J. Hydrol. Hydromech., 70, 2022, 2, 234–243
https://doi.org/10.2478/johh-2022-0005

sciendo Journal of Hydrology and Hydromechanics Institute of Hydrology SAS

Estimation of hydrodynamic properties of a sandy-loam soil by two analysis methods of single-ring infiltration data

Vincenzo Bagarello*, Gaetano Caltabellotta, Massimo Iovino

Department of Agricultural, Food and Forest Sciences, University of Palermo, Italy, Viale delle Scienze, Building 4, 90128, Palermo, Italy.
* Corresponding author. Tel.: +39 09123897053. E-mail: vincenzo.bagarello@unipa.it

Abstract: Beerkan infiltration runs could provide an incomplete description of infiltration with reference to either the near steady-state or the transient stages. In particular, the process could still be in the transient stage at the end of the run or some transient infiltration data might be loss. The Wu1 method and the BEST-steady algorithm can be applied to derive soil hydrodynamic parameters even under these circumstances. Therefore, a soil dataset could be developed using two different data analysis methods. The hypothesis that the Wu1 method and BEST-steady yield similar predictions of the soil parameters when they are applied to the same infiltration curve was tested in this investigation. For a sandy-loam soil, BEST-steady yielded higher saturated soil hydraulic conductivity, K_s, microscopic pore radius, λ_m, and depth of the wetting front at the end of the run, d_{wf}, and lower macroscopic capillary length, λ_c, as compared with the Wu1 method. Two corresponding means differed by 1.2–1.4 times, depending on the variable, and the differences appeared overall from moderate to relatively appreciable, that is neither too high nor negligible in any circumstance, according to some literature suggestions. Two estimates of K_s were similar (difference by < 25%) when the gravity-driven vertical flow and the lateral capillary components represented the 71–89% of total infiltration. In conclusion, the two methods of data analysis do not generally yield the same predictions of soil hydrodynamic parameters when they are applied to the same infiltration curve. However, it seems possible to establish what are the conditions making the two methods similar.

Keywords: Soil hydrodynamic properties; Beerkan infiltration run; Data analysis methods; BEST methodology; Wu1 method.

INTRODUCTION

In the last thirty years, single-ring infiltration experiments have become popular for field determination of soil hydrodynamic parameters, mainly thanks to the progresses by the Canadian school (Elrick and Reynolds, 1992a; Iovino et al., 2017; Reynolds and Elrick, 1990; Reynolds et al., 2000). A single-ring experiment makes use of a ring with a small radius that is inserted into the initially unsaturated soil to a short depth. A constant depth of ponding is established on the soil surface confined by the ring and the three-dimensional infiltration process into the soil is monitored. Steady-state infiltration is attained after a transient phase of decreasing infiltration rates (Elrick and Reynolds, 1992a). Soil hydrodynamic properties are determined with different approaches using transient (Wu et al., 1999) or steady-state (Reynolds and Elrick, 1990) infiltration rates or a combination of both (Stewart and Abou Najm, 2018a, b).

An impulse to single-ring experiments was given by the French school nearly fifteen years ago, when the Beerkan Estimation of Soil Transfer parameters (BEST) procedure of soil hydraulic characterization was proposed for the first time (Angulo-Jaramillo et al., 2016; Lassabatere et al., 2006; Yilmaz et al., 2010). The beerkan experimental protocol is very simple since it only needs a small ring, a few liters of water and a stopwatch (Lassabatere et al., 2006). The ring is inserted to a small depth into the soil to avoid lateral loss of the applied water. Fixed, small volumes of water are repeatedly poured into the cylinder and the time elapsed during infiltration of each water volume is measured. The dataset thus describes an experimental cumulative infiltration curve that should include both transient and steady-state stages. These data can be analyzed to obtain the soil hydrodynamic parameters with three alternative algorithms based on the infiltration model by Haverkamp et al. (1994), known as BEST-slope (Lassabatere et al., 2006), BEST-intercept (Yilmaz et al., 2010) and BEST-steady (Bagarello et al., 2014), respectively. BEST-steady appears particularly attractive from a practical point of view since it can also be applied with a reduced experimental information for a run, that is total duration, total infiltrated water and steady-state infiltration rate (Bagarello and David, 2020; Bagarello et al., 2021). In other words, a failure for any reason in collecting transient infiltration data or a poor representation of this stage impede application of BEST-slope and BEST-intercept since these algorithms require fitting the transient infiltration model to the data. However, BEST-steady remains usable. An alternative method for estimating the soil hydrodynamic properties with a beerkan infiltration run is the so-called method 1 by Wu et al. (1999) or Wu1 method. This method is based on a different infiltration model from that of Haverkamp et al. (1994) and it does not necessarily require achievement of steady-state conditions (Stewart and Abou Najm, 2018a), whose attainment is instead necessary to apply any BEST algorithm.

Although performing an individual beerkan run is easy, the need to intensively sample the soil to obtain a good representation of its hydrodynamic behavior poses many practical problems that can make field work extremely expensive and demanding, especially on large areas (Bagarello et al., 2019a; Braud et al., 2017; Gonzalez-Sosa et al., 2010). Consequently, some runs could provide an incomplete description of the infiltration process. For example, especially in remote zones, water may represent a limiting factor. The decision could be performing as short as possible runs to save water. However, the risk is to poorly describe the near steady-state phase of the infiltration process (Gonzalez-Sosa et al., 2010). In other situations, performing almost simultaneously several replicated runs could be a good means to make field work more rapid (Lassabatere et al., 2019). In this case, the risk is to poorly describe the transient phase of the process, and hence to miss some hydrologically valuable information on capillarity effects or water repellency, since the operator has to follow simultaneously different runs in different rings, maybe spaced a few meters from each other.

In principle, a reduced experimental information at a sampling point does not necessarily compromise estimation of soil hydrodynamic parameters at that point. For example, the Wu1 method could be used if there are doubts about achievement of steady-state conditions by the end of the run whereas BEST-steady could be applied if the description of the transient phase is uncertain or incomplete (Figure 1). However, the use of these two data analysis methods to obtain comparable soil hydrodynamic parameters is possible if they yield similar results when they are applied to the same infiltration curve. This similarity has to be verified since predictions of soil hydrodynamic parameters can be expected to vary with the applied method of data analysis (Elrick and Reynolds, 1992b; Verbist et al., 2009; Xu et al., 2012). Therefore, the risk of using different data analysis methods for developing a single dataset is that it will be noised or heterogeneous since the chosen methods are not equivalent. To our knowledge, only Bagarello and David (2020) synthetically compared the Wu1 method and BEST-steady. The results were encouraging since a similarity between the two methods was recognized but a comparison limited to a single dataset does not demonstrate that these two methods should generally be expected to yield similar estimates of soil hydrodynamic properties.

The hypothesis of this investigation was that the Wu1 and BEST-steady methods yield the same prediction of soil hydrodynamic parameters when they are used to analyze the same infiltration process. An implication of a successful check of this hypothesis will be that an incomplete information on either the steady-state or the transient stage of the process at a sampling point, does not prevent the run from being considered for the development of a dataset of soil hydrodynamic parameters for an area of interest.

Therefore, the objective of this investigation was to compare BEST-steady with the Wu1 method. A relatively permeable soil was chosen for this investigation to be confident that attainment of steady-state flow conditions was not an expected factor influencing the established comparison.

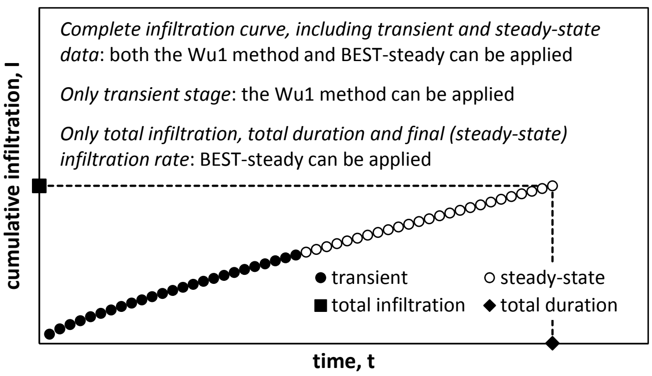

Fig. 1. Example of a hypothetical cumulative infiltration curve including transient and steady-state stages.

