Run duration effects on the hydrodynamic properties of a loam soil estimated by steady-state infiltration methods

Vincenzo Bagarello, Sonia Maria David

Department of Agricultural, Food and Forest Sciences, University of Palermo, Italy

Abstract

Steady-state methods for the analysis of single-ring infiltration data are commonly applied. However, the duration of an infiltrometer experiment is often established quite subjectively based on the assumption that in general infiltration stabilizes rather quickly in the field. For a loam soil, the effect of the duration of a beerkan run on sorptivity, S, and saturated hydraulic conductivity, K_s, was tested by using the BEST (*Beerkan Estimation of Soil Transfer parameters*)-steady method and SSBI (*Steady version of the Simplified method based on a Beerkan Infiltration run*) method for data analysis. The standard experiment, based on a total of 15 water volumes each establishing an initial ponding depth of ~0.01 m (on average, 0.32 hours of infiltration), yielded approximately two and >100 times higher S and K_s values, respectively, than a long run (117 water volumes or 8.1 hours). Stabilization was faster for S (approximately in 3 hours) than K_s (6 hours). Similar K_s values were obtained with BEST-steady (192-261 mm/h) and the SSBI method (177-184 mm/h) for the standard run but not for the long-duration run (1.5-2.1 and 20-21 mm/h, respectively). This discrepancy was due to the fact that more information on the infiltration process is used by BEST-steady (total duration, total infiltrated water, steady-state infiltration rate) than the SSBI method (only the latter variable). In conclusion, K_s estimates are very sensitive to the used water volume for the run. The run duration should not only depend on the attainment of near steadiness, but also on the possibility of capturing the soil hydraulic behaviour in a representative situation for the hydrological process under study. In the near future, the possibility of using the hydrodynamic soil properties determined with the tested methodology to simulate rainfall effects on soil structure should be investigated.

Correspondence: Vincenzo Bagarello, Department of Agricultural, Food and Forest Sciences, University of Palermo, Italy, viale delle Scienze, Building 4, 90128 Palermo, Italy.
E-mail: vincenzo.bagarello@unipa.it

Key words: beerkan infiltration run; experimental protocol; soil sorptivity; saturated soil hydraulic conductivity; BEST-steady; SSBI method.

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Introduction

The simulation of surface soil hydrological processes, such as rainfall partitioning into infiltration and rainfall excess and, therefore, surface runoff generation, requires the measurement of sorptivity, S, and saturated hydraulic conductivity, K_s. Field measurement methods should be preferred over laboratory methods, since they make it possible to maintain the functional connection of the sampled soil volume with the surrounding soil. Ponding single-ring infiltration methods are largely used for field soil hydraulic characterization, because they are rather simple to apply and based on robust theories (Reynolds, 2008). Some single-ring methodologies, such as the beerkan infiltration run coupled with BEST (*Beerkan Estimation of Soil Transfer parameters*) algorithms for data analysis (Angulo-Jaramillo *et al*., 2016), can yield a complete soil hydraulic characterization, that is the water retention and hydraulic conductivity functions. Many single-ring methods, including all BEST algorithms, require attainment of flow steadiness. The general tendency in field determination of soil hydraulic properties by infiltrometer methods is to use a small water volume at a sampling point and to perform fairly short infiltration runs. This approach is justified by the following reasons: i) transporting small amounts of water is easy in remote areas; ii) many locations can be sampled with an overall limited water volume; iii) the assumption of a homogeneous soil and uniform initial water content, that is commonly used in the theoretical representation of the porous medium, is realistic since the sampled soil volume is small (Vandervaere *et al*., 2000); and iv) near steady-state infiltration rates should be attained quite rapidly in many cases (Reynolds *et al*., 2000; Stewart and Najm, 2018; Lassabatere *et al*., 2019).

A beerkan infiltration run with 15 sequentially applied water volumes, each establishing an initial ponded depth of water on the soil surface of approximately 0.01 m, was adopted as a sort of standard protocol (Lassabatere *et al*., 2006), although other procedures could be followed. For example, water can be added until two (Mubarak *et al*., 2009) or three (Mubarak *et al*., 2010) consecutive infiltration times are equal or until the differences in infiltration times between consecutive water applications become negligible (Lassabatere *et al*., 2019). The practical advantage of the protocol by Lassabatere *et al*. (2006) is that the amount of water to be used for an experiment is rather small and it can be established in advance, which greatly simplifies the planning of sampling campaigns in general and, in particular, in remote areas. On the contrary, two or three equal infiltration times do not always ensure the attainment of steady-state (Bagarello *et al*., 1999). Furthermore, it is difficult and fairly subjective to establish when differences between two infiltration times are actually negligible.

A common experience made in the field is that final infiltration rates are easily perceived as nearly constant even with rather short infiltration experiments. However, this implies the risk of overestimating steady-state infiltration rates under several circumstances. An obvious way to reduce this risk is performing infiltration experiments which last as long as possible, since in this case it is easier to attain steady-state conditions (Elrick and Reynolds, 1992b). For example, steady-state infiltration values could be considered reliable when the process is stable for two hours (Gómez *et al*., 2005) or 5-min infiltration volumes remain constant for 30 min (Lai and Ren, 2007). Moreover, long runs may be necessary to quantify management practices where long irrigation times are used (Wu *et al*., 1997). Therefore, there are reasons to use either short or long duration runs. A longer run at a sampling point also implies more use of water and, therefore, more possibilities of altering the sampled soil volume during the experiment due, for example, to swelling and weakening of particle bonds. Moreover, a longer run explores a larger soil volume (Elrick and Reynolds, 1992b) with a possible effect of small-scale spatial variability on the calculated soil hydraulic properties. Therefore, long runs are not always a valid alternative to short runs under all circumstance (Alagna *et al*., 2016). Currently, there is a general lack of information on soil properties determined with both short and long infiltrometer experiments, since, to the best of our knowledge, long or relatively long infiltration runs were carried out only rarely.

