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ORIGINAL ARTICLE

Comparison of the single-ring pressure infiltrometer and SATURO methods for determination of field-saturated soil hydraulic conductivity

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Abstract

Both the classical pressure infiltrometer (PI) method and the recently introduced SATURO device can be used to determine field-saturated soil hydraulic conductivity (K_{fs}) through a single-ring, steady-state experiment with two pressure heads. The introduction of this automated device raised questions about the validity criteria for infiltration data, its performance compared to the classical method, and the impact of a quick literature estimate of the α^* (sorptive number) parameter on K_{fs} calculations. For two sandy-loam soils and a clay soil, the SATURO criterion, denoted as Criterion 1, differed from the classical, more stringent Criterion 2 in terms of valid measurements (success rates of 47%–100% vs. 13%–87%, respectively) but not greatly in summary statistics (${K_{fs}}^{TPD}$ [where TPD represents two-ponding-depth] means equal to 65–527 mm h^{-1} in the former case and 70–300 mm h^{-1} in the latter one). The PI and SATURO yielded similar mean ${K_{fs}}^{E}$ (E stands for experimental) values (81–345 vs. 78–192 mm h^{-1}, respectively), but SATURO tended to give relatively smaller individual values. Using the first approximation value of α^* instead of the experimental value led to differences in K_{fs} by 1.5 times at most, depending on the site. The classical data validity criterion should be applied to exclude physically impossible results. In practical use, both methods with similar run durations and water volumes yield comparable K_{fs} values. The first approximation value of α^* could replace the experimental value in several cases. SATURO is a promising alternative to the PI for determining field-saturated soil hydraulic conductivity via single-ring, steady-state

Abbreviations: CV, coefficient of variation; K_{fs}, field-saturated soil hydraulic conductivity; OPD, one-ponding-depth; PI, pressure infiltrometer; TPD, two-ponding-depth.

infiltration. There is room for improving its performance and also for simplifying its application in the field.

Plain Language Summary

Field-saturated soil hydraulic conductivity (K_{fs}) is a key parameter that determines how quickly water moves through soil, influencing processes like infiltration, drainage, and erosion. There are several methods to measure K_{fs}, including the classical pressure infiltrometer (PI) and a new automated SATURO device. This study compares the effectiveness of the classical PI method with the new SATURO method for determining K_{fs} at three different field sites with varying soil types. The aim is to assess which method provides more reliable data and to understand how differences in data validity criteria affect the results. SATURO offers an automated and simpler approach compared to the PI method but tends to provide slightly lower K_{fs} values. Overall, both methods yield similar results, although SATURO shows greater variability in the data. The classical PI method has a higher success rate in tests compared to SATURO.

1 INTRODUCTION

Saturated soil hydraulic conductivity governs water movement through the soil, influencing various processes such as infiltration, runoff, drainage, and erosion (Hillel, 2003). Accurate measurement of this property is essential for effective soil and water management in both agricultural and environmental contexts. Under natural conditions, air entrapment could yield field-saturated soil hydraulic conductivity (K_{fs}) values lower than those corresponding to full saturation that can only be achieved under laboratory conditions (Basile et al., 2003, 2006; Reynolds & Elrick, 2002).

Among the various field methods for determining K_{fs}, the steady, constant-head infiltration technique using a single ring is widely adopted, largely due to the physically based analysis of the process by Reynolds and Elrick (1990). This analysis considers the effects of soil capillarity, ponding depth, ring radius, and ring insertion depth on the flow process. It provides the basis for calculating, in addition to K_{fs}, the matric flux potential, ϕ_m (Gardner, 1958), and the α^* (sorptive number) parameter that represents the inverse of the macroscopic capillary length, λ_c (White & Sully, 1987). Practical reasons why single-ring pressure infiltrometer (PI) experiments have received much interest in the literature (e.g., Bagarello et al., 2000; Ciollaro & Lamaddalena, 1998; Gómez et al., 2005; Mertens et al., 2002; Reynolds et al., 2000; Vauclin et al., 1994, among others) include (i) the higher reliability of steady-state infiltration data compared to the transient ones (Yilmaz et al., 2024), and (ii) the availability of various approaches for conducting a PI experiment and analysing the data, which gives the methodology a certain flexibility. The most applied steady-state approaches are the one-ponding-depth (OPD) approach that uses a single depth of ponding, H, on the infiltration surface and requires an a priori estimate of α^* for determining K_{fs}, and the two-ponding-depth (TPD) approach that uses two H levels to simultaneously estimate K_{fs}, ϕ_m, and α^*. Three or more H levels can also be used to simultaneously estimate all mentioned parameters (multiple-ponding-depth [MPD] approach).

The persistent interest in methods for determining K_{fs} using single-ring ponded infiltration experiments and steady-state data analysis procedures is evident from the recent development of SATURO (METER Group, Inc.). This device, constituting an automated version of the PI method, features specific peculiarities in its methodological approach. In particular, the run with SATURO includes an initial soak time, aimed to reach soil saturation, before beginning the so-called pressure cycles. SATURO automatically calculates K_{fs} by the TPD equation, in accordance with Reynolds and Elrick (1990).

The scientific community is starting to show some interest in SATURO. For example, Ravi et al. (2017) performed SATURO measurements to study ecohydrological processes associated with the so-called fairy circles in the Namib Desert. Zhang et al. (2019) used the device in a living filter wastewater tertiary treatment system. In a review paper on the determination of K_{fs} in urban green infrastructures, Ebrahimian et al. (2020) included SATURO as one of the usable methods, together with the single- and double-ring infiltrometers and the modified Philip–Dunne method. Saha et al. (2024) used SATURO in a silt to silty-clay-loam soil to determine soil use and management effects on K_{fs}. More recently, Welker et al. (2025) applied SATURO in an investigation on K_{fs} in rain gardens, and Garg et al. (2025) used the device to compare the effects of conventional and conservative management on the field-saturated hydraulic conductivity of the surface layer in two silty-loam soils. The availability of the new equipment leads to the recognition that there is the need for further investigations on soil hydrodynamic characterization using steady-state, single-ring infiltration data.

An important question to consider is the validity of the TPD calculations. With SATURO, the experiment is deemed successful if K_{fs} is positive, which happens when the steady-state infiltration rate is higher for the larger pressure head than the smaller one. However, K_{fs} could be positive but ϕ_m could be negative and α^* could assume unreliable values (Bagarello et al., 2013; Mertens et al., 2002; Reynolds & Elrick, 2002). Therefore, it seems that SATURO tends to consider K_{fs} values as valid even when they would be considered invalid according to other validity criteria. However, the extent to which these two validity criteria, positive K_{fs} values for SATURO versus positive K_{fs} and ϕ_m values along with reliable α^* values (Reynolds & Elrick, 2002), differ in their impact on creating a K_{fs} dataset for an area of interest remains unclear.

The performances of SATURO still need to be compared to those by other methods (Ebrahimian et al., 2020). As pointed out by Reynolds et al. (2000), comparing techniques for determining K_{fs} is an imprecise and perhaps even dubious enterprise due to the lack of independent data upon which evaluation and judgments can be made. However, these comparisons are important, as they provide one of the few sources of information that practitioners can draw upon to select the most appropriate K_{fs} determination methods for their specific conditions. Comparisons between SATURO and other methods are starting to appear in the literature. For example, Zhang et al. (2019) compared SATURO with the double-ring infiltrometer, and they concluded that the application procedure and settings of the new device should be optimized depending on the circumstances instead of using the default settings. The conclusion of a numerical study by Tecca et al. (2022) was that SATURO should yield estimates of K_{fs} differing by no more than nearly two times from the true value with a run of 3 h or less. In the laboratory, Naik et al. (2024) compared SATURO with the mini-disk infiltrometer, a permeameter, and a rainfall simulator for a loam and a sandy soil, and they suggested that SATURO also shows promise for spatial variability investigations at the catchment scale. Using SATURO, Atalar et al. (2025) failed to capture significant differences between covers that were instead detected with other methods such as a rainfall simulator and a steady-state simplified method based on Beerkan infiltration runs (Bagarello et al., 2017). These comparisons are overall encouraging, but they are still too few to suggest conclusions of general validity.