THEORY

The so-called Wu1 method (Wu et al., 1999) is based on the assumption that the following model can be used to describe the infiltration process:

$$I = A_w t + B_w t^{0.5} \tag{1}$$

where I (L) is the cumulative infiltration, t (T) is the time and A_w (L/T) and B_w (L/T$^{0.5}$) are the parameters of the model. Eq. (1) is fitted to the (t, I) data pairs measured from the beginning of the single-ring experiment to obtain an estimate of A_w and B_w. Then, the saturated soil hydraulic conductivity, K_s (L/T), is calculated as (Wu et al., 1999):

$$K_s = \frac{\lambda_c \, \Delta\theta}{T_c} \tag{2a}$$

$$\lambda_c = \frac{1}{2}\left[\sqrt{(H + G^*)^2 + 4G^* C} - (H + G^*)\right] \tag{2b}$$

where λ_c (L) is the macroscopic capillary length, expressing the relative importance of capillary over gravity forces (White and Sully, 1987), $\Delta\theta$ (L^3/L^3) is the difference between the saturated, θ_s (L^3/L^3), and the initial, θ_i (L^3/L^3), volumetric soil water contents, H (L) is the steady ponded depth of water on the infiltration surface, and the G^* (L), C (L) and T_c (T) terms have the following expressions, respectively (Wu et al., 1999):

$$G^* = d + \frac{r}{2} \tag{3a}$$

$$C = \frac{1}{4\,\Delta\theta}\left(\frac{B_w}{b}\right)^2 \frac{a}{A_w} \tag{3b}$$

$$T_c = \frac{1}{4}\left(\frac{B_w\, a}{b\, A_w}\right)^2 \tag{3c}$$

where d (L) is the ring insertion depth, r (L) is the ring radius and a and b are dimensionless constants (a = 0.9084, b = 0.1682). The Wu1 method is also usable with very small d values and a null H value (Wu and Pan, 1997).

The BEST-steady algorithm yields and estimate of K_s using the intercept, b_s (L), and the slope, i_s (L/T), of the straight line fitted to the data describing steady-state conditions on the cumulative I vs. t plot (Bagarello et al., 2014):

$$K_s = \frac{C_B\, i_s}{A\, b_s + C_B} \tag{4}$$

in which A (1/L) and C_B are constants that can be defined for the specific case of the Brooks and Corey (1964) hydraulic conductivity function as (Lassabatere et al., 2006):

$$A = \frac{\gamma}{r\Delta\theta} \tag{5a}$$

$$C_B = \frac{1}{2(1-\beta)\left[1 - \left(\frac{\theta_i}{\theta_s}\right)^{\eta}\right]} \ln\left(\frac{1}{\beta}\right) \tag{5b}$$

where β and γ are infiltration constants that are commonly set at 0.6 and 0.75, respectively, for $\theta_i < 0.25\ \theta_s$, and η is the shape parameter of the hydraulic conductivity function by Brooks and Corey (1964) which, in BEST, is estimated using soil textural and dry bulk density data (Lassabatere et al., 2006; Minasny and McBratney, 2007). According to Di Prima et al. (2020), λ_c can also be estimated from b_s as:

$$\lambda_c = 0.861 \frac{b_s}{\Delta\theta} \tag{6}$$

The characteristic microscopic pore radius, λ_m (L), is given by (White and Sully, 1987):

$$\lambda_m = \frac{\sigma}{\rho\, g\, \lambda_c} \tag{7}$$

where σ (M/T^2) is surface tension of water, ρ (M/L^3) is density of water, and g (L/T^2) is acceleration due to gravity. Taking the properties of pure water at 20 °C as appropriate, Eq. (7) reduces to $\lambda_m \approx 7.4/\lambda_c$, which is valid when λ_m and λ_c are expressed in mm. The λ_m value represents an effective equivalent mean radius of the pores that participate in the infiltration process (Iovino et al., 2016). The larger λ_m the greater the effect of gravity compared to capillarity as the infiltration driving force (Souza et al., 2014).

According to Wu et al. (1997), λ_c can be used to estimate the depth of the wetting front at the end of a single-ring infiltration run, d_{wf} (L), taking into account for lateral flow divergence:

$$d_{wf} = \frac{I_{tot}}{f\, \Delta\theta} \tag{8a}$$

where I_{tot} (L) is total infiltration and f is given by:

$$f = \frac{H + \lambda_c}{G^*} + 1 \tag{8b}$$

The empirical Horton (1940) infiltration model, also used in this investigation, is written as:

$$I = i_f t + \frac{i_0 - i_f}{k}\left(1 - e^{-kt}\right) \tag{9}$$

where i_0 (L/T) is the initial infiltration rate (t = 0), i_f (L/T) is the infiltration rate as $t \rightarrow \infty$ and the constant k (1/T) expresses the rate at which i_0 approaches i_f.

MATERIALS AND METHODS

The field experiment was carried out at the so-called "Aranceto" site of the Department of Agricultural, Food and Forest Sciences, University of Palermo (Italy) (38°06'24'' N, 13°21'06'' E). An approximately 150 m^2 flat area of an organic citrus orchard under no-tillage management, with trees of more than 35–40 years spaced 4 m × 4 m apart, was selected. Disturbed soil samples were collected from the upper 0–0.10, 0.10–0.20 and 0.20–0.30 m of the profile in June 2020 to determine the soil particle size distribution using conventional methods following H_2O_2 pre-treatment to eliminate organic matter and clay deflocculation with sodium hexametaphosphate and mechanical agitation (Gee and Bauder, 1986). The soil texture of the upper 0.3 m of the profile was sandy-loam according to the USDA classification system (clay = 14.4–15.5%, depending on the sampling depth; silt = 29.6–30.2%; sand = 54.9–55.4%; Bagarello et al., 2021). The mean organic carbon content, *OC* (%), of the upper few centimeters of the soil, determined with the Walkley-Black method, was equal to 3.1%.

Field infiltration experiments of the beerkan type (Lassabatere et al., 2006) were carried out during the months of June 2020 to April 2021. The main features of these experiments were: i) insertion of 0.08-m-diam. rings to a depth of 0.01 m on the soil surface; ii) filling plastic glasses with 57 mL of water for each glass; iii) infiltration runs carried out by successively pouring the water contained in a glass on the confined infiltration surface from a height of nearly 0.03 m. In particular, a given volume of water was poured in the ring in approximately 3 s at the start of the measurement and the elapsed time during complete infiltration was measured. An identical amount of water was subsequently poured into the ring, and the time needed for this water to infiltrate was logged. Although the existing guidelines suggest that 15 water volumes should generally be enough to collect nearly steady infiltration data (Lassabatere et al., 2006), 20 water volumes, corresponding to a total cumulative infiltration of 226.8 mm, were used in this investigation to possibly improve estimation of the steady-state infiltration rate (Lassabatere et al., 2019; Souza et al., 2014). This choice was considered reasonable not to violate the assumptions of homogeneous soil and uniform water content of the sampled soil volume with a longer experiment (Vandervaere et al., 2000).

A total of five sampling campaigns were carried out on different dates, even with other scientific objectives (Bagarello et al., 2021; Caltabellotta et al., 2021), by performing 16 runs at random points of the field site on each date. In particular, the first sampling campaign was carried out in ten days from June 29 to July 14, 2020. The soil was sampled again on July 20–21 and then on August 25 and 27. The fourth and the fifth sampling campaigns were carried out in autumn (nine days from November 3 to 16) and the subsequent spring (April 14–15, 2021), respectively. At each campaign, the spontaneous herbaceous vegetation was removed with shears while the roots remained in situ, as suggested by Lassabatere et al. (2006). Soil was repeatedly sampled during the experimental period to determine the dry soil bulk density, ρ_b (g/cm^3), and the volumetric soil water content, θ (m^3/m^3). On a given sampling day, undisturbed soil cores (0.05 m in height by 0.05 m in diameter) were collected at the 0 to 0.05 m and 0.05 to 0.10 m depths at three randomly chosen sampling points. These six cores were used to determine ρ_b and the gravimetric soil water content, w (g/g), and hence θ, in the laboratory. The data were averaged to obtain, for a given day, a ρ_b and an antecedent, θ_i, water content value of the upper 0.10 m of the soil. The saturated soil water content, θ_s (m^3/m^3), necessary for calculating soil hydrodynamic parameters, was estimated from ρ_b assuming that θ_s coincided with porosity (Mubarak et al., 2009).