Run duration effects on the estimated soil hydrodynamic parameters should be tested by analysing a given infiltration experiment with different data analysis procedures. The reason is that different procedures can differ in terms of input experimental information and are expected to yield different estimates of soil hydrodynamic parameters (Verbist *et al*., 2010). Consequently, an analysis of run duration effects performed with a given calculation procedure may not be representative by definition, since other results could be obtained by changing the calculation procedure. For example, with reference to the BEST and BEST-derived procedures, the calculation of K_s with the BEST-steady method (Bagarello *et al*., 2014) requires the determination of both the intercept, b_s, and the slope, i_s, of the straight line fitted to the data describing steady-state cumulative infiltration. On the contrary, only the latter information is required by the SSBI (*Steady version of the Simplified method based on a Beerkan Infiltration run*) method (Bagarello *et al*., 2017). Therefore, a possible time dependency of K_s calculations could be induced by temporal changes of both b_s and i_s in the former case and of i_s only in the latter case. The link between run duration and calculation of soil hydrodynamic parameters with different analysis procedures is still an open issue.

The investigation reported in this paper was carried out on a loamy soil to: i) test the effects of the duration of a beerkan infiltration run on the BEST-steady estimation of soil sorptivity and saturated soil hydraulic conductivity; and ii) verify the effects of time on saturated soil hydraulic conductivity calculated with two alternative data analysis procedures, *i.e*. the BEST-steady method and the SSBI method.

Description of BEST-steady and SSBI methods

The BEST-steady algorithm yields an estimate of soil sorptivity, S (L/T$^{0.5}$), and saturated soil hydraulic conductivity, K_s (L/T), 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 plot of cumulative infiltration, I (L), *versus* time, t (T) (Bagarello *et al*., 2014):

$$S = \sqrt{\frac{i_s}{A + \frac{C}{b_s}}} \tag{1a}$$

$$K_s = \frac{C\,i_s}{A b_s + C} \tag{1b}$$

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

$$A = \frac{\gamma}{r(\theta_s - \theta_i)} \tag{2a}$$

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

where θ_i (L^3/L^3) and θ_s (L^3/L^3) are the antecedent and the saturated volumetric soil water content, respectively, r (L) is the radius of the ring used for the infiltration run, β and γ are infiltration constants that are commonly set at 0.6 and 0.75, respectively, for $\theta_i < 0.25\times\theta_s$, 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). If the soil is relatively dry at the beginning of the experiment, the ratio between the initial and the saturated hydraulic conductivity can be considered negligible which, for β=0.6, leads to C=0.639. In practice, BEST-steady can be applied if only total duration, d_t (T), total infiltrated water, I_t (L), and steady-state infiltration rate are known for an infiltration experiment, since simple geometric considerations indicate that b_s can be expressed as:

$$b_s = I_t - d_t \times i_s \tag{3}$$

With the SSBI method, an estimate of K_s is obtained on the basis of the following relationship (Bagarello *et al*., 2017):

$$K_s = \frac{i_s}{\frac{\gamma\,\gamma_w}{r\alpha^*} + 1} \tag{4}$$

where γ_w is a dimensionless constant set equal to 1.818 and the α^* (1/L) parameter can be estimated on the basis of a general description of soil textural and structural characteristics (Elrick and Reynolds, 1992a). The α^* parameter, also named sorptive number, accounts for capillarity effects in the unsaturated soil (Reynolds, 2013).

Materials and methods

Field site

The study was performed at the Department of Agricultural, Food and Forest Sciences of Palermo (Italy) University, in a citrus orchard with trees spaced 4×4 m apart and the use of a no tillage management practice (coordinates 38.107282 N 13.351922 E). The soil, having a relatively high gravel content, was classified as loam in the upper 0.10 m (clay=15.4%, silt=36.2%, sand=48.4%, mean of four replicates, USDA classification system) and its organic matter content, determined with the Walkley and Black method, was of 5.4%. This soil was selected because other investigations indicated that its saturated hydraulic conductivity was sensitive to the applied water volume for a beerkan run (Alagna *et al*., 2016). The soil surface was gently levelled and smoothened before sampling. The superficial herbaceous vegetation was cut with a knife, while the roots remained *in situ*.

Experiment

Small diameter (0.08 m) rings were inserted in the soil surface to a depth of 0.01 m for the beerkan infiltration runs (Lassabatere *et al*., 2006). Small rings were used since a possible soil disturbance due to water application was more clearly detectable when the wetted area was small (Alagna *et al*., 2016) and also because the BEST methods proved to be effective even with smaller rings (Lassabatere *et al*., 2019). The ring insertion was conducted manually or by gently using a rubber hammer and ensuring that the upper rim of the ring remained horizontal during insertion. A total of 22 infiltration runs were carried out at randomly selected locations. Each run had a duration of no less than seven hours mainly due to practical factors, such as water availability or changes in weather conditions. In other words, the run was planned to continue even if two or three consecutive infiltration times were equal or differences in infiltration times between consecutive water applications appeared negligible (Mubarak *et al*., 2009, 2010; Lassabatere *et al*., 2019). The common beerkan methodology was applied for a run, but a large number of water volumes was used at a sampling point. A water volume of 57 mL was poured in approximately 3 seconds on the confined infiltration surface to establish an initial ponded depth of water of 0.011 m. The infiltration time was measured from the water application to the disappearance of all the water, when the subsequent equal water volume was poured on the infiltration surface.

Two undisturbed soil cores (0.05 m in height by 0.05 m in diameter), collected close to a sampling point at a depth of 0 to 0.05 m and 0.05 to 0.10 m, were used to determine the dry soil bulk density, ρ_b (g/cm^3), and the antecedent volumetric soil water content, θ_i (m^3/m^3). The data were averaged over the two depths and were associated with the run performed in the vicinity of the soil sampling location.

