

Effect of a Heavy Rainstorm on the Surface Hydrodynamic Properties of a Sandy-Loam Soil

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Abstract: Changes in surface-soil hydrodynamic properties associated with torrential natural rainstorms are largely unknown. This investigation aimed at verifying if the surface hydrodynamic properties of a sandy-loam soil varied due to the heavy rainfall event (130 mm in nearly three hours) that occurred in the summer of 2020 at Palermo (Italy) and also to establish if soil recovery processes occurred soon after the event. The soil of an orchard was sampled immediately before the rainstorm and a few days and 1.5 months later. The rainstorm determined a moderate decrease (by 1.8 times) of the saturated soil hydraulic conductivity, K_s , and an increase of its relative variability. In the subsequent weeks, the lowest K_s values detected soon after rainfall tended to disappear but the soil remained moderately less conductive (by 1.4 times) than before rainfall. Wetting and subsequent drying did not influence the means of macroscopic capillary length, λ_c , characteristic microscopic pore radius, λ_m , and depth of the wetting front, d_{wf} , but reduced relative variability of these parameters. Therefore, this investigation confirmed that K_s is a sentinel soil property. It also suggested that a torrential rainstorm can have no more than a moderate impact on the surface-soil hydrodynamic properties. Additional investigations are necessary to (1) verify if the canopy should have a key role on the stability of the soil properties in meteorologically critical conditions; (2) determine if a link between natural and soil-perturbing artificial events can be established to investigate the short-term dynamics of the surface soil properties more easily; and (3) test the hypothesis that the greater the disturbance the faster the onset of reorganization processes. DOI: 10.1061/(ASCE)HE.1943-5584.0002179. © 2022 American Society of Civil Engineers.

Introduction

Temporal variability of soil hydrodynamic properties can be noticeable since soil pore characteristics change with different temporally variable factors such as land use, tillage practices and meteorological conditions (Jarvis et al. 2013; Logsdon and Jaynes 1996). Temporal changes in soil hydrodynamic parameters should be taken into account to accurately simulate soil hydrological processes (Mubarak et al. 2009).

Usually, temporal variability of soil properties is determined by performing a limited number of sampling campaigns over a monitoring period such as one or several seasons (Bagarello and Sgroi 2007; Das Gupta et al. 2006; Messing and Jarvis 1990). The results obtained in a certain date are then considered representative for a time period with a presumably similar soil status. In the Mediterranean environment, for example, the rather long duration of the hot and dry season, lasting approximately from June to September, can suggest that a single sampling campaign performed in summer is adequate to characterize dry soil.

However, heavy and isolated rainstorms can occur in this season. This circumstance raises some doubt about the possibility to perform a single campaign in summer even if the soil reaches the

preevent water content rather soon since the environmental conditions favor a rapid drying after rainfall. A reason of perplexity is that slaking phenomena can be appreciable when the soil is nearly dry (Martínez-Mena et al. 1998). Therefore, a heavy rainfall event occurring in summer could significantly alter the surface-soil characteristics. A contrasting information can be found with reference to the rate of soil structure reorganization. For example, Bagarello et al. (2020) reported that this reorganization could start a few days after disturbance, at least in certain circumstances. An isolated event occurring in summer could perhaps be considered negligible in the perspective to capture the temporal behavior of the soil hydrodynamic properties because an altered soil quickly recovers its original features. However, the majority of the investigations suggests that, in reality, soil structure recovery is generally a slow process (Drewry 2006; Fohrer et al. 1999; Lozano-Baez et al. 2019; Morin and Benyamini 1977). Therefore, it can also be speculated that a heavy rainfall appreciably modifies the soil for a longer time than that strictly necessary for returning to a nearly dry condition.

Availability of soil data collected both before and after an isolated rainfall event allows to improve our knowledge of the soil dynamics over short periods but, unfortunately, it is not common that a soil is sampled shortly before the occurrence of a heavy rainfall event. Most of the available information at this purpose was collected with rainfall simulators (Ndiaye et al. 2005; Somaratne and Smettem 1993).

Soil hydrodynamic properties should be determined directly in the field to minimize disturbance of the porous medium due to sampling and also to maintain the functional connection of the sampled soil volume with the surrounding soil. The Beerkan Estimation of Soil Transfer parameters (BEST) methodology (Lassabatere et al. 2006) appears appropriate to determine these parameters in the field since BEST is theoretically robust and practically simple. Moreover, the method can be applied in different circumstances due to the availability of different data analysis algorithms (Bagarello et al. 2014; Lassabatere et al. 2006; Yilmaz et al. 2010). BEST appears

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usable to verify the effect of a rainfall event on the soil's hydrodynamic response because it was already applied in temporal variability investigations (Mubarak et al. 2009) and also because the experiment, using small water volumes and small ring insertion depths, should not induce appreciable soil structure changes that make data interpretation uncertain. The BEST-steady algorithm is particularly attractive from a practical point of view since it is the only algorithm also usable when the experimental information is incomplete (Bagarello and David 2020).

