infiltration area increases. The residual variance represents about 28% of the general variance and apparently, as in case (a), the infiltration area seems to be the main factor influencing the k value. However, the conditioned variance of 72% of general variance is related to the devices' infiltration areas which cover different surfaces with different characteristics (e.g., cracks). To estimate if the infiltration area is the main factor which influences the k value, it is necessary to refer to a unit infiltration area, as in cases (c) and (d).

Case (*c*)—The correlation analysis between the ratio of the hydraulic conductivity value and the infiltration area k/A and the size of the infiltration area A was performed by the same methodology for all methods (Table 6 case (c)). The graph of Figure 9a, constructed with the ungrouped values of the parameters k/A and A, suggests a possible linear correlation between these two variables. The correlation ratio indicates a connection between k/A and the infiltration area A. The correlation coefficient, by its negative value, shows an inverse relationship between the two variables. That means that with increasing infiltration area, the value of the hydraulic conductivity related to a surface unit decreases. There is a higher degree of confidence for the values obtained with the test devices having larger infiltration areas. The value of the parabolic regression coefficient being much higher than that of the correlation coefficient $C_{rp} = 0.839 \geq \eta_{D(A)} = 0.577$, signify that the parabolic regression (Figure 9b) better approximates the relation between the two variables. The conditioned and residual variances represent 33% and 67% of the general variance, respectively. This means that other factors which were not considered at the beginning of the tests have a strong influence on the infiltration process and the comparative analysis between different methods of the k/A ratio values better emphasizes this influence. In this way, the differences in amplitude of the graphs from Figure 5 can be better explained. On the other hand, the decreasing values on k/A ratio with increasing A values (Figure 9b) confirm hypothesis "0", stated above, that the infiltration area is the main factor which influences k values and none of the other factors, taken separately, has a greater weight than 33%, and that the average value of the saturated hydraulic conductivity for all methods k_{avg} = 1.058 m/d (Table 5) better approximates the analyzed REV.

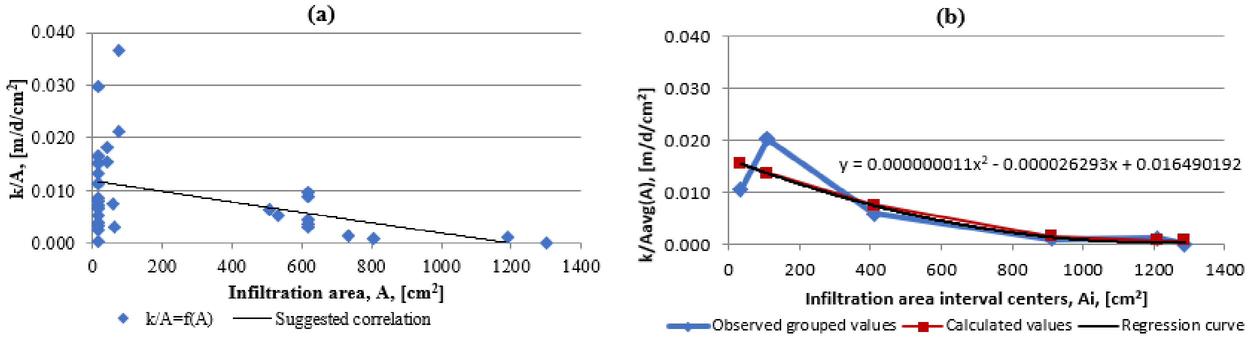

Figure 9. The correlation between *k/A* ratio and *A* values for all methods: (**a**)—ungrouped observed mean values; (**b**)—grouped observed and simulated mean values.

Case (d)—Keeping only the values of the *k/A* ratio for the test methods that characterize the terrain surface (TI, DRI and MDI) and eliminating the values for the IA method, the statistical parameters are presented in Table 6 case (d). The value of the correlation coefficient, $r = -0.237$, is about half that where all test methods were considered and indicates a poor inverse correlation between the two variables. Since the r value can be influenced by other variables, the strength of a correlation is better highlighted by the correlation ratio $\eta_{D(A)} = 0.434$, which indicates a moderate correlation between k/A ratio and infiltration area A for these methods. In conjunction with the value of the residual variance $s^2{}_{Do}$= 0.0000554, which represents 81% of the general dispersion $s^2{}_{D}$= 0.0000682, it means that the TI, DRI, and MDI methods are strongly influenced by other variables (roots, superficial cracks, wormholes, etc.). In Figure 10a, the ungrouped mean values of k/A ratio suggest a parabolic correlation between independent and dependent variables, which is confirmed by Figure 10b. The value of the parabolic regression coefficient is $C_{rp} = 1$.

