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DETERMINING SHORT-TERM CHANGES OF THE HYDRAULIC PROPERTIES OF A SANDY-LOAM SOIL BY A THREE-RUN INFILTRATION EXPERIMENT

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ABSTRACT

Soil structure dependent parameters can rapidly vary as a consequence of perturbing events such as intense rainfalls. Investigating their short-term evolution is therefore essential to understand the general behavior of a porous medium. This investigation aimed to give an insight on wetting, perturbation and recovery processes during different sequences of Beerkan infiltration experiments performed on a sandy-loam soil. Two different three-run infiltration experiments (i.e., LHL and LLL) were carried out by performing low (L, non-perturbing) and high (H, perturbing) runs at short time intervals (hours, days). The results demonstrated that the proposed method allows to capture short-term variations in soil structure dependent parameters. Recovery processes of soil hydraulic properties started to occur a few days after soil perturbation. Short-term changes were more noticeable for the saturated soil hydraulic conductivity, K_s, indicating that this variable, more than others, is able to signal the soil dynamics over short time periods.

Keywords: Soil hydrodynamic parameters; Temporal variability; Beerkan run; ccc.

1. INTRODUCTION

Interpreting and simulating hydrological processes, such as rainfall excess generation, need taking into account that, as shown by many rainfall simulation investigations (e.g., Fohrer *et al.*, 1999; King & Bjorneberg, 2012; Le Bissonnais & Singer, 1992; Levy *et al.*, 1986; Morin & Benyamini, 1977; Torri *et al.*, 1999), soil surface characteristics are highly dynamic and can change even over short times, i.e., during rainfall events or between closely spaced rainstorms. Therefore, determining short term variability of soil properties as a consequence of wetting and drying is necessary to properly capture the general hydrodynamic behavior of a porous medium.

Single-ring infiltration experiments are an attractive alternative to rainfall simulation for investigating short term variability of soil hydraulic properties. Infiltrometer experiments are easier to perform in the field as compared with rainfall simulation experiments (e.g., Di Prima *et al.*, 2017, 2018a), the analysis of the data relies on robust physical theories, and the application of the technique generally requires a rather simple, parsimonious and rapid experiment. A single-ring infiltration methodology that could be applied to investigate the short term dynamics of the surface soil properties makes use of subsequent Beerkan infiltration runs (Lassabatere *et al.*, 2006). A Beerkan run is very simple since it only needs a cylinder, no more than a few liters of water and a stopwatch, and therefore it is particularly appropriate for field campaigns. The measured infiltration, in conjunction with the BEST (Beerkan Estimation of Soil Transfer parameters) algorithms of data analysis (Bagarello *et al.*, 2014c; Lassabatere *et al.*, 2006; Yilmaz *et al.*, 2010), allows estimation of soil structure dependent parameters, that is sorptivity, S, saturated soil hydraulic conductivity, K_s, and scale parameter of the water retention curve, h_g. The procedure seems usable to determine how these properties vary over time since the Beerkan methodology was applied by Mubarak *et al.* (2009) in an investigation on temporal variability of soil hydraulic properties due to changes in soil structure under high-frequency drip irrigation.

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.*, 2018, Dohnal *et al.*, 2016, Votrubova *et al.*, 2017). Perhaps, a 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 to one another. Another reason could be some 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. For example, Ben-Hur *et al.* (1987) signaled the impossibility to predict infiltration rates in rainfall conditions from infiltration measured by double-ring infiltrometers. Indeed, in a sealed soil, infiltration rates are strongly affected by the structure of the surface seal and hence by a number of factors that may influence seal formation (e.g., rainfall intensity, soil type, etc.), while the structure of the bulk soil is the main factor controlling infiltration under water ponding conditions. The infiltration rates measured by Cerdà (1996, 1999) in some Spanish sites by cylinder infiltrometers were 3-8 times greater than those obtained by rainfall simulation due to water depth pressure established in the cylinders and crust development under simulated rainfall. Working in Côte d'Ivoire, van de Giesen *et al.* (2000) obtained a too high K_s value, precluding runoff occurrence although runoff was measured, and a similar result was obtained by Bagarello *et al.* (2013) on a clay soil in Sicily.

