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Automation of the measurement of time record in determining the hydraulic conductivity of saturated soil[1]

Automação da medição de registro do tempo na determinação da condutividade hidráulica do solo saturado

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HIGHLIGHTS:

Auto Ksat allows real-time data visualization, enabling discrepant data verification.
The created and tested system improved the precision of the measurement of soil water flux in laboratories of soil physics.
The automated system is a viable option to determine the hydraulic conductivity by the falling head method.

ABSTRACT: The objective of this study was to automate the acquisition of water travel time, as well as the computation of hydraulic conductivity of saturated soil by the falling head method, using water sensors and the Arduino platform. To automate the measurement of travel time, the Arduino Uno board was used, and two water sensors were installed at the initial (h_0) and final (h_1) heights of the water inside the core. When the water flows across the soil and the water level passes the bottom part of the initial sensor (h_0), the time recording starts; it ends when the water is absent from the final height of the second sensor (h_1). The equation for calculating the hydraulic conductivity was inserted into the algorithm so the calculation was automatic. Undisturbed soil samples were taken in a long-term no-tillage area. There were no significant differences for the time and hydraulic conductivity means between the permeameters. The coefficient of the residual mass index showed an overestimation of the time variable; thus, the automated permeameter improves the precision of time recording and saturated hydraulic conductivity estimated by the falling head method.

Key words: Arduino, water sensors, falling head method

RESUMO: Objetivou-se com esse estudo automatizar a aquisição da variável tempo bem como o cálculo da condutividade hidráulica do solo saturado pelo método da carga decrescente usando sensores de água e a plataforma Arduino. Para automatizar a medição da variável tempo, foi utilizado a placa Arduino Uno e instalados dois sensores de nível de água analógico nas alturas inicial (h_0) e final (h_1). Quando a água flui pelo solo e o nível da água passa pela parte inferior do sensor inicial (h_0), o registro do tempo começa; termina quando a água está ausente da altura final do segundo sensor (h_1). A equação para cálculo da condutividade hidráulica foi inserida no algoritmo para se ter o cálculo automaticamente. Amostras de solo indeformadas foram coletadas em uma área de plantio direto de longo prazo. Os valores médios do tempo e da condutividade hidráulica não apresentaram diferenças significativas entre os permeâmetros. O índice coeficiente de massa residual (CRM) mostrou superestimação da variável tempo, indicando que o permeâmetro automático melhora a precisão da medição do tempo e da condutividade hidráulica do solo saturado estimada pelo método da carga decrescente.

Palavras-chave: Arduino, sensores de água, método da carga decrescente

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Introduction

Soil hydraulic conductivity represents the ease with which water moves into the porous soil system and is an important variable in studies on soil management, crop production, and the transport of chemical elements (Oliveira et al., 2003; Mesquita & Moraes, 2004; Gonçalves & Libardi, 2013).

There are several methods to determine hydraulic conductivity both in the field and in the laboratory. Tests under laboratory conditions have some advantages, such as the control of boundary conditions (saturation, hydraulic load, and flux direction), time efficiency, and low costs (Marques et al., 2008).

Among the laboratory methods, the falling head method uses undisturbed soil samples previously saturated and submitted to variable hydraulic loads (Reynolds & Elrick, 2002). Using this approach, the time spent by the water to pass from the initial to the final height is determined via a chronometer. The automation of the measurement of time through the water sensors and algorithms represents an improvement in obtaining the hydraulic conductivity of saturated soils.

Di Prima (2015) and Fatehnia et al. (2016) have developed an apparatus for automating the measurement of hydraulic conductivity in the field. In the same way, Juárez et al. (2018) have developed an automated apparatus to monitor water flux rates and hydraulic conductivity in intermittent rivers and areas considered recharge zones to study and quantify infiltration volumes. None of them have used methods to determine hydraulic conductivity in the laboratory with the falling head method.

The objective of this study was to automate the acquisition of the water travel time, as well as the computation of the hydraulic conductivity of saturated soil by the falling head method, using water sensors and the Arduino platform.