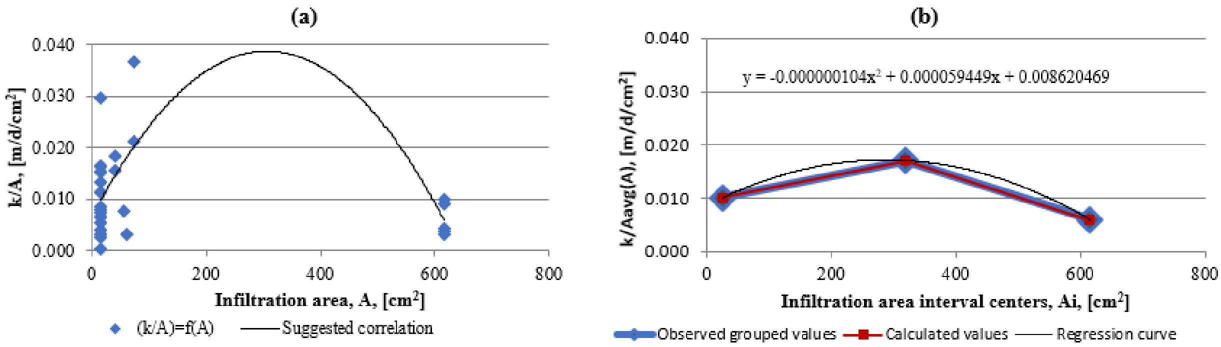

Figure 10. The correlation between *k/A* ratio and *A* values for the TI, DRI, and MDI methods: (**a**)—ungrouped observed mean values; (**b**)—grouped observed and simulated mean values.

If we compare the percentage values of unconditioned variances for the last two analyzed situations for the *k/A* ratio (67% for all methods and 81% for testing methods only on the land surface), the following observations can be made: (1) the lower value obtained in the first case is due to the fact that the influence of the other variables is attenuated by the values obtained by the IA method, where the drying cracks or roots have a lower weight with increasing depth; (2) starting from the hypothesis "0", it is observed that even for heterogeneous soil, the value of the ratio *k/A* decreases with the increase in the infiltration area (Figure 9). Even if the cumulative influence of other variables is 67%, all of them still exceed the value of the conditioned variable (33%), the infiltration area being the independent variable with the most important weight. In the second case, where the share of unconditioned variables is very high (81%), in Figure 10b, it is observed that on the left side of the graph, the value of the *k/A* ratio increases with the increase in the infiltration area, which confirms hypothesis "1". This means that for values lower than 350 cm^2 (approximately), the infiltration area no longer represents the predominant independent variable. The right side of the curve described by the simulated values indicates a decrease in the *k/A* ratio with the increase in the infiltration area. The infiltration area becomes the main independent variable, the cumulative effect of the other unconditioned variables being attenuated by the increase in the infiltration surface, confirming hypothesis “0”. In this sense, the determination of the independent variable with the largest weight (on the left side of the graph) can be achieved by multiple regression analysis, which is not part of this study. Based on pumping tests on natural saturated and fissured (structurally heterogeneous) rocks, Rovey and Charles [40] showed that in order to obtain a characteristic value of the hydraulic conductivity, it is necessary that the surface on which the tests are performed must be representative from the point of view of heterogeneity, so it must be higher than that considered statistically “homogeneous”. In this study, we demonstrated this by analyzing the variation of *k/A* ratio values versus the variation of *A* values for anthropogenic soil starting from a unit surface (1 cm^2) hypothetically considered homogeneous. When the *k/A* values decrease with increasing A values, then the variation of soil “homogeneity” from the microscale to the macroscale is insignificant; vice versa, when the values of the ratio *k/A* increase with the increase in A, then this variation is significant.

It should be noted that the graphs in Figures 8 and 10 have an indicative and explanatory character because the number of values representing the infiltration area was diminished by extracting those corresponding to the IA method. Those values covered a range between 508 and 1303 cm^2 (Table 5), the series of values being very narrow and represented by those methods with very small area (MDI) or much larger (DRI). This has led to a small number of grouping intervals with unequal dimensions, which does not ensure accuracy of the simulated values. At the same time, the domains defined by the graphs should not be extrapolated because, even in the case of more data where the values of the infiltration area would have a uniform distribution, extrapolation is limited by the physical meaning of the variables. Thus, in the graph of Figure 10b, for values greater than 800 cm^2 of the infiltration area, the value of the *k/A* ratio will not take negative values as the value of *k* can never be less than zero.