For each infiltration run, both the Wu1 method and the BEST-steady algorithm were used to analyze the data. An estimate of A_w and B_w was obtained by fitting Eq. (1) to the experimental (t, I) data pairs using the SOLVER routine of Microsoft Excel software with the default settings (Microsoft Company, Redmond, WA). The quality of the fit was evaluated by calculating the relative error, *Er* (%), as suggested by Lassabatere et al. (2006):

$$Er = 100 \sqrt{\frac{\sum_{i=1}^{k}\left(I_i^{\exp} - I_i\right)^2}{\sum_{i=1}^{k}\left(I_i^{\exp}\right)^2}} \tag{10}$$

where $I_i^{\exp}$ and I_i are the experimental and modeled cumulative infiltration, respectively, and k is the number of data points describing an infiltration curve.

Considering that the last part of all infiltration processes appeared steady, as denoted by a nearly linear relationship between I and t, an estimate of i_s and b_s was obtained with linear regression analysis procedures by considering the last three data points in most cases (RE criterion, RE = regression).

BEST-steady theoretically assumes that steady-state conditions have been reached by the end of the run but steady-state estimation is unavoidably empirical. A means to possibly perceive anomalies in the applied i_s estimating criterion was thought to be establishing comparisons with other possible criteria. Therefore, five additional criteria taken from the literature were also applied to estimate i_s. In particular, steady-state was considered to be reached when two (Mubarak et al., 2009) or three (Mubarak et al., 2010) consecutive infiltration times, and hence infiltration rates, were identical. These two criteria were denoted as 2E and 3E (E = equal), respectively. Other two criteria were based on the largest percentage difference, Δ (%), between three consecutive infiltration rates, i_r (L/T), defined as:

$$\Delta i_r = \frac{\max(i_r) - \min(i_r)}{\min(i_r)} 100 \qquad (11)$$

In this case, the steady-state infiltration rate was estimated as the mean infiltration rate for the first three consecutive time intervals yielding a Δi_r value of less than 3% (3Q3 criterion; Q = quasi-equal; Bagarello and Giordano, 1999) or 5% (3Q5 criterion; Jabro, 1996) during an experiment. Taking into account that not less than eight water volumes should be used to perceive near steady-state conditions (Lassabatere et al., 2006), the 2E, 3E, 3Q3 and 3Q5 criteria were applied starting from the ninth water volume onwards. The last applied criterion, denoted as HO (HO = Horton), implied fitting the Horton (1940) infiltration model (Eq. 9) to the (t, I) data pairs, using the SOLVER routine of Microsoft Excel software (Microsoft Company, Redmond, WA), and setting i_s equal to i_f, in accordance with the applied methodology by Ciollaro and Lamaddalena (1998). As an example, the application of the different criteria to one of the infiltration curves of this investigation is shown in Figure 2.

An estimate of K_s, λ_c, λ_m and d_{fw} was obtained for each run with both the Wu1 method (denoted by the Wu1 subscript) and the BEST-steady algorithm (BS). In particular, Eqs. (2) and (3) were used to calculate $K_{s,Wu1}$ and $\lambda_{c,Wu1}$, respectively, whereas Eqs. (4)–(6) were used to determine $K_{s,BS}$ and $\lambda_{c,BS}$. Eq. (7) was applied to determine $\lambda_{m,Wu1}$ and $\lambda_{m,BS}$ from $\lambda_{c,Wu1}$ and $\lambda_{c,BS}$, respectively, considering a water temperature of 20 °C. An estimate of $d_{wf,Wu1}$ and $d_{wf,BS}$ was finally obtained with Eq. (8) using the appropriate estimates of λ_c.

The Lilliefors (1967) test was applied at P = 0.05 to test the normal distribution hypothesis of both the untransformed (NO) and the ln-transformed (LNO) K_s, λ_c, λ_m and d_{fw} values obtained with the two methods of analysis. The arithmetic mean and the associated coefficient of variation, CV, were used to summarize the data when the hypothesis of normally distributed untransformed data was not rejected. The geometric mean and the associated CV were calculated (Lee et al., 1985) when the non-rejected hypothesis was that of ln-normally distributed data. Several comparisons were then established between the two datasets for a given variable by performing two-tailed, paired t tests at P = 0.05 on the untransformed or the ln-transformed data, depending on their distribution. Linear regression analysis procedures and calculation of 95% confidence intervals for both the intercept and the slope of the linear regression line were also used to test the correspondence between two variables. The statistical significance of a fitted regression line to the data was established with a two-tailed t test at P = 0.05. The Tukey Honestly Significant Difference (THSD) test at P = 0.05 was used to determine the sampling date effect on the soil hydrodynamic parameters calculated with the two data analysis methods. Two

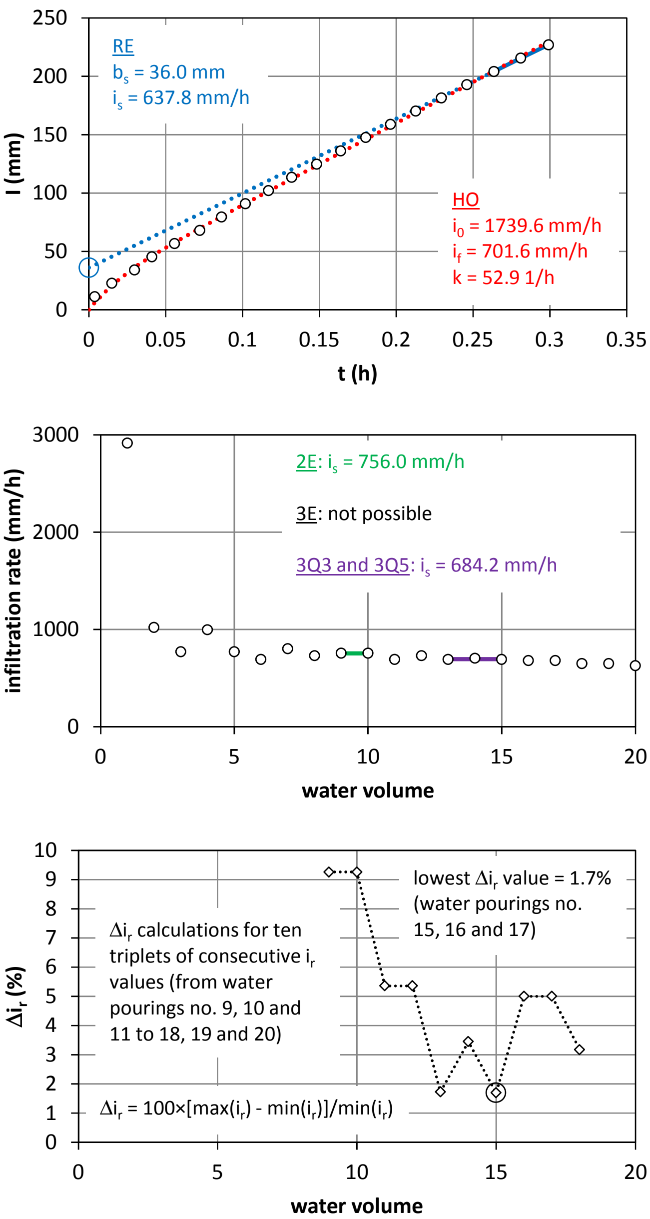

Fig. 2. Application example (P1 experiment of June 29, 2020) of the different criteria for estimating the steady-state infiltration rate, i_s (RE = regression criterion; HO = Horton criterion, 2E and 3E = identity of two and three consecutive infiltration rates, respectively; 3Q3 and 3Q5 = three consecutive infiltration rates, i_r, differing by less than 3% and 5%, respectively; I = cumulative infiltration; t = time; b_s = intercept of the straight line fitted to the data describing steady-state conditions on the I vs. t plot; i_0, i_f and k = fitting parameters of the Horton model).

tailed, paired t tests at P = 0.05 were also made to compare a soil hydrodynamic parameter obtained on a sampling date with the two methods.