A more encouraging information can also be found in the literature and, particularly, that a ring infiltration experiment could be adapted to agree with the hydrological information that has to be collected. For example, the height of water application can be used to induce some alteration at 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 be conducted. Di Prima *et al.* (2018a) successfully verified the capability of the H runs to catch the formation of the seal and related consequences on water infiltration. According to these authors, the estimated soil hydrodynamic parameters were representative of the seal, which controlled the infiltration process, and the H runs allowed to properly characterize the seal layer formed during the repeated impact of the poured water volumes onto an initially unsealed soil surface. 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 in initially near-saturated conditions. Firstly, the L run is carried out and then the sampled soil is allowed to drain for no more than a few dozens of minutes. Subsequently, the L or the H procedure are 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 in the field.

During the pause between two subsequent runs (either LL or LH), water redistribution processes occur and perhaps even some soil reorganization. Therefore, the information collected with the new run will likely depend on i) soil characteristics before any water application, ii) soil changes induced by the first run, such as some swelling, iii) possible structure recovery during drying, and iv) possible additional changes in the soil determined by the new run itself. Studying in some detail the multi-run procedure is necessary to confidently understand what kind of information is contained in the infiltration curves that will be collected in the field. Morin and Benyamini (1977) showed that the duration of the drying period after a water application event can influence the subsequent infiltration process.

Therefore, an improved knowledge of the potentials and limitations of the subsequent runs methodology presupposes establishing what happens when the duration of the pause between the non-perturbing and another either perturbing or non-perturbing run changes since water redistribution and short term rearrangement of soil structure can be expected to depend on the time interval between runs.

The repeated Beerkan run methodology could also be used, with a limited increase in the field workload, to verify what happens at the soil surface following disturbance (Fohrer *et al.*, 1999) but, till now, data were never collected after performing an LH run. The expectation is that performing an L run after the perturbing one should yield some information on possible recovery processes. 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 (Di Prima *et al.*, 2018, Drewry, 2006, Fohrer *et al.*, 1999, Hu *et al.*, 2018, Lozano-Baez *et al.*, 2019, Morin & Benyamini, 1977). However, this suggestion could also depend on the lack of experimental information on short term recovery of soil hydraulic properties.

The general objective of this investigation was to check short-term, i.e., hours or days, changes in soil structure dependent hydraulic parameters associated with subsequent infiltration runs. The specific objectives were to: i) investigate changes in soil sorptivity, S, saturated soil hydraulic conductivity, K_s, and scale parameter of the water retention curve, h_g, during a three-stage Beerkan infiltration experiment including a sequence of non-perturbing, perturbing and again non-perturbing runs; ii) to distinguish between wetting, perturbation and recovery processes during the experiment.

2. MATERIALS AND METHODS

2.1. 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 in Alagna *et al.* (2016). More specifically, fifteen volumes of water of 57 mL were repeatedly poured 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 runs, namely LHL and LLL, were carried out in summer months and precisely on July-August 2015 and June-July 2016 (**Figure 1**), respectively, to sample the soil with two different run sequences under similar initial wetness conditions, i.e., rather dry in both cases.

For the LHL experiment (**Figure 2a**), 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 some time to the system to experience a redistribution of the infiltrated water and, perhaps, short-term soil structure reorganization process following changes due to wetting. Subsequently, the H procedure was used to pour other 15 volumes of water (H2 run). After 1, 48 or 96 h, depending on the sampling point, other 15 volumes of water were finally poured by using again the L procedure (L3 run). At a given sampling point, the Δt value did not vary between subsequent runs (e.g., 1 h between the L1 and H2 runs and 1 h between the H2 and L3 runs). A very 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., L2 run instead of H2 run). 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 (2 experiments × 3 Δt values × 5 replicated three-stage runs × 3 curves per run) were collected. 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; Lassabatere *et al.*, 2019; Ugarte Nano *et al.*, 2015).