5. Conclusions

Four methods (TI, DRI, MDI, and IA), with different infiltration areas *A* of the devices, were used to quantify the saturated hydraulic conductivity *k* for an anthropogenic unsaturated soil consisting of sand, gravel, boulder elements, brick residues, glass, and concrete, trapped in a clayey matrix with roots of plants at the terrain surface. The ratio between test perimeter length and width is 17.7 m/3.81 m, so that the close locations of the different test methods led to a relative compensation to the effect of soil heterogeneity [38]. The average values of the saturated hydraulic conductivity obtained by the four test methods show significant differences between them. For the TI and IA methods, the saturated hydraulic conductivity values *k* determined for ungrouped values are relatively close (k_{TI} = 1.062 m/day and k_{IA} = 1.56 m/day). Comparing them to DRI values, they are more than two times lower (k_{DRI} = 3.687 m/day), and comparing to MDI values, they are higher by one order of magnitude (k_{MDI} = 0.160 m/day). For the TI and IA tests, several attempts were performed in the same location. Since the test procedure does not allow the assessment of the degree of saturation of the soil without disturbing it, this assessment was carried out after performing the tests by defining the domain of validity. The lower limit of the domain is represented by the average values of hydraulic conductivity determined on the basis of the average value of the hydraulic head variation. The upper limit represents the simple arithmetic mean of the observed values. The values above the upper limits are either considered overvalued or correspond to the unsteady state flow. Those below the lower limit are undervalued and could be explained either by temporary blocking of the water flow paths or due to the interaction of clay particles with the water, which can lead to the swelling of the clay material, or by the presence of entrapped air. For the selected hydraulic conductivity values inside the domain of validity, the values of standard deviation and of the variation coefficient are considerably lower compared to those for the observed values. The domain of validity presents the advantage that the final obtained values express the evolution of the physical phenomenon itself and does not consider only the statistically determined confidence interval on a range of values where, sometimes, the lower limit can be negative, which physically is not possible. The regression line inside the validity area indicates a steady state water seepage when it is horizontal or a steady state initial stage when the gradient is close to zero (answer to question (1) raised in the Introduction section).

The amplitudes calculated between the average values of the saturated state hydraulic conductivity, obtained for each method, present the highest values for the devices with the largest infiltration surfaces. Apparently, this would contradict the hypothesis, stated by various authors, that the value determined for the hydraulic conductivity k (saturated state) approaches the real value as the infiltration surface A increases. In this sense, a new parameter $k^* = k/A$ was introduced which represents the hydraulic conductivity corresponding to a surface unit (1 cm^2) ideally considered homogeneous. Thus, the lowest values of the amplitudes of the k/A ratio, determined for each test method, were obtained for the methods with the largest test area, DRI and IA, and the highest values for the methods with the smallest surface areas of infiltration, MDI and TI (answer to question (2)). The statistical significance of the amplitude of the k/A ratio is in accordance with the physical reality. The decrease in the k/A value with the increase in the A value, within the same method or between different methods, indicates that the infiltration area represents the main independent variable that controls the variability of the hydraulic conductivity. The increase in the k/A value with the increase in the A value indicates that the infiltration area no longer represents the main independent variable on which the k value depends for the saturated state. With other words, in the first case, the variation of the terrain homogeneity is not significant from a small scale to a large scale, while in the second case, this variation is significant and there are one or more variables with a greater influence on the k value, such as cracks, roots, etc. (answer to question (3)).

The results obtained in this study should be applied to select a method from the point of view of its applicability function of the urban soil composition and should not be interpreted as confirming or invalidating the utility of one or another method. Correct evaluation of the saturated hydraulic conductivity has multiple urban uses and a correct lithological recognition is needed to choose a test method on unsaturated urban soil. For example, to evaluate the saturated hydraulic conductivity for a supporting layer (considered homogeneous) below a pervious pavement, devices with small infiltration area could be used. When evaluating shallow aquifer recharge or hypodermic flow, devices with large infiltration surfaces must be used and the obtained results must be based on a large number of tests imposed by the heterogeneity of the anthropogenic terrain (answer to question (4)).

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/w16131908/s1.

