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A Short Review of the Methods for Determining Saturated Hydraulic Conductivity and a Comparison of Large and Small-Scale In-Situ Methods

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Abstract

Saturated hydraulic conductivity (K_S) can be determined with correlation or hydraulic methods. Hydraulic methods can be classified as laboratory and large-scale or small-scale in-situ methods. Auger-hole, inversed auger-hole and Guelph Permeameter are the most common small-scale in-situ methods. The K_S determined by small-scale methods has high spatial variability, has different values in the horizontal and vertical directions, and varies in different depths. Large scale methods enter an extensive soil body into the measurement process to eliminate variation. This paper aimed to evaluate the conventional field methods of measuring K_S using the drain outflow as the reference method and investigate the effect of initial soil moisture on K_S's measuring accuracy by the inversed auger-hole method. Experiments were conducted in two 10-hectare research fields in south Khuzestan. K_S was measured by the inversed auger-hole method in barren, dry soil before constructing the irrigation and drainage network. After the construction, the K_S was measured by drainage water outflow as a large-scale method, as well as by auger-hole and inversed auger-hole methods in moist soil after several irrigations. The K_S measured by conventional small-scale in-situ methods in Fields One and Two were respectively 42.5% and 62.9% lower than the drainage water outflow method. Considering the drain outflow as the reference method, there is no significant advantage between the auger-hole and inverse auger-hole methods. As in Field One, the values obtained from the auger-hole method were closer to the reference method, and in Field Two, the values obtained from the inversed auger-hole method were closer.

Keywords: Auger-Hole method, Inversed Auger-Hole method, Drainage water outflow method, Soil matrix suction, Drains distance.

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Introduction

History shows that wherever human beings have achieved success in irrigation techniques, the process of territorial development, population growth, and improvement of living conditions has accelerated, and great steps have been taken in cultural progress. On the other hand, wherever drainage was not adequate or has been neglected, this progress has failed, like what happened for Ancient civilizations in Mesopotamia, China, and America (Hillel, 2000; Hanjra & Qureshi, 2010; Pessarakli, 2019). One of the most important reasons for the failure of irrigation projects around the world is still the lack of proper drainage, as more than one-third of irrigated lands in the world face salinity or waterlogging problems (Heuperman et al., 2002; Valipour, 2014; Singh, 2015 a,b). An irrigation project's sustainable success requires excess water and salt removal, which should be done by natural or artificial drainage. Construction of subsurface drainage systems using buried pipes is the most common activity to combat waterlogging and salinity. Drainage spacing equations have been developed to design such a system, and all of them use saturated hydraulic conductivity (K_S) as an input parameter. Saturated hydraulic conductivity is one of the most important hydrodynamic characteristics of the soils and its determination is difficult, time-consuming, and costly (Amoozegar & Warrick, 1986; Severino et al., 2003).

Saturated hydraulic conductivity from field investigations in alluvial soils shows a high spatial variability (Gallichand et al., 1991; De Pue et al., 2019). The K_S can also have a different value in the horizontal and vertical directions (Deb & Shukla, 2012) and vary in different depths. Grismer and Todd (1991) studied a clay soil where the vertical conductivity was about ten times lower than horizontal in the topsoil layer and almost five times lower in the deeper layers. Different methods have been developed to determine the K_S value, so besides the spatial non-uniqueness nature of K_S, depending on the measuring and calculation method, the K_S values in the same point, the same depth and the same direction could be significantly different (Verbist et al., 2013; Rezaei et al. 2016; Morbidelli et al., 2017).

As shown in Figure (1), the drainage streamlines flow in different depths and directions and, of course, in the whole field area. This implies that a lot of K_S data is needed to characterize the field K_S value adequately, but most projects do not have the budget to perform many field tests (Chapuis, 2012).

K_S can be determined with correlation or hydraulic methods (Ritzema, 2006). Correlation methods are based on predetermined relationships between an easily determined soil property and the K_S value. Quick-find or easily determined soil properties are those properties that are easy or cheap to measure and common in most soil science and soil mapping studies. These properties include soil texture, bulk density, clay content, and organic matter content. Many researchers have tried to establish such a relationship (Kunze et al. 1968; Gupta and Larson 1979; Puckett et al., 1985; Haverkamp & Parlange, 1986; Wösten & van Genuchten 1988; Vereecken et al., 1990; Jabro, 1992; Leij et al., 1997; Schaap et al., 1998, 2001; Cronican & Gribb, 2004; Nakano & Miyazaki, 2005; Costa, 2006; Ghanbarian-Alavijeh et al., 2010; Vienken & Dietrich, 2011; Chapuis, 2012). Although the correlation method is often simpler and quicker than its direct measuring, the relationship can be inaccurate (Ritzema, 2006).

