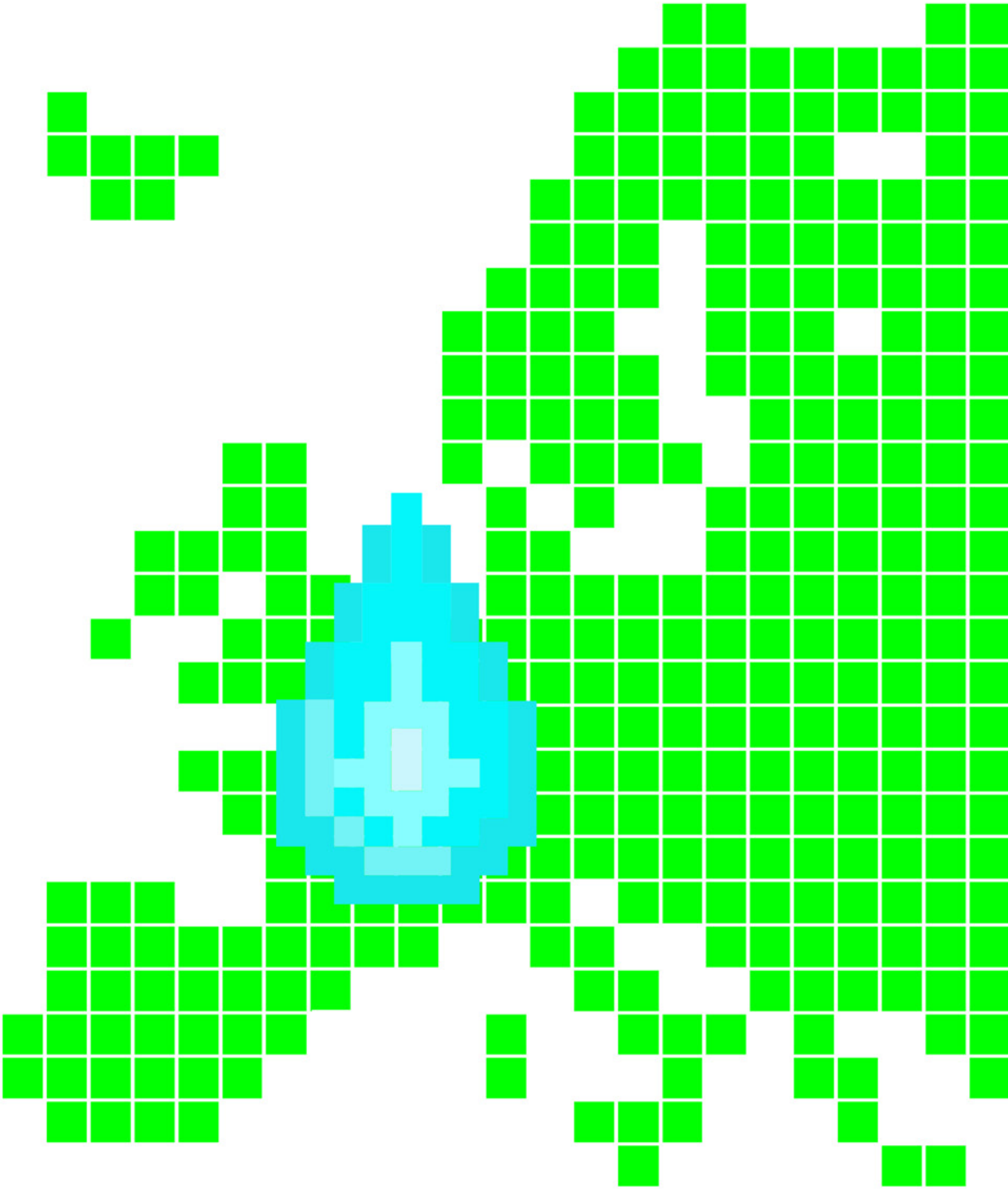
IMPROVEMENT OF BEST (BEERKAN ESTIMATION OF SOIL TRANSFER PARAMETERS) METHOD FOR SOIL HYDRAULIC CHARACTERIZATION



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Improvement of BEST (Beerkan Estimation of Soil Transfer parameters) method for soil hydraulic characterization

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Abstract

Interpreting and modeling soil hydrological processes require the determination of the soil hydraulic characteristic curves, i.e. the relationships between volumetric soil water content, pressure head, and hydraulic conductivity. Using traditional methods to determine these properties is expensive and time consuming. Haverkamp et al. (1996) pioneered a specific method for soil hydraulic characterization known as the "Beerkan method". An improved version of this methodology, called the Beerkan Estimation of Soil Transfer parameters (BEST) procedure, was developed by Lassabatère et al. (2006) to simplify soil hydraulic characterization. BEST considers certain analytic formulae for hydraulic characteristic curves and estimates their shape parameters, which are texture dependent, from particle-size analysis by physical-empirical pedotransfer functions. Structure dependent scale parameters are estimated by a three-dimensional field infiltration experiment at zero pressure head, using the two-term transient infiltration equation by Haverkamp et al. (1994).

BEST is very attractive for practical use since it substantially facilitates the hydraulic characterization of unsaturated soils, and it is gaining popularity in soil science. The signs of a promising ability of the BEST procedure to yield a reasonably reliable soil hydraulic characterization can be found in the existing literature but there is still work to do.

In fact, several problems yet arise with the BEST method, including: (1) the need to carry out many calculations to analyze a single run, which may demand a lot of time; (2) the need to analyze the transient phase of the infiltration process, which may be uncertain for different reasons; (3) the absence of an extensive assessment of the BEST predictions against independent measurements, i.e. with soil data collected by other experimental methods; and (4) the possible sensitivity of the data to soil disturbance and air entrapment during repeated water application, according to the BEST experimental procedure.

The main objective of the present thesis was to study and improve the BEST method in order to understand or give a solution to all the former problems and consequently to contribute towards its widespread application throughout the world.

With this aim, improvements to BEST method were proposed in terms of analysis of the collected data, estimation of hydrodynamic parameters and automation of the experimental procedure. In particular, a workbook to easily and rapidly analyze databases including several BEST runs, an alternative algorithm to analyze the Beerkan infiltration data and a compact infiltrometer to automate data collection with open source technology were developed. The proposed workbook is a practically useful contribution to an expeditious, intensive soil hydraulic characterization. The alternative algorithm can be considered a promising alternative procedure to analyze the Beerkan infiltration data. Finally, the cheap and automated infiltrometer constitutes a very cost effective alternative to previous proposed equipment.

Moreover, BEST was tested in different soils and compared with several alternative field and laboratory methodologies highlighting the pros and cons that characterize the method and allowing to design BEST as a promising, easy, robust, and inexpensive way of characterizing soil hydraulic behavior. The main result of these studies was that BEST yields physically possible scale parameters of the soil characteristic curves in most of the replicated infiltration runs. Moreover, the water retention model used by BEST reproduced satisfactorily the laboratory data. Possible saturated soil hydraulic conductivity values were also obtained.

The dependence of the measured hydrodynamic parameters on the experimental procedure used in BEST was also studied with the objective to improve our ability to interpret the field data and the linked hydrological processes. These studies led to the main conclusion that the choice of the procedure should vary with the intended use of the data. If the objective of the field campaign is to obtain data usable to explain surface runoff generation phenomena during intense rainfall events, for

example, the most appropriate choice among the tested ones should be a perturbative run, to mimic relatively prolonged rainfall effects on the soil surface. A less perturbative run is more appropriate to determine the saturated hydraulic conductivity of a soil that is not directly impacted by rainfall, due for example to the presence of a mulching on the soil surface.

Finally, a simplified method based on a Beerkan infiltration run to determine the saturated soil hydraulic conductivity by only a transient infiltration process was developed. This method is a good candidate method for intensive field campaign with a practically sustainable experimental effort.

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1. Introduction

Water flow in heterogeneous, variably saturated porous media is an important topic in any branch of hydrology, soil science, and agricultural engineering dealing with both surface and subsurface flow and chemical transport processes. Most current and potential groundwater pollution problems result from the release of contaminants from near surface sources such as landfills, septic tanks, tailing ponds, etc.. Through the unsaturated zone the groundwater contaminants usually reach the aquifer. More specifically, the unsaturated zone is the hydrological connection between the surface water component of the hydrologic cycle and the groundwater component. The surface water component includes natural precipitation and artificial water application, such as irrigation, surface runoff, stream flow and lakes. The unsaturated zone plays an important role for the runoff process by splitting up the precipitation into two fractions: infiltration and infiltration excess, which can become surface runoff (e.g. Hortonian overland flow) on sloping land. The unsaturated zone may lose water through evaporation, transpiration, and drainage.

Regardless of the scales involved, the soil hydraulic properties that affect the flow behavior are incorporated into two fundamental characteristics: (1) the soil water retention curve, describing the relation between volumetric soil water content, θ (L^3L^{-3}), and soil water pressure head, h (L); and (2) the hydraulic conductivity function, describing the relation between θ or h and soil hydraulic conductivity, K ($L\ T^{-1}$). This latter soil hydraulic property was originally introduced by Darcy (1856) for saturated soils and extended to unsaturated soils by Buckingham (1907) and Richards (1931). The soil hydraulic conductivity depends on the soil pores characteristics, the moving fluid and the fluid content in the soil. The hydraulic conductivity at saturation is referred to as the saturated soil hydraulic conductivity, K_s ($L\ T^{-1}$). When expressed as a function of the volumetric soil water content, the hydraulic conductivity function is strongly nonlinear. Generally speaking, it behaves like a power function. For decreasing soil water content, the hydraulic conductivity decreases rapidly.

Knowledge of these properties is important for characterizing the above mentioned aspects of unsaturated water flow i.e. rainfall partition between infiltration and runoff, aquifer recharge, migration of nutrients, pesticides and contaminants through the soil profile, design and monitoring of irrigation and drainage systems (Hillel, 1998).

Many experimental investigations have been devoted over the last decades to the development of measurement or estimation methodologies of soil hydraulic characteristics. Roughly speaking, two categories of methods can be distinguished for the determination of the unknown soil hydraulic parameters: (1) the measurement techniques (direct or indirect) and (2) the predictive methods. The first category of techniques has been developed mainly for measurement of the soil hydraulic parameters at a local scale and is difficult to apply over large areas. The second category allows to estimate soil hydraulic parameters through the use of Pedo-Transfer Functions or PTFs. These are generally empirical relationships that allow the hydraulic properties of a given soil to be predicted from more widely available data, such as textural characteristics (% of sand, silt, and clay) and bulk density. The PTFs can either be applied at the local scale using point properties or at the watershed scale where textural information has been aggregated (soil maps).

In general, the measurement techniques rely on precise and time-consuming experimental procedures that can be categorized as being either laboratory- or field-based. While laboratory methods allow accurate measurement of flow processes, they are performed on samples taken from the field and, as a result, their representativeness of field conditions can be questioned. The presence of aggregates, stones, fissures, fractures, tension cracks, and root holes, commonly encountered in unsaturated soil profiles, is difficult to represent in small-scale laboratory samples. Field techniques can be more difficult to control in terms of initial and imposed boundary conditions, but they have the advantage of estimating in situ soil hydraulic properties that are more representative, which is of considerable value in the subsequent use of the hydraulic information. Therefore, it is desirable to aim at field methods that can ease, to some extent, the time-consuming constraints.

Unlike the water retention soil characteristic curve, which can be considered as a quasistatic soil property, the hydraulic conductivity function is always related to water movement into or through the soil. The transient and steady movement of water in the unsaturated zone of soils depend to a large extent upon the pore network resulting from the assemblage of soil particles and aggregates. This dependence of $K(\theta)$ on the pore-size distribution underlines that exists a link between the water retention and hydraulic conductivity functions. It implies at the same time that the optimization of soil water characteristic parameters over measured field data should be carried out simultaneously with a combined objective function. As only very little information is available in the literature on this problem (e.g., Yates et al., 1992), it seems most likely that combined optimization of water retention and hydraulic conductivity parameters is unfortunately rarely used in practice.

Infiltration-based methods are recognized as valuable tools to investigate hydraulic and solute transport soil properties. In particular, two complementary methods appear to be interesting in the study of near saturated and field saturated soil behavior (Angulo-Jaramillo et al., 2000). They are the tension disk infiltrometer and the pressure ring infiltrometer.

In the tension disk infiltrometers, a graduated reservoir tower provides the water supply; the bubble tower with a moveable air-entry tube permits to impose different boundary condition pressure head values at the cloth base, which allows the determination of hydraulic conductivity values close to saturation avoiding the influence of macroporosity. For every imposed pressure head value, the cumulative infiltration, I, is recorded, against time, t, either by noting the water level drop in the reservoir tower or by using pressure transducers (i.e. Ankeny et al., 1988). The transient infiltration flux is then obtained by the derivative: $q(t) = \mathrm{d}I/\mathrm{d}t$. By the use of an inverse procedure, these flux data allow the calculation of the spot values of hydraulic conductivity and sorptivity, S, valid for the initial and boundary conditions chosen. In particular, this last parameter characterizes the ability of the soil to absorb water in the absence of gravity (Philip, 1957).

The single ring pressure infiltrometer (Reynolds and Elrick, 1990) is attractive for field use because is simple and reasonably rapid. It is a routinely used K_s measurement method (Vauclin et al., 1994; Ciollaro and Lamaddalena, 1998; Bagarello and Iovino, 1999; Bagarello et al., 2000; Reynolds et al., 2000; Bagarello and Sgroi, 2004; Angulo et al., 2000, Mertens et al., 2002; Gómez et al., 2005). The method uses a metal ring that is inserted into the soil to a given, small, depth. A constant hydraulic head, H, is established within the infiltration ring, and the flow rate into the soil is monitored. Flow goes through an initial decreasing phase, and then it approaches steady state conditions. Three dimensional, steady, ponded flow out of the ring is then used to estimate K_s (Reynolds and Elrick, 1990).

Recently, a portable field method has been reported in the literature that allows for the simultaneous characterization of both soil hydraulic characteristics, $h(\theta)$ and $K(\theta)$, unlike the previous infiltration-based methods which provide a partial soil hydraulic characterization. The method, termed as the "Beerkan method", was initially pioneered by Haverkamp et al. (1996). An improved version of this methodology, called the Beerkan Estimation of Soil Transfer parameters (BEST) procedure, was developed by Lassabatère et al. (2006) to simplify soil hydraulic characterization. BEST considers certain analytic formulae for hydraulic characteristic curves and estimates their shape parameters, which are texture dependent, from particle-size analysis by physical-empirical pedotransfer functions. Structure dependent scale parameters are estimated by a three-dimensional (3D) field infiltration experiment at zero pressure head, using the two-term transient infiltration equation by Haverkamp et al. (1994). BEST is very attractive for practical use since it substantially facilitates the hydraulic characterization of unsaturated soils, and it is gaining popularity in soil science. The BEST procedure has been used to characterize temporal variability of soil hydraulic properties under high-frequency drip irrigation (Mubarak et al., 2009b), review the soil hydraulic properties of a field sampled in the past (Mubarak et al., 2010), study the effect of sediment accumulation on the water infiltration capacity of two urban infiltration basins (Lassabatere et al., 2010), document the spatial variability of the water retention and soil hydraulic conductivity curves in a small watershed (Gonzalez-Sosa et al., 2010), study the hydraulic parameters of basic oxygen furnace slag (Yilmaz et al., 2010).

Therefore, the signs of a promising ability of the BEST procedure to yield a reasonably reliable soil hydraulic characterization can be found in the existing literature but there is still work to do.

In fact, several problems yet arise with the BEST method, including: (1) the need to carry out many calculations to analyze a single run, which may demand a lot of time; (2) the need to analyze the transient phase of the infiltration process, which may be uncertain for different reasons; (3) the absence of an extensive assessment of the BEST predictions against independent measurements, i.e. with soil data collected by other experimental methods; (4) the possible sensitivity of the data to soil disturbance and air entrapment during repeated water application, according to the BEST experimental procedure.

The main objective of the present thesis was to study and improve the BEST method in order to understand or give a solution to all the former problems and consequently to contribute towards its widespread application through the world.

2. Explanation of dissertation format

This dissertation consists of twelve manuscripts arising from my Ph.D. activity (Appendices from A to L). The first manuscript (Appendix A) was presented at the "*1st CIGR Inter-Regional Conference on Land and Water Challenges*" on 2013. The second manuscript (Appendix B) was published on *Soil Science Society of American Journal* in 2014. The third manuscript (Appendix C) was published on *Computer and Electronics in Agriculture* in 2015. Other five manuscripts (Appendices D, E, F, G and I) were published on *Geoderma* in 2016, 2011 and 2014. Other two manuscripts (Appendices H and K) were published on *Hydrological Processes* in 2015 and 2014. Another manuscript (Appendix J) was submitted to *Geoderma*. The last manuscript (Appendix L) was presented to the "*Four Decades of Progress in Monitoring and Modeling of Processes in the Soil-Plant-Atmosphere System: Applications and Challenges*" conference on 2013 and published in *Procedia Environmental Sciences*.

Six chapters precede the manuscripts: (1) *Introduction*; (2) the present chapter: *Explanation of dissertation format*; (3) *Theory*, where the BEST method is presented; (4) *Literature review*; (5) *Present study*, where all the manuscripts are briefly presented; and (6) *Conclusions*. In particular, in chapter 5.1. all the proposed improvements to BEST method were presented.

In chapter 5.2. all the tests carried out in different soils and the comparisons with alternative field and laboratory methodologies were summarized. In the latter chapter, the studies concerning the dependence of the measured hydrodynamic parameters on the experimental procedure used in BEST were also summarized. Finally, in chapter 5.3. a simplified method based on a Beerkan infiltration run to determine the saturated soil hydraulic conductivity was presented.

3. Theory: Beerkan Estimation of Soil Transfer parameters (BEST) procedure

As prescribed by Lassabatère et al. (2006), the Beerkan infiltration method uses a simple annular ring. The surface vegetation is removed while the roots remain in the soil. A soil sample is collected for particle-size analysis and to determine its initial gravimetric water content. Another sample of known volume is extracted to determine its dry bulk density, ρ_b (M L^{-3}). Then, the cylinder is inserted to a depth of about 0.01 m to avoid lateral loss of the ponded water. A known volume of water is poured in the cylinder at the start of the measurement and the elapsed time during infiltration is measured. When the amount of water has completely infiltrated, an identical amount of water is poured into the cylinder, and the time needed for the water to infiltrate is logged. The procedure is repeated for a series of about 8 to 15 known volumes of water and cumulative infiltration is recorded. An experimental cumulative infiltration, I (L), vs. time, t (L), relationship including a total of N_{tot} discrete points, is then deduced. At the end of the experiment, the saturated soil is sampled to determine the saturated gravimetric water content and thus the saturated volumetric water content, θ_s (L^{3}L^{-3}), from ρ_b and the gravimetric water content. However, θ_s can alternatively be approximated by total soil porosity, determined from ρ_b (Mubarak et al., 2009b).

The BEST method allows for the simultaneous determination of both the water retention curve, $h(\theta)$, and the hydraulic conductivity function, $K(\theta)$. The water retention curve describes the soil's ability to store or release water. It is a highly nonlinear S-shaped curve and varies typically with soil texture and structure. In the past, many different functional relations have been proposed in the literature. BEST focuses specifically on the van Genuchten (1980) relationship with the Burdine (1953) condition:

$$\frac{\theta-\theta_r}{\theta_s-\theta_r}=\left[1+\left(\frac{h}{h_g}\right)^n\right]^{-m} \qquad (1)$$

$$m=1-\frac{2}{n} \qquad (2)$$

where the water pressure head, h, is usually taken to be negative; h_g (L) is the van Genuchten pressure scale parameter; θ_r (L^{3}L^{-3}) is the residual soil water content (θ_r is assumed to be zero in BEST), and m and n are water retention shape parameters.

The hydraulic conductivity function highly depends on soil structure. BEST focuses specifically on the Brook and Corey (1964) relationship:

$$\frac{K(\theta)}{K_s}=\left(\frac{\theta-\theta_r}{\theta_s-\theta_r}\right)^\eta \qquad (3)$$

where the conductivity shape parameter η can be estimated from the capillary model (Haverkamp et al., 1999):

$$\eta=\frac{2}{m\times n}+2+p \qquad (4)$$

where the tortuosity parameter p is assumed equal to 1 in BEST (Burdine, 1953).

The shape parameters m, n and η are strongly linked to the soil textural properties, whereas the scale parameters h_g and K_s are related to soil structure (Haverkamp and Reggiani, 2002). BEST estimates shape parameters on the basis of particle size analysis and soil porosity determination. More specifically, estimation of n is based on the soil particle size distribution (PSD), which is modeled as:

$$P(D)=\left[1+\left(\frac{D_g}{D}\right)^N\right]^{-M} \qquad (5)$$

where $P(D)$ is the fraction by mass of particles passing a particular diameter, D (L); D_g (L) is a scale parameter; and N and $M = 1 - 2/N$ are shape factors. Fitting Eq. (5) to the measured PSD allows to calculate the shape index for PSD, p_M:

$$p_M = \frac{MN}{1+M} \tag{6}$$

The m parameter of Eq.(1) is calculated by:

$$m = \frac{1}{p_m}\left(\sqrt{1+p_m^2}-1\right) \tag{7}$$

where:

$$p_m = p_M(1+\kappa)^{-1} \tag{8}$$

$$\kappa = \frac{2s-1}{2s(1-s)} \tag{9}$$

$$(1-f)^s + f^{2s} = 1 \tag{10}$$

where f (L^3L^{-3}) is the soil porosity and s is the fractal dimension of the media, varying from 0.5 to 1 (Fuentes et al., 1998; Minasny and McBratney, 2007). Then the parameters n and η can be calculated by Eqs. (2) and (4), respectively.

An alternative way to estimate the n parameter used in the BEST procedure from the soil sand, sa (%, USDA classification), and clay, cl (%), content was proposed by Minasny and McBratney (2007):

$$n = 2.18 + 0.11[48.087 - 44.954\,S(x_1) - 1.023\,S(x_2) - 3.896\,S(x_3)] \tag{11a}$$

where:

$$x_1 = 24.547 - 0.238\,sa - 0.082\,cl \tag{11b}$$

$$x_2 = -3.569 + 0.081\,sa \tag{11c}$$

$$x_3 = 0.694 - 0.024\,sa + 0.048\,cl \tag{16d}$$

$$S(x) = \frac{1}{1+\exp(-x)} \tag{11e}$$

A list of n values for the twelve USDA texture classes was also proposed (Minasny and McBratney, 2007).

The infiltration theory of the BEST method starts from the one-dimensional (1D) implicit equation for cumulative infiltration, I_{1D}, into an initially uniform unsaturated soil profile under any zero or negative value of the pressure head at the soil surface, h_{surf} ($h_{surf} \leq 0$), derived by Haverkamp et al. (1990), who analytically solved the 1D Richards equation. In particular, the following equation applies to the case of zero pressure head and water saturation at soil surface:

$$\frac{2\Delta K^2}{S^2}t = \frac{1}{1-\beta}\left[\frac{2\Delta K}{S^2}\left(I_{1D}(t) - K_0 t\right) - \ln\left(\frac{\exp\left(2\beta\frac{\Delta K}{S^2}\left(I_{1D}(t) - K_0 t\right)\right) + \beta - 1}{\beta}\right)\right] \tag{12}$$

where ΔK ($=K_s - K_0$) stands for the difference between K_s and the initial hydraulic conductivity, K_0 ($=K(\theta_0)$); θ_0 is the initial volumetric soil water content; t is the time; β is a coefficient that is commonly set at 0.6 for $\theta_0 < 0.25\ \theta_s$ (Haverkamp et al., 1994); and S ($=S(\theta_0, \theta_s)$) stands for the sorptivity, which can be estimated from soil hydraulic properties in the interval of volumetric soil water content, θ, between θ_0 and θ_s as follows (Parlange, 1975):

$$S^2 = \int_{\theta_0}^{\theta_s}(\theta + \theta_s - 2\theta_0)D(\theta)\,d\theta \tag{13}$$

where D stands for soil diffusivity (Haverkamp et al., 2005).

One dimensional infiltration model (Eq. 12) was extended to three-dimensional (3D) infiltration from a surface disk source by Smettem et al. (1994), adding a term representing 3D geometrical effects:

$$I(t) = I_{1D}(t) + \frac{\gamma\,S^2}{r\Delta\theta}t \tag{14}$$

where I is 3D cumulative infiltration; r is the radius of the disk source; γ is a shape parameter for geometrical correction of the infiltration front shape, commonly set at 0.75 for $\theta_0 < 0.25\ \theta_s$ (Haverkamp et al., 1994); and $\Delta\theta$ is equal to θ_s - θ_0. Lassabatère et al. (2009) validated the analytical model [Eqs. (12-14)] using numerically generated data for the case of a zero pressure head at surface and for a large range of initial pressure heads.

The 3D cumulative infiltration, I (L), and the infiltration rate, i (L T^{-1}), can be approached by the following explicit transient [Eqs.(15a) and (15b)] and steady-state [Eqs.(15c) and (15d)] expansions (Haverkamp et al., 1994; Lassabatère et al., 2006):

$$I(t) = S\sqrt{t} + \left(AS^2 + BK_s\right)t \tag{15a}$$

$$i(t) = \frac{S}{2\sqrt{t}} + \left(AS^2 + BK_s\right) \tag{15b}$$

$$I_{+\infty}(t) = \left(AS^2 + K_s\right) t + C\frac{S^2}{K_s} \tag{15c}$$

$$i_s = AS^2 + K_s \tag{15d}$$

where A (L^{-1}), B and C are constants defined for the specific case of a Brook and Corey (1964) relation (Eq. 3) and taking into account initial conditions as (Haverkamp et al., 1994):

$$A = \frac{\gamma}{r(\theta_s - \theta_0)} \tag{16a}$$

$$B = \frac{2-\beta}{3}\left[1 - \left(\frac{\theta_0}{\theta_s}\right)^{\eta}\right] + \left(\frac{\theta_0}{\theta_s}\right)^{\eta} \tag{16b}$$

$$C = \frac{1}{2\left[1 - \left(\frac{\theta_0}{\theta_s}\right)^{\eta}\right](1-\beta)} \ln\left(\frac{1}{\beta}\right) \tag{16c}$$

In the BEST procedure sorptivity can be expressed as a function of the scale parameters by the following relationship:

$$S^2(\theta_0, \theta_s) = -c_p \theta_s K_s h_g \left(1 - \frac{\theta_0}{\theta_s}\right)\left[1 - \left(\frac{\theta_0}{\theta_s}\right)^{\eta}\right] \tag{17}$$

where:

$$c_p = \Gamma\left(1 + \frac{1}{n}\right)\left\{\frac{\Gamma\left(m\eta - \frac{1}{n}\right)}{\Gamma(m\eta)} + \frac{\Gamma\left(m\eta + m - \frac{1}{n}\right)}{\Gamma(m\eta + m)}\right\} \tag{18}$$

where Γ stands for the Gamma function.

The saturated hydraulic conductivity and the scale parameter for the water retention curve, h_g, are estimated from a three-dimensional field infiltration experiment at zero pressure head (Lassabatère et al., 2006). More specifically, this last parameter is derived from the concomitant estimation of K_s and S through fitting the simplified expansions defined by Eq. (15) onto the experimental cumulative infiltration and estimated by the following relation obtained from Eq. (17):

$$h_g = -\frac{S^2}{c_p(\theta_s - \theta_0)\left[1 - \left(\frac{\theta_0}{\theta_s}\right)^{\eta}\right] K_s} \tag{19}$$

For the derivation of K_s and S, two different BEST algorithms were proposed that differ by the way Eq. (15) is fitted to experimental infiltration data.

3.1. BEST-slope

The BEST-slope algorithm by Lassabatere et al. (2006) considers Eq. (15a) for modelling the transient cumulative infiltration data. Eq. (15a) is modified with the replacement of hydraulic conductivity as a function of sorptivity and the experimental steady-state infiltration rate, i_s^{exp}, using Eq. (15d), leading to:

$$K_s = i_s^{\exp} - AS^2 \tag{20a}$$

$$I(t) = S\sqrt{t} + \left[A(1-B)S^2 + B\, i_s^{\exp}\right] t \tag{20b}$$

where, i_s^{exp} is estimated by linear regression analysis of the last data points describing steady-state conditions on the I vs. t plot and corresponds to the slope of the regression line. Eq. (20b) is fitted to experimental data to estimate sorptivity, S. Establishing a constraint like Eq. (20a) between the estimator for sorptivity and the one for saturated hydraulic conductivity and inverting cumulative infiltration data through optimizing only sorptivity avoids parameter non-uniqueness and increases the robustness of the inverse procedure (Lassabatere et al., 2013). The fit is performed by minimizing the classical objective function for cumulative infiltration:

$$f(S,\ K_s,\ k) = \sum_{i=1}^{k}\left[I^{\exp}(t_i) - I_{est}(t_i)\right]^2 \tag{21}$$

where k is the number of data points considered for the transient state, I^{exp} is the experimental cumulative infiltration and I_{est} is the estimated cumulative infiltration using Eq. (20b). Once S is estimated, K_s is calculated by Eq. (20a). As the infiltration model is valid only at transient state, the fit may not be valid for large values of k. Therefore, BEST fits data for a minimum of five points to a maximum of N_{tot} points, representing the whole dataset. For each data subset containing the first k points, corresponding to a duration of the experiment equal to t_k, S and K_s are estimated and the time, t_{max} (T), defined as the maximum time for which the transient expression can be considered valid, is determined:

$$t_{\max} = \frac{1}{4(1-B)^2}\left(\frac{S}{K_s}\right)^2 \quad (22)$$

where $(S/K_s)^2$ is the gravity time defined by Philip (1969). Then, t_k is compared with t_{max}. The values of S and K_s are not considered valid unless t_k is lower than t_{max}. Among all values of S and K_s that fulfill this condition, the S and K_s values corresponding to the largest k (k_{step}) are retained since they are considered more precise.

3.2. BEST-intercept

Yilmaz et al. (2010) determined the hydraulic parameters of Basic Oxygen Furnace slag (BOF) through BEST. These authors introduced a new BEST algorithm, named BEST-intercept, to allow the inversion of experimental data on a highly sorptive porous material such as BOF slag.

Furthermore, according to these authors, BEST-slope may lead to erroneous K_s values, especially when $i_s \approx AS^2$. Under such conditions, attempting to estimate K_s by Eq. (20a) appears to be inappropriate. More specifically, when the estimated AS^2 value exceeds the measured infiltration rate at the end of the experiment, the values obtained for K_s are negative. In the BEST-intercept algorithm by Yilmaz et al. (2010), the constraint between S and K_s is defined by using the intercept of the asymptotic expansion in Eq. (15c):

$$b_s^{\exp} = \frac{C\ S^2}{K_s} \quad (23)$$

Therefore, b_s^{exp} is estimated by linear regression analysis of the data describing steady-state conditions on the I vs. t plot, and the following relationship is applied to determine K_s:

$$K_s = C\frac{S^2}{b_s^{\exp}} \quad (24)$$

This procedure leads to the use of the division operator rather than the subtraction operator and thereby avoids obtaining negative values for the estimation of K_s. Combining Eqs. (15a) and (24) yields the following relationship to fit onto the transient state of the experimental cumulative infiltration:

$$I(t) = S\sqrt{t} + \left(AS^2 + BC\frac{S^2}{b_s^{\exp}}\right)t \quad (25)$$

Eq. (25), that is alternative to Eq. (20b), is applied to determine S by the same procedure described for BEST-slope, including the assessment of the time validity of the transient infiltration model by calculation of t_{max}. The estimated sorptivity is then used to calculate K_s by Eq. (24).

4. Literature review

Due to its simplicity and the physical soundness of the employed relationships and procedures, BEST is receiving increasing attention by the scientific community.

For example, Mubarak et al. (2009a, 2009b) used the BEST method to characterize temporal variability of soil hydraulic properties and to explore the effects of the detected variability on the simulated water transfer processes. In particular, these authors analyzed the behavior of a loamy soil under drip irrigation using the BEST method to identify the temporal variability of its hydraulic properties caused by high frequency irrigation during a maize cropping season. Their results demonstrated that the soil porosity and the hydraulic properties varied over time. This behavior was explained by the “hydraulic” compaction of the surface soil following irrigation.

Cannavo et al. (2010) showed the effect of the variability of sediment content on some of the physical transfer properties in the soil of a retention/infiltration basin. These authors mapped the infiltration capacity to supplement more punctual data previously acquired on the basin. In particular, they used the BEST method on the basin to characterize the saturated hydraulic conductivity. On the basis of the established correlations, the authors proposed satisfactory relationships between sediment content and physical transfer properties in order to predict these last variables through modelling.

Mubarak et al. (2010) reviewed the spatial analysis of soil hydraulic properties after 17 years of repeated agricultural practices for tillage and planting. Surface infiltration tests were performed using BEST to characterize the soil. These authors compared the soil hydraulic properties and their spatial structures to those reported in 1990 (Vauclin et al., 1994), through the exponential form of the soil hydraulic conductivity given by the Gardner equation, using the Guelph Pressure Infiltrometer technique. They reported that the spatial analysis of soil hydraulic properties is independent of the infiltration methods used in the two studies, suggesting BEST as a promising, easy, robust, and inexpensive way of characterizing soil hydraulic behavior and its spatial and temporal variability across a field.

Lassabatère et al. (2010) established the effect of sediment accumulation on the water infiltration capacity of two urban infiltration basins. In particular, these authors performed a full characterization of the unsaturated properties of sediments and subsoil by means of the BEST inverse analysis. These properties were used to model the effect of sediments on 1D water infiltration at basin scale, simulating real operating conditions for three model rainfalls (shower, rainfall and light rainfall) and the full year 2008. Their results clearly proved that sediments reduced local water infiltration capacities, due to their lower saturated hydraulic conductivities. Moreover, numerical results showed that this finding could have a drastic impact on water infiltration at the basin scale through increasing the number and duration of water pondings. From the technical point of view, their study underlined the need for efficient monitoring of infiltration basin sedimentation and its impact on water infiltration capacity.

Gonzalez-Sosa et al. (2010) documented the spatial variability of soil hydraulic properties (including both the retention and the hydraulic conductivity curves) linked to pedology and land use within the catchment using two types of infiltration tests, i.e. BEST method and tension-disk infiltration tests. The complementary use of tension-disk and positive head infiltration tests highlighted a sharp increase of hydraulic conductivity between near saturation and saturated conditions, attributed to macroporosity effects. Their study suggested that soil texture, such as used in most pedo-transfer functions, might not be sufficient to properly map the variability of soil hydraulic properties. Land use information should be considered in the parameterizations of topsoil within hydrological models to better represent in situ conditions.

Yilmaz et al. (2010) highlighted the evolution with time of BOF slag hydraulic parameters due to their physicochemical changes when exposed to rainfall events, and also the spatial variability of the hydrodynamic characteristics, which after a certain period shifts to mostly homogeneous behavior. Differences by a factor of more than an order of magnitude were reported by these authors for the K_s values obtained with the BEST-slope and BEST-intercept algorithms. However, a conclusion by these authors was that BEST-intercept yielded a more reliable soil hydraulic characterization than BEST-slope.

Xu et al. (2012) compared four methods for analyzing single-ring infiltrometer data to estimate K_s and the scale parameter of the soil water retention function, α (L^{-1}). These methods were: (1) BEST-slope; (2) BEST-intercept; (3) Wu1 (Wu et al., 1999) which attempts the best fit of a generalized solution to the infiltration curve using the whole infiltration curve; and (4) Wu2 (Wu et al., 1999) which is suitable for the steady state flow case. The first three methods are suitable for the transient flow state. These authors used infiltration data of 54 different cases within four soil texture classes (sand, sandy loam, loam, and clay loam). Their results suggested that BEST-intercept had a better performance (more reasonable estimates) than BEST-slope. Both BEST algorithms performed poorly for the sandy soils. The Wu1 method performed better in fitting the experimental infiltration curve, and produced more cases with reasonable values (normally positive values) of K_s and α than both BEST algorithms. Therefore they concluded that in order to apply these existing methods to wider conditions (e.g., sandy soils, wet soils, basic oxygen furnace slag), the inversion estimation algorithms and the experimental operations in the field require further improvement.

Bagarello and Iovino (2012) studied the suitability of the BEST procedures to predict the soil water retention curve. In their investigation, the authors suggested that: (1) the van Genuchten water retention equation can be considered appropriate for most soils although a relatively poor description of retention data is expected for low θ values; (2) determining the clay content of the soil allows to predict sensitivity of the particle-size shape index to the calculation procedure; (3) the procedure developed by Minasny and McBratney (2007) to estimate the *n* parameter used with the BEST procedure should be preferred as compared with the original one, especially in clay-rich soils. Finally, these authors concluded that the BEST procedure shows promise for a reasonably rapid and simple soil hydraulic characterization. Therefore, an experimental assessment of the complete BEST procedure is advisable. At this aim, the reliability of the scale parameters determined by the infiltration experiment should also be evaluated.

Nasta et al. (2012) carried out a sensitivity analysis of the BEST algorithm regarding the choice of tortuosity (p) and infiltration constants (γ and β) in their feasible range. These authors demonstrated that tortuosity (p) plays only a secondary role compared with constants β and γ, which are more important for the estimation of the scale parameters. Numerical simulations performed using HYDRUS 2D/3D with the soil hydraulic parameters estimated by BEST provided a good description of experimental cumulative infiltration curves, indicating reliability of this technique. They offered an interpretation of the role of the two infiltration constants, highlighting the pros and cons that characterize the analytical model by Haverkamp et al. (1994). The proper calibration of these two constants, as a function of the soil type, could significantly further improve the estimates of the soil hydraulic parameters. They therefore concluded that, for soil surface horizons not significantly affected by macroporosity or preferential flow, the soil hydraulic parameters derived using the BEST algorithm can be used in numerical models to accurately describe water infiltration.

Finally, according to Souza et al. (2014), single-ring infiltration along with BEST algorithm and shear strength measures showed high potential to assess, under field and natural rainfall conditions, the effect of soil surface crusting on the mechanical and hydrodynamic properties of a cropped soil.

5. Present study

BEST is very attractive for practical use since it substantially facilitates the hydraulic characterization of unsaturated soils and, as shown before, it is gaining popularity in soil science (e.g., Bagarello and Iovino, 2012; Cannavo et al., 2010; Gonzalez-Sosa et al., 2010; Lassabatere et al., 2010, 2007; Mubarak et al., 2010, 2009a, 2009b; Nasta et al., 2012; Souza et al., 2014; Xu et al., 2012; Yilmaz et al., 2010). The signs of a promising ability of the BEST procedure to yield a reasonably reliable soil hydraulic characterization can be found in the existing literature but there is still work to do. During my Ph.D. work, the BEST method was studied and improved in order to contribute towards its widespread application throughout the world.

With this aim, improvements to BEST method were proposed in terms of analysis of the collected data, estimation of hydrodynamic parameters and automation of the experimental procedure. Moreover, BEST was tested in different soils and compared with several alternative field and laboratory methodologies highlighting the pros and cons that characterize the method and allowing to design BEST as a promising, easy, robust, and inexpensive way of characterizing soil hydraulic behavior. The dependence of the measured hydrodynamic parameters on the experimental procedure used in BEST was also studied with the objective to improve our ability to interpret the field data and the linked hydrological processes. Finally, a simplified method based on a Beerkan infiltration run to determine the saturated soil hydraulic conductivity by only a transient infiltration process was developed. This method is a good candidate method for intensive field campaigns with a practically sustainable experimental effort.

In this chapter all the above mentioned topics are briefly presented.

5.1. Improvements of BEST method

5.1.1. Automatic analysis of multiple Beerkan infiltration experiments

Alternative algorithms have been suggested to determine soil sorptivity and saturated soil hydraulic conductivity from a simply measured cumulative infiltration curve. With these algorithms, calculations have to be repeated several times, depending on the number of collected infiltration data, that should vary between eight and 15. The need to consider a variable number of infiltration data is related to the fact that the infiltration model used in BEST is valid for the transient phase of the process, and only experimental data representative of this phase of the infiltration process have to be selected. The fitting of the theoretical model to the data is carried out by minimizing the sum of the squared residuals between model-predicted and measured infiltration data. Therefore, analyzing a single run may demand a lot of time, since many calculations have to be carried out. This circumstance complicates soil hydraulic characterization based on an intensive soil sampling, and it also increases the risk to make mistakes. These problems are expected to be substantially reduced, or even eliminated, if an automatic procedure of data analysis is applied. With this aim, **Di Prima (2013; Appendix A)** developed a workbook to easily and rapidly analyze databases including several BEST runs. The developed workbook makes use of the Microsoft Excel Solver add-in routine. A Visual Basic for Applications (VBA) macro was written to automate creation and manipulation of Microsoft Excel Solver. A looping structure was used in the VBA macro to automate data analysis of BEST experiments. The developed workbook can be viewed as a practically useful contribution to an expeditious, intensive soil hydraulic characterization, also in terms of analysis of the collected data.

5.1.2. Alternative algorithms to analyze the Beerkan infiltration experiment

A further problem arising with BEST method is the analysis of the transient phase of the infiltration process, which may be uncertain for several reasons. According to Wu et al. (1999), ponded infiltration data collected in the first few minutes are less reliable than the ones measured later. Moreover, when the influence of capillary forces is very short, S is estimated with only a small number of points, which is theoretically adequate but it can be detrimental to the robustness of the optimization (Gonzalez-Sosa et al., 2010). With the aim to avoid possible problems associated with the use of the transient infiltration data, **Bagarello et al. (2014c; Appendix B)** proposed an alternative BEST algorithm, labeled by the same authors as BEST-steady, making exclusive use of the steady-state phase of the infiltration run. The authors also compared the alternative algorithms for analyzing the Beerkan infiltration experiment. In particular, they carried out a comparison between BEST-slope and BEST-intercept with reference to approximately 400 infiltration runs carried out in Sicily (Italy) and Burundi. Then, they developed and tested the new BEST-steady algorithm, that combines selected procedures embedded in BEST-slope and BEST-intercept. The BEST-steady algorithm has several theoretical and practical advantages as compared with the existing algorithms, including (1) high probability of success of the run; (2) simplified calculation of S and K_s; (3) no need to use potentially invalid S and K_s calculations to establish the time validity of the transient infiltration model; (4) possibility to adjust the run duration directly in the field to obtain the most representative possible infiltration curve for the sampled location; and (5) possibility to assign the measured soil properties to a specific stage of the water infiltration process in an initially unsaturated soil. Therefore, BEST-steady should be considered a promising alternative procedure to analyze the Beerkan infiltration data.

5.1.3. Automation of the Beerkan infiltration experiment

According to Alagna et al. (2015a) and Bagarello et al. (2014a, 2014b), the infiltration experiment prescribed by Lassabatère et al. (2006) can be sensitive to soil disturbance and air entrapment during repeated water application. These alterations are expected to have a more appreciable impact on the measured conductivity with the BEST technique than a ponding infiltration experiment since a constant ponded depth of water is maintained during the run with the latter technique whereas water is repeatedly poured with the former one. Moreover, several problems yet arise with BEST method, including (1) the need for an operator over the whole duration of the experiment; (2) the need to reach steady state infiltration, which can be extremely long in certain cases; and (3) the experimental error and the variable skillness among operators. Furthermore, since hydraulic conductivity is determined essentially at points on a field, a large number of determinations is required to assess the magnitude and structure of the variation within the selected area (Logsdon and Jaynes, 1996). Spatially distributed determinations of hydraulic conductivity have to be repeated at different times, particularly in soils where structure varies over time because of natural or anthropogenic factors (Prieksat et al., 1994). For structured soils in particular, saturated hydraulic conductivity has to be measured directly in the field to minimize disturbance of the sampled soil volume and to maintain its functional connection with the surrounding soil (Bouma, 1982). Therefore, since reliable field data should be collected with a reasonably simple and rapid experiment, and a ponding infiltration experiment with a constant ponded depth is expected to minimize soil disturbance, the use of a single-ring infiltrometer along with BEST method could be advisable. An automated single-ring infiltrometer was first developed by Prieksat et al. (1992). The infiltrometer maintains a quasi-constant head in a containment ring, allowing to calculate flow rates from changes in water height in a Mariotte reservoir with time. Automated measurements of reservoir water levels using a differential transducer were first tested by Casey and Derby (2002). The voltage output from the transducer is linearly related to the difference between head-space tension and the height of water in the Mariotte reservoir (Constantz and Murphy, 1987). Nevertheless, the advantage of simplified methodologies, such as BEST, is their simplicity as well as their economy (Dohnal et al., 2010; Madsen and Chandler, 2007). The use of expensive devices or time consuming procedures could contradict their original purpose. In fact, automatic data collection increases measurement speeds and improves measurement precision but monitoring equipment often contains proprietary technology with prohibitive cost for this purpose. Recently, advances in electronic technologies have provided researchers to access to low-cost, solid-state sensors and programmable microcontroller-based circuits (Fisher and Gould, 2012). **Di Prima (2015; Appendix C)** developed a device to automate data collection with a compact infiltrometer under constant head conditions and through low-cost and open source technology. The device consists of a containment ring and the infiltrometer itself, including a Mariotte system and a reservoir, to supply water during infiltration and maintain a small quasi-constant head of water (i.e., 2-3 mm). The new infiltrometer is equipped with a differential pressure transducer to measure the stepwise drop of water level in the reservoir, and, in turns, to quantify water cumulative infiltration into the soil. The measures of pressure transducers are collected and stored by a specific data acquisition system, designed with low cost components and based on the open source Arduino system and the MPXV5004DP differential pressure sensor. Furthermore, a new approach to process the data for determining an accurate cumulative infiltration curve from transducer output was developed. The proposed electronic data acquisition system constitutes a very cost effective alternative to previously proposed equipment, which could represent a step towards a cheaper and more widespread application of accurate and automated infiltration rate measurement.

5.1.4. Testing the new automated single ring infiltrometer and the three BEST algorithms

Afterwards, **Di Prima et al. (2016; Appendix D)** tested the infiltrometer with the aim to check the usability of the device to automatize the Beerkan infiltration experiment and to analyse the infiltration data to characterize soil hydraulic properties. The focus was put on the derivation of saturated soil hydraulic conductivity and soil sorptivity by using the combination of the automated infiltrometer and the three BEST algorithms, i.e. BEST-slope, BEST-intercept and BEST-steady. The proposed combination was assessed by using both analytically generated and field data. In particular, these authors used analytically generated data to assess the accuracy of the BEST predictions of K_s and S obtained by the infiltration of 130 mm of water, sampled every 5 mm, through a 150 mm diameter soil surface as fixed by the device. Then, a sensitivity analysis was performed to investigate the influence of total cumulative infiltration and infiltration increments. Different soils and experimental conditions were chosen to test the infiltrometer over a wide range of situations including problematic cases for hydraulic characterization with the Beerkan method, such as hydrophobia or high measured infiltration rate (Gonzalez-Sosa et al., 2010; Lassabatere et al., 2010). Field experiments were carried out in western Sicily in order to compare the automated and the original BEST procedure (Beerkan method). Three different sites, showing appreciable differences in both soil texture and land use (Bagarello et al., 2014a), were sampled. Other field experiments were carried out in an infiltration basin located in the pumping well field of Crépieux-Charmy, which provides drinking water for the Lyon metropolitan area. It is the largest well field in Europe (375 ha, 1 280 000 inhabitants supplied). Several infiltration basins have been settled on the site to create a hydraulic barrier against pollution events from the Rhone River and to improve aquifer recharge. The basins were built by excavation of natural soils and were covered with a layer of calibrated sand about 20 cm thick. The sand layers aim at filtrating the water and preventing the subsoil from clogging. Suitability of infiltration basins can be altered by clogging processes that reduce their hydraulic performance (Gette-Bouvarot et al., 2014). Consequently, the top layer of the basins is periodically removed and substituted with a new sand layer. In the selected basin, during dredging, the subsoil corresponding to a coarse fluvio-glacial deposit (Goutaland et al., 2013), a layer of sand recently embedded and the old clogged sand were sampled. Di Prima et al. (2016) suggested that the new automated infiltrometer should be an efficient and easy-to-use device to characterize water infiltration at the surface of contrasting soils. In particular, the quantification of water infiltration in coarse soils, usually considered as very challenging, was successful. The use of BEST algorithms lead to proper estimates when the conditions for their use were respected. In more details, all algorithms require a proper attainment of steady state and estimates may suffer from an insufficient infiltration of water. BEST-steady is more robust than the other algorithms and provides always estimations of the hydraulic parameters, whereas BEST-slope and BEST-intercept may fail when the transient state is not enough detailed. In terms of estimate accuracy, BEST-steady and BEST-intercept gave similar trends, with poorer estimates for BEST-intercept. BEST-slope provided more accurate estimates but failed to provide values in certain cases.

5.2. Application of BEST method and comparison with others methodologies

5.2.1. Testing different approaches to characterize the soil by the BEST procedure

Further efforts were undertaken to test the applicability of the BEST procedure through the world. For example, **Bagarello et al. (2011; Appendix E)** applied the BEST procedure for hydraulic characterization and physical quality evaluation of some Burundian soils. These authors determined the fitting ability of the soil particle size distribution used in the procedure, concluding that a reduced amount of experimental information did not compromise the soil hydraulic characterization. Therefore, the BEST procedure seems also to be usable when only a rough description of the PSD is available. This result has practical importance especially in areas of the world where soil hydraulic characterization is difficult due to the lack of laboratories and skilled personnel.