A sampling campaign was performed on a dry sandy-loam soil immediately before a torrential rainfall event in the frame of another experiment (Bagarello et al. 2021). This favorable condition triggered the opportunity to plan the present investigation to determine if the surface hydrodynamic properties of this soil changed as a consequence of the heavy rainstorm that occurred in summer and also to establish if soil recovery processes were detectable soon after the soil-perturbing event.

Theory

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

$$K_s = \frac{Ci_s}{Ab_s + C} \quad (1)$$

where $A(L^{-1})$ and C = constants that are defined for the specific case of the Brooks and Corey (1964) hydraulic conductivity function as (Lassabatere et al. 2006)

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

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

where r (L) = ring radius; θ_s (L^3/L^3) and θ_i (L^3/L^3) = saturated and the initial volumetric soil water content, respectively; β and γ = infiltration constants that are commonly set at 0.6 and 0.75, respectively; for $\theta_i < 0.25\theta_s$, and η = shape parameter of the hydraulic conductivity function by Brooks and Corey (1964) which, in BEST, is estimated using soil textural and dry bulk density data (Lassabatere et al. 2006; Minasny and McBratney 2007).

According to Di Prima et al. (2020), an estimate of the macroscopic capillary length, λ_c (L), can be obtained with a Beerkan infiltration experiment by the following relationship:

$$\lambda_c = 0.861 \frac{b_s}{(\theta_s - \theta_i)} \quad (3)$$

The characteristic microscopic pore radius, λ_m (L), of the soil can then be obtained as (White and Sully 1987)

$$\lambda_m = \frac{\sigma}{\rho g \lambda_c} \quad (4)$$

where σ (M/T²) = surface tension of water; ρ (M/L³) = density of water; and g (L/T²) = acceleration due to gravity. Taking the properties of pure water at 20°C as appropriate, Eq. (4) yields $\lambda_m \approx 7.4/\lambda_c$, where λ_m and λ_c are expressed in mm.

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

$$d_{wf} = \frac{I_{tot}}{f(\theta_s - \theta_i)} \quad (5a)$$

with f given by

$$f = \frac{H + \lambda_c}{d + \frac{\lambda_c}{2}} + 1 \quad (5b)$$

where I_{tot} (L) = total infiltration at the end of the run; H (L) = depth of ponding on the infiltration surface; and d (L) = ring insertion depth into the soil. Both H and d are assumed equal to zero in the BEST equations (Haverkamp et al. 1994; Lassabatere et al. 2006).

In practice, calculation of λ_c , λ_m , and d_{wf} only requires determining, for an infiltration run, b_s and $\theta_s - \theta_i$. The i_s term is also required to calculate K_s . As shown by Bagarello and David (2020), b_s can be obtained from I_{tot} , i_s , and total duration of the run, d_{tot} . Consequently, a limited and simple approach to collect experimental information (I_{tot} , i_s , d_{tot} , and $\theta_s - \theta_i$) is enough to characterize the maximum rate of water flow due solely to gravity in a completely saturated soil (K_s , Touma et al. 2007), the relative importance of capillary over gravity forces during water movement in unsaturated soil or the mean height of capillary rise above a water table (λ_c , Raats and Gardner 1971; White and Sully 1987), the effective equivalent mean radius of the pores that participate in the infiltration process (λ_m , Reynolds et al. 1995; Iovino et al. 2016), and the vertical size of the wetted soil layer at the end of the run (d_{wf} , Wu et al. 1997). In other terms, a very simple experimental protocol provides much information about capillarity and gravity effects on soil water movement.

Materials and Methods

Field Site

The field experiment was carried out at the so-called "Aranceto" site, established at the Department of Agricultural, Food, and Forest Sciences of Palermo University in Italy (38°06'24"N, 13°21'06"E). An approximately 150 m² flat area of a citrus orchard, with trees spaced 4 m × 4 m apart, was selected. Disturbed soil samples were collected from the upper 0–0.10, 0.10–0.20, and 0.20–0.30 m of the profile in June 2020 to determine the soil particle size distribution using conventional methods following H₂O₂ pretreatment to eliminate organic matter and clay deflocculation with sodium hexametaphosphate and mechanical agitation (Gee and Bauder 1986). The soil texture of the upper 0.3 m of the profile was sandy-loam according to the USDA classification (clay = 14.4%–15.5%, depending on the sampling depth; silt = 29.6%–30.2%; sand = 54.9%–55.4%; Bagarello et al. 2021). The mean organic carbon content, OC (%), of the upper few centimeters of the soil, determined by Auteri et al. (2020) with the Walkley-Black method, was equal to 3.1%. The structural stability index by Pieri (1992), which is related to the resilience of the soil structure, was equal to 11.9%, which denotes a generally stable structure (Reynolds et al. 2009).