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 the 0 to 0.05 m and 0.05 to 0.10 m depths. 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, a total of 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 other randomly selected locations to obtain some information on ρ_b and θ_i immediately before the H2, L2 and L3 runs (**Figure 2b**). 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 run or an LL run were carried out with a given Δt value (1, 48 or 96 h) and the soil was sampled after the same Δt had elapsed. A total of 24 additional infiltration runs were therefore 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.

Other two LHL experiments were carried out at the same field site, in new randomly selected locations and in a simplified manner, in autumn and spring, i.e., on October 2015 and April-May 2016, respectively (**Figure 1**). 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 of 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, a total of 30 additional infiltration curves were collected. Replicating the LHL experiment was aimed to check the influence of the initial soil conditions on the collected data by a three-run infiltration methodology. Only Δt = 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 the H2 (initially close to saturation soil) runs. The simplified experimental protocol was applied because K_s was found to be the most sensitive soil property to repeated water applications in the LHL experiment of July-August 2015 and simplified procedures can be applied to determine K_s from a Beerkan experiment (Bagarello *et al.*, 2017).

2.2. Calculation of soil hydraulic parameters

The infiltration data collected with the summer LHL (July-August 2015) and LLL (June-July 2016) experiments were analyzed 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 some 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 (Di Prima *et al.*, 2018). On the contrary, 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.

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

$$K_s = \frac{i_s}{\frac{\gamma \gamma_w}{r\alpha^*} + 1} \quad (1)$$

where i_s (L T^{-1}) is the steady-state infiltration rate, γ (= 0.75) and γ_w (= 1.818) are two constants, r (L) is the radius of the source, and α^* (L^{-1}) is a soil parameter that depends on the soil textural and structural characteristics (Elrick & 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 Lillefors (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).

2.3. Data analysis

A comparison was initially 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 the summer LHL and LLL experiments to verify if, at the beginning of these two experiments, the soil exhibited physical and hydraulic similarities or not. A two-tailed t test ($P < 0.05$) was used to make this check.

For each summer experiment, the results obtained with the L1 runs were then 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 vs. H2 or L2; H2 or L2 vs. L3; L1 vs L3) was then carried out with a two tailed t test ($P < 0.05$). A pairwise comparison was preferred to other statistical tests since establishing what happens 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 some of the valid experimental data. Applying this statistical approach in all cases avoided developing a methodologically heterogeneous comparison (paired and unpaired tests).

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 & Reynolds, 1992; Reynolds & Lewis, 2012), i.e., very different porous media than the sampled soil.

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).

3. RESULTS

3.1. Summer LHL and LLL experiments

The ρ_b, S, K_s and $|h_g|$ values associated with the L1 runs did not show statistically significant differences between the experiments and hence the two sampling years, i.e., 2015 and 2016 (**Table 1**). 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 other cases) was enough to make the two

θ_i datasets statistically similar, with a mean θ_i value for 2016 equal to 0.097 m^3/m^3 (CV = 30.2%). Therefore, the LHL and LLL 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.

For both experiments, 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**). This result made the subsequent interpretation of the data easier since it suggested that different time intervals before resampling were considered at sampling locations that, at the beginning of the experiment, had similar hydraulic properties.

For the LHL experiment, a decrease of both S (by 2.4-2.7 times, depending on Δt) and K_s (6.4-14.5 times) and an increase of $|h_g|$ (2.3-3.0 times) were detected in the passage from the L1 run to the H2 run, and all tested differences (9 comparisons, i.e., 3 variables × 3 Δt values) were statistically significant (**Table 2**). Therefore, changes were more appreciable for K_s than the other two properties. For S and $|h_g|$, there was not an influence of Δt on the detected variations, and the factors of difference between the two runs did not vary much for a given property and also between the two properties. For K_s, there was not a monotonic trend of the changes with Δt but 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 $\Delta t = 1$ h).

Changes in the three soil properties also occurred between the H2 and L3 runs and some effect of Δt on these changes was perceivable. In particular, S did not vary for the largest Δt values ($\geq$ 48 h) but it continued to decrease for the shortest time interval since, in this case, the mean of S for the L3 runs was 1.5 times lower than the corresponding mean for the H2 runs. 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 in the passage from the H2 run to the L3 one for the longest Δt value.