RESULTS

The ρ_b, θ_i and θ_i/θ_s values measured in the N = 25 sampling days were summarized in Table 1. An inverse linear relationship (coefficient of determination, R^2 = 0.767, R > 0) was detected between ρ_b and θ_i. Therefore, the infiltration data were collected in different conditions, varying from a relatively compacted dry soil to a less compacted wet soil. The highest

θ_i/θ_s value was equal to 0.27 and θ_i/θ_s values marginally greater than 0.25 were recorded in three days. Consequently, BEST-steady was usable for estimating the soil hydrodynamic parameters (Lassabatere et al., 2006). Fitting Eq. (1) to the cumulative infiltration data yielded *Er* values never exceeding 3.1% and equal on overage to 1.2% (N = 80 infiltration curves). Therefore, Eq. (1) accurately described the measured infiltration processes (Lassabatere et al., 2006).

The mean duration of the infiltration runs was of nearly 0.3 *h* (CV = 49%). With reference to the K_s and d_{wf} datasets developed with the two analysis methods, only the LNO hypothesis was not rejected by the Lilliefors (1967) test (Table 2). For λ_c, the only non-rejected hypothesis was the NO one. For λ_m, the normal distribution hypothesis was rejected with reference to both the untransformed and the ln-transformed data but the largest difference between the empirical cumulative distribution function and the corresponding theoretical function was smaller in the latter case. Consequently, the geometric mean and the associated *CV* were used to summarize K_s, λ_m and d_{wf} whereas the arithmetic mean and the associated *CV* were used for λ_c.

The two calculation methods (BS, Wu1) yielded significantly different estimates of K_s, λ_c, λ_m and d_{fw} (Table 3). In particular, BEST-steady yielded higher means of K_s, λ_m and d_{fw} and a lower mean of λ_c as compared with the Wu1 method. For each parameter, the correlation between the two methods was statistically significant although not very strong (R^2 = 0.53–0.70, depending on the variable; R > 0 in all cases; Figure 3). According to the calculated 95% confidence intervals for the intercept and the slope (Table 3), the linear regression line between the data obtained with the BS and Wu1 methods did not coincide with the identity line. In particular, the former method tended to yield higher predictions of K_s, λ_c, λ_m and d_{fw} than the Wu1 method in the range of the lowest values of the considered variables and lower predictions in the range of the highest values. Finally, BEST-steady yielded consistently lower *CV* values than the Wu1 method.

According to the THSD test, there was not any difference between two sampling dates for λ_c, λ_m and d_{wf}, regardless of the applied data analysis method (Table 4). With reference to K_s, a time effect was noticed with BS (June-July 2020 > August 2020 = July 2020 = April 2021 = November 2020) but not with the Wu1 method. The two data analysis methods yielded significantly different K_s, λ_c, λ_m and d_{wf} results in four of the five sampling dates, that is with the exception of November 2020 (Table 4). Detecting statistically significant differences between two datasets is not enough to summarize the results of the comparison since it is necessary to also establish the relevance in practice of the significant differences. Literature allowed us to get an idea on the practical importance of these differences. In particular, Elrick and Reynolds (1992b) suggested that two K_s values differing by two or three times could be considered relatively similar given that, in the field, K_s can be expected to vary up to five orders of magnitude. A more stringent similarity criterion between two corresponding K_s values was adopted by Reynolds (2013), working with numerically generated data. In this last case, two estimates were considered similar when their ratio fell in the 0.75 to 1.25 range (differences by <25%). In this investigation, the two means of K_s differed by 1.3 times (Table 3) and two corresponding estimates of K_s at a sampling location differed at the most by 3.2 times. The individual $K_{s,BS}/K_{s,Wu1}$ ratios fell in the 0.75–1.25 range for the 26% of the experiments and the factor of difference between $K_{s,BS}$ and $K_{s,Wu1}$ did not exceed two and three in the 90% and 99% of the cases, respectively. Relative variability of K_s was high according to Warrick (1998) regardless of the calculation method. Therefore, BEST-steady yielded higher and less variable K_s values as compared with the Wu1 method but the differences between the two methods were overall moderate and perhaps negligible, at least in some circumstances. Also Bagarello and David (2020) obtained means of K_s differing by 1.3 times with these two methods but differences were not statistically significant in that case.

Table 1. Dry soil bulk density, ρ_b, antecedent volumetric soil water content, θ_i, and ratio between θ_i and the volumetric saturated soil water content, θ_s, during the sampling period (N = 25 sampling days).

Variable	**Min**	**Max**	**Mean**	***CV* (%)**
ρ_b (g/cm^3)	1.014	1.209	1.106	5.4
θ_i (m^3/m^3)	0.049	0.163	0.107	38.5
θ_i/θ_s	0.090	0.271	0.181	35.6

For a given sampling day, a value of ρ_b and a value of θ_i were obtained by averaging six individual determinations of ρ_b and θ_i, respectively.
Min = minimum value; Max = maximum value; *CV* = coefficient of variation.

Table 2. Results of the Lillefors (1967) test for each developed dataset (sample size, N = 80 for each dataset).

Variable	**Analysis method**	D_{max}		**Assumed distribution**
		NO	**LNO**	
K_s	BS	0.083	0.056	LNO
	Wu1	0.168	0.047	
λ_c	BS	0.065	0.106	NO
	Wu1	0.084	0.113	
λ_m	BS	0.163	0.106	LNO
	Wu1	0.328	0.113	
d_{wf}	BS	0.116	0.089	LNO
	Wu1	0.146	0.087	

K_s = saturated soil hydraulic conductivity; λ_c = macroscopic capillary length; λ_m = characteristic microscopic pore radius; d_{wf} = depth of the wetting front at the end of the run; D_{max} = largest difference between the empirical cumulative frequency distribution and the corresponding theoretical distribution; D_{crit} = critical value of D_{max} = 0.099; NO = normal; LNO = ln-normal.

With reference to λ_c, λ_m and d_{fw}, two corresponding means differed by 1.2–1.4 times, depending on the considered variable (Table 3). Even these differences did not seem very high but an examination of the literature suggested that they could have some practical relevance. In particular, the two calculation methods led to a different categorization of soil capillarity (Di Prima et al., 2020) since the λ_c data obtained with BEST-steady clearly suggested that the soil had a moderate capillarity (42 ≤ λ_c ≤ 125 mm) whereas, with the Wu1 method, the soil's capillarity was between moderate and strong (125 < λ_c < 1000 mm). Mubarak et al. (2009) concluded that a change by nearly 1.3 times in the depth of the wetted bulb under drip irrigation has to be considered marked. In this investigation, the two estimates of d_{wf} differed by 1.2 times suggesting at least a relatively appreciable difference. Finally, according to Warrick (1998), λ_c and λ_m exhibited a medium variability when they were deduced with BEST-steady but they were classified as highly variable with the Wu1 method. This different classification of the relative variability of the data could lead to a different perception of the required experimental efforts for characterizing an area of interest with a representative value of λ_c and λ_m.