Hydraulic methods can be classified as laboratory and in-situ methods. These methods are based on Darcy's Law; therefore, by observing hydraulic head and discharge values under imposed conditions, the K_S could be calculated. In laboratory hydraulic methods, the sample size is relatively small, and therefore the presence of slight heterogeneity in the sample causes drastic changes in the results. Besides, it is not easy to collect real undisturbed soil samples, and usually, not enough care is taken to prepare and transport these samples, so such methods are not recommended (Ankeny et al., 1991).

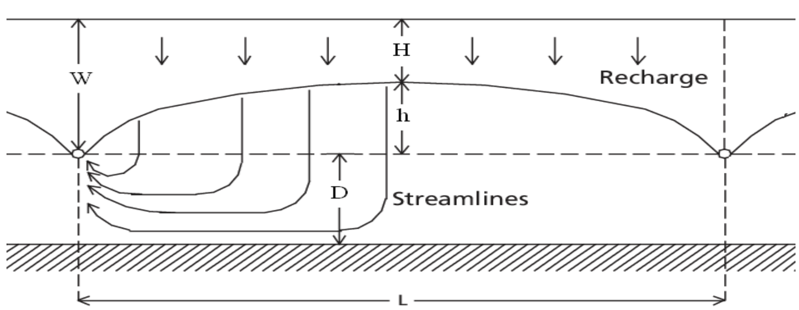

Fig. 1- Typical pipe drainage flow pattern (Van der Molen et al., 2007)

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In-situ or field methods can be either large-scale and small-scale. In small-scale methods, a borehole is dug into the soil with an auger to a certain depth. The K_S value will be determined based on the flow observation through the borehole wall. Depending on whether or not the water table is reachable in the desired depth, the methods can be divided into two categories: below the water table and above the water table; auger-hole and inversed auger-hole methods are widely used for these two situations, respectively.

Guelph Permeameter method, introduced by Elrick et al. (1989), is another small-scale method to measure in-situ saturated hydraulic conductivity above the water table. This method uses one-ponded water height under a quasi-steady-state condition. This calculation requires an empirical constant called the reciprocal of the macroscopic capillary length, α^*, ranging between 1 m^{-1} for compacted clays and 36 m^{-1} for course sands. α^* could be eliminated using two- or multiple-ponded heights, but not recommended because this procedure often produces invalid, i.e., negative, K_S values (Noborio et al., 2018). After introducing the Guelph Permeameter, some research worldwide has been done to eliminate or simplify the estimation of α^* like Reynolds and Elrick (1990), up to Noborio et al., (2018).

The soil volume engaged in the measurement process in the small-scale in-situ methods is larger than the laboratory methods, so the variability of the results is less but can often still be considerable. Another disadvantage is that the imposed flow conditions are often not representative of the flow condition accrue in the drainage process (Oosterbaan &Nijland, 1994). The large scale in-situ methods enter a very large soil body into the measurement process to eliminate variation as much as possible. For a single test, these methods are more expensive and time-consuming. Nevertheless, since they are more reliable, the required number of tests will be reduced, so time and money could be saved on the project scale. Pumping from wells and drain outflow are considered as large scale in-situ methods.

The drain outflow method uses observation of the drainage process and drainage equations to estimate hydraulic conductivity. In other words, in a land with installed subsurface drains like experimental or existing fields, all the effective parameters in the drainage process are measured, so the hydraulic conductivity can be determined and calculated as the only unknown parameter (which is usually the drain distance). Since the volume of soil involved in the process is much larger than in other methods (even pumping from wells as a large-scale method), it could be considered as the representative K_S more confidently.

The drain outflow method has two major advantages over other in-situ methods of measuring hydraulic conductivity:

- The variability of K_S in different depths and directions during the drainage flow paths in the soil profile (Figure 1) is considered automatically, so measuring the K_S in vertical and horizontal directions in different depths is unnecessary as well.
- The variability of K_S values estimated by the drain outflow method is much less than that in small-scale methods. EL-Mowelhi and VanSchilfgaarde (1982) found the K_S Values using the drain outflow method in a clay soil to vary from 0.086 to 0.120 m/d, which seems very desirable compared with the small-scale methods.