With reference to the L1 vs. L3 runs comparison, the differences for S were statistically significant in all cases, with the L1 runs signaling more sorptivity than the L3 runs. However, these differences decreased as Δt increased since the factors of discrepancy ranged from 3.7 for Δt = 1 h to 2.1 for Δt = 96 h. Also for K_s all differences were significant, with the L1 runs yielding higher values than the L3 runs. In this case, however, differences were lower for the two extreme Δt values (3.8 times for Δt = 1 h and 2.6 times for Δt = 96 h) than for the intermediate interval (Δt = 48 h, 13.6 times). For $|h_g|$, the differences were significant only for Δt = 48 h with the L3 runs yielding a 2.8 times higher $|h_g|$ value than the L1 runs. Therefore, a monotonic trend of the differences with Δt was only detected for S. However, the lowest differences between the L1 and L3 runs were associated with the longest time interval for both S and K_s and, in this case, $|h_g|$ did not show significant differences between the two runs.

In summary, the LHL experiment suggested that a soil perturbing run occurring 1-96 hours after a non-perturbing run determined a decrease of S and K_s and an increase of $|h_g|$. With the subsequent non-perturbing run, S continued to decrease in the short term (Δt = 1 h) but not after the soil had more time to dry up (Δt = 48-96 h). Neither K_s nor $|h_g|$ changed soon after the perturbing run (Δt = 1-48 h) but they appeared to evolve in the direction of an increase of K_s and a decrease of $|h_g|$ as more time elapsed (Δt = 96 h). A longer time interval between subsequent runs reduced the differences between the measured soil properties at the beginning and at the end of the three-run experiment.

For the LLL experiment, the comparison between the L1 and L2 runs revealed that neither S nor $|h_g|$ varied significantly, regardless of Δt. The K_s values did not change for Δt = 96 h whereas they decreased by a significant factor of 2.2 for Δt = 1 h and 2.0 for Δt = 48 h.

Even the comparison between the L2 and L3 runs showed that neither S nor $|h_g|$ varied significantly, regardless of Δt. The K_s values decreased by 2.4 times for Δt = 1 h and they did not change for Δt = 48 and 96 h.

The comparison between the L1 and L3 runs showed that the differences for S and K_s decreased as Δt increased. In particular, S was 2.7 (Δt = 1 h) and 1.5 times (Δt = 48 h) lower for the L3 runs than the L1 runs and the two runs yielded statistically equivalent S values for Δt = 96 h. The saturated conductivity for the L3 runs was 5.2 (Δt = 1 h), 3.1 (Δt = 48 h) and 2.0 (Δt = 96 h) lower than for the L1 runs. Finally, $|h_g|$ did not vary significantly between the two runs, regardless of Δt.

In summary, the LLL experiment suggested that a non-perturbing run performed after another non-perturbing run did not have any statistically detectable effect on both 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. 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. The longest time interval between subsequent runs reduced the differences between the measured soil properties at the beginning and at the end of the three-run experiment.

Comparing the LHL and LLL experiments indicated that the second run determined a decrease of both S and $|h_g|$, regardless of Δt, when it had a soil perturbing nature (H2) but not when water was applied with care (L2). A perturbing run also induced a noticeable decrease of the measured K_s, particularly if the soil had several hours to dry-up, whereas a non-perturbing run determined only small reductions in K_s or it did not affect at all the measured values if this run was carried out a relatively long time after the previous one. 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. For both experiments, the similarities between the L1 and L3 run results were clearer with reference to Δt = 96 h. However, when the second run was carried out without perturbing the soil, there was a statistical equivalence for both S and $|h_g|$ and K_s of the third run remained two times smaller. When the second run perturbed the soil, there was a statistical equivalence only for $|h_g|$ whereas S and K_s of the third run remained 2.1 and 2.6 times smaller, respectively.

3.2. SSBI method

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 3**). In this case, the means of K_s were significantly different but they differed by a non-substantial factor of 1.4 (Elrick & Reynolds, 1992). Relative variability of K_s was similar for the two approaches (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 & Reynolds (1992), i.e., a factor of three.