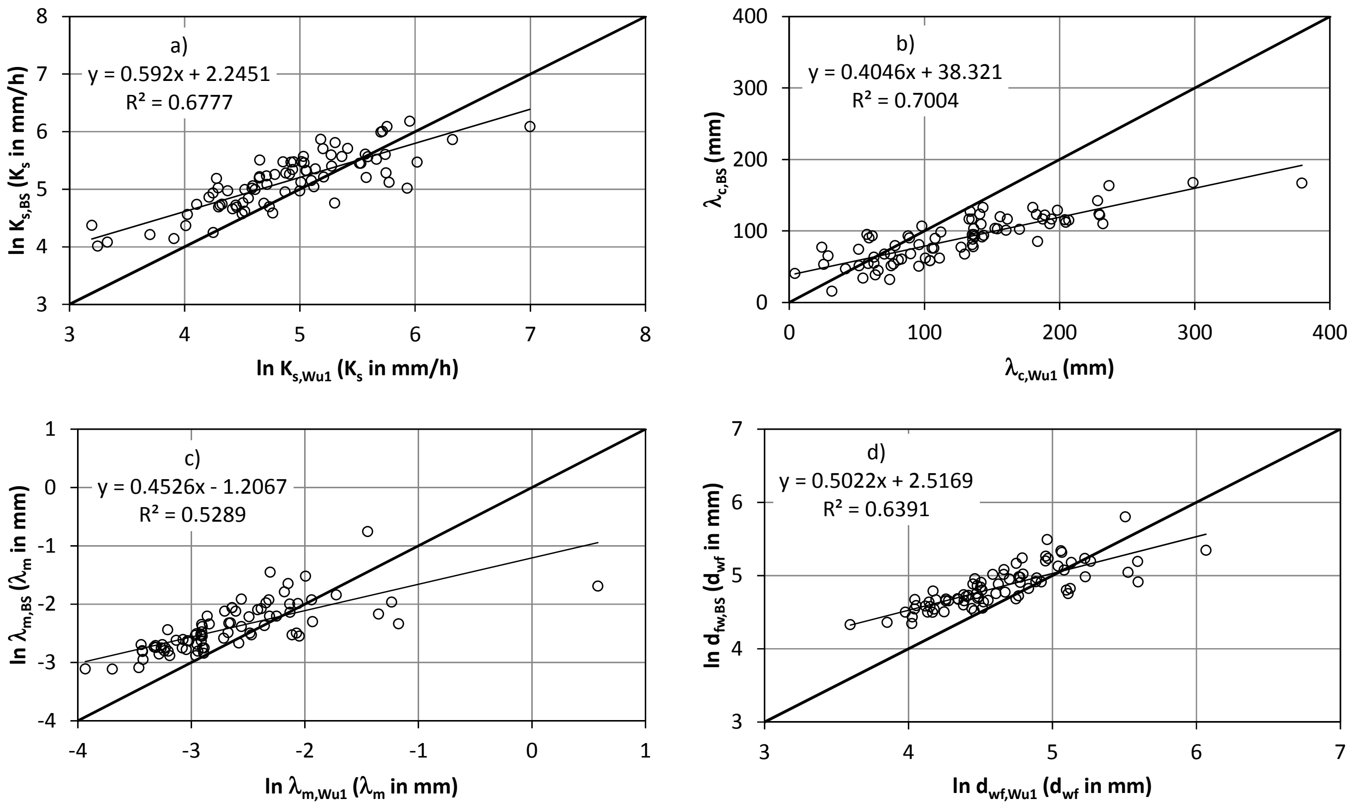

Fig. 3. Comparison between the a) saturated soil hydraulic conductivity (K_s), b) macroscopic capillary length (λ_c), c) characteristic microscopic pore radius (λ_m) and d) depth of the wetting front at the end of the run (d_{wf}) obtained by using the BEST-steady and Wu1 methods of data analysis.

Table 3. Summary statistics of the K_s, λ_c, λ_m and d_{wf} values obtained by BEST-steady and the Wu1 method (sample size, N = 80 for each variable).

Variable	BEST-steady				Wu1				95% confidence interval	
	Min	Max	Mean	*CV* (%)	Min	Max	Mean	*CV* (%)	Intercept	Slope
K_s (mm/h)	55.3	483.7	171.3(a)	52.0	24.4	1093.6	133.8(a)	76.8	1.79 – 2.70	0.50 – 0.68
λ_c (mm)	15.8	167.6	89.2(a)	36.0	4.2	379.3	125.8(a)	52.8	29.8 – 46.8	0.34 – 0.46
λ_m (mm)	0.044	0.47	0.090(a)	43.6	0.020	1.79	0.070(a)	75.3	–1.47 – –0.94	0.36 – 0.55
d_{wf} (mm)	75.8	331.2	126.6(a)	28.9	36.5	431.4	102.3(a)	47.5	2.12 – 2.91	0.42 – 0.59

K_s = saturated soil hydraulic conductivity; λ_c = macroscopic capillary length; λ_m = characteristic microscopic pore radius; d_{wf} = depth of the wetting front at the end of the run; Min = minimum value; Max = maximum value; *CV* = coefficient of variation.
For a given variable, the means followed by the same lower case letter enclosed in parenthesis were significantly different according to a two-tailed paired t test at P = 0.05. The confidence intervals were calculated for the linear regression line of the BEST-steady vs. Wu1 results. Calculations were performed on the ln-transformed data for K_s, λ_m and d_{wf}. The untransformed data were considered for λ_c.

Table 4. Summary statistics of the K_s, λ_c, λ_m and d_{wf} values obtained by BEST-steady and the Wu1 method on each sampling date (sample size, N = 16 for a variable, a data analysis method and a sampling date).

Variable	Method	June-July 2020		July 2020		August 2020		November 2020		April 2021	
		Mean	*CV* (%)	Mean	*CV* (%)	Mean	*CV* (%)	Mean	*CV* (%)	Mean	*CV* (%)
K_s (mm/h)	BEST-steady	264.5aA	34.5	151.0bA	51.2	188.2abA	30.4	136.8bA	49.8	143.4bA	58.1
	Wu1	192.1aB	49.5	113.0aB	67.4	120.3aB	45.5	151.9aA	98.4	108.0aB	103.9
λ_c (mm)	BEST-steady	84.0aA	37.2	87.3aA	50.3	85.6aA	22.9	95.3aA	32.7	93.9aA	34.8
	Wu1	124.9aB	46.4	128.7aB	70.2	137.9aB	29.1	103.2aA	63.3	134.4aB	53.0
λ_m (mm)	BEST-steady	0.095aA	44.5	0.098aA	66.3	0.089aA	23.2	0.083aA	38.6	0.084aA	41.1
	Wu1	0.067aB	56.5	0.071aB	74.1	0.056aB	28.6	0.101aA	141.5	0.063aB	54.4
d_{wf} (mm)	BEST-steady	125.7aA	28.2	138.0aA	41.7	122.6aA	16.9	121.2aA	27.3	126.1aA	27.9
	Wu1	95.7aB	40.4	108.3aB	55.3	85.4aB	23.2	127.1aA	64.5	99.5aB	41.8

K_s = saturated soil hydraulic conductivity; λ_c = macroscopic capillary length; λ_m = characteristic microscopic pore radius; d_{wf} = depth of the wetting front at the end of the run; *CV* = coefficient of variation. For given variable and data analysis method, means followed by the same lower case letter were not significantly different according to the Tukey Honestly Significant Difference test at P = 0.05. Means followed by a different lower case letter were significantly different. For given variable and sampling date, means followed by the same upper case letter were not significantly different according to a two-tailed paired t test at P = 0.05. Means followed by a different upper case letter were significantly different.
The statistical tests were performed on the ln-transformed data for K_s, λ_m and d_{wf}. The untransformed data were considered for λ_c.

In summary, the effect of the infiltration data analysis method on the K_s, λ_c, λ_m and d_{fw} calculations was statistically significant and it appeared overall from moderate to relatively appreciable.

DISCUSSION

The results of this experiment reinforced previous investigations demonstrating a dependence of the calculated soil hydrodynamic parameters on the applied data analysis method (Verbist et al., 2009). In particular, a greater effect of gravity compared to capillarity as the infiltration driving force was perceived for the sampled soil with BEST-steady than the Wu1 method (Mubarak et al., 2009; White and Sully, 1987). Moreover, a different conclusion was reached with reference to temporal variability of K_s since the BS method signaled a significant time variation that was not suggested by the Wu1 method.

Erroneously or imprecisely assuming that the flow process has stabilized when, in fact, it is still in the transient phase implies overestimating the steady-state infiltration rate, i_s, and underestimating the b_s intercept. In this case, BEST-steady overestimates K_s, λ_m and d_{wf} (Eqs. 4, 7 and 8, respectively) and underestimates λ_c (Eq. 6). The detected differences between BEST-steady and the Wu1 method (Tables 3 and 4) appeared consistent with a non-stabilized process since the former method yielded higher K_s, λ_m and d_{wf} values and lower λ_c values than the latter method. Moreover, this interpretation had some support. In particular, the equilibration time is longer as soil permeability to water decreases (Elrick and Reynolds, 1992a) and $K_{s,BS} > K_{s,Wu1}$ was generally obtained for the lowest K_s values in this investigation (Figure 3a). In other words, the suggestion was that steady-state infiltration rate was particularly overestimated in low permeability soil conditions.