5.2.2. A test of the BEST procedure

Moreover, the large interest for the BEST procedure justifies comparisons of the predicted soil properties with independent measurements, i.e. with soil data collected by other experimental methods. An extensive assessment of the BEST predictions against alternative methods has still to be carried out, although some contributions can now be found in the literature (Yilmaz et al., 2010). With this aim, **Bagarello et al. (2014b; Appendix F)** tested the applicability of the BEST procedure at the near point scale, i.e. within an area of a few square meters, in different Sicilian soils. The predicted soil hydraulic parameters were used to establish a comparison with laboratory measured water retention data and field measured saturated and unsaturated soil hydraulic conductivities. In the investigation, BEST yielded physically possible scale parameters of the soil characteristic curves in most of the replicated infiltration runs and the measured water retention was satisfactorily predicted. Reasonable saturated soil hydraulic conductivity values were also obtained, although some trace of soil disturbance by the infiltration run was detected. The predicted unsaturated soil hydraulic conductivity was higher than the measured one, probably because the unimodal hydraulic conductivity function used in BEST does not reproduce the changes in the pore system of a real soil in the pressure head range close to saturation.

5.2.3. An assessment of the BEST procedure

Another investigation conducted by **Aiello et al. (2014; Appendix G)** tested the applicability of the BEST procedure in a sandy loam soil supporting a young orange orchard in eastern Sicily. At this aim, the predicted soil hydraulic parameters were used to establish a comparison with laboratory measured water retention data. The saturated soil hydraulic conductivity, K_s, obtained with several BEST scenarios, method 2 by Wu et al. (1999) applied to the BEST infiltration run and the SFH technique (Bagarello et al., 2004) were also compared. In the investigation, the water retention model used by BEST reproduced satisfactorily the experimental data. In particular, a good correspondence between the predicted and the experimental water retention was detected when the original BEST-slope algorithm was applied with the infiltration constants set at β = 1.9 and γ = 0.79. In this case, BEST also yielded plausible K_s values, i.e. differing by not more than a factor of two from the corresponding estimates obtained by applying the Wu et al. (1999) solution for single ring infiltrometers to the steady-state part of the measured infiltration process. The SFH technique yielded K_s values approximately five times higher than those of BEST, probably because with the former technique soil disturbance during water application, swelling and air entrapment phenomena had a less noticeable impact on the measured infiltration.

5.2.4. Determining hydraulic properties by alternative infiltrometer techniques

Afterwards, **Alagna et al. (2015b; Appendix H)** assessed usability of different infiltrometer techniques for determining the soil hydraulic properties of a loam soil. These authors compared the soil hydraulic properties predicted by the BEST procedure with independent measurements of these properties. Six infiltration techniques to determine the saturated soil hydraulic conductivity were also compared. In particular, K_s

was determined with BEST, the pressure infiltrometer (PI) (Reynolds and Elrick, 1990), the SFH technique, the tension infiltrometer (TI) (Ankeny et al., 1991; Perroux and White, 1988), the mini disk infiltrometer (MDI) (Dohnal et al., 2010), and the bottomless bucket (BB) method (Nimmo et al., 2009). BEST yielded water retention values statistically similar to those obtained in the laboratory and K_s values practically coinciding with those determined in the field with the PI. The unsaturated soil hydraulic conductivity measured with the TI was reproduced satisfactorily by BEST only close to saturation. BEST, the PI, one-potential experiments with both the TI and the MDI, the SFH technique and the BB method yielded statistically similar estimates of K_s, differing at the most by a factor of three. Smaller values were obtained with longer and more soil-disturbing infiltration runs. Any of the tested infiltration techniques appears usable to obtain the order of magnitude of K_s at the field site but the BEST, BB and PI data appear more appropriate to characterize the soil at some stage during a rainfall event.

5.2.5. Soil hydraulic properties determined by infiltration experiments and different heights of water pouring

Other efforts were undertaken in order to study the dependence of the measured conductivity on the water application procedure. In fact, water application procedures can influence measurement of K_s due to hydrodynamic shearing determining particle removal and rapid self-filtration of soil particles (Dikinya et al., 2008). With this aim, **Bagarello et al. (2014a; Appendix I)** determined the effect of the height of water application on the hydraulic properties obtained with the SFH technique and the BEST procedure. Since porous media differ by their susceptibility to external alteration phenomena (e.g., Ben-Hur et al., 1985; Ramos et al., 2000; Shainberg and Singer, 1988), water application effects were established at four different Sicilian sites. These authors concluded that the height of pouring did not affect significantly and/or appreciably the measured conductivities with the SFH technique. On the other hand, the height of water application influenced significantly and substantially the measured conductivities with BEST. In particular, with a great height of pouring, the BEST technique yielded substantially lower K_s values than the SFH technique. The different sensitivity of the two techniques to water application height was attributed to the fact that water was applied once with the SFH technique and several times with the BEST procedure. Each water application generally contributed to alter the soil surface, and total energy of the applied water was a more appropriate predictor of the changes in K_s when soil deterioration was not completed before concluding the infiltration run. Therefore, the choice of the methodology to be applied (SFH, BEST) and the height of water application should vary with the intended use of the K_s data. If the objective of the field campaign is to obtain data usable to explain surface runoff generation phenomena during intense rainfall events, the most appropriate choice among the tested ones should be BEST with a high run, to mimic relatively prolonged rainfall effects on the soil surface. A low run is more appropriate to determine the saturated conductivity of a soil that is not directly impacted by rainfall, due for example to the presence of a mulching on the soil surface. In this case, the SFH and BEST techniques appear to yield relatively similar results in sandy loam and clay soils, which suggests that the more rapid SFH technique should be applied if only K_s is the variable of interest.

5.2.6. Testing infiltration run effects on the water transmission properties

Moreover, it should be established if, for a given soil, the effect of the height of water pouring on the calculated hydrodynamic parameters varies with the initial soil water content, taking into account that changes in soil structure due to wetting depend on the antecedent wetness conditions (Cerdà, 1998; Le Bissonnais, 1996).

With this aim, **Alagna et al. (2015a; Appendix J)** checked the effect of the height of water application on the saturated hydraulic conductivity and the sorptivity determined with the BEST procedure for different values of the initial soil water content. They found that height of water application effects were particularly noticeable for K_s. In fact, this property depends strongly on soil structure that was altered by pouring water from a great height. Sorptivity was less affected by the height of water pouring since this property depends more than K_s on soil matrix, which is less affected by the water application procedure. Height of water pouring had more appreciable effects on K_s in the initially drier soil conditions, and a more soil perturbing experiment (high infiltration runs) reduced the dependence of K_s on the initial soil water content detected with the low and less perturbing runs. High runs also had a homogenizing effect on the measured conductivity. Therefore, their results suggest that a water application determining a noticeable disturbance of the soil surface reduces in general infiltration but it also attenuates the effect of the initial soil water content on this process. In other words, the height of water application has a reduced impact on the measured soil properties in relatively wet soil conditions.

5.3. Simplified field methodology based on Beerkan experiment

Other studies were oriented to simplify the soil hydraulic characterization. In particular, on the basis of the BEST procedure, **Bagarello et al. (2014d; Appendix K)** developed a Simplified method based on a Beerkan Infiltration run (SBI method) to determine K_s by only a transient infiltration process through a soil surface confined by a ring and an estimate of the α^* parameter (expressing the relative importance of gravity and capillary forces during an infiltration process) (Reynolds and Elrick, 1990). An $\alpha^* = 0.012$ mm^{-1}, suggested as the value of first approximation for most agricultural soils, was found to be usable in the agricultural tropical soils sampled in Burundi. In particular, this value of α^* allowed to obtain an estimate of K_s differing at the most by a practically negligible factor of two from the K_s values obtained by the complete BEST procedure of soil hydraulic characterization. A more important result was however the empirical detection of a physically plausible relationship between α^* and the slope of the linearized infiltration curve, that implies that the measured infiltration curve contained the necessary information to estimate α^*. The developed α^* predictive relationship allowed to reproduce accurately the K_s values obtained by BEST in terms of means and individual predictions, and it should be robust enough to be used in soils similar to the sampled ones since it was obtained by considering a reasonably large dataset.

Bagarello et al. (2013; Appendix L) carried out further studies with the general objective to validate the new method for determining K_s with reference to a larger dataset. The K_s values obtained by the simplified method were compared with the ones determined by BEST and the One Ponding Depth (OPD) approach for the single ring pressure infiltrometer technique, detecting a clear similarities between the procedures. The developed method is cheap, rapid and parsimonious in terms of both the devices that have to be transported and the measurements that have to be carried out in the field. Therefore, it is a good candidate method for intensively sampling an area of interest with a practically sustainable experimental effort and, hence, it could allow improved interpretation and simulation of soil hydrological processes, such as runoff generation.

6. Summary and conclusions

During my Ph.D. work, the BEST method was studied and improved in order to contribute towards its widespread application throughout the world. In particular, improvements to BEST method were proposed in terms of analysis of the collected data, estimation of hydrodynamic parameters and automation of the experimental procedure. Concerning the first topic, the workbook developed by **Di Prima (2013; Appendix A)** can be viewed as a practically useful contribution to an expeditious, intensive soil hydraulic characterization, also in terms of analysis of the collected data. Secondly, the alternative algorithm to analyze the Beerkan infiltration data, introduced by **Bagarello et al. (2014c; Appendix B)** and named BEST-steady, could be considered a promising alternative procedure to analyze the Beerkan infiltration data. In fact, this algorithm has both theoretical and practical advantages as compared with the existing algorithms, including (1) high probability of success; (2) simplified calculation of S and K_s; (3) no need to use potentially invalid S and K_s calculations to establish the time validity of the transient infiltration model; (4) possibility to adjust the run duration directly in the field to obtain the most representative possible infiltration curve for the sampled location; and (5) possibility to assign the measured soil properties to a specific stage of the water infiltration process in an initially unsaturated soil. Thirdly, the cheap and automated infiltrometer designed by **Di Prima (2015; Appendix C)** to automate Beerkan infiltration experiments constitutes a very cost effective alternative to previously proposed equipment. **Di Prima et al. (2016; Appendix D)** suggested that the new automated infiltrometer should be an efficient and easy-to-use device to characterize water infiltration at the surface of contrasting soils. In particular, these authors reported a reliable quantification of water infiltration in coarse soils, usually considered as very challenging. Finally, their study proposed guidance for the optimization of the design of future devices, in terms of reservoir capacity, with the aim to improve the soil hydraulic characterization by the BEST method.

BEST was also tested in different soils and compared with several alternative field and laboratory methodologies highlighting the pros and cons that characterize the method and allowing to design BEST as a promising, easy, robust, and inexpensive way of characterizing soil hydraulic behavior. In particular, **Bagarello et al. (2011; Appendix E)** determined the fitting ability of the soil particle size distribution used in the procedure, concluding that a reduced amount of experimental information did not compromise the soil hydraulic characterization. Therefore, the BEST procedure seems also to be usable when only a rough description of the PSD is available. This result has practical importance especially in areas of the world where soil hydraulic characterization is difficult due to the lack of laboratories and skilled personnel. The tests carried out by **Bagarello et al. (2014b; Appendix F)**, **Aiello et al. (2014; Appendix G)** and **Alagna et al. (2015b; Appendix H)** highlighted that BEST yields physically possible scale parameters of the soil characteristic curves in most of the replicated infiltration runs. In their investigations the water retention model used by BEST reproduced satisfactorily the laboratory data. Possible saturated soil hydraulic conductivity values were also obtained. Therefore, BEST is promising to simply characterize a soil but additional investigations should be carried out in other soils to understand if the methodology performing reasonably well in these investigations can also be applied in other soils.

The dependence of the measured hydrodynamic parameters on the experimental procedure used in BEST was also studied with the objective to improve our ability to interpret the field data and the linked hydrological processes. With this aim, **Bagarello et al. (2014a; Appendix I)** determined the effect of the height of water application on the hydraulic properties obtained with the BEST procedure. These authors concluded that the choice of the height of water application should vary with the intended use of the K_s data. If the objective of the field campaign is to obtain data usable to explain surface runoff generation phenomena during intense rainfall events, the most appropriate choice among the tested ones should be high run, to mimic relatively prolonged rainfall effects on the soil surface. A low run is more appropriate to determine the saturated conductivity of a soil that is not directly impacted by rainfall, due for example to the presence of a mulching on the soil surface. Afterwards, **Alagna et al. (2015a; Appendix J)** checked the effect of the height of water application on the saturated hydraulic conductivity and the sorptivity determined with the BEST procedure for different values of the initial soil water content. Their results suggested that water application determining a noticeable disturbance of the soil surface reduce in general infiltration but it also attenuates the effect of the initial soil water content on this process. In other words, the height of water application has a reduced impact on the measured soil properties in relatively wet soil conditions. In the future, the effects of the water pouring height on the measured water transmission properties should be tested for different initial soil water conditions in other soils. More in general, establishing the information contained in the measured soil properties, with particular reference to those that strongly depend on soil structural characteristics, appears necessary to understand the practical usability, in practice, of the collected data and hence to improve our ability to interpret and simulate hydrological processes. With this aim, a comparison between K_s values measured by applying water at a relatively large distance from the soil surface with those obtained by rainfall simulation experiments is desirable in order to verify if these values measured with an extremely simple procedure are in line with the occurrence of runoff measured with a more robust methodology.

Finally, the simplified method to determine the saturated soil hydraulic conductivity developed by **Bagarello et al. (2014d; Appendix K)** and based on a Beerkan infiltration run can be viewed as a good candidate for intensive field campaigns with a practically sustainable experimental effort. In particular, the method allows to determine K_s by only a transient infiltration process through a soil surface confined by a ring and an estimate of the α^* parameter. The method was validated by **Bagarello et al. (2013; Appendix L)** with reference to a larger dataset. The developed method is cheap, rapid and parsimonious in terms of both the devices that have to be transported and the measurements that have to be carried out in the field. Therefore, it is a good candidate method for intensively sampling an area of interest with a practically sustainable experimental effort and, hence, it could allow improved interpretation and simulation of soil hydrological processes, such as runoff generation.

In conclusion, this thesis and the joint effort of the researchers working on BEST in different parts of the world had allowed to improve this procedure, and the signs of a promising ability of BEST to simply yield a reasonably reliable soil hydraulic characterization are clear, but points needing additional developments were also detected.

In particular, other investigations should be carried out on different soils with the aim of developing more general procedures for BEST application. In fact, field data may contain unpredictable uncertainties that could influence the interpretation of the linked hydrological processes. Very accurate experimental procedures and large sample sizes, averaging errors, are therefore particularly important to establish and possibly improve the applicability of BEST with reference to specific soils. In this view, the proposed automated infiltrometer should be considered for a routinely applying the procedure in order to reduce the uncertainty of the calculated hydraulic parameters and also increase the success rate of the BEST analysis. Moreover, the effect of the applied algorithm on S and K_s calculations is less noticeable for the data obtained with the infiltrometer. This is considered another advantage of the new device since a reduced effect of the algorithm implies more confidence in the calculated hydraulic parameters.

Moreover, more investigations should also be carried out to establish what information is contained in the soil hydraulic characterization achieved through a particular experimental method, including BEST. In this view, practical support for the choice of the most appropriate measurement method could be given by functional evaluation, which involves comparing an experimentally measured hydrological process (i.e., surface runoff at the base of a plot) with the corresponding process simulated with mechanistic models and the measured soil hydraulic properties. For example, the hypothesis that the height from which water is poured onto the soil surface is a parameter usable in infiltration experiments to mimic the effect of high intensity rain on the soil hydraulic properties needs specific experimental testing. At this aim, comparisons could be established between infiltration rates measured by applying water at a relatively large distance from the soil surface and those obtained by rainfall simulation experiments.

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Appendix A: Automatic analysis of multiple Beerkan infiltration experiments for soil Hydraulic Characterization

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ABSTRACT

The BEST (Beerkan Estimation of Soil Transfer parameters) procedure of soil hydraulic characterization appears promising for intensively sampling field areas with a reasonable effort in terms of both equipment and time passed in the field. Alternative algorithms have been suggested to determine soil sorptivity and saturated soil hydraulic conductivity from a simply measured cumulative infiltration curve. With these algorithms, calculations have to be repeated several times, depending on the number of collected infiltration data, that should vary between eight and 15. The need to consider a variable number of infiltration data is related to the fact that the infiltration model used in BEST is valid for the transient phase of the process, and only experimental data representative of this phase of the infiltration process have to be selected. The fitting of the theoretical model to the data is carried out by minimizing the sum of the squared residuals between model-predicted and measured infiltration data. Therefore, analyzing a single run may demand a lot of time, since many calculations have to be carried out. This circumstance complicates soil hydraulic characterization based on an intensive soil sampling, and it also increases the risk to make mistakes. These problems are expected to be substantially reduced, or even eliminated, if an automatic procedure of data analysis is applied. The general objective of this investigation was to develop a workbook to easily and rapidly analyze databases including several BEST runs. The developed workbook makes use of the Microsoft Excel Solver add-in routine. A Visual Basic for Applications (VBA) macro was written to automate creation and manipulation of Microsoft Excel Solver. A looping structure was used in the VBA macro to automate data analysis of BEST experiments. The workbook can be viewed as a practically useful contribution to an expeditious, intensive soil hydraulic characterization, also in terms of analysis of the collected data.

Keywords: Soil hydraulic properties; Measurement methods; BEST (Beerkan Estimation of Soil Transfer parameters) procedure; Automatic data processing tool.

INTRODUCTION

Interpreting and modeling soil hydrological processes require the determination of the soil hydraulic characteristic curves, i.e. the relationships between volumetric soil water content, soil water pressure head, and soil hydraulic conductivity. Using traditional methods to determine these properties is expensive and time consuming. Haverkamp et al. (1996) pioneered a specific method for soil hydraulic characterization known as the “Beerkan method”. An improved version of this methodology, called the Beerkan Estimation of Soil Transfer parameters (BEST) procedure, was developed by Lassabatère et al. (2006) to simplify soil hydraulic characterization. BEST considers certain analytic formulae for hydraulic characteristic curves and estimates their shape parameters, which are texture dependent, from particle-size analysis by physical-empirical pedotransfer functions. Structure dependent scale parameters are estimated by a three-dimensional (3D) field infiltration experiment at zero pressure head, using the two-term transient infiltration equation by Haverkamp et al. (1994).

According to Yilmaz et al. (2010), the original algorithm to analyze the infiltration data, named BEST-slope, may lead to erroneous values of saturated soil hydraulic conductivity, K_s, especially when a very high level of precision relative to the steady-state infiltration rate cannot be obtained. These authors introduced a revised version of BEST (BEST-intercept) to avoid obtaining negative K_s values. Differences by a factor of more than an order of magnitude were reported by Yilmaz et al. (2010) for the K_s values of basic oxygen furnace slag obtained with the two algorithms. The conclusion by these Authors was that BEST-intercept yielded a more reliable soil hydraulic characterization than BEST-slope.

Bagarello et al. (2013) proposed a third alternative algorithm (BEST-steady) making exclusive use of the steady-state phase of the infiltration run. The expected advantage of BEST-steady algorithm is that the possible problems associated with the use of the transient infiltration data are avoided.

The general objective of this investigation was to develop a workbook to easily and rapidly analyze databases including several BEST runs. The developed workbook makes use of the Microsoft Excel Solver add-in routine. A Visual Basic for Applications (VBA) macro was written to automate creation and manipulation of Microsoft Excel Solver models. A looping structure was used in the VBA macro to automate data analysis of BEST experiments.

THEORY

Beerkan Estimation of Soil Transfer parameters (BEST) procedure

The BEST procedure for soil hydraulic characterization (Lassabatère et al., 2006) focuses specifically on the van Genuchten (1980) relationship for the water retention curve with the Burdine (1953) condition and the Brooks and Corey (1964) relationship for hydraulic conductivity:

$$\frac{\theta-\theta_r}{\theta_s-\theta_r}=\left[1+\left(\frac{h}{h_g}\right)^n\right]^{-m} \tag{1a}$$

$$m=1-\frac{2}{n} \tag{1b}$$

$$\frac{K(\theta)}{K_s}=\left(\frac{\theta-\theta_r}{\theta_s-\theta_r}\right)^\eta \tag{2a}$$

$$\eta=\frac{2}{m\times n}+3 \tag{2b}$$

where θ (L^3L^{-3}) is the volumetric soil water content, h (L) is the soil water pressure head, K (L T^{-1}) is the soil hydraulic conductivity, n, m and η are shape parameters, and h_g (L), θ_s (L^3L^{-3}, saturated soil water content), θ_r (L^3L^{-3}, residual soil water content) and K_s (L T^{-1}, saturated soil hydraulic conductivity) are scale parameters. In the BEST procedure, θ_r is assumed to be zero. Estimation of n is based on the soil particle size distribution (PSD), which is modeled as:

$$P(D)=\left[1+\left(\frac{D_g}{D}\right)^N\right]^{-M} \tag{3}$$

where $P(D)$ is the fraction by mass of particles passing a particular diameter, D (L), D_g (L) is a scale parameter, and N and M = 1 - 2/N are shape factors. Fitting eq.(3) to the measured PSD allows to calculate the shape index for PSD, p_M:

$$p_M=\frac{MN}{1+M} \tag{4}$$

The m parameter of eq.(1) is calculated by:

$$m=\frac{1}{p_m}\left(\sqrt{1+p_m^2}-1\right) \tag{5}$$

where:

$$p_m=p_M\left(1+\kappa\right)^{-1} \tag{6}$$

$$\kappa=\frac{2s-1}{2s(1-s)} \tag{7}$$

$$(1-f)^s+f^{2s}=1 \tag{8}$$

where f (L^3L^{-3}) is the soil porosity and s is the fractal dimension of the media, varying from 0.5 to 1 (Minasny and McBratney, 2007).

An alternative way to estimate the n parameter used with the BEST procedure from the soil sand, sa (%, USDA classification), and clay, cl (%), content was proposed by Minasny and McBratney (2007):

$$n=2.18+0.11\left[48.087-44.954S(x_1)-1.023S(x_2)-3.896(x_3)\right] \tag{9a}$$

where:

$$x_1=24.547-0.238\ sa-0.082\ cl \tag{9b}$$

$$x_2=-3.569+0.081\ sa \tag{9c}$$

$$x_3=0.694-0.024\ sa+0.048\ cl \tag{9d}$$

$$S(x)=\frac{1}{1+\exp(-x)} \tag{9e}$$

For an infiltration experiment with zero pressure on a circular surface of radius r (L) above a uniform soil with a uniform initial water content (θ_0), the three dimensional cumulative infiltration, I (L), and steady state infiltration rate, i_s (L T^{-1}), can be approximated by the following explicit transient two term relationship and steady state expansion:

$$I(t) = S\sqrt{t} + \left(A\,S^2 + B\,K_s\right)t \tag{10}$$

$$i_s = A\,S^2 + K_s \tag{11}$$

where t (T) is the time, S (L T$^{-1/2}$) is soil sorptivity, and A (L^{-1}) and B are constants that can be defined for the specific case of a Brooks and Corey (1964) relationship (eq.2a) as:

$$A = \frac{\gamma}{r\left(\theta_s - \theta_0\right)} \tag{12}$$

$$B = \frac{2-\beta}{3}\left[1 - \left(\frac{\theta_0}{\theta_s}\right)^{\eta}\right] + \left(\frac{\theta_0}{\theta_s}\right)^{\eta} \tag{13}$$

where β and γ are coefficients that are commonly set at 0.6 and 0.75, respectively, for $\theta_0 < 0.25\ \theta_s$ (Smettem et al., 1994; Haverkamp et al., 1994), although a recent investigation suggested that they have a large impact on the estimation procedure (Nasta et al., 2012). Sorptivity can be expressed as a function of the scale parameters by the following relationship:

$$S^2(\theta_0, \theta_s) = -c_p \theta_s K_s h_g \left(1 - \frac{\theta_0}{\theta_s}\right)\left[1 - \left(\frac{\theta_0}{\theta_s}\right)^{\eta}\right] \tag{14}$$

where:

$$c_p = \Gamma\left(1 + \frac{1}{n}\right)\left\{\frac{\Gamma\left(m\eta - \frac{1}{n}\right)}{\Gamma(m\eta)} + \frac{\Gamma\left(m\eta + m - \frac{1}{n}\right)}{\Gamma(m\eta + m)}\right\} \tag{15}$$

where Γ stands for the Gamma function. BEST estimates shape parameters (m, n and η) on the basis of particle size analysis and soil porosity determination whereas the infiltration experiment is used to estimate scale parameters (h_g and K_s). The initial water contents is measured at the beginning of the infiltration experiment. BEST was applied by setting θ_s equal to total soil porosity determined from a bulk density measurement (Mubarak et al., 2009). BEST first estimates sorptivity by fitting the transient cumulative infiltration on eq.(10) with K_s replaced by its sorptivity function and the experimental steady state infiltration rate through eq.(11):

$$K_s = i_s - A\,S^2 \tag{16}$$

The fit is performed by minimizing the classical objective functions for cumulative infiltration *I(t)*:

$$f_I(S, K_s, k) = \sum_{i=1}^{k}\left[I^{\exp}(t_i) - I(t_i)\right]^2 \tag{17}$$

where k is the number of considered (t, I) data points for the transient state. Once sorptivity is estimated, K_s is driven through eq.(16), assuming that steady state has been reached. As eq.(10) is valid only at transient state, the fit may not be valid for large values of k. Therefore, BEST fits data for a minimum of five points to a maximum of k_{tot}, i.e. the whole dataset. For each data subset containing the first k points (duration of the experiment equal to t_k), S and K_s are estimated and the time, $t_{\max}$ (T), defined as the maximum time for which the transient expressions can be considered valid, is determined:

$$t_{\max} = \frac{1}{4(1-B)^2}\left(\frac{S}{K_s}\right)^2 \tag{18}$$

Then, t_k is compared with $t_{\max}$. The values of S and K_s are not considered valid unless t_k is lower than $t_{\max}$. Among all values of S and K_s that fulfill this condition, the S and K_s values corresponding to the largest k (k_{step}) are retained. The pressure head scale parameter, h_g, is then estimated:

$$h_g = \frac{S^2}{c_p\left(\theta_s - \theta_0\right)\left[1 - \left(\frac{\theta_0}{\theta_s}\right)^{\eta}\right]K_s} \tag{19}$$

The algorithm described above was named BEST-slope by Yilmaz et al. (2010).

An alternative algorithm, named BEST-intercept, was developed by these last Authors since attempting to estimate K_s by eq.(11) was considered to be inappropriate when i_s approaches AS^2, especially if a very high level of precision relative to the steady state infiltration rate cannot be obtained. More specifically, when the estimated AS^2 value exceeds the infiltration rate at the end of the experiment, the values obtained for K_s are negative. In the new algorithm, Yilmaz et al. (2010) proposed replacing such a constraint by using the intercept ($b_{+\infty}^{end}$) of the asymptotic expansion, $I_{+\infty}(t)$, as defined by the following equation:

$$I_{+\infty}(t) = \left(AS^2 + K_s\right)\,t + C\frac{S^2}{K_s} \tag{20}$$

where C is equal to:

$$C = \frac{1}{2\left[1 - \left(\frac{\theta_0}{\theta_s}\right)^{\eta}\right](1-\beta)}\ln\left(\frac{1}{\beta}\right) \tag{21}$$

Therefore, the following relationship is applied to determine K_s:

$$K_s = C\frac{S^2}{b_{+\infty}^{end}} \tag{22}$$

This procedure leads to the use of the division operator rather than the subtraction operator and thereby avoids obtaining negative values for the estimation of K_s.

A third algorithm, named BEST-steady, was developed by Bagarello et al. (2013). BEST-steady, makes use of the intercept ($b_{+\infty}^{end}$) and the slope (i_s) of the straight line fitted to the data describing steady-state conditions on the I vs. t plot. Combining equations (16) and (22) yields to:

$$i_s = AS^2 + C\frac{S^2}{b_s^{\exp}} \qquad (23)$$

and hence S can be calculated as:

$$S = \sqrt{\frac{i_s}{A + \frac{C}{b_s^{\exp}}}} \qquad (24)$$

Then, K_s can be obtained by using either eq. (16) or (22). In summary, the experiment has to be performed until steady-state conditions have been reached for all algorithms, but the data analysis procedure differs with the algorithm. A fitting of the infiltration model to the transient data is common to BEST-slope and BEST-intercept that differ by the use of steady-state conditions (i_s for the former algorithm and $b_{+\infty}^{end}$ for the latter one). Both of these last terms are required by BEST-steady that does not need data fitting for the transient stage of the run but relies solely on steady state.

BASIS OF WORKBOOK

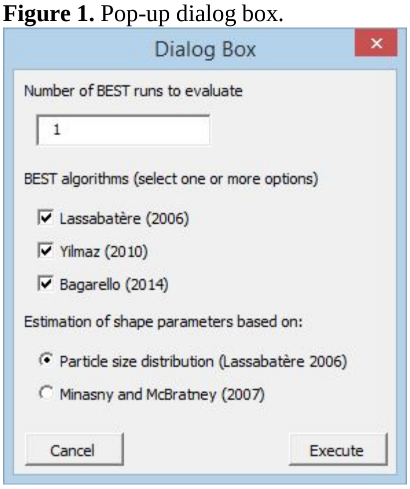
The user-friendly analysis of BEST runs makes use of Microsoft Office EXCEL 2007 and the Microsoft Windows operating system (e.g. Windows 7). Microsoft Excel has been widely used by scientists for data collection, calculation, and analysis. Custom designed worksheet templates can easily be built, sophisticated and highly customizable macros can also be compiled using Excel Visual Basic for Applications (VBA). The workbook makes use of the Microsoft Excel Solver add-in routine. A VBA macro was written to automate creation and manipulation of Microsoft Excel Solver add-in. Before using this function, it is necessary to establish a reference to the Solver add-in. In the Visual Basic Editor, with a module active, click References on the Tools menu, and then select the Solver.xlam check box under Available References. If Solver.xlam does not appear under Available References, click Browse and open Solver.xlam in the office12\library\Solver subfolder.

WORKBOOK DESCRIPTION

The workbook consists of 4 worksheets: "*input*", "*back end*", "*output*" and "*charts*". In the worksheet "*input*", data for computation can be entered from column 3 and 4 (C and D) to follow. Several BEST runs can be added.

In cells from D2 to D6 (D2:D6) the user can enter the BEST run's ID, the diameter of the circular surface (cm), the number of the data describing steady-state conditions on the I vs. t plot, the initial soil water content (m^3m^{-3}) and bulk density ($g\ cm^{-3}$); in cells C8:C27 and D8:D27, respectively the diameter (mm) and frequency of the soil particle size distribution (PSD), with a maximum of 20 data points, are given; in cells C29:C128 and D29:D128, respectively the time (s) and the volume (mm) of the cumulative infiltration experiment, with a maximum of 100 data points, is reported. The workbook only accepts a rigid input structure. The others worksheets are important for computation routines but they don't require an user customization.

Figure 1. Pop-up dialog box.



COMPUTATION ROUTINES

Once the data have been entered into the Excel workbook, the first task is to perform the macro. In the worksheet ''*Input*'' the user finds the ''*EXECUTE*'' button. After a click a pop-up dialog box appears. The next step is to enter into the input dialog box the number of BEST runs to evaluate (**Fig. 1**). Then, it is possible to select between the different BEST algorithms by three check-boxes (by default all the options are selected). Finally, the user can chose the method for the treatment of PSD data by selecting the opportune option button [whole PSD or the method of Minasny and Mc Bractney (2006) using the USDA fractions] and click to *Execute* to run the macro.

For a given run, the selected algorithms are applied to determine soil sorptivity, S. The SolverAdd function is used to minimize eq. (17). The function is repeated for a minimum of five points to a maximum of k_{tot}, i.e. the total number of collected (t, I) data points. Then, the saturated soil hydraulic conductivity, K_s, is determined. The relative error, E_r (%), is calculated to evaluate the quality of the data fitting on the transient cumulative infiltration model by the following relationship (Lassabatère et al., 2006):

$$E_r = 100 \times \sqrt{\frac{\sum_{i=1}^{k_{\max}} \left[I^{\exp} - I_{est} \right]^2}{\sum_{i=1}^{k_{\max}} \left[I^{\exp} \right]^2}} \qquad (25)$$

With a For...Next structure (Visual Basic) the statements are repeated a specified number of times equal to the number of BEST runs to evaluate. At the end of the calculations, the macro directly displays the resulting parameters ordered by rows from cell A5 to X5 (A5:X5) by opening the worksheet ‘‘*output*’’.

WORKING EXAMPLES

A BEST run was carried out according to the methodology by Lassabatère et al. (2006). In particular, a ring of a given radius, r = 15 cm, was inserted to a short depth, d = 1 cm, into the soil surface. A known volume of water (70.7 mL) was poured in the cylinder at the start of the measurement and the elapsed infiltration time was measured. When the amount of water had completely infiltrated, an identical amount of water was poured into the cylinder and the time needed for the water to infiltrate was logged. The procedure was repeated until the difference in infiltration time between consecutive trials became negligible. The procedure is repeated for a series of 18 known volumes. An experimental cumulative infiltration, I (mm), vs. time, t (s), relationship, including a total of k_{tot} discrete points, was then deduced. The experimentally measured cumulative infiltration curve is examined to visually establish when the slope of the curve became constant (i.e. linearity in I vs. t).

Before conducting the experiment, a disturbed soil sample was collected to determine the PSD. Close to the infiltrometer ring an undisturbed soil core was collected to estimate the initial water content, θ_0 (m^3m^{-3}), and the dry soil bulk density, ρ_b (g cm^{-3}). According to other investigations, the saturated water contents, θ_s (m^3m^{-3}), was assumed to coincide with the estimated porosity, f (m^3m^{-3}), from ρ_b (Mubarak et al., 2009, 2010; Xu et al., 2009; Yilmaz et al., 2010; Bagarello et al., 2011).

Table 1 lists the input of the BEST run

Table 1. List of input data

row	column C	column D	column C	column D	row	column C	column D	column C	column D
BEST run's ID					Cumulative infiltration curve [t (s), I (mm)]				
2	example		example_MM		**29**	60	4	60	4
Diameter of the circular surface (cm)					**30**	213	8	213	8
3		15		15	**31**	370	12	370	12
Number of data points describing steady-state					**32**	585	16	585	16
4		3		3	**33**	780	20	780	20
Initial water content (m^3m^{-3})					**34**	980	24	980	24
5		0.169		0.169	**35**	1164	28	1164	28
Dry soil bulk density (g cm^{-3})					**36**	1380	32	1380	32
6		1.2		1.2	**37**	1620	36	1620	36
PSD [D (mm), F]					**38**	1885	40	1885	40
8	2.000	1.000	2.000	1.000	**39**	2118	44	2118	44
9	1.000	0.962	0.050	0.500	**40**	2360	48	2360	48
10	0.500	0.812	0.002	0.310	**41**	2645	51	2645	51
11	0.250	0.649			**42**	2936	55	2936	55
12	0.106	0.551			**43**	3234	59	3234	59
13	0.053	0.514			**44**	3530	63	3530	63
14	0.047	0.492			**45**	3832	67	3832	67
15	0.033	0.481			**46**	4134	71	4134	71
16	0.023	0.457							
17	0.016	0.434							
18	0.012	0.422							
19	0.008	0.399							
20	0.006	0.387							
21	0.004	0.363							
22	0.003	0.340							
23	0.002	0.317							
24	0.001	0.293							

Di Prima S., 2013. Automatic analysis of multiple Beerkan infiltration experiments for soil hydraulic characterization.
CIGR Inter-Regional Conference on Land and Water Challenges – Bari (Italy), 10-14 September, 2013.

analysed with the three BEST algorithms and corresponding cells references. Both procedures to estimate the shape parameters were considered, i.e. whole PSD and the method of Minasny and Mc Bractney (2006), for the runs named, respectively, "*example*" and "*example_MM*". **Table 2** shows the output parameters.

Table 2. Output parameters

ID	example_MM	example
k_{tot}	18	18
ρ_b (m^3m^{-3})	1.2	1.2
θ_0 (m^3m^{-3})	0.169	0.169
θ_s (m^3m^{-3})	0.547	0.547
m	0.067	0.042
n	2.144	2.088
η	16.9	25.8
steady state	3	3
slope (mm s^{-1})	0.013	0.013
intercept (mm)	17.1	17.1
Lassabatère et al. 2006		
S (mm $s^{-0.5}$)	0.495	0.495
K_s (mm s^{-1})	0.007	0.007
h_g (mm)	-39.5	-36.6
k_{step}	18	18
E_r %	1.9	1.9
Yilmaz et al. 2010		
S (mm $s^{-0.5}$)	0.477	0.477
K_s (mm s^{-1})	0.009	0.009
h_g (mm)	-28.5	-26.4
k_{step}	13	13
E_r %	2.6	2.6
Bagarello et al. 2013		
S (mm $s^{-0.5}$)	0.453	0.453
K_s (mm s^{-1})	0.008	0.008
h_g (mm)	-28.5	-26.4

CONCLUSIONS

In summary, the developed workbook provides a practically useful contribution to an expeditive, intensive soil hydraulic characterization, also in terms of analysis of the collected data. It was developed using the VBA language and runs under Microsoft Excel 2007. Data input and processing can be performed directly within Microsoft Excel.

The workbook is available from server at: https://bestsoilhydro.wordpress.com/downloads/.

In any case, it has to be tested extensively and unexpected behaviour of the workbook could be reported for improving the workbook.

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Appendix B: Comparing Alternative Algorithms to Analyze the Beerkan Infiltration Experiment

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ABSTRACT

The increasing interest in the Beerkan Estimation of Soil Transfer parameters (BEST) procedure of soil hydraulic characterization justifies an assessment of alternative methods to analyze infiltration data. The BEST-slope and BEST-intercept algorithms allow estimation of soil sorptivity, S, and saturated soil hydraulic conductivity, K_s, using the transient part of the experimental infiltration curve and the slope and the intercept, respectively, of the linear portion of this curve. With reference to 401 runs carried out in Sicily (Italy) and Burundi, this investigation showed that these two algorithms differed by the number of successful runs (positive S and K_s values),,with BEST-intercept yielding a higher success percentage (93%) than BEST-slope (66%) at the expense of a poorer performance in terms of data representation by the infiltration model. On average, the two algorithms yielded S values differing by 3.3% and K_s values differing by a factor of 3.1. High discrepancies between two alternative K_s estimates, i.e. by even more than two orders of magnitude, were occasionally detected at individual sampling points. The BEST-steady algorithm developed in this investigation, using steady-state cumulative infiltration data, was closer to BEST-intercept (individual S and K_s values differing at the most by 17% and a factor of 1.5, respectively) than to BEST-slope (differences by 22% for S and a factor of 186 for K_s). Data should initially be analyzed with BEST-slope and an attempt to apply BEST-intercept should be made only if the former algorithm fails in giving physically plausible S and K_s values. BEST-steady is an alternative algorithm to be considered in practice for a variety of reasons, including a success percentage of 100%, a simplified calculation of S and K_s, and the possibility to adjust the run duration directly in the field.

INTRODUCTION

Interpreting and modeling soil hydrological processes require the determination of the soil hydraulic characteristic curves, i.e. the relationships between volumetric soil water content, pressure head, and hydraulic conductivity. Using traditional methods to determine these properties is expensive and time consuming. Haverkamp et al. (1996) pioneered a specific method for soil hydraulic characterization known as the “Beerkan method”. An improved version of this methodology, called the Beerkan Estimation of Soil Transfer parameters (BEST) procedure, was developed by Lassabatère et al. (2006) to simplify soil hydraulic characterization. BEST considers certain analytic formulae for hydraulic characteristic curves and estimates their shape parameters, which are texture dependent, from particle-size analysis by physical-empirical pedotransfer functions. Structure dependent scale parameters are estimated by a three-dimensional

(3D) field infiltration experiment at zero pressure head, using the two-term transient infiltration equation by Haverkamp et al. (1994). The BEST procedure has been used to characterize temporal variability of soil hydraulic properties under high-frequency drip irrigation (Mubarak et al., 2009), review the soil hydraulic properties of a field sampled in the past (Mubarak et al., 2010), study the effect of sediment accumulation on the water infiltration capacity of two urban infiltration basins (Lassabatère et al., 2010), document the spatial variability of the water retention and soil hydraulic conductivity curves in a small watershed (Gonzalez-Sosa et al., 2010), and determine the hydraulic properties of soils that are practically difficult to characterize with other laboratory and field methods (Bagarello et al., 2011a).

According to Yilmaz et al. (2010), the original algorithm to analyze the infiltration data, named BEST-slope, may lead to erroneous values of saturated soil hydraulic conductivity, K_s, especially when a very high level of precision relative to the steady-state infiltration rate cannot be obtained. These authors introduced a revised version of BEST (BEST-intercept) to avoid obtaining negative K_s values. Differences by a factor of more than an order of magnitude were reported by Yilmaz et al. (2010) for the K_s values of basic oxygen furnace slag obtained with the two algorithms. The conclusion by these authors was that BEST-intercept yielded a more reliable soil hydraulic characterization than BEST-slope. Xu et al. (2012) also suggested that BEST-intercept performed better than BEST-slope. However, it is still not clear if such appreciable differences between the K_s results mean that only the BEST-intercept method should be used. Obviously, the problem of which algorithm to use is of great practical impact for soil hydraulic characterization. Therefore, additional testing of the two algorithms is necessary.

Both BEST-slope and BEST-intercept establish a constraint between soil sorptivity, S, and K_s, i.e. they express K_s as a function of S, using the experimental information collected during the practically steady-state phase of the infiltration process. The transient phase of the run is then considered to determine S. With both algorithms, the maximum time for which the two-term transient infiltration model can be considered valid, t_{max}, has to be predicted. The analysis of the transient phase of the infiltration process may be uncertain for several reasons, including that non-linear fitting of the transient model to the cumulative infiltration data set offers no check for the adequacy of the form of the two-term equation with the data (Vandervaere et al., 2000; Bagarello and Iovino, 2003), and an early-time perturbation of the process can be expected since it was found to also occur with numerically simulated, i.e. error-free, data (Minasny and McBratney, 2000). According to Wu et al. (1999), ponded infiltration data collected in the first few minutes are less reliable than the ones measured later. Another problem, specific to the BEST procedure, is that some of the S and K_s values used to calculate t_{max} can be uncertain since they are based on the assumption that the transient infiltration model can be applied with data collected at relatively long times (Bagarello et al., 2011a). Moreover, when the influence of capillary forces is very short, S is estimated with only a small number of points, which is theoretically adequate but it can be detrimental to the robustness of the optimization (Gonzalez-Sosa et al., 2010). On the other hand, detecting quasi steady-state conditions during a 3D infiltration process is generally straightforward, also considering that different objective criteria can be applied to establish if and when these conditions have been reached (Bagarello et al., 1999; Reynolds et al., 2000; Mubarak et al., 2009), although the risk to overestimate steady values cannot be excluded in principle (Cook, 1994; Bagarello and Giordano, 1999; Vandervaere et al., 2000). In general, quasi steady flow is expected to occur rather rapidly, since it should be attained within a few dozen minutes with the ring diameters and insertion depths and the heights of water ponding commonly used with the BEST procedure (Reynolds and Elrick, 2002; Reynolds, 1993). Moreover, the scale of the infiltration process is generally expected to be detectable in a short time after initiation of a ponding infiltration run into an unsaturated soil (Bagarello and Giordano, 1999). Therefore, a BEST algorithm making exclusive use of the steady-state phase of the infiltration run might be an alternative to the existing BEST solutions. The expected advantage of a BEST-steady algorithm is that the possible problems associated with the use of the transient infiltration data are avoided. Moreover, the duration of the run can be adjusted directly in the field to obtain reliable experimental information with reference to the specific sampled point.

The general objective of this investigation was to compare alternative algorithms for analyzing the Beerkan infiltration experiment. In particular, a comparison between BEST-slope and

BEST-intercept was carried out with reference to approximately 400 infiltration runs carried out in Sicily (Italy) and Burundi. A BEST-steady algorithm, that combines selected procedures embedded in BEST-slope and BEST-intercept, was then developed and tested.

THEORY

BEST focuses on the van Genuchten (1980) relationship for the water retention curve with the Burdine (1953) condition and the Brooks and Corey (1964) relationship for hydraulic conductivity:

$$\frac{\theta-\theta_r}{\theta_s-\theta_r}=\left[1+\left(\frac{h}{h_g}\right)^n\right]^{-m} \tag{1a}$$

$$m=1-\frac{2}{n} \tag{1b}$$

$$\frac{K(\theta)}{K_s}=\left(\frac{\theta-\theta_r}{\theta_s-\theta_r}\right)^{\eta} \tag{2a}$$

$$\eta=\frac{2}{m\times n}+2+p \tag{2b}$$

where θ (L^3L^{-3}) is the volumetric soil water content, h (L) is the soil water pressure head, K (L T^{-1}) is the soil hydraulic conductivity, n (> 2), m and η are shape parameters, p is a tortuosity parameter set equal to 1 following Burdine's (1953) condition, and h_g (L), θ_s (L^3L^{-3}, field saturated soil water content), θ_r (L^3L^{-3}, residual soil water content) and K_s (L T^{-1}, field saturated soil hydraulic conductivity) are scale parameters. In BEST, θ_r is assumed to be zero. The shape parameters, which are texture dependent, are estimated from particle-size analysis and the soil bulk density measurement. The scale parameter for water pressure (h_g) is estimated by the following relationship:

$$h_g=-\frac{S^2}{c_p(\theta_s-\theta_0)\left[1-\left(\frac{\theta_0}{\theta_s}\right)^{\eta}\right]K_s} \tag{3}$$

where S (L $T^{-1/2}$) is soil sorptivity, θ_0 (L^3L^{-3}) is the initial soil water content and c_p is a coefficient dependent on n, m and η according to eq.(6b) by Lassabatère et al. (2006). Both θ_0 and θ_s should be measured directly. An infiltration experiment with zero water pressure on a circular surface of radius, r (L), above a homogeneous soil with a uniform water content is used to determine S and K_s and hence h_g. The 3D cumulative infiltration, I (L), and the infiltration rate, i (L T^{-1}), can be approached by the following explicit transient two-term expressions and steady-state expansions (Haverkamp et al., 1994; Lassabatère et al., 2006):

$$I(t)=S\sqrt{t}+\left(A\,S^2+B\,K_s\right)t \tag{4a}$$

$$i(t)=\frac{S}{2\sqrt{t}}+\left(A\,S^2+B\,K_s\right) \tag{4b}$$

$$I_{+\infty}(t)=\left(AS^2+K_s\right)t+C\frac{S^2}{K_s} \tag{4c}$$

$$i_s=A\,S^2+K_s \tag{4d}$$

where t (T) is the time and i_s (L T^{-1}) is the steady-state infiltration rate. The A (L^{-1}), B and C constants are defined for the specific case of a Brooks and Corey (1964) relationship as:

$$A=\frac{\gamma}{r\,(\theta_s-\theta_0)} \tag{5a}$$

$$B=\frac{2-\beta}{3}\left[1-\left(\frac{\theta_0}{\theta_s}\right)^{\eta}\right]+\left(\frac{\theta_0}{\theta_s}\right)^{\eta} \tag{5b}$$

$$C=\frac{1}{2\left[1-\left(\frac{\theta_0}{\theta_s}\right)^{\eta}\right](1-\beta)}ln\left(\frac{1}{\beta}\right) \tag{5c}$$

where β and γ are coefficients that are commonly set at 0.6 and 0.75, respectively, for $\theta_0 < 0.25\ \theta_s$ (Smettem et al., 1994; Haverkamp et al., 1994). The experimental steady-state infiltration rate, i_s^{exp} (L T^{-1}), is given by:

$$i_s^{exp}=slope_{\,i=(N_{tot}-N_{end})\rightarrow N_{tot}}\ (t_i,I_i) \tag{6}$$

where N_{end} is the number of points considered for the linear regression.

Two alternative algorithms, i.e. BEST-slope and BEST-intercept, were proposed in the past to analyze the measured infiltration. A new algorithm, named BEST-steady, was developed in this investigation.