Experiments

Field infiltration experiments of the Beerkan type (Lassabatere et al. 2006) were carried out during the months of June to August 2020. The main features of these experiments were (1) insertion of

0.08-m-diameter rings to a depth of 0.01 m on the soil surface; (2) filling plastic glasses with 57 mL of water for each glass; and (3) 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 and the elapsed time during complete infiltration was measured. An identical amount of water was subsequently poured into the ring, and the time needed for this water to infiltrate was logged. Although 8–15 water volumes should generally be enough to collect nearly steady infiltration data (Lassabatere et al. 2006), 20 water volumes were used at a sampling point in this investigation to possibly improve estimation of the steady-state infiltration rate (Lassabatere et al. 2019).

A total of three infiltration data sets were developed by performing, for each data set, 16 runs at randomly chosen points of the field site. In particular, the first sampling campaign was carried out in ten days from June 29 to July 14 as part of another experiment (Bagarello et al. 2021). On the afternoon of July 15, the city of Palermo was hit by a torrential rainfall event. In particular, 130 mm fell in some zones of the city in three hours [Fig. 1(a)]. A rain gauge located a few dozen meters from the field site recorded 10-min rainfall intensities exceeding 50 mm/h two times during the event, although the cumulative rainfall was 56.6 mm [Fig. 1(b)]. Despite the canopy by the orchard protecting the soil surface to some degree, the rainfall event was so intense that signs of soil splash phenomena were perceived after the event [Fig. 1(c)]. This circumstance, in addition to confirming that raindrop splash can have a dominant effect on short-time erosion behavior in situations where the raindrop energy is relatively high (Jomaa et al. 2010), suggested that the surface-soil layer sampled immediately before the rainstorm could have experienced a sudden change in its hydrodynamic properties. Consequently, the soil was sampled again on July 20 and 21 (second campaign). The time lapse allowed to establish initially rather dry soil conditions as requested to apply any BEST method of data analysis (Lassabatere et al. 2006). The third campaign was performed on August 25 and 27, in an attempt to perceive possible, relatively short-term, soil recovery processes. No rainfall occurred between these last two sampling dates.

Soil was repeatedly sampled during the experimental period to determine the dry soil bulk density, ρ_b (g/cm³), and the volumetric soil water content at the time of the infiltration runs, θ_i (m³/m³). On a given day, undisturbed soil cores (0.05 m in height by 0.05 m in diameter) were collected at the 0 to 0.05 m and 0.05 to 0.10 m depths at three randomly chosen sampling points. These six cores were used to determine ρ_b and the gravimetric soil water content, w_i (g/g), and hence θ_i , in the laboratory. The data were averaged to obtain, for a given day, a ρ_b and a θ_i value of the upper 0.10 m of the soil. The saturated soil water content, θ_s (m³/m³), necessary to apply BEST, was estimated from ρ_b assuming that θ_s coincided with the soil porosity (Mubarak et al. 2009).

Calculations and Data Analysis

Taking into account that the last part of all infiltration processes appeared steady, as denoted by a nearly linear relationship between I and t , i_s and b_s were estimated with linear regression analysis procedures, considering the last three data points in most cases. An estimate of K_s , λ_c , λ_m , and d_{fw} was obtained for each run by Eqs. (1)–(5), respectively.

The Lilliefors (1967) test was applied at $P = 0.05$ to test the normal distribution hypothesis of both the untransformed (NO) and the ln-transformed (LNO) K_s , λ_c , λ_m , and d_{fw} values estimated from each infiltration data set.

Several pairwise comparisons were then established between two data sets by performing F and two-tailed t -tests at $P = 0.05$. A pairwise comparison was preferred to other alternative statistical tests since establishing, for example, the immediate effect of the rainfall event on the soil hydrodynamic parameters does not depend on what happened later. Unpaired t -tests were performed since the sampling points changed between two campaigns.