However, there were other reasons inducing to believe that the differences between the two methods were not attributable, at least exclusively, to non-attainment of steady-state infiltration rate. One of these reasons was provided by the comparison among alternative estimating criteria of i_s, although only the RE criterion was usable for all infiltration experiments. In particular, the success rate of the alternative criteria, defined as the percentage of runs yielding an estimate of i_s, varied from the 12% for the 3E criterion to the 96% for the HO criterion (Table 5). The correlation between the i_s values obtained with any alternative criterion (2E, 3E, 3Q3, 3Q5, HO) and those estimated with the RE criterion was statistically significant (R^2 = 0.90–0.97; $R > 0$). For the 2E, 3Q3 and 3Q5 criteria, however, the linear regression line did not coincide with the identity line according to the calculated 95% confidence intervals for the intercept and the slope (Table 5). In particular, the detected tendency for these three criteria was to yield higher estimates of i_s as compared with the linear regression criterion (Figure 4). This result was plausible since the infiltration experiment was generally shorter in the former cases than the latter one. To be clearer, the prescribed condition by the 2E, 3Q3 and 3Q5 criteria was generally detected before considering the entire infiltration curve. For the 3E and HO criteria, the linear regression line coincided with the identity line. Therefore, this analysis showed that commonly used criteria for estimating i_s yielded similar or higher values as compared with the regression criterion applied in this investigation. In other words, the analysis did not provide any suggestion that the RE criterion overestimated i_s.

In addition, times to steady-state are shorter in initially wetter soil conditions. Therefore, an equilibration time explanation of the differences between BEST-steady and the Wu1 method could be supported by larger differences between the two methods in initially drier soil conditions. Instead, $K_{s,BS}/K_{s,Wu1}$ was not significantly related with θ_i (R^2 = 0.022, R = 0) in the $0.05 < \theta_i < 0.16$ m^3/m^3 range.

Table 5. Parameters of the linear regression line between the steady-state infiltration rate, i_s (mm/h), estimated with the 2E, 3E, 3Q3, 3Q5 and HO criteria and that obtained with the RE criterion.

Criterion	N	Intercept	Slope	R^2
2E	64 (80.0%)	–45.1 (–113.4 to 23.2)	1.229 (1.15 to 1.31)	0.9336 ($R > 0$)
3E	10 (12.5%)	–139.0 (–514.6 to 236.6)	1.297 (0.95 to 1.65)	0.9013 ($R > 0$)
3Q3	51 (63.8%)	–70.4 (–119.0 to –21.7)	1.199 (1.13 to 1.26)	0.9657 ($R > 0$)
3Q5	70 (87.5%)	–31.6 (–74.6 to 11.5)	1.152 (1.10 to 1.21)	0.9620 ($R > 0$)
HO	77 (96.2%)	9.94 (–50.5 to 70.4)	1.040 (0.96 to 1.12)	0.9065 ($R > 0$)

2E = equality of two consecutive infiltration rates; 3E = equality of three consecutive infiltration rates; 3Q3 = three consecutive infiltration rates differing at the most by 3%; 3Q5 = three consecutive infiltration rates differing at the most by 5%; HO = final infiltration rate according to the Horton model. N = sample size (in percentage of the complete sample size, i.e. 80 infiltration runs, in parenthesis); R^2 = coefficient of determination.
Intercept and Slope columns: the values in parenthesis represent the 95% confidence interval.

Another perspective to interpret the differences between the two considered methods of data analysis was prompted by Xu et al. (2012), emphasizing the conceptual difference between the infiltration equations used by the two methods. In particular, the parameters of the infiltration model by Haverkamp et al. (1994) have a physical meaning. Instead, the A_w and B_w parameters of Eq. (1) were derived from several semi-empirical relations involving the fitted constants a and b and defined through relations with no clear physical meaning. Therefore, a possible interpretation of the differences between BEST-steady and the Wu1 method could be that the former method performed better than the latter one since it was based on a physically more reliable description of infiltration.

In a recent numerical investigation, Bagarello et al. (2019b) established a link between the reliability of the K_s estimates with the Wu1 method and the relative importance of the two terms of Eq. (1), i.e. A_wt and $B_wt^{0.5}$. In particular, a weight of A_wt that does not reach approximately the 75–82% of total infiltration (= $A_wt + B_wt^{0.5}$) did not allow to obtain accurate (differences by <25%) K_s predictions, that were too low as compared with the true values. A weight greater than 97–98% of total infiltration implied an unacceptable overestimation of K_s. Therefore, the estimates of K_s were accurate for a weight of the A_wt term varying from 75–82% to 97–98% of total infiltration. With reference to a three-dimensional infiltration process, the $B_wt^{0.5}$ term corresponds to vertical capillary flow while the A_wt term encompasses the gravity-driven vertical flow and the lateral capillary components (Angulo-Jaramillo et al., 2016; Vandervaere et al., 2000). Therefore, these last two components have to play a prevalent but not exclusive role in controlling infiltration to yield a reliable estimate of K_s with the Wu1 method. In this investigation, a statistically significant relationship (R^2 = 0.68, $R > 0$) was detected between $K_{s,BS}/K_{s,Wu1}$ and $(A_wt)/(A_wt+B_wt^{0.5})$ (Figure 5). According to the fitted regression line, the two estimates of K_s coincided for a relative weight of the A_wt term equal to 79.5% and they differed by no more than