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References

1. Dijkstra, J.J.; Comans, R.N.; Schokker, J.; van der Meulen, M.J. The geological significance of novel anthropogenic materials: Deposits of industrial waste and by-products. *Anthropocene* **2019**, *28*, 100229. [CrossRef]
2. Vasquez-Sune, E.; Sanchez-Vila, X.; Carrera, J. Introductory review of specific factors influencing urban groundwater, an emerging branch of hydrogeology with reference to Barcelona, Spain. *Hydrogeol. J.* **2005**, *13*, 522–533. [CrossRef]
3. Boukhemacha, M.A.; Gogu, C.R.; Serpescu, I.; Gaitanaru, D.; Bica, I. A hydrogeological conceptual approach to stydy urban groundwater flow in Bucharest city, Romania. *Hydrogeol. J.* **2015**, *23*, 437–450. [CrossRef]
4. Gogu, C.R.; Gaitanaru, D.; Boukhemacha, M.A.; Serpescu, I.; Litescu, L.; Zaharia, V.; Moldovan, A.; Mihailovici, M.J. Urban hydrogeology studies in Bucharest City, Romania. *Procedia Eng.* **2017**, *209*, 135–142. [CrossRef]
5. Gogu, R.C.; Boukhemancha, M.A.; Gaitanaru, D.; Moraru, I. Interaction between City Subsurface Infrastructure and Groundwater. In Proceedings of the International Conference on Urban Drainage Modelling, Palermo, Italy, 23–26 September 2018.
6. Morbidelli, R.; Saltalippi, C.; Flammini, A.; Cifrodelli, M.; Picciafuoco, T.; Corradini, C.; Govindaraju, R.S. In situ measurements of soil saturated hydraulic conductivity: Assessment of reliability through rainfall–runoff experiments. *Hydrol. Process.* **2017**, *31*, 3084–3094. [CrossRef]
7. Youngs, E.G. Estimating hydraulic conductivity values from ring infiltrometer measurements. *J. Soil Sci.* **1987**, *38*, 623–632. [CrossRef]
8. Reynolds, W.D.; Elrick, D.E. Chapter 6: Measurement and Characterization of Soil Hydraulic Properties. In *Soil-Water-Solute Process Characterization: An Integrated Approach*; CRC Press: Boca Raton, FL, USA, 2005.
9. Lai, J.; Ren, L. Assessing the size dependency of measured hydraulic conductivity using double-ring infiltrometers and numerical simulation. *Soil Sci. Soc. Am. J.* **2007**, *71*, 1667–1675. [CrossRef]
10. Lai, J.; Luo, Y.; Ren, L. Buffer index effects on hydraulic conductivity measurements using numerical simulations of double-ring infiltration. *Soil Sci. Soc. Am. J.* **2010**, *74*, 1526–1536. [CrossRef]
11. Köhne, J.M.; Alves, J.J.; Köhne, S.; Tiemer, B.; Lennartz, B.; Kruse, J. Double-ring and tension infiltrometer measurements of hydraulic conductivity and mobile soil regions. *Pesqui. Agropecuária Trop.* **2011**, *41*, 336–347.
12. Fallico, C.; Migliari, E.; Troisi, S. Comparison of three measurement methods of saturated hydraulic condutivity. *Hydrol. Earth Syst. Sci. Discuss.* **2006**, *3*, 987–1019.
13. Lee, D.M.; Elrick, D.E.; Reynolds, W.D.; Clothier, B.E. A comparison of three field methods for measuring saturated hydraulic conductivity. *Can. J. Soil Sci.* **1985**, *65*, 563–573. [CrossRef]
14. Reynolds, W.D.; Bowman, B.T.; Brunke, R.R.; Drury, C.F.; Tan, C.S. Comparison of tension infiltrometer, pressure infiltrometer, and soil core estimates of saturated hydraulic conductivity. *Soil Sci. Soc. Am. J.* **2000**, *64*, 478–484. [CrossRef]
15. Beven, K.; Germann, P. Macropores and water flow in soils. *Water Resour. Res.* **1982**, *18*, 1311–1325. [CrossRef]
16. Van Hoorn, J.W. Determining hydraulic conductivity with the inversed auger hole and infiltrometer methods. In Proceedings of the International Drainage Workshop, Wageningen, The Netherlands, 16–20 May 1978; Wesseling, J., Ed.; ILRI publication: Nairobi, Kenya, 1979; pp. 150–154.
17. Bagarello, V.; Iovino, M.; Lai, J. Testing steady-state analysis of single-ring and square pressure infiltrometer data. *Geoderma* **2015**, *261*, 101–109. [CrossRef]
18. Bockheim, J.G. *Nature and Properties of Highly Disturbed Soils, Philadelphia, Pennsylvania*; Paper Presented before Div. S-5; Soil Science Society of America: Chicago, IL, USA, 1974.
19. Craul, P. A description of urban soils and their desired characteristics. *J. Soc. Arboric.* **1985**, *11*, 330–339. [CrossRef]
20. Meng, X.; Liao, H.; Zhang, J. Infiltration law of water in undisturbed loess and backfill. *Water* **2020**, *12*, 2388. [CrossRef]
21. Batsilas, I.; Angelaki, A.; Chalkidis, I. Hydrodynamics of the Vadose Zone of a Layered Soil Column. *Water* **2023**, *15*, 221. [CrossRef]
22. Císlerová, M.; Šimůnek, J.; Vogel, T. Changes of steady-state infiltration rates in recurrent ponding infiltration experiments. *J. Hydrol.* **1988**, *104*, 1–16. [CrossRef]
23. Sakaguchi, A.; Nishimura, T.; Kato, M. The effect of entrapped air on the quasi-saturated soil hydraulic conductivity and comparison with the unsaturated hydraulic conductivity. *Vadose Zone J.* **2005**, *4*, 139–144. [CrossRef]
24. Dikinya, O.; Hinz, C.; Aylmore, G. Decrease in hydraulic conductivity and particle release associated with self-filtration in saturated soil columns. *Geoderma* **2008**, *146*, 192–200. [CrossRef]
25. Bomboe, P. *Geologie Matematica. Volumul I. Analiza Statistica a Datelor Geologice (Mathematical Geology. Volume I. Statistical Analysisis of the Geological Data)*; University of Bucharest: Bucharest, Romania, 1979.
26. Wu, L.; Pan, L. A generalized solution to infiltration from single-ring infiltrometers by scaling. *Soil Sci. Soc. Am. J.* **1997**, *61*, 1318–1322. [CrossRef]
27. Wu, L.; Pan, L.; Mitchell, J.; Sanden, B. Measuring saturated hydraulic conductivity using a generalized solution for single-ring infiltrometers. *Soil Sci. Soc. Am. J.* **1999**, *63*, 788–792. [CrossRef]
28. Reynolds, W.D.; Lewis, J.K. A drive point application of the Guelph Permeameter method for coarse-textured soils. *Geoderma* **2012**, *187–188*, 59–66. [CrossRef]
29. Angulo-Jaramillo, R.; Bagarello, V.; Iovino, M.; Lassabatere, L. *Infiltration Measurements for Soil Hydraulic Characterization*; Springer: Berlin, Germany, 2016.