Material and Methods

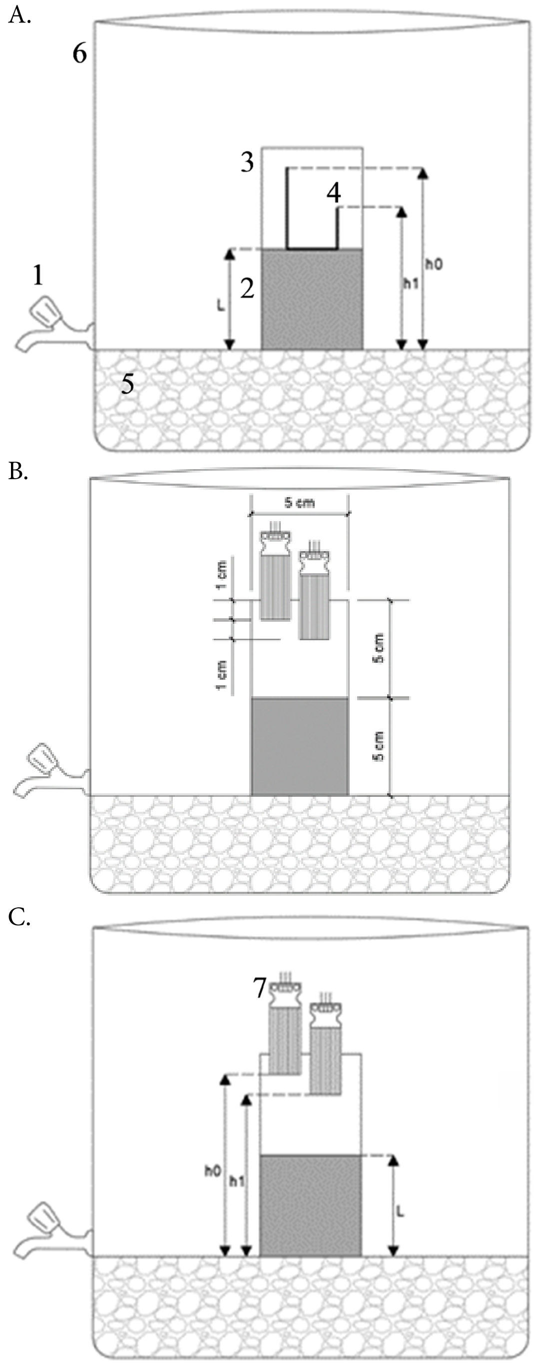
The conventional permeameter of the falling head method was built according to the methodology described by Reynolds & Elrick (2002) (Figure 1A), developed from August 2018 to March 2019 at the Soil Laboratory of Federal University of Paraná (UFPR) at Campus of Jandaia do Sul (23° 35' 47" S, 51° 38' 55" W, altitude of 803 m). The conventional permeameter is composed of a plastic recipient with a porous system (little pebbles) at the bottom (Figure 1A). The cylinders used were 0.05 m in diameter and 0.05 m in height (Figure 1B). In the metallic height measurer, the distance between h_0 and h_1 is 0.01 m (Figure 1A). The same distance was used in the automated permeameter (Figures 1B and C).

The assembly to estimate the hydraulic conductivity from the conventional permeameter was done as follows: a cylinder without soil was fixed on the cylinder with the undisturbed soil sample, and both were placed inside a recipient that is filled with water. The height measurer (h_0 and h_1) was gently positioned on the top of the undisturbed soil sample. Subsequently, the bottom hole of the recipient was opened, and water flowed through the soil sample, whose length (L) across the time (t) corresponds to the water displaced between the h_0 and h_1 markers. The hydraulic conductivity of the saturated soil (K_{sat}) was calculated using Eq. 1:

$$K_{sat} = \left(\frac{L}{t}\right)\ln\left(\frac{h_0}{h_1}\right) \quad (1)$$

where:

L, h_0, and h_1 - given in mm;
t - time in hours; and,
K_{sat} - hydraulic conductivity of saturated soil, mm h^{-1}.