BEST-slope

The BEST-slope algorithm by Lassabatère et al. (2006) first estimates sorptivity by fitting eq.(4a) on the transient cumulative infiltration data. The fit is based on the replacement of hydraulic conductivity by its sorptivity function and the

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experimental steady-state infiltration rate through eq.(4d):

$$K_s = i_s^{exp} - A\,S^2 \tag{7a}$$

$$I(t) = S\sqrt{t} + \left[A(1-B)S^2 + B\,i_s^{\exp}\right]t \tag{7b}$$

Establishing a constraint between the estimator for sorptivity and the one for saturated hydraulic conductivity avoids parameter non-uniqueness, increasing the robustness of the inverse procedure (Yilmaz et al., 2010). The fit is performed by minimizing the classical objective function for cumulative infiltration:

$$f(S, K_s, k) = \sum_{i=1}^{k}\left[I^{exp}(t_i) - I_{est}(t_i)\right]^2 \tag{8}$$

where k is the number of data points considered for the transient state, and I^{exp} is the measured and I_{est} the estimated cumulative infiltration (eq.7b), respectively. Once sorptivity is estimated, the saturated hydraulic conductivity is calculated by eq.(7a). The pressure head scale parameter (h_g) is then estimated using eq.(3). As the infiltration model is valid only at transient state, the fit may not be valid for large values of k. Therefore, BEST fits data for a minimum of five points to a maximum of N_{tot} points. For each data subset containing the first k points (duration of the experiment equal to t_k), S and K_s are estimated and the time, t_{max} (T), defined as the maximum time for which the transient expression can be considered valid, is determined:

$$t_{max} = \frac{1}{4(1-B)^2}\left(\frac{S}{K_s}\right)^2 \tag{9}$$

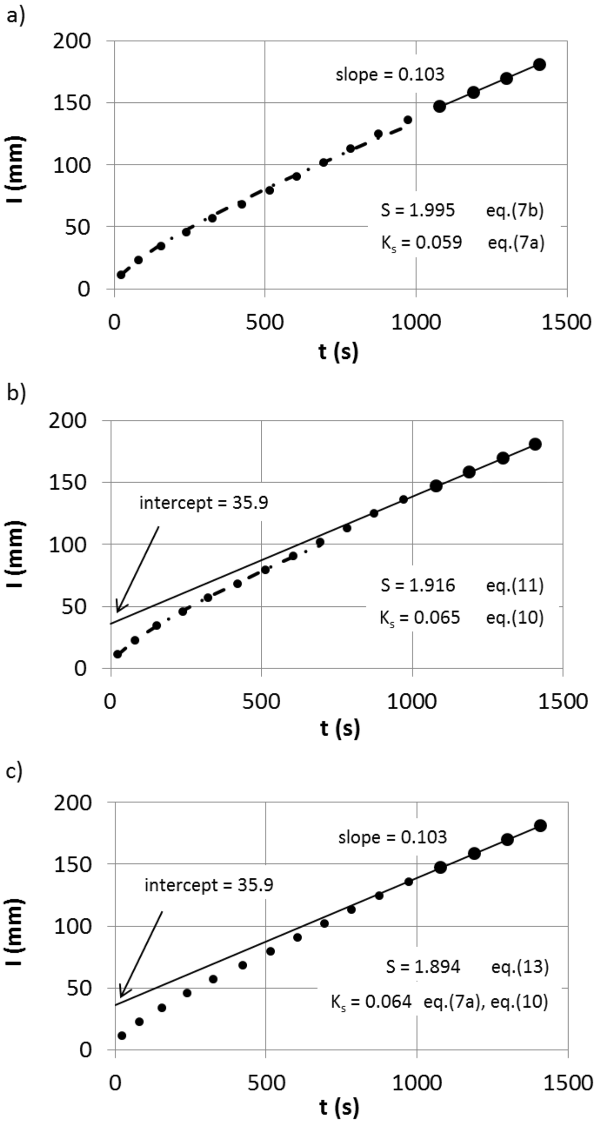
where $(S/K_s)^2$ is the gravity time defined by Philip (1969). Then, t_k is compared with t_{max}. The values of S and K_s are not considered valid unless t_k is lower than t_{max}. Among all values of S and K_s that fulfill this condition, the S and K_s values corresponding to the largest k (k_{max}) are retained since they are considered more precise (**Fig.1a**).

BEST-intercept

According to Yilmaz et al. (2010), BEST-slope may lead to erroneous K_s values, especially when $i_s \approx AS^2$. Under such conditions, attempting to estimate K_s by eq.(7a) appears to be inappropriate. More specifically, when the estimated AS^2 value exceeds the measured infiltration rate at the end of the experiment, the values obtained for K_s are negative. In the BEST-intercept algorithm by Yilmaz et al. (2010), the constraint between S and K_s is defined by using the intercept ($b_{+\infty}^{end} = C \times S^2 / K_s$),$I_{+\infty}(t)$, i.e. of eq.(4c). Therefore, $b_{+\infty}^{end}$ is estimated by linear regression analysis of the data describing steady-state conditions on the I vs. t plot, and the following relationship is applied to determine K_s:

$$K_s = C\frac{S^2}{b_{+\infty}^{end}} \tag{10}$$

Figure 1. Illustrative example of the calculation procedure of soil sorptivity, S (mm s$^{-1/2}$), and saturated soil hydraulic conductivity, K_s (mm s^{-1}), by applying different BEST algorithms to analyze the measured cumulative infiltration, I (mm), vs. time, t (s), curve: a) BEST-slope; b) BEST-intercept; c) BEST-steady. The A, B and C constants of eq.(5) were equal to 0.011 mm^{-1}. 0.4667 and 0.639, respectively. The slope i_s^{exp} (mm s^{-1}) is the experimental steady-state infiltration rate and $b_{+\infty}^{end}$ (mm) is the experimental intercept of the straight line interpolating the I vs. t data points at steady-state. The dotted line is the fitted cumulative infiltration model, i.e. eq.(7b) in a) and eq.(11) in b), to the transient infiltration data



This procedure leads to the use of the division operator rather than the subtraction operator and thereby avoids obtaining negative values for the estimation of K_s. Combining eqs.(4a) and (10) yields the following relationship:

$$I(t) = S\sqrt{t} + \left(A\,S^2 + B\,C\,\frac{S^2}{b_{+\infty}^{end}} \right) t \qquad (11)$$

Eq.(11), that is alternative to eq.(7b), is applied to determine S by the same procedure described for BEST-slope, including the assessment of the time validity of the transient infiltration model by calculation of t_{max}. The estimated sorptivity is then used to calculate K_s by eq.(10) (**Fig.1b**).

BEST-steady

An alternative approach, named BEST-steady, makes use of the intercept ($b_{+\infty}^{end}$) and the slope (i_s^{exp}) of the straight line fitted to the data describing steady-state conditions on the I vs. t plot. Combining eqs.(7a) and (10) yields:

$$i_s^{exp} = A\,S^2 + C\,\frac{S^2}{b_{+\infty}^{end}} \qquad (12)$$

and hence S can be calculated as:

$$S = \sqrt{\frac{i_s^{exp}}{A + \dfrac{C}{b_{+\infty}^{end}}}} \qquad (13)$$

Then, K_s can be obtained by using either eq.(7a) or eq.(10) (**Fig.1c**).

In summary, the experiment has to be carried out until steady-state conditions have been reached for all algorithms, but the data analysis procedure differs with the algorithm. A fitting of the infiltration model to the transient data is common to BEST-slope and BEST-intercept, that differ by the term expressing steady-state conditions (i_s^{exp} for the former algorithm and $b_{+\infty}^{end}$ for the latter one). Both of these last terms are required by BEST-steady, that does not need data fitting for the transient stage of the run. Monitoring this last stage is however necessary to establish when a steady-state condition begins (estimating i_s^{exp}) and how much water infiltrates the soil before reaching this condition (determining $b_{+\infty}^{end}$). In all BEST algorithms, K_s seems to vary with the initial conditions since it depends upon S. In reality, K_s calculation also depends on the measured infiltration, and an increase in S as soil dries determines more cumulative infiltration at a given time and higher infiltration rates (eqs.4). Therefore, the physical and computational scheme is that the initial conditions influence both sorptivity and infiltration but not K_s. Using soil sorptivity to determine soil hydraulic conductivity by an infiltration run is not a peculiarity of BEST, being common to other data analysis procedures (e.g. White et al., 1992; Warrick, 1992).

MATERIALS AND METHODS

A large dataset was considered in this investigation by supplementing all available Beerkan infiltration experiments carried out by this research team in Sicily (Italy) and Burundi. **Table 1** lists the sampled sites and the soil textural characteristics at each site. The runs were carried out at a total of 407 sampling points. **Table 2** gives details on the runs carried out at a given site, together with the soil bulk density, ρ_b, and organic matter content at the time of sampling. This large dataset was chosen as it included runs differing by many factors (e.g., site, soil, ring diameter, height of water pouring, operator, etc.) to maximize the robustness of the analysis and therefore the possibility to generalize the results of this investigation.

All infiltration runs were carried out according to

Table 1. Name, location, and soil textural characteristics for each sampled site

Country	Site	Coordinates	N	clay (%)				silt (%)				sand (%)			
				min	max	Me	CV	min	max	Me	CV	min	max	Me	CV
Burundi	Kinyami	2°54’30”S, 29°49’06” E	4	22.7	31.8	28.0	14.0	44.4	49.7	46.9	5.1	18.4	32.9	25.1	24.8
	Nyamutobo	3°27’50”S, 30°15’40” E	35	39.0	56.7	52.1	16.8	20.7	36.0	25.3	28.6	12.3	40.8	21.8	26.8
Italy	Caccamo	37°52’34”N, 13°38’43”E	4	29.4	40.8	34.6	14.2	42.9	47.8	45.8	4.6	13.5	22.9	19.6	21.4
	Corleone	37°48’35”N, 13°17’49”E	20	12.2	58.2	45.1	33.1	28.2	38.5	33.1	8.1	10.2	59.5	21.8	74.3
	Giampilieri	38°4’8”N, 15°28’26”E	12	14.1	19.6	16.8	9.8	15.4	19.5	17.7	7.3	63.1	67.5	65.6	2.1
	Palermo – Faculty of Agriculture	38°6’25”N, 13°21’6”E	9	15.6	20.1	17.3	10.8	26.9	33.0	29.6	9.4	47.0	57.3	53.1	8.7
	Palermo – Parco d’Orleans	38°6’26”N, 13°20’59”E	8	26.6	34.5	29.9	9.5	31.1	36.4	34.1	5.1	34.3	37.2	36.0	3.5
	Pietranera	37°32’25”N, 13°30’44”E	4	48.8	58.1	53.3	7.4	26.1	27.7	27.0	2.5	14.2	23.9	19.7	21.4
	Sparacia	37°38’10”N, 13°45’59”E 37°38’11”N, 13°45’50”E	16	10.1	73.8	44.2	64.6	16.9	26.4	22.3	10.2	4.0	69.0	33.5	88.8
	Villabate	38°4’53”N, 13°25’7”E	8	10.6	20.9	14.5	23.1	18.9	25.2	22.7	9.0	60.2	64.9	62.8	2.8
	Villagrazia	38°5’8”N, 13°2’23” E	10	32.6	45.2	37.4	9.7	31.6	37.5	33.7	4.7	22.2	32.9	28.9	10.7

N = sample size; *min* = minimum value; *max* = maximum value; *Me* = mean value; *CV* (%) = coefficient of variation

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Table 2. Summary of the datasets included in the single dataset for this investigation

Dataset No.	Site	Sampling period	ρ_b			OM			N_r	r	V_L	Note
			N	Me	CV	N	Me	CV				
1	Kinyami	August 2011	24	0.90	6.4	12	2.0	47.2	20	75	150	in general, five infiltration runs at different points within a 7 m^2 area; process monitored until three consecutive infiltration rates were similar (number of water volumes = 14-33, depending on the run); each area was characterized by a single value of ρ_b, θ_0 and θ_s, obtained by averaging six individual determinations, and by a single PSD
2	Nyamutobo	August 2008	92	0.91	6.2	16	4.6	17.4	77	75	150	as for dataset No.1 (number of water volumes = 12-37, depending on the run)
3	Nyamutobo	August-September 2011	90	0.90	4.3	15	4.1	12.8	75	75	150	as for dataset No.1 (number of water volumes = 11-24, depending on the run)
4	Caccamo	September 2010	8	1.21	7.4	4	1.5	50.7	4	75	200	four infiltration runs at different points within a 7 m^2 area; process monitored until three consecutive infiltration rates were similar (number of water volumes = 20); each area was characterized by a single value of ρ_b, θ_0 and θ_s, obtained by averaging eight individual determinations, and by four PSD obtained by averaging four individual determinations
5	Caccamo	September 2010							4	150	800	as for dataset No.4 (number of water volumes = 15-20, depending on the run)
6	Corleone	July-September 2010	40	1.22	10.3	20	2.0	29.0	20	75	200	as for dataset No.4 (number of water volumes = 18-40, depending on the run)
7	Corleone	July-September 2010							20	150	800	as for dataset No.4 (number of water volumes = 14-37, depending on the run)
8	Giampilieri	October 2011	12	1.51	14.4	12	2.0	47.2	11	75	150	eleven infiltration runs at different points within a 7 m^2 area; process monitored until three consecutive infiltration rates were similar (number of water volumes = 8-18, depending on the run); two sampled depths (0 and 30 cm); each depth was characterized by a single value of ρ_b, θ_0 and θ_s, obtained by averaging six individual determinations, and by a single PSD obtained by averaging six individual determinations
9	Palermo – Faculty of Agriculture	July-October 2010	16	1.14	8.7	8	4.0	14.0	8	75	200	as for dataset No.4 (number of water volumes = 26-40, depending on the run)
10	Palermo – Faculty of Agriculture	July-October 2010							8	150	800	as for dataset No.4 (number of water volumes = 15-37, depending on the run)
11	Palermo – Faculty of Agriculture	October-December 2011 February 2012	25	1.1	6.0				38	75	176	infiltration runs at different points within a 20 m^2 area; process monitored until three consecutive infiltration rates were similar (number of water volumes = 12-15, depending on the run); the area was characterized by 38 values of ρ_b, θ_0 and θ_s, and a common PSD obtained by previous measurements
12	Palermo – Faculty of Agriculture	June 2012	8	1.13	3.6				4	75	200	four infiltration runs at different points within a 7 m^2 area; process monitored until three consecutive infiltration rates were similar (number of water volumes = 14-18, depending on the run); each area was characterized by a single value of ρ_b, θ_0 and θ_s, obtained by averaging eight individual determinations, and by a single PSD obtained by averaging four individual determinations
13	Palermo – Faculty of Agriculture	June 2012							4	150	800	as for dataset No.12 (number of water volumes = 15-17, depending on the run)
14	Palermo – Faculty of Agriculture	July 2012	10	1.13	4.2	2	3.9	19.4	10	42.5	64.2	ten infiltration runs at different points within a 50 m^2 area; number of water volumes = 15; each area was characterized by a single value of ρ_b, θ_0 and θ_s, obtained by averaging ten individual determinations, and by a single PSD obtained by averaging eight individual determinations
15	Palermo – Faculty of Agriculture	July 2012							10	42.5	64.2	as for dataset No.14, but with a particularly high height of water pouring, i.e. 1.50 m
16	Palermo – Parco d'Orleans	July 2012	10	1.12	5.5	2	2.2	4	10	42.5	64.2	as for dataset No.14
17	Palermo – Parco d'Orleans	July 2012							10	42.5	64.2	as for dataset No.14, but with a particularly high height of water pouring, i.e. 1.50 m
18	Pietranera	May 2012	8	0.99	39.3				4	75	200	as for dataset No.12 (number of water volumes = 20-35, depending on the run)
19	Pietranera	May 2012							4	150	800	as for dataset No.12 (number of water volumes = 13-26, depending on the run)
20	Sparacia	July-October 2010	16	1.46	5.5	8	0.5	29.2	8	75	200	as for dataset No.4 (number of water volumes = 8-31, depending on the run)
21	Sparacia	July-October 2010							8	150	800	as for dataset No.4 (number of water volumes = 13-24, depending on the run)
22	Sparacia	July 2012	10	1.08	6.3	2	1.1	53.9	10	42.5	64.2	as for dataset No.14
23	Sparacia	July 2012							10	42.5	64.2	as for dataset No.14, but with a particularly high height of water pouring, i.e. 1.50 m
24	Villabate	July 2012	10	1.32	8.0	2	2.0	15.7	10	42.5	64.2	as for dataset No.14
25	Villabate	July 2012							10	42.5	64.2	as for dataset No.14, but with a particularly high height of water pouring, i.e. 1.50 m
26	Villagrazia	July 2009	10	1.03	10.3				10	75	150	Ten infiltration runs at different points within a 10 m^2 area; process monitored until three consecutive infiltration rates were similar (number of water volumes = 14-20, depending on the run); the area was characterized by ten values of ρ_b, θ_0 and θ_s, and by ten PSDs

ρ_b (Mg m^{-3}) = dry soil bulk density; *N* = sample size; *Me* = mean value; *CV* (%) = coefficient of variation; *OM* (%) = organic matter content; N_r = number of infiltration runs; *r* (mm) = radius of the cylinder; V_L (mL) = water volume applied with each pouring; θ_0 = initial soil volumetric water content; θ_s = saturated soil volumetric water content.

the methodology by Lassabatère et al. (2006). In particular, a cylinder of a given radius, r (L) (**Table 2**), was inserted to a short depth (i.e., approximately 0.01 m) into the soil surface. A known volume of water was poured in the cylinder at the start of the measurement and the elapsed infiltration time was measured. When the amount of water had completely infiltrated, an identical amount of water was poured into the cylinder and the time needed for the water to infiltrate was logged. The procedure was repeated until the difference in infiltration time between consecutive trials became negligible, suggesting approximately steady-state infiltration, or after application of a pre-established number of water volumes, never lower than eight, i.e. the minimum value suggested by Lassabatère et al. (2006) (**Table 2**). An experimental cumulative infiltration, I (L), vs. time, t (T), relationship including N_{tot} discrete points, N_{tot} being the number of collected (t, I) data, was then deduced for each individual infiltration run. The infiltration rates, i_r (L T^{-1}), were then calculated and plotted against t. The i_r vs. t data were preliminary fitted with a power relationship to objectively detect anomalous behaviors, i.e. infiltration rates that did not decrease during the run, indicated by a positive exponent of the fitted relationship. These runs were considered failed and they were excluded from the dataset. A total of 401 runs were retained for the investigation after this preliminary analysis. The experimentally measured cumulative infiltration curve at a sampling point was examined to visually establish when the slope of the curve became constant (i.e. linearity in I vs. t). The intercept ($b_{+\infty}^{end}$) and the slope ($i_s^{\exp}$) of the line describing steady-state conditions were then calculated by least squares regression analysis of the visually selected linear portion of the I vs. t data points.

For a given sampling point, the shape parameters of the soil characteristic curves were determined according to Lassabatère et al. (2006), i.e. on the basis of the measured particle-size distribution and the estimated porosity, f, from ρ_b. The A, B and C constants were then estimated using the shape parameters and the initial and saturated volumetric soil water contents. According to other investigations, θ_s was assumed to coincide with f (Mubarak et al., 2009, 2010; Xu et al., 2009; Yilmaz et al., 2010; Bagarello et al., 2011a). BEST-slope, BEST-intercept and BEST-steady were then applied to determine soil sorptivity, S, and saturated soil hydraulic conductivity, K_s, at a sampling point. For each infiltration run, the relative error, E_r (%), was calculated for both BEST-slope and BEST-intercept to evaluate the quality of the fitting of the transient cumulative infiltration model on the data by the following relationship (Lassabatère et al., 2006):

$$E_r = 100 \times \sqrt{\frac{\sum_{i=1}^{k_{max}} \left[I_i^{exp} - I_{est,i} \right]^2}{\sum_{i=1}^{k_{max}} \left[I_i^{exp} \right]^2}} \qquad (14)$$

At first, a comparison between BEST-slope and BEST-intercept was carried out. In particular, the success (i.e., positive S and K_s values) rate of the two algorithms was determined and the possible effect of the measured $i_s^{\exp}$ and $b_{+\infty}^{end}$ values on the outcome of the run (success, failure) was investigated. Then the impact of the algorithm on the quality of the fitting of the transient cumulative infiltration model on the data was assessed by comparing the E_r values corresponding to BEST-slope and BEST-intercept. Subsequently, the two algorithms were compared in terms of estimated S and K_s values. For comparative purposes, the S and K_s data published by Yilmaz et al. (2010) were also considered. The success rate of BEST-steady was then determined and a comparison of this algorithm with the former ones was carried out in terms of estimated S and K_s values. The choice to initially compare the two existing algorithms was motivated by the reasoning that comparing BEST-steady with both BEST-slope and BEST-intercept made sense if these last algorithms performed differently with reference to the considered dataset.

RESULTS AND DISCUSSION

Comparison between BEST-slope and BEST-intercept

BEST-slope yielded positive values of S and K_s for 266, or 66.3%, of the 401 infiltration runs. BEST-intercept was successful for 374, or 93.3%, of the runs. The range of steady-state infiltration rates yielding successful calculations was similar for BEST-slope (0.0013-1.04 mm s^{-1}) and BEST-intercept (0.0013-1.41 mm s^{-1}). Some differences were detected in terms of intercept of the asymptotic expansion, since the two algorithms were usable for $7.0 \leq b_{+\infty}^{end} \leq 98.4$ mm and $13.5 \leq$

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$b_{+\infty}^{end}$ < 301.4 mm, respectively.

To establish a possible effect of the measured i_s^{exp} value on the outcome of the two algorithms, the 401 runs were ordered by increasing i_s^{exp} values and eight groups of 50 runs (51 runs for the first group) were established (**Table 3**).

This choice was made to have a detailed (relatively high number of groups) and representative (relatively large sample size for each group) picture of the calculation results. The success percentages of the two algorithms were then calculated for each group. With BEST-intercept, the success rates were not lower than 82% (**Fig.2a**). A success of practically 100% of the runs was detected for the lowest i_s^{exp} values (first three groups) and another, slightly lower, maximum was noted for the highest i_s^{exp} values (last two groups). For BEST-slope, the success percentages were never higher than 90%, and failure was relatively frequent for the lowest i_s^{exp} values (first three groups). A similar performance of the two algorithms was detected in the intermediate range of i_s^{exp} values (groups 4-7), but poorer performances were detected again with BEST-slope than BEST-intercept for the highest i_s^{exp} values (last group). The same calculations were carried out after ordering the runs by increasing $b_{+\infty}^{end}$ values (**Table 3** and **Fig.2b**).

With BEST-intercept, a success percentage of 100% was detected for all groups with the exception of the first one (lowest $b_{+\infty}^{end}$ values), showing failure of almost half of the runs. For this group, BEST-slope performed slightly better, but failure percentages were still noticeable

Table 3. Values of the experimental steady-state infiltration rate, i_s^{exp}, and the intercept of the asymptotic expansion of the cumulative infiltration curve, $b_{+\infty}^{end}$, for each of the eight established groups of data

Group	i_s^{exp} (mm s^{-1})	$b_{+\infty}^{end}$ (mm)
1	0.0013 - 0.0207	0.273 - 17.95
2	0.0207 - 0.0317	17.97 - 23.66
3	0.0319 - 0.0639	23.80 - 28.60
4	0.0641 - 0.1156	28.70 - 34.23
5	0.1164 - 0.1519	34.91 - 45.30
6	0.1533 - 0.2042	45.72 - 65.92
7	0.2050 - 0.3399	66.06 - 90.34
8	0.3482 - 1.4147	90.80 - 301.40

Eight groups of 50 runs (51 runs for the first group) were established by ordering the 401 runs by increasing i_s^{exp} (second column) and $b_{+\infty}^{end}$ (third column) values

(approximately, 40%). High success percentages, close to the 100%, were detected with the original BEST algorithm for intermediate values of $b_{+\infty}^{end}$ (groups 2-5). Then, failure rates increased substantially with $b_{+\infty}^{end}$ (groups 6-8). Therefore, both algorithms were usable with a similar degree of success for intermediate values of i_s^{exp} and $b_{+\infty}^{end}$. However, BEST-intercept performed better than BEST-slope for both low and high values of i_s^{exp} and for high values of $b_{+\infty}^{end}$. Performances of both algorithms were relatively poor for low values of $b_{+\infty}^{end}$.

A small intercept of the steady-state expansion is indicative of a practically linear

Figure 2. Success rates of the BEST-slope and BEST-intercept for each of the eight groups of runs arranged by increasing values of a) the experimental steady-state infiltration rate, i_s^{exp} (mm s^{-1}), and b) the intercept of the asymptotic expansion of the cumulative infiltration curve, $b_{+\infty}^{end}$ (mm), and c) relationship between $b_{+\infty}^{end}$ and i_s^{exp}. The i_s^{exp} and $b_{+\infty}^{end}$ values for each group are given in Table 3

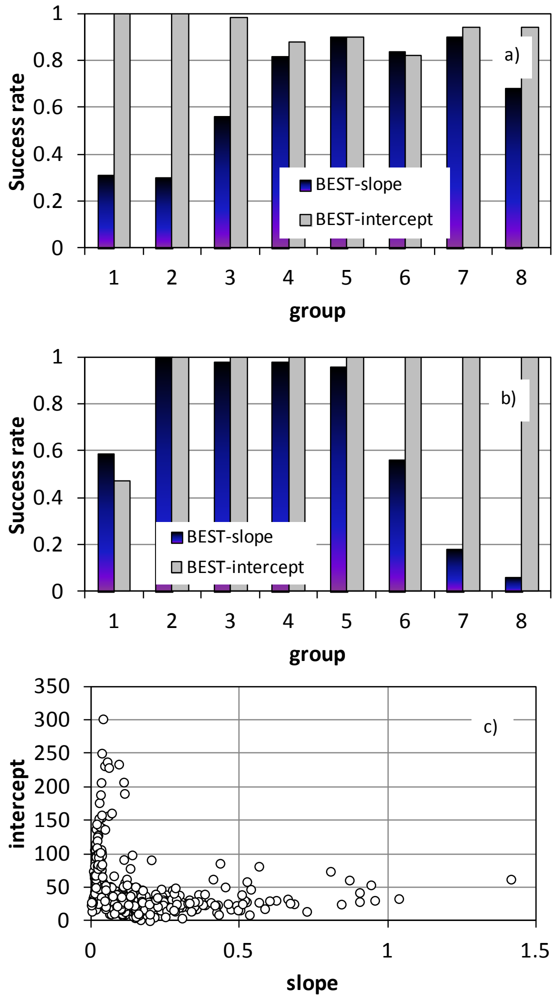

Table 4. Relative errors of the fitting of the infiltration model to the transient phase of the run

Statistic	BEST-slope		BEST-intercept		
	All valid runs	Runs analyzable with both algorithms	All valid runs	Runs analyzable with both algorithms	Runs analyzable only with BEST-intercept
N	266	256	374	256	118
Min	0.42	0.42	0.58	0.58	1.69
Max	19.01	19.01	36.38	21.32	36.38
Mean	3.23	3.17	7.99	4.03	16.57
Md	2.53	2.48	4.51	3.34	16.85
CV (%)	86.0	88.2	96.1	75.7	46.3

N = sample size; Min = minimum value; *Max* = maximum value; *Md* = median; *CV* = coefficient of variation. All valid runs include all runs yielding positive soil sorptivity, *S*, and saturated soil hydraulic conductivity, K_s, values with the indicated algorithm. Runs analyzable with both algorithms include the runs yielding positive *S* and K_s values with both BEST-slope and BEST-intercept. Runs analyzable only with BEST-intercept include the runs yielding positive *S* and K_s values with BEST-intercept but not with BEST-slope

infiltration curve from the beginning of the run or a very rapid attainment of quasi steady-state conditions. In these cases, the transient phase of the infiltration process is short or very short and, therefore, it is not surprising that an approach making use of the transient phase of the infiltration process fails frequently, independently of the considered algorithm. High values of $b_{+\infty}^{end}$ are expected to occur when steady-state conditions are detected late during the run, i.e. after infiltration of relatively large amounts of water. According to theory (Reynolds and Elrick, 2002), long equilibration times are typical of low permeability soils. Data of this investigation were consistent with theory since the largest $b_{+\infty}^{end}$ values were associated with low infiltration rates at steady-state (**Fig.2c**). In low-permeability soils, the risk to overestimate the steady-state infiltration rates is relatively high (e.g., Bagarello et al., 1999; Reynolds and Elrick, 2002). Moreover, measurement errors can have a noticeable impact on the experimental infiltration rates, also because a water volume has to be poured after disappearance of the previously applied volume, that may not occur uniformly from the entire infiltration surface when the infiltration process is particularly slow. This investigation showed that in low permeability soils it is better to use the intercept rather than the slope to obtain positive *S* and K_s values. This result may be viewed as a confirmation of the conclusion by Yilmaz et al. (2010) that BEST-intercept is expected to be more robust and capable of performing an efficient inverse analysis of cumulative infiltration as compared with BEST-slope. With reference to the dataset of this investigation, BEST-intercept is expected to yield positive *S* and K_s values when $b_{+\infty}^{end}$ varies from 18.0 to 300 mm. The possibility of failure of this algorithm occurs in the $0.3 \leq b_{+\infty}^{end} < 18.0$ mm range.

Considering all valid runs with a given algorithm (*N* = 266 for BEST-slope, *N* = 374 for BEST-intercept), the fitting accuracy of the transient infiltration model, expressed by E_r, was better for the former algorithm than the latter one (**Table 4**). Taking into account that $E_r \leq 5.5\%$ denotes an acceptable error for transient cumulative infiltration (Lassabatère et al., 2006), the mean error was acceptable for BEST-slope but not for BEST-intercept. In addition, E_r was less than 5.5% for approximately 90% of the valid runs analyzed with BEST-slope and 58% of the ones processed with BEST-intercept. When only the runs analyzable with both BEST-slope and BEST-intercept were considered (*N* = 256), more similar E_r values for the two algorithms were obtained and, on average, a satisfactory performance of the fitting was also detected for BEST-intercept (**Table 4**). In any case, the relative error was higher with this latter algorithm, as compared with BEST-slope, for the 91% of the considered runs. A different result was obtained by Xu et al. (2012) where BEST-intercept was found to have a similar performance to BEST-slope. Runs analyzable with BEST-intercept alone (*N* = 118) had appreciably higher errors compared with runs analyzable with both algorithms (**Table 4**). Therefore, BEST-slope allowed in general a more accurate description of the transient data as compared with BEST-intercept, suggesting that the larger success percentages of this last algorithm were attained at the expense of a poorer performance in terms of data representation by the transient model. In practice, testing first the applicability of BEST-slope seems advisable, since this algorithm allowed in general a better description of the transient infiltration data. BEST-intercept should the second choice, i.e. to be applied if BEST-slope does not work.

BEST-slope and BEST-intercept yielded significantly different estimates of both *S* and K_s for the 256 runs analyzable with both algorithms (**Table 5**). In particular, a lower sorptivity and a

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Table 5. Soil sorptivity, S, and saturated soil hydraulic conductivity, K_s, obtained with the BEST-slope (Slope in the table), BEST-intercept (Intercept) and BEST-steady (Steady) algorithms for different datasets

Statistic	Valid runs with Slope and Intercept			Valid runs with Slope and Intercept, and $E_r \leq 5.5\%$		Valid runs with Intercept		All runs	Yilmaz et al. (2010)	
	Slope	**Intercept**	**Steady**	**Slope**	**Intercept**	**Intercept**	**Steady**	**Steady**	**Slope**	**Intercept**
					S (mm s$^{-1/2}$)					
N	256	256	256	211	211	374	374	401	18	18
Min	0.166	0.153	0.134	0.501	0.499	0.153	0.134	0.134	0.93	0.90
Max	4.284	4.106	3.918	4.173	4.060	5.584	4.788	4.788	14.36	14.17
Mean	2.046(a)(b)	1.980(a)(c)	1.869(b)(c)	2.186(d)	2.118(d)	1.815(e)	1.654(e)	1.629	3.94(f)	3.87(f)
Md	2.010	1.938	1.864	2.151	2.099	1.770	1.612	1.535	2.26	2.20
CV	39.9	40.0	40.6	33.2	33.2	49.4	51.7	51.5	106.7	107.9
					K_s (mm s^{-1})					
N	256	256	256	211	211	374	374	401	16	16
Min	3.3×10^{-5}	6.3×10^{-4}	4.9×10^{-4}	1.2×10^{-4}	5.3×10^{-3}	6.3×10^{-4}	4.9×10^{-4}	4.9×10^{-4}	7.0×10^{-4}	0.017
Max	0.346	0.395	0.375	0.346	0.395	0.454	0.456	0.456	2.37	2.52
Mean	0.077(a)(b)	0.105(a)(c)	0.094(b)(c)	0.086(d)	0.116(d)	0.082(e)	0.073(e)	0.078	0.208(f)	0.283(f)
Md	0.063	0.087	0.079	0.071	0.097	0.059	0.052	0.057	0.036	0.068
CV	86.7	80.8	81.9	75.5	70.6	105.9	109.5	105.6	281.8	222.9

N = sample size; *Min* = minimum value; *Max* = maximum value; *Md* = median; *CV* (%) = coefficient of variation. For a given variable, the values in a row followed by the same lower case letter enclosed in parentheses were significantly different according to a paired, two tailed t test (P = 0.05)

higher saturated soil hydraulic conductivity were obtained with the latter algorithm. The two estimates of a variable were significantly correlated but the regression line did not coincide with the identity one according to the calculated 95% confidence intervals for the intercept and the slope (**Table 6** and **Fig.3**). The percentage difference between the individual estimates of S obtained with BEST-intercept and BEST-slope varied from -9.2% to 6.7% (mean = median = -3.3%). The former algorithm yielded higher K_s values than BEST-slope in the 98% of the cases and the individual K_s estimates were equal to 0.8-211 times the ones obtained with the latter algorithm (mean = 3.1, median = 1.4). The results of the algorithm comparison did not vary appreciably when the analysis was limited to the 211 runs characterized by a fitting error of the infiltration model not exceeding 5.5% in both cases (**Tables 5** and **6**). Repeating the same analysis with the data published by Yilmaz et al. (2010) yielded similar results, with the only exception that the linear regression line between the two estimates of K_s was not significantly different from the identity one (**Tables 5** and **6**). Therefore, the general result was that the two algorithms yielded significantly different but similar (i.e., differing by not more than a few percentage units) estimates of S. The impact of the algorithm was more noticeable for K_s. In particular, BEST-intercept showed a tendency to yield higher values of this variable as compared with BEST-slope, with differences even equal to more than two orders of magnitude. A satisfactory agreement between the transient data and the infiltration model ($E_r \leq 5.5\%$) was not enough to remove the detected differences. Higher K_s values with BEST-intercept than BEST-slope were also obtained by Xu et al. (2012).

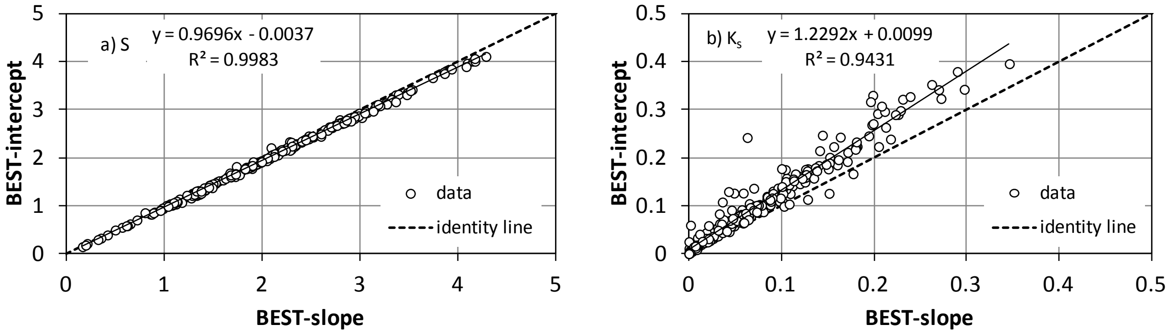
An uncertainty in the estimate of K_s by a factor of two or three can often be considered practically negligible since K_s ranges from 10^{-9} m s^{-1} for tight clays to 10^{-4} m s^{-1} for coarse sands and given the extreme spatial variability of K_s found

Table 6. Results of the linear regression analysis between the estimates of soil sorptivity, S, and saturated soil hydraulic conductivity, K_s, obtained with the BEST-slope, BEST-intercept and BEST-steady algorithms

Statistic	Valid runs with Slope and Intercept			Valid runs with Slope and Intercept, and $E_r \leq 5.5\%$	Valid runs with Intercept	Yilmaz et al. (2010)
	Intercept vs. Slope	**Steady vs. Slope**	**Steady vs. Intercept**	**Intercept vs. Slope**	**Steady vs. Intercept**	**Intercept vs. Slope**
				S (mm s$^{-1/2}$)		
N	256	256	256	211	374	18
b_0	-0.004	-0.027	-0.025	0.006	-0.051	-0.046
	-0.015 – 0.007	*-0.049 – -0.004*	*-0.042 – -0.007*	*-0.007 – 0.019*	*-0.085 – -0.016*	*-0.072 – -0.020*
b_1	0.970	0.927	0.956	0.966	0.939	0.995
	0.964 – 0.975	*0.916 – 0.937*	*0.948 – 0.964*	*0.960 – 0.972*	*0.922 – 0.956*	*0.990 – 0.999*
R^2	0.998	0.992	0.995	0.998	0.970	0.9999
				K_s (mm s^{-1})		
N	256	256	256	211	374	16
b_0	0.010	0.007	-0.0009	0.011	-0.002	0.062
	0.006 – 0.014	*0.004 – 0.010*	*-0.002 – 0.0004*	*0.006 – 0.016*	*-0.003 – -0.0007*	*-0.001 – 0.126*
b_1	1.229	1.127	0.906	1.210	0.910	1.064
	1.192 – 1.267	*1.098 – 1.156*	*0.897 – 0.915*	*1.166 – 1.254*	*0.899 – 0.920*	*0.958 – 1.169*
R^2	0.943	0.959	0.993	0.934	0.987	0.971

N = sample size; b_0 = intercept of the linear regression line; b_1 = slope of the linear regression line, R^2 = coefficient of determination. The values in italics denote the 95% confidence interval. All R values were > 0 according to an one tailed t test (P = 0.05)

Figure 3. Comparison between the BEST-intercept and BEST-slope estimates of a) soil sorptivity, S (mm s$^{-1/2}$), and b) saturated soil hydraulic conductivity, K_s (mm s^{-1}), for the N =256 infiltration runs analyzable with both algorithms



in the field (Elrick and Reynolds, 1992). In this investigation, carried out with reference to a large dataset and a variety of soils and experimental conditions, a difference between the two estimates of K_s of more than a factor of three was detected for the 9% (i.e., 23) of the runs. On the basis of this criterion, the two algorithms yielded practically similar K_s results both on average and in general. A practical implication of these results is that using BEST-intercept if BEST-slope fails and developing a set of S and K_s data by pooling together calculations carried out with the two algorithms introduces an additional source of heterogeneity in the developed dataset that however should not be substantial. However, the occasionally detected large discrepancies have to be viewed as a warning message that cannot be ignored. A hypothesis to be tested with independent K_s data is that, particularly in these cases, the most reliable algorithm is the one allowing the most accurate description of the transient infiltration process.

BEST-steady

BEST-steady yielded positive values of S and K_s for all infiltration runs (N = 401), that were characterized by $1.34\times10^{-3} \leq i_s^{exp} \leq 1.41$ mm s^{-1} and $0.3 \leq b_{+\infty}^{end} < 301.4$ mm. As expected, eqs.(7a) and (10) were equivalent in terms of K_s calculation. The calculated S values varied by more than an order of magnitude whereas K_s varied by approximately three orders of magnitude (**Table 5**).

For the 256 runs analyzable with the three algorithms, BEST-steady yielded significantly lower S values as compared with both BEST-slope (by approximately 9%) and BEST-intercept (by 6%, **Table 5**). The estimates of S obtained with the new algorithm were significantly correlated with the ones obtained with the algorithms by Lassabatère et al. (2006) and Yilmaz et al. (2010) but the linear regression line did not coincide with the identity line (**Table 6**) notwithstanding that the calculated S values were generally close to this last line (**Fig.4**). The percentage differences between the individual calculations of S made with BEST-steady and BEST-slope varied between -22% and 9%. For BEST-intercept, these differences ranged from -17% to 3%. The estimates of K_s obtained with BEST-steady differed significantly from the ones obtained with the other two algorithms (**Table 5**) and also in this case the regressions were significant but the regression lines differed from the identity lines (**Table 6**). BEST-steady yielded higher K_s values than BEST-slope and lower values than BEST-intercept (**Fig.4**). The estimates of K_s obtained with BEST-slope and BEST-steady differed by a maximum factor of three in the 93% of the cases even if the maximum factor of difference was equal to 186 (mean = 2.7, median = 1.2). The estimates of K_s obtained with BEST-intercept and BEST-steady differed at the most by a factor of 1.5 (mean = median = 1.1). Therefore, BEST-steady was closer to BEST-intercept than to BEST-slope.

Comparing BEST-steady and BEST-intercept with reference to a larger dataset, including the 374 runs analyzable with this last algorithm, yielded a similar information (**Tables 5** and **6**), i.e. statistically significant differences between the algorithms both for S and K_s, lower values of both variables with the BEST-steady approach as compared with BEST-intercept, closeness of the data points to the line of identity (**Fig.5**), statistically significant regressions but regression lines differing from the identity ones. The percentage differences between individual calculations of S varied between -45% and 11% (mean = -10%, median = -7%), whereas two corresponding estimates of K_s differed at the most by 3.3 times (factor of difference < 3 in the 99.7%

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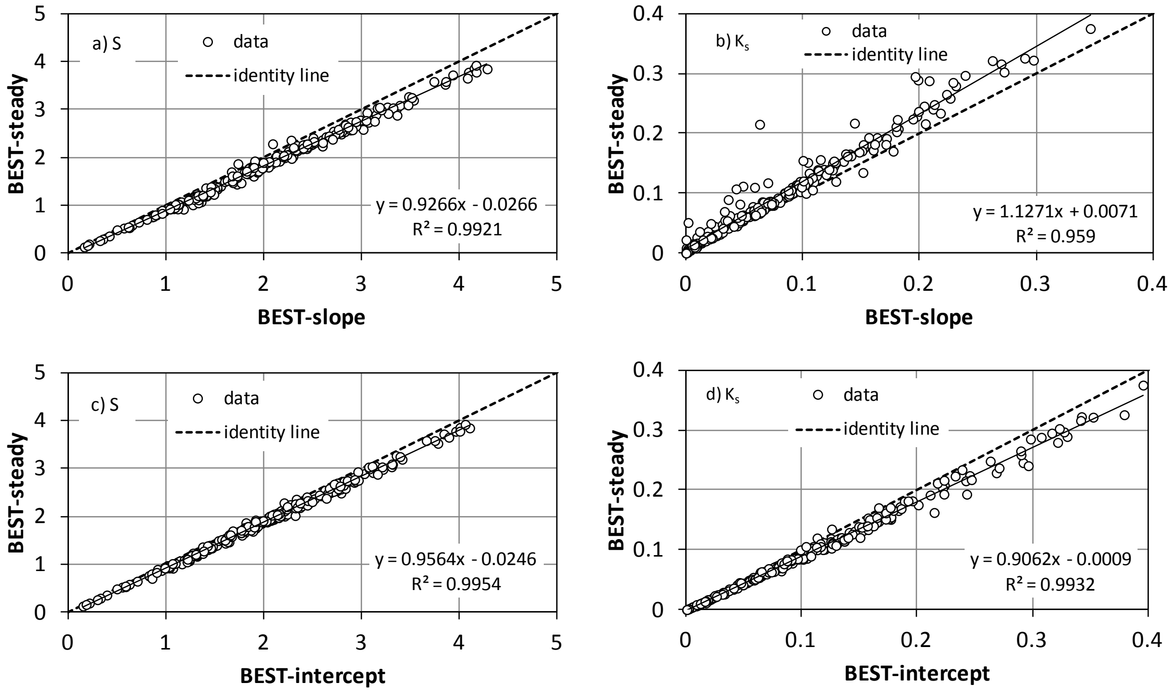
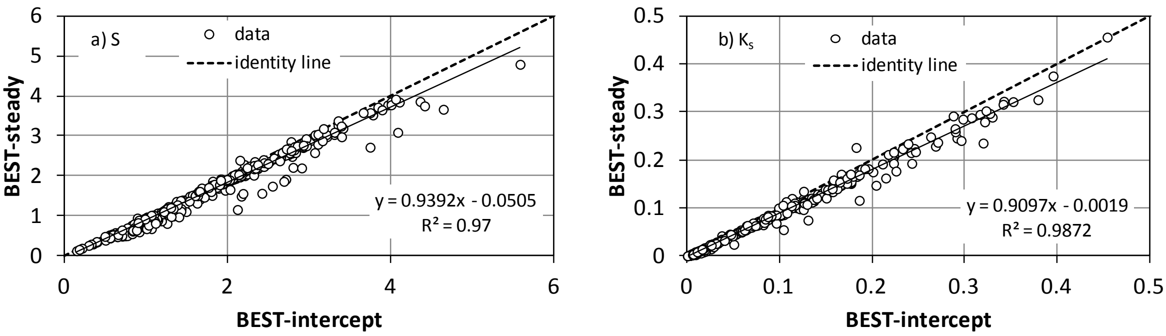
Figure 4. Comparison between alternative estimates of soil sorptivity, S (mm $s^{-1/2}$), and saturated soil hydraulic conductivity, K_s (mm s^{-1}), for the N =256 infiltration runs analyzable with all algorithms: a) BEST-steady vs. BEST-slope, S; b) BEST-steady vs. BEST-slope, K_s; c) BEST-steady vs. BEST-intercept, S; and d) BEST-steady vs. BEST-intercept, K_s



of the cases, mean and median of the factor of difference equal to 1.3 and 1.2, respectively). Therefore, with the larger dataset (N = 374), the percentage differences between individual calculations of S (BEST-steady, BEST-intercept) were appreciably higher, in absolute terms, than the ones detected with the smaller (N = 256) dataset. The additional runs included in the larger dataset were generally characterized by high E_r values (**Table 4**).

The investigation confirmed that BEST-steady represents an alternative algorithm to be considered for analyzing the Beerkan infiltration experiment, because the results were close to the ones obtained with other existing algorithms, or relatively large differences with other algorithms were detected when there were signs suggesting a problematic application of these last data analysis procedures. Considering that BEST-steady uses the information representative of the steady-state phase of the process, the longest possible infiltration run, within practically reasonable limits, should be carried out to improve data representativeness. For example, the Cumulative Drop procedure, originally developed with reference to the Guelph permeameter method (Bagarello and Giordano, 1999; Bagarello et al., 1999), could be adapted and used with the Beerkan infiltration experiment. The algorithm simplifies calculation of S and K_s because it does not require repeated determinations of t_{max}. BEST-steady could be expected to yield more reliable K_s than S data. The reason is that K_s is expressive of what happens at late times of an infiltration process whereas S, being a measure of the ability of the unsaturated soil to absorb water as a result

Figure 5. Comparison between the BEST-steady and BEST-intercept estimates of a) soil sorptivity, S (mm $s^{-1/2}$), and b) saturated soil hydraulic conductivity, K_s (mm s^{-1}), for the N =374 infiltration runs analyzable with both algorithms



of capillarity (Philip, 1957), is expected to have a more noticeable impact in the early stages of the process. However, this distinction is made with reference to one-dimensional infiltration. For a 3D Beerkan infiltration run, S also influences infiltration at steady-state as shown by eq.(4d). Therefore, it is logical to assume that both S and K_s are estimable from the steady-state phase of this last infiltration run. Moreover, the soil is not, in general, really rigid and there are many experimental evidences suggesting that the soil hydraulic properties change during water application for a variety of reasons, including for example crusting and particle sorting during a rainfall event (Arya et al., 1998; Ramos et al., 2000; van de Giesen et al., 2000; Assouline, 2004; Dikinya et al., 2008; Ben-Hur et al., 2009; Bagarello et al., 2011b, 2012). An implication of these effects on infiltration is that a soil hydraulic characterization performed by combining early- and late-time infiltration data (BEST-slope, BEST-intercept) can be expected to be more noisy, and hardly attributable to a specific stage of a field infiltration process, than a characterization based exclusively on a stabilized infiltration process (BEST-steady). In other terms, there are reasons supporting the hypothesis that a characterization made with BEST-steady may be more appropriate to give a picture of the soil properties during the advanced stage of the wetting process of an initially unsaturated porous medium.

A soil hydraulic characterization simultaneously carried out with BEST and other, well tested methods (e.g., laboratory measurement of soil water retention, field measurement of K_s and K with the pressure and the tension infiltrometers) is necessary to understand if and to what extent BEST-steady is a practical alternative to BEST-slope and BEST-intercept. In general, there is the need to experimentally assess the predictive performances of the BEST procedure, that are still largely unknown notwithstanding that simple and rapid methods of soil hydraulic characterization have a noticeable practical interest. In any case, this is a complicated step in the BEST assessment route due to the lack of independent data upon which evaluations and judgments can be made, especially with reference to hydrynamic parameters (Reynolds et al., 2000). Perhaps, the availability of different procedures to analyze the infiltration data should imply more opportunities to find a satisfactory approach to apply BEST in practice.

CONCLUSION

This investigation improved our knowledge of the two alternative algorithms developed to analyze a Beerkan infiltration experiment. BEST-slope has a higher chance not to give positive estimates of soil sorptivity, S, and saturated soil hydraulic conductivity, K_s, as compared with BEST-intercept. The largest differences between the two algorithms were detected in low permeability soils where BEST-slope, but not BEST-intercept, failed frequently. This last algorithm was always successful for an intercept of the steady-state expansion of the cumulative infiltration curve of 18.0 mm or more and the risk of failure of BEST-intercept was limited to lower values of this parameter. Therefore, the intercept of the steady-state expansion can be considered diagnostic of the expected outcome (success, risk of failure) of the run.

However, the larger success percentages of BEST-intercept were attained at the expense of a poorer performance in terms of data representation by the transient model. Therefore, in practical use of the BEST procedure, data should initially be analyzed with BEST-slope and the attempt to apply BEST-intercept should be made only if the former algorithm fails in giving physically plausible S and K_s values.

A possible problem with the suggested combined use of the two algorithms is that they were not equivalent. In general, this should not be a problem of practical importance because the calculations of S and K_s did not vary substantially between the two data analysis procedures. However, exceptions to this general result were detected and there is the risk of an undervaluation of this problem in the practical application of BEST. The reason is that, according to the suggested procedure, these exceptions will not be detectable because not more than a single S-K_s data pair will be obtained at a sampling point. Therefore, the link between the reliability of the estimated soil properties and the used algorithm should be specifically explored.

The BEST-steady algorithm developed in this investigation combines procedures already included in BEST-slope and BEST-intercept to obtain an estimate of S and K_s on the basis exclusively of the intercept and the slope of the linear relationship between the cumulative infiltration at steady-state and the time. This algorithm has both theoretical and practical advantages as compared with the existing algorithms, including i) high probability of

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success; ii) simplified calculation of S and K_s; iii) no need to use potentially invalid S and K_s calculations to establish the time validity of the transient infiltration model; iv) possibility to adjust the run duration directly in the field to obtain the most representative possible infiltration curve for the sampled location; and v) possibility to assign the measured soil properties to a specific stage of the water infiltration process in an initially unsaturated soil. Therefore, BEST-steady should be considered a promising alternative procedure to analyze the Beerkan infiltration data.