Results

The soil water content was higher and the dry soil bulk density was smaller in the second sampling campaign (July), that is a few days after heavy rainfall, than in the first campaign (June through July; Table 1). Subsequently (August), both θ_i and ρ_b returned to the before rainfall values. Therefore, the dry soil was significantly more compact than the relatively wet soil. Even in the wettest conditions, the ratio between θ_i and θ_s , equal at the most to 0.262, was very close to the threshold value discriminating between possible and nonrecommended application of the BEST methodology ($\theta_i/\theta_s = 0.25$; Lassabatere et al. 2006). Therefore, there was no theoretical impediment to the use of BEST for calculation of soil hydrodynamic parameters.

According to the Lilliefors (1967) test (Table 2), the LNO distribution hypothesis of a variable (K_s , λ_c , λ_m , d_{fw}) for a given sampling date was never rejected and it performed always better than the NO distribution hypothesis. Therefore, geometric means and the associated coefficients of variation, CVs (Lee et al. 1985), were used to summarize the K_s , λ_c , λ_m , and d_{fw} values. In addition, the statistical tests were performed on the ln-transformed data.

The saturated soil hydraulic conductivity was significantly lower in the second sampling campaign than the first campaign and the two mean values differed by 1.8 times (Table 3). Afterward, K_s remained statistically stable given that it increased by a nonsignificant factor of 1.2 from the second to the third campaigns. Moreover, the K_s values measured in the third campaign were significantly smaller than those measured in the first campaign, with a difference between these two sampling campaigns by a factor of 1.4. Therefore, the rainstorm determined a significant decrease of K_s . Subsequently, there was some weak sign of a recovery of this hydrodynamic parameter but this sign was not statistically relevant. The relative variability of K_s was highest immediately after rainfall and lowest in the other two campaigns, in which the CV values were similar. The increase of the relative variability of K_s immediately after rainfall was associated with a decrease of both the highest and the lowest measured values (Fig. 2). The sampling performed 1.5 months later showed that the highest K_s values continued to decrease but particularly low K_s values tended to disappear. More precisely, eight of the 16 values of K_s measured in the second campaign, representing half of the collected data, were smaller than the lowest value obtained in the first campaign (139 mm/h) since they were equal to 79–117 mm/h. At the end of the sampling period (August), only two K_s values (112–114 mm/h) were smaller than the lowest value measured initially (June through July).

With reference to λ_c , λ_m , and d_{fw} , no temporal variability was detected among the three sampling campaigns but, even for these variables, the highest CVs were noticed soon after the heavy rainfall event (Table 3). Moreover, the CV values were appreciably lower in August than in June–July. Detecting a temporal variability for K_s but not for λ_c and λ_m was consistent with previous investigations suggesting that the former parameter should be considered a sentinel soil property, since it is particularly able to signal the soil