The field experiment was carried out over a seven-month period, from November 2016 to May 2017, in order to sample the soil under different initial conditions with reference to ρ_b and, especially, θ_i. Table 1 summarizes these two parameters and also provides information on duration of infiltration of the first 15 water volumes, d_{15} (h), total duration of the runs, d_t (h), number of applied water volumes, N_v, and total infiltrated water, I_t (mm). Porosity, f, calculated from the measured ρ_b value and assuming a soil particle density of 2.65 g/cm^3, varied from 0.55 to 0.64 m^3/m^3. Such high values were probably indicative, at least in part, of a large presence of macropores formed by earthworms, which were frequently observed. However, they could also be due to the fact that the collection of undisturbed soil cores was not always easy due to the widespread presence of gravel and stones at the field site. The initial saturation degree, θ_i/f, ranged between 0.20 and 0.36, with a mean of 0.28. This rather narrow range of θ_i/f values was representative of the initial hydric conditions that were present for long periods of time over that year at the field site.

Calculations and data analysis

Infiltration data were initially plotted on cumulative infiltration, I (L), and infiltration rate, i_r (L/T), *vs* time, t (T), plots to take an initial look at the general response of the long duration infiltration runs. Early, i_{15} (L/T), and late time, i_f (L/T), estimates of near steady infiltration rates were then obtained by linear regression analysis of the last three data points on the I *vs* t plot by considering the first 15 applied water volumes and the complete infiltration run, respectively. In particular, i_{15} was determined because it represents the final infiltration rate for the standard beerkan experiment (Lassabatere *et al*., 2006), whereas i_f was determined because it expresses infiltration rates at the end of a long duration infiltration run. Three data points were considered to obtain only information on the final stage of the run in both cases. A comparison was then established between i_{15} and i_f. For each run, Eqs. (1) and (2), *i.e*. the BEST-steady algorithm, were applied to calculate soil sorptivity, S (L/T$^{0.5}$), and saturated soil hydraulic conductivity, K_s (L/T), using the last three (I, t) data points to determine b_s (L) and i_s (L/T) by linear regression analysis.

Table 1. Summary statistics of dry soil bulk density, ρ_b (g/cm^3), initial volumetric soil water content, θ_i (m^3/m^3), duration of the infiltration of the first 15 water volumes, d_{15} (h), total duration of the infiltration run, d_t (h), number of applied water volumes, N_v, total infiltrated water volume, I_t (mm), estimated steady-state infiltration rate by a standard beerkan run, i_{15} (mm/h), and final infiltration rate, i_f (mm/h) (sample size, N=22 for each variable).

Statistic	ρ_b	θ_i	d_{15}	d_t	N_v	I_t	i_{15}	i_f
Minimum	0.962	0.112	0.10	7.26	45	510.3	76.7	49.4
Maximum	1.187	0.218	1.50	8.90	203	2302.0	1338.3	119.4
Arithmetic mean	1.084	0.165	0.32	8.09	116.6	1322.1	685.2	80.8
Median							706.9	77.7
Geometric mean							566.1	78.2
Coefficient of variation (%)	5.5	17.2	9.7	5.0	29.1	29.1	51.6	25.9
Skewness							–0.18	0.44

Each run was repeatedly analysed to detect possible changes of the calculated S and K_s values with the number of used water volumes and, therefore, with the run duration. In particular, calculations were repeated by considering a variable number of collected data points, ranging from a minimum of 15 to a maximum of 45-203, depending on the run, which corresponded to the longest infiltration process (Table 1). Essentially, an estimate of S and K_s was obtained by considering the first 15 collected (I, t) data points (shortest run duration, t_{15}). Then, the subsequent (I, t) data pair was included in the dataset to be analysed and a new estimate of S and K_s was obtained by considering the last three data pairs (run duration=t_{16}, $t_{16}>t_{15}$). This procedure was repeated until all collected data pairs were included in the analysed dataset (longest run duration). According to other investigations, the field saturated soil water content, θ_s, used for the BEST-steady calculations was assumed to coincide with f (Angulo-Jaramillo *et al*., 2016). In this investigation, the constraint that θ_i did not exceed $0.25\times\theta_s$ (Lassabatere *et al*., 2006) was met approximatively and on average. This circumstance was not considered a major limit, since other investigations suggested that the performance of the BEST methods should be satisfactory even if the soil is slightly wetter than theoretically required (Di Prima *et al*., 2016). Changes in both S and K_s with the totally applied water volume were checked. For a given soil property, a comparison was established between the dataset developed with reference to the standard beerkan experiment and the dataset obtained with the longest possible experiment.

The BEST-steady algorithm was applied in this investigation instead of other available algorithms, *i.e*. BEST-slope (Lassabatere *et al*., 2006) and BEST-intercept (Yilmaz *et al*., 2010), because: i) the latter two algorithms, accounting for transient data, can be perturbed by a progressive soil structure deterioration (Di Prima *et al*., 2018a); and ii) BEST-steady was expected to yield a higher success rate of the calculations than both BEST-slope and BEST-intercept (Di Prima *et al*., 2018b).

Another estimate of K_s was obtained for each run and each considered duration by Eq. (4), that is by the SSBI method. For these calculations, the first approximation value of α*, equal to 12 1/m (Elrick and Reynolds, 1992a), was used, in agreement with the loamy texture of the soil. Changes in the SSBI calculations of K_s with the used water volume were also checked and a comparison was made, with reference to the two scenarios (standard beerkan run; longest possible experiment), between the two developed K_s datasets (BEST-steady, SSBI method).