Confidence in the results can be suggested since they were obtained on the basis of an unusually large and varied dataset. In the future, soil hydraulic characterization should be simultaneously carried out with the alternative BEST algorithms and with independent measurement methods to better establish the potential of BEST and also to detect the most appropriate algorithm for a general use in the field.

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Appendix C: Automated single ring infiltrometer with a low-cost microcontroller circuit

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ABSTRACT

A method to automate data collection with a compact infiltrometer under constant head conditions was developed. The infiltrometer consists of a containment ring with a small quasi-constant head of water (i.e., 2–3 mm) that is controlled by a Mariotte reservoir and a data acquisition system based on the open source microcontroller platform Arduino and a differential pressure transducer. The presented design can be easily reproduced and operated. The infiltrometer was tested in a citrus orchard on a sandy loam soil. A simple methodology was applied for accurate data acquisition from the initial stage of the process and to minimize the disturbance of the soil surface. A new approach to process the data was proposed for determining an accurate cumulative infiltration curve from transducer output. The BEST algorithm by Lassabatère et al. (2006) was applied to determine the hydraulic properties of the soil. A comparison between the automated procedure and the original BEST procedure was made. Automatic data collection increases measurement speed, permits measurement at shorter time intervals, improves measurement precision, and allows for more efficient data handling and analysis. The proposed electronic data acquisition system based on the open source Arduino board has proved to be accurate and reliable, constituting a very cost effective alternative to previous proposed equipment. The very limited cost could represent a step toward a cheaper and widespread application of accurate and automated infiltration rate measurement. This infiltrometer could be used for situations where a large number of readings need to be collected.

Keywords: Automated single-ring infiltrometer, Arduino, BEST (Beerkan Estimation of Soil Transfer parameters), hydraulic properties.

1. INTRODUCTION

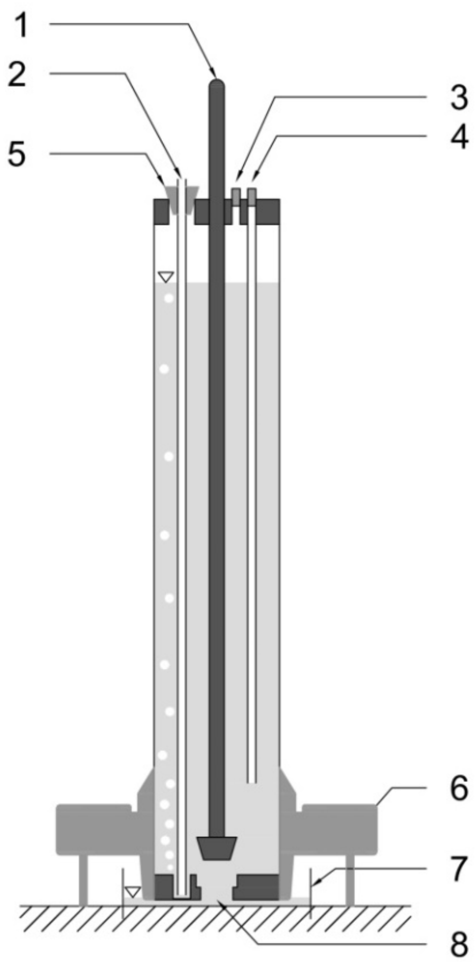
The hydraulic conductivity of saturated soil is one of the most important soil properties controlling water infiltration and surface runoff, leaching of pesticides from agricultural lands, and migration of pollutants from contaminated sites to the ground water (Reynolds et al., 2000). Saturated hydraulic conductivity depends strongly on soil texture and structure, and therefore can vary widely in space. Since hydraulic conductivity is determined essentially at points on a field scale, a large number of determinations is required to assess the magnitude and structure of the variation within the selected area (Logsdon and Jaynes, 1996). Spatially distributed determinations of hydraulic conductivity have to be repeated at different times, particularly in soils where structure varies over time because of natural or anthropogenic factors (Prieksat et al., 1994). For structured soils in particular, saturated hydraulic conductivity has to be measured directly in the field to minimize disturbance of the sampled soil volume and to maintain its functional connection with the surrounding soil (Bouma, 1982). Reliable field data should be collected with a reasonably simple and rapid experiment.

Haverkamp et al. (1996) pioneered a method, termed as the "Beerkan method", that allows for simultaneous characterization of both the soil water retention curve and the hydraulic conductivity function. An improved version of this methodology, called the Beerkan Estimation of Soil Transfer parameters (BEST) procedure, was developed by Lassabatère et al. (2006) to simplify soil hydraulic characterization. With BEST procedure, cumulative infiltration data have to be collected. Lassabatère et al. (2006) suggested to measure the infiltration time of small volumes of water repeatedly poured on the soil surface confined by a ring inserted to a depth of about 1 cm into the soil. BEST considered a zero ponded infiltration model which was assumed respected under infiltration run performed with small, but positive, pressure head. This assumption was supported by numerical tests carried out by Touma et al. (2007). According to Alagna et al. (2015) and Bagarello et al. (2014a, 2014b), the infiltration experiment prescribed by Lassabatère et al. (2006) can be sensitive to soil disturbance and air entrapment during repeated water application. These alterations were expected to have a more appreciable impact on the measured conductivity with the BEST technique than a ponding infiltration experiment since a constant ponded depth of water was maintained during the run with the latter technique whereas the water is repeatedly poured with the former one. Moreover, several problems yet arise with BEST method, including (1) the need for an operator over the whole duration of the experiment; (2) the need to reach steady state infiltration, which can be extremely long in certain cases; and (3) the experimental error and the variable skillness among operators. Therefore, since reliable field data should be collected with a reasonably simple and rapid experiment, and a ponding infiltration test is expected to minimize soil disturbance, the use of a single-ring infiltrometer along with BEST algorithm could be advisable. Different single-ring infiltrometers were developed (e.g., Prieksat et al. 1992; Matula and Kozáková 1997). These infiltrometers maintain a quasi-constant head in a containment ring, allowing to calculate flow rates from changes in water height in a Mariotte reservoir with time. Automated measurements of reservoir water levels using a differential transducer were first tested by Casey and Derby (2002). The voltage output from the transducer is linearly related to the difference between head-space tension and the height of water in the Mariotte reservoir (Constantz and Murphy, 1987). Nevertheless, the advantages of simplified methodologies, such as BEST, are their simplicity and cheapness (Madsen and Chandler, 2007; Dohnal et al., 2010). The use of expensive devices or time consuming procedures could contradict their original purpose. In fact, automatic data collection increases measurement speed and improves measurement precision but monitoring equipment often contains proprietary technology with prohibitive cost for this purpose. Recently, advances in electronic technologies have provided researchers to access to low-cost, solid-state sensors and programmable microcontroller-based circuits (Fisher et al., 2012). In this work, it is presented a compact automated infiltrometer (**Fig. 1**) which consists of a containment ring with a small quasi-constant head of water (i.e., 2–3 mm) that is controlled by a Mariotte reservoir and a data acquisition system based on the open source microcontroller platform Arduino (protected trademark of Arduino LLC).

Figure 1. Single ring infiltrometer and data acquisition system.

The infiltrometer was tested in a citrus orchard on a sandy loam soil. The BEST algorithm by Lassabatère et al. (2006) was applied to determine the hydraulic properties of the soil using a total of ten infiltration experiments performed using both the proposed infiltrometer and the BEST procedure. A comparison between the automated procedure and the original BEST procedure was made.

Figure 2. Schematic diagram of the single-ring infiltrometer. (1) Piston; (2) air entry tube; (3) connector for vacuum side of the pressure sensor; (4) connector for pressure side of the pressure sensor; (5) rubber; (6) tripod; (7) water containment ring and (8) outlet.



2. MATERIALS AND METHODS

2.1. THE MARIOTTE RESERVOIR

The automatic infiltrometer allows to maintain a small constant water head on a soil surface confined by a 150 mm inner diameter ring using a Mariotte bottle for water supply. Depending on the surface roughness, the Mariotte bottle can be regulated in height so that the surface confined by the ring is entirely submerged under a practically negligible water depth, i.e. 2-3 mm. A schematic diagram of the infiltrometer is reported in **Fig. 2**. The bottle consists of a transparent cylinder with an inner diameter of 94 mm, a height of 520 mm and a base outlet of 26 mm. Allowing to store a maximum volume of water corresponding to a total cumulative infiltration of 130 mm (i.e., 2.3 L). An air entry tube (6.5 mm inner diameter) controls the level inside the ring by allowing air entry at very close distance from the reservoir base. Detailed scheme of all components can be consulted in **Appendix C1**.

A standard practice to minimize the impact of the water application procedure on the saturated soil hydraulic conductivity values measured by a ponding infiltration experiment has not been established, although several suggestions have been formulated to minimize this impact, including slowly raising the piston of the device, carefully pouring water on the soil surface to a given depth before opening the infiltrometer reservoir, and dissipating the energy of the water on the fingers of the hand or a wire net placed on, or suspended at a small distance from the infiltration surface, depending on the circumstances (e.g., Reynolds, 1993; Bagarello and Sgroi, 2004).

In this investigation, to minimize disturbance on the soil surface and to have an accurate data acquisition from the beginning of the run, the water head is initially applied to a fine plastic film positioned on the infiltration surface inside the ring. Then, after that the water is discharged from the base outlet, through lifting a piston, the data acquisition can be started. The infiltration starts when the plastic film is removed. When the water level in the ring goes down, the Mariotte bottle provides a certain amount of water to the ring. At this moment, some bubbles can be seen through the bottle from the air entry tube. Avoiding the direct detachment of the bubbles from the bottom outlet allows to minimize turbulence which could affect the soil surface. A specific tripod designed for the reservoir allows to pose the infiltrometer very close to the surface and hence to maintain a small water during the infiltration process.

2.2. DATA ACQUISITION SYSTEM

The core of the data acquisition system consists of a microcontroller board, an Ethernet Shield with an onboard micro-SD card slot (only the shield's store files capability is exploited here), a LCD display and a differential pressure transducer (cost

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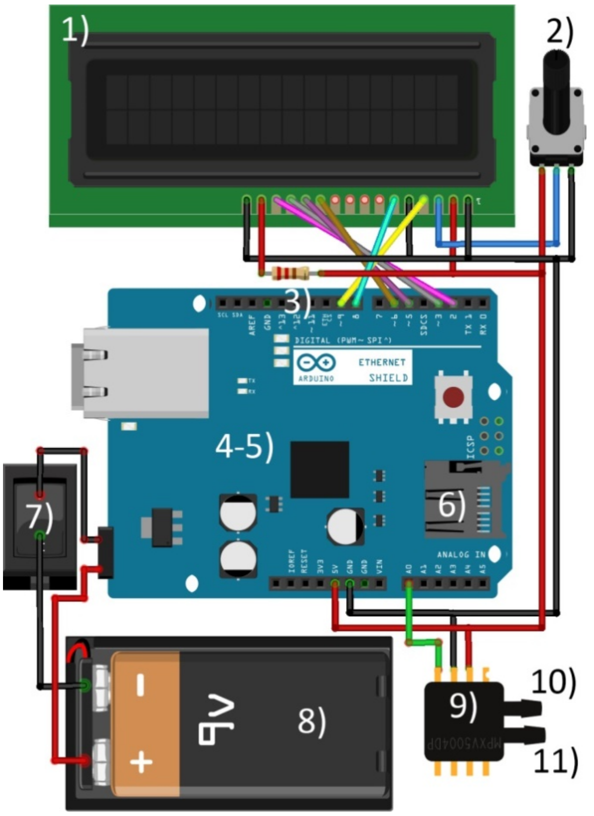
Figure 3. Electrical scheme of the data acquisition system. (1) Display LCD 16x2; (2) rotary potentiometer; (3) 220 ohm resistor; (4) Arduino Uno board; (5) Arduino Ethernet Shield plugged onto the Arduino Uno board; (6) onboard micro-SD card slot; (7) power switch; (8) nine volt battery; (9) Freescale Semiconductor MPXV5004DP differential pressure sensor; (10) vacuum side of the pressure sensor; (11) pressure side of the pressure sensor.



of the components in **Table 1**). The schematic diagram of the circuit is presented in **Fig. 3**.

The voltage output from the transducer is linearly related to the difference between head-space tension and the height of water in the mariotte reservoir (Constanz and Murphy, 1987). Automated measurements of reservoir water levels using a differential transducer were first tested by Casey and Derby (2002). This improvement makes it easy to obtain early infiltration rate measurement and increase the accuracy of the steady flow rate.

The differential pressure transducer is connected by small tubes to head-space of the reservoir and to a tube (inside diam. = 6.5 mm, length = 400 mm) descending inside the reservoir so that the pressure difference between the head-space and the bottom of the column of water can be measured.

The sensor used for this application is the piezoresistive differential pressure transducer MPXV5004DP from Freescale Semiconductor requiring a power supply of 5 V and with integrated temperature compensation and signal amplification circuit. The transducer provides a linear voltage output for a differential pressure range from 0 to 400 mm H_2O.

There is a wide choice of commercially available microcontrollers. Most of them require additional external components and/or specific programming interfaces to become fully operational units, and therefore demand a substantial degree of technical expertise both for assembly and programming. In recent years, an open source project has been launched, designed to make the use of microcontrollers in multidisciplinary projects more easily accessible (Thalheimer, 2013). The Arduino Uno is a board based on the Atmel ATmega328 microcontroller. The Arduino Uno can be powered via the USB connection or with an external power supply like a 9V battery. Detailed reference about boards and the programming language, including explanatory examples, can be found on the Arduino website (http://www.arduino.cc).

A suitable software code for the microcontroller is available (**Appendix C2**). The data were stored on a SD card for later retrieval and simultaneously displayed on a LCD display. The software generates a new comma-separated values (CSV) file every time that the microcontroller is alimented. The name of the generated file can be displayed on the LCD for the first few seconds.

Tab 1. Indicative prices (without VAT and shipping) of the components of the data acquisition system.

Components	Price (€)
Arduino Uno board	20.00
Arduino Ethernet Shield	29.00
Display LCD 16x2	9.90
Micro SD card 2GB with SD adapter	7.90
Freescale Semiconductor MPXV5004DP differential pressure sensor	10.62
Total	77.42

2.3. LABORATORY TESTING

Laboratory calibration was done measuring the sensor output at successive decreases in the height of the water Mariotte column from a start height of 385 mm to 18 mm H_2O. The resulting calibration function between differential pressure and sensor output was deduced. Moreover, the infiltrometer was tested maintaining a constant head inside a 146 mm inside diameter cylinder and measuring the water flowing (rate of 1 $cm^3 s^{-1}$) through a pipe positioned at the bottom of the cylinder. At the same time, readings of the transducer were made at the rate of 5 s^{-1}. When the water level in the cylinder went down, the Mariotte bottle provided a certain amount of water into the cylinder. Water supply was signaled by a sudden rise of air bubbles from the air entry tube that caused a disturbance in pressure transducer measurement, leading to outliers which could easily be identified and eliminated (Ankeny et al., 1988). Between two consecutive water supplies, the height of water in the reservoir remained constant which resulted in a step-shaped water level vs. time relationship. The cumulative infiltration curve was deduced by sampling the recorded water levels, I_i^{end} mm, at time immediately preceding each bubble detachment. At this time, the previous volume poured inside the ring had completely infiltrated but the subsequent volume was not still supplied, thus automatically mimicking the procedure that is followed when executing manually a Beerkan experiment. Then, the experimental cumulative flow data, I_i^{exp} mm (10 measured points), were calculated by measuring the water flowing through the pipe. Finally, the recorded I_i^{end} data were compared with the measured I_i^{exp} values.

2.4. FIELD TEST

Lastly, a total of ten field infiltration experiments were performed, five with the automated procedure and five with the original BEST procedure. The runs were performed at the Department of Agricultural and Forestry Sciences of the Palermo (Italy) University, in a citrus orchard (UTM: 355500E, 4218950N) with trees spaced 4 m x 4 m apart. The soil (Typic Rhodoxeralf) with a relatively high gravel content was classified as sandy loam. A total of 4 undisturbed soil cores (0.05 m in height by 0.05 m in diameter) were collected at the 0–0.05 m and 0.05–0.10 m depths in two randomly chosen sampling points. These cores were used to determine the dry soil bulk density, ρ_b (Mg m^{-3}), and the soil water content at the time of sampling, θ_0 (m^3 m^{-3}). The soil porosity, ε (m^3 m^{-3}), was calculated from the ρ_b data, assuming a soil particle density of 2.65 Mg m^{-3}. According to other investigations, the field saturated soil water content, θ_s (m^3 m^{-3}), was assumed to coincide with ε (Mubarak et al., 2009; Bagarello et al., 2011, 2014a). Taking into account that a low to medium spatial variability is expected for both θ_0 and ρ_b at the field scale (Warrick, 1998), representative values of these parameters were obtained by averaging the individual determinations. The disturbed soil was used to determine the particle size distribution using conventional methods (Gee and Bauder, 1986).

Water height in the Mariotte reservoir was recorded at the rate of 5 s^{-1} for 258-959 seconds, with a total volume of infiltrated water of 2140-2288 cm^3, depending of the run.

As prescribed by the BEST experimental procedure (Lassabatère et al., 2006), a known volume of water (150 cm^3) was poured in the cylinder at the start of the measurement and the elapsed time during the infiltration was measured. When the amount of water had completely infiltrated, an identical amount of water was poured into the cylinder and the time needed for the water to infiltrate was logged. A total of 15 water volumes, each of 150 cm^3, were poured to apply BEST. The duration of these runs varied from 429 to 1229 seconds, with a total volume of infiltrated water of 2250 cm^3.

Tab 2. Clay, *cl*, silt, *si* and sand, *sa* content (USDA classification system) in the 0–0.1 m depth range, dry soil bulk density, ρ_b, initial volumetric soil water content, θ_0 and porosity, ε, for the samples collected at the Department of Agricultural and Forestry Sciences of the Palermo University.

Variable	*cl* %	*si* %	*sa* %	ρ_b (Mg m^{-3})	θ_0 (m^{3}m^{-3})	ε (m^{3}m^{-3})
N	4	4	4	4	4	4
Min	15.6	26.9	56.1	1.137	0.105	0.527
Max	16.4	27.4	57.3	1.255	0.120	0.571
M	15.9	27.2	56.9	1.176	0.111	0.556
CV	2.6	1.0	0.9	4.6	5.8	3.7

N = sample size; *Min* = minimum value; *Max* = maximum value; *M* = mean; *CV* (%) = coefficient of variation.

A total of ten experimental cumulative infiltration, *I* (mm), versus time, *t* (s), was then deduced, five for each methodology. The workbook by Di Prima (2013) was applied for a user-friendly analysis of BEST runs making use of Microsoft Excel software (Microsoft Company, Redmond, WA). Data sets were summarized by calculating the mean, *M*, and the associated coefficient of variation, *CV*. In particular, the arithmetic mean and the associated *CV* were calculated for ρ_b, θ_0, ε, clay, silt and sand content (percentages, USDA classification) (**Table 2**). For soil sorptivity, *S* (mm s$^{-0.5}$), *M* and the associated *CV* were also calculated. For the saturated soil hydraulic conductivity, K_s (mm s^{-1}), the statistical frequency distribution of the data was assumed to be log-normal, as is common for this variable (e.g., Mohanty et al., 1994;Warrick, 1998), and geometric means and associated *CV* were calculated using the appropriate “log-normal equations” (Lee et al., 1985).

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3. RESULTS AND DISCUSSION

The resulting calibration function (**Fig. 4**) described a perfect linearity between differential pressure and sensor output (r^2=1 for 47 measured points). The experimentally established sensitivity of the sensor was of 10 mV/mm H_2O.

Figure 4. Experimental calibration curve of an MPXV5004DP sensor. The sensor sensitivity is 0.01 V/mm H_2O (r^2=1).

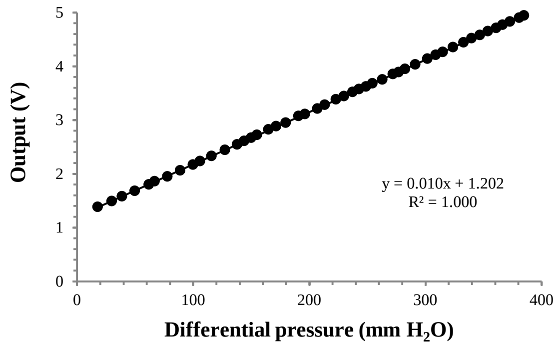
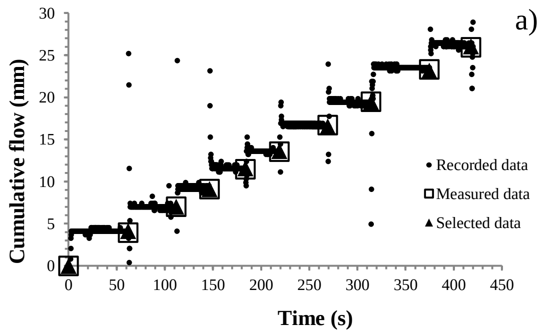


Figure 5a. Measured cumulative flow data, I_i^{exp} mm (determined maintaining a constant head inside a cylinder and measuring the water flowing with a rate of 1 cm^3 s^{-1} through a pipe positioned at the bottom of the cylinder), and recorded data from transducer. The last recorded data, I_i^{end} mm, of the constant height stages in Mariotte bottle were selected as good predictors of measured data.

Figure 5b. Comparison between the measured cumulative flow data, I^{exp} mm, and the selected recorded data, I^{end} mm.



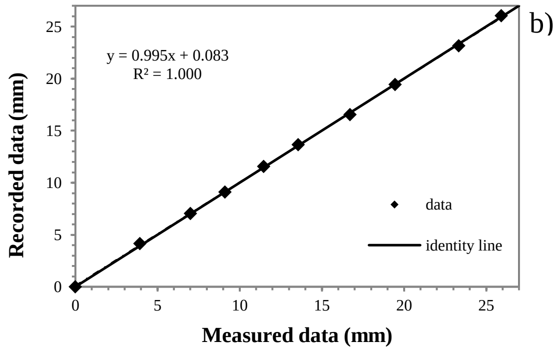
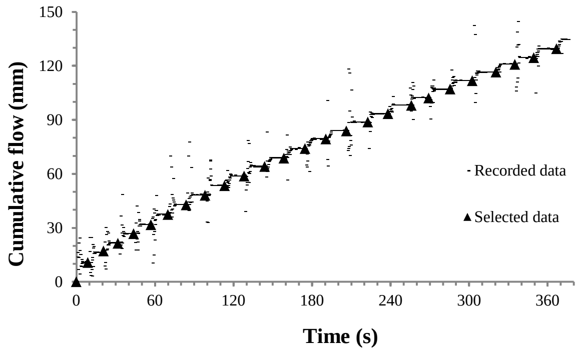


Figure 6. Illustrative example of the selection of cumulative infiltration values recorded at the end of the constant height stages in Mariotte bottle.



During the laboratory test, the sampled I_i^{end} data appeared close to the measured I_i^{exp} values (**Fig. 5a**). The 95% confidence intervals for the intercept and the slope of the linear regression line of I_i^{end} against I_i^{exp} were equal to -0.087 to 0.252 and 0.983–1.006, respectively, suggesting that the regression line coincided with the identity line. The goodness of the predictions is also visually detectable (**Fig. 5b**).

Five infiltration experiments were carried out with the infiltrometer on a sandy-loam soil. According to the procedure described above the cumulative infiltration curve was deduced for each run visually detecting the I_i^{end} values (**Fig. 6**).

With the infiltrometer data, BEST algorithm yielded positive values of S and K_s for 4 of the 5 infiltration runs. With the Beerkan data also 4 of the 5 runs were successful. As showed in **Table 3** the means of K_s were 0.107 and 0.106 mm s^{-1} for the infiltrometer and the Beerkan method respectively, the associated coefficients of variation (*CV*) were equal to 23.1 and 47.8 % (*CV* differing by 2.1 time). The means obtained from the two procedure were similar but a difference was detected in terms of variability, with the Beerkan data that showed a tendency to yield higher *CV* values. The relative error, E_r (%), calculated with Eq. (26) by Lassabatère et al. (2006), express the quality of the data fitting on the transient

cumulative infiltration model. With the infiltrometer data, the E_r values were lower ($0.8 \leq E_r \leq 4.0\%$, M = 2.1%) than the Beerkan data ($1.6 \leq E_r \leq 4.7\%$, M = 2.7%) suggesting more accuracy in data fitting (Lassabatère et al., 2006). Attempts to explain these differences with the applied procedure are advisable to establish what is the more accurate approach for determining K_s.

A possible factor determining this result was that establishing the exact application time of

Tab. 3. Total number of cumulative infiltration value, k_{tot}, total volume infiltrated, V_{tot}, saturated soil hydraulic conductivity, K_s, soil sorptivity, S, and fit relative error, E_r, obtained with the BEST algorithm for each run of the two datasets.

Methodology	k_{tot}	V_{tot} (cm^3)	K_s (mm s^{-1})	$M(K_s)$	CV (K_s)	S (mm s$^{-0.5}$)	$M(S)$	$CV(S)$	E_r %	$M(E_r)$
BEERKAN	15	2250	0.059	0.106	47.8	1.193	1.828	23.3	2.6	2.7
	15	2250	0.166			1.971			4.7	
	15	2250	0.134			2.077			1.9	
	15	2250								
	15	2250	0.097			2.071			1.6	
INFILTROMETER	25	2227	0.123	0.107	23.1	2.135	2.050	28.2	4.0	2.1
	29	2220	0.134			1.268			1.8	
	21	2140								
	27	2180	0.080			2.134			1.7	
	25	2288	0.101			2.663			0.8	

M = mean; CV (%) = coefficient of variation.

the new volume of water was not easy because ponding conditions did not disappear uniformly from the infiltration surface. Due to this circumstance, some uncertainty in the measured cumulative infiltration curve was unavoidable. Maintaining a small water head upon the soil surface and monitoring the supply reservoir with a continuous recording system avoided this problem and increased the number of the sampled data points. Another possible reason of the relatively poor fitting was that a repeated perturbation of the soil surface might determine a greater departure of the sampled porous medium from the ideal one assumed by the theory (Bagarello et al., 2014a), whereas the use of the infiltrometer avoided the soil disturbance during the infiltration process and increased the reliability of the soil hydraulic characterization.

4. CONCLUSIONS

A method to automate data collection with a compact infiltrometer under constant head conditions was developed. The proposed electronic data acquisition system based on the open source Arduino system and MPXV5004DP differential pressure sensor, constitutes a very cost effective alternative to previous proposed equipment. The estimate of the total cost of the system amounts to 77 euros. From a technical point of view, the system has proved to be accurate and reliable.

Automatic data collection increases measurement speed, permits measurement at shorter time intervals, improves measurement precision, and allows for more efficient data handling and analysis. The comparison with the original Beerkan method suggests that the automated infiltrometer reduces the uncertainty of the calculated hydraulic parameters. In particular, the increased accuracy of the data fitting on the transient cumulative infiltration model and the lower variability of the K_s data allow for more accurate hydraulic characterization. Moreover, the system automates the measurement of the infiltration process, thus significantly reducing the amount of effort involved and the potential for human error.

The presented infiltrometer can be easily fabricated and operated. It can be used for situations where a large number of readings need to be collected.

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APPENDIX C1

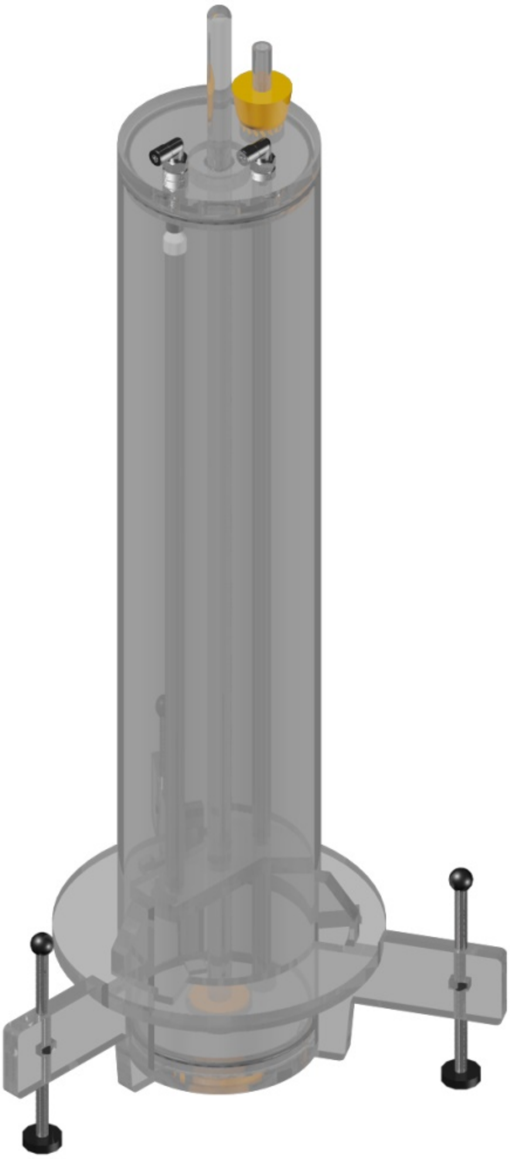

Figure 1. Realistic view of the infiltrometer with tripod.

Di Prima, S., 2015. Automated single ring infiltrometer with a low-cost microcontroller circuit.
Computer and Electronics in Agriculture 118, 390–395. doi:10.1016/j.compag.2015.09.022

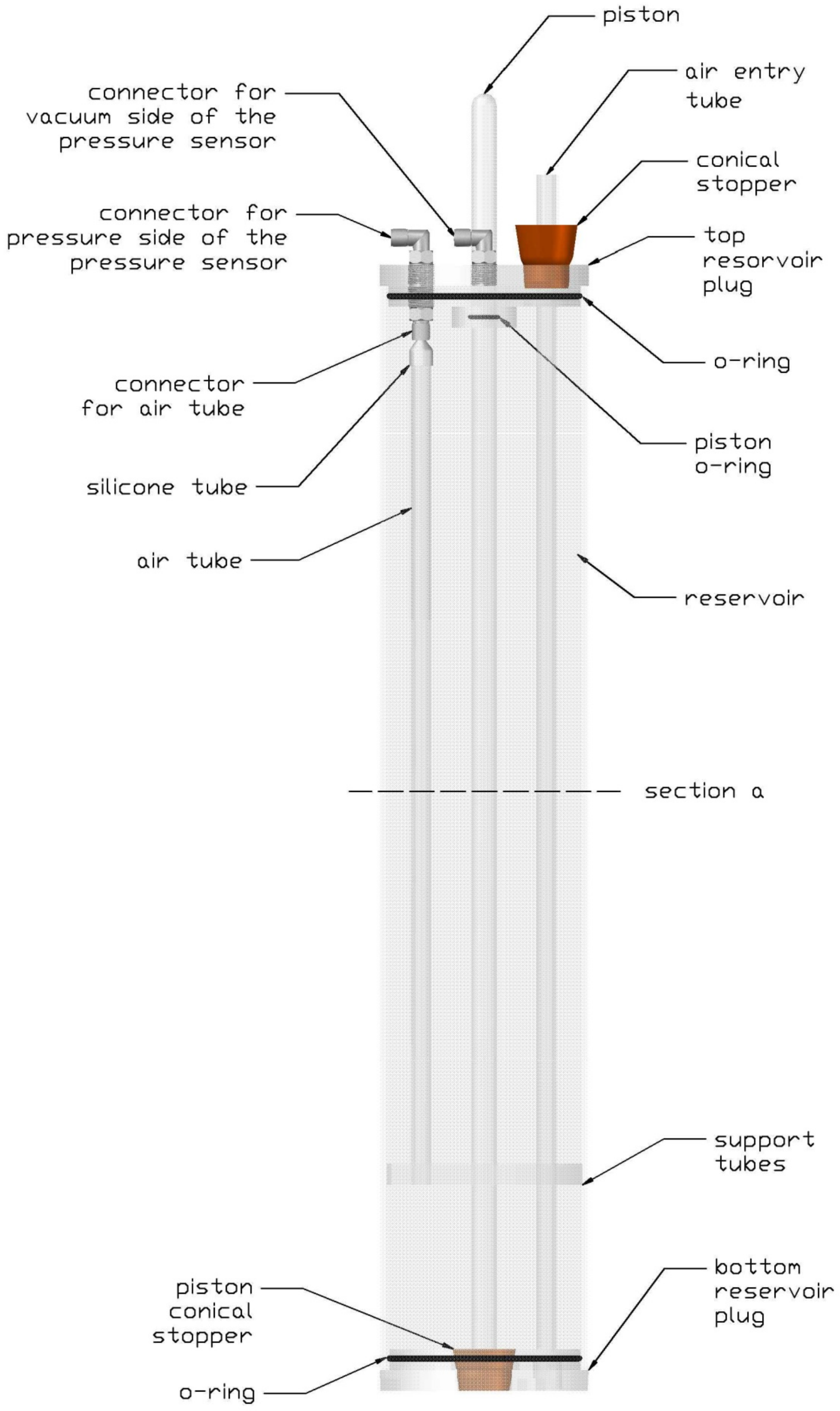

Figure 2. Detailed scheme of the infiltrometer.

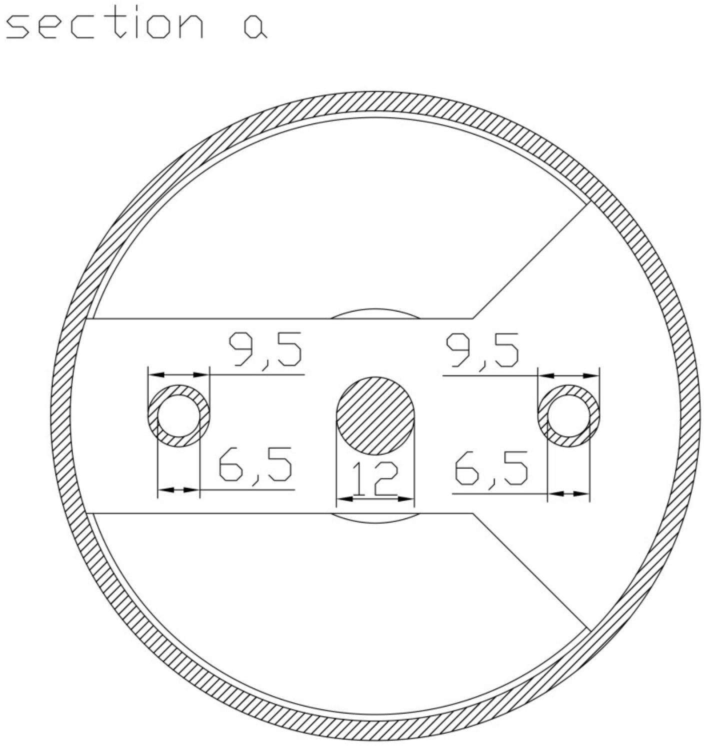

Figure 3. Section “a“ of the infiltrometer (measuraments in mm).

Di Prima, S., 2015. Automated single ring infiltrometer with a low-cost microcontroller circuit.
Computer and Electronics in Agriculture 118, 390–395. doi:10.1016/j.compag.2015.09.022

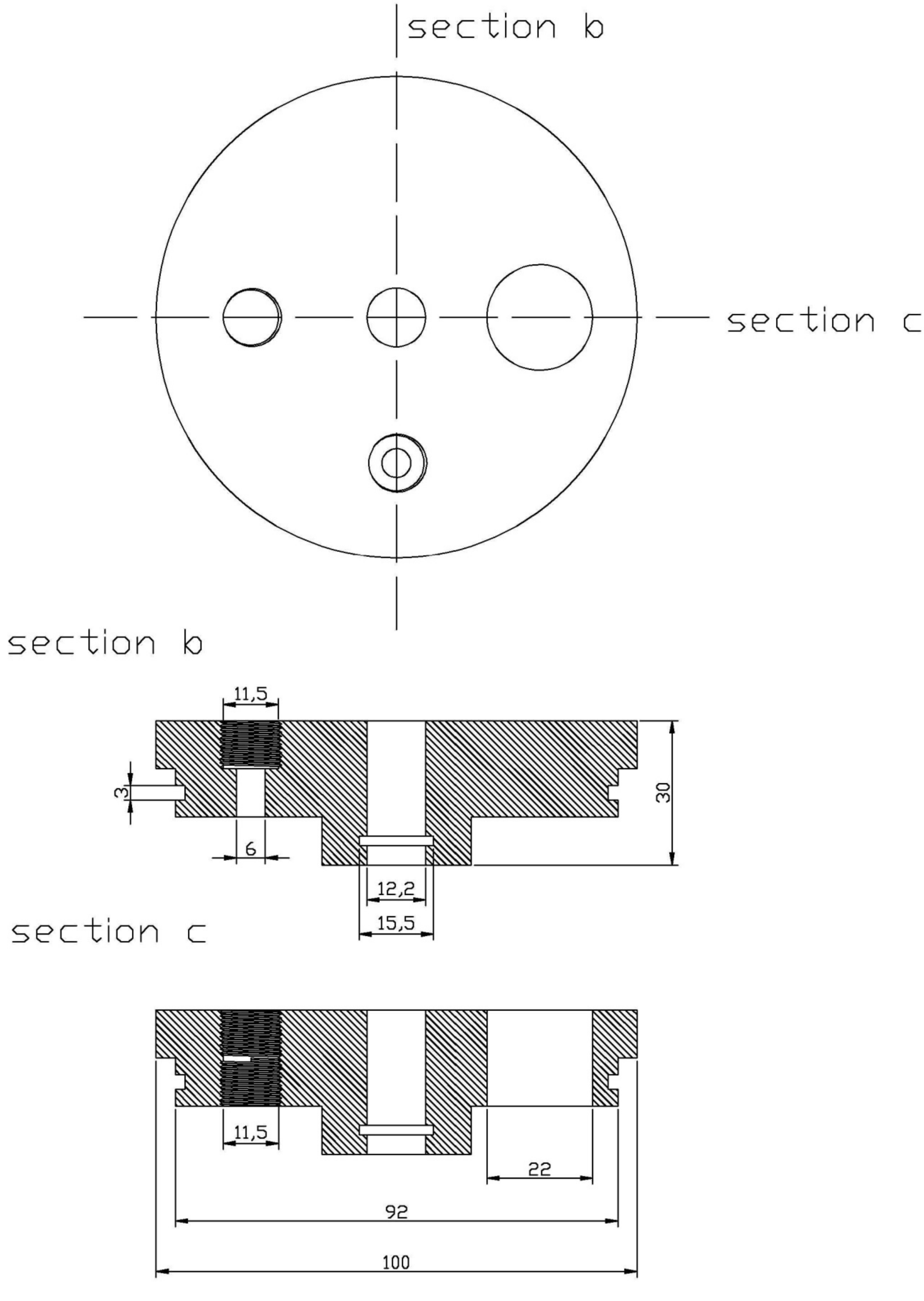

Figure 4. Top reservoir plug (measuraments in mm).

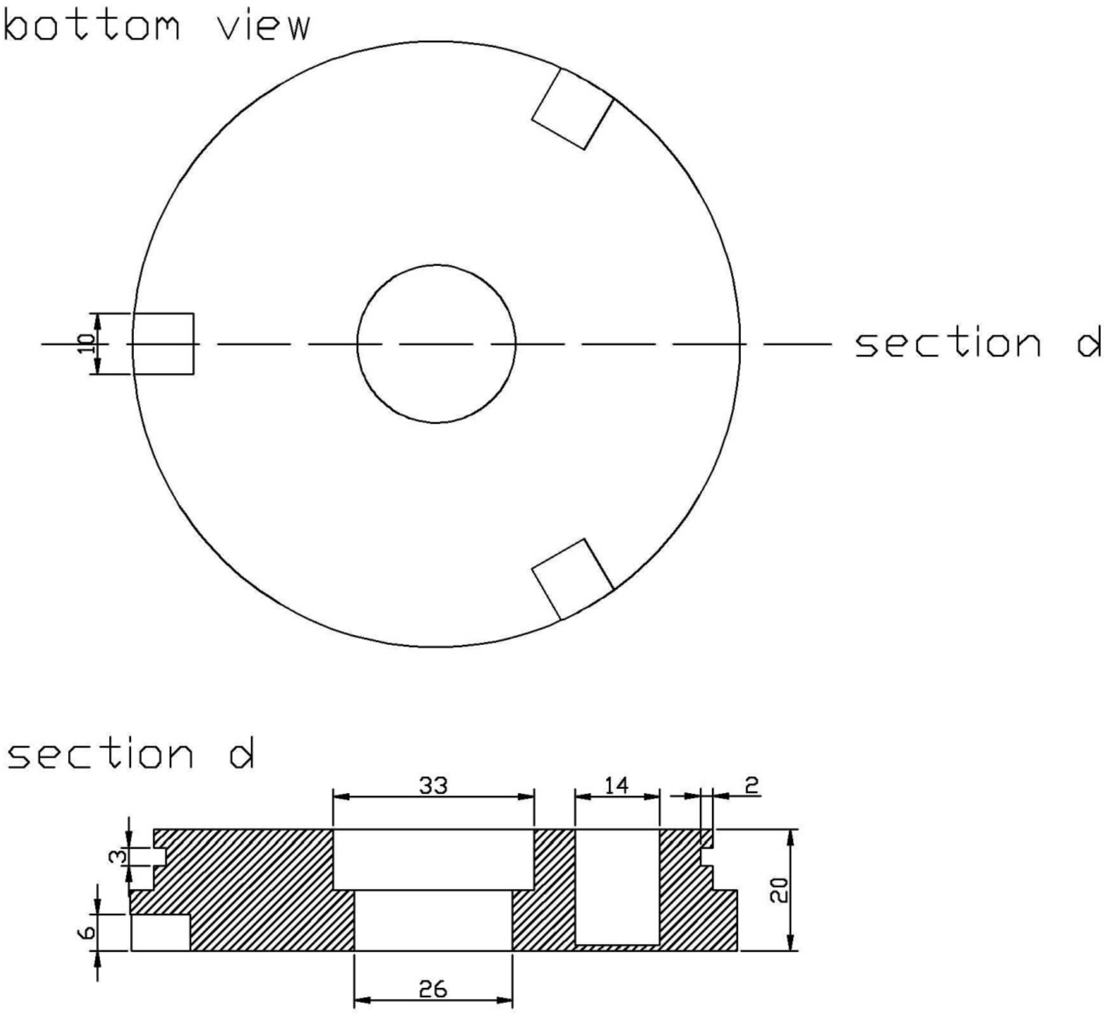

Figure 5. Bottom reservoir plug (measuraments in mm).

Di Prima, S., 2015. Automated single ring infiltrometer with a low-cost microcontroller circuit.
Computer and Electronics in Agriculture 118, 390–395. doi:10.1016/j.compag.2015.09.022

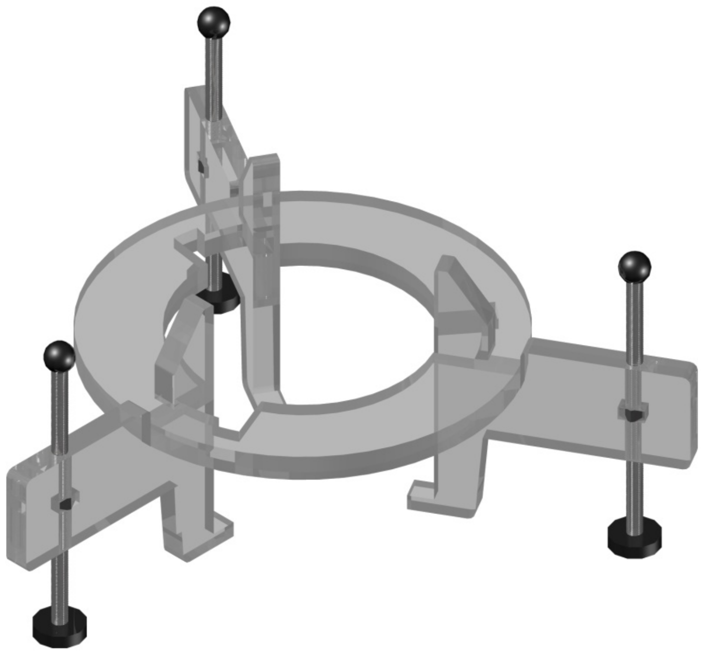

Figure 6. Realistic view of the tripod.

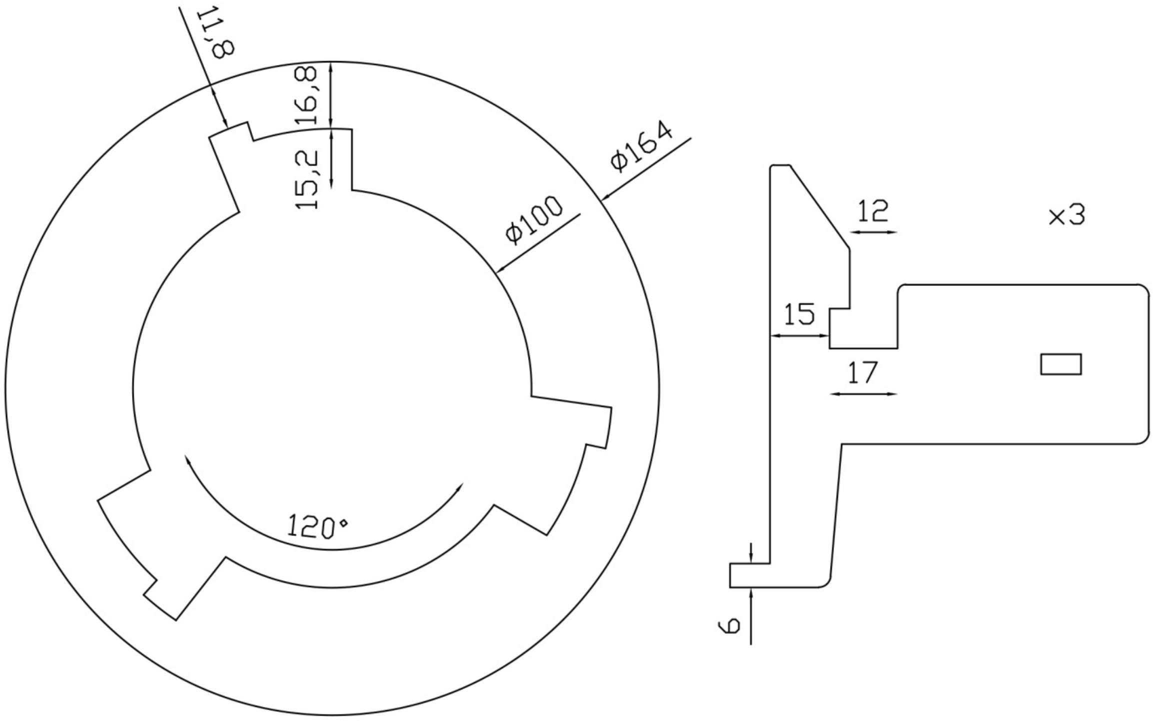

Figure 7. Components of the tripod (measuraments in mm). Thickness of the components = 10 mm.

```
/*
APPENDIX C2
Di  Prima,  S.,  2015.  Automated  single  ring  infiltrometer  with  a  low-cost
microcontroller    circuit.    Computer    and    Electronics    in    Agriculture.
doi:10.1016/j.compag.2015.09.022
*/
// include the library code:
#include <LiquidCrystal.h>
// initialize the library with the numbers of the interface pins
LiquidCrystal lcd(9, 8, 6, 5, 3, 2);
#include <SD.h>
// On the Ethernet Shield, CS is pin 4. Note that even if it's not
// used as the CS pin, the hardware CS pin (10 on most Arduino boards,
// 53 on the Mega) must be left as an output or the SD library
// functions will not work.
const int chipSelect = 4;
// the logging file
File dataFile;
void setup(void)
{
// Open serial communications and wait for port to open.
Serial.begin(9600);
lcd.begin(16, 2);
Serial.println("Initializing SD card...");
lcd.setCursor(0, 0);
lcd.print("Initializing SD");
// make sure that the default chip select pin is set to
// output, even if you don't use it:
pinMode(10, OUTPUT);
// see if the card is present and can be initialized.
if (!SD.begin(chipSelect)) {
Serial.println("Card failed");
lcd.clear();
// set the cursor to column 0, line 0.
lcd.setCursor(0, 0);
lcd.print("Card failed");
delay(5000);
// don't do anything more.
return;
}
Serial.println("Card initialized.");
lcd.clear();
lcd.setCursor(0, 0);
lcd.print("Card initialized.");
delay(2000);
// create a new file
char filename[] = "RUN_00.CSV";
for (int i = 0; i < 100; i++) {
filename[4] = i/10 + '0';
filename[5] = i%10 + '0';
if (! SD.exists(filename)) {
// only open a new file if it doesn't exist
dataFile = SD.open(filename, FILE_WRITE);
dataFile.print("time (s)");
dataFile.print(",");
dataFile.println("Volt");
break; // leave the loop!
}
}
Serial.println(filename);
lcd.clear();
// set the cursor to column 0, line 0
lcd.setCursor(0, 0);
lcd.print(filename);
delay(5000);
}
void loop(void)
{
```


Di Prima, S., 2015. Automated single ring infiltrometer with a low-cost microcontroller circuit.
Computer and Electronics in Agriculture 118, 390–395. doi:10.1016/j.compag.2015.09.022

```
int sensorPin = A0;
int sensorValue = 0; // Variable stores value coming from the sensor
float voltage = 0;
sensorValue = analogRead(sensorPin); // Read sensor
voltage = (sensorValue/1024.0) * 5; // convert the ADC reading to voltage
long time = 0;
long sec = 0;
time = millis();
sec = (time/1000)-7; // Initialize from 0
// print to SD card.
dataFile.print(time);
dataFile.print(",");
dataFile.println(voltage, 2);
dataFile.flush();
// print to the serial port too.
Serial.print(time);
Serial.print(",");
Serial.println(voltage, 2);
// print to the LCD too.
lcd.clear();
// set the cursor to column 0, line 0
lcd.setCursor(0, 0);
lcd.print("time: ");
lcd.print(sec);
lcd.print(" sec");
// set the cursor to column 0, line 2
lcd.setCursor(0, 2);
lcd.print("Volt: ");
lcd.print(voltage, 2);
delay(200); // Wait
}
```

Appendix D: Testing a new automated single ring infiltrometer for Beerkan infiltration experiments

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ABSTRACT

The Beerkan method along with BEST algorithms is an alternative technique to conventional laboratory or field measurements for rapid and low-cost estimation of soil hydraulic properties. The Beerkan method is simple to conduct but requires an operator to repeatedly pour known volumes of water through a ring positioned at the soil surface. A cheap infiltrometer equipped with a data acquisition system was recently designed to automate Beerkan infiltration experiments. In this paper, the current prototype of the automated infiltrometer was tested to validate its applicability to the Beerkan infiltration experiment under several experimental circumstances. In addition, the accuracy of the estimated saturated soil hydraulic conductivity, K_s, and sorptivity, S, was assessed by applying different BEST algorithms to the data obtained with the infiltrometer. At this purpose, both analytically generated and real experimental data were used. The analytical assessment showed that the use of the infiltrometer along with BEST methods could lead to accurate estimates of the considered soil properties in most cases, which validated the design of the infiltrometer and its combination with BEST algorithms. Loamy soils and high initial water contents led to misestimating K_s and S or to failure of BEST algorithms, but advices about the infiltrometer design were developed to alleviate such problems. A comparison between the automated procedure and the original BEST procedure was made at three field sites in Sicily (Italy). Other experiments were carried out in an infiltration basin located in the pumping well field of Crépieux-Charmy (Lyon, France), in order to assess the ability of the automated infiltrometer to check clogging effects on K_s. The experiments showed that the automatic data collection increased measurement speed, allowed a more efficient data handling and analysis, and reduced sensitivity of the calculated hydraulic parameters on the applied BEST algorithm.