Although using the drain outflow method to determine K_S is recommended by drainage reference books (Ritzema, 2006; Vlotman et al., 2020), the number of research on this method is very limited. This paper aimed to evaluate the conventional field methods of measuring K_S using the drain outflow as the reference method and investigate the effect of initial soil moisture on the accuracy of K_S by the inversed auger-hole method. In other words, this study sought to examine how much conventional small-scale methods and large-scale methods determine different K_S values.

Materials and Methods

This study was conducted in Khuzestan province, approximately 50 km west of Ahvaz, in the village of Jalalieh in Azadegan plain, from April to September 2017. The research area is part of the southern Karkheh Noor development plan, located in the Karkheh River basin, and categorized as hot and dry areas in climate terms. The soils of this region are composed of alluvial sediments of the Karkheh River and its branches. The plain has a very low altitude, and the overall and lateral slopes are less than one percent. The main soil and land limitations of the Azadegan plain are related to salinity and sodicity, which is due to the heavy texture of surface soil, low permeability, high average annual air and soil temperature, and shallow saline groundwater. Subsurface drainage is inevitable to provide root aeration, salinity control, leaching, and land reclamation.

This research was conducted in two research fields with dimensions of 200 m by 500 m, each with an area of 10 hectares. In each of the research fields, nine observation wells were constructed at a depth of 230 cm between two lateral lines to observe the water table, as illustrated in Figure (2). The position of the observation wells was determined using a surveying camera. Three boreholes were drilled separately at a depth of 230 cm to measure the K_S by auger-hole and inverse auger-hole methods in each field. Two boreholes were drilled down to 120 cm, and drilled soil was transferred to the laboratory to measure its physical and chemical properties.

The observation wells were dug manually by an auger with a diameter of 10 cm. To prevent the well's wall from collapsing, observation wells were equipped with a 7 cm diameter mesh PVC pipe, and the distance between the pipe and the well's wall was filled with gravel. To prevent the entrance of surface water and other materials, the non-mesh PVC pipe was extended up to 30 cm above the soil surface, and around the drilling points were covered with sand-cement mortar. The walls were abraded using a hand scratcher to avoid the compaction of the well's wall porous media. Drilling a well in each field continued until the impermeable layer was reached. This layer was observed in both fields at a depth of about four meters.

For calculations related to the drain outflow method, the groundwater level had to be read relative to the reference level. For this reason, the level of the top of the pipes of each observation well was measured by a theodolite, which was used to calculate the groundwater level.

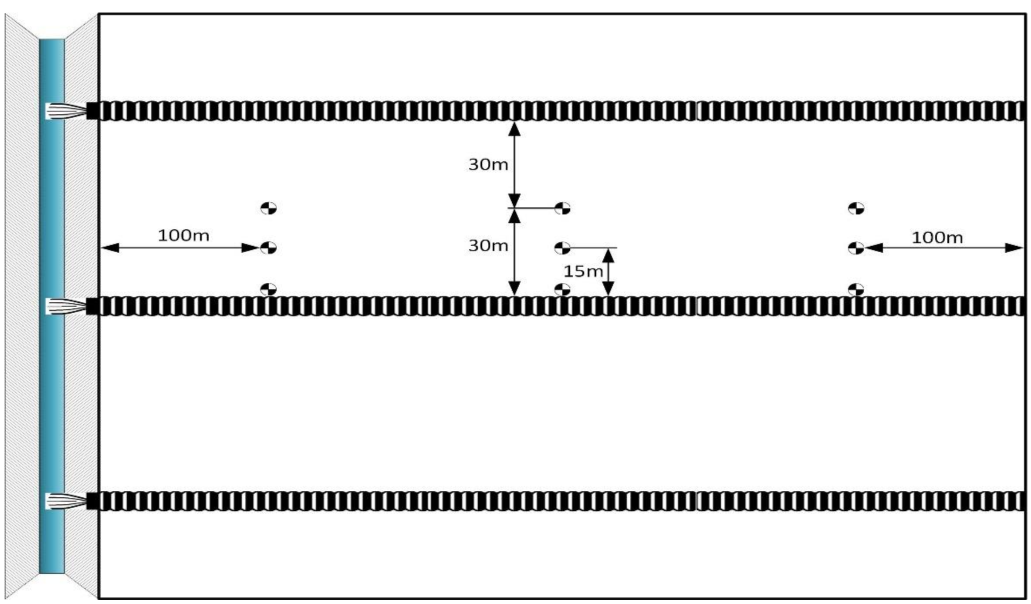

Fig. 2- Observation wells positioning at research fields

To investigate the effect of initial soil moisture on the measurement of K_S by the inversed auger-hole method, these measurements were performed under two initial soil moisture conditions. The first series of measurement was in barren land that had not been irrigated for a long time. These conditions usually govern when studying the plains of arid areas. The second series of measurement was done after equipping the land with a gravity irrigation system. After several heavy irrigations and performing tests of the drain outflow method, it took a while for the groundwater level to subside and the outflow water to cut off from the subsurface drains. Then the inversed auger-hole method experiments were repeated. In both cases, before measuring K_S, soil samples were taken at different depths to measure the initial moisture.

