



A four-year monitoring of beerkan infiltration rates in a sandy-loam soil

Gaetano Caltabellotta, Dario Autovino*, Massimo Iovino, Vincenzo Bagarello

Department of Agricultural, Food and Forest Sciences, University of Palermo, Viale delle Scienze, 90128 Palermo, Italy.

* Corresponding author. E-mail: dario.autovino@unipa.it

Abstract: Long-term investigations on temporal variability of infiltration rates are important for characterizing the porous medium but they are challenging and infrequent. Infiltration rates were measured in a sandy-loam soil by performing 16 beerkan infiltration runs on 14 sampling dates during a nearly four-year period. The means of the initial infiltration rates (i_0) varying by approximately four times, were less variable than the means of both the final (i_f) and the mean (i_{med}) infiltration rates, varying by 13 and nine times, respectively. The means of all considered parameters decreased as the antecedent soil water content (θ_i) increased but the θ_i effect was stronger for i_0 (coefficient of determination, $R^2 = 0.84$) than both i_f and i_{med} ($R^2 = 0.55-0.68$). With reference to these last two parameters, θ_i effects were significant for the lowest measured values ($R^2 = 0.63-0.76$) but not for the highest ones ($R^2 = 0.12-0.13$). Particularly small i_f and i_{med} values were obtained in initially very wet soil conditions. The antecedent soil water content can be expected to strongly control infiltration rates in a sandy-loam soil. Sampling the widest possible range of θ_i values is recommended to obtain the most complete information about temporal variability of infiltration rates.

Keywords: Single-ring infiltration; Soil hydrodynamic behaviour; Time variations; Early- and late-time infiltration rates; Soil water content effects.

1 INTRODUCTION

The soil hydrodynamic behaviour can notoriously show a more or less appreciable temporal variability, depending on many factors that include soil nature and stability, climate, land use, dynamics of plant canopy and roots and tillage operations (e.g., Messing and Jarvis, 1990; Priekšat et al., 1994; Bagarello and Sgroi, 2004; Jirků et al., 2013; Kargas et al., 2016; Nikodem et al., 2021). Considering temporal variation of soil hydrodynamic properties is necessary to simulate soil water content and water balance components (Guo et al., 2025) although not under any circumstance (Brunetti et al., 2025). The soil hydrodynamic behaviour can vary sharply in agricultural soils as a consequence of tillage but subsequent variations could occur more or less slowly. In the absence of any anthropic activity, or when anthropic pressure is limited, changes could be gradual since they mainly depend on whether fluctuations and biological activity. However, it is not possible to generalize about the rate of these variations since time scales can vary from a few hours following a rainfall event to seasonal, depending on local and annual climatic conditions (Bodner et al., 2008). This circumstance makes temporal variability investigations complex since the sampling frequency should follow in some manner the rate at which variations occur but this information is unavailable before performing the measurements. Therefore, temporal variability of infiltration rates and soil hydrodynamic properties is still an open issue.

Investigations on time changes of infiltration rates and soil hydrodynamic properties differ by many factors, such as considered properties, sample sizes or measurement methods. In general, different investigations also differ with reference to the number of sampling campaigns and the overall duration of the sampling period. For example, two dates in a year or in two different seasons were considered by Asare et al. (1993) and Perrone and Madramootoo (1994). Two dates in two

experimental years were instead considered by Bodner et al. (2008). In other investigations, the soil was sampled four times in a year (Cerdà, 1996, 1997, 1999), over one and a half growing season (Logsdon and Jaynes, 1996), from 2004 to 2006 (Zhou et al., 2008), from May to August 2005 (Hu et al., 2009) or from May to November 2016 (Šípek et al., 2019). The vegetation periods of 2007, 2008, 2009 and 2009 were considered by Jirků et al. (2013). Five sets of measurements over a 18-month period were collected by Bagarello and Sgroi (2004) and seven sets of measurements during a cropping season were performed by Mubarak et al. (2009). Ten sampling dates over a 28-month period were considered by Bagarello and Sgroi (2007) and the soil was sampled twelve times between September 2009 and July 2012 by Bodner et al. (2013).

This brief review indicates that, in many cases, temporal variability has been investigated for relatively short time periods and/or considering a relatively limited number of measurement dates. Therefore, a general lack of long- or relatively long-term investigations has to be acknowledged. A notable exception is the investigation by Votrubova et al. (2017), reporting data collected on a coarse sandy-loam soil once a year for a total of 13 years. The long-term monitoring allowed the authors to recognize a sharp variation of infiltration rates after several years of data collection, which probably would not have been detected with a shorter sampling.

Votrubova et al. (2017) also recognized that the temporal changes of the considered hydrodynamic parameters were independent of the initial soil moisture conditions. A limited effect of the initial soil water content on the hydrodynamic response of another sandy-loam soil was also reported by Hu et al. (2009). Instead, different results were obtained in the sandy-loam soils sampled by Cerdà (1997) and Zhou et al. (2008) since, in these cases, infiltration rates or soil hydraulic conductivity were smaller in wetter soil conditions. Therefore, soil water content effects on hydrodynamic properties of sandy-loam soils

should further be investigated, also in the perspective to establish why a different information can be found in the literature.

Especially for structured soils, soil hydrodynamic properties should be measured directly in the field to minimize disturbance of the sampled soil volume and to maintain its functional connection with the surrounding soil (Bouma, 1982). A widely used experimental method in temporal variability investigations is the single-ring, ponding infiltration method, as documented in Table 1 (see Appendix). A practical way for making this type of measurements is performing beerkan infiltration runs according to Lassabatere et al. (2006). In short, the ring is inserted a little into the soil to avoid lateral water loss. Fixed and small water volumes are repeatedly poured on the soil surface and the infiltration time of each volume is measured. Finally, a cumulative infiltration curve is obtained. The limited insertion depth of the ring into the soil preserves its integrity and ensures a three-dimensional infiltration process (Angulo-Jaramillo et al., 2016).

Another advantage of the beerkan run method is that it allows to simply obtain experimental data on both initial and final infiltration rates. It can therefore be verified if temporal variability of early and final stages of an infiltration process coincide or not. In principle, a difference can be expected since the sampled soil volume varies during the run (Vandervaere et al., 2000) and possible soil structure modification processes due to wetting could occur with more applied water (Bagarello and David, 2020). A distinction between the soil hydrodynamic response at different stages of the infiltration process can be hydrologically relevant in temporal variability investigations but it does not seem that this issue has been widely considered in the scientific literature.

In summary, antecedent soil water content effects on infiltration rates at different stages of the process need to be further investigated in sandy-loam soil and long or relatively long sampling campaigns should be carried out at this aim to explore a wide range of antecedent conditions.

Starting from this premise, the general objective of this investigation was to determine temporal variability of the hydrodynamic behaviour of a sandy-loam soil cultivated with a citrus orchard in which anthropic activity is minimal. The soil was sampled 14 times during a nearly four-year period with the following specific objectives: i) determine temporal variability of initial, final and mean infiltration rates; and ii) establish the effects of dry soil bulk density and antecedent soil water content on infiltration rates.

2 MATERIALS AND METHODS

2.1 Field site

The field experiment was carried out at the so-called “Aranceto” site of the Department of Agricultural, Food and Forest Sciences of the University of Palermo (Italy) (38°06'24'' N, 13°21'06'' E). An approximately 150 m² flat area of a citrus orchard under no-tillage management, with trees of more than 40 years spaced 4 m × 4 m apart, was selected. The soil texture of the upper 0.3 m of the profile was vertically uniform and classified as sandy-loam according to the USDA classification system (clay = 14.4–15.5%, depending on the sampling depth; silt = 29.6–30.2%; sand = 54.9–55.4%; Bagarello et al., 2021). The mean organic carbon content (OC in %), of the upper few centimeters of the soil, determined by the Walkley-Black method, was equal to 3.1%. According to the IUSS Working Group WRB (2022) guidelines, the soil was classified as a Terric Chromic Cambisol (Loamic) (Autovino et al., 2026).

The soil at the field site was not tilled during the entire sampling period and not even before, and anthropic activity in the area, including a sporadic survival irrigation, was limited. Therefore, the investigation was mainly focused on determining natural variability of soil hydrodynamic properties.

2.2 Experiment

Fourteen sampling campaigns involving infiltration experiments of the beerkan type (Lassabatere et al., 2006) were carried out from June 2020 to March 2024 (Table 2 and Fig. 1). The main features of these experiments were: i) insertion of 0.08-m-diam. rings to a depth of 0.01 m on the soil surface; ii) filling plastic glasses with 57 mL of water for each glass; iii) infiltration runs carried out by successively pouring the water contained in a glass on the confined infiltration surface from a height of nearly 0.03 m. In particular, a given volume of water was poured in the ring in approximately 3 s at the start of the measurement and the elapsed time during complete infiltration was measured. An identical amount of water was subsequently poured into the ring, and the time needed for this water to infiltrate was logged. A total of 20 water volumes, corresponding to a total cumulative infiltration of 226.8 mm, were applied to be confident enough that steady-state infiltration rates were attained by the end of each run (Souza et al., 2014; Lassabatere et al., 2019). At each sampling point, the spontaneous herbaceous vegetation was removed with shears before inserting the ring into the soil while the roots remained in situ.