When the TPD approach provides an invalid result, Reynolds and Elrick (2002) suggested to apply the OPD approach separately to each head and then averaging the two resulting estimates of the soil hydrodynamic parameter of interest. In other words, the failure of a TPD run does not impede estimation of K_{fs} at a given measurement site. The suggestion by Reynolds and Elrick (2002) is therefore useful for not losing the collected experimental information. Two alternative choices can be made to calculate K_{fs}. A possibility is using the valid TPD results to determine a site-specific estimate of α^* and hence using this value for applying the OPD approach to all infiltration runs. Another possible option is to consider a literature estimate of α^* (Reynolds & Elrick, 1990). This last choice is rather common in practical applications of the single-ring PI method and of other single-ring methods to determine K_{fs} (Bagarello & Sgroi, 2004; Bagarello et al., 2014; Di Prima et al., 2018; Stewart & Abou Najm, 2018; Verbist et al., 2009, 2010). In particular, $\alpha^* = 12\ \text{m}^{-1}$ appears to be a generally usable value since it represents the first choice for most soils (Elrick & Reynolds, 1992b) and the value most frequently applicable or most appropriate (Reynolds, 2008) for agricultural soils. The use of a literature value of α^* could therefore be expected to be accurate enough for practical applications. However, according to recent investigations, this suggestion does not seem to be always valid since using either the first approximation value of α^* or a soil-dependent estimate of this parameter could induce differences in K_{fs} predictions by up to 500%–600% (Di Prima et al., 2020). The conflicting information available in the literature suggests that further comparisons are needed between K_{fs} values obtained by a literature estimate of α^* and those obtained by its experimental determination.

Core Ideas

- SATURO and pressure infiltrometer provide similar means of K_{fs} despite different data validity rates.
- Classical validity criteria are essential to exclude unrealistic K_{fs} values.
- Approximated α^* can replace measured values but may affect K_{fs} accuracy.

The general objective of this investigation was to examine factors influencing field determination of saturated soil hydraulic conductivity by steady-state, constant-head, single-ring infiltration methods. With reference to three distinct field sites, the specific objectives were to (i) evaluate the effect of the assumed validity criterion of a TPD run on K_{fs} determination with the PI and SATURO methodological approaches, (ii) establish a comparison between these two K_{fs} determination methods, and (iii) compare the K_{fs} values obtained by a literature estimate of α^* with those calculated by its experimental determination.

2 | THEORY

Both the classical PI and SATURO methods utilize the analytical expression for three-dimensional steady, ponded flow out of a ring into rigid, homogeneous, isotropic, and uniformly unsaturated soil (Reynolds & Elrick, 1990):

$$Q_s = \frac{r}{G}\left(K_{fs}H + \phi_m\right) + \pi r^2 K_{fs} \tag{1}$$

where Q_s ($L^3\,T^{-1}$) is the steady-state flow rate, r (L) is the ring radius, K_{fs} ($L\,T^{-1}$) is the field-saturated soil hydraulic conductivity, H (L) is the ponded head of water on the infiltration surface, ϕ_m ($L^2\,T^{-1}$) is the matric flux potential, and G is a dimensionless shape factor expressing the complex interactions between ring radius, depth of ring insertion, d (L), depth of ponding in the ring, soil capillarity, and gravity. In practice, an estimate of G, denoted as G_e, can be obtained from the d/r ratio by the following relationship, which is strictly valid for $0.03 \le d \le 0.05$ m, $0.05 \le r \le 0.10$ m, and $0.05 \le H \le 0.25$ m (Reynolds & Elrick, 1990):

$$G_e = 0.316\frac{d}{r} + 0.184 \tag{2}$$

According to Equation (1), steady-state flow rate out of the ring is the sum of three components, that is, flow due to the hydrostatic pressure of the established depth of water on the infiltration surface (first term on the right of the equation), flow due to the capillarity of the unsaturated soil under and adjacent to the ring (second term), and flow due to gravity (third term).

With the single-ring PI method, both K_{fs} and ϕ_m can be obtained by the TPD approach (Reynolds & Elrick, 1990), also named two-head analysis (Reynolds & Elrick, 2002). The approach requires measuring the steady-state flow rates, Q_{s1} and Q_{s2}, corresponding to two ponding depths of water, H_1 and H_2 ($H_2 > H_1$), consecutively established on the infiltrating surface without occurrence of a drainage phase in the passage from H_1 to H_2. The following relationships yield K_{fs} and ϕ_m:

$$K_{fs} = \frac{G_e}{r}\left(\frac{Q_{s2} - Q_{s1}}{H_2 - H_1}\right) \tag{3}$$

$$\phi_m = \frac{G_e}{r}\left(\frac{H_2 Q_{s1} - H_1 Q_{s2}}{H_2 - H_1} - \pi r G_e \frac{Q_{s2} - Q_{s1}}{H_2 - H_1}\right) \tag{4}$$

Simultaneous calculation of K_{fs} and ϕ_m also yields an estimate of the α^* (L^{-1}) parameter (Reynolds & Elrick, 2002):

$$\alpha^* = \frac{K_{fs}}{\phi_m} \tag{5}$$

A limitation of the TPD approach is that unrealistic or negative, and therefore invalid, values for K_{fs}, ϕ_m, or α^* may be obtained when strong heterogeneity, an extreme vertical antecedent water content gradient, or insufficient equilibration time result in inappropriate Q_s values. When the TPD approach yields a negative result for either K_{fs} or ϕ_m, or an α^* value that falls substantially outside the realistic range of $1 \le \alpha^* \le 100\ \text{m}^{-1}$, both K_{fs} and ϕ_m calculations have to be discarded (Angulo-Jaramillo et al., 2016; Reynolds & Elrick, 2002). In this case, the OPD approach (Reynolds & Elrick, 1990), also named single-head analysis, should be applied to each H value, and the resulting K_{fs} and ϕ_m values averaged (Reynolds & Elrick, 2002). With the OPD approach, an estimate of K_{fs} is obtained from a single Q_s value by the following relationship:

$$K_{fs} = \frac{\alpha^* G_e Q_s}{r\left(\alpha^* H + 1\right) + G_e \alpha^* \pi r^2} \tag{6}$$

where α^* can be estimated from a field evaluation of soil textural and structural characteristics or an a priori knowledge of a field representative value of α^* (Elrick & Reynolds, 1992a, 1992b).

3 | MATERIALS AND METHODS

3.1 | Field sites

This investigation was carried out in three distinct study areas: Acerra, Altofonte, and Villabate (Figure 1).

The Acerra field is located in a flat region, approximately 20 km northeast of Naples, Italy (40°57′58″ N, 14°25′47″ E, 27 m above sea level). The area experiences a Mediterranean climate, characterized by a mean annual temperature of approximately 16.9°C and an average annual precipitation of 876 mm. The primary land use in this area is the cultivation of vegetable crops. The soil developed on volcanic material, exhibiting high chemical and physical fertility. According to the USDA soil classification system, the soil texture is sandy-loam, consisting of 11.9% clay, 35.8% silt, and 52.3% sand.