To measure the K_S by inverted auger-hole method, a water tank was moved to the site and the wells were kept continuously filled with water for at least an hour. After saturation of the soil around the well, the tests were performed by inverted auger-hole method and water subsidence was accurately recorded using a floating meter and stopwatch. This measurement was performed in three different points in each field and were repeated three times in each point.

After measuring the K_S in dry and barren soil by the inverted auger-hole method, subsurface drainage system was installed in the research fields and adjacent lands by a chain driven trencher. The drainage system consists of subsurface lateral pipe drains with an artificial envelope with a length of 500 meters, an installation depth of 1.30 meters, and a slope of 0.0008 m/m, which were discharged into open drains.

To measure the K_S by the drain outflow method, the whole area was irrigated every two weeks from May to September to get the area out of its initial dry state. Irrigation water was supplied from the main network canal, and a gravity irrigation system was used to irrigate the experimental fields. After the wetting stage, the research fields were irrigated for 24 hours. After the subsidence of water from the soil surface, the discharge of the two middle lateral drains of each field (to eliminate the marginal effect) was measured at the lateral outlet to the collector drain every day at a specific time, and the groundwater level in the observation wells was read simultaneously. According to Figure (1), by knowing the impermeable layer's depth, the distance and depth of the subsurface drain, the water table level, and the drainage coefficient (using the drainage flow), the K_S could be calculated using the Hooghoudt equation.

To measure the K_S by the auger-hole method, when the water table was high, three auger-hole were drilled in each field, and the measuring operation in each of these wells was repeated three times.

Results and Discussion

The soil particle size distribution of the research fields is presented in Table (1). As mentioned, to investigate the effect of initial soil moisture on the measurement of K_S by the inversed auger-hole method, these measurements were performed in Field One and Field Two, under two initial moisture conditions. In the first case, the land was barren and had not been irrigated for a long time. In the second case, one week after the last irrigation, when the groundwater level subsided and drains outflow was stopped, the K_S measuring tests by the inversed auger-hole method was repeated. Soil moisture status is measured in two moisture conditions, and its results are presented in Table (2). In general, the difference between the amounts of volumetric moisture decreases with depth, which is probably due to the rise of moisture by the capillary force from the groundwater. Also, there is more evaporation from the upper soil layers.

Table 1- Particle size distribution of and soil texture of research fields

Depth (cm)	particle size distribution						Soil texture	
	Clay		Silt		Sand			
	Field 1	Field 2	Field 1	Field 2	Field 1	Field 2	Field 1	Field 2
0-40	25	31	58	48	17	21	Silt Loam	Clay Loam
40-80	23	37	66	50	11	13	Silt Loam	Silty Clay Loam
80-120	39	53	54	36	7	11	Silty Clay Loam	Clay

Table 2- Moisture of soil layers in barren condition and after irrigation

Depth (cm)	Volumetric moisture content In barren soil before irrigation		Volumetric moisture content in Irrigated soil	
	Field 1	Field 2	Field 1	Field 2
0-40	27.75	24.15	42.3	34.5
40-80	33	32.55	45.15	36.9
80-120	40.95	37.95	51	47.4
120-180	43.5	42.75	Water table	51.45
180-220	46.95	45.75		47.4
220-260	34.5	37.2		Water table
260-300	31.8	Water table		
300-340	Water table			

Table 3- K_S measurement results by small-scale methods

	K_S (m/day)		
	Auger-hole method	Inversed auger-hole method in barren soil before irrigation	Inversed auger-hole method in irrigated soil
Field 1	1.019	1.06	0.90
	1.125	1.17	0.905
	1.70	1.14	0.95
Field 2	0.653	0.9	0.75
	0.70	0.97	0.71
	0.69	0.86	0.70

Measurement of K_S by conventional small-scale in-situ methods

K_S measurement results by small-scale methods, including auger-hole, inversed auger-hole in barren soil before irrigation, and inversed auger-hole in irrigated soil are presented in Table (3). The experiments were repeated three times at each point, and the reported number is the average of three repetitions. According to this table, the mean K_S obtained by the auger-hole method in Fields 1 and 2 were 1.28 and 0.68, respectively. There is less scattering between the K_S values obtained in this method in Field 2 as the coefficient of variation (*CV*) of the measured values by this method in this field was 5.39% while it was 24.83% in Field 1. This could be due to more heterogeneity of soil properties on Field 1.