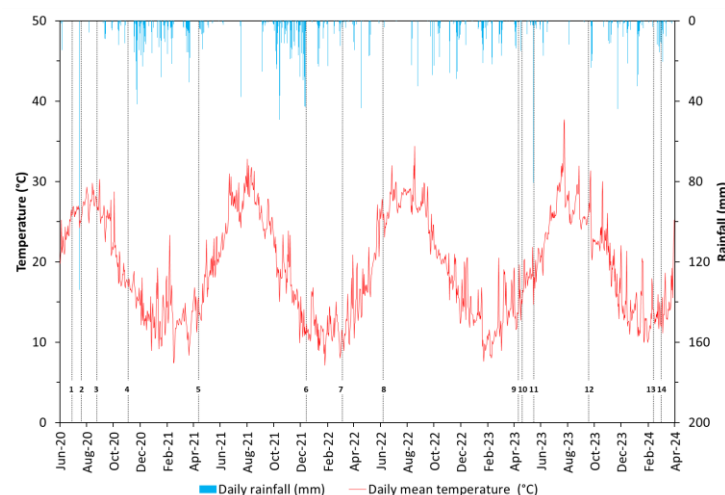


Fig. 1. Daily rainfall, average daily air temperature and sampling dates (dotted vertical lines) during the sampling period.

Table 2. Details on the sampling campaigns and summary statistics of dry soil bulk density, ρ_b , antecedent gravimetric soil water content, w_i , and antecedent volumetric soil water content, θ_i , for each sampling campaign.

Sampling campaign	Period	Abbreviation	Sampling days	N	ρ_b (g/cm ³)		w_i (g/g)		θ_i (m ³ /m ³)	
					Mean	CV (%)	Mean	CV (%)	Mean	CV (%)
1	29 June – 14 July 2020	Jul20/I	10	60	1.156	6.0	0.059	38.5	0.068	36.6
2	20 – 21 July 2020	Jul20/II	2	12	1.031	6.2	0.154	8.4	0.159	9.7
3	25 – 26 August 2020	Aug20	2	12	1.191	3.9	0.055	11.9	0.066	10.3
4	3 – 16 November 2020	Nov20	9	54	1.059	5.2	0.130	13.3	0.138	13.4
5	14 – 15 April 2021	Apr21	2	12	1.063	4.3	0.143	13.2	0.152	13.3
6	14 – 16 December 2021	Dec21	3	18	1.205	6.5	0.220	6.0	0.265	8.2
7	7 March 2022	Mar22	1	6	1.206	4.1	0.170	9.9	0.205	12.7
8	7 June 2022	Jun22	1	6	1.201	6.6	0.074	22.8	0.088	18.2
9	12 April 2023	Apr23/I	1	6	1.218	4.3	0.155	4.4	0.189	7.2
10	19 April 2023	Apr23/II	1	6	1.220	4.8	0.168	7.0	0.205	7.1
11	17 May 2023	May23	1	6	1.169	8.8	0.202	3.5	0.235	7.8
12	18 September 2023	Sep23	1	6	1.242	3.9	0.052	20.2	0.064	16.8
13	13 February 2024	Feb24	1	6	1.161	6.4	0.191	4.7	0.222	9.4
14	1 Mar 2024	Mar24	1	6	1.140	8.2	0.184	17.9	0.211	21.5

Each infiltration run was characterized by three parameters. In particular, the mean infiltration rate, i_{med} (mm/h), was calculated in accordance with Lassabatero et al. (2019) and Votrubova et al. (2017) since this parameter is indicative of the bulk soil capacity to infiltrate water. The initial infiltration rate, i_0 (mm/h), was determined by considering the time necessary for infiltration of the first applied water volume. The final infiltration rate, i_f (mm/h), was finally obtained by considering the last applied water volume. The choice to consider i_0 and i_f was made to obtain the most representative information about the initial and final stages of the infiltration process, respectively.

On each sampling campaign, 16 beerkan infiltration runs were performed at randomly selected points of the site. Durations of the field campaigns were different as a few campaigns were also performed with other objectives (Bagarello et al., 2021, 2022; Caltabellotta et al., 2022). In particular, 11 campaigns were completed in one or two days, a campaign required three days and two campaigns were completed in nine or ten days since the field activity also implied simultaneously performing other experiments. The study therefore consisted of a total of 36 sampling days (Table 2).

Soil was repeatedly sampled during the experimental period to determine the dry soil bulk density (ρ_b in g/cm³), and the antecedent volumetric soil water content (θ_i in m³/m³). On a given sampling day, undisturbed soil cores (5 cm in height by 5 cm in diameter) were collected at the 0 to 5 cm and 5 to 10 cm depths at three randomly chosen sampling points. These six cores were used to determine ρ_b and the antecedent gravimetric soil water content (w_i in g/g), and hence θ_i , in the laboratory. Overall, 216 ρ_b , w_i and θ_i values were obtained during the experimental period (36 sampling days $\times$ 3 replicates $\times$ 2 depths).

2.3 Data analysis

Data were analyzed according to the following sequence: i) dry soil bulk density and soil water content; ii) infiltration parameters; and iii) relationship between infiltration parameters, dry soil bulk density and soil water content.

The individual θ_i values ($N = 216$) were initially plotted against the sampling date to evaluate if a link between soil water content and period of the year existed, as expected.

The relationship between ρ_b and w_i was then examined to verify if soil compaction status changed with its moisture conditions (Lardy et al., 2022).

Finally, each sampling campaign was characterized by a single value of ρ_b , w_i and θ_i , that was obtained by averaging all individual determinations made during a campaign. Consequently, six values were averaged when the sampling campaign was completed in a single day whereas 60 values were considered for a 10-day long campaign.

With reference to the individual determinations of the considered infiltration parameters ($N = 224 = 16$ runs $\times$ 14 campaigns), the relationships between i_{med} , i_0 and i_f were initially examined to establish a comparison between different parameters characterizing the same infiltration run.

For each sampling campaign, the common summary statistics of the $N = 16$ infiltration rates, that is mean, coefficient of variation (CV) maximum and minimum values, were calculated and differences between the i_{med} , i_0 and i_f values during the experimental period were evaluated.

Finally, an analysis was carried out to verify if the infiltration parameters varied with dry soil bulk density and antecedent soil water content during the experimental period. At this aim, the relationships between the means and the CVs of i_{med} , i_0 and i_f and the means of ρ_b and θ_i obtained for each sampling campaign were examined.

Taking into account that θ_i was an important variable explaining the soil hydrodynamic response at the field site, the analysis was completed by also testing θ_i effects on i) the largest and the smallest values of each parameter (i_{med} , i_0 and i_f) obtained in the 14 sampling campaigns; and ii) the difference between the means of i_0 and i_f .

2.4 Statistical methods

Soil bulk density and water content data were assumed to be normally distributed as usual and, consequently, the arithmetic mean and the associated CV value were calculated to summarize these data.

The Lilliefors (1967) test was applied at $P = 0.05$ to test the normal distribution hypothesis of both the untransformed (NO) and the ln-transformed (LNO) i_{med} , i_0 and i_f values obtained on each sampling campaign. The most common result was that of a better performance of the LNO distribution hypothesis than the NO distribution one. In particular, this result was obtained for 33 of the 42 tested datasets (3 parameters $\times$ 14 sampling campaigns), that is in the 79% of the cases. Therefore, geometric means and the associated CVs (Lee et al., 1985) were used to summarize the infiltration parameters.

A two-tailed, paired t test at $P = 0.05$ was used to compare two corresponding infiltration parameters ($N = 224$) since the data were collected at the same sampling point. According to other investigations (Logsdon and Jaynes, 1996; Bagarello and Sgroi, 2004; Mubarak et al., 2009), two-tailed t tests at $P = 0.05$ were applied for testing differences between sampling dates. The test was not paired in this case since the data were obtained at different points of the field site. The untransformed ρ_b , w_i and θ_i values and the $\ln$ -transformed i_{med} , i_0 and i_f values were considered for performing the t tests.

Linear regression analysis procedures and calculation of 95% confidence intervals for both the intercept and the slope of the linear regression line were also used to test the correspondence between two variables. Instead, regression analysis of i_{med} , i_0 and i_f vs. ρ_b and θ_i was performed by considering the exponential, linear, logarithmic and power relationships and retaining the relationship having the highest coefficient of determination (R^2) for further analysis since the shape of the relationship was not predictable in advance. The statistical significance of a fitted regression line to the data was established by a two-tailed t test at $P = 0.05$ (Glantz, 2012).

All data statistical analyses were performed with the Microsoft Excel® spreadsheet.

3 RESULTS

3.1 Dry soil bulk density and antecedent soil water content

Fig. 2a reports the individual θ_i values ($N = 216$) against the sampling date. This figure also shows the volumetric soil water content values at field capacity (FC) and permanent wilting point (PWP) in which the soil water pressure head (h) values are equal to -100 and -15000 cm, and corresponding θ values = 0.245 and 0.120 m^3/m^3 , respectively, obtained for the field site according to Castellini et al. (2018), applying the evaporation method originally introduced by Wind (1968). The individual θ_i values, varying between 0.041 and 0.297 m^3/m^3 , that is by 7.3 times, ranged from substantially less than the PWP value to appreciably above the FC value. In particular, $\theta_i < \text{PWP}$ was obtained in the June to September months and also in November. The $\theta_i > \text{FC}$ values were obtained exclusively in December with two exceptions (a data point in February and another data point in May). Therefore, the developed dataset provided a good range of soil water content values for examining the effect of the initial soil water content on infiltration rates in the experimental area.

The individual values of ρ_b varied by 1.5 times (0.93-1.37 g/cm^3) whereas those of w_i varied by 7.2 times (0.033-0.238 g/g). Plotting ρ_b against w_i suggested that relatively high ρ_b values ($> 1.2 \text{ g}/\text{cm}^3$) were obtained in both dry (w_i smaller than approximately 0.075 g/g) and wet (w_i larger than nearly 0.15 g/g) soil but not, or much less frequently, in intermediate conditions (Fig. 2b). In this last case, the most common result was obtaining relatively small ρ_b values.