The optimized α^* parameter, equal to 0.019 mm^{-1}, was rather close to α^* = 0.012 mm^{-1} and it did not allow to reduce the maximum error (**Table 3**). 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 these two methods (**Figure 3**). Therefore, Eq.(1) with 0.019 mm^{-1} was used in the subsequent analysis.

3.3. Replicated LHL experiment

The three replicated LHL experiments (Δt = 1 h; July-August 2015, October 2015, April-May 2016) were carried out in very similar dry soil bulk density conditions (ρ_b = 1.09-1.11 g cm^{-3}, depending on the period, **Table 4**). At the beginning of the LHL experiment, the soil was relatively dry in spring and summer, with similar θ_i values between the two dates (0.081-0.097 m^3m^{-3}), and it was significantly wetter in autumn (θ_i = 0.161 m^3m^{-3}).

The L1 runs yielded significantly greater K_s values than the H2 runs at all sampling dates, with ratios between the two means varying from 4.1 in July-August 2015 to 9.2 in October 2015 (**Table 4**). The H2 and L3 runs yielded statistically similar results in 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.

In all sampling dates, the coefficient of variation of K_s decreased in the passage from the L1 runs ($0.42 \leq CV \leq 0.70$) to the H2 runs ($0.33 \leq CV \leq 0.36$) and it further decreased, increased or did not change in the passage to the L3 runs ($0.17 \leq CV \leq 0.55$).

4. 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. Taking into account that the experiment was carried out on a real soil, different factors have to be considered to explain the data, including i) greater resistance of the soil aggregates to the forces of impact and flowing water (Truman *et al.*, 1990) and decreasing slaking effects (Le Bissonnais, 1996) in initially wetter soil conditions, ii) weakening of the interparticle bonds reducing macropore volume in wet soil (Bagarello & Sgroi, 2007) and inducing soil particle mobilization with flowing water (Dikinya *et al.*, 2008), iii) reduction of infiltration rates as a consequence of greater water impact energies (Ben-Hur & Lado, 2008; Smith, 1990) and hence soil seal development (Armenise *et al.*, 2018; Assouline, 2004; Di Prima *et al.*, 2018a), and iv) swelling and subsequent shrinking phenomena, that were also specifically signaled for the soil sampled in this investigation (Alagna *et al.*, 2016). Time evolution, or recovery, of soil physical and hydraulic properties after some disturbing action has also to be considered, being frequently documented in the literature (Drewry, 2006; Fohrer *et al.*, 1999; Hu *et al.*, 2018; Morin & Benyamini, 1977; Rab, 2004), especially with reference to longer time periods (weeks to years) than those considered in this experiment, that appear to be less investigated. The beating action of water takes place only when water with energy is applied and no crust is formed when water without energy is used to wet the soil (Levy *et al.*, 1986). Therefore, the LLL experiment revealed the effects of subsequent wetting events that did not have a great mechanical effect on the soil whereas the LHL experiments also yielded some information about the impact of a run that intentionally altered the exposed soil surface. 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 among the three that were tested (S, K_s and h_g). Plausibly, this result was a consequence of the fact that K_s most strongly depends on the structural macropores that dominate flow at saturation and are known to be fragile structures (Jarvis *et al.*, 2013).

The results of the LLL experiment appeared consistent with the occurrence of slaking, swelling and shrinking, and soil particle mobilization phenomena. In particular, all L1 runs were carried out on an initially relatively dry soil and this circumstance favored some slaking phenomena and hence the formation of microaggregates (Le Bissonnais, 1996) that could be dislodged at least to a certain degree. Moreover, wetting during the infiltration run also weakened interparticle bonds and induced soil particle and microaggregate mobilization. Mobile soil particles and microaggregates did not move for long distances since the run durations were relatively short and also as a consequence of a possibly tortuous pattern of flowing lines. These phenomena had a similar impact on the soil pore arrangement at the end of all L1 runs, i.e., regardless of the time before the subsequent resampling. Some soil swelling occurred during the wetting stages of the experiment whereas shrinking occurred between subsequent runs. This last phenomenon was more effective for the longest Δt values because the soil had more time to dry-up. Swelling reduced macroporosity whereas shrinking restored it. Therefore, a K_s reduction from the L1 to the L3 run occurred in all cases, i.e., regardless of Δt, since soil particle mobilization 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 recover and the reduced drying time also implied that the subsequent runs were carried out in an initial condition of more effectively weakened interparticle bonds. Therefore, soil particle mobilization was more relevant or more effective for short Δt values. 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. According to Elrick & Reynolds (1992), a variation of K_s by a factor of two or three could be considered uninfluential for several practical purposes since this soil property varies by many orders of magnitude in the field. Therefore, it can be suggested that the changes in K_s detected with the LLL experiment were altogether rather small which also imply that even slaking, swelling and shrinking, and soil particle mobilization were not particularly relevant phenomena. Probably for this reason, the other two soil properties varied only a little (S) or they did not vary at all (h_g).