Keywords: Automated single-ring infiltrometer, BEST (Beerkan Estimation of Soil Transfer parameters) procedure, Soil hydraulic properties
.

1. INTRODUCTION

The saturated soil hydraulic conductivity, K_s, and the soil sorptivity, S, are important soil properties controlling water infiltration and movement into the unsaturated soil profile. Saturated hydraulic conductivity depends strongly on soil texture and structure whereas sorptivity also depends on the initial and final soil water contents and, when present, the water depth at soil surface (Touma et al., 2007). Both soil hydraulic properties thus exhibit strong spatial and temporal variations and a large number of determinations are required to assess the magnitude of the variation within the selected area (Logsdon and Jaynes, 1996). Assessment of simple and rapid field techniques is therefore important to obtain reliable data with a sustainable effort.

The Beerkan Estimation of Soil Transfer (BEST) parameters procedure by Lassabatere et al. (2006) is very attractive for practical use since it allows an estimation of both the soil water retention and the hydraulic conductivity functions from cumulative infiltration collected during a ponded field experiment and a few routinely laboratory determinations. Lassabatere et al. (2006) suggested to measure the infiltration time of small volumes of water repeatedly poured on the soil surface confined by a ring inserted to a depth of about 1 cm into the soil. BEST considers a zero ponded infiltration model which was assumed to be appropriate for an infiltration run performed with small, but positive, pressure heads. This assumption was supported by numerical tests carried out by Touma et al. (2007). Yet, several problems arise with this method, including (i) the need for an operator over the whole duration of the experiment; (ii) the need to reach steady state infiltration, which can be extremely long in certain cases; and (iii) the experimental error in the measured infiltration times and the variable skillness among operators. Moreover several algorithms were developed to analyze the infiltration data, i.e., BEST-slope (Lassabatere et al., 2006), BEST-intercept (Yilmaz et al., 2010) and BEST-steady (Bagarello et al., 2014b), but the relative performance of the alternative algorithms has not yet been tested.

Automatic data collection increases measurement speed, permits measurement at short time intervals, improves measurement precision, allows for more efficient data handling and analysis, and reduces the amount of effort involved and the potential for errors that may occur when manual procedures are applied (Madsen and Chandler, 2007; Dohnal et al., 2010). Nevertheless, the advantages of simplified methodologies, such as BEST, are their simplicity and cheapness. The use of expensive devices or time consuming procedures contradicts the original purpose of these simplified methodologies and monitoring equipment often contains proprietary technology with prohibitive cost. Yet, rapid advances in electronic technologies have allowed researchers and practitioners access to low-cost, solid-state sensors and programmable microcontroller-based circuits (Fisher et al., 2012).

Recently, Di Prima (submitted for publication) developed a method to automate data collection with a compact infiltrometer under constant head conditions. The device, maintaining a small quasi-constant head of water (i.e., 2-3 mm) on the infiltration surface, is equipped with a differential pressure transducer to measure the stepwise drop of water level in the reservoir, and, in turn, to quantify cumulative infiltration into the soil. The data acquisition system has been designed with low cost components and it is based on the open source microcontroller platform, Arduino. Total measurable cumulative infiltration and the increment between two successive experimental points are fixed, since they depend on the capacity of the Mariotte reservoir and the radius of air entry tube, respectively. The very limited cost of the system could represent a step towards a cheaper and more widespread application of accurate and automated infiltration rate measurement. However, the current version of the infiltrometer has not been tested yet against a wide range of experimental conditions in terms of soils and initial water contents.

The main objective of this paper was to check the usability of the device to automatize the Beerkan infiltration experiment and to analyze the infiltration data to characterize soil hydraulic properties. The focus is put on the derivation of saturated soil hydraulic conductivity and soil sorptivity by using the combination of the automated infiltrometer and the three BEST algorithms. The proposed combination is assessed by using both analytically generated and field data and with regard to reliable predictions of the saturated soil hydraulic conductivity and soil sorptivity.

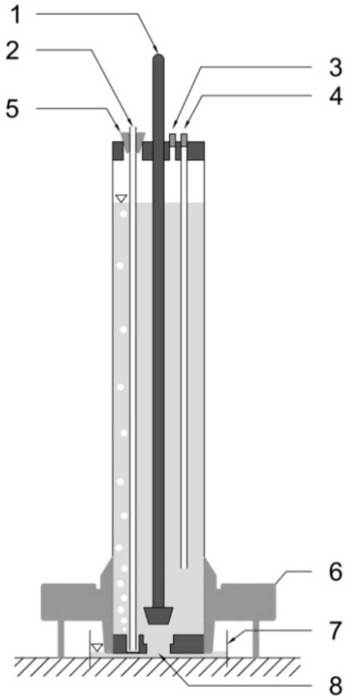
2. AUTOMATED INFILTROMETER ALONG WITH BEST METHOD FOR ESTIMATING HYDRAULIC PARAMETERS

2.1. AUTOMATED INFILTROMETER

The automatic infiltrometer by Di Prima (submitted for publication) (**Figure 1**) allows to maintain a small constant water head on a soil surface confined by a 150 mm inner diameter ring using a Mariotte bottle for water supply. Depending on the surface roughness, the Mariotte

Figure 1. Schematic diagram of the automated single-ring

infiltrometer: 1) piston; 2) air entry tube; 3) connector for vacuum side of the pressure sensor; 4) connector for pressure side of the pressure sensor; 5) rubber; 6) tripod; 7) water containment ring and 8) outlet.



bottle can be regulated in height so that the surface confined by the ring is entirely submerged under a practically negligible water depth, i.e., 2-3 mm. The bottle has an inner diameter of 94 mm and a height of 520 mm, allowing to store a maximum volume of water corresponding to a total cumulative infiltration of 130 mm. An air entry tube with a 6.5 mm inner diameter controls the level inside the ring by allowing air entry at very close distance from the reservoir base. To minimize disturbance on the soil surface and to have an accurate data acquisition from the beginning of the run, the water head is initially applied to a fine plastic film positioned on the surface inside the ring. Then, after that water is discharged from a base outlet of 26 mm in diameter, through lifting a piston, the data acquisition can be started. The infiltration starts when the plastic film is removed. When the water level in the ring goes down, the Mariotte bottle provides a certain amount of water to the ring. At this moment, some bubbles can be seen through the bottle from the air entry tube. Avoiding the direct detachment of the bubbles from the bottom outlet allows to minimize turbulence which could affect the soil surface. A specific tripod designed for the reservoir allows to pose the infiltrometer very close to the surface and hence to maintain a small water during the infiltration process.

The core of the data acquisition system consists of a microcontroller board, a shield with an onboard micro-SD card slot, a LCD display and a differential pressure transducer. The voltage output from the transducer is linearly related to the difference between head-space tension and the height of water in the Mariotte reservoir (Constanz and Murphy, 1987). Automated measurements of reservoir water levels using a differential transducer were first tested by Casey and Derby (2002). This improvement makes it easy to obtain early infiltration rate measurements and increases the accuracy of the measured steady flow rate. The differential pressure transducer is connected by small tubes to head-space of the reservoir and to a tube (inside diam. = 6.5 mm, length = 400 mm) descending inside the reservoir so that the pressure difference between the head-space and the bottom of the column of water can be measured. The sensor used for this application is the piezoresistive differential pressure transducer MPXV5004DP from Freescale Semiconductor requiring a power supply of 5 V and with integrated temperature compensation and signal amplification circuit. The transducer provides a linear voltage output for a differential pressure range from 0 to 400 mm H_2O. The data are collected at a rate of 5 s^{-1} and stored on a SD card for later retrieval and simultaneously displayed on a LCD display. The software generates a new comma-separated values (CSV) file every time that the microcontroller is alimented. The name of the generated file can be displayed on the LCD for the first few seconds.

According to the procedure described by Di Prima (submitted for publication), when the water level in the cylinder goes down, the Mariotte bottle provides a certain amount of water into the ring corresponding to 5 mm increments ($\Delta I \approx 5$ mm). Water supply is signaled by a sudden rise of air bubbles from the air entry tube that causes a disturbance in pressure transducer measurement, leading to outliers which can easily be identified and eliminated (Ankeny et al., 1988). Between two consecutive water supplies, the height of water in the reservoir remains constant which results in a step-shaped water level vs. time relationship. The cumulative infiltration curve is deduced by sampling the water levels at time immediately preceding each bubble detachment. At this time, the previous volume poured inside the ring has completely infiltrated but the subsequent volume is not still supplied, thus automatically mimicking the procedure that is followed when executing manually a Beerkan

Di Prima, S., Lassabatere, L., Bagarello, V., Iovino, M., Angulo-Jaramillo, R., 2016. Testing a new automated single ring infiltrometer for Beerkan infiltration experiments. Geoderma 262, 20–34. doi:10.1016/j.geoderma.2015.08.006

experiment. This procedure cannot be adopted in the case of an extremely rapid infiltration process. In fact, the continuous bubble detachment from the air entry tube spoils the measures and triggers too many outliers between transducer readings. In this case, a simple moving median can be used to estimate the underlying trend of the infiltration cumulative curve.

2.2. INFILTRATION EQUATIONS

Water infiltration data from both the use of the automatized infiltrometer or manual Beerkan method can be modeled by BEST procedures (Lassabatere et al., 2006) that rely on the mathematical approach outlined below. Haverkamp et al. (1990) analytically solved the one-dimensional (1D) Richards equation and derived the following 1D implicit equation for cumulative infiltration, I_{1D}, into an initially uniform unsaturated soil profile under any zero or negative value of the pressure head at the soil surface, h_{surf} ($h_{surf} \leq 0$) (Haverkamp et al., 1994). In particular, this equation applies to the case of zero pressure head and water saturation at soil surface:

$$\frac{2\Delta K^2}{S^2}t = \frac{1}{1-\beta}\left[\frac{2\Delta K}{S^2}\left(I_{1D}(t)-K_0 t\right)-\ln\left(\frac{\exp\left(2\beta\frac{\Delta K}{S^2}\left(I_{1D}(t)-K_0 t\right)\right)+\beta-1}{\beta}\right)\right] \tag{1}$$

where ΔK ($=K_s - K_0$) stands for the difference between the saturated hydraulic conductivity at the soil surface, K_s, and the initial hydraulic conductivity, K_0 ($=K(\theta_0)$), θ_0 is the initial volumetric soil water content, t is the time, β is a coefficient that is commonly set at 0.6 for $\theta_0 <$ 0.25 θ_s (Haverkamp et al., 1994), θ_s is the saturation volumetric soil water content, and S ($=S(\theta_0, \theta_s)$) stands for the sorptivity, which can be estimated from soil hydraulic properties in the interval of volumetric soil water content, θ, between θ_0 and θ_s as follows (Parlange, 1975):

$$S^2 = \int_{\theta_0}^{\theta_s}\left(\theta+\theta_s-2\theta_0\right)D(\theta)\,d\theta \tag{2}$$

where D stands for soil diffusivity (Haverkamp et al., 2005).

A one dimensional infiltration model (Eq. 1) was extended to three-dimensional (3D) infiltration from a surface disk source by Smettem et al. (1994), adding a term representing 3D geometrical effects [see Eq. (23) of Smettem et al., 1994]:

$$I(t) = I_{1D}(t) + \frac{\gamma\, S^2}{r\Delta\theta}t \tag{3}$$

Where I is 3D cumulative infiltration, r is the radius of the disk source, γ is a shape parameter for geometrical correction of the infiltration front shape, commonly set at 0.75 for $\theta_0 <$ 0.25 θ_s (Haverkamp et al., 1994), and $\Delta\theta$ is equal to $\theta_s - \theta_0$. Lassabatere et al. (2009) validated the analytical model [Eqs. (1)-(3)] using numerically generated data for the case of a zero pressure head at surface and for a large range of initial pressure heads.

The 3D cumulative infiltration, I (L), and the infiltration rate, i (L T-1), can be approached by the following explicit transient and steady-state expansions (Haverkamp et al., 1994; Lassabatere et al., 2006):

$$I(t) = S\sqrt{t} + \left(AS^2 + BK_s\right)t \tag{4a}$$

$$i(t) = \frac{S}{2\sqrt{t}} + \left(AS^2 + BK_s\right) \tag{4b}$$

$$I_{+\infty}(t) = \left(AS^2 + K_s\right)t + C\frac{S^2}{K_s} \tag{4c}$$

$$i_s = AS^2 + K_s \tag{4d}$$

where i_s (L T^{-1}) is the steady-state infiltration rate. The A (L^{-1}), B and C constants are defined as follows:

$$A = \frac{\gamma}{r(\theta_s - \theta_0)} \tag{5a}$$

$$B = \frac{2-\beta}{3}\left(1-\frac{K_0}{K_s}\right)+\frac{K_0}{K_s} \tag{5b}$$

$$C = \frac{1}{2(1-\beta)\left(1-\frac{K_0}{K_s}\right)}\ln\left(\frac{1}{\beta}\right) \tag{5c}$$

According to Bagarello et al. (2014a), if the soil is relatively dry at the beginning of the experiment, the ratio between the initial and saturated hydraulic conductivity can be considered negligible, i.e., $K_0 \ll K_s$, leading to the following approximations for B and C:

$$B \approx \frac{2-\beta}{3} \tag{6a}$$

$$C \approx \frac{1}{2(1-\beta)}\ln\left(\frac{1}{\beta}\right) \tag{6b}$$

In fact, under such conditions, constant A depends on the disk radius and the initial and final water contents, and B and C are equal to 0.467 and

0.639, respectively, when the default values for β and γ (i.e., 0.6 and 0.75, respectively) are considered.

2.3. BEERKAN ESTIMATION OF SOIL TRANSFER (BEST) PARAMETERS ALGORITHMS

The BEST approach was developed to estimate the whole set of parameters for water retention and hydraulic conductivity curves in the form of van Genuchten–Mualem model with the Burdine condition (Lassabatere et al., 2006). Residual water content is supposed to be close to zero, saturated water content can be derived from direct measurement of soil bulk density, shape parameters are deduced from particle size distribution using specific pedo-transfer functions (PTF) and saturated hydraulic conductivity and the scale parameter for the water retention curve are derived from the analysis of water infiltration data (Lassabatere et al., 2006). For the derivation of K_s and S, different BEST algorithms were proposed that differ by the way that Eq. (4a) is fitted to experimental infiltration data.

2.3.1. BEST-slope

The BEST-slope algorithm by Lassabatere et al. (2006) considers Eq. (4a) for modeling the transient cumulative infiltration data. Eq. (4a) is modified with the replacement of hydraulic conductivity as a function of sorptivity and the experimental steady-state infiltration rate, i_s^{exp}, using Eq. (4d), leading to:

$$K_s = i_s^{exp} - AS^2 \tag{7a}$$

$$I(t) = S\sqrt{t} + \left[A(1-B)S^2 + B\, i_s^{\exp}\right] t \tag{7b}$$

where, i_s^{exp} is estimated by linear regression analysis of the last data points describing steady-state conditions on the I vs. t plot and corresponds to the slope of the regression line. Eq. (7b) is fitted to the experimental data to estimate sorptivity, S. Establishing a constraint like Eq. (7a) between the estimator for sorptivity and the one for saturated hydraulic conductivity and inverting cumulative infiltration data through optimizing only sorptivity avoids parameter non-uniqueness and increases the robustness of the inverse procedure (Lassabatere et al., 2013). The fit is performed by minimizing the classical objective function for cumulative infiltration:

$$f(S,\ K_s,\ k) = \sum_{i=1}^{k}\left[I^{\exp}(t_i) - I_{est}(t_i)\right]^2 \tag{8}$$

where k is the number of data points considered for the transient state, I^{exp} is the experimental cumulative infiltration and I_{est} is estimated using Eq. (7b). Once S is estimated, K_s is calculated by Eq. (7a). As the infiltration model is valid only at transient state, the fit may not be valid for large values of k. Therefore, BEST fits data for a minimum of five points to a maximum of N_{tot} points, representing the whole dataset. For each data subset containing the first k points, corresponding to a duration of the experiment equal to t_k, S and K_s are estimated and the time, t_{max} (T), defined as the maximum time for which the transient expression can be considered valid, is determined:

$$t_{\max} = \frac{1}{4(1-B)^2}\left(\frac{S}{K_s}\right)^2 \tag{9}$$

Where $(S/K_s)^2$ is the gravity time defined by Philip (1969). Then, t_k is compared with t_{max}. The values of S and K_s are not considered valid unless t_k is lower than t_{max}. Among all values of S and K_s that fulfill this condition, the S and K_s values corresponding to the largest k (k_{step}) are retained since they are considered more precise.

2.3.2. BEST-intercept

According to Yilmaz et al. (2010), BEST-slope may lead to erroneous K_s values, especially when $i_s \approx AS^2$. Under such conditions, attempting to estimate K_s by Eq. (7a) appears to be inappropriate. More specifically, when the estimated AS^2 value exceeds the measured infiltration rate at the end of the experiment, the values obtained for K_s are negative. In the BEST-intercept algorithm by Yilmaz et al. (2010), the constraint between S and K_s is defined by using the intercept of the asymptotic expansion, $I_{+\infty}(t)$: $b_s^{exp} = C \times S^2 / K_s$ in Eq. (4c). Therefore, b_s^{exp} is estimated by linear regression analysis of the data describing steady-state conditions on the I vs. t plot, and the following relationship is applied to determine K_s:

$$K_s = C\,\frac{S^2}{b_s^{\exp}} \tag{10}$$

This procedure leads to the use of the division operator rather than the subtraction operator and thereby avoids obtaining negative values for the estimation of K_s. Combining Eqs. (4a) and (10)

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yields the following relationship to fit onto the transient state of the experimental cumulative infiltration:

$$I(t) = S\sqrt{t} + \left(AS^2 + BC\frac{S^2}{b_s^{\exp}} \right) t \qquad (11)$$

Eq. (11), that is alternative to Eq. (7b), is applied to determine S by the same procedure described for BEST-slope, including the assessment of the time validity of the transient infiltration model by calculation of t_{max}. The estimated sorptivity is then used to calculate K_s by Eq. (10).

Table 1. Soil hydraulic parameters for the five soils used to model the Beerkan infiltration experiments (from Carsel and Parrish, 1988).

Soil texture	θ_r	θ_s	α (mm^{-1})	n	K_s (mm s^{-1})	l
Sand	0.045	0.43	0.0145	2.68	8.3×10^{-2}	0.5
Sandy Loam	0.065	0.41	0.0075	1.89	1.2×10^{-2}	0.5
Sandy Clay Loam	0.100	0.39	0.0059	1.48	3.6×10^{-3}	0.5
Loam	0.078	0.43	0.0036	1.56	2.9×10^{-3}	0.5
Clay	0.068	0.38	0.0008	1.09	5.6×10^{-4}	0.5

2.3.3. BEST-steady

According to Bagarello et al. (2014b), BEST-steady makes use of the intercept (b_s^{exp}) and the slope (i_s^{exp}) of the straight line fitted to the data describing steady-state conditions on the I vs. t plot. Combining Eqs. (7a) and (10), which are related to the definition of the slope and the intercept of the steady state expansion, yields to:

$$i_s^{\exp} = AS^2 + C\frac{S^2}{b_s^{\exp}} \qquad (12)$$

and hence S can be calculated as:

$$S = \sqrt{\frac{i_s^{\exp}}{A + \frac{C}{b_s^{\exp}}}} \qquad (13)$$

Then, K_s can be obtained by using either Eq. (7a) or (10), or calculated as:

$$K_s = \frac{C\ i_s^{\exp}}{A\ b_s^{\exp} + C} \qquad (14)$$

In summary, the experiment has to be performed until steady-state conditions have been reached for all algorithms, but the data analysis procedure differs with the algorithm. A fitting of the infiltration model to the transient data is common to BEST-slope and BEST-intercept that differ by the use of steady-state conditions described by i_s^{exp} for the former algorithm and b_s^{exp} for the latter one. Both of these last two terms are required by BEST-steady that does not need data fitting for the transient stage of the run but relies solely on the steady state.

3. METHODOLOGY

3.1. TESTING THE INFILTROMETER WITH ANALYTICALLY GENERATED DATA

As a first step, analytically generated data were used to assess the accuracy of the BEST predictions of K_s and S obtained by the infiltration of 130 mm of water, sampled every 5 mm, through a 150 mm diameter soil surface. Then, a sensitivity analysis was performed to investigate the influence of total cumulative infiltration and infiltration increments. The Beerkan infiltration experiments were modeled for five soils (sand, sandy loam, sandy clay loam, loam and clay), using the parameters listed by Carsel and Parrish (1988) to describe the water retention curve and the hydraulic conductivity function according to the van Genuchten–Mualem model (van Genuchten, 1980; Mualem, 1976) (**Table 1**):

$$\begin{cases} \theta(h) = \theta_r + (\theta_s - \theta_r)\ \left[1 + \alpha|h|^n\right]^{-m} & h < 0 \\ \theta(h) = \theta_s & h \geq 0 \end{cases} \qquad (15a)$$

$$m = 1 - \frac{1}{n} \qquad (15b)$$

$$K(h) = K_s\ Se^l \left[1 - \left(1 - Se^{1/m}\right)^m\right]^2 \qquad (15c)$$

where h is the soil water pressure head, α is an empirical parameter related to the inverse of the air-entry pressure head, n is the pore size distribution index, $Se = (\theta - \theta_r)/(\theta_s - \theta_r)$ is the effective saturation degree, l is the pore connectivity parameter, assumed to be 0.5 by Mualem (1976). To also test the effect of the initial soil water content on BEST predictions, initial values of Se ranging from 0 to 0.8 were considered when modeling infiltration. This test was carried out because θ_0 should not exceed 0.25 θ_s according to Lassabatere et al. (2006) but wetter conditions can occur in practice (Xu et al., 2012). For a given soil and an initial Se value, soil sorptivity was first calculated using Eq. (2). Then, Eqs. (1) and (3) were used to generate cumulative infiltration curves. Shape parameters β and γ were assumed equal to the default values, i.e., 0.6 and 0.75, respectively (Haverkamp et al., 1994; Nasta et al., 2012). These analytical data were then inverted with the three BEST algorithms, using the workbook proposed by Di Prima (2013).

Table 2. Coordinates, mean values of clay, *cl*, silt, *si* and sand, *sa* content (USDA classification system) in the 0–0.05 m depth range, soil textural classification, mean values of dry soil bulk density, ρ_b, initial volumetric soil water content, θ_0 and porosity, ε, for the sampled sites. In parenthesis the coefficients of variation are reported.

	Sicily (Italy)			Crépieux-Charmy (France)		
	Aranceto (AR)	**Orleans (ORL)**	**Sparacia (SPA)**	**CC - new**	**CC - old**	**CC - subsoil**
Coordinates	13°21'6" E 38°6'25" N	13°20'56" E 38°6'26" N	13°45'59" E 37°38'10" N	4°53'19" E 45°47'42" N	4°53'19" E 45°47'42" N	4°53'19" E 45°47'42" N
cl %	16 (2.7)	32.9 (4.5)	72.2 (1.2)	0.0 (-)	1.9 (30.7)	0.0 (-)
si %	27.3 (1.1)	32.6 (4.3)	23.4 (2.3)	3.2 (22.8)	11.7 (6.7)	2.2 (32.8)
sa %	56.7 (0.9)	34.5 (0.7)	4.4 (8.1)	96.8 (0.7)	86.4 (1)	97.8 (0.7)
Textural classification	Sandy loam	Clay loam	Clay	Sand	Sand	Sand
ρ_b **(Mg m^{-3})**	1.191 (2.1)	1.208 (3.8)	1.036 (3.8)	1.447 (2.1)	1.632 (1.9)	1.739 (5.3)
θ_0 **(m^{3}m^{-3})**	0.237 (9.7)	0.203 (2.5)	0.321 (8.4)	0.067 (4.7)	0.064 (40)	0.043 (19.2)
ε **(m^{3}m^{-3})**	0.551 (1.7)	0.544 (3.2)	0.609 (2.4)	0.454 (2.5)	0.384 (3)	0.344 (10.2)

Then, the BEST-deduced soil hydraulic conductivity, K_s (L T^{-1}), and soil sorptivity, S (L T$^{-1/2}$), were compared with the corresponding targeted values, i.e., the K_s values by Carsel and Parrish (1988) and the S values estimated with Eq. (2), using the relative error, Er, defined as follows:

$$Er(x) = \frac{\hat{x} - x}{x} \tag{16}$$

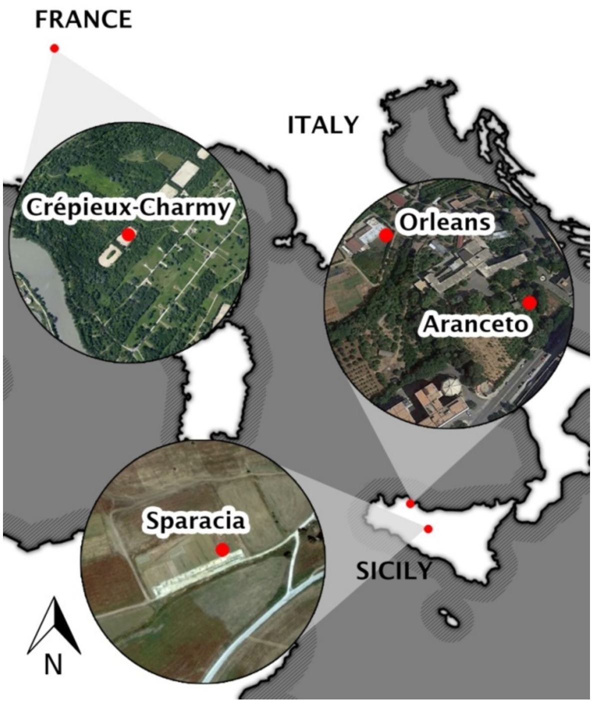
where x is the targeted value for K_s or S and $\hat{x}$ is the corresponding value deduced using one of the BEST algorithms. Note that positive Er values indicate overestimations whereas negative values indicate underestimation. Small deviations, i.e., $Er(x) \sim 0$, suggest that the BEST-derived soil hydraulic parameters are close to targeted values. Failures and miscalculation were analyzed and additional analytical calculations were performed to establish if modifying total infiltrated water volume and sampling increment allows greater success percentages and more accurate predictions of the soil hydraulic parameters.

3.2. FIELD ASSESSMENT OF THE INFILTROMETER

Different soils and experimental conditions were chosen to test the infiltrometer over a wide range of situations including problematic cases for hydraulic characterization with the Beerkan method (Gonzales et al., 2010, Lassabatere et al., 2010).

Field experiments were carried out in western Sicily in order to compare the automated and the original BEST procedure (Beerkan method). Three different sites, showing appreciable differences in both soil texture and land use (Bagarello et al., 2014c) (**Table 2**), were sampled in April 2015. In particular, a structured sandy loam soil (USDA classification) and an unstructured clay loam soil were sampled at the Department of Agriculture and Forestry Sciences of the Palermo University and hereinafter referred to as Aranceto (AR) and Orleans (ORL) sites. A clay soil (SPA site) was located at the Sparacia experimental station for soil erosion measurement of the University of Palermo, approximately 100 km south of Palermo (**Figure 2**).

Figure 2. Location of the experimental sites.



Other field experiments were carried out in an infiltration basin located in the pumping well field of Crépieux-Charmy (CC site), which provides drinking water for the Lyon metropolitan area. It is the largest well field in Europe (375 ha, 1 280 000 inhabitants supplied). Several infiltration basins have been settled on the site to create a hydraulic barrier against pollution events from the Rhone River and to improve aquifer recharge. The basins were built by excavation of natural soils and were covered with a layer of

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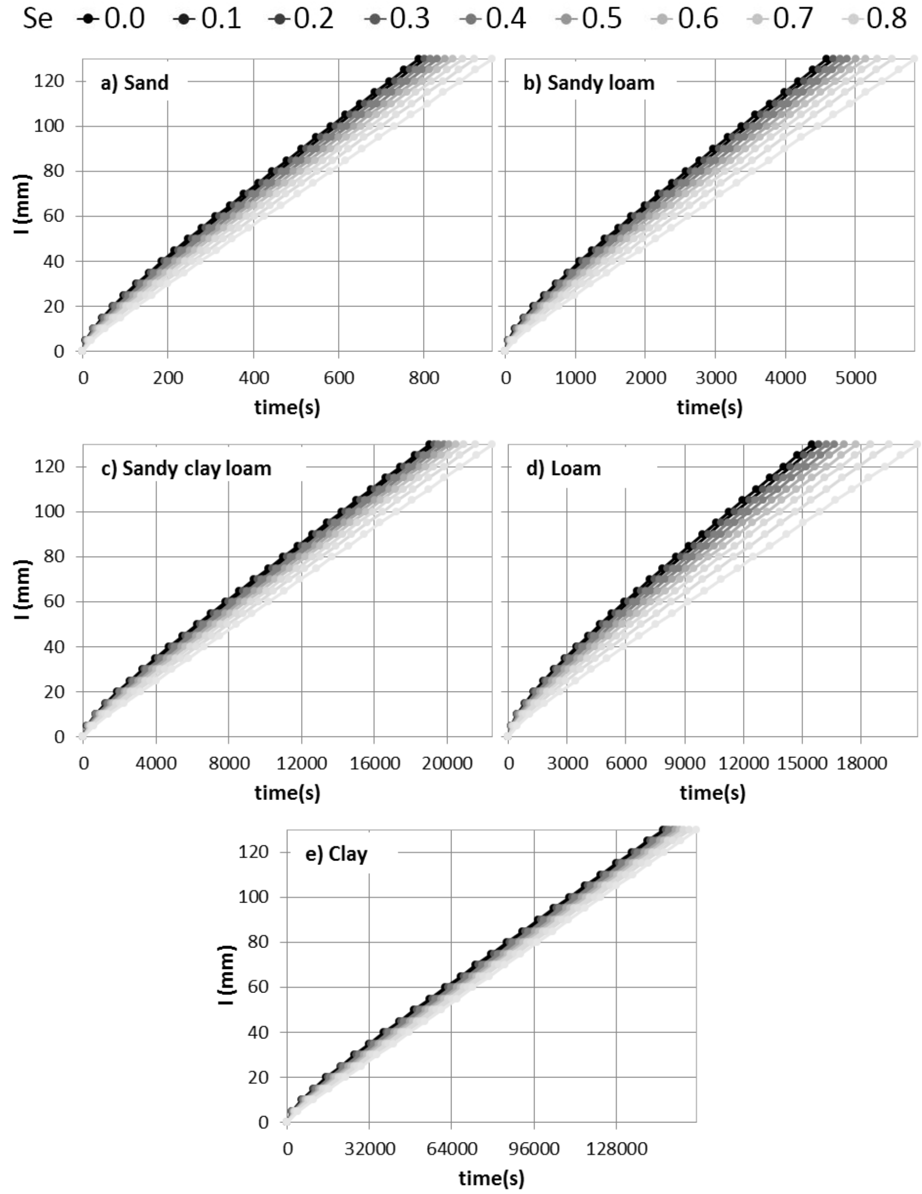
Figure 3. Cumulative infiltration curves for different soils and initial effective saturation degrees, *Se*. The same total amount of water was supposed to infiltrate, i.e., 130 mm with 5 mm increments to reproduce functioning of the infiltrometer under study.



calibrated sand about 20 cm thick. The sand layers aim at filtrating the water and preventing the subsoil from clogging. Suitability of infiltration basins can be altered by clogging processes that reduce their hydraulic performance (Gette-Bouvarot et al., 2014). Consequentially, the top layer of the basins is periodically removed and substituted with a new sand layer. In the selected basin, during dredging on September 2014, the subsoil corresponding to a coarse fluvio-glacial deposit (Goutaland et al., 2013), a layer of sand recently embedded and the old clogged sand were sampled.

For all sites, soil samples were collected to determine the particle size distribution by conventional methods (Gee and Bauder 1986).

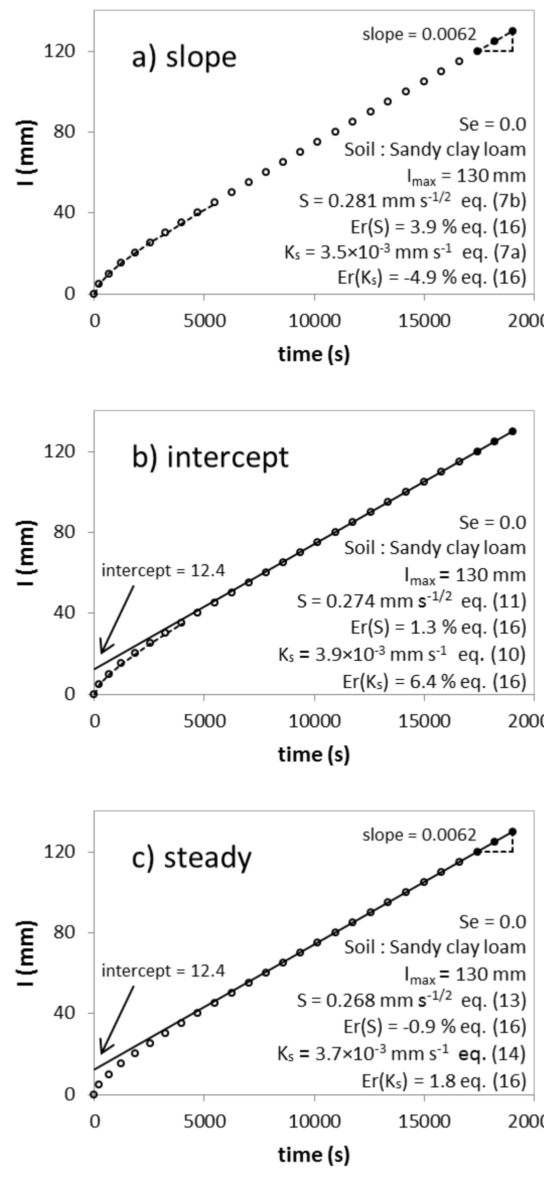
Percentages of clay, silt and sand are reported in table 2. A total of 18 undisturbed soil cores (3 for each soil layer in France and site in Sicily) were collected at a 0 to 0.05 m depth in randomly chosen sampling points. These cores were used to determine the dry soil bulk density, ρ_b (Mg m^{-3}), and the volumetric soil water content, θ_0 (m^3 m^{-3}), at the time of sampling. Porosity, ε (m^3 m^{-3}), was calculated on the basis of ρ_b, assuming the density of the soil particles equal to 2.65 Mg m^{-3} ($\varepsilon = 1 - \rho_b / 2.65$) (**Table 2**). According to other investigations, the saturated soil water content, θ_s (m^3 m^{-3}), was assumed to coincide with ε (Mubarak et al., 2009, 2010; Xu et al., 2009; Yilmaz et al., 2010; Bagarello et al., 2011). At Crépieux-Charmy, a total of 9 experiments were carried out with the infiltrometer, 3 for each kind of soil. At each Sicilian site, five infiltration experiments were performed with the infiltrometer and other five runs were carried out with the manual Beerkan method. For the infiltrometer, water height in the Mariotte reservoir was recorded for 90-4110 s depending on the run, with a total volume of infiltrated water of 120-132 mm. According to the procedure previously described, the cumulative infiltration curves were deduced for each run visually detecting the last values before bubbling (I_i), except for runs with high infiltration rate. In this last case, a simple moving median provided an alternative solution to properly determine the cumulative infiltration curves. The Beerkan experiments were carried out in agreement with the method suggested by Lassabatere et al. (2006). A known volume of water (150 mL) was poured in the cylinder at the start of the measurement and the elapsed time during the infiltration was measured. When the amount of water had completely infiltrated, an identical amount of water was poured into the cylinder and the time needed for the water to infiltrate was logged. A total of 15 water volumes, each of 150 mL, were poured. The duration of these runs varied from 182 to 8298 s, with a total volume of infiltrated water of 2250 mL, i.e., 127.3 mm. Finally, the three BEST algorithms were applied on the experimental data including the particle size distributions and cumulative infiltrations, to derive the unsaturated hydraulic parameters for all the tests and also the saturated hydraulic conductivity and sorptivity. For the saturated soil hydraulic conductivity, K_s, the statistical frequency distribution of the data was assumed to be log-normal, as commonly found for this variable (e.g., Mohanty et al., 1994; Warrick, 1998), and geometric means were calculated.

4. RESULTS AND DISCUSSION

4.1. COMPARISON BETWEEN BEST-deduced PARAMETERS AND TARGETED VALUES

As a first step, a total infiltration of 130 mm of water with 5-mm increments and through a 150 mm diameter source was considered (**Figure 3**). Cumulative infiltration could be calculated for all cases and exhibited usual shapes, with a concave part corresponding to the transient state and a linear part at the end of the curves related to the steady state. Note that the time for infiltration of a given water volume increased with the initial effective saturation degree. A lower initial *Se* value decreases the pressure head in the profile, increases the water pressure gradient, and logically triggers higher infiltration rates at the surface (Lassabatere et al., 2009).

Figure 4. Illustrative example of the calculation procedure of soil sorptivity, *S*, and saturated soil hydraulic conductivity, K_s, by applying different BEST algorithms to analyze the measured cumulative infiltration, *I* (mm), vs. time, *t* (s), data: (a) BEST-slope; (b) BEST-intercept and (c) BEST-steady. The slope i_s^{exp} (mm s^{-1}) is the experimental steady-state infiltration rate and b_s^{exp} (mm) is the experimental intercept of the straight line interpolating the last three *I* vs. *t* data points. The dotted line is the fitted cumulative infiltration model, i.e., Eq. (7b) in (a) and Eq. (11) in (b), to the transient infiltration data. The relative error of the soil sorptivity, *Er(S)*, and saturated soil hydraulic conductivity, *Er(K_s)*, predictions (expressed as a percentage of the reference value) are reported.



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These analytically generated data were inverted using the three BEST algorithms. An example is given in **Figure 4** for the sandy clay loam soil with initial *Se* = 0. The differences among the BEST algorithms are clearly illustrated. BEST-slope makes use of the slope of the three last points to estimate the steady state infiltration and adjusts data on Eq. (7b) (**Figure 4a**). The transient state model is adjusted only on the first ten points that verify the condition $t_k \leq t_{max}$ where t_{max} is calculated using Eq. (9). BEST-intercept makes use of the intercept of the line defined by the three last points and adjusts data on Eq. (11). As for BEST-slope, the transient model is fitted to a data subset that ensures its validity. Finally, BEST-steady only makes use of the intercept and the slope of the line defined by the three last points. The BEST-deduced parameters shown in **Figure 4** were then compared numerically with the corresponding targeted values (**Table 1**) using the relative error [Eq. (16)]. Note that, for this case, all methods worked and gave estimates close to the targeted values, with relative errors of the soil sorptivity, *Er(S)*, and saturated soil hydraulic conductivity, $Er(K_s)$, equal to 3.9% (BEST-slope), 1.3% (BEST-intercept), -0.9% (BEST-steady) and -4.9%, 6.4% and 1.8%, respectively. These errors were low, meaning that all three methods were successful and appropriate.

The analysis of all cases, i.e., cumulative infiltration curves depicted in **Figure 3**, led to a certain number of failures or miscalculation. As a first step, the failure rate and precision of estimates were depicted for all BEST algorithms. The estimated values were considered accurate when relative errors did not exceed 10% in absolute value and very accurate when they did not exceed 5%. Such a stringent accuracy criterion was used because the BEST-deduced parameters were derived by analytically generated data, and therefore they were free of the perturbations embedded in field and laboratory measurements (e.g., measurement error, random noise and natural variability).

BEST-slope yielded positive values of *S* and K_s for 30 of the 45 infiltration runs (5 soils × 9 *Se* values), which corresponds to a failure rate of 33.3% (**Table 3**), which is an intermediate value between BEST-intercept and BEST-steady. BEST-slope provided always over-estimations for sorptivity and often under-estimation for hydraulic conductivity (**Figures 5a and d**). Estimates could be considered as very accurate for sorptivity in all cases and for saturated hydraulic conductivity in most cases. Otherwise, relative errors remained below 10% in absolute value for all cases, indicating trustworthy estimates. The loam with an initial *Se* = 0 was the sole exception (**Figure 5d**).

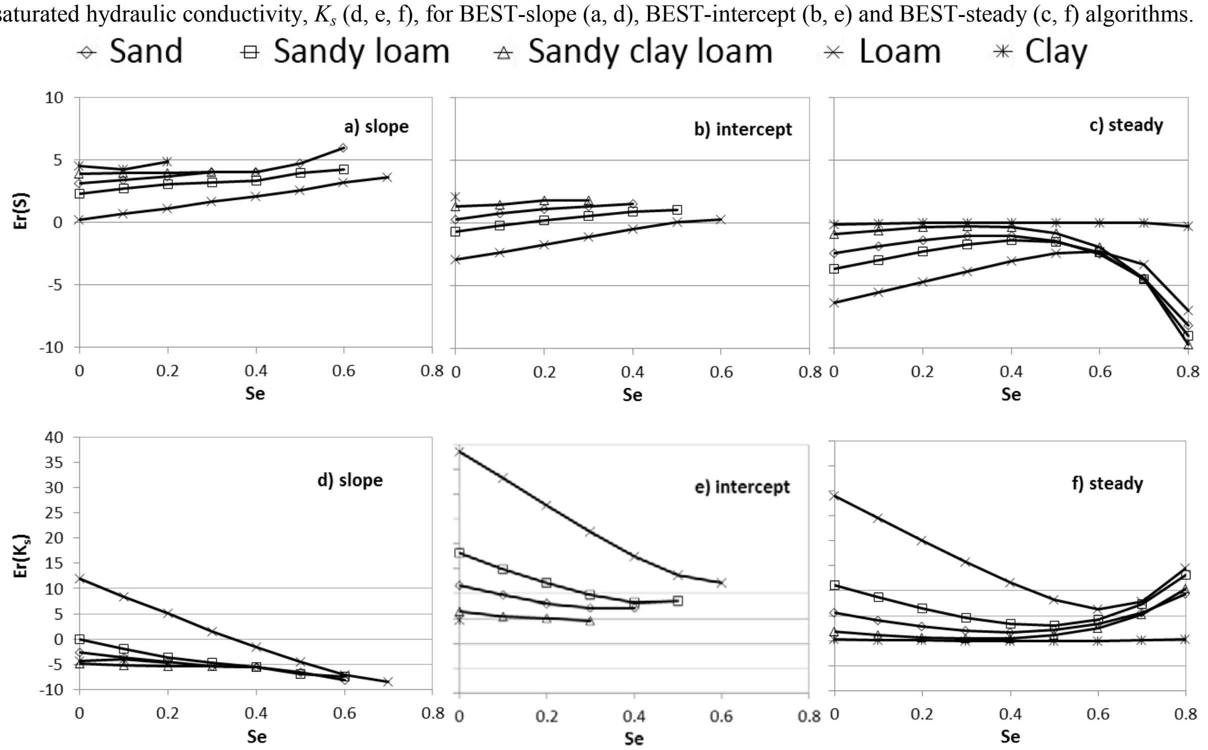
BEST-intercept allowed to estimate *S* and K_s for 23 out of the 45 infiltration runs (**Table 3**), meaning a failure rate of 48.9%, which constituted the worst case. Sorptivity was accurately estimated with a ratio between estimated and targeted values around unity (**Table 4**) and relative errors always below 5% in absolute value (**Figure 5b**). Saturated hydraulic conductivity was always overestimated with significant discrepancies between estimates and targeted values. Relative errors below 5% were reached for only 2 out of the 23 runs exploitable with BEST-intercept, but *Er* remained below 10%, meaning acceptable estimates for most cases (**Figure 5e**). However, Poor estimates of K_s were obtained for the sandy loam and loam soil.

Table 3. Number of successful runs for each algorithm depending on the soil and the initial effective saturation degree, *Se*. In parenthesis the success rate is reported.

	BEST-slope	**BEST-intercept**	**BEST-steady**
Soil			
Sand	7	5	9
Sandy loam	7	6	9
Sandy clay loam	5	4	9
Loam	8	7	9
Clay	3	1	9
Tot.	**30 (66.7)**	**23 (51.1)**	**45 (100)**
Se			
0.0	5	5	5
0.1	5	4	5
0.2	5	4	5
0.3	4	4	5
0.4	4	3	5
0.5	3	2	5
0.6	3	1	5
0.7	1	0	5
0.8	0	0	5
Tot.	**30 (66.7)**	**23 (51.1)**	**45 (100)**

Finally, BEST-steady provided values for *S* and K_s for all infiltration runs, meaning a success rate of 100% (**Table 3**). BEST-steady underestimated sorptivity and overestimated saturated hydraulic conductivity in all cases (**Table 4**). Yet, the ratio between estimated and targeted values never lowered 0.902 for *S* and never exceeded 1.289 for K_s, revealing that estimation of *S* and K_s was acceptable in most cases. The sorptivity estimates (**Figure 5c**), were always accurate and very accurate in most cases. For saturated hydraulic conductivity (**Figure 5f**), the estimates were less accurate but still acceptable, i.e., with relative errors lower than

Figure 5. Relative error [Eq.(16)] as a function of initial effective saturation degree, *Se*, for sorptivity, *S* (a, b, c), and saturated hydraulic conductivity, K_s (d, e, f), for BEST-slope (a, d), BEST-intercept (b, e) and BEST-steady (c, f) algorithms.



10%, except for the loam soil, indicating that, in this case, estimations were not trustworthy.

Briefly, these results showed that the combination of the infiltrometer under study and one of the BEST methods is efficient to characterize accurately the hydraulic parameters for most soils. The choice of the method influenced the failure rate but it did not appreciably affect the accuracy of the valid results. In more details, BEST-intercept and BEST-steady gave similar results except that BEST-steady was more robust and always provided estimates. BEST-slope appeared to yield more accurate estimates, especially of K_s, but it was affected by a failure rate higher than BEST-steady. On the basis of these results, two problems arise: (i) possible failure of BEST algorithms using the transient stage of the infiltration process and (ii) poor estimation of K_s for the loam soil. These problems were specifically investigated testing the hypothesis that possible factors affecting these results were the number of the sampled data points during infiltration and attainment of steady state with the current version of the infiltrometer.

4.2. NUMBER OF SAMPLED DATA POINTS

The failure of BEST-slope and BEST-intercept algorithms mainly occurred for high values of the initial effective saturation degree (**Table 3**). In this case, the transient state is shorter and steady state is reached more quickly than under initially dry conditions. The infiltrometer under study provides 26 points for the *I* vs. *t* plot, which corresponds to the 26 5-mm increments needed to complete the total 130 mm of infiltrated water height. For a fixed total number of points describing the curve, a shorter transient state means less points for the transient state and more for the steady state. Therefore, there may be a lack of points to properly describe the transient state.

Table 4. Ratio between estimates and targeted values for the soil sorptivity, *S*, and the saturated soil hydraulic conductivity, K_s, obtained with the BEST-slope (Slope in the table), BEST-intercept (Intercept) and BEST-steady (Steady) algorithms.

Statistic	Slope	Intercept	Steady	Slope	Intercept	Steady
	S / S_{tar}			$K_s / K_{s,tar}$		
N	30	23	45	30	23	45
Min	1.002	0.971	0.902	0.916	1.046	1.000
Max	1.059	1.021	1.000	1.120	1.386	1.289
Mean	1.033	1.003	0.975	0.966	1.133	1.058
Md	1.036	1.006	0.981	0.953	1.098	1.033
CV	1.2	1.3	2.6	4.8	8.2	6.3

N = sample size; *Min* = minimum value; *Max* = maximum value; *Md* = median and *CV* (%) = coefficient of variation.