1 - Bottom hole; 2 - Undisturbed soil sample; 3 - Cylinder without soil; 4 - Height measurer; 5 - Porous system; 6 - Recipient; 7 - Sensor

Figure 1. Conventional permeameter of the falling head method according to Reynolds & Elrick (2002) (A); automated permeameter of the falling head: design with sensors and measurements (B) and design with the sensors and the variables of the K_{sat} equation (C)

To automate the time measurement, the WiFi ESP8266 NodeMcu ESP-12 module was used (Figure 2A), and two Fundino FD-10 model analogic sensors were installed for measuring the water level (Figure 2B) at the initial (h_0) and final (h_1) heights. The sensor characteristics are shown in Table 1; according to the manufacturer, if the drop sensor were completely dry, the value would be zero. Whenever a drop of water touches the contacts of the sensor, the value would be at about 480. With this information, the sensors were tested and calibrated in the laboratory, and the values obtained were entered into the algorithm. The algorithm to determine the time the water travels between h_0 and h_1 was developed using the Arduino platform. The circuit mounting of the WiFi ESP8266 NodeMcu ESP-12 module with analogic sensors is shown in Figure 2C.

When the bottom hole of the recipient is open, the water flow across the soil sample starts, and the water level passes by

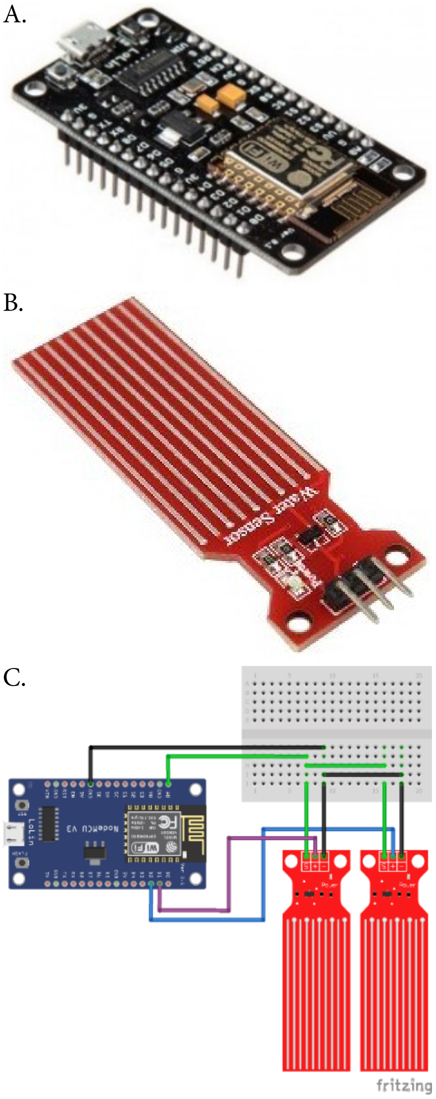


Figure 2. WiFi ESP8266 NodeMcu ESP-12 module (A); FD-10 analogic water level sensor, (B); circuit mounting of the WiFi ESP8266 NodeMcu ESP-12 module with two analogic sensors (C)

Table 1. Characteristics of the analogic water level sensor

Feed (V)	Current (mA)	Tension (V)	Temperature (ºC)	Area (mm²)	Humidity (%)
3-5	>20	0-2.3	10-30	40 × 16	10 to 90

the bottom part of the sensor (h_0) (Figure 1C). The time is then measured until the water level reaches the bottom of the second sensor (h_1). Subsequently, the time measurement is automated by the Arduino algorithm, and then hydraulic conductivity is calculated by the software. The design of the sensors in the automated permeameter is shown in Figures 1B and C.

The computational logic was developed through the Integrated Development Environment (IDE) of Arduino, adopting the following steps:

- The microcontroller starts the system, variables, and defined constants.
- From the serial communication, sensor reading is done by the conditions imposed on the algorithm.
- Based on the reading, variable transformation is performed to obtain the actual condition and time.
- The data collected by the sensors are sent from the serial port and exhibited on a serial monitor.

To calculate the hydraulic conductivity of saturated soil by the algorithm, the dimensions of volumetric cylinders 0.05 x 0.05 m were considered (most used for undisturbed soil samples). The values of h_0, h_1, and L were fixed, and time was determined via the software. To simplify the user interface, software was created that saves the data in an output table. This software was developed using the Visual Platform Studio Code version 1.36 and Eléctron version 5.0.5 (Visual Studio Code, 2019; Eléctron, 2019).

The Wi-Fi module was chosen because of its practicality; it does not need to be connected to the board by a USB cable but is powered by a 127-V plug. The module communicates in wireless mode with the computer, and the collected data are sent and stored. To fix the sensors at their height, double-sided tape was used, allowing the sensors to be removed without damaging the cylinder or the sensor and facilitating replacement if necessary.

