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Determining short-term changes in the hydraulic properties of a sandy-loam soil by a three-run infiltration experiment

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ABSTRACT
Soil structure-dependent parameters can vary rapidly as a consequence of perturbing events such as intense rainfall. Investigating their short-term changes is therefore essential to understand the general behaviour of a porous medium. The aim of this study is to gain insight into the effects of wetting, perturbation and recovery processes through different sequences of Beerkan infiltration experiments performed on a sandy-loam soil. Two different three-run infiltration experiments (LHL and LLL) were carried out by pouring water at low (L, non-perturbing) and high (H, perturbing) heights above the soil surface and at short time intervals (hours, days). The results demonstrate that the proposed method allows one to capture short-term variations in soil structure-dependent parameters. The developed methodology is expected to simplify the parameterization of hydrological models with temporally variable soil hydraulic properties.

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Introduction

The interpretation and simulation of hydrological processes, such as rainfall excess generation, need to take into account that, as shown by many rainfall simulation investigations (Morin and Benyamini 1977, Levy *et al.* 1986, Le Bissonnais and Singer 1992, Fohrer *et al.* 1999, Torri *et al.* 1999, King and Bjorneberg 2012), soil surface characteristics are highly dynamic and can change even over short times, i.e. during rainfall events or between closely spaced rainstorms. Therefore, it is necessary to determine the short-term variability of soil properties as a consequence of wetting and drying to properly capture the general hydrodynamic behaviour of a porous medium and hence to choose input parameters to physically based hydrological models that are appropriate for a particular application, soil and soil condition (Reynolds *et al.* 2000, Assouline and Mualem 2002, Ndiaye *et al.* 2005). Moreover, in general, improving our ability to measure and monitor soil hydraulic properties goes towards achievement of the Sustainable Development Goals (SDGs), delineated by the General Assembly of the United Nations (UN) in 2015, given that SDGs 2, 6, 13 and 15 have a direct relationship with soil-water interactions, while a more indirect relationship applies to SDGs 7, 8, 11 and 12 (Bouma 2016).

Soil sorptivity, S, and saturated soil hydraulic conductivity, K_s, are the necessary soil parameters to describe infiltration in physically based models of surface hydrological processes (e.g. Touma *et al.* 2007). Sorptivity defines the ability of a soil to conduct water by capillarity; it varies with the initial and final soil water content and, when present, the depth of the water head at the soil surface. The saturated soil hydraulic conductivity represents the maximum rate of water flow due solely to gravity in a completely saturated soil. The S^2/K_s ratio allows one to calculate the time to ponding during rainfall infiltration (White *et al.* 1989), as well as the scale parameter of the water retention curve, h_g (Lassabatere *et al.* 2006), and hence the macroscopic capillary length (Souza *et al.* 2014) that represents the relative magnitude of the capillarity and gravity forces which prevail during an infiltration process (Angulo-Jaramillo *et al.* 2016, 2019). Both S and K_s often show non-easily predictable dynamics, which makes the application of hydrological models complicated and even uncertain with reference to the input parameters to be used for simulations. For example, in an investigation by Ndiaye *et al.* (2005), the influence of cumulative rainfall since tillage was more noticeable for K_s than S along a transect but not along another transect established on the same field.

Single-ring infiltration experiments are an attractive alternative to more complex experiments, such as rainfall simulations, for investigating short-term variability of soil hydraulic properties. Infiltrometer experiments are easier to perform in the field as compared with rainfall simulation experiments (Di Prima *et al.* 2017, 2018). The analysis of infiltrometer data relies on robust physical theories and the application of these techniques generally requires simple, parsimonious and rapid experiments. Subsequent single-ring infiltration experiments of the Beerkan type could easily be performed to investigate the short-term dynamics of the surface soil properties. The Beerkan protocol is very simple since it only needs a cylinder, a few litres of water and a stopwatch; therefore, it is particularly appropriate for field campaigns (Lassabatere *et al.* 2006). The

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measured infiltration, in conjunction with the three Beerkan Estimation of Soil Transfer (BEST) parameter algorithms of data analysis (Lassabatere *et al.* 2006, Yilmaz *et al.* 2010, Bagarello *et al.* 2014c), allows the estimation of soil structure-dependent parameters, i.e. S, K_s and h_g. The study by Mubarak *et al.* (2009), who investigated the temporal variability of soil hydraulic properties due to changes in soil structure under high-frequency drip irrigation, proved that the Beerkan methodology is a valid approach to determine the short-term variability of the selected soil parameters.

Use of ring infiltration methods to explore changes in soil hydraulic properties over short time periods, i.e. hours or days, is uncommon (e.g. Alagna *et al.* 2018b, Dohnal *et al.* 2016, Votrubova *et al.* 2017). Perhaps, one reason is of theoretical nature since the methods of data analysis assume a homogeneous soil water content at the beginning of the run and this assumption could not be valid when two infiltration runs at a point are carried out at small time intervals from one another. Another reason could be skepticism about the ability of infiltrometer techniques to capture in detail the soil dynamics, given that, according to several investigations, these techniques could yield excessively high infiltration rates or K_s values in the perspective of explaining surface hydrological processes (Ben-Hur *et al.* 1987, Cerdà 1996, 1997, van De Giesen *et al.* 2000, Bagarello *et al.* 2013).

However, more encouraging information can also be found in the literature, in particular that a ring infiltration experiment could be adapted to agree with the hydrologically relevant information that has to be collected. For example, the height of water application can be used to alter the soil surface and hence to reproduce, at least to a certain degree, a sealed soil layer at the infiltration surface. Using Beerkan infiltration runs, Bagarello *et al.* (2014a) and Alagna *et al.* (2016) proposed an experimental methodology that combines low (L runs) and high (H runs) heights of water pouring to approximate in the field the effects of rainfall events of varying energy on the hydraulic characteristics of the surface soil layer. Di Prima *et al.* (2017) suggested that rainfall simulation and H runs determined a similar degree of surface soil alteration, but the latter experiment was easier to conduct. Di Prima *et al.* (2018) successfully verified the capability of the H runs to catch the formation of the seal and related consequences on water infiltration.

Bagarello *et al.* (2017a) and Alagna *et al.* (2018a) recently developed a simple and parsimonious two-stage Beerkan run methodology to specifically determine in the field the effects of water pouring height on the measured infiltration rates under initially near-saturated conditions. First, the L run is carried out and then the sampled soil is allowed to drain for a few tens of minutes. Subsequently, the L or H procedure is used to pour other water onto exactly the same infiltration surface. The double two-stage experiment (LL and LH) allowed Alagna *et al.* (2018a) to distinguish between wetting and mechanical disturbance effects on single-ring infiltration rates in the field.

During the pause between the two subsequent runs (either LL or LH), water redistribution processes occur and perhaps even soil reorganization. Therefore, the information collected with the new run will likely depend on (a) soil characteristics before any water application, (b) soil changes induced by the first run, such as swelling or soil particle mobilization, (c) possible structure recovery during short-term drying, and (d) possible additional changes in the soil determined by the new run itself. Morin and Benyamini (1977) showed that the duration of the drying period after a water application event can influence the subsequent infiltration process. Therefore, specifically considering the impact of the drying time on the soil hydraulic properties under given temperature, solar radiation and soil cover conditions appears necessary to enable the measured properties to be used confidently as input data to physically based hydrological models.