The Altofonte site is situated in a hilly area, approximately 11 km southwest of Palermo, Italy (38°02′31″ N, 13°16′18″ E, 420 m above sea level). The site experiences a Mediterranean climate with a mean annual temperature of around 17°C and an average annual precipitation of 843 mm. This field hosts a 50-year-old olive orchard, where the soil is not tilled and weed control is managed exclusively through mechanical means. According to the USDA soil classification system, the soil texture is classified as clay, with 47.6% clay, 39.0% silt, and 13.4% sand.

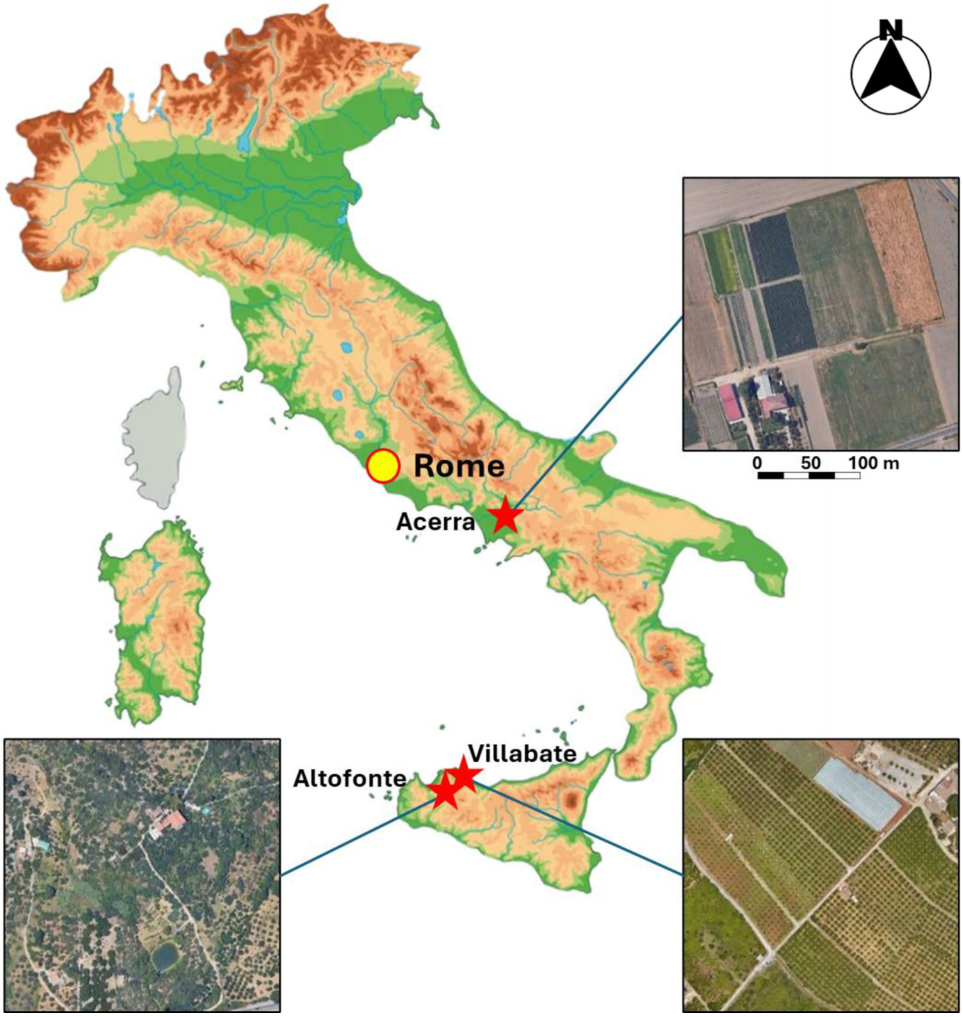

FIGURE 1 Geographical location of the sampled field sites.

The Villabate experimental site (38˚04′53.1″ N, 13˚25′08.4″ E, 35 m above sea level) is located near Palermo in the flat area historically referred to as the Conca d'Oro (Golden Basin). The region experiences a Mediterranean climate with a mean annual temperature of approximately 19˚C and an average annual precipitation of 803 mm. The field comprises a 30-year-old mandarin orchard with a 5 m × 5 m plant space. Like the Altofonte site, no-till farming management is employed, and weed control is conducted mechanically. Based on the USDA soil classification, the soil texture is sandy-loam, consisting of 17.1% clay, 19.0% silt, and 63.9% sand.

3.2 | Infiltration experiments

At each field site, infiltration runs were conducted over an area of approximately 350 m^2 using the PI and SATURO methods. At each site, sample locations for a method were selected randomly, and the PI and SATURO measurements were randomly interspersed.

The PI, manufactured according to Ciollaro and Lamaddalena (1998), consisted of a stainless-steel ring with a radius (r) = 7.5 cm, inserted to a depth (d) = 5 cm into the initially unsaturated soil. A Mariotte bottle maintained a constant-head infiltration process by supplying water as needed during the test. The infiltration rate was determined by measuring the rate of water level decrease in the Mariotte bottle. Two constant water depths, $H_1 = 5$ cm followed by $H_2 = 10$ cm, were established in uninterrupted sequence on the soil surface confined by the ring. The test durations were site-specific, depending on the soil's hydraulic properties and initial soil moisture conditions, which determine the time required to reach steady-state flow conditions. At the Acerra site, H_1 was maintained for a minimum of 30 min and H_2 for 20 min. At the Altofonte site, the minimum durations were 60 min for H_1 and 30 min for H_2. At the Villabate site, shorter durations of 20 min for H_1 and 11 min for H_2 were used. In total, 45 two-level infiltration runs were performed with this apparatus, that is, 15 runs at each field site.

The other device used in this study was SATURO, intended for fully automatic K_{fs} determination without requiring post-processing of the data. The device includes two insertion rings, each with $r = 7.5$ cm and options for insertion depths of 10 or 5 cm. For consistency with the PI experiments, the 5-cm depth ring was selected at all sites. The ring was inserted into the soil using a driving plate and a hammer. The infiltrometer head, comprising an airtight chamber, was connected to the ring via a quick-release mechanism. A control unit within the infiltrometer head pumps water to maintain a ponded water depth of approximately 5 cm on the soil surface and applies air pressure to establish the required pressure head. Infiltration rates were measured and logged at 1-min intervals throughout each test. The procedure began with an initial soaking phase, during which the infiltrometer applied water to saturate the soil while maintaining a pressure head of approximately 5 cm. The soaking phase lasted 25 min at all three study sites. After soaking, the infiltrometer performed a series of infiltration cycles alternating with two different pressure heads. Each cycle included a high-pressure head ($H_2 = 10$ cm) applied for 15 min, followed by a low-pressure head ($H_1 = 5$ cm) for another 15 min. These cycles ensured that steady-state infiltration rates were achieved.

The control unit takes the average infiltration rates at the two different pressure heads during the last pressure cycle to only calculate K_{fs} by the TPD equation, that is, by Equation (3). Therefore, compared to theory and consolidated practical recommendations, the SATURO method is characterized by (i) an inversion of the established pressure heads for determining K_{fs} (first the higher value and then the lower one) and (ii) a lack of consideration for the possibility that the determination of K_{fs} is invalid because ϕ_m is negative or α^* falls outside the range of acceptable values. Instead, the method does not exclude that K_{fs} could be invalid when Q_{s2} is unrealistically smaller than Q_{s1}.