For data acquisition, software was developed that communicates with the Arduino platform, transferring the collected values to the software. The interface is simple; the START command is pressed to initiate data collection. This command opens a box for entering information such as the computer's IP address, value update time, and the name of the file to be saved. When clicking SAVE, the data are collected automatically. The program stops collecting data automatically, and the STOP command is pressed to stop data collection if necessary. The EXPORT command is used to export data in .xls format; when it is pressed, a DOWNLOAD box appears, and clicking that box saves the data.

When the Wi-Fi network is not available, hydraulic conductivity analysis can be performed using the Arduino serial board. For this, the Arduino serial board should be connected by USB to the computer, and data must be typed in by the user because the serial board does not automatically save the data.

During the tests, it was observed that the analogic sensor is extremely sensitive. Thus, it is suggested that for each data collection, the sensors must be cleaned. Before the analysis, a test should be done to assure the sensors are working properly. The assembly of the sensors is shown in Figures 3A and B.

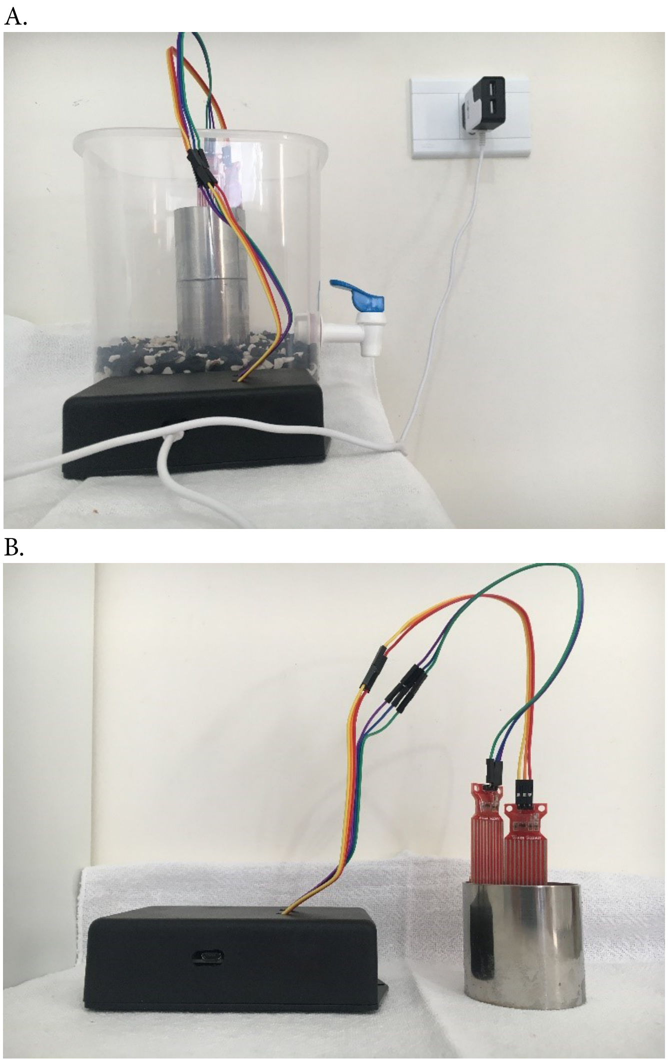


Figure 3. Final assembly of the automated permeameter (A); the assembly of the sensors is shown on the cylinder (B)

To test the automated permeameter, ten undisturbed soil samples were taken using volumetric cylinders (0.05 x 0.05 m) from a depth of 0–0.10 m in soil under long-term (since 1997) no-tillage in Borrazópolis, Paraná State, Brazil (23° 52' S and 51° 32' W, altitude of 444 m). The soil is an Oxisol with a clayey texture (Table 2). The soil samples were saturated and split into two groups for K_{sat} estimation by the falling head method using an automated permeameter (Arduino) and the conventional permeameter applying a chronometer.