For each run and each considered duration, the value of the α* parameter yielding the same K_s prediction with BEST-steady and the SSBI method was then calculated by equating Eqs. (1b) and (4) and solving for α*, by also considering Eq. (3):

$$\alpha^* = \frac{C\gamma_w(\theta_s-\theta_i)}{b_s} = \frac{C\gamma_w(\theta_s-\theta_i)}{I_t-d_t\times i_s} \quad (5)$$

A comparison was then made with the α* values suggested in the literature for a rapid estimation of K_s by single-ring, steady-state infiltration methods (Reynolds *et al*., 2002). These suggested values are often used without any check but, in this investigation, it was possible to verify if α*=12 1/m was a plausible assumption, at least with a view to obtain similar estimates of K_s with an objective method (BEST-steady) and a method requiring a possibly subjective choice (SSBI method).

Two-tailed, paired t tests were used to compare two datasets. A two-tailed t test was also used to establish the statistical significance of a fitted regression line to the data (Glantz, 2012). Data distribution hypotheses were tested according to Lillefors (1967). All statistical tests, including calculation of confidence intervals, *ci*, for both the intercept and the slope of a linear regression line, were carried out at P<0.05.

Results

Infiltration process

Both the cumulative infiltration (I *vs* t) and the infiltration rate (i_r *vs* t) curves showed that all measured infiltration processes were consistent with the theory, because the concavity of the I *vs* t curves was facing downwards (Figure 1A) and the infiltration rates decreased with time (Figure 1B).

Both i_{15} and i_f were easily and convincingly estimated from the (I, t) curve, since the R^2 values were ≥0.9947 (mean=0.9992) in the former case (Figure 1C) and ≥0.9959 (mean=0.9996) in the latter one (Figure 1D). Depending on the considered central tendency measure (arithmetic or geometric mean, median), i_f was 7.2-9.1 times smaller than i_{15} (Table 1). The coefficient of variation, CV, decreased between i_{15} and i_f from 52% to 26%. According to the calculated skewness coefficients, the distribution of i_f was more positively skewed as compared to that of i_{15} which was closer to being symmetric. The correlation between i_f and i_{15} was not significant (R^2=0.1484, R=0).

BEST-steady

For each infiltration run, both the intercept, b_s, and the slope, i_s, of the straight line fitted to the data describing steady-state conditions on the I *vs* t plot varied with the considered run duration. On average (N=22 runs), the ratio between the largest and the smallest value during a run was equal to 68.6 (CV=181%) for b_s and to 9.5 (CV=55%) for i_s, thus showing a larger variation and a greater variability for the intercept than the slope. Overall, BEST-steady was applied 2257 times and calculations failed in only eight cases (0.35% of the total), suggesting that the applied methodology was appropriate to collect both positive and, therefore, physically possible S and K_s values.

Soil sorptivity, S, and saturated soil hydraulic conductivity, K_s, varied with both the run and the considered run duration. In particular, S appeared to stabilize after nearly 3 hours (Figure 2A). Although most of the changes in K_s occurred during the first part of the run (Figure 2B), the estimates of this soil property appeared to become nearly stable approximately six hours after starting the process.

For S, the ratio between the highest and the lowest calculated value (N=2249) was equal to 4.9 (=149.8/30.8, Table 2), whereas this ratio was 667 (=690.6/1.04) for K_s. Both variables decreased at a sampling point with the run duration, but the decrease was more noticeable for K_s than S. In particular, in the passage from the standard (15 water volumes) to the long-duration (on average, 117 water volumes) run, the estimates of S decreased by 1.2 to 3.5 times, depending on the run (mean=2.2), and those of K_s by 2.8 to 581 times (mean=173). Depending on the considered central tendency measure, the long duration run yielded 2.1-2.3 and 105-148 times smaller S and K_s values, respectively, as compared to the standard run (Table 2). For a given type of run (standard, long-duration), K_s was more variable than S. When the run duration was increased, less variable values were obtained (smaller *CV*s), but the transition towards more homogeneous conditions was clearer for *S* (*CV* decreasing by 2.2 times) than K_s (*CV* decreasing by only 1.1 times). The final *S* value was independent of the value obtained by the standard run (Figure 3). Instead, the final value of K_s was greater in situations yielding the lowest K_s values with the standard procedure, although the relationship between $K_{s,f}$ (long-duration run) and $K_{s,15}$ (standard run) was rather scattered (R^2=0.4758, R>0). With the standard experiment, neither the normal, N, nor the ln-normal, LN, distribution hypotheses were rejected for both *S* and K_s, but the N distribution hypothesis was better than the LN one in both cases. With the long-duration experiment, the two distribution hypotheses were not rejected for *S*, but the LN hypothesis was better than the N one. Only the LN distribution hypothesis was not rejected for K_s. Therefore, the two soil hydrodynamic parameters were more normally distributed when the standard protocol was applied and more ln-normally distributed with the long-duration experiment.

SSBI method against BEST-steady

With the standard Beerkan experiment (15 water volumes), BEST-steady and the SSBI method with α^*=12 1/m did not yield statistically equivalent estimates of K_s (Table 2 and Figure 2C, first points of the curves), since the means were significantly different.