The values of K_S measured by inverse auger-hole method in barren soil are less scattered compared to the values obtained by the auger-hole method as the coefficient of variation of these values in Field 1 has decreased from 24.83% in the auger-hole method to 5.06% in the inversed auger-hole method in barren soil. The values in Table (3) show even less scatter in measuring K_S by inverse auger-hole method in irrigated soil than in the previous two methods. The *CV* of K_S values in this method in Fields1 and 2 was 3.0 and 3.67 percent, respectively. This indicates that the reasons for experimental error in the inverse auger-hole method in irrigated soil are fewer than in the inverse auger-hole method in dry barren soil. It can be said that the difference in soil matric suction between the measuring points in the barren condition was the main cause of more error in this method.

The average K_S measured by the inversed auger-hole method in irrigated soil moisture conditions in Fields 1 and 2 is 22.5% and 26.9% less than the measured values in barren soil conditions. It can be said that the increase in the measured values in barren soil conditions is due to the higher matrix suction of the soil around the measuring point, which increases the water seepage in the direction of the suction gradient to the surrounding environment.

K_S measurement by drain outflow method

Drainage conditions in irrigated lands in arid and semi-arid regions are naturally unsteady; however, drainage conditions in these areas can be assumed steady in short time steps. This assumption explains the uses of the steady-state equations for calculating K_S by the drain outflow method. Equation 1 is the Hooghoudt equation for drainage under steady-state conditions:

$$q = \frac{8K_S h(d + \frac{h}{2})}{L^2} \quad (1)$$

where

q: drainage coefficient (m/day), which is equal to the sum of the discharge of two middle lateral pipe drains (in cubic meters per day) divided by the area under drainage by both of them (in square meters).

h: hydraulic head over pipe drain flow; the difference between the average level of pipe drain installation depth and the average water level in the middle observation wells between two middle lateral pipe drains.

L: the distance between the lateral pipe drains (m).

D: distance of pipe drains level to the impermeable layer (m).

K_S: Saturated hydraulic conductivity (m/day).

d: Equivalent depth to the impermeable layer, as described by Equation (2) (m).

$$d = \frac{D}{\left(\frac{8D}{\pi \mathrm{L}} \ln\frac{D}{u}\right) + 1} \quad (2)$$

As mentioned, in any measurement (in any data set), the conditions can be considered stable. That is, by placing the rest of the parameters, a K_S is calculated.

By rewriting Equation (1) based on K_S, we have:

$$K_S = \frac{qL^2}{8h(d + \frac{h}{2})} \quad (3)$$

Even though *L* and *d* are constant, the parameters q and h will have different values in the days after irrigation. Therefore, the K_S values calculated by this method in the days after irrigation are calculated separately and are presented in Table 4. In each field, three observation wells were drilled in the midline of two subsurface pipe drains. The values are shown inTable (4), which report the average value of parameter h in these three wells.

Table 4- Values of effective parameters in Hooghoudt equation for calculation of K_S by drain outflow method

Calculation time	*L* (m)	*d* (m)	*h* (m)		*q* (mm/day)		K_S (m/day)	
	fields 1 & 2	fields 1 & 2	field 1	field 2	field 1	field 2	field 1	field 2
Two days after watering	60	1.65	0.59	1.34	5.4	11.3	2.23	1.68
Three days after irrigation	60	1.65	0.43	1.05	3.0	10.2	1.83	2.08
Four days after watering	60	1.65	0.32	0.61	2.1	5.2	1.71	2.46

According to Table (4), changes in K_S values calculated by the drain outflow method on different days after irrigation do not follow a specific trend. As in Field 1, this trend has gone to less K_S values in the days after irrigation and in Field 2 to higher values. In the days after irrigation, the water table decreases from the upper layers of the soil, and thus the role of these layers in the calculation of K_S disappears. On the other hand, when there is a higher hydraulic head between two drains, the flow lines will be deeper. Therefore, in the first days after irrigation, deeper layers play a greater role in the K_S calculation by the drain outflow method. In other words, it can be said that in the drainage process during the days after irrigation, the volume of soil involved in the process becomes more limited to the middle layers closer to the subsurface drains. This has led to significant changes in K_S values measured by this method.