The K_{sat} data were compared between the two methods, using the following statistical indices:

a) Agreement index - d (Legates & McCabe, 1999):

$$d = 1 - \frac{\sum_{i=1}^{N} |O_i - P_i|}{\sum_{i=1}^{N} \left(|P_i - \bar{O}| + |O_i - \bar{O}| \right)} \quad (2)$$

b)Deviation ratio - RD (Loague & Green, 1991):

$$RD = \frac{\sum_{i=1}^{N} (O_i - \bar{O})^2}{\sum_{i=1}^{N} (P_i - \bar{O})^2} \quad (3)$$

c) Efficiency coefficient - EF (Legates & McCabe, 1999):

$$EF = 1 - \frac{\sum_{i=1}^{N} |O_i - P_i|}{\sum_{i=1}^{N} |O_i - \bar{O}|} \quad (4)$$

d) Mean absolute error - MAE (Willmott et al., 1985):

$$MAE = N^{-1} - \sum_{i=1}^{N} |O_i - P_i| \quad (5)$$

e) Square root of the normalized quadratic mean error - RMSE (Loague & Green, 1991):

$$RMSE = \left[N^{-1} - \sum_{i=1}^{N} (O_i - P_i)^2 \right]^{0.5} \left(\frac{100}{\bar{O}} \right) \quad (6)$$

f) Unsystematic (RMSEu) and systematic (RMSEs) components of the normalized total error (Legates & McCabe, 1999):

$$RMSEu = \left[N^{-1} - \sum_{i=1}^{N} \left(\hat{P}_i - P_i \right)^2 \right]^{0.5} \left(\frac{100}{\bar{O}} \right) \quad (7)$$

$$RMSEs = \left[N^{-1} - \sum_{i=1}^{N} \left(\hat{P}_i - O_i \right)^2 \right]^{0.5} \left(\frac{100}{\bar{O}} \right) \quad (8)$$

g) Coefficient of residual mass - CRM (Loague & Green, 1991):

$$CRM = 1 - \frac{\sum_{i=1}^{N} O_i - \sum_{i=1}^{N} P_i}{\sum_{i=1}^{N} O_i} \quad (9)$$

Here, O is the arithmetic mean:

$$\bar{O} = N^{-1} \sum_{i=1}^{N} O_i \quad (10)$$

and P_i is the estimate of the dependent variable (Willmott et al., 1985):

Table 2. Soil physical-chemical characterization

Depth	pH	P	OC	Al^{3-}	Ca^{2+}	Mg^{2+}	K^{+}	Clay	Sand	Silt
(m)	$CaCl_2$	(mg dm^{-3})	(g dm^{-3})	($cmol_c$ dm^{-3})				(g kg^{-1})		
0-0.20	4.92	9.69	16.52	0.05	7.98	1.37	0.34	685	175	140

P - phosphorous; OC - organic carbon; Al - aluminum; Ca - calcium; Mg - magnesium; K - potassium

$$\hat{P}i = a + bO_i \quad (11)$$

where:

O_i - corresponds to conventional permeameter data;
P_i - corresponds to automated permeameter data; and,
N - number of experimental observations.

The student´s t-test was used to analyze the data means at p ≤ 0.05:

$$t = \frac{\bar{x} - \mu_0}{\frac{s}{\sqrt{n}}} \quad (12)$$

where:

x - arithmetic mean of time and conductivity variables from the automated permeameter;
μ_0 - arithmetic mean of time and conductivity variables from the conventional permeameter;
s - standard deviation; and,
n - number of experimental observations.

Results and Discussion

The descriptive statistics of the conventional and automated permeameter are shown in Table 3. According to Warrick & Nielsen (1980), the coefficients of variation are classified as low (< 12%), average (12 to 60%), and high (> 60%). The K_{sat} and time variables for both permeameters presented moderate coefficient of variation values. However, Klein et al. (2015) and Almeida et al. (2017) obtained high CV values for K_{sat} by the falling head method at the laboratory, varying from 54 to 108%. In addition, Lima et al. (2006) found CV values between 112 to 248% for K_{sat} determined by the constant head method. Gubiani et al. (2010) also found higher variability in K_{sat} measurements using the constant head method.

The CV values of K_{sat} and time were similar when comparing between permeameters in laboratory boundaries (Table 3). On the other hand, Di Prima et al. (2015), when evaluating field permeameters, found smaller CV values for automated versus conventional systems. All these results showed that K_{sat} is a variable measurement in the field or laboratory, which is directly dependent on soil structure heterogeneity rather than the determination methods.