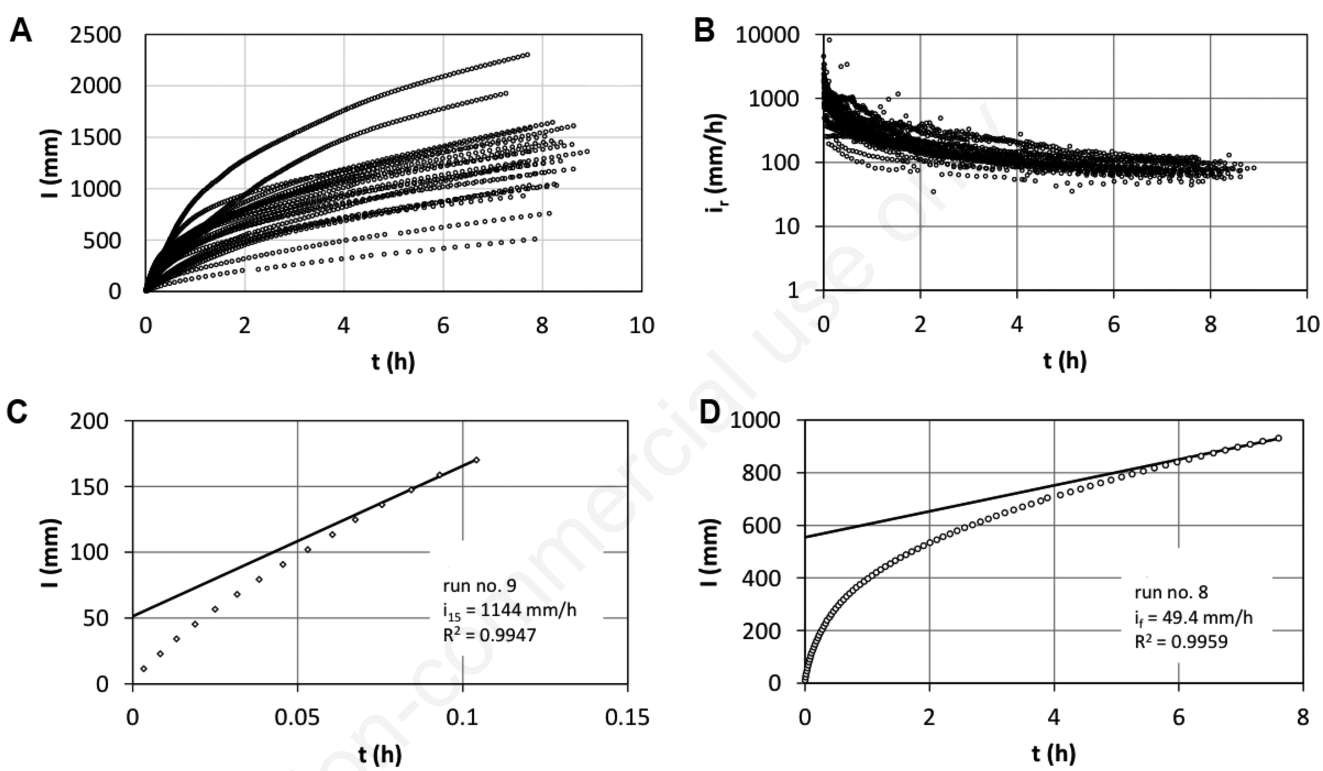

Figure 1. Cumulative infiltration, *I* (A), and infiltration rate, i_r (B), against time, *t* (sample size, *N*=22 infiltration runs), and examples of estimation of steady-state infiltration rate after applying 15 water volumes (i_{15}, C) and at the end of a long run (i_f, D).

Table 2. Summary statistics of soil sorptivity, S (mm/h$^{0.5}$), and saturated soil hydraulic conductivity, K_s (mm/h), obtained with the standard and the long-duration beerkan infiltration runs by BEST-steady and the SSBI method with an α^* parameter of 12 1/m, and optimized α^* (1/m) for the standard and the long-duration runs (sample size, *N*=22).

Statistic	BEST-steady Sorptivity, S		BEST-steady Saturated soil hydraulic conductivity, K_s		SSBI method Saturated soil hydraulic conductivity, K_s		Optimized α^* parameter	
	Standard protocol	Long duration run	Standard protocol	Long duration run	Standard protocol	Long duration run	Standard protocol	Long duration run
Minimum	35.9	30.8	15.0	1.04	20.0	12.9	6.5	0.34
Maximum	149.8	51.9	690.6	5.43	348.5	31.1	63.8	4.1
Arithmetic mean	93.4	41.9	261.4	2.07	177.0	21.0	23.4	0.97
Median	94.3	41.1	228.4	1.54	184.1	20.2	19.5	0.73
Geometric mean	88.4	41.5	192.5	1.84	146.4	20.4	19.1	0.83
Coefficient of variation (%)	31.8	14.4	65.3	57.5	51.8	25.9	68.3	79.2

Moreover, the two variables were significantly correlated (R^2=0.5721, R>0), but the 95% confidence intervals of the linear regression line between $K_{s,BS}$ (K_s obtained with BEST-steady) and $K_{s,SSBI}$ (K_s obtained with the SSBI method) did not include 0 for the intercept (*ci*=20.1-121.6) and 1 for the slope (*ci*=0.24-0.57). However, two corresponding estimates of K_s differed by no more than 2.5 times (mean=1.6) and differences by a factor of two or three can be neglected for many practical purposes (Elrick and Reynolds, 1992a). Therefore, the simpler method, which did not require any information on soil water content and was based on the first approximation value of α*, yielded a relatively similar result to that obtained with a less subjective method requiring more input data.

Much larger discrepancies between $K_{s,BS}$ and $K_{s,SSBI}$ were detected with reference to the long-duration run scenario (Table 2 and Figure 2C, end of the curves). Even in this case the means were significantly different, but $K_{s,SSBI}$ was 2.4-26.1 times greater than $K_{s,BS}$, depending on the run. The mean discrepancy factor between the two K_s estimates was equal to 12.2 and the two variables were not correlated (R^2=0.0098; R=0).

With reference to the standard beerkan experiment, the α* parameter yielding $K_{s,BS}$=$K_{s,SSBI}$, calculated by Eq. (5) was equal to 19.1-23.4 1/m, depending on the considered central tendency measure (Table 2). This value is intermediate between the used value, α*=12 1/m, which represents the first approximation α* value and also the suggested parameter for most structured soils and medium and fine sands (Elrick and Reynolds, 1992a), and α*=36 1/m, suggested for coarse sands and highly structured soils. Therefore, using α*=12 1/m was a reasonable choice overall, although a slightly larger α* value would have led to a greater similarity between $K_{s,BS}$ and $K_{s,SSBI}$. The optimized α* values decreased rather abruptly in the early part of the long-duration run (approximately during the first 1.5-2 hours) and then they nearly stabilized or continued to decrease to low values (Figure 2D). At the end of the experiment, α* approached a value of 0.7-1.0 1/m (Table 2).