The repeated Beerkan run methodology could also be used, with a limited increase in the field workload, to verify changes at the soil surface following disturbance (Fohrer *et al.* 1999), but data were never collected after performing an LH run. The expectation is that performing an L run after the perturbing one should yield information on possible recovery processes. The literature suggests that recovery processes should occur at lower rates than those typically associated with water impact effects, that are almost instantaneous or very rapid (Morin and Benyamini 1977, Fohrer *et al.* 1999, Drewry 2006, Hu *et al.* 2018, Lozano-Baez *et al.* 2019). However, this suggestion could also depend on the lack of experimental information on short-term recovery of soil hydraulic properties.

In any case, analysing recurrent infiltration runs with the BEST algorithms could be challenging since these algorithms also require soil water content both before and after infiltration. An implication is the need to perform additional runs to specifically collect these data for the analysis of a multi-run experiment with BEST. A possible alternative that simplifies experimental procedures could be to use the so-called Steady Simplified method based on the Beerkan Infiltration run (SSBI) (Bagarello *et al.* 2017b) that is usable to determine K_s without any information on soil water content. However, the suitability of this method to analyse a multi-run infiltration experiment was never checked.

The general objective of this investigation is to check short-term (hourly or daily) changes in soil structure-dependent hydraulic parameters associated with subsequent infiltration runs. In particular, two three-run infiltration experiments differing by a single factor, that is soil disturbance at an intermediate stage of the process, were carried out to:

(a) explore how soil sorptivity, S, saturated soil hydraulic conductivity, K_s, and scale parameter of the water retention curve, h_g, vary as a consequence of closely spaced wetting and drying phases;
(b) check the effect of the drying time between two runs on these soil properties;
(c) determine the suitability of the double three-run methodology for distinguishing between wetting and mechanical disturbance effects on S, K_s and h_g;
(d) verify if soil recovery processes occur soon after mechanical disturbance; and
(e) test a simplified procedure to determine K_s with a perturbing experiment under different antecedent soil conditions.

Materials and methods

Infiltration experiments

The field experiments were carried out on a sandy-loam soil covered by a citrus orchard at the Department of Agricultural, Food and Forest Sciences of the Palermo University, Italy. Ponding infiltration experiments of the Beerkan type (Lassabatere *et al.* 2006) were carried out following the procedure described by Alagna *et al.* (2016). More specifically, 15 volumes of 57 mL of water were repeatedly poured, each in approx. 3–4 s, inside a 0.08-m inner-diameter ring inserted shallowly (0.01 m) into the soil and the time needed for each volume to infiltrate was logged. The water was poured into the confined surface from two different heights, namely 0.03 m (low, L, infiltration run) and 1.5 m (high, H, infiltration run). A transparent tube was used for the H experiments in order to shield the falling water from the wind.

Two types of three-stage infiltration run, namely LHL (perturbing soil experiment) and LLL (non-perturbing soil experiment), were carried out in the summer months, in July–August 2015 and June–July 2016 (Fig. 1), respectively, to sample the soil with two different run sequences under similar initial wetness conditions, i.e. dry in both cases.

For the LHL experiment (Fig. 2(a)), 15 volumes of water were applied with the L procedure (L1 run) and then the sampled soil was allowed to drain for a pre-established time, Δt, equal to 1, 48 or 96 h, depending on the sampling point, to give the system time to experience a redistribution of the infiltrated water and, perhaps, short-term soil structure reorganization following changes due to wetting. Subsequently, the H procedure was used to pour a further 15 volumes of water (H2 run). After 1, 48 or 96 h, depending on the sampling point, another 15 volumes of water were finally poured, again using the L procedure (L3 run). At a given sampling point, the Δt value did not vary between subsequent runs (e.g. for 1 h between the L1 and H2 runs, there was 1 h between the H2 and L3 runs).

A similar procedure was applied for the LLL experiment. The only difference was that, in this case, the L procedure was applied for all infiltration runs (i.e. the second run was L2 instead of H2). For each Δt value, five LHL runs and five LLL runs were carried out at randomly selected sampling points. Therefore, a total of 90 infiltration curves were collected (2 experiments × 3 Δt values × 5 replicated three-stage runs × 3 curves per run). A sample size of $N = 5$ for a given treatment was chosen taking into account that a small area in the field could satisfactorily be characterized by averaging a few closely spaced replicated measurements (Fodor *et al.* 2011, Ugarte Nano *et al.* 2015, Lassabatere *et al.* 2019).

The initial soil conditions, in terms of dry soil bulk density, ρ_b (g cm^{-3}), and volumetric soil water content at the time of the experiment, Θ_i (m^3 m^{-3}), were determined by inserting, at randomly selected locations, cylinders of 0.05 m in height by 0.05 m in diameter to collect undisturbed soil cores at depths of 0–0.05 and 0.05–0.10 m. These cores were used to determine ρ_b and the gravimetric soil water content, w_i (g g^{-1}) and, hence Θ_i, in the laboratory. For the LHL experiment, six cores were collected and the associated ρ_b and Θ_i values were averaged to characterize the soil before all runs, i.e. regardless of the considered Δt value. For the LLL experiment, five cores were collected before the runs with a pre-established Δt value and the resulting ρ_b and Θ_i values were averaged. A few additional infiltration runs were carried out in duplicate at different randomly selected locations to obtain information on ρ_b and Θ_i immediately before the H2, L2 and L3 runs (Fig. 2(b)). To determine the soil conditions before the H2 and L2 runs, only L1 infiltration runs were carried out and the wetted soil volume was sampled 1, 48 or 96 h after this run. To determine ρ_b and Θ_i before the L3 infiltration runs, an LH or LL run was carried out with a given Δt value (1, 48 or 96 h) and the soil was sampled after the same Δt had elapsed. Thus, a total of 24 additional infiltration runs were carried out. The information on the ρ_b and Θ_i conditions before the L2, H2 and L3 runs was not free from uncertainties, since collecting an undisturbed soil core after an infiltration run was not easy. However, using these data was considered to be better than assuming that ρ_b and Θ_i did not change between runs regardless of Δt.

Two other LHL experiments were carried out at the same field site, in new randomly selected locations and in a simplified manner, in the autumn and spring, i.e. October 2015 and April–May 2016, respectively (Fig. 1), to check the possible effect of the antecedent soil conditions on the results of a soil perturbing experiment and to verify the usability of the SSBI method (Bagarello *et al.* 2017b) to analyse a multi-run, perturbing experiment. The opportunity to test the simplified experimental protocol that does not require soil water content data was supported by the circumstance that K_s was found to be the most sensitive soil property to repeated water applications in the LHL experiment of July–August 2015. On these occasions, ρ_b and Θ_i data were only collected at the beginning of the experiment, i.e. before the L1 runs, and the time interval between two subsequent runs was only 1 h. The other factors of the experiment, including ring and sample sizes, applied water volumes and height of water application, did not change as compared with the LHL experiment of July–August 2015. Therefore, 30 additional infiltration curves were collected. Only $\Delta t = 1$ h was considered since the shortest time interval between two subsequent runs was expected to induce the largest soil differences between the L1 (initially unsaturated soil) and H2 (initially close to saturation soil) runs.

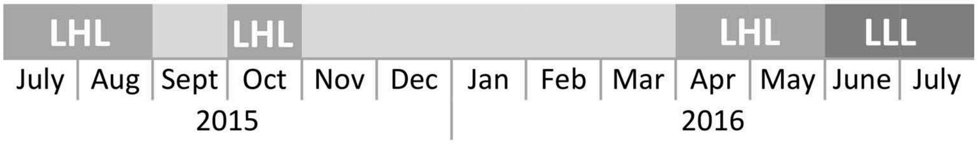

Figure 1. Timeline of the sampling campaigns.