The variables K_{sat} and time were not significantly different between the conventional and automated approaches (Table 3). The linearity obtained for K_{sat} and time (Figures 4A and B) corroborates with the absence of significance. This similarity suggests that the automated permeameter did not change how the data were collected. However, the difference between the means of the conventional and automated permeameter indicates a delay for the conventional permeameter due to the manual setting of the chronometer.

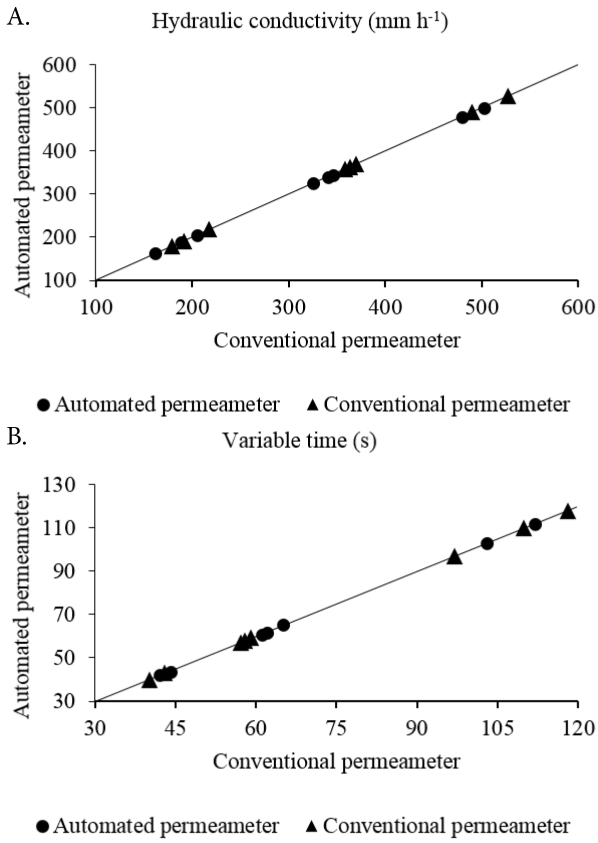


Figure 4. Relationship of the hydraulic conductivity (mm h^{-1}) data obtained by automated and conventional permeameters (A); relationship of the time data obtained by automated and conventional permeameters (B)

Corroborating these results, Fatehnia et al. (2016) did not find different means of K_{sat} between conventional and automated systems for double-ring infiltrometers. However, they stated that the numeric difference in K_{sat} promotes higher precision for data obtained from automated systems compared to those from conventional ones.

The statistical indices obtained from the relationship between automated and conventional permeameters to obtain time and K_{sat} are shown in Table 4. The values of R^2 for both measured variables demonstrate a better precision of the automated permeameter compared to the conventional one. If the adjusted degrees between the permeameters were perfect, the statistical indices would be as follows: d = RD = EF = 1 and MAE = RSME = RSMEa = RSMEs = CRM = 0.

Table 3. Descriptive statistics of the hydraulic conductivity of saturated soil (K_{sat}) and time obtained by conventional and automated permeameters

Variable	Mean	Median	Minimum	Maximum	SD	CV (%)
			Automated data acquisition			
K_{sat} (mm h^{-1})	318.32 a	332.24	162.19	502.03	128.22	40.28
Time (s)	77.38 a	63.50	42.00	130.00	33.05	42.72
			Conventional data acquisition			
K_{sat} (mm h^{-1})	337.01 a	360.46	178.69	527.13	132.21	39.23
Time (s)	72.75 a	58.50	40.00	118.00	30.79	42.32

For each variable, means followed by the same letter do not differ significantly by Student´s t-test at p ≤ 0.05. SD - standard deviation; CV - coefficient of variation

Table 4. Statistical indices for the relationship between automated and conventional permeameters

Variable	Statistical indices								
	R^2	D	RD	EF	MAE	CRM	RMSE	RMSEu	RMSEs
K_{sat} (mm h^{-1})	0.995	0.907	1.038	0.823	18.69	5.19×10^{-6}	6.203	12.078	6.505
Time (s)	0.993	0.914	0.848	0.826	4.62	-0.064	7.821	13.954	6.156

K_{sat} - hydraulic conductivity of saturated soil; R^2 - coefficient of determination; d - agreement index; RD - Deviation ratio; EF - efficiency coefficient; MAE - mean absolute error; CRM - coefficient of residual mass; RMSE - square root of the normalized quadratic mean error (%); RMSEu - unsystematic component of the normalized total error (%); RMSEs - systematic component of the normalized total error

The index d shows the homogeneity of data dispersion; the values were close to one for both variables (time = 0.914 and K_{sat} = 0.907). This indicates that the data acquisition affected the measurement precision, which is corroborated by the difference in the mean values (Table 3) of time and K_{sat}.