Comparison of K_S measurement by different in-situ methods

Based on Duncan's test results, indicated in Table (5), there is no significant difference between the K_S by small-scale in-situ measurement methods at the level of 5%. Measurement of K_S by drain outflow method, which was considered a reference method in this study, shows higher values than other methods and its difference is significant at the level of 1%. As in Field 1, the K_S values by the auger-hole method, the inversed auger-hole method in barren soil, and the inversed auger-hole in irrigated soil were obtained 33.4%, 41.8% and 52.2% less than those by the drain outflow method, respectively. In Field 2, the K_S values obtained by the auger-hole method, inversed auger-hole method in barren soil, and inversed auger-hole method in irrigated soil were calculated 67.2%, 56.2%, and 65.3% lower than those by the drain outflow method, respectively. In summary, K_S measured by conventional small-scale in-situ methods in Fields 1 and 2 were 42.5% and 62.9% less than those measured by the reference method of drain outflow, respectively. Mohanty et al. (1994) also reported that hydraulic conductivity measurement methods with smaller sample sizes show lower K_S values, and the method with the biggest sample size shows maximum K_S values.

Besides the drain outflow method, auger-hole method in Field 1 and inversed auger-hole method in barren soil before irrigation in Field 2 have shown bigger K_S values than other methods. This could be strange, but in another case on a stony loam soil, Vanderlinden et al. (1998) observed larger K_S values with the constant-head well permeameter than with the tension infiltrometer. However, Mohanty et al. (1994) reported contrasting results on a similar soil after (Verbist et al., 2013). Various K_S trends for different soil types, structures, textures, and field conditions have been reported in other research works (Kanwar et al., 1990; Gupta et al., 1993; Reynolds & Zebchuk, 1996; Reynolds et al., 2000).

Table 5- Comparison of K_S measurements by large and small-scale methods

	Drain outflow method		Inversed auger-hole method in barren soil before irrigation		Inversed auger-hole method in irrigated soil		Auger-hole method	
	K_S (m/day)	*CV* %	K_S (m/day)	*CV* %	K_S (m/day)	*CV* %	K_S (m/day)	*CV* %
Field 1	1.92a	14.2	1.12b	5.1	0.92b	3.0	1.28b	24.8
Field 2	2.08a	18.8	0.91b	6.6	0.72b	3.7	0.68b	5.4

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The *CV* of K_S calculated by drain outflow method in the second to fourth days after irrigation in Field 1 and 2 was 14.2 and 18.8%, respectively. Except for the auger-hole method in Field 1, the other methods have shown less *CV* than the drain outflow method. This shows that despite the advantages of the drain outflow method, the results of this method were more variable in this research. Other researchers have noted that there is no standard benchmark method for measuring hydraulic conductivity (Dirksen, 1999; McKenzie & Cresswell, 2002; Jačka et al., 2014). However, due to the much larger sample size, similar flow lines, and similarity of the layers involved with the actual drainage process, it can be considered a reference method for land drainage purposes.

The drain's distance has a direct relation to K_S; the higher the K_S, the greater the distance of the drains. In other words, the distance of the drains will change approximately in proportion to the square root of K_S. Therefore, if K_S is less than the actual value, the drains' distance will be less, the density of drains per unit area will be more, and the drainage costs will increase. By generalizing these cases, it can be seen that should the K_S values obtained from conventional in-situ methods be used to calculate the distance of drains, the distance of the drains will be less than when the K_S values obtained by the drain outflow method are used, and the cost of the drainage system will increase unnecessarily.

Conclusions

In the inversed auger-hole method in dry barren soil, the higher matrix suction led to increased water seepage in the direction of the suction slope to the surrounding environment. Therefore, the K_S values obtained in these conditions are higher than the real K_S of irrigated lands. Considering the drain outflow as the reference method, there is no significant advantage that can be attributed to either the auger-hole or the inverse auger-hole method. In Field 1, the values obtained from the auger-hole method were closer to the reference method, and in Field 2, the values obtained from the inversed auger-hole method were closer. However, all of these methods estimated K_S less than the reference method of the drain outflow (which simulates the main drainage process). Therefore, it is suggested that, to determine K_S in large drainage projects, a similar study on a larger scale be carried out on pilot fields. Then, guidelines for estimating K_S values should be created using a database obtained from this method and matched with easily determined soil properties (such as soil texture).

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