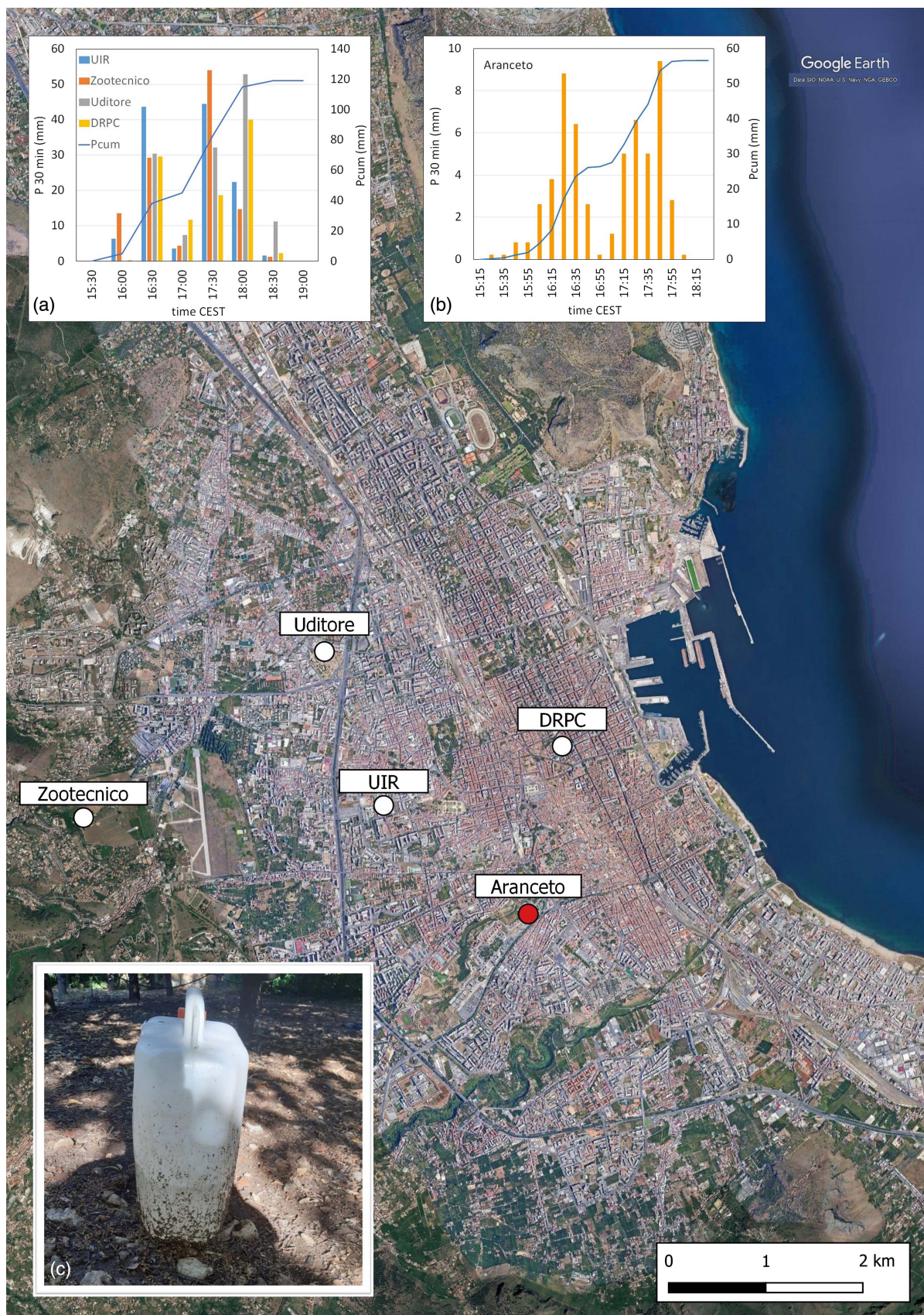


Fig. 1. Locations of the sampling site and rain gauges in Palermo, Italy: (a) characteristics of the rainfall event occurred on July 15, 2020; (b) 10-min rainfall intensities recorded near the sampling site; and (c) evidence of splash erosion phenomena. (Satellite image @ Google, Data SIO, NOAA, US Navy, NGA, GEBCO.)

Table 1. Dry soil bulk density (ρ_b), volumetric soil water content at the beginning of a sampling day (θ_i), and ratio between θ_i and the volumetric saturated soil water content (θ_s) for the three sampling campaigns

Sampling campaign	Number of sampling days	ρ_b (g/cm ³)		θ_i (m ³ /m ³)		θ_i/θ_s	
		Mean	CV (%)	Mean	CV (%)	Mean	CV (%)
June–July 2020	10	1.156(a)c	2.7	0.068(a)c	26.5	0.120(a)c	27.0
July 2020	2	1.031(a)(b)	2.4	0.159(a)(b)	2.3	0.260(a)(b)	0.8
August 2020	2	1.191(b)c	2.1	0.066(b)c	0.5	0.119(b)c	1.1

Note: For a given sampling day, a value of ρ_b and a value of θ_i were obtained by averaging six individual determinations of ρ_b and θ_i , respectively. The means of a variable followed by the same lower case letter enclosed in parenthesis were significantly different according to a two-tailed t test at $P = 0.05$. The means followed by the same lower case letter not enclosed in parenthesis were not significantly different.

Table 2. Results of the Lillefors (1967) test for each developed data set

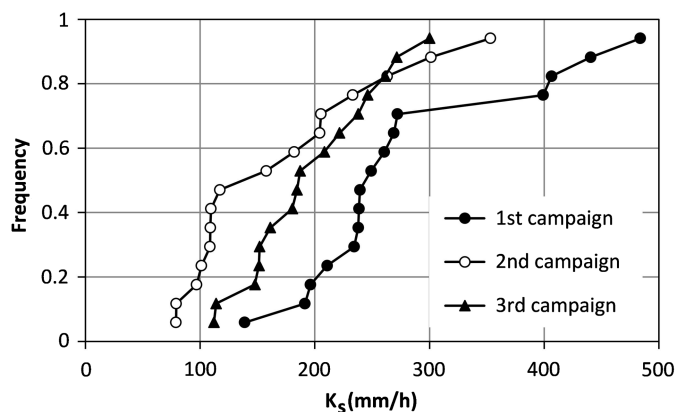
Variable	Sampling campaign	Dmax		Sampling campaign
		NO	LNO	
K_s	First	0.235	0.173	LNO
	Second	0.200	0.171	
	Third	0.091	0.078	
λ_c	First	0.150	0.146	LNO
	Second	0.130	0.117	
	Third	0.108	0.107	
λ_m	First	0.167	0.146	LNO
	Second	0.220	0.117	
	Third	0.121	0.107	
d_{wf}	First	0.193	0.178	LNO
	Second	0.135	0.104	
	Third	0.125	0.104	

Note: Sample size, $N = 16$ for each data set; K_s = saturated soil hydraulic conductivity; λ_c = macroscopic capillary length; λ_m = characteristic microscopic pore radius; d_{wf} = depth of the wetting front at the end of the run; D_{max} = largest difference between the empirical cumulative distribution function and the corresponding theoretical function; D_{crit} = critical value of D_{max} ($= 0.213$); NO = normal; LNO = ln-normal; first campaign: June–July 2020; second campaign: July 2020; and third campaign: August 2020.