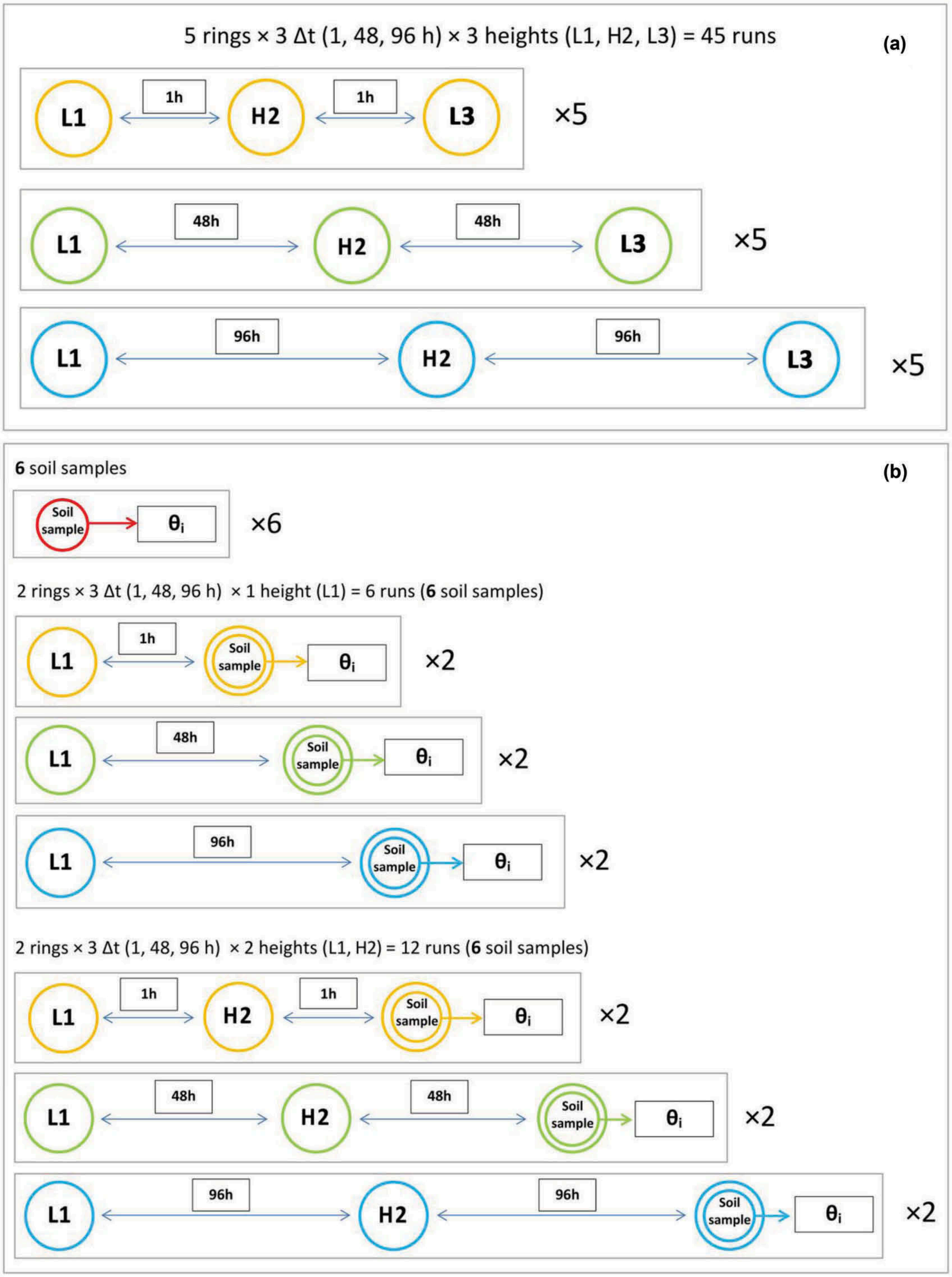

Figure 2. Schematic diagrams of: (a) the LHL infiltration experiment carried out with different time intervals (Δt = 1, 48 and 96 h) and heights of water pouring (L1, H2 and L3) and (b) the procedures applied to obtain a representative value of the initial volumetric soil water content, θ_i ($m^3 m^{-3}$), at the time of the different infiltration runs carried out with different time intervals, Δt, and different water pouring heights (L1, H2 and L3).

Calculation of soil hydraulic parameters

The infiltration data collected in the summer LHL (July–August 2015) and LLL (June–July 2016) experiments were analysed with the BEST-steady algorithm (Bagarello *et al.* 2014c) to calculate, for each infiltration run, the saturated soil hydraulic conductivity, K_s [L T^{-1}], the soil sorptivity, S [L $T^{-0.5}$] and the scale parameter of the water retention curve, h_g [L]. This choice was made since some infiltration runs (H2) were aimed to intentionally trigger a disturbance of the exposed soil surface during infiltration and the alternative BEST algorithms, i.e. BEST-slope (Lassabatere *et al.* 2006) and BEST-intercept (Yilmaz *et al.* 2010), were found not to work well when a seal was progressively formed at the soil surface during the run, owing to the pronounced concavity of the cumulative infiltrations (Di Prima *et al.* 2018). In contrast, BEST-steady was expected to allow a proper estimation of soil hydraulic parameters even for the H2 runs, since this algorithm only considers the stabilized phase of the process, i.e. after the seal had time enough to develop.

The BEST-steady algorithm makes use of the intercept, b_s [L], and the slope, i_s [L T^{-1}], of the straight line fitted to the data describing steady-state conditions of the cumulative infiltration, i.e. the I [L] *versus* time, t [T] curve. The following relationships are used to calculate S, K_s and h_g:

$$S = \sqrt{i_s / \left(A + \frac{C}{b_s} \right)} \tag{1}$$

$$K_s = \frac{C i_s}{A b_s + C} \tag{2}$$

$$h_g - \frac{S^2}{c_p(\theta_s - \theta_i)\left[1 - \left(\frac{\theta_i}{\theta_s}\right)^{\eta}\right] K_s} \tag{3}$$

$$A = \frac{\gamma}{r(\theta_s - \theta_i)} \tag{4}$$

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

where c_p is a coefficient that depends on the shape parameters of the soil hydraulic characteristic curves. BEST estimates c_p on the basis of soil textural characteristics and dry soil bulk density (Lassabatere *et al.* 2006); Θ_s and Θ_i [L^3 L^{-3}] are the saturated and the antecedent, or initial, volumetric soil water content, respectively; η is the shape parameter of the soil hydraulic conductivity curve (Brooks and Corey 1964); β and γ are coefficients usually set at 0.6 and 0.75, respectively; and r [L] is the radius of the infiltration surface.

A homogeneous dataset for the replicated LHL experiment (summer, autumn, spring; Δt = 1 h) was obtained by calculating K_s with the SSBI method that was developed with specific reference to the steady-state phase of a Beerkan infiltration run (Bagarello *et al.* 2017b):

$$K_s = \frac{i_s}{\frac{\gamma \gamma_w}{r \alpha *} + 1} \tag{6}$$

where γ_w (= 1.818) is a constant and α^* [L^{-1}] is a soil parameter that depends on the soil textural and structural characteristics (Elrick and Reynolds 1992). In particular, four values of α^* (0.036, 0.012, 0.004 and 0.001 mm^{-1}) were suggested for practical use of permeameters and infiltrometers in soils varying from coarse sands to compacted clays and α^* = 0.012 mm^{-1} was suggested to be the value of first approximation for most field soils (Reynolds *et al.* 2002).