During the experimental period, the means of ρ_b varied between 1.03 and 1.24 g/cm^3 , that is by 1.2 times (Table 2). The means of w_i ranged from 0.052 to 0.220 g/g (4.2 times) and those of θ_i varied between 0.064 and 0.265 m^3/m^3 (4.1 times). According to Warrick (1998), variation was low ($CV < 15\%$) for ρ_b on all sampling dates and for w_i and θ_i in ten dates. In the other cases, variation was medium since the highest CV value was equal to 38.5%, i.e. it did not exceed the threshold of 50%.

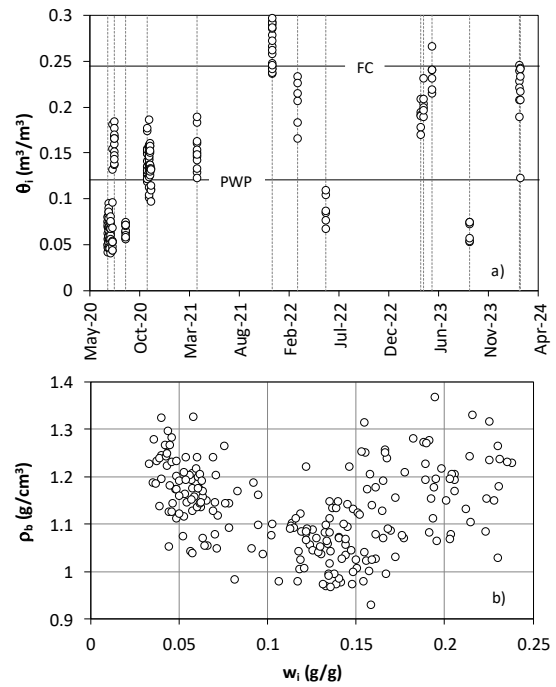


Fig. 2. Volumetric soil water content (θ_i) values measured during the sampling period (a) and relationship between the dry soil bulk density (ρ_b) and the gravimetric soil water content (w_i) (b) (sample size, $N = 216$; FC = field capacity soil water content; PWP = permanent wilting point soil water content).

3.2 Infiltration rates

The individual i_{med} , i_0 and i_f values varied by 45.5 ($59 \leq i_{med} \leq 2695 \text{ mm}/\text{h}$), 59.5 ($343 \leq i_0 \leq 20412 \text{ mm}/\text{h}$) and 48.9 ($38 \leq i_f \leq 1856 \text{ mm}/\text{h}$) times, respectively. However, relative variability of the data was a little larger for i_f ($CV = 92\%$) than both i_{med} ($CV = 81\%$) and i_0 ($CV = 79\%$). On average, i_0 (mean = 2408 mm/h) was 4.5 times larger than i_f (536 mm/h) and 3.2 times larger than i_{med} (747 mm/h) whereas i_f was 1.4 times smaller than i_{med} . All tested differences between i_{med} , i_0 and i_f were statistically significant.

The linear regression analysis between the three tested parameters yielded statistically significant relationships in all cases (Fig. 3) even if the $\ln(i_f)$ vs. $\ln(i_{med})$ relationship ($R^2 = 0.96$) was appreciably stronger than those between these two variables and $\ln(i_0)$ ($R^2 = 0.35$ -0.44). According to the calculated 95% confidence intervals for the intercept and the slope of the regression line, no regression line was found to coincide with the identity line.

Two means of i_{med} varied by up to 8.5 times ($149 \leq i_{med} \leq 1258 \text{ mm}/\text{h}$) (Table 3). Of the 91 comparisons made between mean i_{med} values at two sampling dates, 43 (the 47.3% of the total) yielded not significant differences and 48 (52.7%) yielded significant differences (Table 4). The i_{med} values decreased appreciably from Jul20/I (1251 mm/h) to Dec21 (149 mm/h) but not monotonically since they were nearly stable in four consecutive dates of this period, that is from Jul20/II to Apr21 (Table 3). After reaching the minimum value, i_{med} started to increase again. This increase was gradual but also appreciable since i_{med} was equal to 541 mm/h in Mar22 and 1049 mm/h in Jun22. In the last six sampling dates, the means of i_{med} ranged around values (650-1258 mm/h) close to those detected in the first five dates (707-1251 mm/h). According to Warrick (1998), variation of the data was medium in seven dates and high ($CV > 50\%$) in other seven dates.

Table 3. Summary statistics of the mean, i_{med} , initial, i_0 , and final, i_f , infiltration rates measured during each sampling campaign.

Parameter	Statistic	Sampling date													
		1 Jul20/I	2 Jul20/II	3 Aug20	4 Nov20	5 Apr21	6 Dec21	7 Mar22	8 Jun22	9 Apr23/I	10 Apr23/II	11 May23	12 Sep23	13 Feb24	14 Mar24
i_{med} (mm/h)	Min	734.2	329.5	413.0	374.2	310.7	59.2	150.4	596.8	513.2	495.1	257.6	934.2	261.9	216.0
	Max	1814.4	2366.6	1481.8	1306.3	1814.4	466.6	2694.6	1755.8	1798.4	2041.2	1238.9	1912.1	1957.9	1480.7
	Mean	1251.4	707.0	926.7	729.8	745.4	148.6	540.6	1048.6	958.4	1103.2	647.9	1258.2	755.3	682.6
	CV (%)	31.3	53.0	38.3	35.6	54.4	79.5	117.6	35.9	41.7	47.6	54.0	20.6	66.7	58.1
i_0 (mm/h)	Min	1944	729.0	1632.9	756.0	972.0	343.1	448.6	1134.0	1103.3	1316.9	559.2	2041.2	887.5	447.5
	Max	20411.6	10205.8	8164.6	4082.3	8164.6	4082.3	5831.9	10205.8	5102.9	4535.9	3140.2	10205.8	4535.9	5102.9
	Mean	5368.9	2196.9	4418.2	1710.2	2509.6	1580.4	1388.9	4036.1	2273.2	2438.8	1500.8	3883.2	1909.1	1805.6
	CV (%)	68.9	75.9	48.2	54.5	56.8	81.7	93.1	71.3	40.3	38.1	59.2	46.0	51.4	69.9
i_f (mm/h)	Min	628.0	287.5	337.4	316.5	241.6	38.0	87.8	504.0	346.0	221.9	160.7	742.2	188.1	171.3
	Max	1570.1	1632.9	1166.4	1020.6	1458.0	295.8	1855.6	1316.9	1701.0	1407.7	1020.6	1407.7	1570.1	1279.3
	Mean	969.3	549.3	715.0	555.0	572.0	78.4	357.8	805.9	679.1	718.0	467.8	1024.0	551.5	461.3
	CV (%)	28.5	45.7	36.3	35.3	54.2	68.1	125.3	28.2	47.9	57.8	54.0	18.6	73.6	60.4

Min = minimum value; Max = maximum value; CV = coefficient of variation.

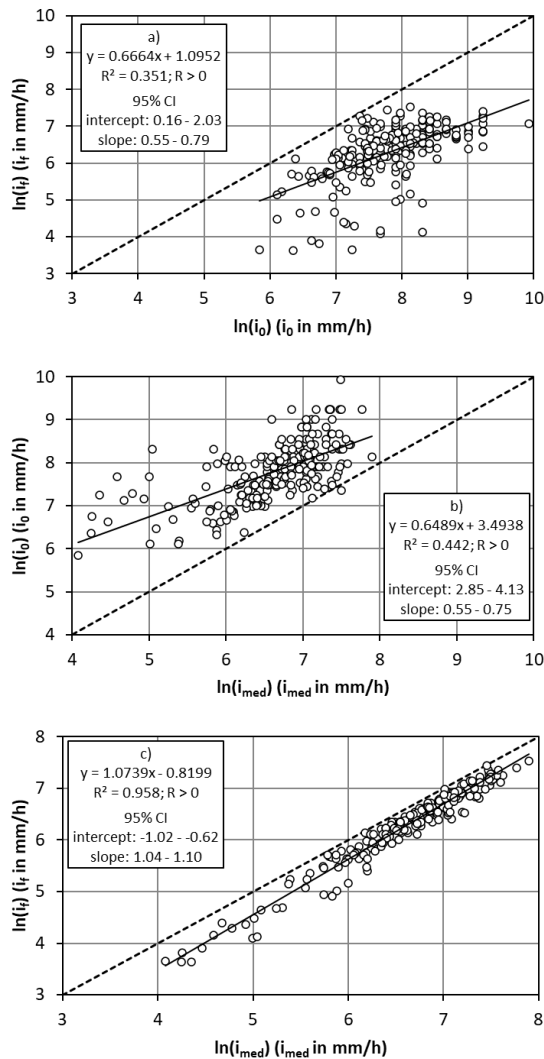


Fig. 3. Results of the linear regression analysis of the ln-transformed values of the initial (i_0) final (i_f) and mean (i_{med}) infiltration rates measured during the sampling campaign (sample size, $N = 224$; R^2 = coefficient of determination; CI = confidence interval).

From a qualitative point of view, similar results were obtained for i_f . In particular, the means of i_f varied by 13.1 times ($78 \leq i_f \leq 1024$ mm/h) (Table 3). With reference to the 91 comparisons between sampling dates, 41 (the 45.1% of the total) yielded not significant differences and 50 (54.9%) yielded significant differences (Table 4). The i_f values decreased appreciably from

Jul20/I (969 mm/h) to Dec21 (78 mm/h) but not monotonically even in this case since they were nearly stable from Jul20/II to Apr21. After reaching the minimum, i_f started to increase gradually but appreciably since it was equal to 358 mm/h in Mar22 and 806 mm/h in Jun22. For the last six sampling dates, the range of the mean i_f values (461–1024 mm/h) was similar to, even if a little wider than, the range detected in the first five dates (549–969 mm/h). Even in this case, variation of the data was medium in seven dates and high in other seven dates.