The RD index describes the ratio between the values obtained by the automated and conventional permeameters. A value close to 1 indicates that the data dispersion was similar for both permeameters. Similarly, the EF had values close to 1, indicating consistency of the data between both permeameters. The MAE indices were 4.62 and 18.69, respectively, for time and K_{sat}. The RMSE, RMSEu, and RMSEs describe the data values as a measurement of the mean deviation between automated and conventional permeameters; they presented values greater than zero (Table 4).

The positive or negative signal of the CRM index indicates if the automated permeameter tends to underestimate or overestimate, respectively, the values of the variables obtained compared to the conventional permeameter. The occurrence of overestimation is desirable because this indicates that automated permeameter promoted a more precise measurement. Thus, as time records presented an overestimation, the automated permeameter was more accurate than conventional ones. However, K_{sat} was underestimated by the automated permeameter, but the calculation of K_{sat} is directly dependent on the time record, which is measured by the sensors. Since K_{sat} is time-dependent, the larger the time variable, the smaller the K_{sat}, and the automated permeameter tends to underestimate this variable. Thus, the results of the CRM index indicate that the automated permeameter provided a good precision to estimate the K_{sat} values.

Ideally, the statistical indices should have values of d = RD = EF = 1 and MAE = RSME = RSMEa = RSMEs = CRM = 0, indicating that there is no difference between the permeameters. However, the ideal adjustment degree is not a desirable condition since it would mean that the automated permeameter would not differ from the conventional permeameter. Overall, the CRM, RMSE, RMSEu, RMSEs, and MAE index values differed from zero, indicating that the use of water sensors improved the precision when measuring the hydraulic conductivity of saturated soil. Similar results were found by Figueiredo (2010) using the same statistical indices and showing that the electrical sampler increased the quality of undisturbed samples compared to the Uhland sampler.

Besides the increase in precision of measurements by the automated permeameter, the Auto Ksat software allows the visualization of K_{sat} values by the serial monitor in real-time. Thus it is possible to verify discrepant data and repeat the test if necessary. This advantage was also reported by Gubiani et al. (2010) when evaluating the use of a falling head permeameter associated with K_{sat} software. They concluded that association brought more practicality and precision to K_{sat} measurements.

Conclusions

1. The absence of statistical differences between the permeameters indicates that time record automation is recommended to estimate saturated hydraulic conductivity.

2. The coefficient of residual mass index showed overestimation for the time variable, which indicates that automated permeameter, improves the precision of the time record and consequently of the saturated hydraulic conductivity estimated by the falling head method.

3. The automated falling head system is a viable option due to the facility of assembly as well as the open-access Arduino platform.

4. The Auto Ksat software provides the K_{sat} values in a serial monitor, allowing the verification of results in real-time.

Literature Cited

Almeida, K. S. S. A. de; Souza L. da S.; Paz, V. P. da S.; Silva, F. T. dos S.; Santos, D. N.; Pereira, J. da S. L. Variabilidade especial da condutividade hidráulica do solo saturado em Latossolo Amarelo distrocoeso, no município de Cruz das Almas. Irriga, v.22, p.259-274, 2017. https://doi.org/10.15809/irriga.2017v22n1p259-274

Di Prima, S. Automated single ring infiltrometer with a low-cost microcontroller circuit. Computers and Electronics in Agriculture, v.118, p.390-395, 2015. https://doi.org/10.1016/j.compag.2015.09.022

Eléctron. 2019. v.5.0.5. Available on: <https://www.electronjs.org/releases/stable>. Accessed on: Apr. 2019.