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. 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 with energy was applied on the soil surface, denoting 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 the already discussed wetting effects (slaking, swelling, particle mobilization) 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 means K_s values obtained with the first and the second run. For the LLL experiment, this ratio was 2.2, 2.0 and a non-significant 1.5 for Δt = 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 Δt = 1 h (6.4/2.2) to 8.3 for Δt = 96 h. Probably, the effect was more noticeable for the longest time intervals between subsequent runs because in this case the soil had more time to recover its original structure before being subjected to a new wetting event. When soil disturbance was noticeable, even 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, $|h_g|$ was close to some 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) (Bagarello *et al.*, 2014b; Coutinho *et al.*, 2016; Lassabatere *et al.*, 2006; Nasta *et al.*, 2012). This results was not detectable with the non-perturbing experiment since $|h_g|$ did not exceed 47 mm with the L2 runs (**Table 2**). After disturbance, there was a soil recovery phase that was signaled by the subsequent increase of K_s and decrease of $|h_g|$ 96 hours after the soil perturbing run. A similar recovery was not detectable for shorter Δt values. Therefore, the sampled soil needed at least four 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 some mechanical stress at the surface and not when it was wetted by applying water carefully, i.e., minimizing impact energy.

Replicating three times the same experiment (LHL, Δt = 1 h) on different dates demonstrated that a perturbing run a short time after a non-perturbing run should generally be expected to yield smaller K_s values. 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 of 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. This investigation also showed that variability of K_s could also increase again soon after perturbation.

These results 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 (Bagarello *et al.*, 2010, 2013; Ben-Hur *et al.*, 1987; Cerdà, 1996, 1999; van De Giesen *et al.*, 2000). 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 choosing experimental methodologies consistent with the process to be interpreted or simulated.

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 need for steadiness could not be a great limit since field runs often denote that this condition is practically reached in a reasonable period of time, i.e., dozens of minutes or a few hours at the most (e.g., Reynolds *et al.*, 2000) and recent investigation have concluded that even fine-textured soils may reach steady-state conditions in similar, relatively short time-scales (Stewart & Abou Najm, 2018). The SSBI method of analysis of a Beerkan infiltration run appears a good way to obtain a simple estimate of K_s since this investigation reinforced the conclusion by Bagarello *et al.* (2017b) that, even with the α* parameter of first approximation, the maximum error should not be expected to exceed a factor of near three.

5. CONCLUSIONS

This investigation demonstrated that a double three-stage infiltration methodology allows 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 that, more than other parameters, is 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 ($\leq$ 96 hours) are expected to yield decreasing K_s values by approximately two times in the absence of an intentional effect of 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 is detectable regardless of the soil water content at the beginning of the experiment and increases with the time interval between the runs. Consequently, the effects of mechanical disturbance should be expected to be more relevant in initially dry or relatively dry soil conditions. A perturbing run also reduces point-to-point variability of K_s. A detectable reorganization of soil structure starts to occur four 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.

Research needs can be delineated with reference to the developed methodology combining low and high runs. A point deserving investigations is testing the applicability of the methodology in other soils and a wider range of initial soil water content conditions. 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 to perform a perturbing run should be established. Further, it should be established if the values of the measured soil parameters are expressive of a near stabilized situation or there was still space for additional variations in the measured soil parameters. In other terms, 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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V.B. and S.D.P. planned the investigation, analyzed the data and wrote the manuscript. N.C. and S.M.D. performed all experimental activities for their Master theses.