Each developed dataset was summarized by calculating the arithmetic mean and the associated coefficient of variation, CV. This choice was made since ρ_b and Θ_i are commonly normally distributed (Warrick 1998) and also because the normal distribution hypothesis was not rejected according to the Lilliefors (1967) test at $P < 0.05$ for the S, K_s and $|h_g|$ values obtained with the L1 runs of the two summer experiments (N = 15 in both cases).

Data analysis

For each summer experiment, the results obtained with the L1 runs were grouped according to Δt. Therefore, the first group of S, K_s, and $|h_g|$ values included the data collected at the sites that were then resampled after 1 h, the second group included the sites that were resampled after 48 h and the third group those resampled 96 h later. A two-tailed t test ($P < 0.05$) was applied to develop a pairwise comparison among the three groups of data for each soil property. This check was made to see if, within an experiment, different treatments (i.e. different time intervals between subsequent runs) were applied on a soil having initially similar characteristics.

For each experiment (LHL, LLL) and Δt value (1, 48, 96 h), a pairwise comparison of the soil properties (S, K_s, $|h_g|$) obtained with the three subsequent runs (L1 *versus* H2 or L2; H2 or L2 *versus* L3; L1 *versus* L3) was then carried out with a two-tailed t test ($P < 0.05$). A pairwise comparison was preferred to other alternative statistical tests since establishing changes in the passage from, e.g. an L1 run to a H2 run separated by an interval of 1 h does not depend on the information collected later (L3 run) or with a different time interval (Δt = 48 or 96 h). Unpaired t tests were performed for methodological homogeneity reasons. Indeed, determination of S, K_s, and $|h_g|$ failed for a run since the intercept of the regression line fitted to the steady-state part of the cumulative infiltration curve was negative (Di Prima *et al.* 2016). Therefore, it was necessary using an unpaired test for some comparisons not to arbitrarily ignore part of the valid experimental data. Applying this statistical approach in all cases avoided developing a methodologically heterogeneous comparison (paired and unpaired tests).

Before comparing the summer LHL and LLL experiments, a comparison was established between the soil physical and hydraulic properties measured before (ρ_b, Θ_i), or with (S, K_s and $|h_g|$) the L1 runs of these experiments to verify if the soil had initially similar physical and hydraulic characteristics or not. A two-tailed t test ($P < 0.05$) was applied.

A decision on the α^* value to be used for calculating K_s with the SSBI method was taken by establishing a comparison between the two K_s calculation procedures (BEST-steady, SSBI method) for all runs of the LHL and LLL experiments (N = 89 valid infiltration runs and hence K_s values). The relative performances of the simplified method were tested for α^* = 0.036, 0.012 and 0.004 mm^{-1} and also by optimizing this parameter. In particular, optimization involved finding the α^* value that minimized the sum of the squared differences between two corresponding estimates of K_s. The α^* value of 0.001 mm^{-1} was not considered since it was suggested for compacted, structureless, clayey or silty materials (Elrick and Reynolds 1992, Reynolds and Lewis 2012), i.e. very different porous media than the sampled soil. With the literature values of α^*, the best correspondence between BEST-steady and the SSBI method was detected for the first approximation value of this parameter, i.e. α^* = 0.012 mm^{-1} (Table 1). In this case, the means of K_s were significantly different but they differed by a non-substantial factor of 1.4 (Elrick and Reynolds 1992). Relative variability of K_s was similar for the two approaches

Table 1. Comparison between the saturated soil hydraulic conductivity, K_s (mm h^{-1}), values calculated with BEST-steady and the corresponding estimates obtained with the SSBI method and different values of the α* parameter (sample size, N = 89). CV: coefficient of variation.

Method	α* (mm^{-1})	Mean	CV (%)	Error*		
				Maximum	Mean	Median
BEST-steady		242.6 (a)(b)(c)d	82.4			
SSBI	0.004	71.6 (a)	75.4	7.7	3.3	3.1
	0.012	177.6 (b)	75.4	3.1	1.6	1.5
	0.036	350.4 (c)	75.4	4.5	2.0	1.6
	0.019 (optimized)	240.4 d	75.4	3.1	1.5	1.3

Means followed by the same letter in parentheses are significantly different according to a two-tailed, paired t test ($P < 0.05$); means followed by the same letter (not in parentheses) are not significantly different.

*Error: (maximum between the K_s values estimated with BEST-steady and the SSBI method)/(minimum between the K_s values estimated with BEST-steady and the SSBI method).

(CV = 75–82%) and the highest error, Er, defined as the maximum between the two K_s values divided by the minimum value was equal to 3.1. This error was only imperceptibly greater than the error that was considered acceptable for most practical purposes by Elrick and Reynolds (1992), i.e. a factor of 3. The optimized α^* parameter, equal to 0.019 mm^{-1}, was close to α^* = 0.012 mm^{-1} and it did not allow to reduce the maximum error (Table 1). However, both the mean and the median of Er decreased, although only slightly (mean error: 1.5 and 1.6 with α^* = 0.019 and 0.012 mm^{-1}, respectively; median error: 1.3 and 1.5), and the mean of K_s did not differ significantly between the two tested methods (Fig. 3). Therefore, the SSBI method was considered to represent a valid alternative to the BEST method for simply determining the K_s values associated with a multi-run experiment. Eq. (6) with α* = 0.019 mm^{-1} was used in the subsequent analysis.

Finally, a two-tailed t test at $P < 0.05$ was used to compare the K_s data obtained with the three runs for each replicated LHL experiment. In this analysis, the K_s values obtained with the SSBI method were also considered for the first sampling date (July–August 2015) instead of those calculated with BEST-steady for homogeneity with the other two sampling dates (October 2015 and April–May 2016).

Results

Soil hydraulic properties determined with two different infiltration experiments

Perturbing soil (LHL) experiment

For each soil property considered in this investigation, i.e. S, K_s and $|h_g|$, a statistical similarity was initially detected among the three groups of data obtained with the L1 runs by considering separately the sites resampled 1, 48 and 96 h later (Table 2). This result suggests that different time intervals were considered at sampling locations that, at the beginning of the experiment, had similar hydraulic properties.

A statistically significant decrease in both S (by 2.4–2.7 times, depending on Δt) and K_s (6.4–14.5 times) and an increase in $|h_g|$ (2.3–3.0 times) were detected in the passage from the L1 run to the H2 run (Table 2 and Fig. 4). Therefore, changes were stronger for K_s than S and $|h_g|$. For these two properties, there was not an influence of Δt on the detected variations. For K_s, the decrease was more appreciable for the longest time intervals (12.4–14.5 times for $\Delta t \geq 48$ h) than the shortest one (6.4 times for Δt = 1 h).