Discussion

The continuing decrease of i_r after applying 15 water volumes could suggest that infiltration did not stabilize at the end of the classical beerkan run, since the process was still in a transient, decreasing phase. This possibility cannot be excluded according to theory of single-ring infiltration (Elrick and Reynolds, 1992b) but, in practice, stabilization of the process should occur soon in many instances. For example, equilibration times of a few tenths of minutes, close to the duration of the standard beerkan run (15 water volumes, Table 1), were reported for other single-ring field investigations on different soils (Reynolds *et al.*, 2000). Moreover, Stewart and Najm (2018) recently concluded that steady-state conditions may be reached in relatively short time-scales (minutes to hours) even in fine-textured soils.

The BEST-steady algorithm assumes that the infiltration process has stabilized at the end of the run. Taking into account that infiltration goes through an initial transient phase of decreasing infiltration rates, the accuracy of the S and K_s determinations will partially depend on the degree to which the quasi steady flow was achieved (Reynolds *et al.*, 2000). According to these authors, a steady method of analysis of single-ring infiltration data can be applied if the measured equilibration time corresponds favourably

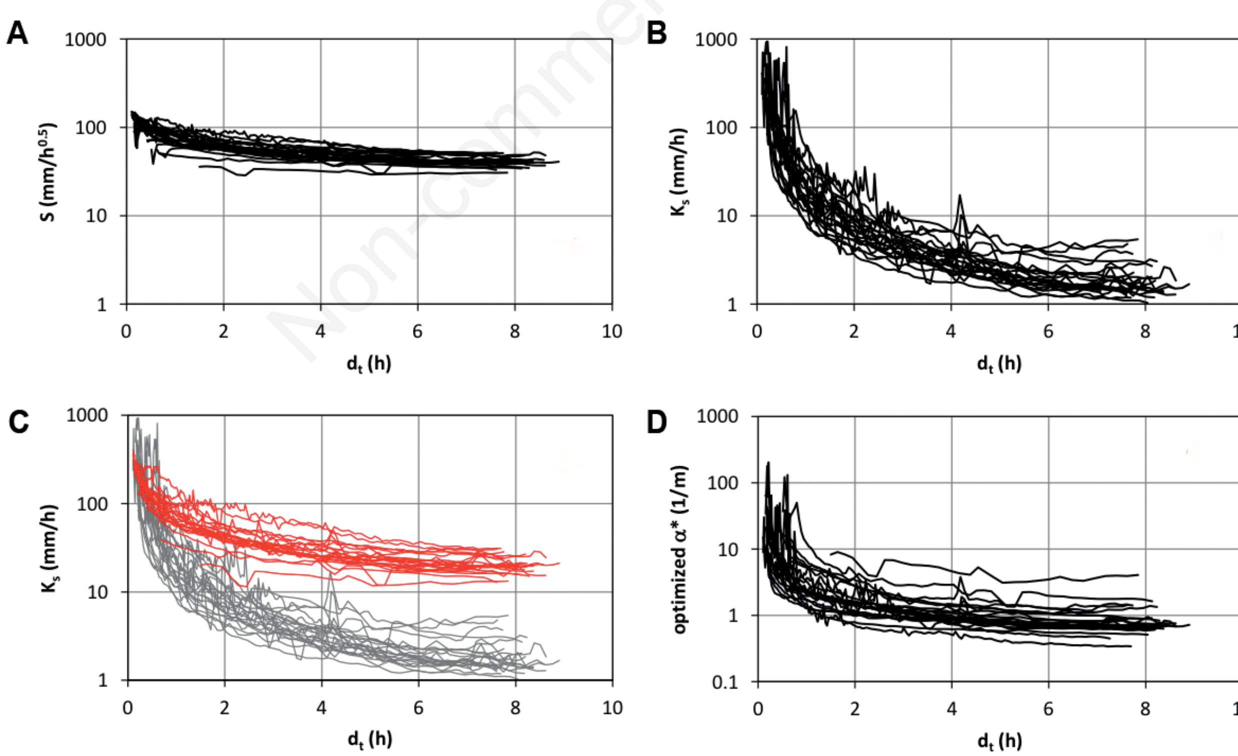

Figure 2. BEST-steady estimates of soil sorptivity, S (A), and saturated soil hydraulic conductivity, K_s (B), comparison between the K_s values obtained with BEST-steady (grey lines) and the SSBI method (red lines) (C), and optimized α* parameter (D) against infiltration run duration, d_t.

to the equilibration time predicted by the Philip (1969) $t_{grav}=(S/K_s)^2$ calculation. In this investigation, equilibration times varied between 0.9 and 1.7 times t_{grav}, depending on the central tendency measure (arithmetic or geometric mean, median) used to summarize the equilibration time/t_{grav} ratios. The correspondence was deemed overall satisfactory also because, in the investigation by Reynolds *et al*. (2000), equilibration times of 20-30 and 15-20 min were considered to correspond favourably to a t_{grav} value of ~15 min. Therefore, this analysis suggested that the infiltration data collected with the standard beerkan run were analysable with BEST-steady. However, all possible uncertainties were not eliminated, because t_{grav} was roughly determined since it was computed from the estimates of S and K_s that depended on the run duration.