At the Altofonte and Villabate sites, three infiltration cycles were conducted, while at the Acerra site, only two cycles were performed due to the faster attainment of steady-state conditions. As a result, the total test durations were 115 min at Altofonte and Villabate and 85 min at Acerra. Upon completing each experiment, the SATURO device displayed the K_{fs} value calculated according to Equation (3) along with the associated standard error, calculated from the final pressure cycle data. The first 2 min of each pressure head setting were excluded from the calculation to allow the instrument to stabilize at the new pressure level. In total, 51 experiments were conducted with SATURO: 12 at Acerra, 24 at Altofonte, and 15 at Villabate.

3.3 | Field-saturated soil hydraulic conductivity calculations

Different estimates of K_{fs} were considered in this investigation, depending on the experimental information used for the calculations and the choice made with reference to α^* (Figure 2). An estimate of K_{fs} was obtained by the TPD approach ($K_{fs}{}^{TPD}$). In this case, ϕ_m and α^* were also calculated using Equations (4) and (5), respectively. For SATURO, the steady-state infiltration rates used by the device to yield $K_{fs}{}^{TPD}$ were also considered to determine ϕ_m and hence α^*.

The infiltration data were also analyzed by applying the OPD approach with each H value and then by averaging the two estimates of K_{fs}, according to Elrick and Reynolds (1992b) and Reynolds and Elrick (2002). Two different α^* values were used at a given field site to apply Equation (6). A field-specific estimate of α^* was calculated by averaging the α^* values obtained from the valid TPD analysis of the PI and SATURO runs, only considering those within the range $1 \leq \alpha^* \leq 100$ m^{-1}. The two methods (PI and SATURO) were considered together since these runs were performed under comparable experimental conditions with reference to ring radius and established H values. The symbol $K_{fs}{}^{E}$ (E stands for experimental) was used to denote the K_{fs} values obtained with the experimentally determined α^* parameter. Another dataset was developed by the first approximation α^* value ($\alpha^* = 12$ m^{-1}), valid for a wide range of soils (Elrick & Reynolds, 1992a, 1992b). The symbol $K_{fs}{}^{L}$ (L stands for literature) was used in this case.

3.4 | Data analysis

The data analysis was performed according to the following steps:

1. Initially, the PI and SATURO data obtained at the three field sites (Acerra, Altofonte, and Villabate) were analyzed by the TPD equations to establish a comparison between the two K_{fs} validity criteria, that is, Criterion 1 (Equation 3 yielding positive $K_{fs}{}^{TPD}$ values) and the more stringent Criterion 2 by Reynolds and Elrick (2002) (Equations 3 and 4 yielding positive values of $K_{fs}{}^{TPD}$ and ϕ_m, respectively, and α^* falling within the pre-established range of $1 \leq \alpha^* \leq 100$ m^{-1}). For a given site and an applied method, these two validity criteria were compared in terms of both the success rates of the two-level infiltration runs and $K_{fs}{}^{TPD}$ estimates.
2. A comparison was then conducted between the K_{fs} values obtained using the PI and SATURO methods at each field site. The $K_{fs}{}^{E}$ data were considered for this comparison to maximize the experimental information available for each developed dataset.
3. Finally, a comparison was established for each site between the estimates of K_{fs} obtained with the first approximation value of α^* (12 m^{-1} according to Elrick and Reynolds [1992b]; $K_{fs}{}^{L}$) and those obtained by the locally

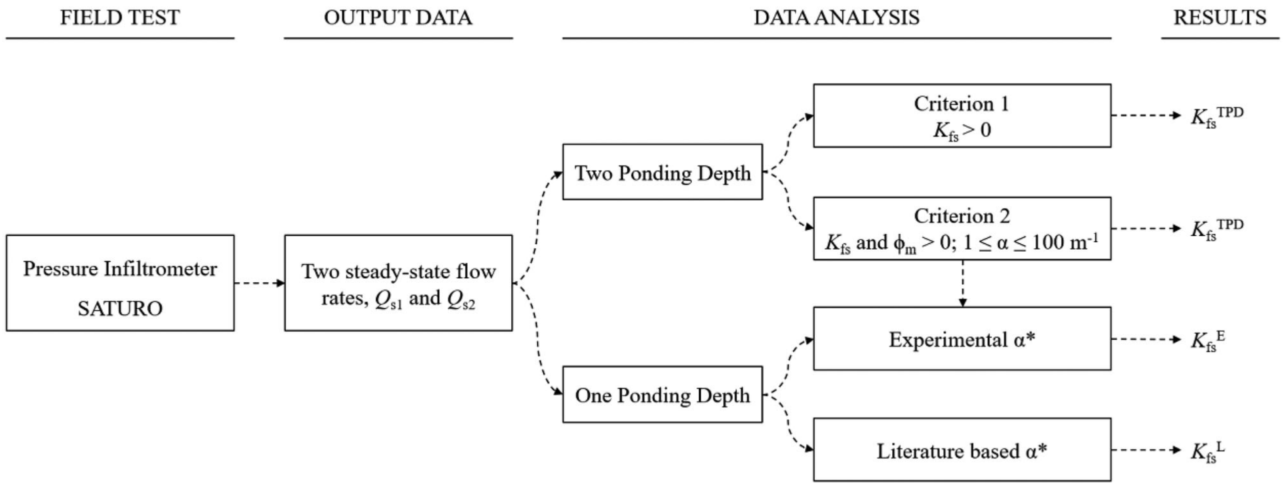

FIGURE 2 Flowchart for estimating field-saturated soil hydraulic conductivity with the pressure infiltrometer (PI) and SATURO methods.

determined α^* value (K_{fs}^{E}). This comparison aimed to assess the extent to which simplifying the estimation of α^* influences K_{fs} calculations.

The distribution of the data was checked with the Lilliefors (1967) test, considering both a normal and a log-normal distribution. An F-test and a two-tailed t-test were applied to compare the two datasets, considering the ln-transformed data in the case of a log-normal distribution. All statistical tests were carried out at a significance level of $p = 0.05$.

4 | RESULTS

4.1 | Comparing Criteria 1 and 2

With the PI, K_{fs}^{TPD} was always positive at Acerra and for 87% and 47% of the runs at Altofonte and Villabate, respectively (Table 1). With SATURO, positive K_{fs}^{TPD} values were always obtained at Acerra and in 71% and 93% of the cases at Altofonte and Villabate. With the validity Criterion 2, the success rates of the PI runs were equal to 60%, 87%, and 27% at Acerra, Altofonte, and Villabate, respectively, and the corresponding percentages for SATURO were equal to 75%, 13%, and 33%.

In general, applying the more stringent Criterion 2, imposing constraints on K_{fs}, ϕ_m, and α^*, resulted in decreased success rates compared to the less stringent Criterion 1, which only imposes constraints on K_{fs}. In some instances, such as for SATURO runs at Altofonte and Villabate, this decrease was particularly notable. However, in a case, and specifically for the PI runs at Altofonte, no difference was observed between Criteria 1 and 2.

With the validity Criterion 2, the overall success rate of the runs was equal to 58% for the PI and 33% for SATURO. Therefore, the classical method (PI) was more appropriate than the automated one (SATURO) to obtain valid estimates of K_{fs}^{TPD} with the more stringent validity criterion. In both cases, however, the number of failures was rather high since one valid run was approximately obtained for every two or three runs performed. This result was not surprising since high failure rates have been reported in several studies using the PI method (Bagarello et al., 2013, 2014; Mertens et al., 2002). According to Reynolds and Elrick (2002), failure rates should not be excessively high, as the experiment is expected to show a reduced dependence on soil heterogeneity or antecedent water content gradients. Large failure rates imply that developing a representative dataset of valid K_{fs}^{TPD} calculations may require performing a rather large number of two-level infiltration runs in the field, with only a portion of the collected data being valid for inclusion.