Changes in the three soil properties also occurred between the H2 and L3 runs and an effect of Δt on these changes was perceivable. In particular, S did not vary for the largest

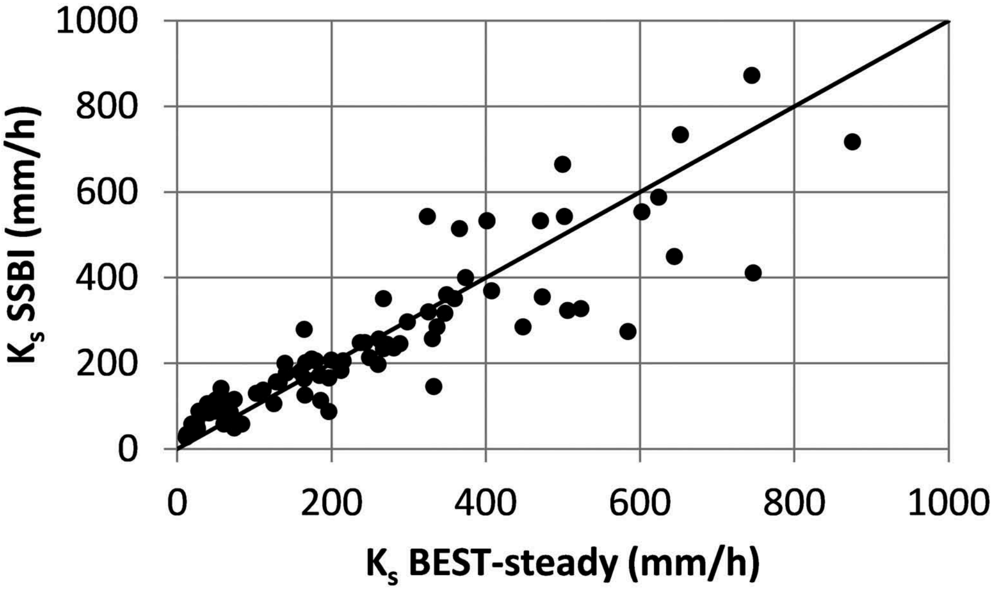

Figure 3. Comparison between the saturated soil hydraulic conductivity, K_s, values obtained with BEST-steady and the SSBI method with α* = 0.019 mm^{-1}.

Table 2. Summary of the soil sorptivity, S (mm h$^{-0.5}$), saturated soil hydraulic conductivity, K_s (mm h^{-1}) and scale parameter of the water retention curve, $|h_g|$ (mm), values obtained with the subsequent runs carried out at different time intervals, Δt (h), during the LHL and LLL experiments.

Variable	Δt	Statistic	LHL experiment			LLL experiment		
			L1	H2	L3	L1	L2	L3
S	1	Mean	128.3	50.4	34.4	130.0	75.0	47.6
			AB (a)(b)	(a)(c)	(b)(c)	AB a(b)	ac	(b)c
		CV (%)	27.6	16.4	24.4	35.7	37.8	13.1
	48	Mean	152.3	55.9	56.2	135.7	107.8	91.8
			AC (a)(b)	(a)c	(b)c	AC a(b)	ac	(b)c
		CV (%)	23.3	31.6	26.6	18.8	13.7	8.0
	96	Mean	158.3	67.3	76.7	117.2	97.8	89.5
			BC (a)(b)	(a)c	(b)c	BC ab	ac	bc
		CV (%)	25.9	14.2	28.7	26.6	10.9	10.8
K_s	1	Mean	321.3	50.2	83.8	466.1	212.4	89.8
			AB (a)(b)	(a)c	(b)c	AB (a)(b)	(a)(c)	(b)(c)
		CV (%)	57.4	86.3	79.7	20.1	40.4	66.0
	48	Mean	457.9	31.5	33.7	595.1	300.3	193.0
			AC (a)(b)	(a)c	(b)c	AC (a)(b)	(a)c	(b)c
		CV (%)	40.4	75.4	41.3	39.4	34.1	42.4
	96	Mean	462.3	37.3	178.4	388.3	265.5	192.8
			BC (a)(b)	(a)(c)	(b)(c)	BC a(b)	ac	(b)c
		CV (%)	37.4	37.6	36.9	28.5	32.1	22.7
$\lvert h_g \rvert$	1	Mean	44.5	110.6	46.5	39.1	46.8	81.9
			AB (a)b	(a)c	bc	AB ab	ac	bc
		CV (%)	25.0	45.3	95.3	65.8	75.0	61.8
	48	Mean	41.3	124.6	116.2	28.7	38.3	41.8
			AC (a)(b)	(a)c	(b)c	AC ab	ac	bc
		CV (%)	12.1	22.0	19.0	42.7	35.1	28.0
	96	Mean	43.7	100.4	31.4	38.8	35.2	42.3
			BC (a)b	(a)(c)	b(c)	BC ab	ac	bc
		CV (%)	25.0	13.4	40.7	68.6	27.3	24.5

For a given experiment and variable and with reference to the L1 runs, means followed by the same uppercase letter not enclosed in parentheses are not significantly different ($P < 0.05$); for a given experiment, variable and Δt value, means followed by the same lowercase letter not enclosed in parenthesis are not significantly different ($P < 0.05$); and means followed by the same letter enclosed in parenthesis are significantly different.

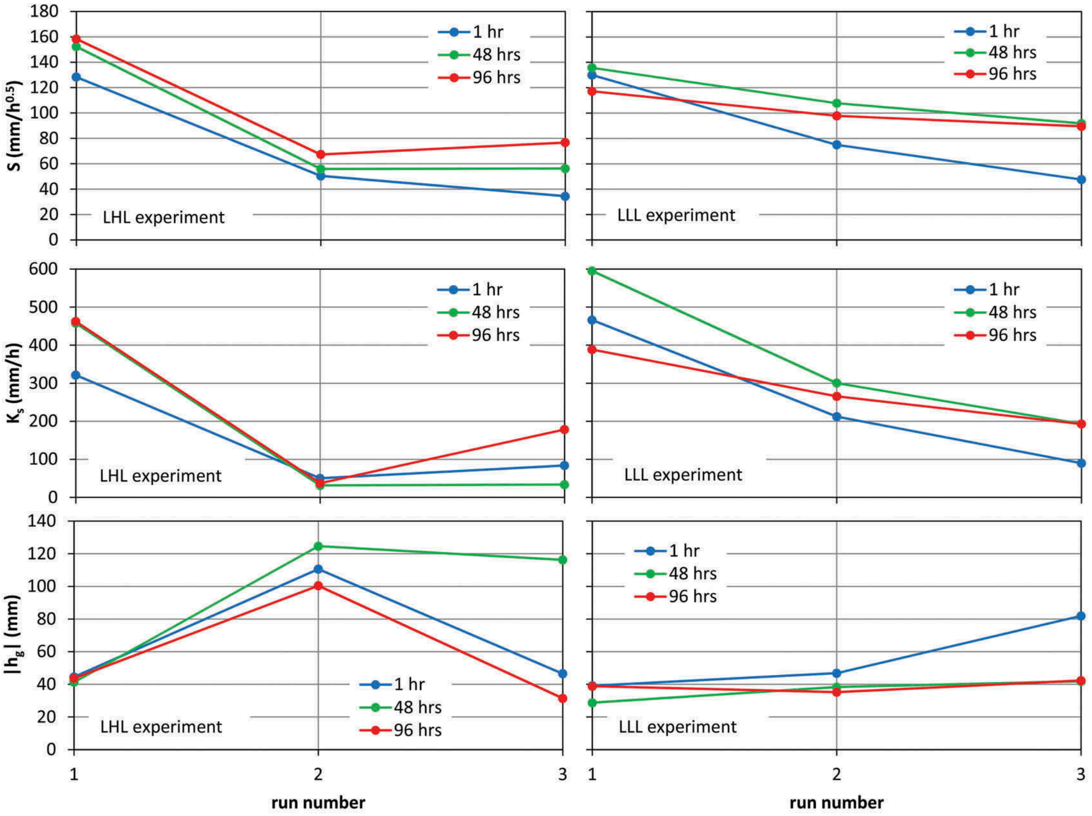

Figure 4. Mean values of soil sorptivity, S, saturated soil hydraulic conductivity, K_s, and scale parameter of the water retention curve, $|h_g|$, for each run and the two summer infiltration experiments.