Consequently, another check was carried with reference to the shortest runs (15 water volumes). In particular, K_s was also calculated with method 1 by Wu *et al*. (1999), since it does not require to attain steady-state conditions (Stewart and Najm, 2018). The stabilization of the late phase of the shortest run was considered plausible if the K_s dataset developed on the basis of this assumption (BEST-steady) compared favourably to the K_s dataset obtained without making any hypothesis on flow steadiness (method 1; Wu *et al*., 1999). The two K_s datasets were statistically similar and their means, medians and geometric means differed by ≤1.29 times. Note that the sample size for this comparison was N=21, since the fitting of Wu *et al*. (1999) model to the data failed for a run. Therefore, the two methods of data analysis yielded similar results, and the hypothesis that BEST-steady was properly applied to the shortest beerkan runs was confirmed again. In other terms, this comparison corroborated the assumption that near steady-state conditions were reached by using 15 water volumes, as expected according to the rule of thumb by Lassabatere *et al*. (2006). Another possible reason why i_r continued to decrease was a progressive modification of the sampled soil volume close to the infiltration surface. In other words, a longer infiltration run implied more opportunities for soil swelling or for a weakening of the bonds between soil particles. As a result, there were more chances that detached soil particles were transported, with a subsequent modification of the soil pore system. This interpretation appeared plausible for the following reasons. First of all, Ben-Hur *et al*. (1987) noticed that surface seal formation induces a reduction of both the mean and the CV of the steady-state infiltration rates and a change of their distribution from near-symmetric (skewness≈0) to positively skewed (skewness >0), and all these changes were detected in this investigation in the passage from i_{15} to i_f (Table 1). The fact that double- and not single-ring infiltrometer data were collected by Ben-Hur *et al*. (1987) was considered at the most a minor difference with this investigation, since the buffer cylinder used for the double-ring infiltrometer measurements is often not effective in preventing flow divergence under the measuring cylinder (Reynolds *et al*., 2002). A laboratory application of the constant head permeameter method on undisturbed samples of the same soil of this investigation revealed that long runs induced structure deterioration processes and yielded consequently lower K_s values than short runs (Bagarello *et al*., 2011). This tendency

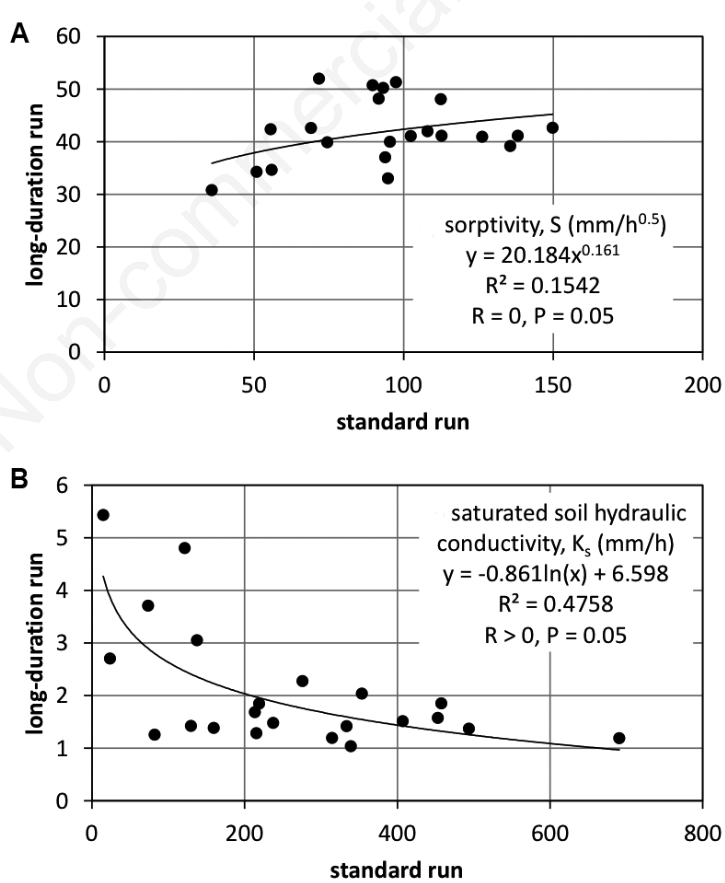

Figure 3. Relationship between A) sorptivity, S, and B) saturated soil hydraulic conductivity, K_s, values obtained with two experimental methodologies.

was similar to that detected in the field with the beerkan runs, although the sampled soil volume did not change with the run duration in the experiment by Bagarello *et al*. (2011).

In a field investigation by Somaratne and Smettem (1993), a simulated rainfall inducing the breakdown of surface soil aggregates determined a decrease of the hydraulic conductivity, while soil sorptivity remained unaffected. Therefore, even the greater sensitivity of K_s than S to the used water volume was consistent with the occurrence of soil deterioration during infiltration. This phenomenon was also shown by the decrease of the *CV* values of both K_s and, particularly, S in the passage from the standard to the long-duration run (Table 2), since an altered soil layer is expected to have a more uniform structure than the underlying bulk soil (Ben-Hur *et al*., 1987).

Changes in K_s between the standard and the long-duration run varied widely with the sampling point, but these changes were of the same order of magnitude of those found in other comparisons between unaltered and altered soils. For example, differences by 47-291 times were reported by Ramos *et al*. (2000) and by 17-115 times by Assouline and Mualem (2002). The K_s values of the sealed/disturbed soils fell in very similar and partially overlapping ranges, *i.e* 1.0-5.4 mm/h (this investigation), 0.35-6.2 mm/h (Ramos *et al*., 2000) and 0.42-1.3 mm/h (Assouline and Mualem, 2002). Therefore, it seems that the saturated conductivity of different disturbed soils tends to collapse towards a rather narrow range of small values, which are likely to be compatible with the surface runoff formation in many instances, regardless of the applied experimental methodology.