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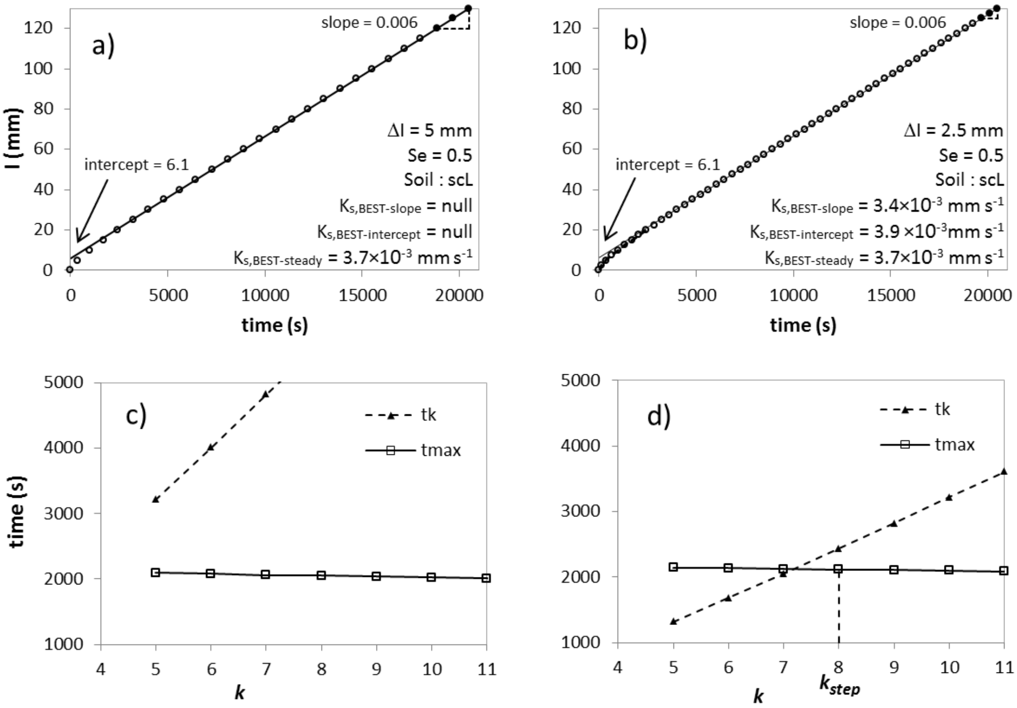
Figure 6. Cumulative infiltration curves of a case in which the steady state is quickly reached with (a) insufficient and (b) sufficient data points at transient flow state. Estimates are given and the targeted value for saturated hydraulic conductivity is equal to 3.6×10^{-3} mm s^{-1}. The dotted line is the fitted cumulative infiltration model, i.e., Eq. (11) to the transient infiltration data. Subpanels c and d depict the longest time of the data subset (t_k) and maximum time (t_{max}) versus the number of points (k) used for the fit in the case of BEST-intercept algorithm.



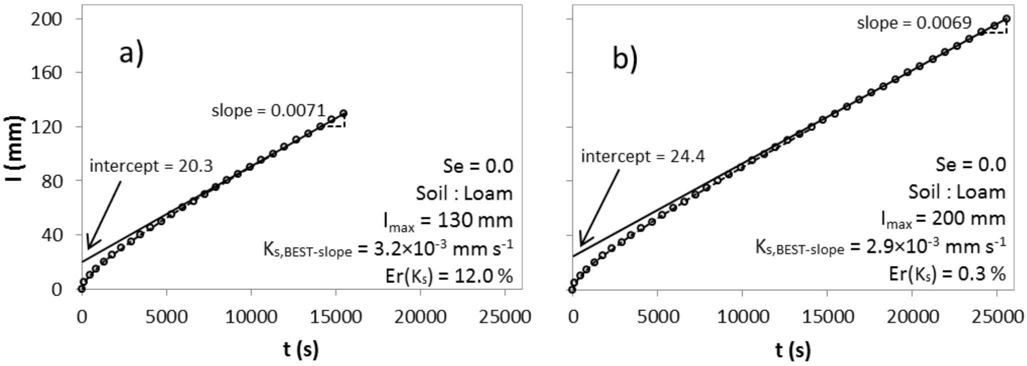
This possible problem is illustrated for the sandy clay loam soil with an initial *Se* value of 0.5 (**Figures 6a and c**). In this case, the fifth point is already out of the validity interval of the transient state model, i.e., it corresponds to a time larger than the maximum time. In such a case, BEST-slope and BEST-intercept fail to provide estimates whereas BEST-steady provides an estimate of K_s close to the targeted value. To alleviate this problem, cumulative infiltration was modeled and then inverted considering a sampling increment of 2.5 mm (**Figures 6b and d**). In this case, the number of points used to describe the same curve and thus the transient part of the curve was doubled. More points could be selected in the validity interval for the transient state and both BEST-slope and BEST-intercept were successful, with estimated values close to the targeted value (**Figure 6d**).

The calculations were extended to all cases. The use of a smaller increment (i.e., ΔI = 2.5 mm instead of 5 mm) yielded a higher success percentage with both BEST-slope and BEST-intercept since the two algorithms yielded positive values of S and K_s for 42 and 36 of the 45 infiltration runs, respectively. In addition, sorptivity values were of good quality, since relative errors were below the threshold of 5% for all the successful cases. With ΔI = 2.5 mm, BEST-slope and BEST-intercept yielded $|Er(K_s)|$ $\leq$ 5% for the 42.2% and 20% of the 45 cases, respectively, versus 31.1% and 4.4% with ΔI = 5 mm. This problem of inaccuracy for the description of the transient state may occur mainly for soils and initial soil water contents for which the influence of capillary forces on the infiltration process is small in comparison with the gravity driven infiltration. This is in particular the case of high values for the initial effective saturation degree. In such cases, transient state is very short, i.e., the steady flow state is quickly reached, and the cumulative infiltration curve contains an insufficient information on transient flow state (Xu et al. 2012). In other terms, too little data points are collected and this circumstance compromises the use of BEST-slope and BEST-intercept.

4.3. ATTAINMENT OF STEADY STATE FLOW

In general, quasi-steady flow is expected to occur rather rapidly, since it should be attained within a few dozen minutes with the ring diameters and insertion depths and the heights of water ponding commonly used with the BEST procedure (Reynolds and Elrick, 2002; Reynolds, 1993).

Figure 7. Example of the influence of the degree of attainment of steady state: (a) steady state is not reached, estimations of steady state slope and intercept are erroneous (K_s is misestimated) and (b) the steady state is reached and BEST estimates are correct. The dotted line is the fitted cumulative infiltration model, i.e., Eq. (7b) to the transient infiltration data.



Nevertheless, if steady state is not reached, estimation of slope and intercept of the line describing steady state can be erroneous and K_s and S are miscalculated (Lassabatere et al. 2013). This possibility is illustrated for the specific case of a loam soil and a null value of initial Se ($\theta_0 = \theta_r$) (**Figure 7**). Two cases were modeled: the first that corresponds to the infiltration of one reservoir, i.e., 130 mm (**Figure 7a**) and the second with a larger volume of water, i.e., 200 mm, mimicking a larger reservoir (**Figure 7b**). In both cases, the algorithms were successful and the fits were accurate. However, the estimate of K_s was larger in the former case, i.e., when steady state was not properly reached. The over-estimation reached 12% when 130 mm of water infiltrated, and it reduced to 0.3%, denoting an almost perfect estimate, when the total infiltrated water increased up to 200 mm.

We extended these calculations to all cases, considering a total infiltration height of 390 mm, corresponding to three reservoirs, with 5 mm increments. Every cumulative infiltration curve was inverted with the three BEST algorithms and relative errors of estimates were calculated. For sorptivity, the relative error increased in algebraic value with the volume of infiltrated water (**Figure 8**). Yet, relative errors remained between -5% and 5% in most cases and rarely exceeded 10% in absolute value. The most critical cases occurred for small volumes of infiltrated water and the BEST-steady algorithm (**Figures 8c, f, i, l, o**), which is plausible since this algorithm makes strong use of the information collected at steady state. One reservoir is enough to get relative errors below 5% in most cases and even below 10% in all cases. The estimation of sorptivity can be considered quite robust and accurate.

The estimates of K_s decreased with the total infiltrated volume, I, regardless of the considered soil and initial Se value (**Figure 9**). In particular, for small I values all the algorithms overestimated the saturated hydraulic conductivity. With BEST-slope, the I values for which K_s is overestimated by not more than 5% were generally smaller than 130 mm (**Table 5**) which means that the current version of the infiltrometer should be usable to obtain accurate estimates of K_s. An exception was detected for the loam soil and an initial Se < 0.3. In this case, more water is needed. In particular, a cumulative infiltration of 165 mm of water implies a higher Mariotte reservoir by 95 mm as compared with the current reservoir. However, the $Er(K_s)$ values tended towards values always smaller than zero, showing that K_s can be underestimated if the infiltration experiment is excessively long. Yet, the under-estimation remained acceptable with relative errors close to 5% in most cases (**Figures 9a, d, g, j, m**).

For BEST-intercept, the errors remained positive, meaning that K_s was always overestimated, but the estimates were sufficiently precise, with relative errors varying between 5% and 10% provided an adequate volume had infiltrated. A total volume of one reservoir was enough to obtain very accurate estimates for clay soil with low initial Se values but more than one reservoir were required for the sandy and sandy clay loam soils, more than two reservoirs for the sandy loam soil and more than three reservoirs for the loam soil (**Table 5**).

For BEST-steady also, K_s was always overestimated and the most precise estimates were obtained for large infiltrated volumes. One reservoir was enough for clay and sandy clay loam soils but more than one reservoir was required for sandy and sandy loam soils and more than two reservoirs were necessary for the loam soil (**Table 5**). For this last soil, the total reservoir capacity should be increased up to approximately

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Figure 8. Relative error of the soil sorptivity predictions (expressed as a percentage of the reference value) for BEST-slope, BEST-intercept and BEST-steady plotted against the considered total volume for each soil type and initial effective saturation degree, *Se*.

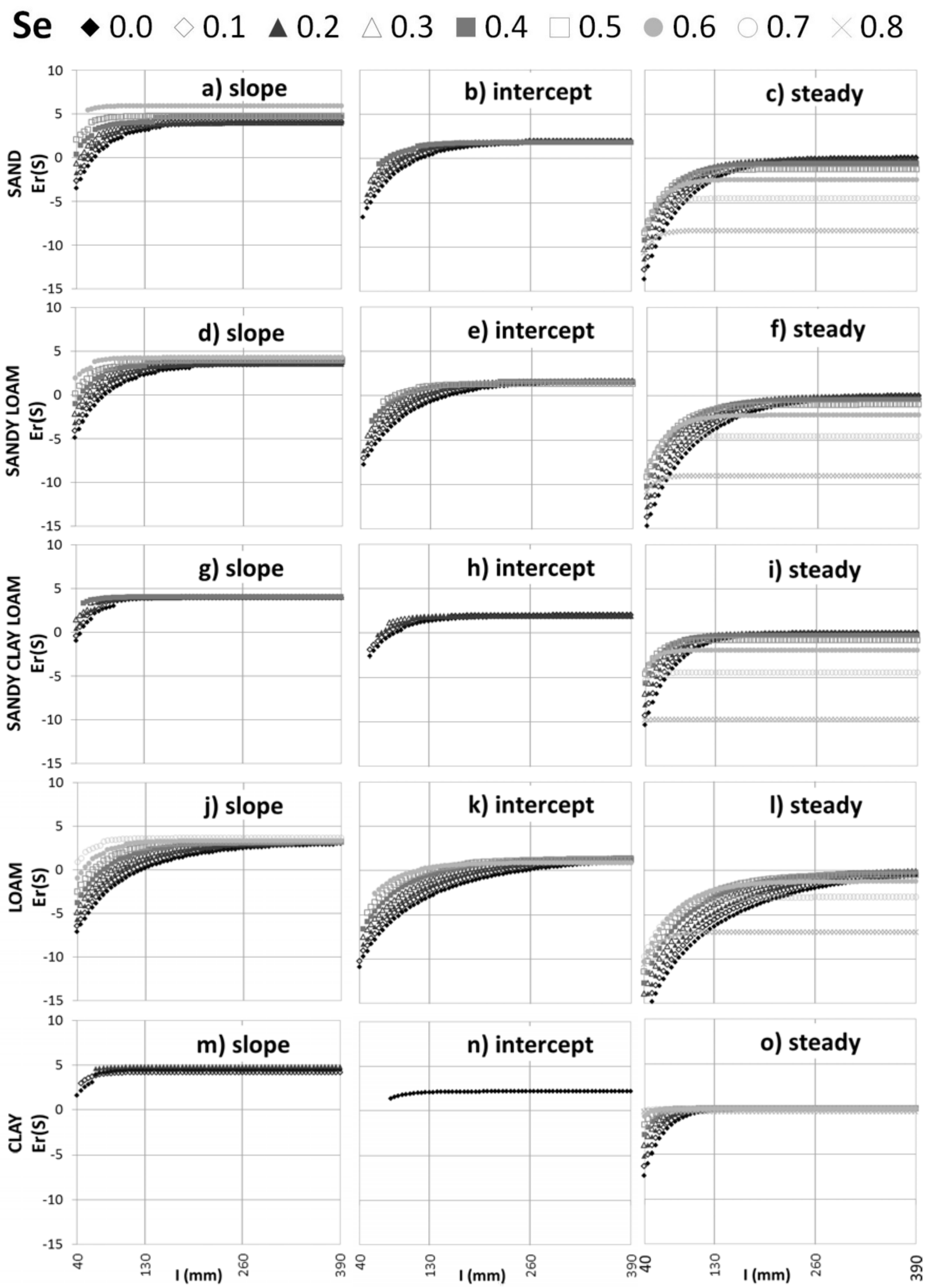

Figure 9. Relative error of the saturated soil hydraulic conductivity predictions (expressed as a percentage of the reference value) for BEST-slope, BEST-intercept and BEST-steady plotted against the considered total volume for each soil type and initial effective saturation degree, *Se*.

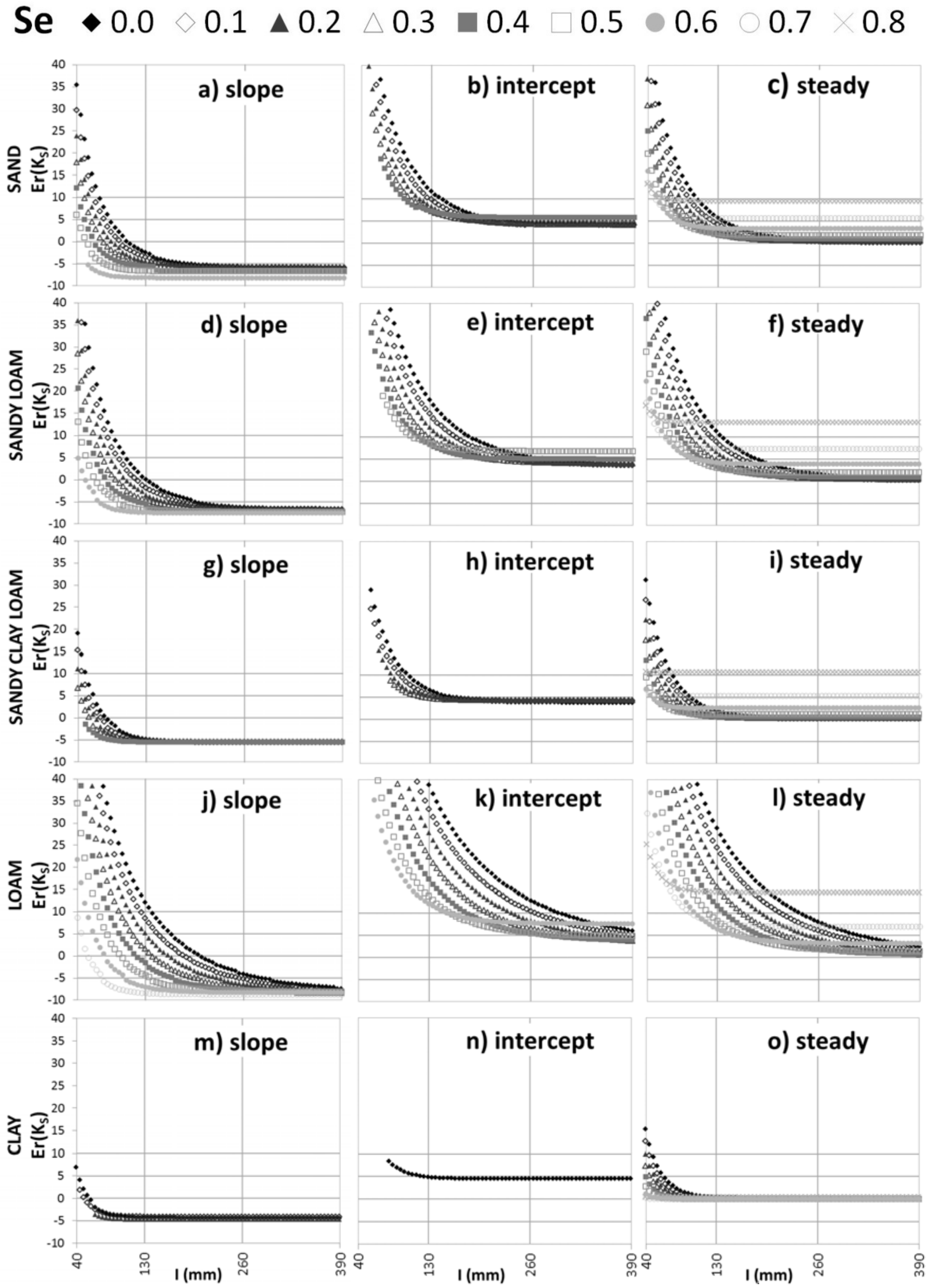

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Table 5. Minimum volumes (mm) necessary to reach an accurate estimation of K_s, i.e., the condition $Er(K_s)$ < 5%, for different soils and initial effective saturation degrees, *Se*. Time (h:mm:ss) in parentheses.

					Se				
Soil	**0.0**	**0.1**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**
					BEST-slope				
Sand	85	80	70	60	50	45			
	(0:07:59)	(0:07:36)	(0:06:39)	(0:05:42)	(0:04:46)	(0:04:23)	-	-	-
Sandy Loam	105	95	85	75	65	55	40		
	(0:59:40)	(0:54:13)	(0:48:47)	(0:43:22)	(0:37:58)	(0:32:36)	(0:23:43)	-	-
Sandy Clay Loam	65	55	50	45					
	(2:23:12)	(2:00:01)	(1:49:59)	(1:39:59)	-	-	-	-	-
Loam	165	150	135	115	100	80	65	50	
	(5:41:30)	(5:12:01)	(4:42:36)	(4:01:07)	(3:31:54)	(2:50:33)	(2:21:39)	(1:52:54)	-
Clay	45	45	65						
	(12:07:15)	(12:23:57)	(19:23:27)	-	-	-	-	-	-
					BEST-intercept				
Sand	215	195	185	185					
	(0:23:01)	(0:20:56)	(0:20:02)	(0:20:20)	-	-	-	-	-
Sandy Loam	270	245	215	205					
	(2:53:25)	(2:37:55)	(2:18:57)	(2:14:04)	-	-	-	-	-
Sandy Clay Loam	155	140	135	120					
	(6:24:40)	(5:48:20)	(5:39:11)	(5:03:01)	-	-	-	-	-
Loam		385	340	300	275				
	-	(14:50:52)	(13:09:26)	(11:40:40)	(10:50:07)	-	-	-	-
Clay	120								
	(13:14:41)	-	-	-	-	-	-	-	-
					BEST-steady				
Sand	140	125	110	100	90	80	80		
	(0:14:17)	(0:12:47)	(0:11:16)	(0:10:21)	(0:09:25)	(0:08:30)	(0:08:48)	-	-
Sandy Loam	180	165	145	130	115	105	105		
	(1:50:59)	(1:42:17)	(1:30:07)	(1:21:28)	(1:12:53)	(1:07:56)	(1:10:26)	-	-
Sandy Clay Loam	100	90	80	70	60	55	50		
	(3:56:23)	(3:33:17)	(3:10:10)	(2:47:06)	(2:24:05)	(2:14:51)	(2:06:02)	-	-
Loam	310	280	245	215	185	165	155		
	(11:35:46)	(10:30:39)	(9:13:12)	(8:08:15)	(7:03:34)	(6:24:38)	(6:12:45)	-	-
Clay	65	60	55	50	40	40	40	40	40
	(18:44:52)	(17:23:21)	(16:01:55)	(14:40:35)	(11:38:32)	(11:58:28)	(12:19:46)	(12:43:07)	(13:11:22)

5.5 L. Therefore, the BEST-slope algorithm allows in general to obtain accurate estimates of K_s with less water and hence shorter experimental times than the other two algorithms.

The ratio between the cumulative infiltration at the gravity time, t_{grav}, and the total volume of the infiltrometer reservoir, i.e., 130 mm, varied in the range 0.08–0.23 for the clay soil and 0.04–0.35 for the sandy clay loam soil, denoting that steady state conditions were established during the run with the current device, regardless of the initial soil water content. For the loam soil, comparable values of this ratio (i.e., <0.35) were only obtained for the highest initial *Se* values (*Se* > 0.7) and, for *Se* = 0, the transient phase was not overpassed with the considered reservoir size. Thus, the good performance of the BEST-steady algorithm in the clay and the sandy clay loam soils was not surprising given that the steady state phase was reached before the run finished.

Generally speaking, infiltrating enough water during the experiment is needed for all the methods. The situation is a little bit more critical for high values of the initial effective saturation degree. In this case, BEST-slope and BEST-intercept can fail, as discussed above, and BEST-steady gives poor estimates.

4.4. FIELD ASSESSMENT

For most of experiments realized in Sicily or in France (Crépieux-Charmy), air bubbling did not impede measurement of the field infiltration process (**Figure 10a**) and the water level at the time immediately preceding each bubble detachment was detectable. For the quickest processes, the data were more affected by air bubbling and moving median helped in selecting the points to be considered (**Figure 10b**). Finally, all cumulative infiltrations could properly be built (**Figure 11**).

With reference to the three Sicilian sites, both the 15 cumulative infiltration curves collected with the infiltrometer and the 15 curves obtained by the classical Beerkan method exhibited a typical concave shape, revealing that water infiltration was initially capillary driven and subsequently both capillary and gravity driven (Smith et al., 2002). Altogether, the three BEST algorithms yielded a higher success percentage, i.e., positive *S* and K_s values, when they were applied to the automated infiltrometer data (percentage = 96%; sample size, *N* = 45 i.e., 15 infiltration curves × 3 algorithms) rather than to the manually collected infiltration curves

Figure 10. Illustrative examples of the determination of cumulative infiltration values from transducer output by (a) selecting the recorded data at the end of the constant height stages in Mariotte bottle (Crépieux-Charmy subsoil), and (b) estimating a simple moving median over 10 s (Crépieux-Charmy new sand layer).

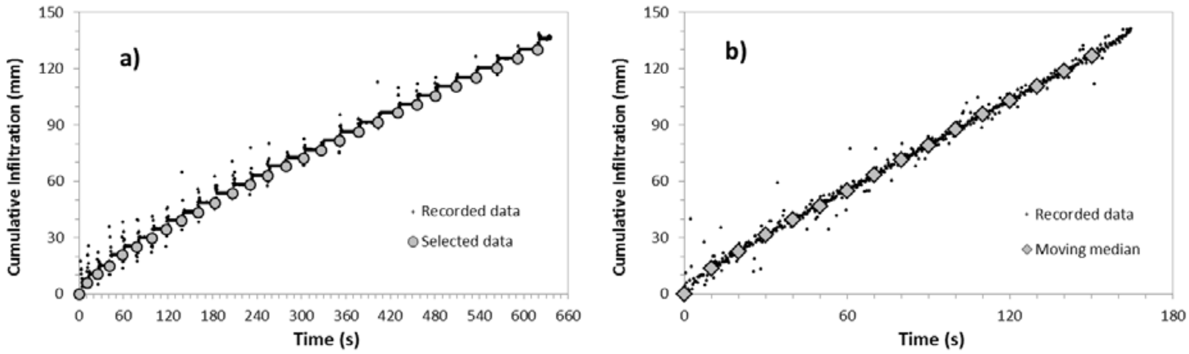
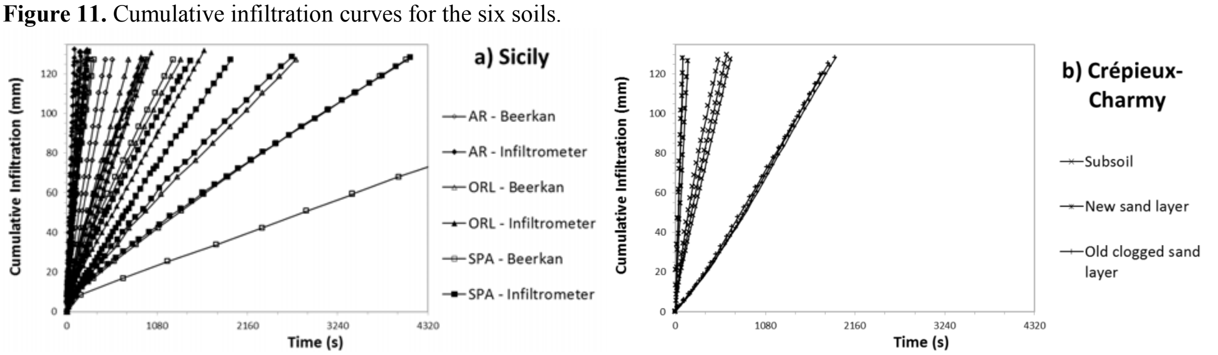


Figure 11. Cumulative infiltration curves for the six soils.



(percentage = 89%; N = 45; **Table 6**). This result suggested a more efficient data handling and analysis of automatically collected data (Ankeny et al., 1988).

For all algorithms, the mean K_s values obtained at a given site with the automated infiltrometer ($0.034 \leq K_s \leq 0.488$ mm s^{-1}) were higher than the corresponding values obtained with the manual Beerkan experiment ($0.018 \leq K_s \leq 0.128$ mm s^{-1}; **Table 6**). This result was in line with the suggestion by Bagarello et al. (2014c) that the repeated water application, as performed in the Beerkan method, promoted some soil disturbance as well as air entrapment and/or soil particle detachment phenomena decreasing K_s. Instead, the infiltrometer probably reduced soil disturbance during the run and certainly prevented air entrapment since a small depth of ponding water was steadily maintained on the infiltration surface. Another possible reason of the detected differences between the two experimental methodologies could be the difficulty to objectively establish, during the Beerkan experiment, the instant at which the new volume of water has to be applied, due to a non-uniform disappearance of the water, depending on the soil surface roughness. This uncertainty could determine an overestimation of the times recorded by the operator, especially if the process is particularly slow, and hence lower K_s values. For a given site, the effect of the applied algorithm on S and K_s calculations was generally more noticeable for the Beerkan data than for those obtained with the infiltrometer (**Table 6**). This was considered another advantage of the new device since a reduced effect of the algorithm implies more confidence in the calculated hydraulic parameters.

The cumulative infiltration curves measured at the Crépieux-Charmy site showed that the automated infiltrometer could help in distinguishing the soil, the clean sand and the clogged sand. Indeed, the new sand infiltrated much more water than the subsoil (**Figure 11**). In opposite, the old clogged sand layer impeded flow since water infiltration at the surface was significantly lower than that for the subsoil. These results justify the concern about clogging in infiltration basins and its impact on their capability to infiltrate water.

For the subsoil, the cumulative infiltration curves exhibited a typical concave shape. BEST- slope and BEST-intercept algorithms led to positive values of S and K_s and also to accurate fits of the transient cumulative infiltration model on the data, with relative errors between measured and estimated cumulative infiltration varying between 1.2 and 2.1% for BEST-slope, and 1.0 and 2.1%

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Table 6. Number of successful runs, *N*, and success rate, mean values of sorptivity, *S*, saturated soil hydraulic conductivity, K_s.

	BEST-slope			BEST-intercept			BEST-steady			Ratio max/min	
	N	***S* (mm s$^{-0.5}$)**	**K_s (mm s^{-1})**	***N***	***S* (mm s$^{-0.5}$)**	**K_s (mm s^{-1})**	***N***	***S* (mm s$^{-0.5}$)**	**K_s (mm s^{-1})**	***S***	**K_s**
					Automated infiltrometer						
Ar	5	3.045 (25.3)	0.452 (64.5)	5	3.122 (30.4)	0.488 (64.2)	5	3.033 (33.5)	0.454 (62.7)	1.03	1.08
Orl	3	1.054 (11.1)	0.073 (65.6)	5	1.225 (47.4)	0.094 (75.3)	5	1.291 (48.1)	0.105 (78.0)	1.23	1.44
Spa	5	1.171 (72.1)	0.034 (114.8)	5	1.160 (68.4)	0.038 (113.1)	5	1.142 (66.7)	0.037 (112.6)	1.02	1.10
Tot.	13 - 87%			15 - 100%			15 - 100%				
					Beerkan method						
Ar	4	2.371 (30.5)	0.100 (86.0)	5	2.143 (32.2)	0.128 (74.6)	5	2.098 (31.8)	0.123 (75.7)	1.13	1.28
Orl	3	1.467 (15.2)	0.028 (68.6)	3	1.409 (14.8)	0.045 (61.5)	5	1.208 (27.0)	0.046 (68.0)	1.22	1.64
Spa	5	1.289 (67.7)	0.018 (75.4)	5	1.236 (65.9)	0.028 (108.0)	5	1.168 (62.9)	0.026 (100.8)	1.10	1.56
Tot.	12 - 80%			13 - 87%			15 - 100%				

In parenthesis the coefficients of variation are reported. Ratio, for each site, between the maximum and minimum mean values of *S* and K_s obtained by the three algorithms.

for BEST-intercept (**Table 7**). These data, in particular the K_s estimates, were in line with the results of Goutaland et al. (2013). Similar results were also obtained with BEST-steady (**Table 7**).

For the new sand layer, the infiltration rates varied between 0.788 and 1.299 mm s^{-1}, which indicates a very high value for saturated hydraulic conductivity. Moreover, the behavior of the cumulative infiltrations appeared linear, with no concavity, which is representative of a gravity driven flow. Therefore, since the influence of capillary forces was reasonably small, the steady flow state was immediately reached and the transient state could not properly be described. As a result, and as previously demonstrated for analytically generated data, both BEST-slope and BEST-intercept algorithms were unable to provide a result. On the other hand, BEST-steady provides estimates for K_s and *S*. The values indicate high hydraulic conductivity, one order of magnitude larger than the hydraulic conductivity for the subsoil.

For the old clogged sand layer, cumulative infiltrations yielded convex shapes, which is specific for hydrophobia (Lassabatere et al., 2013). Such hydrophobia may result from significant amounts of organic matter content (Goebel et al., 2005; Lipsius and Mooney, 2006), originating from fauna and flora (Buczko et al., 2002), as well as from organic pollutants such as hydrocarbons (Durand et al., 2005; Badin et al., 2008). In this case, all BEST algorithms were unable to provide positive values of *S* and K_s, showing that BEST can only be used when the soil does not exhibit hydrophobic effect, as recently suggested by Lassabatere et al. (2013). In particular, the model used for the transient state [Eq. (4a)] produces always a concave shape and cannot be fitted to convex shaped data.

These experimental results suggested that the new device should be a useful tool to characterize water infiltration at the surface of many soils. Even if, for rapid processes, air bubbling during infiltration can influence the detection of the points to be selected for the determination of the cumulative infiltration curve, a moving median can be used to characterize water infiltration. In addition, when the soil infiltration process is not impacted by additional mechanisms like water repellence, and the initial conditions are sufficiently dry, the use of BEST algorithms can provide reliable estimates of soil hydraulic parameters.

5. CONCLUSIONS

The BEST method is an alternative technique to conventional laboratory or field measurements for rapid and low-cost estimation of soil hydraulic properties that is based on trustworthy and robust analytical solution. In this paper, the potential of a new automated infiltrometer, allowing infiltration under a practically null constant head of water at the soil surface, was tested. The relative performance of the three existing BEST algorithms, i.e., BEST-slope, BEST-intercept and BEST-steady, to derive saturated hydraulic conductivity, K_s, and sorptivity, *S*, were also investigated.

The infiltration run with the infiltrometer was simulated using analytically generated data for five differently textured soils, and different initial effective saturation degrees, i.e., from very dry to very wet initial soil water conditions. In general, using the infiltrometer and one of the BEST algorithms allowed to obtain a satisfactory hydraulic characterization of the soils. However a poor estimation of K_s and *S* or even a failure of the experiment can occur. Both BEST-slope and

Table 7. Total volume infiltrated, V_{tot} (mL), experimental steady-state infiltration rate, i_s^{exp} (mm s^{-1}), experimental intercept, b_s^{exp} (mm), saturated soil hydraulic conductivity, K_s (mm s^{-1}), soil sorptivity, S (mm s$^{-1/2}$) and fit relative error, Er (%), obtained with the three BEST algorithms for each site of the studied basin.

Site				BEST-slope			Best-intercept			Best-steady	
	V_{tot}	i_s^{exp}	b_s^{exp}	K_s	S	Er	K_s	S	Er	K_s	S
New sand layer	128.2	1.299	11.1	-	-	-	-	-	-	0.895	3.948
	120.7	1.166	15.7	-	-	-	-	-	-	0.712	4.186
	126.8	0.788	8.4	-	-	-	-	-	-	0.589	2.777
M				-	-	-	-	-	-	0.721	3.637
Old clogged sand layer	128.3	0.073	-10.8	-	-	-	-	-	-	-	-
	125.6	0.071	-6.1	-	-	-	-	-	-	-	-
	119.9	0.075	-12.0	-	-	-	-	-	-	-	-
M				-	-	-	-	-	-	-	-
Subsoil	129.8	0.172	23.6	0.065	1.788	1.2	0.081	1.733	1.7	0.077	1.686
	127.6	0.163	19.6	0.081	1.568	2.1	0.080	1.569	2.1	0.080	1.571
	127.2	0.195	26.3	0.062	1.997	1.5	0.092	1.944	1.0	0.082	1.839
M				0.069	1.784	1.6	0.084	1.749	1.6	0.080	1.699

M = mean

BEST-intercept may fail when the influence of capillary forces on infiltration is very short, i.e., steady state flow is quickly reached, and the transient state of the infiltration process is described by a too small number of data points. Therefore, a more precise description of the first part of the curve is needed to reduce the risk of failure of the run in these cases. BEST-steady makes exclusive use of the steady-state phase of the infiltration run, which avoids possible problems associated with the use of the transient infiltration data. Yet, this method may lead to less accurate estimates than BEST-slope when transient state is accurately described. Non-attainment of steady state, may compromise estimation of K_s and S and in some cases, the total volume applied with the current version of the infiltrometer may not be enough to have a good evaluation of the steady-state phase. Long infiltration runs are advised to obtain a reliable characterization with BEST-intercept and BEST-steady. BEST-slope can under-estimate K_s if too much water is infiltrated, but the discrepancies between targeted and estimated values remain in an acceptable range.

The automated infiltrometer was tested in the field. The comparison with the original Beerkan method suggests that the automated infiltrometer should increase the success rate of the BEST analysis and also reduce the uncertainty of the calculated hydraulic parameters. Moreover, the automatic data collection avoided possible overestimation of the recorded times, increased measurement speed and eased data handling and analysis. A simple moving median provided an alternative solution to properly determine the cumulative infiltration curve from the transducer output when measured infiltration rate were particularly high.

The automated infiltrometer was also tested to characterize the impact of clogging on the saturated hydraulic conductivity of a layer of sand embedded in an infiltration basin located in the pumping well field of Crépieux-Charmy. For the subsoil, all BEST methods proved efficient to provide estimates for saturated hydraulic conductivity. For the clean sand, only BEST-steady provided estimates, the other methods having failed because of imprecise description of the transient state that was too short. Finally, all methods failed to characterize the clogged sand, due to its water repellent behavior resulting from its high organic matter content.

This study suggested that the new automated infiltrometer should be an efficient and easy-to-use device to characterize water infiltration at the surface of contrasting soils. In particular, the quantification of water infiltration in coarse soils, usually considered as very challenging, was a success. The use of BEST algorithms leads to proper estimates when the conditions for their use were respected. In more details, all algorithms require a proper attainment of steady state and estimates may suffer from an insufficient infiltration of water. BEST-steady is more robust than the other algorithms and always provides estimates of the hydraulic parameters, whereas BEST-slope and BEST-intercept may fail when the transient state is not detailed enough. In terms of estimate accuracy, BEST-steady and BEST-intercept gave similar trends, with poorer estimates for BEST-intercept. BEST-slope provided more accurate estimates but failed to provide values in certain cases. Finally, this study proposed guidance for the optimization of the design of future devices, in terms of reservoir capacity, with the aim to improve the soil hydraulic characterization by the BEST method.

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Appendix E: Testing different approaches to characterize Burundian soils by the BEST procedure

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ABSTRACT

The Beerkan Estimation of Soil Transfer parameters (BEST) procedure seems attractive for soil hydraulic characterization but it has received little testing so far. The objective of this investigation was to test BEST with different application approaches for some soils of Burundi, where there is the need of using simple methods to characterize soils. Most (14) of the 19 sampled sites had a clay soil texture whereas texture ranged from silty clay to loam in the other cases. On average, the fitting ability of both the particle size distribution (PSD) model (mean relative error, $Me(E_r)$ = 2.0%) and the cumulative infiltration model ($Me(E_r)$ = 2.3%) was good according to recommended evaluation criteria. Using the complete set of measured cumulative infiltration data instead of the limited data set required by the transient infiltration equation did not affect the predicted scale parameters and the calculated soil physical quality indicators. Using reduced experimental information on the PSD (sedimentation time $\leq$ 60 min instead of $\leq$ 2880 min; percentages of particles lower than 0.002, 0.05 and 2.0 mm) did not have any statistically significant effect on the predicted parameters of the water retention curve and hydraulic conductivity function, and yielded minimal change in the assessed soil physical quality measures. Worse results were obtained with recently proposed pedotransfer functions to estimate the water retention shape parameter. In conclusion, the BEST procedure should be expected to yield a reliable hydraulic characterization of the sampled soils. From a practical point of view, estimating the duration of the transient phase of infiltration does not seem to be a crucial step of the data analysis procedure; and limited experimental information on the PSD can be used to predict soil hydraulic properties in fine-textured soils.

Keywords: BEST procedure; Burundian soils; Soil hydraulic conductivity; Soil water retention; Soil physical quality

INTRODUCTION

Studying soil hydrological processes requires the determination of soil hydraulic properties. Several methods have been developed to determine the hydraulic characteristic curves of the soil, i.e. the relationships between volumetric soil water content, θ (L^3L^{-3}), soil water pressure head, h (L), and soil hydraulic conductivity, K (L T^{-1}), both in the laboratory and the field. However, determining these properties using traditional methods is both expensive and time consuming. Haverkamp et al. (1996) pioneered a specific method for soil hydraulic characterization known as the “Beerkan method”. An improved version of this methodology, called the Beerkan Estimation of Soil Transfer parameters (BEST), was developed by Lassabatère et al. (2006). BEST considers certain analytic formulae for hydraulic characteristic curves (Burdine, 1953; Brooks and Corey, 1964; van Genuchten, 1980) and estimates their shape parameters, which are texture dependent, from simple particle size analysis by physical-empirical pedotransfer functions (PTFs). Structure dependent scale parameters are estimated from a three-dimensional field infiltration experiment at zero pressure head, using the two-term infiltration equation developed by Haverkamp et al. (1994).

BEST is very attractive for practical use since it substantially facilitates the hydraulic characterization of unsaturated soils, and it is gaining popularity in soil science (Lassabatère et al., 2007; 2010; Mubarak et al., 2009; 2010; Xu et al., 2009; Gonzalez-Sosa et al., 2010; Yilmaz et al., 2010). However, few studies have been conducted to assess the real potential of the procedure. Moreover, simplifying the application approach of the BEST procedure may allow a larger use of the methodology, including areas where soil hydraulic characterization is difficult or even impossible due to the lack of laboratories and skilled personnel. Minasny and McBratney (2007) proposed simple methods to predict shape parameters of the water retention and hydraulic conductivity curves, considering that sand and clay content or the USDA soil textural class can be the only available data. Also Bagarello et al. (2009) suggested that a reduced experimental information on the soil particle size distribution may be used to estimate shape parameters. These alternative methods have practical interest but they have not been tested with field data.

A potential attraction of the BEST procedure is that it allows a field evaluation of the soil physical quality, which is a subject that increasingly receives attention. According to Topp et al. (1997) and Reynolds et al. (2007), an agricultural soil with a good physical quality has the ability to store and transmit water, air, nutrients and agrochemicals in ways which promote both maximum crop performance and minimum environmental degradation. Therefore, evaluating soil physical quality for an area of interest is an important diagnostic tool and may help in the arrangement of effective development programs for agriculture. These objectives are particularly important in developing areas of the world, where increasing human well-being depends, among many things, on an improved agriculture that does not compromise the environment quality.

Burundi is a country in Central Africa that has a great agricultural potential given its favourable surface water availability and climate. According to Eswaran et al. (1997) and Bationo et al. (2006), Oxisol are the most dominant Soil Taxonomy order in Burundi. The hydraulic properties of Burundian soils are largely unknown and these properties are rarely measured directly, due to the scarcity of resources for experimental soil research (Bagarello et al., 2007, 2009). The BEST procedure appears to be simple from a methodological point of view, and seems to be potentially suitable to characterize Burundian soils. The beerkan method has already been applied in other tropical African countries (Galle et al., 2001).

An alternative, reasonably simple means to estimate hydraulic properties of Burundian soils could be using exclusively PTFs. Most of the available PTFs for estimating soil water retention, developed in temperate regions, appear to be inadequate in tropical areas, due to chemical and physical differences between temperate and tropical soils (Tomasella and Hodnett, 2004). However, several PTFs were specifically developed for use in tropical soils (e.g., Pidgeon, 1972; Lal, 1979; Tomasella and Hodnett, 1998; Tomasella et al., 2000; 2003). To our knowledge, less work has been carried out to develop PTFs for predicting saturated hydraulic conductivity, K_s, of tropical soils, and the few existing studies suggest a poor performance of temperate PTFs in predicting K_s of tropical soils (Mbagwu, 1995; Sobieraj et al., 2001). Moreover, PTFs should not be used to predict point values of K_s due to the differences between measurement scales of K_s and the soil data used as predictors (Timlin et al., 2004). The BEST procedure, in which infiltration is measured locally in the field, could potentially yield a more representative estimate of in-situ K_s compared to PTFs.

Testing soil hydraulic characterization methods on Burundian soils has both a local and a general interest since Burundi is rarely considered in soil investigations and Burundian soils are not widely represented in international soil databases – if represented at all.

The general objective of this investigation was to test the BEST procedure with different approaches to collect and analyze input data for hydraulic characterization and physical quality evaluation of some Burundian soils. The specific objectives were to: i) determine the fitting ability of the soil particle size distribution and infiltration models used in the procedure; ii) evaluate the physical quality of the sampled soils; iii) test an alternative analysis of the infiltration data; and iv) test simplified methods to estimate water retention shape parameters.

THE BEST PROCEDURE FOR SOIL HYDRAULIC CHARACTERIZATION

The BEST procedure for soil hydraulic characterization (Lassabatère et al., 2006) may be applied using either cumulative infiltration or infiltration rates. The former version is shortly described here because it was found to perform better than the latter one by the original authors (Lassabatère et al., 2006). BEST focuses specifically on the van Genuchten (1980) relationship for the water retention curve with the Burdine (1953) condition and the Brooks and Corey (1964) relationship for hydraulic conductivity:

$$\frac{\theta-\theta_r}{\theta_s-\theta_r}=\left[1+\left(\frac{h}{h_g}\right)^n\right]^{-m} \tag{1a}$$

$$m=1-\frac{2}{n} \tag{1b}$$

$$\frac{K(\theta)}{K_s}=\left(\frac{\theta-\theta_r}{\theta_s-\theta_r}\right)^{\eta} \tag{2a}$$

$$\eta=\frac{2}{m\times n}+3 \tag{2b}$$

where θ (L^3L^{-3}) is the volumetric soil water content, h (L) is the soil water pressure head, K (L T^{-1}) is the soil hydraulic conductivity, n, m and η are shape parameters, with $n > 2$ (Minasny and McBratney, 2007), and h_g (L), θ_s (L^3L^{-3}, saturated soil water content), θ_r (L^3L^{-3}, residual soil water content) and K_s (L T^{-1}, saturated soil hydraulic conductivity) are scale parameters. In the BEST procedure, θ_r is assumed to be zero.

Estimation of n is based on the soil particle size distribution (PSD), which is modeled as:

$$P(D)=\left[1+\left(\frac{D_g}{D}\right)^N\right]^{-M} \tag{3}$$

where $P(D)$ is the fraction by mass of particles passing a particular diameter, D (L), D_g (L) is a scale parameter, and N and $M = 1 - 2/N$ are shape factors. Fitting eq.(3) to the measured PSD allows to calculate the shape index for PSD, p_M:

$$p_M=\frac{MN}{1+M} \tag{4}$$

The m parameter of eq.(1) is calculated by:

$$m=\frac{1}{p_m}\left(\sqrt{1+p_m^2}-1\right) \tag{5}$$

where:

$$p_m=p_M\left(1+\kappa\right)^{-1} \tag{6}$$

$$\kappa=\frac{2s-1}{2s(1-s)} \tag{7}$$

$$(1-f)^s+f^{2s}=1 \tag{8}$$

where f (L^3L^{-3}) is the soil porosity and s is the fractal dimension of the media, varying from 0.5 to 1 (Fuentes et al., 1998; Minasny and McBratney, 2007).

For an infiltration experiment with zero pressure on a circular surface of radius r (L) above a uniform soil with a uniform initial water content (θ_0), the three-dimensional cumulative infiltration, I (L), and steady-state infiltration rate, i_s (L T^{-1}), can be approximated by the following explicit transient two-term relationship and steady-state expansion:

$$I(t)=S\sqrt{t}+\left(A\,S^2+B\,K_s\right)t \tag{9}$$

$$i_s=A\,S^2+K_s \tag{10}$$

where t (T) is the time, S (L $T^{-1/2}$) is soil sorptivity, and A (L^{-1}) and B are constants that can be defined for the specific case of a Brooks and Corey (1964) relationship (eq.2a) as:

$$A=\frac{\gamma}{r\left(\theta_s-\theta_0\right)} \tag{11}$$

$$B=\frac{2-\beta}{3}\left[1-\left(\frac{\theta_0}{\theta_s}\right)^{\eta}\right]+\left(\frac{\theta_0}{\theta_s}\right)^{\eta} \tag{12}$$

where β and γ are coefficients equal to 0.6 and 0.75, respectively, for $\theta_0 < 0.25\ \theta_s$ (Smettem et al., 1994; Haverkamp et al., 1994). Sorptivity can be expressed as a function of the scale parameters by the following relationship:

$$S^2(\theta_0,\theta_s)=-c_p\theta_sK_sh_g\left(1-\frac{\theta_0}{\theta_s}\right)\left[1-\left(\frac{\theta_0}{\theta_s}\right)^{\eta}\right] \tag{13}$$

where:

$$c_p=\Gamma\left(1+\frac{1}{n}\right)\left\{\frac{\Gamma\left(m\eta-\frac{1}{n}\right)}{\Gamma(m\eta)}+\frac{\Gamma\left(m\eta+m-\frac{1}{n}\right)}{\Gamma(m\eta+m)}\right\} \tag{14}$$

where Γ stands for the Gamma function.

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BEST estimates shape parameters (m, n and η) on the basis of particle size analysis and soil porosity determination whereas the infiltration experiment is used to estimate scale parameters (h_g and K_s). The initial and saturated water contents are measured at the beginning and at the end of the infiltration experiment, respectively. However, in a recent application of BEST, θ_s was calculated as total soil porosity determined from a bulk density measurement (Mubarak et al., 2009). BEST first estimates sorptivity by fitting the transient cumulative infiltration on eq.(9) with K_s replaced by its sorptivity function and the experimental steady-state infiltration rate through eq.(10). Once sorptivity is estimated, K_s is driven through eq.(10), assuming that steady-state has been reached. The pressure head scale parameter, h_g, is then estimated by eq.(13).

As eq.(9) is valid only at transient state, the fit may not be valid for large values of k, k being the number of considered (t, I) data points. Therefore, BEST fits data for a minimum of five points to a maximum of N_{tot}, i.e. the total number of collected (t, I) data points. For each data subset containing the first k points (duration of the experiment equal to t_k), S and K_s are estimated and the time, $t_{\max}$ (T), defined as the maximum time for which transient expressions can be considered valid, is determined:

$$t_{\max} = \frac{1}{4(1-B)^2}\left(\frac{S}{K_s}\right)^2 \tag{15}$$

Then, t_k is compared with $t_{\max}$. The values of S and K_s are not considered valid unless t_k is lower than $t_{\max}$. Among all values of S and K_s that fulfill this condition, the S and K_s values corresponding to the largest k ($k_{\max}$) are retained.

An alternative way to estimate the n parameter used with the BEST procedure from the soil sand, sa (%, USDA classification), and clay, cl (%), content was proposed by Minasny and McBratney (2007):

$$n = 2.18 + 0.11[48.087 - 44.954\, S(x_1) - 1.023\, S(x_2) - 3.896\, S(x_3)] \tag{16a}$$

where:

$$x_1 = 24.547 - 0.238\, sa - 0.082\, cl \tag{16b}$$

$$x_2 = -3.569 + 0.081\, sa \tag{16c}$$

$$x_3 = 0.694 - 0.024\, sa + 0.048\, cl \tag{16d}$$

$$S(x) = \frac{1}{1+\exp(-x)} \tag{16e}$$

A list of n values for the twelve USDA texture classes was also proposed (Minasny and McBratney, 2007).