Considering the Acerra and Villabate sites, there was a consistency between the PI and SATURO results since, with Criterion 2, the success rates for the two methods were similar at each of these two sites (60%–75% at Acerra and 27%–33% at Villabate) and higher at the former site than the latter one (Table 1). At Altofonte, the success rate differed appreciably between the two methods since it was equal to 87% for the PI and 13% for SATURO. These discrepancies suggested that the soil at Acerra was likely more homogeneous than at Altofonte and Villabate since it had been tilled shortly before the infiltration runs, which may have contributed to greater homogeneity. Moreover, macropores at the soil surface were not noticed at Acerra, while they were observed at both Altofonte and Villabate. Therefore, the success rates of the two tested methods were similar and relatively high in the soil that was homogenized by tillage. In more undisturbed conditions, the situation was more diversified because, in addition to a large number of successes (PI at Altofonte), it also happened that preferential flow zones and other local soil heterogeneities caused a more frequent failure of one (at Altofonte) or both (at Villabate) methods.

TABLE 1 Summary of the valid runs and the valid field-saturated soil hydraulic conductivity values obtained by the two-level analysis, K_{fs}^{TPD} (where TPD represents two-ponding-depth), for each site (Acerra, Altofonte, and Villabate) and method (pressure infiltrometer [PI], classical single-ring pressure infiltrometer, and SATURO).

			Criterion 1				Criterion 2				
					K_{fs}^{TPD}				K_{fs}^{TPD}		
Site	Method	Number of runs	Valid runs	Success rate (%)	Mean (mm h^{-1})	CV (%)	Valid runs	Success Rate (%)	Mean (mm h^{-1})	CV (%)	Δ (%)
Acerra	PI	15	15	100	64.7a	52.2	9	60	70.1a	62.5	−7.6
	SATURO	12	12	100	88.8a	92.6	9	75	75.6a	99.1	+17.5
Altofonte	PI	15	13	87	241.7	51.1	13	87	241.7	51.1	0
	SATURO	24	17	71	518.1a	173.3	3	13	300.3a	14.8	+72.6
Villabate	PI	15	7	47	125.9a	84.9	4	27	197.0a	75.5	−36.1
	SATURO	15	14	93	526.6a	254.1	5	33	194.2a	58.3	+171.1

Note: Criterion 1 only implies positive K_{fs}^{TPD} values, while Criterion 2 requires positive K_{fs}^{TPD} and ϕ_m (matric flux potential) values and acceptable α^* values. Δ is the percentage difference between the means of K_{fs}^{TPD} obtained with the validity Criteria 1 and 2. For the given site and method, means of K_{fs}^{TPD} followed by the same letter were not significantly different according to an F-test and a two-tailed t-test at $p = 0.05$. The means of K_{fs}^{TPD} obtained at Altofonte with the PI and the two applied criteria were not statistically compared since the two datasets were identical.
Abbreviation: CV, coefficient of variation.

The distribution of K_{fs}^{TPD} was checked for 10 of the 12 developed datasets, that is, for three sites (Acerra, Altofonte, and Villabate) × two methods (PI and SATURO) × two validity criteria (Criteria 1 and 2). Two datasets were excluded from this check for the following reasons. At Altofonte with the PI, the same K_{fs}^{TPD} dataset was developed with the two validity criteria, and therefore, the distribution of the data was checked only once. At Altofonte with SATURO and Criterion 2, the sample size was too small ($N = 3$) according to Lilliefors (1967). The normal distribution hypothesis was not rejected in eight cases, but it was rejected in two cases. Instead, the log-normal hypothesis was never rejected. Therefore, the K_{fs}^{TPD} data were considered to be log-normally distributed, and they were summarized by calculating the geometric mean and the associated coefficient of variation (CV) according to Lee et al. (1985).

For a given site and method, a comparison was carried out between the two developed K_{fs}^{TPD} datasets (Criteria 1 and 2). The corresponding mean values of K_{fs}^{TPD} were identical in one case (PI at Altofonte) and not significantly different in the other cases (Table 1). Therefore, the validity criterion did not significantly influence the determination of a mean K_{fs}^{TPD} value. However, compared to Criterion 1, Criterion 2 determined in some cases an appreciable decrease of the relative variability of K_{fs} and also resulted in smaller mean values (SATURO at both Altofonte and Villabate).

Therefore, the two validity criteria can generally be expected to differ in terms of a number of valid measurements but not appreciably with reference to the summary statistics of the data. However, the less stringent criterion may result in excessively high mean values and higher CV values of K_{fs}^{TPD} compared to the more stringent criterion, at least occasionally.

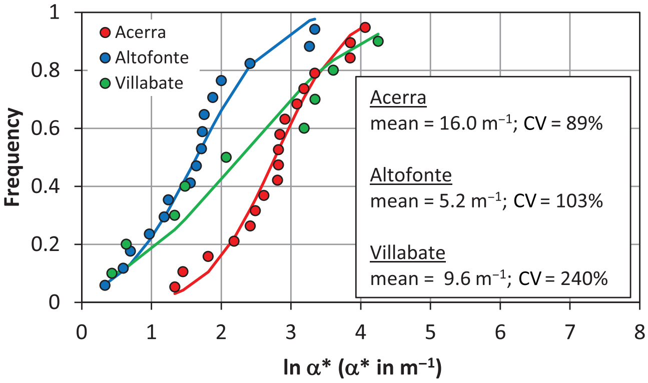

FIGURE 3 Cumulative empirical frequency distribution of the α^* parameter values at the three sampled field sites (CV in the figure indicates the coefficient of variation).

Jointly considering the measurements performed with the PI and SATURO methods, the valid TPD calculations according to Criterion 2 varied from a minimum of 9 at Villabate to a maximum of 18 at Acerra (Table 1). The normal distribution hypothesis of the α^* values experimentally obtained by Equation (5) was rejected at Altofonte, whereas the log-normal distribution hypothesis was not rejected at any site. Therefore, a field-specific estimate of α^* was obtained by the geometric mean of the individual α^* values for that site (Figure 3). The data were highly variable ($89\% \leq \text{CV} \leq 240\%$), especially at Villabate. However, the means ($5.2 \leq \alpha^* \leq 16$ m^{-1}) fell within the range of α^* values suggested by Reynolds and Elrick (1990) for estimating K_{fs} by the OPD approach ($1 \leq \alpha^* \leq 36$ m^{-1}). Therefore, these site-specific estimates of α^* were then considered for calculating K_{fs} with the OPD approach as an alternative to the literature value of this parameter.

TABLE 2 Summary statistics of the field-saturated soil hydraulic conductivity, $K_{fs}{}^{E}$, values obtained at the three field sites (Acerra, Altofonte, and Villabate) with the classical single-ring pressure infiltrometer (PI) method and with SATURO.

	PI			**SATURO**			
Site	N	**Mean (mm h^{-1})**	**CV (%)**	N	**Mean (mm h^{-1})**	**CV (%)**	**Δ (%)**
Acerra	15	81.0aA	100.7	12	77.9aA	79.0	4.0
Altofonte	15	294.2aB	27.0	24	174.7bB	47.6	68.4
Villabate	15	345.0aB	82.0	15	191.8bB	58.3	79.9

Note: Δ, percentage difference between the means of $K_{fs}{}^{E}$ obtained with the PI and SATURO. For the given site, means of $K_{fs}{}^{E}$ followed by the same lowercase letter were not significantly different according to an F-test and a two-tailed t-test at $p = 0.05$. Means followed by a different lowercase letter were significantly different. For the given method, means of $K_{fs}{}^{E}$ followed by the same uppercase letter were not significantly different according to an F-test and a two-tailed t-test at $p = 0.05$. Means followed by a different uppercase letter were significantly different.