Table 3. Summary statistics of the K_s , λ_c , λ_m , and d_{wf} values obtained by BEST-steady in the sampling campaigns preceding (first campaign) and following (second and third campaigns) the heavy rainfall event

Variable	Sampling campaign	Mean	CV (%)
K_s (mm/h)	First	264.5 (a)(c)	34.5
	Second	151.0 (a)(b)	51.2
	Third	188.2 b(c)	30.4
λ_c (mm)	First	77.8 ac	44.5
	Second	75.5 ab	66.3
	Third	83.5 bc	23.2
λ_m (mm)	First	0.095 ac	44.5
	Second	0.098 ab	66.3
	Third	0.089 bc	23.2
d_{wf} (mm)	First	125.7 ac	28.2
	Second	138.0 ab	41.7
	Third	122.6 bc	16.8

Note: First campaign = June 29–July 14, 2020; second campaign = July 20–21, 2020; third campaign = August 25–27, 2020; K_s = saturated soil hydraulic conductivity; λ_c = macroscopic capillary length; λ_m = characteristic microscopic pore radius; d_{wf} = depth of the wetting front at the end of the run; CV = coefficient of variation; sample size, $N = 16$ for each data set. For a given variable, the means followed by the same lower case letter not enclosed in parenthesis were not significantly different according to a two-tailed paired t-test at $P = 0.05$. The means followed by the same lower case letter enclosed in parenthesis were significantly different.

**Fig. 2.** Cumulative empirical frequency distribution of the saturated soil hydraulic conductivity, K_s , values obtained on three sampling campaigns (first campaign: June–July 2020; second campaign: July 2020; third campaign: August 2020).

dynamics over short time periods (Auteri et al. 2020; Bagarello et al. 2020; Somaratne and Smettem 1993).

Discussion

Soil Parameters

The decrease of K_s between the first two sampling dates suggested that rainfall altered the soil structure since a constant K_s value was expected for a stable soil. However, the collected information did not explain what processes specifically determined the decrease of K_s . In particular, soil swelling induced by the wetting process and rainfall mechanical impact altering the upper soil layer could be considered the two main mechanisms responsible for soil structural degradation. The former appeared plausible since the antecedent soil water content was higher before the second campaign as compared with the first one (Table 1) and moderate swelling phenomena in wet conditions were signaled for the same soil sampled in this investigation (Bagarello and Sgroi 2007). However, the first and the third (August) campaigns were carried out under similar antecedent wetness conditions ($\theta_i = 0.07$ m³/m³) but higher K_s values were obtained for the first experiment than for the latter one (Table 3). Therefore, swelling did not explain the differences detected after rainfall, and some additional mechanical alteration of the exposed soil surface due to rainfall should be invoked.

Taking into account that K_s values differing by two or three times could be considered relatively similar, at least in some circumstances (Elrick and Reynolds 1992), the impact of rainfall

on K_s was moderate. Two possible reasons of a moderate impact were that (1) the soil surface was shielded to some degree by the canopy, and (2) the soil structure was stable (Pieri 1992). A moderate effect of rather heavy natural rainstorms on soil hydrodynamic properties was recently reported by Alagna et al. (2019) for another Mediterranean loam soil. Therefore, soil hydrodynamic properties can decrease significantly but not substantially as a consequence of a heavy rainfall event. More data should be collected in the future to support or refuse this suggestion.

The rainstorm determined an increase of the relative variability of K_s (Table 3). A possible reason was that rainfall impact effects were spatially heterogeneous due to the presence of the orchard. Soil structure alteration was more noticeable when the soil surface was directly exposed to rainfall and less appreciable when the canopy acted as a shield, protecting the soil to some extent.