SOIL PHYSICAL QUALITY INDICATORS

Soil physical quality indicators are soil parameters allowing to quantify the level or degree of physical quality of the soil (Topp et al., 1997). In agricultural soils, for example, indicators quantify, directly or indirectly, the soil's ability to store and to provide crop-essential water, air and nutrients (e.g., Reynolds et al., 2007). Several indicators and associated optimal ranges or critical limits have been suggested to evaluate soil physical quality (e.g., Topp et al., 1997; Reynolds et al., 2002; 2003; 2009). Below is a short description of the indicators considered in this investigation and the associated optimal ranges or critical limits, mainly selected on the basis of a recent investigation by Reynolds et al. (2009).

For a large range of soils (medium to fine textured soils), the *optimal* bulk density, ρ_b, range for field crop production is 0.9-1.2 Mg m^{-3}. Taking into account that poor conditions can occur for ρ_b values appreciably higher than 1.2 Mg m^{-3} (i.e., 1.25-1.30 Mg m^{-3}, Reynolds et al., 2009), in this investigation a gradual passage from optimal to poor quality was also assumed in the range of the low ρ_b values. In particular, the $0.85 \le \rho_b < 0.9$ Mg m^{-3} and $1.2 < \rho_b \le 1.25$ Mg m^{-3} values were considered to be *near-optimal* whereas $\rho_b < 0.85$ or > 1.25 Mg m^{-3} was assumed to be indicative of a *poor* quality.

The proposed *optimal* soil organic carbon content, OC (% by weight), for general plant breeding or crop growing is 3-5%. *Poor* conditions occur for both $OC < 2.3\%$ and $OC > 6\%$. The quality can be considered *intermediate* for $2.3 \le OC < 3\%$ and $5 < OC \le 6\%$.

The structural stability index, SSI (%), is defined as (Pieri, 1992):

$$SSI = \frac{1.724 \times OC}{si + cl} \times 100 \tag{17}$$

where si (%) and cl (%) are the silt and clay content, respectively. An $SSI > 9\%$ indicates *stable* structure, $7\% < SSI \le 9\%$ indicates *low risk* of structural degradation, $5\% < SSI \le 7\%$ indicates *high risk* of degradation, and $SSI \le 5\%$ indicates a structurally *degraded* soil.

The air capacity, AC (m^{3}m^{-3}), of an undisturbed field soil is defined by:

$$AC = \theta_S - \theta_{FC} \tag{18}$$

where θ_{FC} (m^3m^{-3}) is the field capacity (gravity drained) soil water content, corresponding to h = -1 m (Reynolds et al., 2002). An $AC \geq 0.14$ m^3m^{-3} was considered to be indicative of a *good* soil quality. *Intermediate* and *poor* conditions occur for $0.10 \leq AC < 0.14$ m^3m^{-3} and $AC < 0.10$ m^3m^{-3}, respectively.

Plant-available water capacity, *PAWC* (m^3m^{-3}), is given by:

$$PAWC = \theta_{FC} - \theta_{PWP} \tag{19}$$

where θ_{PWP} (m^3m^{-3}) is the permanent wilting point soil water content (h = -150 m). A $PAWC \geq 0.20$ m^3m^{-3} can be considered *ideal* for maximum root growth and function, $0.15 \leq PAWC < 0.20$ m^3m^{-3} is *good*, $0.10 \leq PAWC < 0.15$ m^3m^{-3} is *limited*, and $PAWC < 0.10$ m^3m^{-3} is *poor*.

The relative field capacity, *RFC* (-), is defined by:

$$RFC = \frac{\theta_{FC}}{\theta_s} \tag{20}$$

The *optimal* balance between root-zone soil water capacity and soil air capacity occurs when $0.6 \leq RFC \leq 0.7$. *Limited* conditions occurs for both $RFC < 0.6$ (water limited soil) and $RFC > 0.7$ (aeration limited soil).

Macroporosity, p_{MAC} (m^3m^{-3}), is defined by:

$$p_{MAC} = \theta_s - \theta_m \tag{21}$$

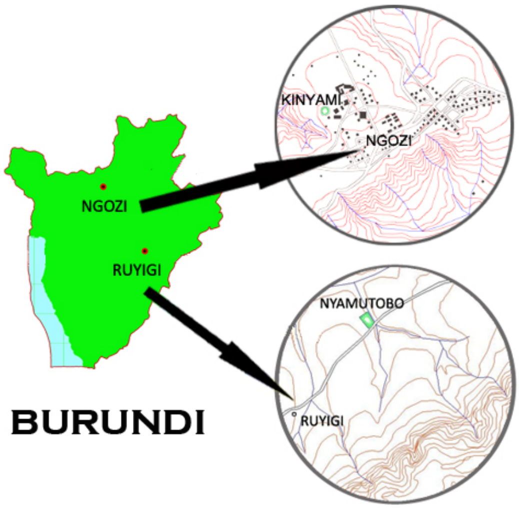
where θ_m (m^3m^{-3}) is the saturated volumetric water content of the soil matrix (h = -0.1 m; Reynolds et al., 2002). A $p_{MAC} \geq 0.07$ m^3m^{-3} was considered to be *optimal* (Reynolds et al., 2009). *Intermediate* conditions occur for $0.04 \leq p_{MAC} < 0.07$ m^3m^{-3} and the quality is *poor* for $p_{MAC} < 0.04$ m^3m^{-3}.

Although acceptable K_s for agricultural field soils ranges from about 0.36 to 360 mm h^{-1} (Topp et al., 1997), the narrower range of 18-180 mm h^{-1} is considered to be *ideal* by Reynolds et al. (2003). Therefore, an *intermediate* condition was assumed to occur for $0.36 \leq K_s < 18$ mm h^{-1} and $180 < K_s \leq 360$ mm h^{-1}, whereas the soil was considered to be *poor* for both $K_s < 0.36$ mm h^{-1} and $K_s > 360$ mm h^{-1}.

MATERIALS AND METHODS

The BEST procedure of soil hydraulic characterization was applied in two selected areas of Burundi (**Fig.1**). The area of Kinyami (2° 54’ 30” S, 29° 49’ 06” E) is located in the agroecological zone of Buyogoma. The mean annual rainfall in the region ranges between 1156 and 1215 mm (www.climateofburundi.org) with a mean annual temperature of 18.6 – 21.9 °C. Savanna with acacia trees is the prevailing land cover, whereas crops for human subsistence cover 26% of the region. Both annuals (cereals, leguminosae, tuberose) and perennial (banana and coffee trees) crops are cultivated. All the sampling sites are located within cropped fields at a mean altitude of 1650-1700 m. The landscape is characterized by moderate slopes (< 5%). According to the FAO classification, Rhodic Ferralsol soils prevail in the middle and the top of the hillslopes, while Humic Cambisol soils are present in the valley bottoms. Soil thermic and moisture regimes are isothermic and ustic, respectively. Clay mineralogy is mainly kaolinitic, but mica and chlorite also occur (Sottiaux et al., 1988). The area of Nyamutobo (3° 27’ 50” S, 30° 15’ 40” E) is located in the agroecological zone of Buyenzi (mean annual rainfall 1362 mm, mean annual temperature 18.9 °C). Crop fields (cereals, leguminosae, tuberose, banana and coffee trees) occupy more than 50% of the area, while the remaining area has natural (savanna) land cover. The soil at the sampling sites is Ferrasol rhodique, isothermic, udic with prevailing kaolinitic clay minerals (Sottiaux et al., 1988). The slope is about 5%. Four and sixteen sites were selected at the Kinyami and Nyamutobo areas, respectively. The different number of sampled sites between the two areas was due to practical constraints, including available lodging facilities.

Figure 1. Location of the sampling areas in Burundi



For a given site, having an area of approximately 7 m^2, infiltration runs were carried out at five different sampling points, with the exception of two sites at Nyamutobo where the number of sampling points was three (NY-MA-01

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site) and four (NY-00-01 site), respectively. Therefore, a total of 97 infiltration runs were carried out. For each site, a total of six 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 in three different sampling points. A disturbed soil sample (0-0.10 m depth) was also collected at the given site.

At each measurement plot, the surface vegetation was removed while the roots remained in the soil, and a 0.075-m-internal radius cylinder was inserted to a depth of about 0.01 m to avoid lateral loss of the ponded water (Lassabatère et al., 2006). A known volume of water (150 mL) was poured in the cylinder at the start of the measurement and the elapsed time during the infiltration was measured. When the amount of water had completely infiltrated, an identical amount of water was poured into the cylinder, and the time needed for the water to infiltrate was logged. The procedure was repeated until the difference in infiltration time between three consecutive trials became negligible, signaling a practically steady-state infiltration. A similar criterion (i.e., two consecutive identical infiltration times) was considered in a similar experiment by Mubarak et al. (2009). An experimental cumulative infiltration, I (L), vs. time, t (L), relationship including N_{tot} discrete points, N_{tot} being the number of collected (t, I) data points, was then deduced. Larger rings than the ones used in this investigation could be expected to yield more reliable data (e.g., Youngs, 1987) since soil spatial heterogeneity may be better represented, which is particularly important if cracks and macropores may affect the infiltration process. However, no cracks were observed at the time of field measurements and the need to transport all equipment on foot for relatively long distances precluded the use of larger rings. In any case, an attempt to average local heterogeneities was carried out by replicating the infiltration process at several sampling points for each site.

The undisturbed soil cores were used to determine the soil bulk density, ρ_b (Mg m^{-3}), at the time of sampling and θ_0. Only a small number of stainless steel cylinders and a battery-operated balance were available in Burundi. Therefore, an undisturbed soil core was weighted in the field immediately after sampling, and the soil was then extracted from the cylinder and stored in a small plastic bag that was labeled and closed. The disturbed soil sample corresponding to a known bulk (undisturbed) soil volume was oven-dried at the laboratory of the SAGA (Sistemi Agro-Ambientali) Department, University of Palermo, Italy. Following Mubarak et al. (2009), θ_s was calculated as total soil porosity considering the density of the soil particles to be 2.65 Mg m^{-3}. This choice was necessary due to practical constraints of the experiment, that prohibited direct measurement of θ_s.

The disturbed soil was used to determine the PSD, using conventional methods following H_2O_2 pre-treatment to eliminate organic matter and clay deflocculation using sodium metaphosphate and mechanical agitation (Gee and Bauder, 1986). Fine size fractions were determined by the hydrometer method, whereas the coarse fractions were obtained by mechanical dry sieving. In particular, sieving analysis was carried out using six sieves with mesh sizes of 2, 0.86, 0.425, 0.25, 0.106 and 0.075 mm. Eight fine fraction data points were obtained by the hydrometer method, measuring the suspension density at times, t_r = 2, 5, 15, 30, 60, 180, 1440 and 2880 min (Bagarello et al., 2009). This yielded a combined 14 PSD points for each sample. Measuring the suspension density at $t_r \leq$ 1440 min is the suggested standard procedure, but it is also suggested that t_r can be modified as needed (Gee and Or, 2002). In this investigation, two fractions finer than 0.002 mm were determined because using a larger range of measured diameters was considered to be advisable to reproduce the complete PSD (Bagarello et al., 2009). Log-linear interpolation was applied to determine the clay (cl), silt (si) and sand (sa) percentages according to the USDA standards (Gee and Bauder, 1986), given that the experimentally determined PSD points assured the closeness of neighboring points (Bagarello et al., 2009). The organic carbon, OC (%), content was measured by the Walkley-Black method. All laboratory analysis were carried out 15-20 days after sampling. Therefore, a chance for a small alteration of the soil characteristics, affecting OC results, cannot be excluded.

A single value of ρ_b, θ_0 and θ_s was obtained for a given site by averaging the six individual determinations. Eq.(3) was fitted to the measured PSD data to obtain a single set of m, n and η values. Eqs.(9)-(15) were used to determine h_g and K_s at a given sampling point using the site-representative values of the other parameters. The individual h_g and K_s values were averaged to obtain site-representative values of these two parameters. The acronym BEST/OR (OR = original) was used to denote the soil hydraulic characterization carried out by the above described procedure.

The need for determining k_{max} complicates the data analysis. Moreover, the S and K_s calculations corresponding to $k_{max} < k \leq N_{tot}$ are uncertain since they are based on the assumption that the transient infiltration model can be applied for $t > t_{max}$. For comparative purposes, the scale parameters, h_g and K_s, were also deduced by considering the whole experimental infiltration curve, i.e. by assuming $k_{max} = N_{tot}$. The acronym BEST/ALL was used in this case.

Generally, less detailed information is expected to be available on the PSD of sampled soils in areas of the world where resources for soil hydraulic characterization are scarce. Therefore, the effect of using less detailed PSD information on the predicted soil hydraulic properties was evaluated by considering four different scenarios, denoted by the acronyms BEST/M1, BEST/M2, BEST/B1 and BEST/B2.

BEST/M1 used eq.(16) (Minasny and McBratney, 2007) to estimate n from soil sa and cl content. BEST/M2 estimated the n parameter from soil textural class, using Table 4 by Minasny and McBratney (2007).

In a recent investigation on some Burundian soils, Bagarello et al. (2009) showed that using a smaller number of PSD data points (11, or $t_r \leq 60$ min, instead of 14, or $t_r \leq 2880$ min) did not yield a substantial increase in the relative fitting error of the PSD model, compared to using all 14 measured data points. These authors also suggested that using experimental information reduced to only three points (i.e., percentages corresponding to 0.002, 0.05 and 2 mm) may be a practical alternative for soils with high clay content. However, the impact of fitting eq.(3) with reduced experimental information on the predicted soil hydraulic properties is unknown. Therefore, in scenario BEST/B1, we used eq.(3) and the first 11 data points of the measured PSD to estimate the n parameter. In scenario BEST/B2, n was estimated by using eq.(3) and the three determined soil textural fractions, sand, silt and clay content.

BEST/B1 was the most data demanding procedure among the four considered simplified procedures for estimating shape parameters. BEST/M1 and BEST/B2 used different approaches but the same input data. BEST/M2 can be applied using only pedological maps, and therefore it can be considered the least demanding approach.

The BEST procedure can also facilitate the evaluation of different soil physical quality indicators that are of great interest (Reynolds et al., 2009). Therefore, the comparison between BEST/OR and the considered alternative approaches (BEST/ALL, BEST/M1, BEST/M2, BEST/B1, BEST/B2) was carried out in terms of both water retention curve and hydraulic conductivity function parameters as well as the listed soil physical quality indicators. The AC, $PAWC$, RFC, p_{MAC} and K_s indicators were obtained by the BEST experiment, whereas the ρ_b, OC and SSI indicators were determined directly. Latter indicators were included in this investigation to obtain a reasonably complete representation of the soil physical quality at each sampled site.

RESULTS AND DISCUSSION

The original BEST procedure

A total of 85 infiltration runs, or 88% of the 97 runs, yielded valid h_g and K_s results with the BEST/OR procedure; all five replicated infiltration runs yielded valid h_g and K_s results for 14 sites. Invalid results ($t_k > t_{max}$, negative K_s) were obtained at a single sampling point for two sites, and at three and four sampling points, respectively, for two other sites. Valid results were obtained at all (four) sampling points for the NY-00-01 site. On the other hand, invalid results were obtained at all (three) sampling points for the NY-MA-01 site. Therefore, this last site, that was characterized by the highest sand content (40.8%) among all sampled sites (**Table 1**), was not considered in the following analysis, leaving a total of N = 19 sites for the analysis. A given site was characterized by averaging all valid K_s and h_g values for the site.

Clay was the most dominant fraction (**Table 1**) and the soil texture class was clay at 14 of the 19 sites. All these sites were located in the Nyamutobo area which area had a site with a silty clay soil. The soil texture in the Kinyami area was slightly coarser, i.e. silty clay loam, clay loam or loam, depending on the site. Therefore, the criterion proposed by Reynolds et al. (2009) to evaluate soil physical quality in terms of bulk density values (valid for medium to fine textured soils) was appropriate for this data set.

A preliminary evaluation of the expected reliability of the water retention curve and hydraulic conductivity function obtained by the BEST procedure can be carried out by evaluating

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Table 1. Minimum, *min*, maximum, *max*, arithmetic mean, *Me*, median, *Md*, and coefficient of variation, *CV*, of the measured soil properties (*cl*, *si*, *sa*, ρ_b, *OC*), the water retention curve and soil hydraulic conductivity function parameters obtained by the BEST/OR procedure (θ_s, h_g, m, n, K_s, η), and the associated soil physical quality indicators (*SSI, AC, PAWC, RFC,* p_{MAC}) for N = 19 Burundian sites

Variable	min	max	Me	Md	CV (%)
cl (%)	22.7	62.6	47.4	49.8	25.0
si (%)	17.4	49.7	31.9	31.2	32.8
sa (%)	12.3	32.9	20.8	20.6	28.3
ρ_b (Mg m^{-3})	0.82	1.03	0.91	0.91	5.7
OC (%)	2.0	4.9	3.0	2.7	28.5
θ_s (m^{3}m^{-3})	0.61	0.69	0.66	0.66	3.0
h_g (mm)	-73.7	-16.0	-42.1	-40.5	30.6
m	0.020	0.067	0.036	0.031	42.5
n	2.040	2.143	2.076	2.064	1.6
K_s (mm h^{-1})	65.9	755.0	288.2	273.7	54.8
η	16.97	52.85	33.93	34.23	35.3
SSI (%)	4.4	11.7	6.5	5.7	32.1
AC (m^{3}m^{-3})	0.08	0.26	0.14	0.13	40.3
PAWC (m^{3}m^{-3})	0.11	0.22	0.15	0.15	23.9
RFC (-)	0.61	0.88	0.79	0.81	10.8
p_{MAC} (m^{3}m^{-3})	0.02	0.11	0.05	0.04	52.6

cl = clay; *si* = silt; *sa* = sand; ρ_b = soil bulk density; *OC* = organic carbon content; θ_s = saturated soil water content; h_g = scale parameter for water pressure; m, n and η = shape parameters; K_s = saturated soil hydraulic conductivity; *SSI* = structural stability index; *AC* = air capacity; *PAWC* = Plant-available water capacity; *RFC* = relative field capacity; p_{MAC} = macroporosity.

the fitting performance of the PSD and infiltration models. Large discrepancies between the model and the experimental data may be due to the inability of the model to reproduce reality due, for example, to soil's bimodality or the validity of the assumed forms of models, or to a poor quality of the experimental data. Therefore, an increase of such discrepancies suggests increasing uncertainties in the soil hydraulic characterization.

According to Lassabatère et al. (2006), the relative error, E_r (%), was calculated to evaluate the fitting performance of the theoretical model to the measured PSD data using:

$$E_r = 100 \times \sqrt{\frac{\sum_{i=1}^{N_d} \left[F_i(d) - P_i(d)\right]^2}{\sum_{i=1}^{N_d} \left[F_i(d)\right]^2}} \quad (22)$$

where N_d is the number of the measured data pairs (diameter, D - frequency by weight, $F_i(D)$) and $P_i(D)$ is the corresponding theoretical probability calculated by the selected model. The E_r values ranged from 0.3% to 4.0% (mean = 2.0%, **Table 2**). Moreover, E_r decreased as the *cl* content of the soil increased (**Fig.2**, r^2 = 0.65, r > 0 according to a one-tailed t test, P = 0.05). Lassabatère et al. (2006) suggested that E_r < 5% denotes a satisfactory fitting ability of the model. Therefore,

Table 2. Minimum, *min*, maximum, *max*, arithmetic mean, *Me*, and coefficient of variation, *CV*, of the relative error, E_r (%), for a different number of data points included in the fitting procedure of the particle size distribution model

Statistic	14 pts	11 pts	3 pts
min	0.3	0.3	0.4
max	4.0	4.7	4.8
Me	2.0	2.3	2.3
CV (%)	52.2	50.3	53.8

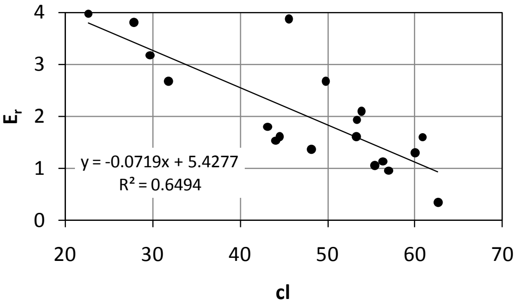
the performance of the PSD model was satisfactory at all sampled sites, and it improved as the *cl* content of the soil increased, maybe because the PSD in high clay texture has a simpler form (Hwang et al., 2002) and the range of values to cover by the model is smaller (Bagarello et al., 2009).

For the considered 85 infiltration runs, the procedure of pouring a fixed volume of water was repeated a series of 13 to 38 times (mean, *Me* = 21), depending on the run, elapsed time between pouring varied from 5 to 808 s. The number of points describing a transient infiltration process, k_{max}, varied from run to run between 5 and 34 (*Me* = 17). For each run, the relative error, E_r (%), was calculated to evaluate the quality of the data fitting on the transient cumulative infiltration model by the following relationship (Lassabatère et al., 2006):

$$E_r = 100 \times \sqrt{\frac{\sum_{i=1}^{k_{max}} \left[I_m - I_e\right]^2}{\sum_{i=1}^{k_{max}} \left[I_m\right]^2}} \quad (23)$$

where I_m (L) is the measured cumulative infiltration and I_e (L) is the corresponding modeled infiltration. The E_r results varied from a minimum of 0.4% to a maximum of 8.1%, with a mean value equal to 2.3% and a coefficient of variation, CV = 63.3%. Values of E_r ranging from 2.3% to 3.5% were obtained by Lassabatère et al. (2006) for the three reported infiltration experiments. In this investigation, based on a much larger sample size, $E_r \leq$ 3.5% was a common

Figure 2. Relationship between the relative error, E_r (%), of the BEST PSD model and the clay content, *cl* (%)

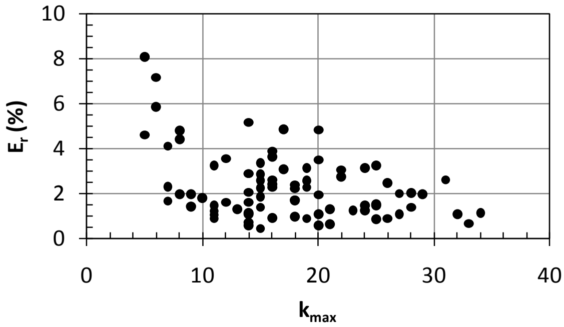


result since it was obtained for 72, or 85%, of the 85 infiltration runs. **Fig.3** shows that E_r decreased as k_{max} increased. In particular, $E_r \leq 3.2\%$ was always obtained for $k_{max} \geq 21$. Therefore, the probability to obtain low E_r values increased as the cumulative infiltration volume that was modeled by the transient infiltration relationship increased.

A regression analysis between E_r (eq.23) and *sa*, *si*, *cl*, ρ_b and *OC* was carried out. Taking into account that different infiltration runs (i.e. different replicates of the infiltration process) were carried out at a given site characterized by a single value of the considered independent variables, two different analyses were developed. In the first analysis, the individual runs were considered and the different E_r values obtained at a given site were associated with unique, site-specific values of the independent variables (sample size, N = 85). In the other analysis, each site was characterized by a single E_r value, $Me(E_r)$, obtained by averaging the individual E_r results for the site (N = 19). With this analysis, $Me(E_r) \leq 3.4\%$ was obtained at all considered sites with a single exception (4.8% at KI-04-01 site). All regression analyses yielded coefficients of determination, r^2, that do not differ significantly from zero (N = 85: $0.002 \leq r^2 \leq 0.023$; N = 19: $0.0007 \leq r^2 \leq 0.096$), with a single exception for *cl*. In particular, $r^2 = 0.033$ ($r = 0.183 > 0$, slope, $b_1 = -0.024$) was obtained for the individual E_r vs. *cl* content relationship. This relationship was weak but significant, suggesting that the quality of the fitting improved as the clay content of the soil increased. However, the very low r^2 value also suggested that this indication should be considered with caution, and that additional testing is necessary.

This analysis showed that, on average, the modeling of experimental data by the transient infiltration model was accurate and, in most cases, the relative errors did not exceed those obtained in the independent test of the BEST procedure by Lassabatère et al. (2006). According to the evaluated criteria, the reliability of the soil hydraulic characterization could be questioned for the KI-04-01 site, although $Me(E_r)$ was not substantially higher than 3.5%. The quality of the fitting is expected to increase when a relatively large number of data points are collected during the transient phase of the infiltration process (i.e., high k_{max}). It can also be suggested, with some caution, that a more accurate fitting is expected as the clay content of the soil increases. Therefore,

Figure 3. Relationship between the relative error, E_r (%), of the infiltration model calculated for each individual infiltration run and the number of data points describing a transient process, k_{max}



this investigation confirmed that the BEST procedure for soil hydraulic characterization should be expected to perform well in fine-textured soils (Bagarello et al., 2009), although the potential presence of cracks/macropores could be an issue needing specific investigation.

The shape and scale parameters calculated for the sampled sites yielded wide ranges of soil physical quality parameters (**Table 1**). All possible categories of soil physical quality were represented for a given indicator (**Table 3**), with the single exception of *PAWC* since *PAWC* < 0.10 m^3m^{-3}, denoting a poor quality, was never obtained (**Table 1**).

The mean ρ_b, *OC*, *AC*, and *PAWC* values (**Table 1**) denoted an optimal or a good soil physical quality. Intermediate results were obtained for p_{MAC} and K_s. However, the risk of structural degradation (*SSI*) was high and the balance between root-zone soil water capacity and soil air capacity (*RFC*) was non-optimal (aeration limited conditions). Therefore, a favorable or nearly favorable physical quality was detected for most indicators, suggesting that soil physical quality should not be expected to have a clear adverse impact on field crop production in the two sampled areas. Among the possible strategies to improve the soil physical quality, a small increase in the *OC* content (i.e., from 3% to slightly more than 3.2%) is expected to be enough to reduce the risk of structural degradation (i.e., from high risk to low risk). According to Reynolds et al. (2002), θ_{FC} is controlled largely by soil matrix properties and an increase in organic matter has a macrostructure-producing function that increases *AC*, decreases ρ_b and leaves θ_{FC} relatively unchanged. Therefore, an increase in organic carbon content is also expected to have a positive effect on *RFC* (i.e., values closer to the optimal range). However, the decrease of ρ_b should be minimal since the mean ρ_b value was close to the

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Table 3. Percentage of sites with a given soil physical quality category for each considered indicator

Indicator	Quality	All data	Nyamutobo	Kinyami
ρ_b	optimal	52.6	60.0	25.0
	near-optimal	42.1	33.3	75.0
	poor	5.3	6.7	0
OC	optimal	26.3	6.7	100.0
	intermediate	63.2	80.0	0
	poor	10.5	13.3	0
SSI	stable	15.8	0	75.0
	low risk	10.5	6.7	25.0
	high risk	63.2	80.0	0
	degraded	10.5	13.3	0
AC	good	42.1	26.7	100.0
	intermediate	31.6	40.0	0
	poor	26.3	33.3	0
PAWC	ideal	15.8	0	75.0
	good	26.3	26.7	25.0
	limited	57.9	73.3	0
	poor	0	0	0
RFC	optimal	15.8	0	75.0
	limited	84.2	100.0	25.0
p_{MAC}	optimal	21.1	6.7	75.0
	intermediate	26.3	26.7	25.0
	limited	52.6	66.7	0
K_s	ideal	15.8	13.3	25.0
	intermediate	73.7	73.3	75.0
	poor	10.5	13.3	0

ρ_b = soil bulk density; *OC* = organic carbon content; *SSI* = structural stability index; *AC* = air capacity; *PAWC* = plant-available water capacity; *RFC* = relative field capacity; p_{MAC} = macroporosity; K_s = saturated soil hydraulic conductivity. Sampled sites: all data, N = 19; Nyamutobo, N = 15; Kinyami N = 4.

lower limit of the optimal ρ_b range for field crop production.

For each indicator, a higher frequency of favorable conditions was detected at Kinyami than Nyamutobo (**Table 3**), suggesting that the latter area is characterized by worse soil physical quality than the former one. However, this comparison should be considered with caution, since the number of sampled sites differed greatly between the two areas and a substantially smaller data set was considered for Kinyami. The analysis developed in this investigation was based on general, empirical guidelines to assess soil physical quality, and the considered indicators represented a heterogeneous pool of indicators that were thought to be suitable as rough evaluators of soil physical quality. Evaluating specific indicators and developing optimal ranges and/or critical limits for tropical soils is desirable, because these soils show differences if compared with temperate soils including, as an example, generally lower bulk densities (Hodnett and Tomasella, 2002).

Alternative analysis of the infiltration data

A total of 93 infiltration runs, or 96% of the 97 runs, yielded valid h_g and K_s results. In particular, all five replicated infiltration experiments yielded valid h_g and K_s results for 17 sites. Valid results were obtained at all (four) sampling points for the NY-00-01 site. Invalid results were obtained at a sampling point for a single site, and at all (three) sampling points for the NY-MA-01 site that was also excluded from the analysis of the BEST/OR results. Therefore, one of the first conclusions is that BEST/ALL yielded a larger number of valid results than BEST/OR. A given site was characterized by averaging all valid results to obtain site representative data, where small scale heterogeneities were averaged. The criterion of averaging, for a given site, all valid results determined that a different number of infiltration runs were considered for a given site, depending on the considered procedure (BEST/OR, BEST/ALL), in a few cases. This choice was thought to be reasonable because a single procedure is expected to be applied in practice.

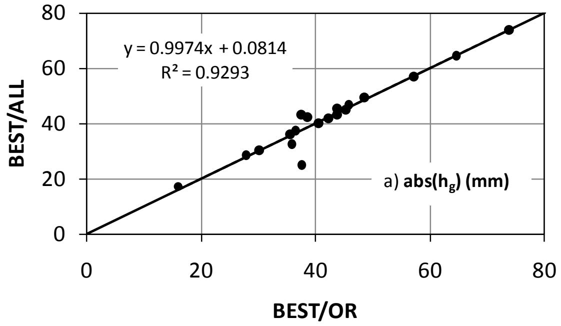
The BEST/OR (**Table 1**) and BEST/ALL (**Table 4**) procedures may differ in terms of h_g and K_s results. According to the Probability Plot Correlation Coefficient test (Helsel and Hirsch, 1992), the two abs(h_g) data sets were better described by the normal (N) distribution than the ln-normal (LN) one (P = 0.05). Therefore, the untransformed values of this variable obtained by the two procedures were compared. The ln(K_s) data were considered for comparative purposes since K_s was better described by the LN distribution than the N one.

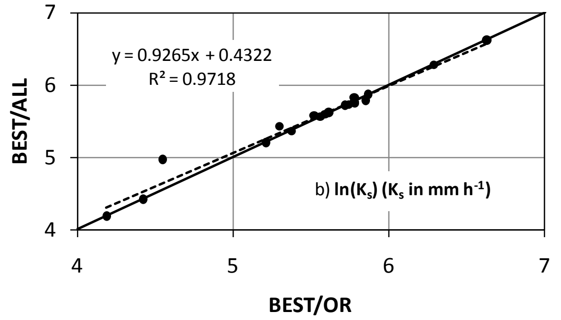
The differences we found between the two data sets were not statistically significant for either of the two variables according to the paired, two-tailed t test (P = 0.05). The regression analysis between the BEST/ALL and BEST/OR results yielded a correlation coefficient significantly higher than zero and the calculated regression line was not significantly different from the 1:1 line (**Fig.4**). Finally, using BEST/ALL instead of BEST/OR did not have any effect on the quality category assigned to *AC*, *PAWC*, *RFC*, p_{MAC} (**Fig.5**) and K_s (evaluated from 95 cases, i.e. five indicators x 19 sites). For example, if the air capacity determined for a

Table 4. Minimum, *min*, maximum, *max*, arithmetic mean, *Me*, median, *Md*, and coefficient of variation, *CV*, of the scale parameter for water pressure, h_g, and saturated soil hydraulic conductivity, K_s, obtained by the BEST/ALL procedure at N = 19 Burundian sites

Variable	min	max	Me	Md	CV (%)
h_g (mm)	-73.7	-17.2	-42.1	-42.2	31.7
K_s (mm h^{-1})	65.9	749.1	291.2	274.8	52.3

Figure 4. Comparison between the BEST/OR and BEST/ALL procedures in terms of a) abs(h_g) results and b) ln(K_s) results

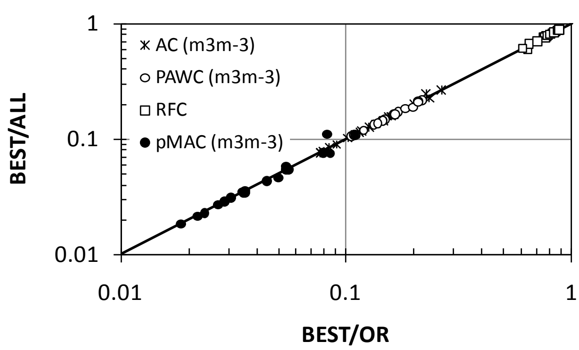




particular site by BEST/OR was good, it also was good with BEST/ALL.

Therefore, this investigation suggested that using the complete data set of measured cumulative infiltration values instead of the reduced (transient) series did not affect soil hydraulic characterization obtained by the BEST procedure, notwithstanding that the number of infiltration runs yielding valid results varied between the two considered procedures in a few sites. An infiltration run carried out until three consecutive infiltration rates were nearly constant, and applying a simplified analysis using the entire measured cumulative infiltration curve seems to be a usable and justifiable approach in practice.

Figure 5. Comparison between the BEST/OR and BEST/ALL procedures in terms of air capacity, *AC*, plant-available water capacity, *PAWC*, relative field capacity, *RFC*, and macroporosity, p_{MAC}, results



Simplified procedures for estimating water retention shape parameters

The BEST/M1, BEST/M2, BEST/B1 and BEST/B2 procedures did not differ from the BEST/ALL procedure in terms of providing valid h_g and K_s results. Therefore, different number of infiltration runs was considered in the comparison between the BEST/OR procedure and each of the simplified ones for a few sampled sites.

The relative error, E_r (%),was calculated by eq.(22) to evaluate the fitting performance of the theoretical model (eq.3) to the measured PSD data. The values of E_r for a given soil sample were calculated across all 14 available *D*, *F(D)* data pairs. In other words, N_d = 14 data points were considered to calculate E_r even if a lower number of data points was used for fitting the model (BEST/B1: 11 data points, i.e., $t_r \leq 60$ min; BEST/B2: three data points, i.e. percentages corresponding to 0.002, 0.05 and 2 mm). The E_r results did not change appreciably with the considered number of data points for fitting and the maximum error did not exceed 4.8% (**Table 2**). Therefore, using somewhat limited or substantially limited information did not have a strong adverse effect on the fitting performance of the PSD model.

For all simplified procedures (BEST/M1, BEST/M2, BEST/B1, and BEST/B2), the N distribution described the abs*(h_g)* data better than the LN one, whereas the opposite result was obtained for K_s. For BEST/OR and the simplified procedures, the N distribution was more appropriate than the LN one for η, whereas the LN distribution was more appropriate than the N one for *m* and *n*. Therefore, the untransformed values of abs*(h_g)* and η and the ln-transformed K_s, *m* and *n* data were considered for comparison between data-sets.

According to the two-tailed, paired t-test (P = 0.05), both the BEST/M1 and BEST/M2 procedures yielded significantly different results in terms of ln(*m*), ln(*n*), η and abs*(h_g)* as compared with the BEST/OR procedure (**Table 5**). Moreover, the linear regression line did not coincide with the 1:1 line for ln(*m*), ln(*n*) and η (**Table 6**). A different result (i.e., not significantly different means and regression line coinciding with the identity line) was obtained for ln*(K_s)*. The ln(*m*), ln(*n*), η, abs*(h_g)* and ln*(K_s)* results obtained with both the BEST/B1 and BEST/B2 procedures did not show any statistically significant difference as compared with the BEST/OR procedure (**Tables 5** and **6**).

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Table 5. Minimum, *min*, maximum, *max*, arithmetic mean, *Me*, and standard deviation, *SD*, of the ln(*m*), ln(*n*), η, abs(h_g) (mm), and ln(K_s) (K_s in mm h^{-1}) values obtained by different BEST application procedures

Procedure	Variable	min	max	Me	SD
BEST/OR	ln(m)	-3.929	-2.706	-3.391 (a) (b) c d	0.404
	ln(n)	0.713	0.762	0.730 (a) (b) c d	0.016
	η	16.970	52.845	33.933 (a) (b) c d	11.972
	abs(h_g)	15.974	73.712	42.118 (a) (b) c d	12.908
	ln(K_s)	4.189	6.627	5.514 a b c d	0.598
BEST/M1	ln(m)	-3.056	-2.496	-2.892 (a)	0.164
	ln(n)	0.741	0.779	0.751 (a)	0.011
	η	14.138	23.246	20.245 (a)	2.717
	abs(h_g)	18.341	76.516	44.774 (a)	14.147
	ln(K_s)	4.189	6.619	5.541 a	0.562
BEST/M2	ln(m)	-3.045	-2.398	-2.951 (b)	0.180
	ln(n)	0.742	0.788	0.748 (b)	0.012
	η	13.000	23.000	21.396 (b)	2.983
	abs(h_g)	18.018	76.549	44.433 (b)	14.165
	ln(K_s)	4.189	6.619	5.541 b	0.562
BEST/B1	ln(m)	-3.926	-2.682	-3.375 c	0.405
	ln(n)	0.713	0.764	0.731 c	0.017
	η	16.617	52.688	33.455 c	11.794
	abs(h_g)	17.460	72.598	42.117 c	13.173
	ln(K_s)	4.189	6.619	5.541 c	0.562
BEST/B2	ln(m)	-4.021	-2.696	-3.394 d	0.422
	ln(n)	0.711	0.763	0.731 d	0.017
	η	16.824	57.751	34.262 d	12.698
	abs(h_g)	16.983	73.969	42.128 d	13.426
	ln(K_s)	4.189	6.619	5.541 d	0.562

For a given variable, mean values followed by the same lower case letter enclosed in parentheses were significantly different according to a two-tailed, paired t-test (P = 0.05); means followed by the same lower case letter not enclosed in parentheses were not significantly different. The a, b, c and d letters were used to denote the comparison of BEST/OR against BEST/M1, BEST/M2, BEST/B1 and BEST/B2, respectively.

For the 19 considered sites, using the BEST/M1 and BEST/M2 procedures instead of the BEST/OR one did not have any effect on the quality category established for K_s, but it had a noticeable impact on categorization of *AC*, *PAWC*, *RFC* and p_{MAC}, given that the assigned quality category changed for seven to 13 sites (BEST/M1) or four to 12 sites (BEST/M2), depending on the considered indicator (**Table 7**). A change in the assigned quality category was detected for a maximum of three sites with the BEST/B1 procedure and two sites with the BEST/B2 one, depending on the chosen indicator (**Table 7**).

Therefore, both the BEST/B1 and BEST/B2 procedures were found to be reliable practical alternatives to the BEST/OR procedure. Poorer results were obtained with the BEST/M1 and BEST/M2 procedures, suggesting that the latter procedures should not be suggested for practical use in soils similar to those sampled in this investigation. Differences between temperate and tropical soils were detected by Hodnett and Tomasella (2002) in terms of van Genuchten soil water retention parameters. Therefore, the relatively poor performance of BEST/M1 and BEST/M2 may have been influenced by tropical soils not being well represented in the databases analyzed by Minasny and McBratney (2007).

A moderate to negligible impact on the estimated soil hydraulic parameters was detected when reduced textural information (three measured PSD data points) was used to deduce the shape parameters. This result cannot be generalized because the number of measured data points was found to have a small effect on the fitting accuracy of the PSD model only for soils with high clay content (Bagarello et al., 2009).

Fitting eq.(3) with three measured data points (BEST/B2 procedure) was found to yield

Table 7. Number of sites with a changed quality category for an indicator (*AC*, *PAWC*, *RFC*, p_{MAC}, K_s) due to the use of a simplified BEST procedure instead of the BEST/OR one (total number of sites = 19)

Procedure	AC	PAWC	RFC	p_{MAC}	K_s
BEST/M1	11	13	7	10	0
BEST/M2	11	12	4	9	0
BEST/B1	1	3	1	0	0
BEST/B2	0	2	1	1	0

AC = air capacity; *PAWC* = Plant-available water capacity; *RFC* = relative field capacity; p_{MAC} = macroporosity; K_s = saturated soil hydraulic conductivity

Table 6. Intercept, b_0, slope, b_1, and coefficient of determination, r^2, of the linear regression line obtained, for a given variable (ln(m), ln(n), η, abs(h_g) in mm, and ln(K_s) with K_s in mm h^{-1}), by comparing each simplified BEST procedure with the BEST/OR one

Procedure	Variable	b_0	b_1	r^2
BEST/M1	ln(m)	−1.5938a	0.3829b	0.8952c
	ln(n)	0.2823a	0.6417b	0.9334c
	η	13.221a	0.207b	0.8319c
	abs(h_g)	0.4402d	1.0526e	0.9224c
	ln(K_s)	0.4322d	0.9265e	0.9718c
BEST/M2	ln(m)	−1.7370a	0.3581b	0.6440c
	ln(n)	0.2828a	0.6367b	0.7201c
	η	15.2680a	0.1806b	0.5253c
	abs(h_g)	0.1391d	1.0517e	0.9184c
	ln(K_s)	0.4322d	0.9265e	0.9718c
BEST/B1	ln(m)	−0.0213d	0.9893e	0.9732c
	ln(n)	−0.0175d	1.0248e	0.9723c
	η	0.4650d	0.9722e	0.9740c
	abs(h_g)	0.7492d	0.9822e	0.9263c
	ln(K_s)	0.4324d	0.9265e	0.9717c
BEST/B2	ln(m)	0.1191d	1.0361e	0.9863c
	ln(n)	−0.0228d	1.0314e	0.9903c
	η	−1.3641d	1.0499e	0.9799c
	abs(h_g)	−0.1186d	1.0031e	0.9300c
	ln(K_s)	0.4324d	0.9265e	0.9717c

a 95% confidence limit for the intercept does not include zero.
b 95% confidence limit for the slope does not include one.
c Coefficient of correlation significantly greater than zero according to a one tailed t- test (P = 0.05).
d 95% confidence limit for the intercept includes zero.
e 95% confidence limit for the slope includes one.

more accurate results than using eq.(16) (BEST/M1) with the same initial information. A possible factor determining this result is that with the BEST/B2 procedure the shape parameters for the water retention curve are still derived on the basis of a measurement of the PSD, as with the BEST/OR procedure. On the other hand, eq.(16) was derived using different data from those used in this investigation, and also on the basis of laboratory-determined water retention curves (Minasny and McBratney, 2007).

CONCLUSIONS

The BEST procedure was applied for hydraulic characterization and physical quality evaluation of some Burundian soils. Clay was the most dominant soil texture class, since it was dominant for 14 of the 19 sampled sites. Silty clay, silty clay loam, clay loam and loam were other represented classes.

On average, the fitting ability of both the particle size distribution (PSD) model (mean relative error, $Me(E_r)$ = 2.0%) and the cumulative infiltration transient model ($Me(E_r)$ = 2.3%) was good according to evaluation criteria suggested in the literature, suggesting that the procedure can be expected to yield a reliable hydraulic characterization of the sampled soils.

An increasing fitting ability of the PSD and infiltration models was observed as the clay content of the soil increased, although the relationship found for the infiltration model was weak. Therefore, additional BEST experiments should be carried out both in fine textured soils, to better establish the E_r vs. clay content relationship, and in coarser soils, to deduce a more general relationship between the model fitting ability and the soil textural characteristics. This relationship has practical importance since it could allow a prediction of the expected quality of soil hydraulic characterization performed by BEST on the basis of knowing soil texture.

Using the complete set of cumulative infiltration measurements instead of the originally proposed reduced data set, strictly usable with the transient two-term infiltration equation, was found not to have practical effects on the predicted scale parameters and soil physical quality indicators. Therefore, an infiltration run carried out until three consecutive infiltration rates are approximately constant and a simplified analysis performed using the whole measured cumulative infiltration curve is acceptable for practical use with the sampled Burundian soils.

A reduced amount of experimental information on the PSD did not compromise the soil hydraulic characterization obtained with the

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BEST procedure. We considered a sedimentation time ≤ 60 min instead of ≤ 2880 min or using only the percentages of particles smaller than 0.002, 0.05 and 2.0 mm, which is expected to be a commonly available information in locally existing databases. Using such limited information i) gave a slightly higher relative error describing the fitting accuracy of complete PSD, ii) did not have any statistically significant effect on the predicted parameters of the water retention curve and hydraulic conductivity function and iii) had a minimal effect on the predicted soil physical quality. Worse results were obtained with recently proposed pedotransfer functions estimating the water retention shape parameter from sand and clay content or the soil textural class. Therefore, the BEST procedure seems also to be usable when only a rough description of the PSD is available. This result has practical importance especially in areas of the world where soil hydraulic characterization is difficult due to the lack of laboratories and skilled personnel. However, it cannot be generalized because it is known that the number of measured data points may have a more noticeable effect on the fitting accuracy of the PSD model in coarse textured soils. It should be expected that limited information on the PSD may compromise the reliability of the soil hydraulic characterization as the clay content of the soil decreases. Detailed testing of this observation is desirable, but such soils were not available in this study.

In this study, we set the saturated soil water content equal to the soil porosity out of practical necessity, which has earlier been done successfully by other authors as well. However, further investigation should be carried out to test the impact of the θ_s evaluation methodology on soil hydraulic characteristics and physical quality attributes deduced by the BEST procedure. In addition, it would also be advisable to compare the soil hydraulic properties obtained by the BEST procedure, and by alternative indirect methods, with independently measured properties, notwithstanding that direct measurement of water retention and hydraulic conductivity of Burundian soils is still very complicated and comparing different methods is often difficult and imprecise. Taking into account that water retention curve parameters may differ between temperate and tropical soils, the indirect approach used in BEST to estimate shape parameters from the measured PSD should be specifically tested in tropical soils.

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Appendix F: A test of the Beerkan Estimation of Soil Transfer parameters (BEST) procedure

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ABSTRACT

The Beerkan Estimation of Soil Transfer parameters (BEST) procedure is attractive for a simple soil hydraulic characterization but testing the ability of this procedure to estimate soil properties is necessary. The BEST predictions were compared with soil water retention and hydraulic conductivity data measured in the laboratory and the field, respectively, at ten Sicilian field sites. Provided that BEST yielded physically possible scale parameters of the soil characteristic curves in most of the four replicated infiltration runs at a site, the measured water retention was satisfactorily predicted (i.e., not statistically significant differences between measurements and predictions, significant correlation between the data, regression line not significantly different from the identity one) when i) the infiltration run was relatively short (11 applied volumes of water); ii) the *n* shape parameter of the water retention curve was estimated on the basis of the measured sand and clay content of the soil; and iii) the saturated soil water content, θ_s, was set equal to 93% of the porosity. Possible field saturated soil hydraulic conductivity values were also obtained, although some trace of soil disturbance by the infiltration run was detected. The predicted unsaturated soil hydraulic conductivity was higher than the measured one, probably because the unimodal hydraulic conductivity function used in BEST does not reproduce the changes in the pore system of a real soil in the pressure head range close to saturation. It was concluded that BEST is promising to simply yield a reasonably reliable soil hydraulic characterization. An improved description of the unsaturated hydraulic conductivity function is desirable.

Keywords: BEST (Beerkan Estimation of Soil Transfer parameters) procedure; Soil water retention; Soil hydraulic conductivity; Simplified Falling Head technique; Tension infiltrometer method.

INTRODUCTION

Determining the relationships between soil water pressure head, *h*, volumetric water content, θ, and hydraulic conductivity, *K*, allows to interpret and numerically simulate soil hydrological processes. These hydraulic characteristic curves are generally determined with laboratory and field methods differing by accuracy and experimental efforts.

Lassabatère et al. (2006) proposed to estimate the θ(*h*) and *K*(θ) curves with the Beerkan Estimation of Soil Transfer parameters (BEST) procedure, using an infiltration experiment in the field with a zero pressure head on a circular soil surface and a few basic soil physical determinations (particle size distribution, PSD, bulk density, and initial and final water content).

BEST is receiving increasing attention by the scientific community since it allows an experimentally simple hydraulic characterization of unsaturated soils. For example, Mubarak et al. (2009a) used the Beerkan infiltration method to characterize temporal variability of soil hydraulic properties under high-frequency drip irrigation, and Mubarak et al. (2009b) used the collected data to decide whether or not the changes in the topsoil parameters over the course of a cropping season should be taken into account to simulate water transfer processes. Mubarak et al. (2010) used the Beerkan method to review the soil hydraulic properties of the field sampled in 1990 by Vauclin et al. (1994), after 17 years of repeated agricultural practices. Lassabatère et al. (2010) used BEST to study the effect of sediment accumulation on the water infiltration capacity of two urban infiltration basins located on two different subsoils. Gonzalez-Sosa et al. (2010) applied BEST to document the spatial variability of the water retention and soil hydraulic conductivity curves within a watershed of 7 km^2. A characterization of the unsaturated hydraulic properties of basin oxygen furnace slag based on Beerkan water infiltration experiments was carried out by Yilmaz et al. (2010). The hydraulic properties of some Burundian soils, that are difficult to characterize with other laboratory and field experimental procedures, were determined by Bagarello et al. (2011).