Δt values (≥48 h) but it decreased by 1.5 times for the shortest time interval. Neither K_s nor $|h_g|$ changed significantly for relatively short time intervals, i.e. $\Delta t \leq 48$ h, but a significant increase of K_s (by 4.8 times) and a significant decrease of $|h_g|$ (by 3.2 times) were detected for the longest Δt value.

With reference to the L1 *versus* L3 runs comparison, the differences for both S and K_s were statistically significant in all cases, with the L1 runs yielding higher values than the L3 runs. For S, the differences decreased from 3.7 to 2.1 times as Δt increased from 1 to 96 h. For K_s, differences were lower for the two extreme Δt values (2.6–3.8 times) than for the intermediate interval (13.6 times). For $|h_g|$, the differences were significant only for $\Delta t = 48$ h with the L3 runs yielding a $|h_g|$ value 2.8 times higher than the L1 runs.

In summary, the LHL experiment suggests that (Table 3):

(a) a soil perturbing run occurring 1–96 h after a non-perturbing run determined a decrease in S and K_s and an increase in $|h_g|$;
(b) with the subsequent non-perturbing run, S continued to decrease in the short term ($\Delta t = 1$ h) but not after the soil has had more time to dry ($\Delta t = 48$–96 h);
(c) neither K_s nor $|h_g|$ changed soon after the perturbing run ($\Delta t = 1$–48 h) but they appeared to evolve in the direction of an increase in K_s and a decrease in $|h_g|$ as more time elapsed ($\Delta t = 96$ h); and
(d) differences between the measured soil properties at the beginning and end of the three-run experiment were lowest for the longest time interval between subsequent runs.

Non-perturbing soil (LLL) experiment

Even in this case, a statistical similarity was detected among the three groups of S, K_s and $|h_g|$ values obtained with the L1 runs by considering separately the sites resampled 1, 48 and 96 h later (Table 2).

The comparison between the L1 and L2 runs reveals that neither S nor $|h_g|$ varied significantly, regardless of Δt (Table 2 and Fig. 4). The K_s values did not change for $\Delta t = 96$ h whereas they decreased by 2.0–2.2 times for the shorter time intervals.

The comparison between the L2 and L3 runs shows that neither S nor $|h_g|$ varied significantly, regardless of Δt. The K_s values decreased by 2.4 times for $\Delta t = 1$ h and they did not change for $\Delta t \geq 48$ h.

The comparison between the L1 and L3 runs shows decreasing differences for longer Δt values with reference to both S (from 2.7 times to non-significant) and K_s (from 5.2 to 2.0 times), and statistical similarity for the $|h_g|$ values regardless of Δt.

In summary, the LLL experiment suggests that (Table 3):

(a) a non-perturbing run performed after another non-perturbing run did not have any statistically detectable effect on S and $|h_g|$, regardless of Δt, and also on K_s if the time interval between the two runs was relatively long. Otherwise, the second run determined a decrease of the measured K_s by nearly two times;
(b) the third non-perturbing run did not modify the previously measured S and $|h_g|$ values, whereas K_s continued to decrease only for the shortest time interval; and
(c) differences between the measured soil properties at the beginning and at the end of the three-run experiment were lowest for the longest time interval between subsequent runs.

Comparing the perturbing and non-perturbing experiments

The ρ_b, S, K_s and $|h_g|$ values associated with the L1 runs did not show statistically significant differences between the LHL and LLL experiments and hence the two sampling years, i.e. 2015 and 2016 (Table 4). A statistical difference was detected for Θ_i that was higher in 2016 than in 2015 by 27.4%. However, deleting for the more recent year one of the two highest Θ_i values (both equal to 0.18 m^3 m^{-3}; $\Theta_i \leq 0.13$ m^3 m^{-3} in all the

Table 4. Comparison between dry soil bulk density, ρ_b (g cm^{-3}), antecedent soil water content, θ_i (m^3 m^{-3}), soil sorptivity, S (mm h$^{-0.5}$), saturated soil hydraulic conductivity, K_s (mm h^{-1}) and scale parameter of the water retention curve, $|h_g|$ (mm), for the L1 infiltration runs carried out in the two sampling years (2015 and 2016). Sample size $N = 15$ for each dataset with the exception of $N = 6$ for ρ_b and θ_i in 2015.

Variable	Statistic	2015	2016
ρ_b	Mean	1.105a	1.141a
	CV (%)	8.3	6.2
θ_i	Mean	0.081(a)	0.103(a)
	CV (%)	6.8	34.3
S	Mean	146.3a	127.6a
	CV (%)	25.4	26.5
K_s	Mean	413.9a	483.2a
	CV (%)	43.7	35.6
$\|h_g\|$	Mean	43.2a	35.5a
	CV (%)	20.5	60.4

Values in a row followed by the same letter not enclosed in parentheses are not significantly different ($P < 0.05$); values followed by the same letter enclosed in parentheses are significantly different.

Table 3. Signs of the differences between subsequent runs of the LHL and LLL experiments and ratios between the mean values for the statistically significant differences with reference to soil sorptivity, S, saturated soil hydraulic conductivity, K_s, and scale parameter of the water retention curve, $|h_g|$.

Soil property	Δt (h)	Second vs First		Third vs Second		Third vs First	
		H	L	L after H	L after L	LHL experiment	LLL experiment
S	1	Smaller (2.5)	nd	Smaller (1.5)	nd	Smaller (3.7)	Smaller (2.7)
	48	Smaller (2.7)	nd	nd	nd	Smaller (2.7)	Smaller (1.5)
	96	Smaller (2.4)	nd	nd	nd	Smaller (2.1)	nd
K_s	1	Smaller (6.4)	Smaller (2.2)	nd	Smaller (2.4)	Smaller (3.8)	Smaller (5.2)
	48	Smaller (14.5)	Smaller (2.0)	nd	nd	Smaller (13.6)	Smaller (3.1)
	96	Smaller (12.4)	nd	Greater (4.8)	nd	Smaller (2.6)	Smaller (2.0)
$\|h_g\|$	1	Greater (2.5)	nd	nd	nd	nd	nd
	48	Greater (3.0)	nd	nd	nd	Greater (2.8)	nd
	96	Greater (2.3)	nd	Smaller (3.2)	nd	nd	nd

nd: no statistically detectable differences between the two runs; smaller (x): smaller by x times; greater (x): greater by x times.

remaining cases) determined a statistical similarity of the two Θ_i datasets, with a mean Θ_i value for 2016 of 0.097 $m^3\ m^{-3}$ (CV = 30.2%). Therefore, the two experiments were directly comparable since they were carried out under similar ρ_b and Θ_i conditions on the whole and the soil hydraulic properties measured with exactly the same experimental methodology did not exhibit statistical differences between the two years.