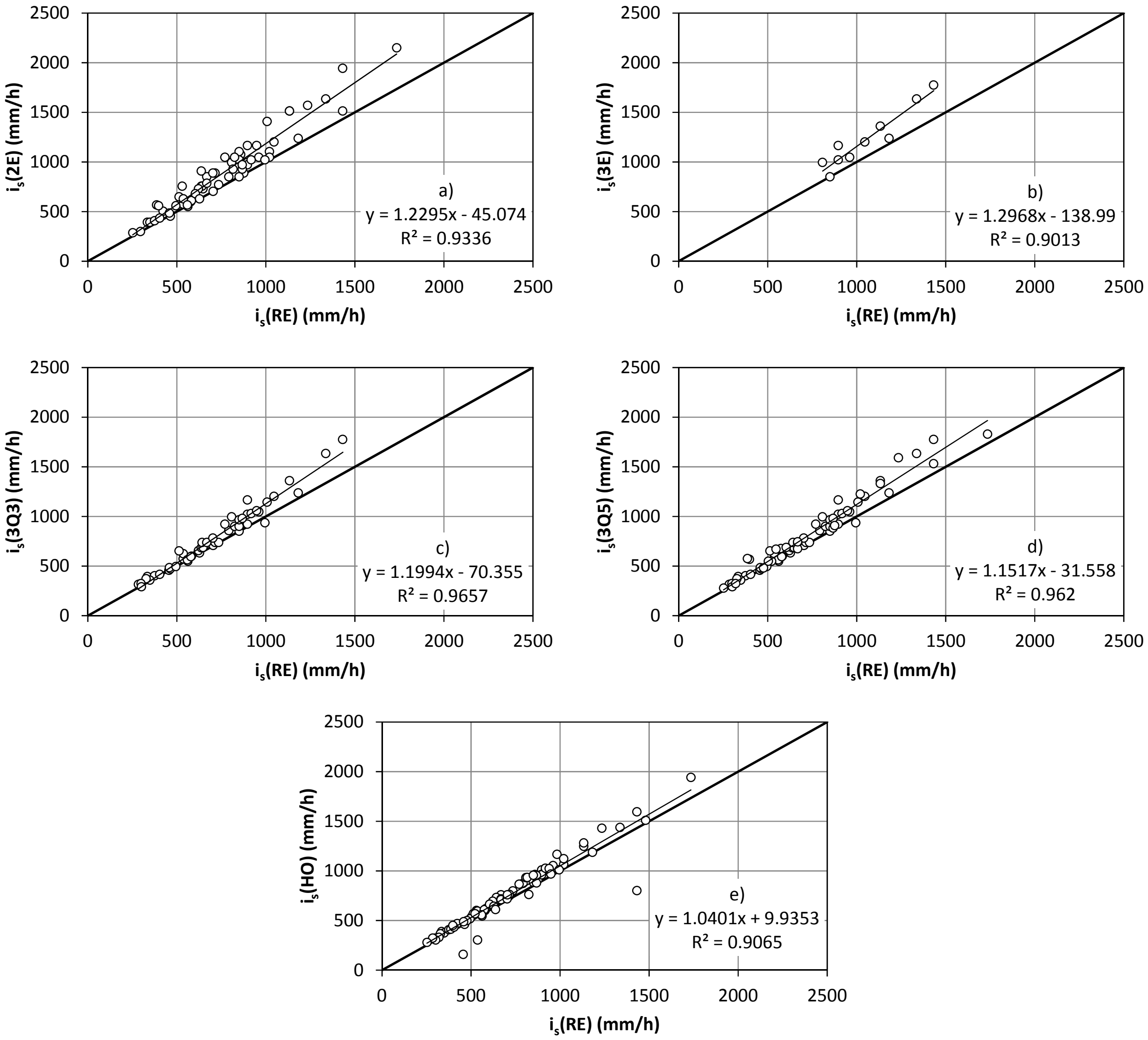

Fig. 4. Comparison between the estimated steady-state infiltration rates, i_s, with the a) 2E, b) 3E, c) 3Q3, d) 3Q5 and e) HO criteria and those obtained with the RE criterion.

25% ($0.75 < K_{s,BS}/K_{s,Wu1} < 1.25$) when the A_wt term represented the 71–89% of total infiltration. Taking into account that, according to Bagarello et al. (2019b), the estimates of $K_{s,Wu1}$ are expected to be reliable in a range of $(A_wt)/(A_wt+B_wt^{0.5})$ values very similar to that reported above, the analysis suggested that the best similarity between the two methods of analysis was detected when the Wu1 method was expected to yield accurate predictions of K_s. This result did not prove that BEST-steady performed well in general, due to the lack of reference data upon which evaluations and judgments could be made (Reynolds et al., 2000), but it induced to be rather confident that the estimates of $K_{s,BS}$, and of the other derived parameters, were reliable.

Another indication of this analysis was that the developed dataset likely included both reliable and unreliable or less reliable $K_{s,Wu1}$ values. The first group of data were those corresponding to a relative weight of the A_wt term ranging from 75 to 98% (23 data points, representing the 29% of the total). The other data (71% of the total) were probably less reliable because the relative weight of the A_wt term varied between 34 and 75%.

The formal analysis by Vandervaere et al. (2000), developed with reference to tension infiltrometer experiments, supported the suggested interpretation of data reliability since they also showed that the weight of the different components of the flow process controls the accuracy of the estimated soil hydrodynamic parameters.

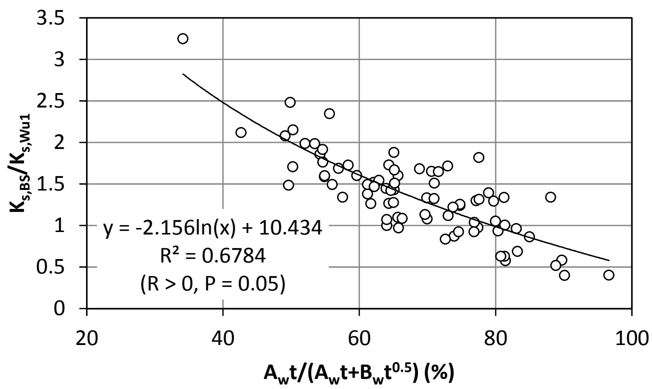

Fig. 5. Ratio between two corresponding estimates of saturated soil hydraulic conductivity ($K_{s,BS}$: BEST-steady; $K_{s,Wu1}$: Wu1 method) against the weight of the A_wt term on total infiltration at the end of the run (sample size, $N = 80$).

CONCLUSIONS

For a sandy-loam soil, the hypothesis that BEST-steady and the Wu1 method yield the same estimates of saturated soil hydraulic conductivity, K_s, macroscopic capillary length, λ_c, characteristic microscopic pore radius, λ_m, and depth of the wetting front at the end of the infiltration run, d_{wf}, was not supported since a moderate to relatively appreciable effect of the infiltration data analysis method on the calculated soil parameters was recognized. However, another conclusion of this investigation was that similarity of the predictions with the two methods can be established by fitting the two-parameter infiltration equation to the data. The two methods are expected to yield similar K_s predictions when most of total infiltration is expressed by the term linear in time, that physically describes gravity-driven vertical flow and lateral capillary flow.

Therefore, soil hydrodynamic parameters obtained with BEST-steady and the Wu1 method should not directly be compared since part of the differences between the data could express an effect of the data analysis method. However, it appears possible to predict this effect since BEST-steady and the Wu1 method are expected to yield similar estimates of K_s if a high percentage of total infiltration is due to gravity and lateral capillarity. The measured infiltration process is enough to make this check.

A limit of this investigation is that the results refer to a single soil. Sampling other soils, and maybe complementing the field experimental research with numerical modeling, is advisable to draw more general conclusions. Performing these additional investigations requires properly selecting the soils to be sampled since the data should contain a reliable information on both the transient and steady-state stages of the infiltration process. Therefore, excessively fine-textured soils should be avoided because steady-state conditions could not be attained by the end of an experiment of a few hours and performing longer experiments could be impractical. Excessively coarse-textured soils should also be avoided since, in this case, the transient stage could be too short to be sampled in practice. These investigations could be helpful in the perspective to develop soil datasets that do not contain a bias due to the applied data analysis method.

REFERENCES

Angulo-Jaramillo, R., Bagarello, V., Iovino, M., Lassabatere, L., 2016. Infiltration Measurements for Soil Hydraulic Characterization. Springer International Publishing, Cham, 383 p.

Bagarello, V., Giordano, G., 1999. Comparison of procedures to estimate steady flow rate in field measurement of saturated hydraulic conductivity with the Guelph permeameter method. J. Agr. Eng. Res., 74, 63–71.

Bagarello, V., David, S.M., 2020. Run duration effects on the hydrodynamic properties of a loam soil estimated by steady-state infiltration methods. J. Agric. Eng., LI:1075, 229–238. DOI: 10.4081/jae.2020.1075

Bagarello, V., Di Prima, S., Iovino, M., 2014. Comparing alternative algorithms to analyze the beerkan infiltration experiment. Soil Sci. Soc. Am. J., 78, 724–736. DOI: 10.2136/sssaj2013.06.0231

Bagarello, V., Baiamonte, G., Caia, C., 2019a. Variability of near-surface saturated hydraulic conductivity for the clay soils of a small Sicilian basin. Geoderma, 340, 133–145. DOI: 10.1016/j.geoderma.2019.01.008

Bagarello, V., Iovino, M., Lai, J., 2019b. Accuracy of saturated soil hydraulic conductivity estimated from numerically simulated single-ring infiltrations. Vadose Zone J., 18, 180122. DOI: 10.2136/vzj2018.06.0122

Bagarello, V., Caltabellotta, G., Iovino, M., 2021. Water transmission properties of a sandy-loam soil estimated with Beerkan runs differing by the infiltration time criterion. J. Hydrol. Hydromech., 69, 2, 151–160. DOI: 10.2478/johh-2021-0010

Braud, I., Desprats, J.F., Ayral, P.A., Bouvier, C., Vandervaere, J.P., 2017. Mapping topsoil field-saturated hydraulic conductivity from point measurements using different methods. J. Hydrol. Hydromech., 65, 3, 264–275. DOI: 10.1515/johh-2017-0017

Brooks, R.H., Corey, C.T., 1964. Hydraulic properties of porous media. Hydrol. Paper 3, Colorado State University, Fort Collins.

Caltabellotta, G., Bagarello, V., Iovino, M., 2021. Effect of a heavy rainstorm on the surface hydrodynamic properties of a sandy-loam soil. Submitted for possible publication on J. Hydrol. Eng.