Results were somewhat different for i_0 . In particular, the means of i_0 changed by 3.9 times ($1389 \leq i_{01} \leq 5369$ mm/h) (Table 3). For the 91 comparisons between sampling dates, 41 (the 45.1% of the total) yielded not significant differences and 50 (54.9%) yielded significant differences (Table 4). In this case, however, a clear minimum value on Dec21 was not detected. Variation of the data was medium in four dates and high in ten dates.

The percentages of not significant and significant differences between any two means did not vary appreciably with the considered parameter since they were equal to 45%–47% and 53%–55%, respectively, depending on the parameter. Nevertheless, there were differences between the considered parameters. For example, with reference to the comparison between the Dec21 and May23 campaigns, the i_0 values were statistically and also numerically very similar, since they differed by 1.05 times, but the i_f values differed significantly and also appreciably, that is by 6.0 times (Tables 3 and 4). Instead, considering the Aug20 and Apr23/II campaigns, the two means of i_0 differed by 1.8 times and differences were significant. On the other hand, not significant differences were detected for i_f and the means were nearly the same since they differed by only 1.004 times. Overall, the comparisons between two datasets made with reference to i_{med} yielded a different response from those made for i_f and i_0 in 11 (or 12.1%) and 28 (30.8%) cases, respectively (Table 4). With reference to initial and final infiltration rates, differences in the response of the statistical test were detected in 24 (26.4%) cases. Therefore, the information provided by the analysis of i_0 differed from that obtained with i_{med} and i_f more frequently than that obtained by considering these last two parameters. In other words, i_{med} and i_f exhibited a similar temporal variability whereas i_0 followed a slightly different trend as compared with the other two parameters.

Temporal variability varied with the considered soil hydrodynamic parameter. It was largest (means differing by even more than an order of magnitude) for the final infiltration rate, a little smaller (a little less than an order of magnitude) for the mean infiltration rate and smallest (by nearly four times at the most) for the initial infiltration rate.

3.3 Effects of dry soil bulk density and antecedent soil water content on infiltration rates

Neither the mean nor the coefficient of variation of the infiltration parameters (i_{med} , i_0 and i_f) were significantly correlated with ρ_b since the R^2 values varied from 0.032 to 0.056 in the former case, depending on the parameter, and from 0.006 to 0.060 in the latter case.

Significant effects of θ_i were instead detected (Fig. 4). In particular, the means of all infiltration parameters decreased as θ_i increased. The relationship was strongest for i_0 ($R^2 = 0.84$) and weakest but significant for i_{med} ($R^2 = 0.55$). In the range of the experimental θ_i values (0.06 – $0.27 \text{ m}^3/\text{m}^3$), the means of i_{med} , i_0 and i_f decreased, according to the fitted regression lines, by 2.3, 3.5 and 2.9 times, respectively.

Relative variability of i_0 did not vary significantly with θ_i . Instead, the CV values of both i_{med} and i_f increased significantly as θ_i increased. In particular, the increase was by 2.5 times in the former case and 3.0 times in the latter one.

Therefore, wetter soil conditions yielded smaller and more variable values of the mean infiltration rate. A particularly

appreciable θ_i effect was recognized at the beginning of the infiltration run (i_0) but this effect remained perceivable in the most advanced stage of the process (i_f). The antecedent soil water content did not influence relative variability of the infiltration rate at the beginning of the run but final infiltration rates were more variable in wetter soil.

The smallest values of any considered soil hydrodynamic parameter (i_{med} , i_0 and i_f) decreased significantly as the antecedent soil water content increased ($0.63 \leq R^2 \leq 0.76$; $R > 0$ in all cases). In particular, according to the fitted relationships (Fig. 5), an increase of θ_i from 0.06 to $0.27 \text{ m}^3/\text{m}^3$ determined a decrease of i_0 and i_{med} by 3.7–3.8 times and of i_f by 5.9 times. With reference to the largest values, neither i_{med} nor i_f varied significantly with θ_i ($0.12 \leq R^2 \leq 0.13$; $R = 0$). Instead, a significant relationship was obtained for i_0 ($R^2 = 0.64$; $R > 0$) and the prediction was that i_0 decreased by 3.3 times.

A significant relationship was obtained by plotting (mean of i_0 – mean of i_f) against the mean of θ_i ($R^2 = 0.77$; $R > 0$; Fig. 6). Therefore, θ_i influenced the decrease of the infiltration rates. In particular, the largest differences between the initial and the final infiltration rates were detected in initially dry soil conditions.

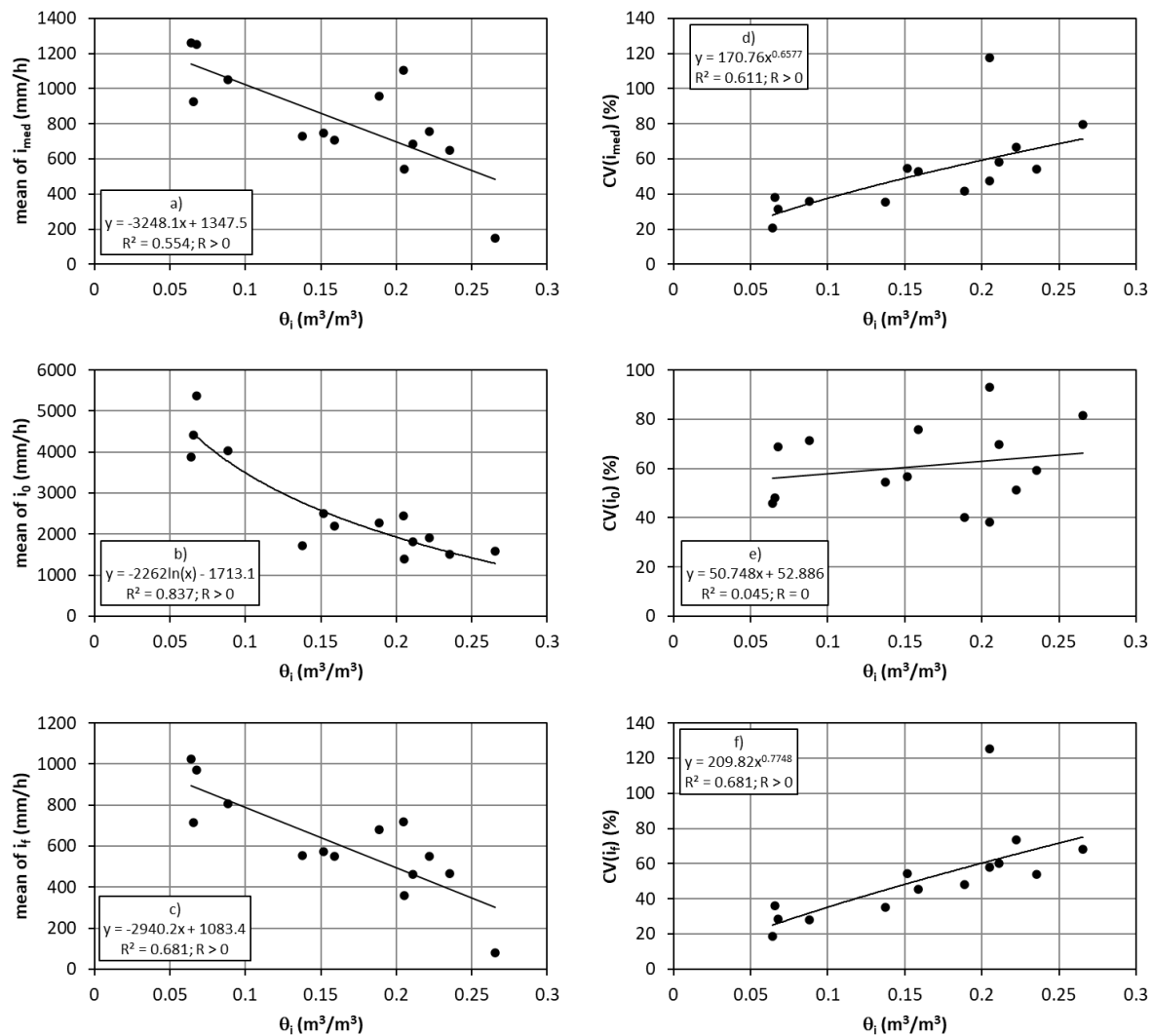


Fig. 4. Relationships between the means [a), b), c)] and the coefficients of variation, CV [d), e), f)], of the mean, i_{med} , initial, i_0 , and final, i_f , infiltration rates and the mean of the antecedent volumetric soil water content, θ_i (sample size, $N = 14$; R^2 = coefficient of determination).

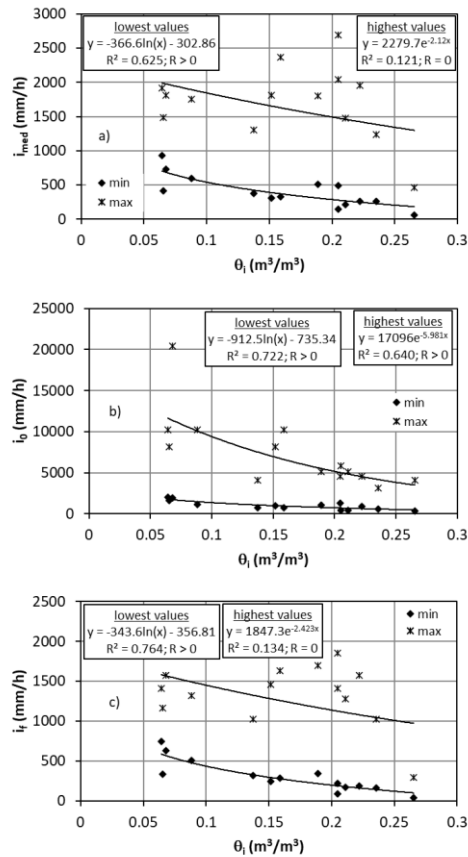


Fig. 5. Relationships between the highest and the lowest values of a) mean infiltration rate (i_{med}), b) initial infiltration rate (i_0) and c) final infiltration rate (i_f) and the mean antecedent soil water content, θ_i (sample size, $N = 14$; R^2 = coefficient of determination).