Fatehnia, M.; Paran, S.; Kish, S.; Tawfiq, K. Automating double ring infiltrometer with na Arduino microcontroller. Geoderma, v.262, p.133-139, 2016. https://doi.org/10.1016/j.geoderma.2015.08.022

Figueiredo, G. C. Avanços metodológicos e instrumentais em física do solo. Piracicaba: ESALQ, 2010. 163p. Tese de Doutorado

Gonçalves, A. D. M. de A.; Libardi, P. L. Análise de determinação da condutividade hidráulica do solo pelo método do perfil instantâneo. Revista Brasileira de Ciência do Solo, v.37, p.1174-1184, 2013. https://doi.org/10.1590/S0100-06832013000500007

Gubiani, P. G.; Reinert, D. J.; Reichert, J. M.; Gelain, S.; Minella, J. P. G. Permeâmetro de carga decrescente associado a programa computacional para determinação da condutividade hidráulica do solo saturado. Revista Brasileira de Ciência do Sol, v.34, p.993-997, 2010. https://doi.org/10.1590/S0100-06832010000300041

Juárez, P. R.; Junez-Ferrerira, H. E.; Trinidad, J. G.; Vargas, J. I. de la R.; Tejada, C. E. G.; Burnes S. Vadose zone hydraulic conductivity monitoring by using na arduino data acquisition system. 2018 International Conference on Electronics, Communications and Computers (CONIELECOMP), p.80-85, 2018. https://doi.org/10.1109/CONIELECOMP.2018.8327179

Klein, C.; Klein, V. A.; Levinski, F.; Bortolanza, D. R. Predição da condutividade hidráulica do solo saturado a partir de propriedades físicas do solo. Vivências, v.11, n.21, p.191-198, 2015.

Legates, D. R.; McCabe, Jr. G. J. Evaluating the use of "goodness-of-fit" measures in hydrologic and hidroclimatic model validation. Water Resources Research, v.35, p.233-241, 1999. https://doi.org/10.1029/1998WR900018

Lima, C. L. R. de; Reinert, D. J.; Reichert, J. M.; Suzuki, L. E. A. S.; Gubiani, P. I. Qualidade físico-hídrico e rendimento de soja (*Glycine max* L.) e feijão (*Phaseolus vulgaris* L.) de um Argissolo Vermelho distófico sob diferentes sistemas de manejo. Ciência Rural, v.36, p.1172-1178, 2006. https://doi.org/10.1590/S0103-84782006000400020

Loague, K.; Green, R. G. Statistical and graphical methods for evaluating solute transport models: overview and application. Journal of Contaminant Hydrology, v.7, p.51-73, 1991. https://doi.org/10.1016/0169-7722(91)90038-3

Marques, J. D. de O.; Teixeira, W. G.; Reis, A. M.; Cruz Junior, O. F.; Martins, G. C. Avaliação da condutividade hidráulica do solo saturado utilizando dois métodos de laboratório numa topossequência com diferentes coberturas vegetais no Baixo do Amazonas. Acta Amazonica, v.38, p.193-206, 2008. https://doi.org/10.1590/S0044-59672008000200002

Mesquita, M. da G. B. de F; Moraes, S. O. A dependência entre a condutividade hidráulica saturada e atributos físicos do solo. Ciência Rural, v.34, p.963-969, 2004. https://doi.org/10.1590/S0103-84782004000300052

Oliveira, L. F. C.; Bonono, R.; Carvalho, D. F. de; Cortês, F. C. Influência da condutividade hidráulica na altura do lençol freático, espaçamento de drenos e na produtividade do milho. Bioscience Journal, v.19, p.35-41, 2003.

Reynolds, W. D.; Elrick, D. E. Falling head soil core (Tank) method. In: Dane, J. H.; Topp, C. Methods of Soil Analyses. Physical methods. Madison: Soil Science Society of America, 2002. Cap.3, p.809-812.

Visual Studio Code. 2019. v.1.36. Available on: <https://code.visualstudio.com/updates/v1_36>. Accessed on: Jun. 2019.

Warrick, A. W.; Nielsen, D. R. Spatial variability of soil physical properties in the field. In: Hillel, D. Applications of soil physics. New York: Academic Press, 1980. 350p. https://doi.org/10.1016/B978-0-12-348580-9.50018-3

Willmott, C. J.; Ackleson, S. G.; Davis, J. J.; Feddema, K. M.; Klink, K. M.; Legates, D. R.; O'Donnell, J.; Rowe, C. M. Statistics for the evaluation and comparison of models. Journal of Geophysical, v.90, p.8995-9005, 1985. https://doi.org/10.1029/JC090iC05p08995