Ciollaro, G., Lamaddalena, N., 1998. Effect of tillage on the hydraulic properties of a Vertic soil. J. Agr. Eng. Res., 71, 147–155.

Di Prima, S., Stewart, R.D., Castellini, M., Bagarello, V., Abou Najm, M.R., Pirastru, M., Giadrossich, F., Iovino, M., Angulo-Jaramillo, R., Lassabatere, L., 2020. Estimating the macroscopic capillary length from Beerkan infiltration experiments and its impact on saturated soil hydraulic conductivity predictions. J. Hydrol., 589, 125159. DOI: 10.1016/j.jhydrol.2020.125159

Elrick, D.E., Reynolds, W.D., 1992a. Infiltration from constant-head well permeameters and infiltrometers. In: Topp, C.G. et al. (Ed.): Advances in Measurement of Soil Physical Properties: Bringing Theory into Practice. SSSA Special Publication 30. SSSA, Madison, WI, pp. 1–24.

Elrick, D.E., Reynolds, W.D., 1992b. Methods for analyzing constant-head well permeameter data. Soil Sci. Soc. Am. J., 56, 320–323.

Gee, G.W., Bauder, J.W., 1986. Particle-size Analysis. In: SSSA Book Series, Soil Science Society of America, American Society of Agronomy, pp. 383–411.

Gonzalez-Sosa, E., Braud, I., Dehotin, J., Lassabatère, L., Angulo-Jaramillo, R., Lagouy, M., Branger, F., Jacqueminet, C., Kermadi, S., Michel, M., 2010. Impact of land use on the hydraulic properties of the topsoil in a small French catchment. Hydrol. Process., 24, 2382–2399.

Haverkamp, R., Ross, P.J., Smettem, K.R.J., Parlange, J.Y., 1994. Three-dimensional analysis of infiltration from the disc infiltrometer: 2. Physically based infiltration equation. Water Resour. Res., 30, 11, 2931–2935.

Horton, R.E., 1940. An approach towards a physical interpretation of infiltration capacity. Soil Sci. Soc. Am. Proc., 5, 399–417.

Iovino, M., Castellini, M., Bagarello, V., Giordano, G., 2016. Using static and dynamic indicators to evaluate soil physical quality in a Sicilian area. Land Degrad., Dev., 27, 200–210. DOI: 10.1002/ldr.2263

Iovino, M., Angulo-Jaramillo, R., Bagarello, V., Gerke, H.H., Jabro, J., Lassabatere, L., 2017. Thematic issue on soil water infiltration. J. Hydrol. Hydromech., 65, 3, 205–208. DOI: 10.1515/johh-2017-0036

Jabro, J.D., 1996. Variability of field-saturated hydraulic conductivity in a Hagerstown soil as affected by initial water content. Soil Sci., 161, 11, 735–739.

Lassabatere, L., Angulo-Jaramillo, R., Soria Ugalde, J.M., Cuenca, R., Braud, I., Haverkamp, R., 2006. Beerkan estimation of soil transfer parameters through infiltration experiments – BEST. Soil Sci. Soc. Am. J., 70, 521–532. DOI: 10.2136/sssaj2005.0026

Lassabatere, L., Di Prima, S., Angulo-Jaramillo, R., Keesstra, S., Salesa, D., 2019. Beerkan multi-runs for characterizing water infiltration and spatial variability of soil hydraulic properties across scales. Hydrolog. Sci. J., 64, 2, 165–178. DOI: 10.1080/02626667.2018.1560448

Lee, D.M., Reynolds, W.D., Elrick, D.E., Clothier, B.E., 1985. A comparison of three field methods for measuring saturated hydraulic conductivity. Canadian J. Soil Sci., 65, 563–573.

Lilliefors, H.W., 1967. On the Kolmogorov-Smirnov test for normality with mean and variance unknown. J. Am. Stat. Assoc., 62, 318, 399–402. DOI: 10.1080/01621459.1967.10482916

Minasny, B., McBratney, A.B., 2007. Estimating the water retention shape parameter from sand and clay content. Soil Sci. Soc. Am. J., 71, 1105–1110.

Mubarak, I., Mailhol, J.C., Angulo-Jaramillo, R., Ruelle, P., Boivin, P., Khaledian, M., 2009. Temporal variability in soil hydraulic properties under drip irrigation. Geoderma, 150, 1–2, 158–165. DOI: 10.1016/j.geoderma.2009.01.022

Mubarak, I., Angulo-Jaramillo, R., Mailhol, J.C., Ruelle, P., Khaledian, M., Vauclin, M., 2010. Spatial analysis of soil surface hydraulic properties: Is infiltration method dependent? Agr. Water Manage., 97, 1517–1526.

Reynolds, W.D., 2013. An assessment of borehole infiltration analyses for measuring field-saturated hydraulic conductivity in the vadose zone. Eng. Geol., 159, 119–130.

Reynolds, W.D., Elrick, D.E., 1990. Ponded infiltration from a single ring: I. Analysis of steady flow. Soil Sci. Soc. Am. J., 54, 1233–1241.

Reynolds, W.D., Bowman, B.T., Brunke, R.R., Drury, C.F., Tan, C.S., 2000. Comparison of tension infiltrometer, pressure infiltrometer, and soil core estimates of saturated hydraulic conductivity. Soil Sci. Soc. Am. J., 64, 478–484.

Souza, E.S., Antonino, A.C.D., Heck, R.J., Montenegro, S.M.G.L., Lima, J.R.S., Sampaio, E.V.S.B., Angulo-Jaramillo, R., Vauclin, M., 2014. Effect of crusting on the physical and hydraulic properties of a soil cropped with Castor beans (*Ricinus communis* L.) in the northeastern region of Brazil. Soil Till. Res., 141, 55–61.

Stewart, R.D., Abou Najm, M.R., 2018a. A comprehensive model for single ring infiltration. I: Initial water content and soil hydraulic properties. Soil Sci. Soc. Am. J., 82, 3, 548–557.

Stewart, R.D., Abou Najm, M.R., 2018b. A comprehensive model for single ring infiltration. II: Estimating field-saturated hydraulic conductivity. Soil Sci. Soc. Am. J., 82, 3, 558–567.

Vandervaere, J.-P., Vauclin, M., Elrick, D.E., 2000. Transient flow from tension infiltrometers: II. Four methods to determine sorptivity and conductivity. Soil Sci. Soc. Am. J., 64, 1272–1284.

Verbist, K., Baetens, J., Cornelis, W.M., Gabriels, D., Torres, C., Soto, G., 2009. Hydraulic conductivity as influenced by stoniness in degraded drylands of Chile. Soil Sci. Soc. Am. J., 73, 471–484.

Warrick, A.W., 1998. Appendix 1: Spatial variability. In: Hillel, D. (Ed.): Environmental Soil Physics. Academic Press, San Diego, pp. 655–675.

White, I., Sully, M.J., 1987. Macroscopic and microscopic capillary length and time scales from field infiltration. Water Resour. Res., 23, 8, 1514–1522.

Wu, L., Pan, L., 1997. A generalized solution to infiltration from single-ring infiltrometers by scaling. Soil Sci. Soc. Am. J., 61, 1318–1322.

Wu, L., Pan, L., Roberson, M.J., Shouse, P.J., 1997. Numerical evaluation of ring-infiltrometers under various soil conditions. Soil Sci., 162, 771–777.

Wu, L., Pan, L., Mitchell, J., Sanden, B., 1999. Measuring saturated hydraulic conductivity using a generalized solution for single-ring infiltrometers. Soil Sci. Soc. Am. J., 63, 788–792.

Xu, X., Lewis, C., Liu, W., Albertson, J.D., Kiely, G., 2012. Analysis of single-ring infiltrometer data for soil hydraulic properties estimation: comparison of BEST and Wu methods. Agr. Water Manage., 107, 34–41.

Yilmaz, D., Lassabatere, L., Angulo-Jaramillo, R., Deneele, D., Legret, M., 2010. Hydrodynamic characterization of basic oxygen furnace slag through an adapted BEST method. Vadose Zone J., 9, 1–10.

Received 30 August 2021
Accepted 3 January 2022