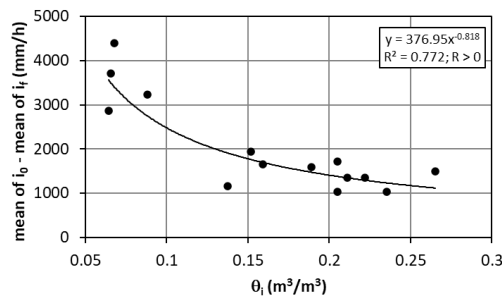


Fig. 6. Differences between the means of the initial (i_0) and final (i_f) infiltration rates against the mean antecedent volumetric soil water content (θ_i) and fitted regression line (sample size, $N = 14$; R^2 = coefficient of determination).

4 DISCUSSION

The results obtained in this investigation suggested that the main questions to be discussed included: i) recognition of soil water content as a primary factor determining temporal variability of infiltration rates at the field site; ii) differences in temporal variability of initial and final infiltration rates; and iii) organization of the sampling campaigns in order to describe temporal variability of infiltration rates in the most complete way possible.

In general, three-dimensional infiltration rates that decrease in initially wetter soil conditions are expected theoretically (Reynolds and Elrick, 1990; Lassabatere et al., 2006; Alagna et al., 2018) but there are also practical reasons why these rates

could decrease with an increase in soil water content. In particular, more water in the soil can induce swelling and weakening of the interparticle bonds, also in soils with a moderate clay content, overall reducing the ability of the largest pores to transport water (Bagarello and Sgroi, 2007; Alagna et al., 2016).

This investigation yielded expected results since monotonically decreasing means of the considered soil hydrodynamic parameters in wetter soil conditions were recognized (Fig. 4). The inverse relationship between (mean of i_0 - mean of i_f) and the mean of θ_i (Fig. 6) also was physically plausible since pressure head gradients are smaller when a ponding infiltration run is carried out in initially wetter soil conditions and hence less differences are expected between initial and final infiltration rates (Youngs et al., 1995).

However, according to several investigations in different sandy-loam soils, soil water content effects on infiltration can be more variable than expected. In particular, a similarity was recognized between this investigation and that by Cerdà (1997) in a Spanish field site, since steady-state infiltration rates were higher during the dry (summer) than the wet (winter, spring and autumn) seasons. Zhou et al. (2008) also found that soil hydraulic conductivity generally decreased as the antecedent soil water content increased in different soils, including a soil classified on average as sandy-loam, and they attributed this result to the increase of macroporosity in drier conditions. Instead, Hu et al. (2009) suggested that antecedent soil water content was no more than a minor factor influencing soil hydraulic conductivity measurements. Moreover, in the long-term investigation performed by Votrubova et al. (2017) on a coarse sandy-loam soil, temporal changes of infiltration rates appeared independent of the initial soil moisture. For the same field site considered in this investigation, Bagarello and Sgroi (2007) determined the field saturated soil hydraulic conductivity, K_s , with a transient one-dimensional infiltration technique and they found that K_s was practically independent of θ_i in both relatively dry (θ_i nearly equal to 0.05–0.20 m^3/m^3) and wet (θ_i varying between 0.20 and 0.30 m^3/m^3) soil conditions but also higher and less variable in the dry soil than the wet one.

Therefore, it cannot be said that an inverse relationship between the hydrodynamic parameters and the antecedent soil water content is the only possible result of any investigation.

The rather large dataset developed in this investigation appeared usable for trying to find an explanation for the contrasting findings about the effects of the initial soil water content on infiltration in sandy-loam soils.

The starting point of the reasoning was that, for a given sampling campaign, and hence for a nearly constant or little variable initial soil water condition, soil hydrodynamic parameters were generally largest when large pores and other preferential flow zones appreciably influenced infiltration and smallest when the process was more governed by soil matrix. Consequently, a decrease of the lowest i_{med} , i_0 and i_f values in wetter soil conditions (Fig. 5) occurred since these data were mainly expressive of the capacity of the soil matrix to infiltrate water. The soil water content effect was consistent with theory and also with development of a less conductive porous medium in wetter conditions, for example as a consequence of swelling (Bagarello and Sgroi, 2007). The highest values of the soil hydrodynamic parameters were instead measured when flow was mainly gravity-driven. Therefore, in this case, the moisture content, and also the bulk density, conditions of the soil matrix had little effects on the infiltration process.

Even the fact that, for the largest values, the relationship with θ_i was not significant for i_f and i_{med} while it was for i_0 can likely

find a physical explanation. In the starting phase of an infiltration process, gravity plays a smaller role whereas soil sorptivity, which expressed the ability of an unsaturated porous medium to adsorb or store water as a result of capillarity (Reynolds and Elrick, 2002) and varies with the soil water content (Stewart et al., 2013; Votrubova et al., 2017), controls the process. Therefore, the initial phase of the process is the phase in which soil water content effects can be expected to be more appreciable.

The sharp decrease of the highest i_f and i_{med} values for the largest θ_i value (Fig. 5) also suggested that soil macroporosity characteristics changed in initially very wet soil conditions. In these conditions, the differences between the largest and smallest values were appreciably smaller than those obtained in drier soil conditions likely because, in very wet conditions, the soil

hydraulic response was generally controlled by soil matrix characteristics.

In summary, mean and final infiltration rates that do not vary with the antecedent soil water content can be expected to indicate that infiltration is mainly controlled by stable macropores and other preferential flow zones. Instead, mean and final infiltration rates that decrease in wetter soil conditions appear indicative of an infiltration process mainly occurring through the soil matrix. The same diagnostic character is not recognized for the initial infiltration rates since, in this case, an inverse relationship with the antecedent soil water content can generally be expected. Jointly considering the soil physical and hydrodynamic results, it seems that the soil matrix could be rather dense under dry soil conditions but this circumstance will not affect appreciably ponded infiltration since, in this case, the process is mainly governed by macropores.

Table 4. Results of the two-tailed t test at $P = 0.05$ for the comparison between two datasets of a given parameter (i_0 = initial infiltration rate; i_f = final infiltration rate; i_{med} = mean infiltration rate) differing by the sampling date (= indicates not significant differences; $\neq$ indicates significant differences).

Comparison	i_{med}	i_0	i_f																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																																												
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Very wet conditions also determine rather dense soil conditions, likely due to moderate swelling phenomena and weakening of the interparticle bonds that reduce macropore volume (Bagarello and Sgroi, 2007). Consequently, in this case, infiltration rates are smaller.

Even if this interpretation is based on a single experiment and it cannot be considered valid in general, it is robust with reference to the overall collected data. Therefore, it could represent a starting point to be validated, or disproved, with other future investigations.

Most ponding infiltration investigations on temporal variability of soil hydrodynamic properties were focused on field determination of final infiltration rates or soil hydraulic conductivity (e.g., Priekšat et al., 1994; Cerdà, 1996, 1997, 1999; Ciollaro and Lamaddalena, 1998; Bagarello and Sgroi, 2004, 2007; Mubarak et al., 2009; Vinatier et al., 2024), which is logical since, for modelling purposes, soil hydrodynamic parameters are mandatory and final infiltration rates can be used for calculating both soil sorptivity, S , and saturated soil hydraulic conductivity, K_s (Reynolds and Elrick, 1990). Less frequent seem the investigations in which temporal variability was also tested with reference to the initial stage of the infiltration process even if some exception can be found in the literature (Votrubova et al., 2017). These investigations are necessary since S and K_s can also be obtained with simpler and shorter field infiltration experiments, that is from the early stage of an infiltration process in an initially unsaturated porous medium (Smith, 1999; Bagarello et al., 2004).

This investigation, yielding means of i_0 and i_f differing during the sampling period by four and 13 times, respectively (Table 3), showed that temporal variability of initial and final infiltration rates can largely differ and also that initial infiltration rates can describe a more stable soil from a hydrodynamic point of view as compared with the final infiltration rates. At the sampled field site, the most striking reason was related to the Dec21 sampling campaign, yielding unusually low i_f values (Table 3). However, this was not the only reason of the differences between the two considered infiltration rates since there were also campaigns in which i_0 did not differ but i_f did or campaigns in which i_0 differed but i_f did not (Table 4).

A different temporal variability of initial and final infiltration rates should not be particularly surprising, taking into account that i_0 was determined with short runs and a small water volume (11.3 mm) whereas obtaining i_f required longer runs and much more water (226.8 mm). Therefore, the information contained in these two parameters differed for different reasons including that the wetted soil volume was not the same (Vandervaere et al., 2000) and using different water volumes and durations for the run perhaps implied different levels of wetting-induced soil structure modifications at a sampling point (Bagarello and David, 2020). In other terms, i_0 and i_f did not exactly refer to the same soil volume for different reasons, all attributable to the unavoidable differences that exist between a short infiltration run performed with small water volumes and a long run making use of larger water volumes.

According to this investigation, temporal variability of infiltration rates can be expected to depend on the considered stage of the infiltration process, being smaller at the beginning of the infiltration process than at later stages.