Soil drying and, perhaps, some soil structure reorganization occurred between the second and the third sampling campaigns (Fohrer et al. 1999). This last process was not particularly relevant given the statistical similarity of the K_s values obtained in the two sampling dates after the rainfall event. At the same field site of this investigation, signs of a soil structure reorganization were perceived soon after a soil disturbing single-ring infiltration experiment that induced a decrease of K_s by more than an order of magnitude as compared with the unaltered soil (Bagarello et al. 2020). Establishing a link between natural (this investigation) and artificial (previous experiment) soil disturbance will require additional investigations. In particular, a hypothesis to be tested should be that the greater the disturbance the faster the onset of reorganization processes.

The relative variability of K_s decreased 1.5 months after rainfall, approaching that observed before rainfall. According to Warrick (1998), the soil was moderately variable with respect to K_s under dry conditions but it became highly variable soon after rainfall. The increase of relative variability was not temporally persistent and there was a recovery of the antecedent CV value as a consequence of soil drying and perhaps some soil structure reorganization. The recovery of K_s was incomplete in the sense that low K_s values disappeared but high K_s value did not appear again (Fig. 2). Macropores were obstructed to some degree as a consequence of soil splash phenomena induced by rainfall impact and obstruction persisted during the sampling period. Small pores apparently reorganized faster than large pores.

On average, the relative importance of capillarity over gravity forces (λ_c) and the effective equivalent mean radius of the pores (λ_m) did not change as a consequence of rainfall and in the subsequent drying phase (Table 3). Moreover, the soil had a moderate capillarity during the whole sampling period (Di Prima et al. 2020). However, an effect of the rainfall event and the subsequent drying phase was perceivable even with reference to λ_c and λ_m . In particular, wetting induced detection of highly variable λ_c and λ_m values that were only moderately variable in the other sampling dates (Warrick 1998). Moreover, the subsequent drying phase had an overall homogenizing effect since appreciably smaller CV values of both characteristic lengths were noticed in the third campaign than in the first campaign. According to Mubarak et al. (2009), a change in λ_c and λ_m indicates a change in the structure of the fine soil fraction. Following this suggestion, fine soil structure became more homogeneous as a consequence of wetting and drying but it remained unchanged in its mean response.

The characteristic microscopic pore radius, λ_m , of the soil is directly related to the ratio between K_s and the matric flux potential, ϕ_m (L^2/T), defined as the integral of the soil hydraulic conductivity, K (L/T), function from the background pore water pressure head in the soil at the time of infiltration (corresponding to θ_i) to 0 (Reynolds et al. 1995). This integral decreases as θ_i increases and K

decreases. Therefore, in a stable soil, the expectation was to perceive signs of an increase of λ_m from the first to the second sampling campaign due to the higher θ_i value in the latter circumstance (Table 1). As shown in this investigation, a stable λ_m value can signal changes in soil structure. In particular, this result occurs if K_s decreases as a consequence of soil disturbance but K_s/ϕ_m (i.e., λ_c) does not change.

The depth of wetting front calculations supported the suggestion of an overall limited variation of the soil characteristics during the experimental period since d_{wf} did not change significantly with the sampling date (Table 3). A practical implication of this last result was that a single sampling campaign was enough to predict d_{wf} during this period even if a heavy rainfall event occurred and the antecedent soil water content changed a little.

Hydrologic Implications of Soil Characterization

The means of K_s were high regardless of the sampling date since they were not smaller than 151 mm/h (Table 3). Moreover, the lowest individual K_s value, equal to 79 mm/h, was measured immediately after the heavy rainstorm and it was greater than the highest 10-min rainfall intensity during the event, equal to 56.4 mm/h. The data indicated the absence of any rainfall excess on the sampled flat area or, extending the reasoning to a sloped area, the lack of any surface runoff formation. This result reinforced the suggestion by Dohnal et al. (2016) that, although the ponded infiltration experiment is a well-established method for determining K_s , ponded formation represents an extreme case which is rarely seen in well permeable soils under natural field conditions.

Attempting to interpret these results in a hydrological perspective, the data obtained at the same field site by Auteri et al. (2020) and Bagarello and David (2020) were also considered since these authors used identical infiltration experiment (Beerkan run), data analysis algorithm (BEST-steady), ring diameter and insertion depth (0.08 and 0.01 m, respectively) and applied water volume with each pouring (57 mL). Auteri et al. (2020) obtained a mean K_s value of 6.3 mm/h by applying 30 water volumes ($I_{tot} = 340.2$ mm) from a height of 1.5 m. For this infiltration run, the calculated gravitational potential energy was $E_p = 5004.2$ J/m². A mean K_s value of nearly 2.0 mm/h was obtained by Bagarello and David (2020) using height of water pouring similar to this investigation (nearly 0.03 m), but performing long infiltration runs, that is by applying on average 117 water volumes, yielding $I_{tot} = 1,322$ mm and $E_p = 390.3$ J/m². For the heavy rainstorm of July 15, 2020, an E_p value of 1,372 J/m² was estimated (Brown and Foster 1987) whereas the dissipated energy with the Beerkan infiltration experiment was of 67 J/m². For $E_p = 1,372 + 67 = 1,438$ J/m², the K_s vs. E_p relationship developed by Auteri et al. (2020) for the Aranceto field site yielded a K_s value of 95.2 mm/h, that is 37% smaller than the measured value after rainfall (Table 3). This difference can be considered small in many circumstances (Elrick and Reynolds 1992) and it could be attributed to the presence of the canopy. As matter of fact, the actual energy dissipated at the soil surface is likely lower thus resulting in higher measured K_s values.