The comparison between the three-run experiment that deliberately induced a soil surface disturbance in the middle of the sequence (LHL) and a similar experiment having a less perturbative character (LLL) yielded the following suggestions (Table 3):

(a) the second run determined a decrease in S and an increase in $|h_g|$, regardless of Δt, when it had a soil perturbing nature (H2) but not when water was applied with care (L2);
(b) a perturbing run (H2) also induced a noticeable decrease in the measured K_s, particularly if the soil had several hours to dry out, whereas a non-perturbing run (L2) determined only small reductions in K_s, or it did not affect the measured values at all if this run was carried out a relatively long time after the previous one;
(c) a partial recovery of both K_s and $|h_g|$ appeared detectable when the soil was mechanically perturbed with the second run and there was time enough before applying water for the third time (L3);
(d) for both experiments, the similarities between the L1 and L3 run results are clearer with reference to the longest time interval between runs (Δt = 96 h).

Saturated soil hydraulic conductivity under varying antecedent conditions

The three replicated LHL experiments (Δt = 1 h; July–August 2015, October 2015, April–May 2016) were carried out in nearly constant dry soil bulk density conditions (ρ_b = 1.09–1.11 g cm^{-3}, depending on the period, Table 5). At the beginning of the LHL experiment, the soil was relatively dry in the spring and summer, with similar Θ_i values between the two dates (0.081–0.097 $m^3\ m^{-3}$), and it was significantly wetter in the autumn (Θ_i = 0.161 $m^3\ m^{-3}$).

The L1 runs yielded significantly greater K_s values than the H2 runs for all sampling dates, with ratios between the two means varying from 4.1 in July–August 2015 to 9.2 in October 2015 (Table 5). The H2 and L3 runs yielded statistically similar results for all sampling dates. Finally, the L1 runs consistently yielded significantly higher K_s values than the L3 ones, by 5.3–12.4 times depending on the sampling period. The largest reduction of K_s in the passage from the L1 to the H2 run (by 9.2 times) was detected in the initially wetter soil (October 2015) but a similar reduction (8.4 times) was recorded when the soil was significantly drier (April–May 2016) and the lowest reduction (4.1 times) was noticed in a similarly dry soil condition. The saturated conductivity decreased by a similar factor (8.4–9.2 times) even if the initial K_s values differed (316–873 mm h^{-1}) but, for similar initial values (316–348 mm h^{-1}), the reduction of K_s did not remain similar, since reductions by 4.1 and 8.4 times were detected. Soon after a perturbing run, the soil characteristics did not continue to change, even if the porous medium was wetted again, given that K_s remained both statistically and practically nearly constant between the H2 (38–95 mm h^{-1}) and L3 (31–71 mm h^{-1}) runs.

For all sampling dates, the coefficient of variation of K_s decreased in the passage from the L1 runs (42% ≤ CV ≤ 70%) to the H2 runs (33% ≤ CV ≤ 36%) and it further decreased, increased or did not change in the passage to the L3 runs (17% ≤ CV ≤ 55%).

Discussion

In the absence of any physical alteration of the porous medium, subsequent infiltration runs should yield near-constant K_s and h_g values and decreasing S values as the antecedent soil water content increases. However, effects of water pouring height and time after soil disturbance on soil hydraulic properties were detected, suggesting that soil physical changes occurred. For both experiments, K_s was the most sensitive property to closely alternating wetting and drying processes, since the largest changes were detected for this soil property as compared with S and h_g. A similar result was obtained by other authors (Mapa *et al.* 1986, Alagna *et al.* 2016). Moreover, Somaratne and Smettem (1993) suggested that larger changes for K_s than S denote variations in structural porosity, that is known to be particularly fragile (Jarvis *et al.* 2013).

The LLL experiment revealed the effects of subsequent wetting events that did not have a great mechanical effect on the soil, whereas the LHL experiment also yielded an information about the impact of a run that intentionally altered the exposed soil surface.

Table 5. Dry soil bulk ρ_b (g cm^{-3}), and antecedent soil water content, θ_i ($m^3\ m^{-3}$), at the beginning of the LHL experiments with a time interval of 1 h between two subsequent runs and saturated soil hydraulic conductivity, K_s (mm h^{-1}), for each run. CV: coefficient of variation.

Period	ρ_b		θ_i		K_s (L1)		K_s (H2)		K_s (L3)	
	Mean	CV (%)	Mean	CV (%)	Mean	CV (%)	Mean	CV (%)	Mean	CV (%)
July–August 2015	1.105 ab	8.3	0.081 (a)b	6.8	348.4 (a)(b)	53.6	84.7 (a)c	32.9	65.3 (b)c	31.7
October 2015	1.088 ac	4.7	0.161 (a)(c)	22.3	872.7 (a)(b)	41.7	95.3 (a)c	36.1	70.6 (b)c	55.2
April–May 2016	1.103 bc	5.9	0.097 b(c)	17.3	316.4 (a)(b)	69.7	37.8 (a)c	33.9	30.9 (b)c	16.5

Sample sizes: $N = 6$ (July–August 2015) or $N = 5$ (October 2015 and April–May 2016) for ρ_b and θ_i and $N = 5$ for each group of K_s values (i.e. given period and run of the sequence).

For ρ_b and θ_i, values followed by the same letter enclosed in parentheses are significantly different ($P < 0.05$); values followed by the same letter not enclosed in parentheses are not significantly different.

For a given sampling period, the K_s values followed by the same letter enclosed in parentheses are significantly different ($P < 0.05$); values followed by the same letter not enclosed in parenthesis are not significantly different.

With the former experiment (Table 3), the differences between two subsequent K_s values did not exceed a factor of 2.4 and, with reference to the complete experiment, K_s varied by slightly more than three only for the shortest time interval. The other two soil properties varied only a little (S) or they did not vary at all (h_g). The reasons why K_s decreased between two runs were not specifically investigated in this study because, according to Elrick and Reynolds (1992), a variation of K_s by a factor of 2 or 3 could be considered negligible for several practical purposes, given that this soil property varies by many orders of magnitude in the field. Therefore, the changes in K_s detected with the LLL experiment were altogether small. However, on the basis of the existing literature, it can be presumed that these changes occurred because soil particle mobilization (Dikinya *et al.* 2008) and swelling (Alagna *et al.* 2016) during a run determined a different soil pore arrangement for the subsequent run. The K_s reduction was more noticeable as the time interval between two runs decreased, because, in this case, the soil had less time to dry out (e.g. less shrinking opportunities after swelling) and the reduced drying time also implied that the subsequent runs were carried out in an initial condition of more effectively weakened inter-particle bonds (Bagarello and Sgroi 2007).