This investigation could help to establish how a long-term monitoring campaign should be organized. In particular, the experimental information collected in relatively dry soil conditions seemed somewhat redundant since, in this case, temporal variability of infiltration rates was overall limited.

However, detecting this redundancy was only possible because the soil was sampled repeatedly. Therefore, sampling the same soil at different dates but under similar antecedent soil water conditions is expected to provide a useful information for determining temporal variability of infiltration rates taking into account, however, that the answer could be that there is no a significant temporal variability.

Excluding from the analysis a single campaign (Dec21) reduced the sample size very little (dataset overall including 208 infiltration runs instead of 224) but it influenced appreciably conclusions about temporal variability of infiltration rates. Means of i_{med} and i_f differed during the sampling period by even more than an order of magnitude with the complete dataset but by no more than three times without the Dec21 data. Moreover, temporal variability was rather similar for the three considered parameters (i_{med} , i_0 and i_f) without these data but not with the complete dataset.

The Dec21 data were obtained under conditions of maximum soil water content during the entire sampling period. Therefore, excluding these data from the analysis implied a lack of information about how the infiltration process occurs in particular soil water conditions.

In light of these results, it can be suggested that sampling the entire range of possible θ_i values in an area of interest could lead to conclusions on temporal variability of infiltration rates that are different and certainly more complete than those that could be reached, with approximately the same overall sample size, by a sampling that excludes part of the possible θ_i values.

For completeness, it is not sure that these intensive experimental campaigns are really necessary in the perspective of interpreting or simulate soil hydrological processes. Logic, as well the physics of the processes, lead to believe that a dynamic description of the soil is preferable to a static representation of the porous medium. However, it cannot be ignored that, at least in some circumstances, considering the soil as static could be enough to simulate the hydrological behavior of an area of interest (Brunetti et al., 2025).

In any case, an intensive sampling is the prerequisite for establishing in which conditions of variability a static representation of the soil is enough for modeling purposes.

6 CONCLUSIONS

According to this investigation, infiltration rates in a sandy-loam soil measured by the beerkan run methodology can be expected to vary during a multi-year monitoring period in a different way, depending on the considered stage of the infiltration process. In particular, a possible occurrence is that a variation of nearly four times of the early-time infiltration rates is associated with a variation of 13 times of the final rates. Temporal variability of infiltration occurs since the antecedent soil water content varies during the sampling period. Differences between early- and late-time infiltration data depend on the fact that they do not exactly refer to the same soil volume for different reasons, all attributable to the existing differences between a short infiltration run performed with small water volumes and a long run making use of larger water volumes. Similarity between initial and final infiltration rates increases in initially wetter soil conditions.

This investigation also provided a possible explanation of the reasons why an antecedent soil water content effect has been reported in some investigations on sandy-loam soils but not in other investigations. Infiltration rates that do not vary with the antecedent soil water content likely occurs since the infiltration process is mainly controlled by stable macropores and other preferential flow zones. Instead, infiltration rates that decrease as the soil becomes

wetter suggest that the infiltration process mainly occurs through the soil matrix. Macropore effects on infiltration rates can be expected to suddenly decrease as the soil becomes very wet, probably because macropores disappear or they become very unstable in very wet soil.

Testing soil water content effects on infiltration rates requires planning appropriately the experiment. In particular, in the perspective to obtain the most complete information, it is recommended to sample the widest possible range of antecedent soil water content values by also independently characterizing soil structure during the sampling period.

The beerkan infiltration runs performed in this experiment can be suggested for investigations in other contexts since they are simple and do not require extensive equipment or water volumes. Moreover, the data could also be used for calculating soil hydraulic properties, and hence for modeling hydrological processes.

In the future, the experiment could be completed or at least expanded by simultaneously carrying out beerkan and tension infiltrometer runs on a sampling date. Performing infiltration runs under a slightly negative pressure head on the soil surface implies excluding the largest pores from the infiltration process and hence it could represent a way for experimentally establishing how infiltration rates depend on antecedent soil water conditions when the hydraulically active pores differ by their size. More long-term experiments should be carried in different environments to improve our knowledge about natural variability of infiltration rates and other soil hydrodynamic parameters.

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REFERENCES

- Alagna, V., Bagarello, V., Di Prima, S., Giordano, G., Iovino, M., 2016. Testing infiltration run effects on the estimated water transmission properties of a sandy-loam soil. *Geoderma*, 267, 24-33, <https://doi.org/10.1016/j.geoderma.2015.12.029>
- Alagna, V., Bagarello, V., Cecere, N., Concialdi, P., Iovino, M., 2018. A test of water pouring height and run intermittence effects on single-ring infiltration rates. *Hydrol. Process.*, 32, 3793-3804, <https://doi.org/10.1002/hyp.13290>
- Angulo-Jaramillo, R., Bagarello, V., Iovino, M., Lassabatere, L., 2016., *Infiltration Measurements for Soil Hydraulic Characterization*. Springer International Publishing, Switzerland, ISBN 978-3-319-31786-1, 978-3-319-31788-5 (eBook), 386 pp. doi: 10.1007/978-3-319-31788-5
- Asare, S.N., Rudra, R.P., Dickinson, W.T., Wall, G.J., 1993., Seasonal variability of hydraulic conductivity. *Trans. of the ASAE*, 36(2), 451-457, <https://doi.org/10.13031/1013.28358>
- Autovino, D., Bagarello, V., Bondi, C., Russo, G., Zanna, F., Zhioua K., 2026. Hydrodynamic behavior of a near-saturated sandy-loam soil shortly after incorporating compost or zeolite. *Soil Till. Res.*, 258, 107035 <https://doi.org/10.1016/j.still.2025.107035>
- Bagarello, V., Sgroi, A., 2004. Using the single-ring infiltrometer method to detect temporal changes in surface soil field-saturated hydraulic conductivity. *Soil Till. Res.*, 76, 13-24, <https://doi.org/10.1016/j.still.2003.08.008>
- Bagarello, V., Sgroi, A., 2007. Using the simplified falling head technique to detect temporal changes in field-saturated hydraulic conductivity at the surface of a sandy loam soil. *Soil Till. Res.*, 94, 283-294, <https://doi.org/10.1016/j.still.2006.08.001>
- Bagarello, V., David, S.M., 2020. Run duration effects on the hydrodynamic properties of a loam soil estimated by steady-state infiltration methods. *J. Agric. Eng.*, LI:1075, 229-238, <https://doi.org/10.4081/jae.2020.1075>
- Bagarello, V., Iovino, M., Elrick, D., 2004. A simplified falling head technique for rapid determination of field-saturated hydraulic conductivity. *Soil Sci. Soc. Am. J.*, 68, 66-73, <https://doi.org/10.2136/sssaj2004.6600>
- Bagarello, V., Caltabellotta, G., Iovino, M., 2021. Water transmission properties of a sandy-loam soil estimated with Beerkan runs differing by the infiltration time criterion. *J. Hydrol. Hydromech.*, 69(2), 151–160, <https://doi.org/10.2478/johh-2021-0010>
- Bagarello, V., Caltabellotta, G., Iovino, M., 2022. Estimation of hydrodynamic properties of a sandy-loam soil by two analysis methods of single-ring infiltration data. *J. Hydrol. Hydromech.*, 70(2), 234-243, <https://doi.org/10.2478/johh-2022-0005>
- Bodner, G., Loiskandl, W., Buchan, G., Kaul, H.-P., 2008. Natural and management-induced dynamics of hydraulic conductivity along a cover-cropped field slope. *Geoderma*, 146,317-325 <https://doi.org/10.1016/j.geoderma.2008.06.012>
- Bodner, G., Scholl, P., Loiskandl, W., Kaul, H.-P., 2013. Environmental and management influences on temporal variability of near saturated soil hydraulic properties. *Geoderma*, 204-205, 120-129, <http://dx.doi.org/10.1016/j.geoderma.2013.04.015>
- Bouma, J., 1982. Measuring the hydraulic conductivity of soil horizons with continuous macropores. *Soil Sci. Soc. of Am. J.*, 46, 438-441, <https://doi.org/10.2136/sssaj1982.03615995004600020047x>
- Brunetti, G., Kodešová, R., Fér, M., Nikodem, A., Klement, A., Šimunek, J., 2025. Modeling the impact of tillage and consolidation on the vadose zone hydrological behavior for data-limited conditions. *Geoderma*, 464, 117607, <https://doi.org/10.1016/j.geoderma.2025.117607>
- Caltabellotta, G., Bagarello, V., Iovino, M., 2022. Effect of a heavy rainstorm on the surface hydrodynamic properties of a sandy-loam soil. *J. Hydrol. Eng.*, Case Study section, 27(7), 05022006, [https://doi.org/10.1061/\(ASCE\)HE.1943-5584.0002179](https://doi.org/10.1061/(ASCE)HE.1943-5584.0002179)
- Castellini, M., Di Prima, S., Iovino, M., 2018. An assessment of the BEST procedure to estimate the soil water retention curve: A comparison with the evaporation method. *Geoderma*, 320, 82-94, <https://doi.org/10.1016/j.geoderma.2018.01.014>
- Castellini, M., Vonella, A.V., Ventrella, D., Rinaldi, M., Baiamonte, G., 2020. Determining soil hydraulic properties using infiltrometer techniques: An assessment of temporal variability in a long-term experiment under minimum- and no-tillage soil management. *Sustainability*, 12, 5019, 18 pp., <https://doi.org/10.3390/su12125019>