In other words, a substantial decrease of K_s , favoring rainfall excess or surface runoff formation, unlikely occurs as a consequence of a rainfall event of 56.6 mm having a mean intensity of 20 mm/h and an estimated energy above the canopy of nearly 1,400 J/m². Previous investigations have shown that a larger decrease of K_s may occur at the field site but it requires more applied water and more dissipated energy at the soil surface. Both factors are expected to weaken the particle bonds (Le Bissonnais 1996) and

therefore they can promote an alteration of the sampled soil volume. For example, in a laboratory flume experiment, detecting an appreciable compaction/consolidation of the upper 1–2 cm of soil required performing a simulated rainfall experiment with an intensity of 60 mm/h for 160 min falling on an initially disaggregated soil (Jomaa et al. 2010).

An implication of this investigation is that performing a single-ring infiltrometer run with standard methodologies, including for example the use of small water volumes, could fail to obtain a soil hydrodynamic characterization relevant for hydrological modeling. A means to take a step forward in this direction could be performing Beerkan infiltration runs before and after simulating rainfall events of known energy characteristics, under the presumption that natural and artificial rainfall events could have similar hydrologic effects. This methodology makes the experiment more complicated but the use of simple devices, such as the portable rainfall simulator by Kamphorst (1987), could limit the increase in the experiment complexity. Maintaining the experiment as simple as possible is particularly desirable in investigations conducted in large and remote areas, since in this case transporting the equipment and stocking up on water could be very complicated.

Finally, the circumstance that the soil tended to naturally reorganize by itself a few weeks after the heavy rainstorm suggested that runoff occurrence is more probable soon after an event appreciably altering the soil surface. In other terms, it can be believed that a given event will induce surface runoff if it occurs soon after a previous event that has altered appreciably the soil but not, or to a lesser degree, as the time interval between these two events increases.

Conclusions

This investigation improved our knowledge on the soil's dynamic nature, since it established how the hydrodynamic properties at the surface of an initially dry sandy-loam soil changed as a consequence of a heavy natural rainstorm and the subsequent drying phase.

The rainstorm determined a moderate decrease of the saturated soil hydraulic conductivity, K_s , and an increase of its relative variability. In the few weeks following rainfall, soil dried and the particularly low K_s values detected soon after the rainstorm tended to disappear. However, this disappearance was not enough for a complete restoration of the preraffail K_s value since 1.5 months after the rainstorm the soil remained moderately less conductive than before rainfall. On average, wetting and subsequent drying were statistically irrelevant with respect to the macroscopic capillary length, λ_c , the characteristic microscopic pore radius, λ_m , and the depth of the wetting front at the end of the run, d_{wf} , but the soil became more homogeneous with reference to these parameters after the wetting and drying cycle.

Therefore, this investigation confirmed that K_s is a sentinel soil property, particularly able to signal the soil dynamics over short time periods and it also suggested that the fine soil structure became more homogeneous as a consequence of wetting and drying. More in general, it appears plausible to suggest that an increase in the relative variability of the soil hydrodynamic parameters induced by a soil-perturbing, wetting event can be perceived but it should not be temporally persistent.

Performing sampling campaigns both in the immediacy of the rainfall event and during the subsequent drying phase is recommended to understand the physical factors that determine time variations of soil hydrodynamic properties.

Additional investigations should be carried out to establish the link between natural and artificial events that can be expected to alter the soil surface. In particular, these comparisons could allow to establish if, as suspected, the greater the disturbance the faster the onset of reorganization processes. The Beerkan methodology can be adapted to also perform infiltration experiments intentionally inducing some soil disturbance at the infiltration surface. Finally, this experiment was carried out in a soil protected to some degree by the canopy of an orchard. In the future, it would be advisable, if possible, to collect similar data on nonprotected soil surfaces to better capture the rainfall effects on the soil hydrodynamic parameters.

Data Availability Statement

All data that support the findings of this study are available from the corresponding author upon reasonable request.

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