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Table 1. 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), 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 sizes 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 parenthesis are not significantly different according to a two-tailed t test at $P < 0.05$. Values followed by the same letter enclosed in parenthesis are significantly different.

Table 2. Summary of the soil sorptivity, S (mm/h$^{0.5}$), saturated soil hydraulic conductivity, K_s (mm/h), 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
$\|h_g\|$	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 given experiment and variable and with reference to the L1 runs, means followed by the same upper case letter not enclosed in parenthesis are not significantly different according to a two-tailed t test at $P < 0.05$. For given experiment, variable and Δt value, means followed by the same lower case letter not enclosed in parenthesis are not significantly different according to a two-tailed t test at $P < 0.05$. Means followed by the same letter enclosed in parenthesis are significantly different.

Table 3. Comparison between the saturated soil hydraulic conductivity, K_s (mm/h), values calculated with BEST-steady and the corresponding estimates obtained with the SSBI method and different values of the α* parameter (sample size, $N = 89$)

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)	240.4d	75.4	3.1	1.5	1.3

CV = coefficient of variation. Means followed by the same letter enclosed in parenthesis are significantly different according to a two-tailed, paired t test at $P < 0.05$. Means followed by the same letter not enclosed in parenthesis 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).

Table 4. Dry soil bulk density, 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), for each run

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-November 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

CV = coefficient of variation. Sample sizes, *N*, equal to 6 (July-August 2015) or 5 (October 2015 and April-May 2016) for ρ_b and θ_i and 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 parenthesis are significantly different according to a two-tailed t test at $P < 0.05$. Values followed by the same letter not enclosed in parenthesis are not significantly different. For a given sampling period, the K_s values followed by the same letter enclosed in parenthesis are significantly different according to a two-tailed t test at $P < 0.05$. Values followed by the same letter not enclosed in parenthesis are not significantly different.

Figure 1. Timeline of the sampling campaigns

Figure 2. Scheme 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 applied procedures 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 steps, Δt, and heights of water pouring (L1, H2 and L3)

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}

Figure 1. Timeline of the sampling campaigns

98x14mm (600 x 600 DPI)