- Castellini, M., Di Prima, S., Giglio, L., Leogrande, R., Alagna, V., Autovino, D., Rinaldi, M., Iovino, M., 2024. Applying a comprehensive model for single-ring infiltration: Assessment of temporal changes in saturated hydraulic conductivity and physical soil properties. *Water*, 16, 2950, 22 pp., <https://doi.org/10.3390/w16202950>
- Cerdà, A., 1996. Seasonal variability of infiltration rates under contrasting slope conditions in southeast Spain. *Geoderma*, 69, 217-232, [https://doi.org/10.1016/0016-7061\(95\)00062-3](https://doi.org/10.1016/0016-7061(95)00062-3)
- Cerdà, A., 1997. Seasonal changes of the infiltration rates in a Mediterranean scrubland on limestone. *J. Hydrol.*, 198, 209-225, [https://doi.org/10.1016/S0022-1694\(96\)03295-7](https://doi.org/10.1016/S0022-1694(96)03295-7)
- Cerdà, A., 1999. Seasonal and spatial variations in infiltration rates in badland surfaces under Mediterranean climatic conditions. *Water Resour. Res.*, 35(1), 319-328, <https://doi.org/10.1029/98WR01659>
- Ciollaro, G., Lamaddalena, N., 1998. Effect of tillage on the hydraulic properties of a vertic soil. *J. Agric. Eng. Res.*, 71, 147-155, <https://doi.org/10.1006/jaer.1998.0312>
- Glantz, S.A., 2012. *Primer of Biostatistics*. 7th edition. The McGraw-Hill Companies.
- Guo, T., Ji, Y., Yan, X., Mady, A.Y., Liu, R., Huang, M., 2025. Temporal variations of soil saturated hydraulic conductivity under different land use types and its impact on water balance components. *Agric. Water Manag.*, 315, 109557, 12 pp., <https://doi.org/10.1016/j.agwat.2025.109557>
- Hu, W., Shao, M., Wang, Q., Fan, J., Horton, R., 2009. Temporal changes of soil hydraulic properties under different land uses. *Geoderma*, 149, 355-366, [doi:10.1016/j.geoderma.2008.12.016](https://doi.org/10.1016/j.geoderma.2008.12.016)
- IUSS Working Group WRB, 2022. World Reference Base for Soil Resources. International soil classification system for naming soils and creating legends for soil maps, fourth ed.. International Union of Soil Sciences (IUSS), Vienna, Austria, p. 236.
- Jirků, V., Kodešová, R., Nikodem, A., Mühlhanslová, M., Žigová, A., 2013. Temporal variability of structure and hydraulic properties of topsoil of three soil types. *Geoderma*, 204-205, 43-58, <https://dx.doi.org/10.1016/j.geoderma.2013.03.024>
- Kargas, G., Kerkides, P., Sotirakoglou, K., Poulouvassilis, A., 2016. Temporal variability of surface soil hydraulic properties under various tillage systems. *Soil Till. Res.*, 158, 22-31, <http://dx.doi.org/10.1016/j.still.2015.11.011>
- Lardy, J.M., DeSutter, T.M., Daigh, A.L.M., Meehan, M.A., Staricka, J.A., 2022. Effects of soil bulk density and water content on penetration resistance. *Agric. Environ. Lett.*, 7, e20096, 7 pp., <https://doi.org/10.1002/ael2.20096>
- Lassabatere, L., Angulo-Jaramillo, R., Soria Ugalde, J.M., Cuenca, R., Braud, I., Haverkamp, R., 2006. Beerkan estimation of soil transfer parameters through infiltration experiments – BEST. *Soil Sci. Soc. Am. J.*, 70, 521-532, <https://doi.org/10.2136/sssaj2005.0026>
- Lassabatere L., Di Prima S., Angulo-Jaramillo R., Keesstra S., Salesa, D., 2019. Beerkan multi-runs for characterizing water infiltration and spatial variability of soil hydraulic properties across scales. *Hydrolog. Sci. J.*, 64(2), 165-178, <https://doi.org/10.1080/02626667.2018.1560448>
- Lee, D.M., Reynolds, W.D., Elrick, D.E., Clothier, B.E., 1985. A comparison of three field methods for measuring saturated hydraulic conductivity. *Can. J. Soil Sci.*, 65, 563-573, <https://doi.org/10.4141/cjss85-060>
- Lilliefors, H.W., 1967. On the Kolmogorov-Smirnov test for normality with mean and variance unknown. *J. Am. Stat. Assoc.*, 62, 399-402, <https://doi.org/10.1080/01621459.1967.10482916>
- Logsdon, S.D., Jaynes, D.B., 1996. Spatial variability of hydraulic conductivity in a cultivated field at different times. *Soil Sci. Soc. Am. J.*, 60, 703-709, <https://doi.org/10.2136/sssaj1996.03615995006000030003x>
- Messing, I., Jarvis, N.J., 1990. Seasonal variation in field-saturated hydraulic conductivity in two swelling clay soils in Sweden. *J. Soil Sci.*, 41, 229-237, <https://doi.org/10.1111/j.1365-2389.1990.tb00059.x>
- Mubarak, I., Mailhol, J.C., Angulo-Jaramillo, R., Ruelle, P., Boivin, P., Khaledian, M., 2009. Temporal variability in soil hydraulic properties under drip irrigation. *Geoderma*, 150, 158-165, <https://doi.org/10.1016/j.geoderma.2009.01.022>
- Mubarak, I., Angulo-Jaramillo, R., Mailhol, J.C., Ruelle, P., Khaledian, M., Vauclin, M., 2010. Spatial analysis of soil surface hydraulic properties: Is infiltration method dependent? *Agric. Water Manag.*, 97(10), 1517-1526, <https://doi.org/10.1016/j.agwat.2010.05.005>
- Nikodem, A., Kodešová, R., Fér, M., Klement, A., 2021. Using scaling factors for characterizing spatial and temporal variability of soil hydraulic properties of topsoils in areas heavily affected by soil erosion. *J. Hydrol.*, 593, 125897, 11 pp., <https://doi.org/10.1016/j.jhydrol.2020.125897>
- Perrone, J., Madramootoo, C.A., 1994. Characterizing bulk density and hydraulic conductivity changes in a potato cropped field. *Soil Technol.*, 7, 261-268, [https://doi.org/10.1016/0933-3630\(94\)90026-4](https://doi.org/10.1016/0933-3630(94)90026-4)
- Prieksat, M.A., Kaspar, T.C., Ankeny, M.D., 1994. Positional and temporal changes in ponded infiltration in a corn field. *Soil Sci. Soc. Am. J.*, 58, 181-184, <https://doi.org/10.2136/sssaj1994.03615995005800010026x>
- Reynolds, W.D., Elrick, D.E., 1990. Ponded infiltration from a single ring: I. Analysis of steady flow. *Soil Sci. Soc. Am. J.*, 54, 1233-1241, <https://doi.org/10.2136/sssaj1990.03615995005400050006x>
- Reynolds, W.D., Elrick, D.E., 2002. 3.4.1.1 Principles and parameter definitions. In *Methods of Soil Analysis, Part 4, Physical Methods*, Dane JH, Topp GC (eds). SSSA Book Series, No. 5. Soil Sci. Soc. Am.: Madison, Wisconsin, USA; 797-801
- Šípek, V., Jačka, L., Seyedsadr, S., Trakal, L., 2019. Manifestation of spatial and temporal variability of soil hydraulic properties in the uncultivated Fluvisol and performance of hydrological model. *Catena*, 182, 104119, 11 pp., <https://doi.org/10.1016/j.catena.2019.104119>
- Smith, R.E., 1999. Technical note: Rapid measurement of soil sorptivity. *Soil Sci. Soc. Am. J.*, 63, 55-57, <https://doi.org/10.2136/sssaj1999.03615995006300010009x>
- Souza, E.S., Antonino, A.C.D., Heck R.J., Montenegro, S.M.G.L., Lima, J.R.S., Sampaio, E.V.S.B., Angulo-Jaramillo, R., Vauclin, M., 2014. Effect of crusting on the physical and hydraulic properties of a soil cropped with Castor beans (*Ricinus communis* L.) in the northeastern region of Brazil. *Soil Till. Res.*, 141, 55-61, <http://dx.doi.org/10.1016/j.still.2014.04.004>
- Stewart, R.D., Rupp, D.E., Abou Najm, M.R., Selker, J.S., 2013. Modeling effect of initial soil moisture on sorptivity and infiltration. *Water Resour. Res.*, 49, 7037-7047, <https://doi.org/10.1002/wrcr.20508>
- Talukder, R., Plaza-Bonilla, D., Cantero-Martínez, C., Di Prima, S., Lampurlanés, J., 2024. Spatio-temporal variation of surface soil hydraulic properties under different tillage and maize-based crop sequences in a Mediterranean area. *Plant*