The LHL experiment was identical to the LLL one for all factors except the energy of the applied water for the second of the three runs. This factor alone was enough to appreciably modify the results of the experiment (Table 3). In particular, the reduction of K_s in the passage from the first to the second run, already observed for the shortest time intervals with the non-perturbing water application, greatly increased when water having more impact energy was applied on the soil surface, denoting, according to Levy *et al.* (1986), development of an altered soil layer in proximity to the infiltration surface. Therefore, the results of the H2 runs were lower than those of the L1 runs in part due to wetting effects, as demonstrated by the comparison with the LLL experiment, and in part because of the great disturbance of the soil surface when water was applied. The relative contribution of these two phenomena was quantified by calculating the ratio between the mean K_s values obtained with the first and second runs. For the LLL experiment, this ratio was 2.2, 2.0 and a non-significant 1.5 for $\Delta t = 1$, 48 and 96 h, respectively. The corresponding values for the LHL experiment were 6.4, 14.5 and 12.4. Therefore, the mechanical effect implied a reduction of K_s by a factor increasing monotonically from 2.9 for $\Delta t = 1$ h (6.4/2.2) to 8.3 for $\Delta t = 96$ h. Taking into account that a longer time interval between subsequent runs could imply more time for soil structure reorganization, mechanical effects on K_s that decrease as Δt becomes shorter suggest that disturbance due to a high height of water pouring could be expected to be less noticeable when the run is carried out on a soil that has already experienced a deterioration. This last interpretation is consistent with the finding by Boiffin (1984) that the void ratio decreased as a function of cumulative rainfall at an increasing rate with initial porosity. White *et al.* (1989) suggested that the effect of high impact energy rainfall on pore sizes should be more noticeable if the soil is freshly cultivated rather than naturally compacted. When soil disturbance was noticeable, S and $|h_g|$ were altered in a statistically detectable manner, suggesting, on the whole, a passage towards a more massive porous medium. In particular, $|h_g|$ (Table 2) was close to literature values for relatively coarse-textured soils with the L1 runs (37–57 mm, depending on the soil) and to values for fine-textured soils with the H2 runs (100–140 mm) (Lassabatere *et al.* 2006, Nasta *et al.* 2012, Bagarello *et al.* 2014b, Coutinho *et al.* 2016). This result was not detectable with the non-perturbing experiment since $|h_g|$ did not exceed 47 mm with the L2 runs.

After disturbance, there was a soil recovery phase that was signalled by the subsequent increase in K_s and decrease in $|h_g|$ 96 h after the soil perturbing run (Table 3). A similar recovery was not detectable for shorter Δt values. Therefore, the sampled soil needed at least 4 days to start with a detectable reorganization of its structure after the event that disturbed its surface. Signs of recovery of the soil hydraulic properties were only detectable when the soil was subjected to mechanical stress at the surface and not when it was wetted by applying water carefully, i.e. minimizing impact energy. Therefore, the soil reacted soon to external mechanical stresses and tended to restore the pre-existing structural organization. Time evolution, or recovery, of soil physical and hydraulic properties after a disturbing action has been frequently documented in the literature (Morin and Benyamini 1977, Fohrer *et al.* 1999, Rab 2004, Drewry 2006, Hu *et al.* 2018), but mainly with reference to longer time periods (weeks to years). To our knowledge, this is one of the first times that signs of soil recovery have been documented soon after disturbance.

Replicating three times the same experiment (LHL, $\Delta t = 1$ h) on different dates and using a simplified method of data analysis demonstrated that a perturbing run carried out a short time after a non-perturbing run should generally be expected to yield smaller K_s values, in agreement with the suggestion of the more complicated experiment. The soil water content at the beginning of the experiment and the initial K_s values could not be expected to play a role in explaining the differences in the dynamics of this soil property. However, a perturbing run reduces point-to-point variability in K_s, in agreement with Ben-Hur *et al.* (1987) who concluded that the hydraulic conductivity of a seal should be expected to be much lower and less variable than that of the bulk soil.

The results of this investigation could have some interest from a hydrological perspective, also considering that several reports have suggested a tendency of field infiltration methods to yield inappropriate infiltration rates or K_s values to explain surface hydrological processes since they are too high (Ben-Hur *et al.* 1987, Cerdà 1996, 1999, van De Giesen *et al.* 2000, Bagarello *et al.* 2010, 2013). This investigation, yielding on the whole means of K_s that differed by even 28 times (31 and 873 mm h^{-1}), depending on the run in the sequence and the height of water application, indicated that a way to solve this problem could be to choose experimental methodologies consistent with the process to be interpreted or simulated. Moreover, the experimental methodology tested in this investigation could be viewed as a relatively simple means to properly parameterize hydrological models, taking into account short-term variation of soil hydraulic properties (e.g. Mapa *et al.* 1986, Mubarak *et al.* 2009).

Taking into account that soils must be properly functioning to provide their ecosystem services, an objective for achieving the

UN SDGs is to approach land degradation neutrality, which also means contrasting soil physical degradation (Keesstra *et al.* 2018). However, our ability to measure and monitor soil hydraulic properties and processes from the specific perspective to reach these goals still needs improvements (Bouma 2016). According to this investigation, both soil proneness to physical alteration and its reaction soon after alteration can be tested directly in the field with a simple, cheap and rapid experimental procedure. Therefore, this investigation also represents a methodological contribution in the perspective to reach the UN SDGs.

Conclusions

This investigation demonstrated that a double three-stage infiltration methodology allows one to capture short-term variations in soil structure-dependent parameters, that is sorptivity, S, saturated hydraulic conductivity, K_s, and scale parameter of the water retention curve, h_g, as a consequence of wetting, perturbation and recovery processes.

Short-term changes were less noticeable for S and h_g than K_s indicating that this last variable can be viewed as a kind of sentinel, able to signal the soil dynamics over short time periods.

For the sampled sandy-loam soil, two subsequent infiltration runs separated by a short or relatively short time interval (≤96 h) are expected to yield decreasing K_s values by a factor of approximately two in the absence of an intentional effect of a mechanical disturbance of the soil surface, i.e. only following wetting and subsequent drying processes.

Mechanical disturbance of the previously sampled soil determines an additional reduction of K_s that can also be noticeable given that it approached one order of magnitude in this investigation. More time for soil reorganization processes after initial wetting seems to make the soil more sensitive to subsequent disturbance.

A perturbing run also reduces point-to-point variability of K_s which suggests that less data could be enough, in this case, to characterize the porous medium as compared with the undisturbed soil.

A detectable reorganization of soil structure starts to occur 4 days after the disturbing event whereas, soon after a perturbing run, the soil characteristics do not continue to change, even if the porous medium is wetted again. Soil reorganization yields higher means but it can also determine an increase of point-to-point variability of K_s. Recovery does not occur, or it is not detectable with the applied methodology, if previous runs were carried out by minimizing water impact energies.

The SSBI method appears to have practical interest since it yields estimates of K_s that are close to those obtained using more data-demanding methods, such as BEST-steady. Estimating K_s by only using, as the experimental information, the steady-state infiltration rate detected with a Beerkan run experiment implies that an intensive, both in space and time, soil sampling could be made in the field with a practically sustainable effort to obtain a robust information on this property.

The developed methodology, using recurrent infiltration runs and both low and high heights of water pouring, appears attractive to parameterize hydrological models with field data that express the dynamic behaviour of the porous medium upon wetting and drying. Therefore, this investigation could be viewed as a contribution to improve our ability to simulate hydrological processes.

Research needs can be delineated with reference to the developed methodology. A point deserving investigation is to test the applicability of the methodology in different soils and under a wider range of initial conditions, to also verify whether the suggested interpretation on the effect of the drying time on the mechanical effects of a perturbing run finds any support. Additional investigations are also necessary with specific reference to the high runs since a given energy can be supplied to the soil surface using, for example, small water volumes and high heights of pouring or more water and lower heights of pouring. Therefore, the response of the soil to varying ways of performing a perturbing run should be established. Further, it should be assessed if the collected data were representative of a fully altered soil layer or a dynamic situation, in which alteration was not concluded. This kind of information is expected to improve our ability to use the experimental methodology to collect data usable for simulating hydrological processes.

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