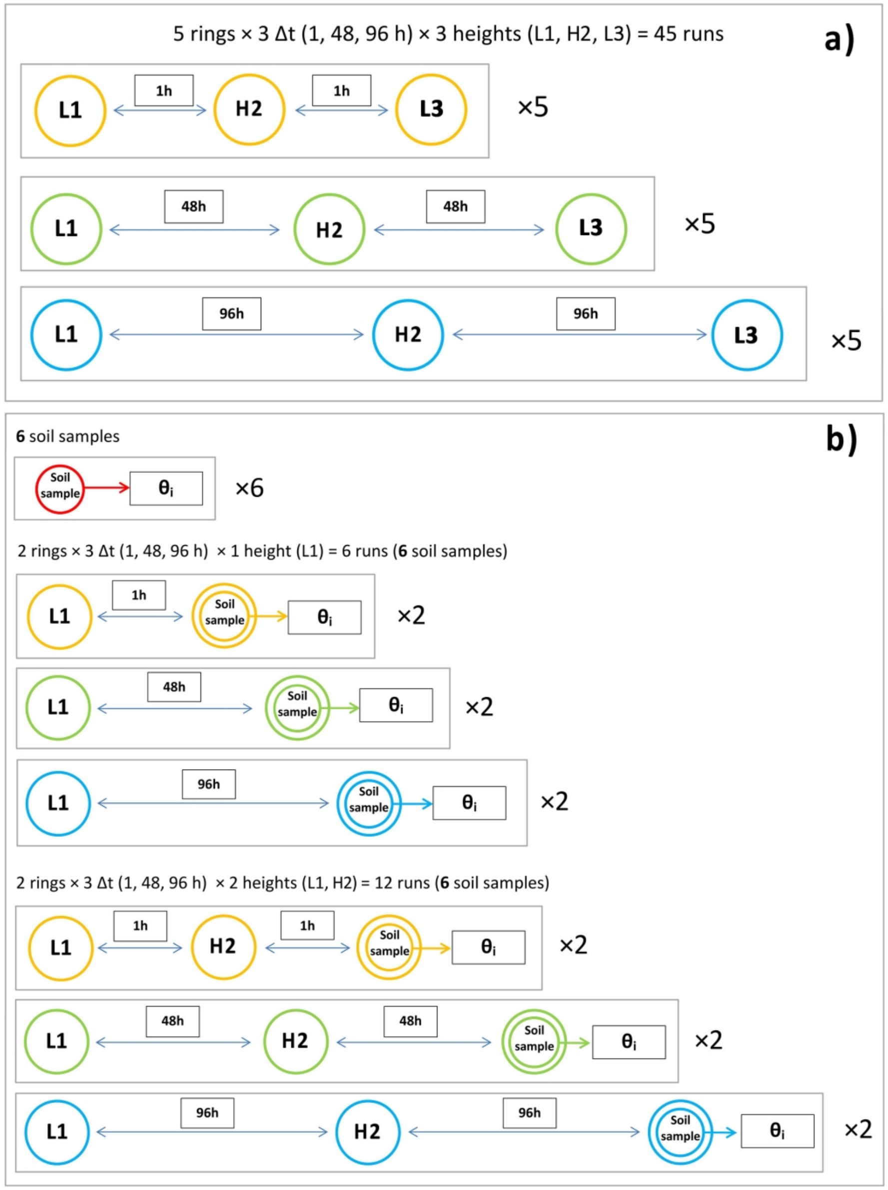

Figure 2. Scheme of a) the LHL infiltration experiment carried out with different time intervals (Δt = 1, 48 and 96 h) and heights of water pouring (L1, H2 and L3) and b) the applied procedures to obtain a representative value of the initial volumetric soil water content, θ_i (m^3/m^3), at the time of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

776x1039mm (72 x 72 DPI)

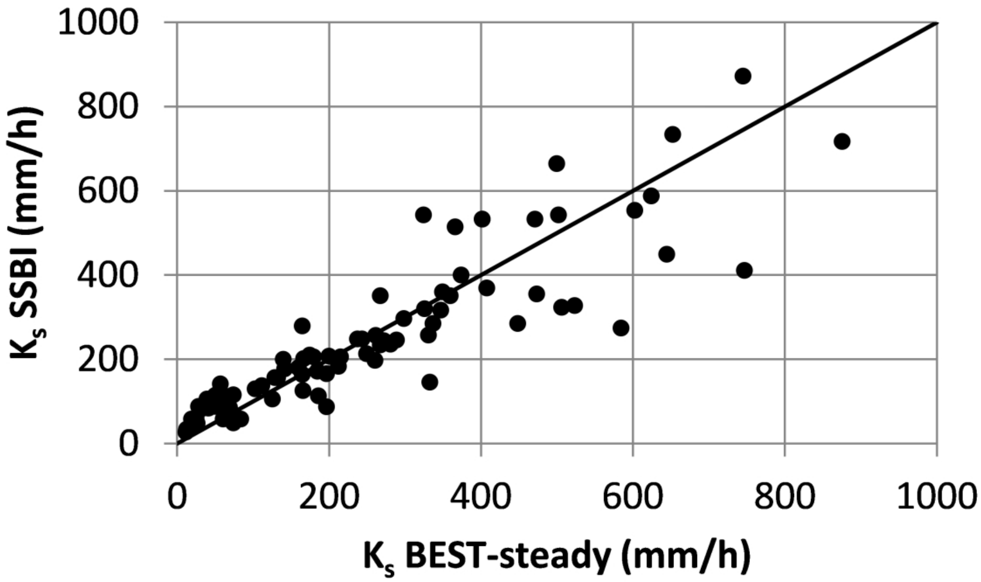

Figure 3. Comparison between the saturated soil hydraulic conductivity, K_s, values obtained with BEST-steady and the SSBI method with α^* = 0.019 mm^{-1}

752x440mm (96 x 96 DPI)