According to the empirical relationship between $K_{s,f}$ and $K_{s,15}$ (Figure 3B), a sampling point having inherently a relatively low saturated conductivity should be less sensitive to wetting-induced soil disturbance than an initially highly permeable location. Similar data were reported by Assouline and Mualem (2002). In particular, sealing induced a decrease of K_s by 17 times when the undisturbed soil had a K_s value of 7 mm/h, but by 79 or more times, when the conductivity of the undisturbed soil was of 45-100 mm/h. High or very high K_s values are typical of macroporous soils and the macropores that dominate flow at saturation are known to be fragile and less stable than matrix pores (Jarvis *et al*., 2013). Therefore, it seems plausible to believe that the reduced sensitivity of relatively small $K_{s,15}$ values to long wetting was a consequence of a more limited presence of large and more or less unstable macropores.

According to Assouline and Mualem (2002), the development of a seal layer can determine a change in the probability distribution of later time infiltration rates, that is from normal in an unsealed condition to log-normal under sealing conditions. This investigation also suggested that the probability distribution of both hydrodynamic parameters can change from nearly normal to nearly ln-normal, when passing from an unaltered to a presumably altered soil condition.

A third possibility of the progressive decrease of i_r, K_s and S with the run duration was related to the circumstance that the sampled soil volume increased in size as more water was used. In particular, radial infiltration had probably some relevance on determining the shape of the wetted zone, since small diameter rings were used, but total infiltrated water volumes were large (Table 1). Therefore, an effect of vertical gradients in antecedent soil water content and soil hydrodynamic parameters on the measured infiltration process represented another possible reason for the results of this experiment. Even this interpretation was supported by literature. In particular, Wu *et al*. (1997) demonstrated, through numerical simulation, that single-ring infiltration rates can vary between homogeneous and layered soils depending on the position of the wetting front relative to the textural discontinuity and the time of measurement. However, all the infiltration rate curves reported by Wu *et al*. (1997) for different layering scenarios maintained the same general shape (i_r continuously decreasing with time), suggesting that layering could not easily be perceived from the measured infiltration process.

Infiltration data encompass many effects, which are difficult to separate from each other (Dohnal *et al*., 2016) and the data collected in this investigation do not represent an exception. The developed analysis led to believe that non-attainment of steady-state infiltration was at the most a minor factor determining the decrease of i_r in the passage from i_{15} to i_f. Instead, a progressive structure deterioration of the upper soil layer represented a plausible reason for this decrease, since this was justified from different points of view. What remained undefined was a possible effect of vertical changes in soil hydrodynamic properties and antecedent water content. Testing this effect is advisable in the near future, also because two alternative scenarios could be delineated in the presence of layering. In particular, a scenario is that soil layering was mainly responsible for the decrease of the infiltration rates and soil surface deterioration had a limited impact on this decrease. Another scenario is that soil surface deterioration made the upper layer less conductive than the lower layers. In such a situation, the restricted flow rate through the less permeable upper layer was the limiting factor, since it was not enough to sustain flow at the saturated hydraulic conductivity of the lower, more permeable, layers (Hillel, 1998). Short infiltration tests could be carried at a closely spaced depth to investigate further this issue (Vandervaere *et al*., 2000). The simplified falling head technique (Bagarello *et al*., 2004) could be a potentially adequate method to determine the vertical profile of K_s in a nearly undisturbed situation, since this technique can be applied to sample soil layers of known thickness directly in the field with a minimum soil disturbance.

The two K_s estimation methods (BEST-steady, SSBI method) were relatively similar with the standard experiment but not with the long-duration run. The reason was that both $K_{s,BS}$ and $K_{s,SSBI}$ decreased with the run duration, but the former estimate of K_s decreased at an appreciably higher rate than the latter one (Figure 2C). In particular, $K_{s,BS}$ decreased because i_s decreased and b_s increased, whereas the decrease of $K_{s,SSBI}$ only depended on the decrease of i_s. Obtaining similar estimates of K_s with BEST-steady and the SSBI method for the entire run duration would require using, in the latter case, α^* values that decrease with the run duration (Figure 2D). In other terms, the decrease of α^* is a substitute for the increase of b_s that does not appear in the SSBI method equation.

Conclusions

Performing a single-ring beerkan infiltration run with more water than required by the standard and commonly employed experimental protocol yielded lower sorptivity, S and, particularly, saturated soil hydraulic conductivity, K_s, values. The lack of attainment of steady state conditions was no more than a minor factor determining the detected decrease. Instead, a progressive deterioration of the continuously wetted soil zone appeared a plausible reason for this result. Vertical gradients in antecedent soil water content and soil hydrodynamic parameters were another factor which possibly influenced the difference between runs of different duration.

The hydraulic characteristics of both the nearly undisturbed soil and the long-wetted soil could be determined with a single experiment by choosing an appropriate part of the infiltration curve to analyse. In particular, it is suggested that the standard run characterizes the nearly undisturbed soil and that continuing the experiment for the longest possible time could yield soil data at least approaching those of the altered surface layer or those required to quantify management practices under prolonged irrigation times.

A great experimental detail with reference to the infiltration process is not required to apply BEST-steady, since the run is completely characterized by its total duration, infiltrated water and final infiltration rate. In other words, it is not strictly necessary to monitor the early-time phase of the infiltration process. The possibility to simplify the experiment increases the attractiveness of the methodology and could be particularly useful when multiple beerkan runs must be carried out simultaneously. However, this cannot be generalized, since the check of the transient stage is done for some specific purposes, such as capturing possible water repellency effects on infiltration.

In conclusion, single-ring infiltration experiments appear potentially usable to describe the soil hydrodynamic behaviour in hydrologically relevant situations. Field experiments remain rather simple and can be completed in a few hours. The usability of the hydrodynamic soil properties determined with the tested methodology to simulate surface hydrological processes deserves further investigation. In particular, it should be verified if infiltration runs may simulate the effect of natural rainfall on the soil structure accurately or rainfall simulators are closer in terms of experimental simulation of the long-term effect of water on the soil structure. In addition, checking vertical variability of hydrodynamic soil properties is necessary in order to better explain the reasons for the decrease of K_s, as the run duration increased.

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