- Soil, 500, 263-277, <https://doi.org/10.1007/s11104-022-05758-x>
- Vandervaere, J.-P., Vauclin, M., Elrick, D.E., 2000. Transient flow from tension infiltrometers: I. The two-parameter equation. *Soil Sci. Soc. Am. J.*, 64, 1263-1272, <https://doi.org/10.2136/sssaj2000.6441263x>
- Vinatier, F., Rudi, G., Coulouma, G., Dagès, C., Bailly, J.-S., 2024. Dynamics of quasi-steady ponded infiltration under contrasting plant cover and management strategies. *Soil Till. Res.*, 237, 105985, 10 pp., <https://doi.org/10.1016/j.still.2023.105985>
- Votrubova, J., Dohnal, M., Vogel, T., Tesar, M., Jelinkova, V., Cislerova, M., 2017. Ponded infiltration in a grid of permanent single-ring infiltrometers: Spatial versus temporal variability. *J. Hydrol. Hydromech.*, 65(3), 244-253, <https://doi.org/10.1515/johh-2017-0015>
- Warrick, A.W. 1998. Spatial variability. In: *Environmental Soil Physics Appendix 1*. D. Hillel, California, pp. 665–675.
- Wind, G.P., 1968. Capillary conductivity data estimated by a simple method. In: P.E. Rijtema and H. Wassink (Editors), *Water in the unsaturated zone*. Proceedings of the Wageningen symposium, June 1966, Vol. 1. IASH Gentbrugge/ Unesco Paris, pp. 181-191.
- Xu, D., Mermoud, A., 2003. Modeling the soil water balance based on time-dependent hydraulic conductivity under different tillage practices. *Agric. Water Manag.*, 63, 139-151, [https://doi.org/10.1016/S0378-3774\(03\)00180-X](https://doi.org/10.1016/S0378-3774(03)00180-X)
- Youngs, E.G., Leeds-Harrison, P.B., Elrick, D.E., 1995. The hydraulic conductivity of low permeability wet soils used as landfill lining and capping material: analysis of pressure infiltrometer measurements. *Soil Technol.*, 8, 153-160, [https://doi.org/10.1016/0933-3630\(95\)00016-X](https://doi.org/10.1016/0933-3630(95)00016-X)
- Zhou X., Lin H.S., White E.A. 2008. Surface soil hydraulic properties in four soil series under different land uses and their temporal changes. *Catena*, 73, 180-188, <https://doi.org/10.1016/j.catena.2007.09.009>

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Appendix

Table 1. List of some investigations collecting data on temporal variability of soil hydrodynamic properties by the single-ring, ponding infiltration method.

Reference	Context of the investigation	Experimental details	Hydrodynamic properties	Data analysis methods
Asare et al. (1993)	Elora Research Station, University of Guelph. Plot of $20 \times 16 \text{ m}^2$ established on a silt loam soil	Guelph Pressure Infiltrometer runs at each point of a $5 \times 4 \text{ m}^2$ grid. Ring diameter = 9.7 cm. Ring insertion depth = 5.0 cm. Determination of steady-state flow rates for pressure heads of 5 and 10 cm. Experiments conducted in October and November 1989 (fall seasons) and March and April 1990 (spring season)	Saturated hydraulic conductivity and matric flux potential calculated by combining the one-head and two-head approaches (Reynolds and Elrick, 1990)	No statistical analysis. Examination of changes over time of the numerical values
Prieksat et al. (1994)	Corn field. Silty-clay-loam soil. Four positions in a field in the U.S.	Rings of 10.2 cm in diameter. Ponded depth of water of 0.5 cm. Insertion depth = 1 cm. Infiltration measurements for 2000 s after reaching steady-state. Three to seven measurement dates after planting in a nearly 120-140 days long period	Steady-state infiltration rate	Given position: regression analysis to verify whether infiltration rates increased during the growing season. Given sampling date: analysis of variance procedures to analyze positional differences in infiltration
Cerdà (1996)	North- and south-facing slopes of a small watershed in south-eastern Spain. Keuper clay soils. Seven positions	Rings of 7 cm in diameter. Ponded depth of water and ring insertion depth not reported. Infiltration measurements for 60 min. 28 measurements (4 seasons $\times$ 7 positions). Infiltration measurements also performed by rainfall simulation	Steady-state infiltration rate	Comparing numerical values to examine changes over time and differences between the two experimental methods. Regression analysis between steady-state infiltration rates obtained by ring infiltration and simulated rainfall
Cerdà (1997)	North- and south-facing slopes in a typical Mediterranean scrubland, in south-eastern Spain. Sandy-loam soil. Seven positions	Rings of 7 cm in diameter. Ponded depth of water and ring insertion depth not reported. Infiltration measurements for 60 min. 28 measurements (4 seasons $\times$ 7 positions). Infiltration measurements also performed by rainfall simulation. Fitting infiltration data with the Horton model	Steady-state infiltration rate	Comparing the numerical values to examine changes over time and differences between the two experimental methods. Regression analysis between steady-state infiltration rates obtained by ring infiltration and simulated rainfall
Ciollaro and Lamaddalena (1998)	Experimental farm on a silty-loam soil, in Italy. No-tilled plot and plots ploughed and rotary tilled	Rings of 15 cm in diameter. Ponded depth of water of 10 cm. Insertion depth = 5 cm. Duration of a run: 5 – 24 h. Five to 11 sampling dates, depending on the plot, from October 1994 to March 1996. Fitting infiltration rates by the modified Kostiakov model	Saturated soil hydraulic conductivity calculated by the One-Ponding-Depth approach (Reynolds and Elrick, 1990)	No statistical analysis. Examination of changes over time of the numerical values

Cerdà (1999)	Two positions (slope and pediment) in a badland in south-east Spain. Silty-clay or silty-clay-loam soil for the slopes. Loam or silty-loam soil for the pediment	Rings of 7 cm in diameter. Ponded depth of water and ring insertion depth not reported. Infiltration measurements for 60 min. 68 measurements (4 seasons $\times$ 17 sampling points). Infiltration measurements also performed by rainfall simulation. Fitting infiltration data with the Horton model	Steady-state infiltration rate	Comparing the numerical values to examine changes over time and differences between the two experimental methods. Regression analysis between steady-state infiltration rates obtained by ring infiltration and simulated rainfall
Xu and Mermoud (2003)	Plot in the north of China. Topsoil layer (0-70 cm) with a high silt fraction. Incorporating temporal variation of soil hydraulic properties into simulation models	Measurements performed at three stages of maize growth. Ring diameter = 9.5 cm. Ring insertion depth = 4.0 cm. Determination of steady-state flow rates corresponding to pressure heads of 5 and 15 cm	Steady-state infiltration rates	Determining the experimental relationship between steady-state infiltration rate and days after emergence
Bagarello and Sgroi (2004)	Silty-clay to clay soil in Sicily (Italy). Long-term wheat-wheat-oats-broad bean rotation before the experiment. Soil not cultivated during the experiment	Rings of 15 cm in diameter inserted 5 cm into the soil. Five sets of measurements over a nearly 1.5-year period in both permanently (P) and not permanently (NP) installed rings. In both cases, 16 replicated runs on each date	Saturated soil hydraulic conductivity calculated by the One-Ponding-Depth approach (Reynolds and Elrick, 1990)	F and t tests to establish differences between site types (P and NP) at a date and also to compare sampling dates for a given site type
Bagarello and Sgroi (2007)	Citrus orchard established on a sandy-loam soil in Sicily (Italy)	Rings of 15 cm in diameter inserted 12 cm into the soil to perform single-ring, pressure infiltrometer runs from March 2003 to January 2005. Constant pressure head = 5.3 cm. Run duration > 2.5 h. In total, 66 runs (11 locations $\times$ 6 sampling dates)	Saturated soil hydraulic conductivity calculated by the One-Ponding-Depth approach (Reynolds and Elrick, 1990)	Correlation analysis between the data obtained with the single-ring pressure infiltrometer and those collected by another field method. Comparison between the two methods for each sampling date by t tests
Mubarak et al. (2009)	Loamy soil in France under two different drip irrigation treatments	Rings of 6.5 cm in diameter driven 1 cm into the soil to perform beerkan infiltration runs. Seven sampling dates for each treatment. Six to eight runs at each date. Application of BEST methods for analyzing the infiltration data	Saturated soil hydraulic conductivity, mean effective pore radius, capillary length	Time and treatment effects tested by t tests
Mubarak et al. (2010)	Establishing if soil hydraulic properties changed after 17 years of repeated agricultural practices in a loamy soil in France	Rings of 6.5 cm in diameter driven 1 cm into the soil to perform a total of 40 beerkan infiltration runs. Application of BEST methods for analyzing the infiltration data	Saturated soil hydraulic conductivity, α parameter of the van Genuchten equation and average pore sizes	Comparison between the old (1990) and the new (2007) data by t tests. Geostatistical analysis of the data to also compare data spatial structure in the two sampling dates

Votrubova et al. (2017)	Liz experimental site, at an altitude of about 830 m a.s.l. Coarse sandy-loam soil	Installing permanently 17 rings of 37.5 cm in diameter to a depth of 10-15 cm in 2003. Infiltration experiments between 2003 and 2015. Generally, 40 L of water or two hours per run. At each date, two runs in two successive days	Parameters of the two term infiltration equation by Philip (1957)	Box plots and visual examination of the data
Castellini et al. (2020)	Clay soil in a long-term experiment on durum wheat under minimum tillage and no tillage	A total of 58 beerkan infiltration runs in three sampling dates during a little more than one year. Application of BEST methods for analyzing the runs	Soil water retention curve, soil hydraulic conductivity function and soil physical quality indices	Tukey Honestly Significant Difference test for checking temporal variability. Two-tailed t test for establishing management effects
Castellini et al. (2024)	Clay soil in a long-term experiment on durum wheat under minimum tillage and no tillage	Rings of 8.5 cm in diameter inserted 1 cm into the soil to perform beerkan runs. Five sampling dates during a crop cycle. Sampling in 5-8 replicates on plots differing by soil management	Field-saturated soil hydraulic conductivity calculated with various methods	Tukey Honestly Significant Difference test for checking temporal variability. Two-tailed t test for establishing management effects
Talukder et al. (2024)	Testing temporal changes of soil hydraulic properties induced by surface crust during high-frequency irrigation in a Spanish silt-loam soil	Rings of 135 or 150 mm diameter inserted nearly 1 cm into the soil. Total of 180 beerkan infiltration runs at five dates in nearly one year. BEST method of analysis of the infiltration data	Soil hydraulic conductivity, sorptivity, mean pore size, number of effective pores per unit area	Analysis of variance to test treatments and interactions effects. When the effects of treatments or interactions were significant, comparison of means by t tests