30. Reynolds, W.D.; Elrick, D.E.; Youngs, E.G. Part 4. Single-ring and double or concentric-ring infiltrometers. In *Method of Soil Analysis: Physical Methods*; Soil Science Society of America, Book Series 5; Soil Science Society of America, Inc.: Madison, WI, USA, 2002.
31. Philip, J.R. Numerical Solution of Equation of the Diffusion Type with Diffusivity Concentration Dependent. II. *Aust. J. Phys.* **1957**, *10*, 29–42. [CrossRef]
32. Philip, J.R. The theory of infiltration: 1. The infiltration equation and its solution. *Soil Sci.* **1957**, *83*, 345–358. [CrossRef]
33. Gupta, R.K.; Rudra, R.P.; Dickinson, W.T.; Patni, N.K.; Wall, G.J. Comparison of saturated hydraulic conductivity measured by various field methods. *Trans. ASAE* **1993**, *36*, 51–55. [CrossRef]
34. Rose, C.W.; Stern, W.R. Determination of withdrawal of water from soil by crop roots as a function of depth and time. *Soil Res.* **1967**, *5*, 11–19. [CrossRef]
35. Zhang, R. Determination of soil sorptivity and hydraulic conductivity from the disk infiltrometer. *Sci. Soc. Am. J.* **1997**, *61*, 1024–1030. [CrossRef]
36. Carsel, R.; Parrish, R.S. Developing joint probability distributions of soil water retention characteristics. *Water Resour. Res.* **1988**, *24*, 755–769. [CrossRef]
37. Decagon Devices, Inc. *Mini Disk Infiltrometer User's Manual*; Decagon Devices, Inc.: Pullman, WA, USA, 2006.
38. Bagarello, V.; Iovino, M.; Lai, J.B. Field and numerical tests of the two-ponding depth procedure for analysis of single-ring pressure infiltrometer data. *Pedosphere* **2013**, *23*, 779–789. [CrossRef]
39. Reynolds, W.D. Chapter 56. Saturated hydraulic conductivity: Field measurement. In *Soil Sampling and Methods of Analysis, Canadian Society of Soil Science*; Lewis Publishers: Boca Raton, FL, USA, 1993; pp. 599–613.
40. Rovey, I.I.; Charles, W. Digital simulation of the scale effect in hydraulic conductivity. *Hydrogeol. J.* **1998**, *6*, 216–225. [CrossRef]