Abbreviation: CV, coefficient of variation.

4.2 | Comparing the PI and SATURO

As with $K_{fs}{}^{TPD}$, the distribution of the $K_{fs}{}^{E}$ data was checked for six datasets, that is, for three sites (Acerra, Altofonte, and Villabate) × two methods (PI and SATURO). The normal distribution hypothesis was rejected in two cases, whereas the log-normal hypothesis was never rejected. Therefore, the data were considered to be log-normally distributed and were summarized using the geometric mean and the associated CV (Table 2).

At Acerra, the two mean values of $K_{fs}{}^{E}$ were numerically similar ($\Delta = 4\%$) and not significantly different. Moreover, a considerable overlap of the two $K_{fs}{}^{E}$ distributions was noticed in a rather wide range of frequency (F) values, that is, for approximately $0.1 \leq F \leq 0.9$ (Figure 4). However, the $K_{fs}{}^{E}$ values obtained with the PI ranged from 22 to 472 mm h^{-1} (by 21.6 times), whereas those determined with SATURO ranged from 37 to 239 mm h^{-1} (by 6.5 times). Therefore, the $K_{fs}{}^{E}$ dataset developed with the PI method included both smaller and larger values than the smallest and the largest estimates obtained with the SATURO method. As a result, while the two methods did not differ in terms of the estimated mean of $K_{fs}{}^{E}$, the SATURO method indicated lower variability in field-saturated hydraulic conductivity compared to the PI method.

At Altofonte, the mean of $K_{fs}{}^{E}$ obtained with the PI method was 68% higher than that obtained with the SATURO method, with the differences being statistically significant. In this case, there was not any overlap of the two $K_{fs}{}^{E}$ distributions. The PI data ($180 \leq K_{fs}{}^{E} \leq 427$ mm h^{-1}; ratio between the two extreme values = 2.4) varied over a narrower range than the SATURO data ($45 \leq K_{fs}{}^{E} \leq 294$ mm h^{-1}; ratio = 6.6). Consequently, a smaller CV was obtained with the PI as compared to SATURO. Both methods yielded individual $K_{fs}{}^{E}$ values in the 180–300 mm h^{-1} range. However, only the PI method yielded $K_{fs}{}^{E} > 300$ mm h^{-1} ($N = 8$), while only the SATURO method yielded $K_{fs}{}^{E} < 180$ mm h^{-1} ($N = 10$). Therefore, the PI experiment suggested a more permeable and homogeneous soil than the SATURO one. Moreover, particularly high $K_{fs}{}^{E}$ values were only obtained with the PI method, whereas particularly low values were only obtained with the SATURO method.

Also at Villabate, the mean $K_{fs}{}^{E}$ value obtained with the PI method was significantly higher than that obtained with the SATURO method, with the two means differing by 80%. Even in this case, there was no overlap between the two $K_{fs}{}^{E}$ distributions. The PI data ($117 \leq K_{fs}{}^{E} \leq 1151$ mm h^{-1}; ratio = 9.8) varied over a wider range than the SATURO data ($71 \leq K_{fs}{}^{E} \leq 408$ mm h^{-1}; ratio = 5.7). Consequently, a smaller CV was obtained with the SATURO method as compared to the PI method. Both methods yielded individual $K_{fs}{}^{E}$ values in the range of 120–410 mm h^{-1}. However, only the PI method yielded $K_{fs}{}^{E} > 410$ mm h^{-1} ($N = 4$), while only the SATURO method yielded $K_{fs}{}^{E} < 120$ mm h^{-1} ($N = 3$). Therefore, the PI experiment suggested a more permeable and heterogeneous soil than the SATURO one. Furthermore, as in the previous case, particularly high $K_{fs}{}^{E}$ values were only obtained with the PI method, whereas particularly low values were only obtained with the SATURO method.

Both methods indicated that $K_{fs}{}^{E}$ varied according to the sequence Villabate = Altofonte > Acerra, even if the PI method suggested a wider variation than the SATURO method, since the ratio between the highest and the lowest mean of $K_{fs}{}^{E}$ was equal to 4.3 with the PI method and to 2.5 with the SATURO method (Table 2).

In summary, the means of $K_{fs}{}^{E}$ were either statistically similar or differed by no more than 1.8 times. At two of the three sampled sites, several $K_{fs}{}^{E}$ values obtained with the SATURO method were smaller than the lowest $K_{fs}{}^{E}$ values obtained with the PI method. Additionally, at all sites, the highest $K_{fs}{}^{E}$ values obtained with the SATURO method were lower than several values obtained with the PI method. Therefore, this investigation suggested a relative similarity between the two methods (Elrick & Reynolds, 1992b), but it also indicated a tendency of the SATURO method to overall yield lower $K_{fs}{}^{E}$ values as compared to the PI method.

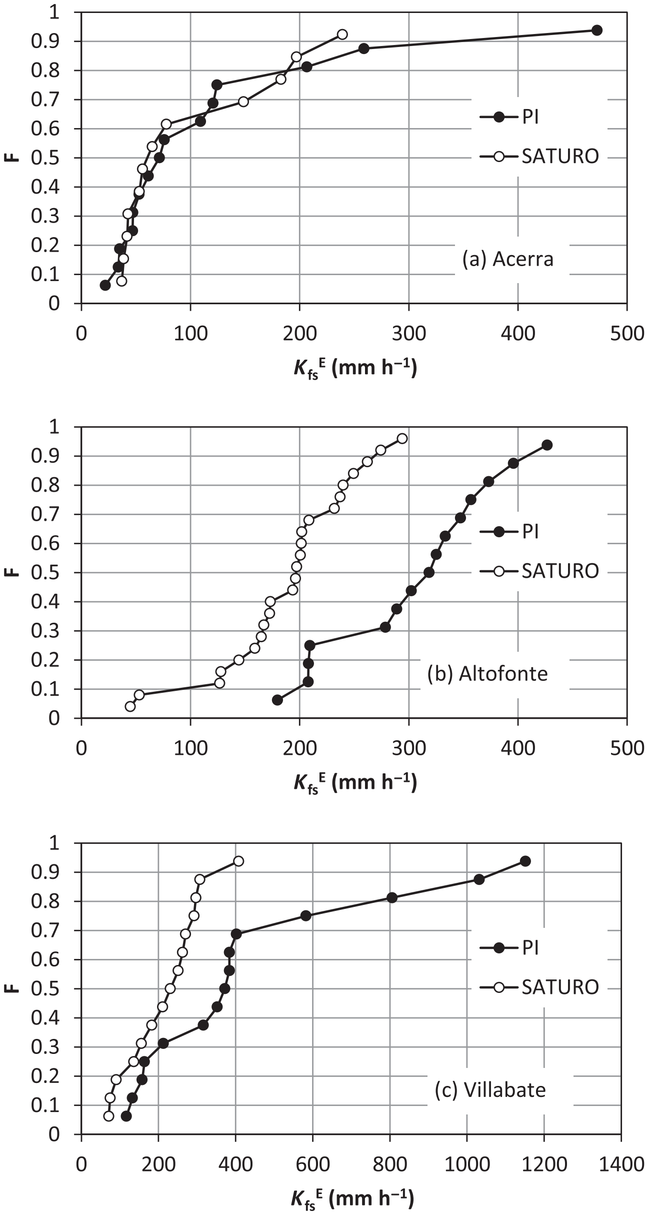

FIGURE 4 Cumulative empirical frequency distribution of the field-saturated soil hydraulic conductivity, K_{fs}^{E}, values obtained with the pressure infiltrometer (PI) and the SATURO methods at the three sampled field sites.

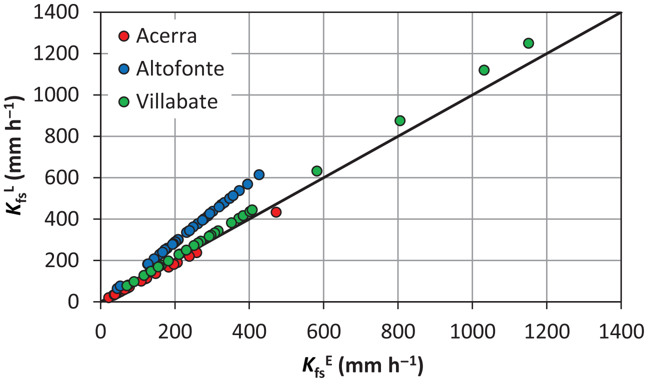

FIGURE 5 Relationship between the field-saturated soil hydraulic conductivity values obtained by the first approximation value of the α^* parameter, K_{fs}^{L}, and the corresponding values obtained by the experimental α^* parameter, K_{fs}^{E}.

4.3 | Using the first approximation value of α^*

At Acerra, using the first approximation value of α^* (12 m^{-1}) instead of the experimental value (16 m^{-1}) determined an underestimation of the saturated hydraulic conductivity by 8.3%–8.5% (N = 27, i.e., 15 PI runs + 12 SATURO runs; Table 1) (Figure 5). At Altofonte, K_{fs}^{L} was higher than K_{fs}^{E} (α^* = 5.2 m^{-1}) by 43.0%–45.2% (N = 39). At Villabate, the estimate of K_{fs} obtained with the first approximation value of α^* was greater than that obtained with the experimental α^* value (9.6 m^{-1}) by 8.0%–8.7% (N = 30). Therefore, the most appreciable effect of the choice of α^* was detected at Altofonte, where two corresponding values differed by nearly 1.5 times. At the other two sites, two corresponding estimates of K_{fs} did not differ by more than 9%.

5 | DISCUSSION

The detected differences between the two data validity criteria considered in this investigation (Criteria 1 and 2; Table 1) implied establishing what is the best approach that should be considered in practice.

There is no doubt that Criterion 1 is preferable to Criterion 2, as it minimizes the risk of discarding data collected in the field. Moreover, the requirement that the run is valid if α^* falls within the 1–100 m^{-1} range could appear too restrictive. Values of α^* falling outside a wider range ($0.1 \leq \alpha^* \leq 1000$ m^{-1}) than the one suggested by Reynolds and Elrick (2002) can be found in the literature (Khaleel & Relyea, 2001; Russo et al., 1997; White & Sully, 1992). Therefore, the restriction of considering only specific α^* values as valid may raise some doubts. However, apart from α^*, the key discriminating factor between the two criteria is the occurrence of negative ϕ_m values. A negative K_{fs}^{TPD} value implies the failure of the run, regardless of the criterion adopted. The matric flux potential is the integral of the soil hydraulic conductivity–pressure head relationship between an initial soil water pressure head and zero (Reynolds & Elrick, 1990). This integral cannot be negative, and if this happens, it indicates an anomaly in the Q_{s1} and Q_{s2} values used for its calculation. Of course, if these values are not usable to obtain a physically realistic value of ϕ_m, they are also unusable for calculating K_{fs}^{TPD}.

Considering that only Criterion 2 explicitly takes this last circumstance into account, it has to be suggested that this criterion should also be used to analyze the SATURO data.

Criterion 1 is inadequate as it is not consistent with the TPD analysis or infiltration theory.

This investigation suggested that both the PI and SATURO methods yielded similar information about relative differences between the three soils. The SATURO method showed a moderate tendency to yield generally lower ${K_{fs}}^{E}$ values compared to the PI method. However, the reasons for this difference appeared to vary between the Acerra and Villabate sites on one hand and the Altofonte site on the other.

At the Acerra and Villabate sites, the runs conducted with the SATURO method were longer and required more water compared to those performed with the PI method. In particular, at Acerra, the mean duration, d_m, of the $N = 15$ PI runs was 63 min, with a mean applied water volume (V_m) of 5.0 L. In contrast, for SATURO ($N = 12$), the corresponding values were $d_m = 93$ min and $V_m = 8.0$ L. Similarly, at Villabate, the PI ($N = 15$) method resulted in $d_m = 51$ min and $V_m =$ 16.2 L, whereas the SATURO method ($N = 15$) required d_m = 115 min and $V_m = 24.7$ L.

A decrease in the measured ${K_{fs}}^{E}$ value with longer runs and/or with more water used for the run can be expected to occur as a consequence of a better stabilization of the infiltration process (Elrick & Reynolds, 1992a; Reynolds et al., 2000), a progressive modification of the sampled soil volume close to the infiltration surface (Bagarello & David, 2020), and an increase in size of the sampled soil volume. Additionally, vertical gradients in antecedent soil water content and soil hydrodynamic properties may also contribute to this decrease (Vandervaere et al., 2000; Wu et al., 1997). Therefore, the differences between the two methods were consistent with differences in run duration and used water volumes. Moreover, with the PI method, the estimate of Q_{s1} was obtained approximately halfway through the run, while that of Q_{s2} was obtained at the end of the run. Instead, with the SATURO method, both Q_{s1} and Q_{s2} were obtained at the end of the run. It can therefore be supposed that the Q_{s1} values obtained with the SATURO method were more reliable than those obtained with the PI method.

At the Altofonte field site, SATURO tended to yield lower ${K_{fs}}^{E}$ values than the PI method. However, the run duration was relatively similar for the PI ($N = 15$, $d_m = 133$ min) and SATURO ($N = 24$, $d_m = 115$ min) runs. The volume of water used was larger for the PI ($V_m = 55.4$ L) compared to SATURO ($V_m = 27.2$ L). In this soil, there was a widespread presence of preferential flow zones, which explains the use of large volumes of water for the PI runs. With this device, water was applied manually, and maintaining a constant depth of water on the infiltration surface, especially in the early stages, was not particularly problematic since it only required a continuous presence of the operator. In contrast, with the automated device, many runs failed from the beginning since the water level remained below 4.3 cm for more than 10 min (METER Group, Inc.). Therefore, a relocation of the ring to alternative sampling points was necessary in an attempt to find suitable conditions compatible with the execution of the run. In particular, immediate failure of the run occurred in 10 cases against never at Acerra and three times at Villabate. Therefore, while with the PI, the sampling was completely random and no measurement point was excluded, with SATURO, it was unavoidable to exclude, due to the presence of preferential flow paths, the most permeable points from sampling. Consequently, SATURO overall yielded a smaller ${K_{fs}}^{E}$ value than the PI for this soil. An implication of this interpretation is that the manual PI method is more versatile than the automated SATURO method.

The reason why SATURO appeared to yield smaller K_{fs} values as compared to the PI can also be discussed, taking into account that, with the automated device, the highest measurable infiltration rate is equal to 1150 mm h^{-1} (METER Group, Inc.). By considering, for the used d and r values in this investigation, the maximum measurable flow rate, the site-specific α^* parameter (Figure 3), and the applied ponded depths of water (5 and 10 cm), the maximum measurable K_{fs} values, calculated by Equation (6), are equal to nearly 470, 300, and 400 mm h^{-1} at Acerra, Altofonte, and Villabate, respectively. Comparing these values with those reported in Figure 4 shows that the maximum K_{fs} value measured with SATURO was well below the maximum measurable value at Acerra, but it was essentially the same as the maximum measurable value at Altofonte and Villabate. It can therefore be supposed that the SATURO K_{fs} data were not high-end truncated at Acerra, but they were very likely high-end truncated at Altofonte and Villabate. Consequently, the SATURO data largely matched the PI ones at Acerra, but they were overall smaller at Altofonte and Villabate (Figure 4). Hence, the SATURO K_{fs} results were likely a fairly good representation of both soil macropore and soil matrix permeability at the Acerra site but appreciably biased toward soil matrix permeability at the Altofonte and Villabate sites. The reason was that the maximum SATURO pumping rate was apparently too slow for adequate measurement of infiltration through the soil structure domain of these agricultural soils.

In practical applications of the PI method, it cannot be excluded that an experimental value of α^* is unavailable, requiring an estimated value for determining K_{fs}. According to Reynolds (2013), two K_{fs} values that differ by less than 25% are practically equal, while differences by two to three times could still be considered relatively small, given the wide range of possible K_{fs} values and the extreme spatial variability of K_{fs} observed in the field (Elrick & Reynolds, 1992b). According to these K_{fs} similarity criteria, this investigation suggested that using the first approximation value of α^* instead of an experimental value of this parameter can be expected not to have any adverse effect on K_{fs} calculation (Acerra and Villabate; Figure 5), or it could have no more than a limited influence on these calculations (Altofonte).

Between the two alternatives, using an experimental value of α^* seems preferable in general since it assures a more site-specific characterization of the soil. However, this suggestion could also represent an excess of caution since, according to this investigation and in agreement with Elrick and Reynolds (1992b), the simpler choice of using a literature estimate of α^* can be expected not to largely distort estimation of K_{fs}.

Given that the SATURO K_{fs} data for the Altofonte clay soil likely excluded most of the preferential or macropore permeability (Figure 4), it could be argued that the most appropriate literature α^* value for this soil was the one associated with matrix-dominated flow in clay soils, that is, 4 m^{-1} rather than 12 m^{-1}, as proposed by Elrick and Reynolds (1992b). This would bring the $K_{fs}{}^{L}$ and $K_{fs}{}^{E}$ datasets for Altofonte much closer together, given that the experimental α^* value was equal to 5.2 m^{-1} at this site (Figure 3). This argument also applies to the untilled Villabate soil (Figure 4), but the α^* value for Villabate (9.6 m^{-1}) remained close to the default value of 12 m^{-1} since this soil was coarser than that at Altofonte. Finally, the experimental α^* values for the Acerra and Villabate sites averaged to a geometric mean of 12.4 m^{-1} and an arithmetic mean of 12.8 m^{-1} and both values were very close to the first approximation value for agricultural soils, that is, $\alpha^* = 12$ m^{-1}, supporting this choice.

More investigations should be performed to definitely demonstrate that a literature estimate of α^* is a generally plausible alternative to the experimental determination of this parameter. Should this be the case, determination of K_{fs} by both manual (PI) and automated (SATURO) methodologies could appreciably be simplified. In particular, a single-level run, which is more rapid and less water demanding than a two-level run, could be enough to determine K_{fs} at a sampling point. It should not be complicated for the manufacturer to adapt SATURO so that the instrument (i) establishes a single value of H for the entire duration of the run, (ii) determines a steady-state flow rate using the last part of the run, and (iii) finally yields an estimate of K_{fs} using a value of α^* chosen by the operator from a short list of possible values. An additional modification might be to allow establishing a wide range of ponded head, which could easily be adapted in the early stages of the experiment to accommodate changing soil conditions both within and between field sites. With these adaptions of the SATURO experiment, possible uncertainties about the validity of the calculated $K_{fs}{}^{TPD}$ values could no longer have any reason to exist. An experimental methodology that could also be evaluated is the one based on the MPD approach (Reynolds & Elrick, 1990). This approach is more complicated and slower than the TPD approach because it uses three or more ponded heads. An advantage, however, is that the MPD approach can be expected to generally be less sensitive to soil heterogeneity than the TPD approach because it uses regression fitting to nullify the effects of random datapoint scattering. Likely, the SATURO methodology could also be adapted to conduct an automated MPD analysis, perhaps without even increasing measurement time. This objective could be reached if the initial presoak phase is dropped and each successive ponded head is greater than the previous head (i.e., $H_3 > H_2 > H_1$), as has been recommended for years to avoid potential hysteresis-induced flow perturbations in the wetting zone (Angulo-Jaramillo et al., 2016).

6 | CONCLUSIONS

The simplest data validity Criterion 1, only requiring a positive K_{fs} value, can generally be expected to differ from the classical, more stringent Criterion 2 by the number of valid measurements. The summary statistics of K_{fs} should not change appreciably between the two criteria even if, at least occasionally, the former criterion could yield excessively high and variable K_{fs} values as compared to the latter one. The classical data validity Criterion 2 is preferable since it ensures that only physically reliable results are included in the dataset. Instead, Criterion 1 is not consistent with the TPD analysis of the infiltration data. Additional studies should be carried out also with reference to Criterion 2. In particular, a question to be considered is that if both K_{fs} and ϕ_m are valid, then also α^* should be valid regardless of its numerical value.

According to this investigation, SATURO and the PI method generally yielded relatively similar mean K_{fs} values, even if SATURO tended to yield rather small individual values of K_{fs} more frequently than the PI method. This result was attributed to differences in run duration, water volume used, and the reliability of the estimated steady-state infiltration rates between the two methods as well as the extremely high heterogeneity of the soil, especially at one of the field sites. In a very heterogeneous soil with highly permeable points, the PI method should be preferred since, with SATURO, several runs can be expected to fail due to the inability of the device to sustain very high flow rates. In other words, the maximum SATURO pumping rate seems too small for adequate measurement of infiltration through the soil structure domain of several agricultural soils.

Using the first approximation value of the α^* parameter for calculating K_{fs} seems a plausible alternative to the use of the experimentally determined value of this parameter. This result requires additional support that it would be practically important trying to obtain. Establishing that using an independent estimate of α^* does not compromise the calculation of K_{fs} implies that the experiment can be simplified by limiting it to a run with a single pressure head, long enough to ensure flow stabilization. With the manual methodology, there is no difficulty in doing this type of test. The automatic methodology could also be appropriately adapted to allow a simplified application of SATURO in the field.

Although the single-ring, steady-state methodology for determining the soil hydrodynamic properties has been in routine use for at least 35 years, some further investigations, also of a methodological nature, are therefore still necessary. Hopefully, the recent introduction of SATURO will give new impetus to these investigations. This device appears to be an interesting alternative to the classical PI method for determining soil hydrodynamic properties. There is room for improving its performance and also simplifying its application in the field.

AUTHOR CONTRIBUTIONS

Dario Autovino: Data curation; formal analysis; investigation; visualization; writing—original draft; writing—review and editing. **Vincenzo Bagarello**: Conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; supervision; validation; writing—original draft; writing—review and editing. **Angelo Basile**: Conceptualization; investigation; methodology; resources; supervision; writing—original draft; writing—review and editing. **Gaetano Caltabellotta**: Investigation; writing—original draft. **Roberto De Mascellis**: Investigation. **Mariachiara Fusco**: Investigation; writing—original draft. **Massimo Iovino**: Conceptualization; supervision; writing—original draft; writing—review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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