Investigations focused on BEST procedures were also carried out. They include, for example, the estimation of the water retention shape parameter (Minasny and McBratney, 2007), the fitting accuracy of the BEST PSD model to the data (Bagarello et al., 2009), the algorithm to analyze the infiltration data (Yilmaz et al., 2010), the constraint on the duration of the infiltration run (Bagarello et al., 2011). More recently, Xu et al. (2012) suggested that the applicability of the method may become questionable in wet conditions, due to a poor fitting performance of the cumulative infiltration curve. Bagarello and Iovino (2012) suggested that determining the soil textural characteristics before the BEST experiment may be an effective means to preliminarily establish if the expected performances of the water retention and particle size models are good or there is the possibility of a poor description of the water retention data. These authors also suggested that, for a general use of BEST, the Minasny and McBratney (2007) procedure should be preferred to estimate the water retention shape parameter as compared with other procedures, including the original one. It should be noted that field validation of BEST was not carried out by Bagarello and Iovino (2012) since these authors focused their investigation on the reliability of the pedotransfer model used by BEST to estimate the water retention curve. According to Nasta et al. (2012), the tortuosity parameter, *p*, is relatively insignificant compared to the β and γ infiltration constants that should be specifically calibrated for each soil type.

The large interest for the BEST procedure justifies comparisons of the predicted soil properties with independent measurements, i.e. with soil data collected by other experimental methods. These comparisons are important for many reason. The most obvious is to establish if the simplified method is a practical alternative to more cumbersome and time consuming methods. Another reason is that they allow to detect points in the indirect procedure needing specific adjustments or developments. For example, the duration of the infiltration run is an issue to be considered taking into account that a long (L) run can theoretically be expected to yield a more reliable estimate of steady-state infiltration rate than a short (S) run at the expense, in practice, of more appreciable deterioration phenomena of the infiltration surface. An extensive assessment of the BEST predictions against alternative methods has still to be carried out, although some contributions can now be found in the literature. For example, field and laboratory measurements of saturated soil hydraulic conductivity were generically found to be of the same order of magnitude in the investigation by Yilmaz et al. (2010).

The objective of this investigation was to test the applicability of the BEST procedure at the near point scale, i.e. within an area of a few square meters, in different Sicilian soils. At this aim, the predicted soil hydraulic parameters were used to establish a comparison with laboratory measured water retention data and field measured saturated and unsaturated soil hydraulic conductivities.

MATERIALS AND METHODS

Field sites, soil sampling and soil parameters calculations

Ten sites located in western Sicily, showing appreciable differences in both soil texture and land use (**Table 1**), were sampled in the second half of 2010.

For a given site, having an area of approximately 25 m^2, eight undisturbed soil cores

Table 1. General characteristics of the sampled sites

Site code	Soil use	Clay (%)	Silt (%)	Sand (%)	Soil textural class	Dry soil bulk density (Mg m^{-3})	Organic matter content (%)
AGR1	Citrus orchard	15.9	27.2	56.9	Sandy loam	1.079	4.5
AGR2	Citrus orchard	19.2	32.5	48.3	Loam	1.195	3.5
CACC	Annual crops	34.6	45.8	19.6	Silty clay loam	1.208	1.5
COR1	Vineyard	49.6	33.2	17.3	Clay	1.140	2.8
COR2	Annual crops	57.1	30.7	12.2	Clay	1.302	1.4
COR3	Vineyard	49.0	35.3	15.7	Clay	1.155	2.0
COR4	Orchard	52.6	35.8	11.6	Clay	1.198	2.1
COR5	Olive grove	17.3	30.5	52.3	Sandy loam	1.328	1.9
SPA1	Orchard	11.6	22.2	66.2	Sandy loam	1.419	0.5
SPA2	Orchard	22.0	19.7	58.2	Sandy clay loam	1.493	0.5

The clay, silt, sand, dry soil bulk density, and organic matter percentages are the means of the replicated measurements taken at four different sampling points within the site.

(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 in four randomly selected points. Four disturbed soil samples (0-0.10 m depth) were also collected. The undisturbed soil cores were used to determine in the laboratory the dry soil bulk density, ρ_b (Mg m^{-3}). The disturbed soil was used to determine the particle size distribution (PSD) and the clay (*cl*), silt (*si*) and sand (*sa*) percentages according to the USDA standards (Gee and Bauder, 1986). The organic carbon, *OC* (%), content measured by the Walkley-Black method was converted to organic matter, *OM* (%), content using the factor of conversion of 1.72.

At each site, four infiltration runs of the BEST (Lassabatère et al. 2006) type were carried out at randomly chosen sampling points using a ring with an inner diameter of 0.30 m, inserted to a depth of about 0.01 m to avoid lateral loss of the ponded water. A known volume of water (800 mL) was poured in the cylinder at the start of the measurement and the elapsed time during the infiltration was measured. When the amount of water had completely infiltrated, an identical amount of water was poured into the cylinder, and the time needed for the water to infiltrate was logged. The procedure was repeated until the difference in infiltration time between three consecutive trials became negligible, signaling a practically steady-state infiltration. A similar criterion (i.e., two consecutive identical infiltration times) was considered in a similar experiment by Mubarak et al. (2009a). An experimental cumulative infiltration, I (L), vs. time, t (L), relationship including N_{tot} discrete points, N_{tot} being the number of collected (t, I) data points ($14 \leq N_{tot} \leq 38$, depending on the run; mean = 23), was then deduced. In the following, these runs were denoted as long (L). The original BEST procedure by Lassabatère et al. (2006) was applied to calculate the soil hydraulic parameters of the van Genuchten (1980) water retention curve with the Burdine (1953) condition and the Brooks and Corey (1964) hydraulic conductivity function, i.e. the n, m and η shape parameters and the h_g, θ_s and K_s scale parameters. The more recent version of BEST developed by Yilmaz et al. (2010) was not considered in this investigation because it does not allow to obtain negative K_s values, that can be viewed as a sign of a locally poor performance of the BEST procedure. The BEST experiment was considered successful when it allowed a complete soil hydraulic characterization according to the original procedure by Lassabatère et al. (2006). For each site, a representative PSD was obtained by averaging the four individual PSDs, taking into account that soil sampling for textural characterization was carried out in randomly selected locations within the experimental area. A mean value of both the soil water content at the time of the infiltration run, θ_i, and the dry soil bulk density was similarly calculated and used to apply BEST. Therefore, each site was assumed to be homogeneous in terms of PSD, θ_i, ρ_b, and estimated soil porosity, ϕ. According to Mubarak et al. (2009a), BEST was applied by assuming $\theta_s = 100\%\phi$ but calculations were repeated by using alternative estimates of both θ_s and n. In particular, $\theta_s = 85\%\phi$ (Mubarak et al., 2009b) and $\theta_s = 93\%\phi$ (Somaratne and Smettem, 1993) were also considered. The procedure developed by Minasny and McBratney (2007) to estimate the BEST n parameter from the soil sand, *sa* (%, USDA classification), and clay, *cl* (%), content was also applied. According to Lassabatère et al. (2006), pouring a given volume of water on the infiltration surface should be repeated 8 to 15 times. In this investigation, more volumes were generally used for a given run (23, on average) in an attempt to improve estimation of steady-state

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infiltration rate. The effect of the number of the applied water volumes on the soil characterization by BEST was taken into account by considering the first 11 data points of each measured infiltration curve (i.e., approximately a mean value between 8 and 15) and repeating all calculations. In the following, these infiltration runs were denoted as short (S).

Four random points were sampled to determine K_s by the Simplified Falling Head (SFH) technique (Bagarello et al., 2004) using 0.30 m diam. rings inserted into the soil to a depth of 0.12 m ($K_{s,SFH}$). An estimate of the so-called α^* parameter equal to 12 m^{-1}, i.e. the value of first approximation according to Elrick and Reynolds (1992), was used to estimate K_s with eq,(15) by Bagarello et al. (2004). A tension infiltrometer (TI) having a 0.24 m diam. base plate unit was also applied at four randomly selected sampling points for a given site. A multipotential experiment was carried out applying an ascending sequence of pressure heads, h_0 (L), at the soil surface (-120, -60, -30 and -10 mm). Soil hydraulic conductivity at the imposed pressure heads (K_{-120}, K_{-60}, K_{-30}, K_{-10}) was calculated with the procedure developed by Ankeny et al. (1991), using the estimated steady-state infiltration rates. Additional details on the SFH and TI runs were reported by Bagarello et al. (2012, 2013), since these data were also used to test ring size effects on field saturated soil hydraulic conductivity measured by the SFH technique and in a comparison between the SFH and single ring pressure infiltrometer techniques.

The water retention curve at high pressure heads ($h \geq -1.5$ m) was determined on four replicated soil cores randomly collected at each site in stainless steel cylinders (inner diameter = 0.08 m, height = 0.05 m). For low pressure heads ($h \leq -3$ m), four replicated samples, obtained by packing sieved soil in rings having an inside diameter of 0.05 m and a height of 0.01 m to the mean ρ_b value of the undisturbed cores, were used. The experimental methodologies described in detail by Bagarello and Iovino (2012) were also applied in this investigation to obtain volumetric water retention data for h values of -0.05, -0.1, -0.2, -0.4, -0.7, -1.2, -3.37, -10.2, -30.6 and -153.0 m.

For a given site, data were summarized by calculating the arithmetic (cl, si, sa, ρ_b, OM, water retention) or the geometric (soil hydraulic conductivity, h_g parameter) mean and the associated coefficient of variation, CV.

Data analysis

The water retention curve and the hydraulic conductivity function of a site were estimated by considering 12 alternative BEST scenarios differing by i) the duration of the infiltration run (L or S); ii) the assumed θ_s value (θ_s = 100%ϕ, code 100; θ_s = 93%ϕ, code 93; θ_s = 85%ϕ, code 85); and iii) the calculation procedure of the n parameter (according to Lassabatère et al. (2006), code LA, or Minasny and McBratney (2007), code MM). As an example, the scenario L100MM indicated that the long runs were used, θ_s = 100%ϕ was assumed, and n was estimated according to Minasny and McBratney (2007). Taking into account that the n estimation procedure did not affect the K_s values obtained by BEST ($K_{s,B}$), six sets of $K_{s,B}$ data were obtained in this investigation. As an example, the scenario S85 denoted the saturated conductivity data obtained with the short runs and a saturated soil water content equal to 85% of the porosity, because the same $K_{s,B}$ values were obtained with the S85LA and S85MM scenarios.

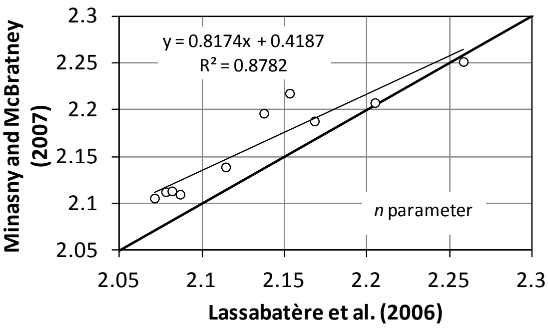
For a given scenario, the measured water retention data were compared with the θ values predicted by BEST. This comparison was carried out by calculating the root mean square error, $RMSE$, and establishing the statistical significance of the differences between the measured and predicted θ values by a two-tailed paired t test (P = 0.05). A linear regression analysis between the two data sets was also carried out. The statistical significance of the correlation coefficient, R, was assessed by a one-tailed t test (P = 0.05). The 95% and 99.9% confidence intervals for the intercept and the slope of the linear regression line were calculated.

As shown later, this analysis allowed to find an application procedure of BEST yielding reliable predictions of $\theta(h)$, i.e. close to the data obtained in the laboratory, for a group of sites. Therefore, the results obtained by the most reliable applicative scenario were further analyzed to also make a test of the soil hydraulic conductivity predictions. In particular, a linear regression analysis of $\ln(K_{s,B})$ against the mean cl, si, sa, ρ_b and OM values was established and the consistency between the TI and BEST techniques was evaluated. This analysis was repeated with the $K_{s,SFH}$ data for comparative purposes. In addition, a comparison between $\ln(K_{s,B})$ and $\ln(K_{s,SFH})$ was carried out at each site. The K_{-10}, K_{-30}, K_{-60} and K_{-120} data obtained by the TI were finally compared with the corresponding values predicted by BEST.

RESULTS AND DISCUSSION

The two applied procedures to determine the *n* parameter (Lassabatère et al., 2006; Minasny and McBratney, 2007) yielded significantly correlated values (R^2 = 0.88, R > 0, N = 10) that were generally higher with the Minasny and McBratney (2007) procedure (**Figure 1**). However, the 95% confidence intervals for the intercept (-0.112 – 0.949) and the slope (0.569 – 1.066) suggested a statistical coincidence of the regression line with the identity one.

Figure 1. Comparison between the estimates of the *n* shape parameter of the water retention curve obtained with the procedures by Lassabatère et al. (2006) and Minasny and McBratney (2007)



For both the long (L) and the short (S) infiltration runs, the success rate of the BEST procedure varied with the assumed θ_s but not with the *n* estimating procedure (**Table 2**). In particular, the highest success rate was detected for θ_s = 100%ϕ whereas the highest failure rate was obtained for θ_s = 85%ϕ. Therefore, a result of this investigation was that the choice of θ_s influenced the success of the BEST experiment. Another factor affecting this success was the duration of the infiltration run. In particular, a lower success rate was obtained with the longer run (**Table 2**) although at least a valid result (i.e., an estimate of the water retention curve and the hydraulic conductivity function) for each sampled site was obtained only in this case. With the shorter runs, the total success rate increased but soil characterization failed at two sites (COR1 and COR2).

At first, a comparison between the measured and the BEST predicted water retention data was carried out by considering the L runs and all sites (N = 96 water retention values, **Table 3**). For each considered scenario, the mean of the measured θ values differed significantly from the mean of the corresponding estimates, the two data sets were significantly correlated but the regression line did not coincide with the identity one. In terms of mean and RMSE, the best results were obtained with the L85MM scenario whereas the L100MM one performed better in terms of both R^2 and closeness of the linear regression line to the identity one. For each assumed θ_s value, the MM scenario was better than the LA one (estimated mean closer to the measured one; linear regression line closer to the identity one).

The comparison between the measured and the predicted water retention data was repeated by considering the S infiltration runs and the eight sites yielding at least a valid soil characterization with BEST (N = 76). Also in this case, the two data sets were significantly correlated. In addition, some sign of a satisfactory correspondence between the predicted and the measured θ values was detected (**Table 3**). In particular, the mean of the measurements was close to, and not significantly different from, the mean of the corresponding estimates obtained by the S85LA scenario. The linear regression line between the two θ data sets did not differ significantly from the identity one, according to the calculated 99.9% confidence intervals for the intercept and the slope, when the S100MM scenario was chosen to apply BEST.

The L runs were preferable as compared

Table 2. Infiltration runs yielding a successful determination of scale parameters according to the BEST methodology for the 12 considered scenarios

Site	L100LA and L100MM	L93LA and L93MM	L85LA and L85MM	S100LA and S100MM	S93LA and S93MM	S85LA and S85MM
AGR1	3	3	3	3	3	3
AGR2	1	1	1	4	4	4
CACC	3	3	3	4	3	2
COR1	3	2	1	0	0	0
COR2	1	1	1	0	0	0
COR3	1	1	1	2	2	1
COR4	3	2	2	4	4	4
COR5	1	1	1	4	4	3
SPA1	4	4	4	4	4	4
SPA2	4	4	3	4	3	2
Total	**24**	**22**	**20**	**29**	**27**	**23**

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Table 3. Statistics of the comparison between the measured water retention values and the corresponding ones predicted by the BEST procedure for the twelve considered scenarios, and assuming that a single valid BEST infiltration run was enough to characterize a site

Statistic	Scenario											
	L100LA	**L100MM**	**L93LA**	**L93MM**	**L85LA**	**L85MM**	**S100LA**	**S100MM**	**S93LA**	**S93MM**	**S85LA**	**S85MM**
Sample size	96	96	96	96	96	96	76	76	76	76	76	76
Measured mean	0.349	0.349	0.349	0.349	0.349	0.349	0.340	0.340	0.340	0.340	0.340	0.340
Estimated mean	0.425s	0.408s	0.403s	0.388s	0.381s	0.370s	0.393s	0.375s	0.370s	0.354s	0.337ns	0.323s
RMSE	0.094	0.076	0.081	0.065	0.075	0.064	0.075	0.056	0.060	0.043	0.056	0.048
Intercept	0.1336	0.0829	0.1423	0.0972	0.1557	0.1179	0.0861	0.0392	0.0865	0.043	0.0795	0.0402
Slope	0.8333	0.9313	0.7455	0.8341	0.6446	0.7218	0.9031	0.9893	0.8351	0.9159	0.7592	0.8329
R^2	0.8152	0.8730	0.7919	0.8448	0.7510	0.7997	0.8529	0.906	0.8592	0.91	0.8353	0.8956
95% confidence	0.103-	0.056-	0.113-	0.070-	0.127-	0.090-	0.054-	0.012-	0.058-	0.019-	0.051-	0.016-
interval	0.164,	0.110,	0.172,	0.125,	0.184,	0.146,	0.118,	0.066,	0.115,	0.067,	0.108,	0.064,
(intercept	0.752-	0.859-	0.667-	0.761-	0.569-	0.648-	0.816-	0.915-	0.757-	0.849-	0.681-	0.767-
and slope)	0.915	1.004	0.824	0.907	0.721	0.796	0.990	1.063	0.913	0.983	0.837	0.899
99.9% confidence	0.082-	0.036-	0.092-	0.050-	0.107-	0.071-	0.031-	-0.007-	0.037-	0.001-	0.030-	-0.001-
interval	0.186,	0.129,	0.192,	0.144,	0.204,	0.165,	0.141,	0.086,	0.136,	0.085,	0.129,	0.082,
(intercept	0.694-	0.807-	0.612-	0.709-	0.515-	0.595-	0.754-	0.862-	0.700-	0.801-	0.625-	0.720-
and slope)	0.972	1.056	0.879	0.959	0.775	0.848	1.052	1.116	0.970	1.031	0.893	0.946

RMSE: Root Mean Square Error. R^2: coefficient of determination. *s*: statistically significant difference. *ns*: not statistically significant difference.

to the S ones because all sites were characterized by at least a successful run only in the former case. On the other hand, choosing a relatively short run had other advantages including a higher success rate as the whole and the possibility to find application scenarios allowing a partially satisfactory agreement between the measured and the predicted data. However, none of the twelve considered scenarios was fully satisfactory (i.e., not statistically different means, significant correlation, regression line not significantly different from the identity one). More clearly, this analysis suggested that short runs should be carried out instead of long runs to better reproduce the measured θ, although some sites can be lost in this case. Moreover, a clear superiority of one of the two *n* estimating procedures or one of the three estimates of θ_s was not detectable with the S runs.

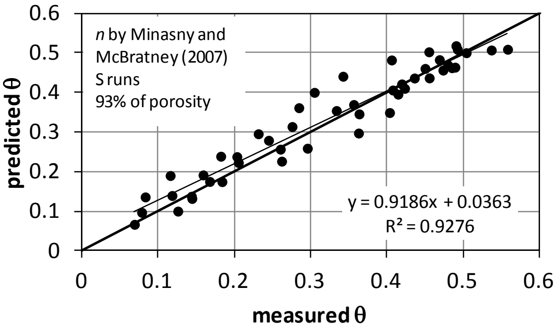
A possible reason of the relatively unsatisfactory prediction of θ by BEST was thought to be a low reliability of the indirect soil characterization for a site yielding a relatively high number of failures with the BEST calculations. In other terms, it was hypothesized that a single success out of four attempts was not enough to properly characterize the field site. Therefore the measured vs. predicted θ comparison was repeated by applying a more restrictive criterion, i.e. by selecting the sites where the scale parameters were averaged on the basis of at least three positive results out of four infiltration runs. This implied considering four sites with the L runs (AGR1, CAC, SPA1 and SPA2, *N* = 39) and five sites with the S runs (AGR1, AGR2, COR4, COR5, and SPA1, *N* = 47). In this case, a satisfactory condition was detected (**Table 4**) given that the S93MM scenario allowed to obtain a mean prediction of θ that was not significantly different from the measured value, a significant correlation between the two data sets, and a regression line not significantly different from the identity one, although only according to the 99.9% confidence intervals for the intercept and the slope (**Figure 2**).

Table 4. Statistics of the comparison between the measured water retention values and the corresponding ones predicted by the BEST procedure for the twelve considered scenarios, and assuming that three or more valid BEST infiltration runs were necessary to characterize a site

Statistic	Scenario											
	L100LA	**L100MM**	**L93LA**	**L93MM**	**L85LA**	**L85MM**	**S100LA**	**S100MM**	**S93LA**	**S93MM**	**S85LA**	**S85MM**
Sample size	39	39	39	39	39	39	47	47	47	47	47	47
Measured mean	0.314	0.314	0.314	0.314	0.314	0.314	0.322	0.322	0.322	0.322	0.322	0.322
Estimated mean	0.372s	0.356s	0.356s	0.343s	0.338s	0.328ns	0.367s	0.346s	0.351s	0.332ns	0.322ns	0.307s
RMSE	0.081	0.062	0.071	0.054	0.063	0.049	0.069	0.044	0.060	0.039	0.062	0.050
Intercept	0.0928	0.054	0.1011	0.0659	0.1065	0.0749	0.077	0.0282	0.0814	0.0363	0.0777	0.0374
Slope	0.8876	0.961	0.8111	0.8808	0.7383	0.8049	0.9001	0.9858	0.837	0.9186	0.7595	0.8356
R^2	0.8286	0.8911	0.8214	0.8816	0.8231	0.8866	0.8659	0.936	0.8652	0.9276	0.815	0.889
95% confidence	0.047-	0.016-	0.058-	0.029-	0.067-	0.042-	0.040-	0.00095-	0.046-	0.009-	0.039-	0.006-
interval	0.139,	0.093,	0.144,	0.103,	0.145,	0.108,	0.114,	0.055,	0.116,	0.063,	0.116,	0.069,
(intercept	0.753-	0.849-	0.685-	0.773-	0.624-	0.709-	0.794-	0.908-	0.738-	0.842-	0.651-	0.747-
and slope)	1.022	1.073	0.937	0.988	0.852	0.901	1.006	1.063	0.936	0.996	0.858	0.924
99.9% confidence	0.012-	-0.013-	0.025-	0.001-	0.038-	0.017-	0.012-	-0.019-	0.020-	-0.011-	0.011-	-0.017-
interval	0.174,	0.122,	0.177,	0.131,	0.175,	0.133,	0.142,	0.076,	0.142,	0.084,	0.145,	0.092,
(intercept	0.650-	0.764-	0.589-	0.691-	0.537-	0.636-	0.714-	0.851-	0.664-	0.784-	0.570-	0.681-
and slope)	1.125	1.158	1.033	1.070	0.939	0.974	1.086	1.121	1.010	1.053	0.949	0.991

RMSE: Root Mean Square Error. R^2: coefficient of determination. *s*: statistically significant difference. *ns*: not statistically significant difference.

Figure 2. Comparison between the measured water retention data, θ, and the corresponding ones predicted by BEST with the S93MM scenario for the AGR1, AGR2, COR4, COR5 and SPA1 sites (sample size, N = 47)



According to Lassabatère et al. (2006), a relative error, Er, calculated with their eq.(26), not exceeding 5.5% denotes a satisfactory fitting ability of the infiltration model to the data. For the 19 infiltration runs considered with the S93MM scenario, the mean and the median of Er were equal to 5.3 and 3.6%, respectively, but a few high Er values, i.e. up to 12%, were also obtained. On the basis of these results, a satisfactory correspondence between the predicted and the measured θ values was associated with an infiltration model well describing the data on average. This correspondence was not adversely affected by an occasionally poor fitting of the model to the data.

Therefore, this investigation suggested that the θ predictions obtained by BEST should be expected to be similar to the directly measured data when most replicates of the infiltration run for a given field site are successful within a small range of plausible θ_s values, which can be viewed as a sign of a reasonably reliable soil hydraulic characterization performed with BEST. In addition, the infiltration run has to be relatively short, according to the original procedure by

Table 5. Geometric mean and associated coefficient of variation, CV, of the field saturated hydraulic conductivity values, in mm h^{-1}, obtained with the SFH technique ($K_{s,SFH}$) and the BEST procedure of soil hydraulic characterization ($K_{s,B}$)

Site	Statistic	$K_{s,SFH}$	$K_{s,B}$
AGR1	Mean	1977.6 (a)	406.7 (a)
	CV (%)	20.2	12.8
AGR2	Mean	1021.4 (a)	45.3 (a)
	CV (%)	27.4	97.7
COR4	Mean	1822.2 (a)	28.2 (a)
	CV (%)	18.7	74.0
COR5	Mean	309.8 (a)	20.1 (a)
	CV (%)	153.9	533.2
SPA1	Mean	83.9 a	48.8 a
	CV (%)	53.2	41.5

For a given site, values followed by the same letter enclosed in parenthesis are significantly different according to a two-tailed t test (P = 0.05). Values followed by the same letter not enclosed in parenthesis are not significantly different.

Lassabatère et al. (2006), the n parameter has to be estimated with the relationship developed by Minasny and McBratney (2007), and the saturated water content has to be assumed equal to 93% of total porosity. We believe that this result has practical importance because, to our knowledge, this was the first time (or one of the first times) that a check of the BEST procedure with other measured water retention data was carried out. Obviously, there is the need of additional confirmations with other datasets. Maybe, the superiority of the short runs over the long ones could be indicative of the fact that an increasing number of water applications on the infiltration surface determined more appreciable soil structure alteration phenomena. This issue should be developed in the future, also by testing alternative water application procedures allowing to steadily maintain a constant, small depth of water on the infiltration surface.

The check of the soil hydraulic conductivity data obtained with BEST was carried out by considering the S93 (saturated conductivity)/S93MM (unsaturated conductivity) scenario and the AGR1, AGR2, COR4, COR5 and SPA1 sites since water retention data were reproduced satisfactorily in this case.

The linear regression analysis of ln($K_{s,B}$) (S93 scenario, N = 5) against cl, si, sa, ρ_b and OM yielded correlation coefficients that were never statistically significant ($R^2 \leq 0.444$). However, stronger correlations were obtained with the structural variables (ρ_b and OM, $R^2 \geq 0.409$) than the textural ones (cl, si, sa, $R^2 \leq 0.151$) and the dependent variable increased with an increase in OM and a decrease in ρ_b. The same analysis was carried out for the SFH results to test the suitability of $K_{s,SFH}$ for a check of $K_{s,B}$. In this case, ln($K_{s,SFH}$) increased with OM (R^2 = 0.687), did not vary with cl (R^2 = 0.295), si (R^2 = 0.301) and sa (R^2 = 0.366), and decreased with ρ_b (R^2 = 0.903). These results were physically plausible according to the existing literature (e.g., Agnese et al., 2011), and they yielded an additional support to the use of the SFH technique for measuring K_s.

The $K_{s,SFH}$ values were higher than the $K_{s,B}$ ones by a factor varying with the site from 1.7 (at SPA1) to 64.7 (at COR4) and the differences were statistically significant with the single exception of SPA1 (**Table 5**). Both $K_{s,SFH}$ and $K_{s,B}$ were higher than K_{-10}, although in three of the five cases, the BEST/TI combination suggested a very small decrease in K in the pressure head range 0 to -10 mm that was not fully convincing (**Figure 3**).

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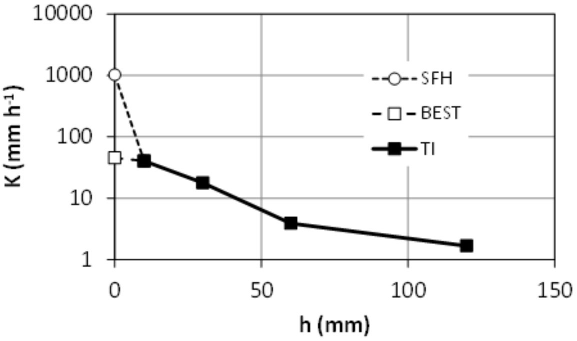
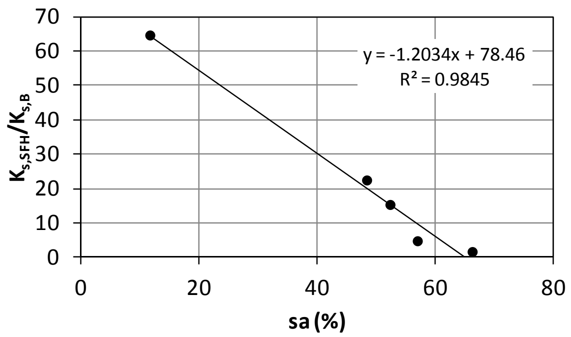
Figure 3. Soil hydraulic conductivity function obtained experimentally at the AGR2 site



The ratio between $K_{s,SFH}$ and $K_{s,B}$, representing the difference between the two measurement methods of K_s, was independent of both ρ_b and *OM* ($R^2 \leq 0.060$), increased with the percentage of fine particles (*cl* and *si*, R^2 = 0.732-0.963) and decreased with the *sa* content (R^2 = 0.985, **Figure 4**). Reasonably, the BEST experiment perturbed the soil surface more appreciably than the SFH experiment because relatively large water volumes (800 mL) were repeatedly applied on the soil surface only in the former case. Therefore, it was supposed that the differences between the two techniques were less substantial in soils with a high sand content because these soils were less sensitive to disturbance phenomena promoted by water application. A partial and indirect support to this conclusion was given by the relationship of ln($K_{s,SFH}$) and ln($K_{s,B}$) against the soil structural index, *SSI*, by Pieri (1992) (Reynolds et al., 2009; Bagarello et al., 2013). In both cases a nonstatistically significant increasing relationship was detected but the coefficient of determination was appreciably higher for the BEST data (0.629) than the SFH ones (0.396). In other terms and with some caution, this last analysis suggested that structurally unstable soil conditions favored detection of relatively low K_s values particularly

Figure 4. Ratio between the field saturated soil hydraulic conductivity values obtained by the SFH technique ($K_{s,SFH}$) and the BEST procedure ($K_{s,B}$) plotted against the sand content (*sa*)



with the BEST procedure. Another possible reason of the lower K_s data obtained with BEST was air entrapment in the sampled soil volume during the infiltration run (Reynolds, 1993; Mertens et al., 2002) because, according to the prescribed procedure (Lassabatère et al., 2006), a new volume of water was applied when the previously poured one had completely infiltrated. In other terms, water ponding conditions were not perfectly maintained during the entire infiltration process. It should also be noted that a different estimate of θ_s was used with the SFH (θ_s = 100%ϕ, according to Bagarello et al., 2004) and BEST (θ_s = 93%ϕ, according to the developed procedure in this investigation) methodologies. Therefore, another factor influencing the detected discrepancies was the choice of θ_s because lower $K_{s,SFH}$ values are calculated for a smaller θ_s. However, this last factor had only a minor effect on the detected differences between the two estimates of K_s because a variation of $\pm$10% in $\Delta\theta = \theta_s - \theta_i$ yields a -9.0 to +11.0% variation in the predicted $K_{s,SFH}$ (Bagarello et al., 2004). Other possible factors affecting the $K_{s,SFH}$ vs. $K_{s,B}$ comparison include different flow dimensionality between the two techniques (1D for SFH, 3D for BEST), more soil compaction with the ring insertion for the SFH test and the choice of the α^* value for the SFH calculations. However, these factors were not considered to alter appreciably the comparison between the two estimates of K_s because i) ring infiltrometers measure mainly vertical soil water transmission parameters (Reynolds and Elrick, 2005); ii) ring compaction effects by the SFH technique procedures were excluded in an investigation on a sandy loam soil (Bagarello et al., 2009) and, in any case, the occurrence of these phenomena implies measurement of lower values than the actual ones and hence a confirmation of the $K_{s,SFH} > K_{s,B}$ result; and iii) an incorrect choice of α^* by a category among the ones listed by Elrick and Reynolds (1992) implies a change in the calculated $K_{s,SFH}$ value by a factor of two or three. Not even a hypothetical error of this level modifies the conclusion that the SFH technique showed in general a tendency to yield higher K_s values as compared with BEST.

Therefore, this investigation did not yield unexpected or even impossible $K_{s,B}$ results (such as, for example, $K_{s,B}$ increasing with ρ_b or $K_{s,B} < K_{-10}$) and the differences with the SFH data were physically explainable. Another way to summarize these results is that an applicative procedure of BEST yielding a satisfactory prediction of water retention data also gave possible K_s values, showing however some trace of soil disturbance by the infiltration run.

BEST with the S93MM scenario yielded unsaturated hydraulic conductivities higher than the TI by a mean factor (i.e., calculated with reference to the AGR1, AGR2, COR4, COR5 and SPA1 sites) that monotonically increased from 4.5 for a pressure head, h, of -10 mm to 15.7 for h = -120 mm. Therefore, the two data sets differed by even more than an order of magnitude and they were more similar for high pressure heads.

These differences were probably attributable to the different experimental information used by the two approaches to determine the unsaturated soil hydraulic conductivity, K. With the TI, the conductivity corresponding to a given (negative) pressure head is calculated on the basis of a measured infiltration process that physically excludes the largest, structural pores. In other words, the collected data are representative of the pore system really governing the flow process for the given pressure head. With BEST, only a field saturated infiltration process is established and this implies that the experimental data are expressive of the contribution of all pores in the sampled soil volume, including the structural ones, to flow transport. The analytical assumption of BEST is that these data are representative of a soil without a structural, rapidly emptying, porosity, but this hypothesis is not true in aggregate, real soils (Coppola, 2000). This is a limit of the current version of BEST, that has also recognized by Nasta et al. (2012). Therefore, it seems reasonable to suggest that BEST predicted a slower decrease in K for more negative pressure heads than the actual one because the assumed hydraulic conductivity function does not reproduce the changes in the pore system of a real soil in the pressure head range close to saturation.

Developing an applicative methodology of BEST allowing a good reproduction of the measured water retention data and plausible K_s values was not enough to also obtain reasonably reliable predictions of K, especially under more unsaturated conditions. Improvements of the BEST procedure seem necessary and they should be aimed to improve the representation of the pore system near saturation. From an experimental point of view, using the TI in conjunction with BEST might be a choice to be considered, because the TI allows to directly obtain K data that exclude macropore effects from the flow process. This is clear in the literature, that also reports data on the pressure head that should be established to avoid the macropore contribution. For example, Jarvis and Messing (1995) suggested that macropores are excluded from the flow process when the pressure head varies between -25 and -60 mm, depending on the soil. According to Topp et al. (1997), the saturated hydraulic conductivity of the soil matrix has to be considered the conductivity corresponding to a pressure head of approximately -30 to -100 mm. Therefore, the saturated conductivity of the soil matrix seems measurable with the TI. An obvious disadvantage of the additional measurements with the TI would be a more complicated experiment in the field as compared with the original one. In other words, one of the most important advantages of the BEST procedure, i.e. the simplicity of the experiment, would be lost or reduced. Perhaps, a way to mitigate this additional complication could be performing a test (or a few tests) with the easily portable and simply usable mini disk infiltrometer (Decagon Devices Inc., Pullman, WA), that was already applied in conjunction with the BEST procedure by other Authors (Gonzalez-Sosa et al., 2010).

The water retention and unsaturated soil hydraulic conductivity data used in this investigation to establish a comparison with the BEST predictions were collected with standard and largely used laboratory and field methods. Therefore, these comparisons, carried out on other soils, may allow to establish the suitability of BEST to reproduce soil data obtained with standard, but experimentally more demanding, methodologies. A standard method to measure K_s does not exist (Bouma, 1983; Reynolds et al., 2000) and, especially for this soil hydrodynamic property, the peculiarities of each particular method and application procedure have to be taken into account to establish what kind of information is contained in a method comparison. In particular, the comparison of BEST with the SFH technique has to be viewed as a test of what can happen when two procedures making use of transient infiltration data are applied on an initially unsaturated soil. However, better establishing the potentialities of BEST in terms of K_s predictions needs additional comparisons with other measurement methods. For example, the single ring pressure infiltrometer (PI) method by Reynolds and Elrick (1990) could be considered since both BEST and the PI method establish in the field an infiltration process through a single ring, imply attainment of steady-state flow, and

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they can sample similar soil volumes with runs that could have relatively similar duration.

CONCLUSIONS

In this investigation, the soil of ten Sicilian sites was characterized at the near point scale by replicating all measurements four times for a given site.

The duration of the infiltration run, the assumed saturated soil water content, θ_s, and the calculation procedure of the *n* shape parameter of the water retention curve influenced the water retention predictions by the Beerkan Estimation of Soil Transfer parameters (BEST) procedure of soil hydraulic characterization. A good correspondence of the BEST water retention predictions with laboratory measurements of soil water retained at different pressure heads was detected when the infiltration run was relatively short (11 volumes of water), *n* was estimated on the basis of the measured sand and clay content of the soil and θ_s was set equal to 93% of the estimated porosity. Another requisite for a good correspondence between predicted and measured water retention values was that most replicates of the four infiltration runs for a given field site were successful, i.e. they allowed a complete soil hydraulic characterization by BEST within a small range of plausible θ_s values. Obtaining at least three successful runs out of the four conducted runs improves the representativeness of the soil hydraulic characterization performed with BEST, and it does not complicate appreciably the field work because a few replicated infiltration runs at the near point scale can easily be carried out almost simultaneously.

BEST also yielded plausible field saturated soil hydraulic conductivity, K_s, data, i.e. that were not unexpected or even impossible when the relationships with other soil physical variables were examined and a comparison with the near saturated conductivity measured with the tension infiltrometer (TI) was carried out. The detected discrepancies with the K_s data collected by the independently applied Simplified Falling Head technique were attributed to several factors, including some soil disturbance and air entrapment during the repeated water application necessary to run BEST and to the use of a slightly different estimate of θ_s.

BEST however overestimated the unsaturated soil hydraulic conductivity measured with the TI, especially for the lowest pressure heads. This result was attributed to a limit of the simplified methodology, that uses unimodal parametric relationships to describe the water retention curve and the soil hydraulic conductivity function. Therefore, an applicative methodology of BEST allowing a good reproduction of the measured water retention data and plausible K_s values was not enough to also obtain reasonably reliable predictions of *K*, especially under more unsaturated conditions.

In conclusion, the signs of a promising ability of the BEST procedure to simply yield a reasonably reliable soil hydraulic characterization were clear, but points needing additional developments were also detected. They include factors determining failure of the experiment, possible advantages associated with alternative methodologies of data analysis such as BEST-intercept, and an analytical description of the unsaturated hydraulic conductivity function closer to the real system of conductive pores near saturation. It seems reasonable to suggest that there is still much work to do, also considering that other factors, such as the choice of the β and γ parameters, are expected to affect the BEST predictions but practical estimating procedures of these parameters are still lacking. A joint effort of the researchers working on BEST in different parts of the world could allow to more definitively improve the indirect procedure of soil hydraulic characterization.

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Appendix G: An assessment of the Beerkan method for determining the hydraulic properties of a sandy loam soil

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ABSTRACT

Establishing the ability of the Beerkan Estimation of Soil Transfer parameters (BEST) procedure to reproduce the soil properties is necessary for specific soil types. In this investigation, the BEST predictions for a sandy loam soil were compared with water retention data obtained by a standard laboratory method and with the saturated soil hydraulic conductivity, K_s, obtained by both the Wu et al. (1999) method, applied to the BEST infiltration data, and the Simplified Falling Head (SFH) technique. When the original BEST-slope algorithm with the infiltration constants fixed at $\beta = 1.9$ and $\gamma = 0.79$ was applied, the agreement between the predicted and the measured retention data was satisfactory in terms of similarity of the means, correlation and coincidence between the regression and the identity lines. The prediction of K_s at a sampling point differed by not more than a factor of two from the K_s value obtained by the Wu et al. (1999) method. The SFH technique yielded K_s values approximately five times higher than those of BEST, probably because soil disturbance during water application, swelling and air entrapment phenomena had a lower impact on the measured infiltration data with the former technique. In conclusion, BEST is promising to easily characterize a soil but its applicative methodology should be adapted to the particular situation under consideration. Additional investigations carried out on different soils would allow development of more general procedures to apply BEST.

Keywords: BEST (Beerkan Estimation of Soil Transfer parameters) procedure; Soil water retention; Saturated soil hydraulic conductivity; Simplified Falling Head technique.

INTRODUCTION

The hydraulic characteristic curves, i.e. the relationships between soil water pressure head, h, volumetric water content, θ, and hydraulic conductivity, K, are generally determined with laboratory and field methods differing by accuracy and experimental efforts. The availability of different methods should allow choosing the most appropriate technique for interpreting and simulating a particular hydrological process occurring in a given soil. However, there is also the need to simplify experimental procedures, especially because the economic resources for soil hydraulic characterization are often scarce.

Lassabatère et al. (2006) proposed the Beerkan Estimation of Soil Transfer parameters

(BEST) procedure to easily and rapidly estimate the θ(*h*) and *K*(θ) curves. BEST uses an infiltration experiment in the field with a zero pressure head on a circular soil surface and a few basic soil physical determinations (particle size distribution, PSD, bulk density, and initial and final water content), and it focuses on the van Genuchten (1980) relationship for the water retention curve with the Burdine (1953) condition and the Brooks and Corey (1964) relationship for hydraulic conductivity. Due to its simplicity and the physical soundness of the employed relationships and procedures, BEST is receiving increasing attention by the scientific community. For example, Mubarak et al. (2009a,b) used the method to characterize temporal variability of soil hydraulic properties and to explore the effects of the detected variability on the simulated water transfer processes. Mubarak et al. (2010) reviewed the soil hydraulic properties at a field site after several years of repeated agricultural practices. Lassabatère et al. (2010) established the effect of sediment accumulation on the water infiltration capacity of two urban infiltration basins. Gonzalez-Sosa et al. (2010) determined the spatial variability of the soil hydraulic properties in a small watershed. The unsaturated hydraulic properties of basin oxygen furnace slag were determined by Yilmaz et al. (2010). BEST was the only usable method in areas where more traditional hydraulic characterization methods were technically and economically unaffordable (Bagarello et al., 2011). Investigations specifically focused on BEST procedures were also carried out, including the estimation of the water retention shape parameter (Minasny and McBratney, 2007), the fitting accuracy of the BEST PSD model to the data (Bagarello et al., 2009), the algorithm to analyze the infiltration data (Yilmaz et al., 2010; Bagarello et al., 2014c), the constraint on the duration of the infiltration run (Bagarello et al., 2011), the applicability of the procedure in initially wet soil conditions (Xu et al., 2012), the suitability of the BEST procedures to predict the soil water retention curve (Bagarello and Iovino, 2012), the role of tortuosity and infiltration constants on the results obtained by the Beerkan method (Nasta et al., 2012).

However, only a few comparisons of the predicted soil properties with independent measurements, i.e. with soil data collected by other experimental methods, can still be found in the literature notwithstanding that they have an obvious importance to establish if the simplified method is a practical alternative to more cumbersome and time consuming methods. For example, field and laboratory measurements of saturated soil hydraulic conductivity, K_s, were generically found to be of the same order of magnitude in the investigation by Yilmaz et al. (2010). In a recent investigation conducted by Bagarello et al. (2014b) at ten Sicilian sites sampled at the near point scale (i.e. a few square meters at each site), satisfactory predictions of the measured water retention were associated with a particular applicative methodology of the BEST procedure, including a short infiltration run (i.e., pouring 11 times 800 mL of water on the soil surface confined by a 0.30 m diameter ring), a shape parameter of the water retention curve estimated on the basis of sand and clay content (Minasny and McBratney, 2007), and a saturated soil water content set at 93% of the estimated porosity. Plausible K_s values were also obtained but the unsaturated soil hydraulic conductivity was higher than that measured with the tension infiltrometer method. Therefore, the signs of a promising ability of the BEST procedure to yield a reasonably reliable soil hydraulic characterization can be found but these signs are not enough to arrive at general conclusions. There is still work to do, including more comparisons between predicted and measured soil data for specific soils, also considering that i) real soils can differ also appreciably from the idealized porous media considered by BEST due to, for example, the presence of macropores in field situations, and ii) Nasta et al. (2012) recently suggested that the proper calibration of the infiltration constants as a function of the soil type should be expected to significantly improve the soil hydraulic parameters estimated by BEST.

The objective of this investigation was to test the applicability of the BEST procedure in a sandy loam soil supporting a young orange orchard in eastern Sicily. At this aim, the predicted soil hydraulic parameters were used to establish a comparison with laboratory measured water retention data. A comparison was also carried out in terms of saturated soil hydraulic conductivity obtained with two approaches to analyze the BEST infiltration run and also with the Simplified Falling Head measurement technique by Bagarello et al. (2004).

MATERIALS AND METHODS

The study site is located at the experimental farm of the Sicilian Citrus Research Centre (37°20’ N;

14°53’ E) in eastern Sicily, Italy. The climate of the area is semi-arid Mediterranean, with a mean annual air temperature of 17 °C and a rainfall close to 600 mm in the period 1990-2012. The area, covered by immature orange orchards (6-years old plants), is rectangular, pretty flat, and extends for approximately 0.7 ha (72 × 98 m^2). It was divided into regular grids, each having a 18 × 32 m^2 area, where undisturbed soil cores (0.05 m in height and 0.05 m in diameter) were collected at the 0-0.05 m and 0.05-0.10 m depths for a total of 32 sampling points and 64 soil samples. The undisturbed soil cores were used to determine the soil bulk density, ρ_b (Mg m^{-3}) and the initial water content, θ_i (m^{3}m^{-3}), i.e. the θ value at the time of the field campaign. A total of 32 disturbed soil samples were also collected at the 0-0.05 m depth to determine the soil textural characteristics using conventional methods following H_2O_2 pre-treatment to eliminate organic matter and clay deflocculation using sodium metaphosphate and mechanical agitation (Gee and Bauder, 1986). Three textural fractions according to the USDA standards, i.e. clay (0-2 μm), silt (2-50 μm) and sand (50-2000 μm), were used in the study to characterize the soil (Gee and Bauder, 1986) (**Table 1**). Most soil textures (i.e. 27 out of 32) were sandy loam and the remaining textures were loamy sand. The organic carbon content, *OC* (%), was determined with the Walkey-Black method (Nelson and Sommers, 1996).

Table 1. Clay, *cl*, silt, *si* (2 – 50 μm), and sand, *sa*, percentages, dry soil bulk density, ρ_b, and organic carbon content, *OC*, at the field experimental site (sample size, N = 32 for *cl*, *si*, *sa* and *OC*, and N = 64 for ρ_b)

Variable	Mean	Coefficient of variation (%)
cl (%)	10.4	7.6
si (%)	19.9	3.8
sa (%)	69.7	5.8
ρ_b (Mg m^{-3})	1.25	6.2
OC (%)	1.25	21.8

An undisturbed soil sample was collected from the surface soil layer (0-0.05 m depth) at each sampling location (sample size, N = 32), using stainless steel cylinders with an inner volume of 10^{-4} m^3 to determine the soil water retention curve. For each sample, the volumetric soil water content at 11 pressure heads, h, was determined by a sandbox (h = –0.01, –0.025, –0.1, –0.32, –0.63, –1.0 m) and a pressure plate apparatus (h = –3, –10, –30, –60, –150 m). For each sample, the parameters of the van Genuchten (1980, vG) model for the water retention curve with the Burdine (1953) condition were determined by fitting the following relationship to the data:

$$\frac{\theta-\theta_r}{\theta_s-\theta_r}=\left[1+\left(\frac{h}{h_g}\right)^n\right]^{-m} \tag{1a}$$

$$m=1-\frac{2}{n} \tag{1b}$$

where θ (L^{3}L^{-3}) is the volumetric soil water content, h (L) is the soil water pressure head, n (> 2), and m are shape parameters, and h_g (L), θ_s (L^{3}L^{-3}, field saturated soil water content), and θ_r (L^{3}L^{-3}, residual soil water content) are scale parameters. The fitting was performed by an iterative nonlinear regression procedure, that finds the values of the optimized parameters by minimizing the sum of the squared residuals between the model and the data. This procedure was applied using the SOLVER routine of Microsoft Excel software (Microsoft Company, Redmond, WA, USA). According to the BEST procedure, θ_r was set equal to zero. To evaluate the fitting performance of the vG model to the measured water retention data, the relative error, *Er* (%), was calculated for each sampling point by the following relationship (Lassabatère et al., 2006):

$$Er=100\times\sqrt{\frac{\sum_{i=1}^{q}\left(\theta_{m,i}-\theta_{vG,i}\right)^2}{\sum_{i=1}^{q}\left(\theta_{m,i}\right)^2}} \tag{2}$$

where $\theta_{m,i}$ denotes the experimental data, i.e. the measured soil water content at a given pressure head, $\theta_{vG,i}$ is the corresponding modelled soil water content and q is the number of the (h, θ) data pairs. According to Bagarello and Iovino (2012), $Er \leq 5\%$ can be assumed indicative of a satisfactory fitting ability of the model. The residuals, $\Delta\theta_i$, were also calculated by the following relationship:

$$\Delta\theta_i=\theta_{vG,i}-\theta_{m,i} \tag{3}$$

For a given pressure head, a good prediction of soil water content would have a mean residual, $Me(\Delta\theta_i)$, close to zero, while positive values indicate overestimation and negative values indicate underestimation. The standard deviation of the residuals, $\sigma(\Delta\theta_i)$, measures the accuracy of prediction, representing the expected magnitude of the error (Minasny and McBratney, 2007). A linear regression analysis of θ_{vG} against θ_m was also carried out. Residual calculation and linear regression analysis were carried out by selecting the six pressure heads (−0.1, −1, −10, −30, −60 and −150 m) yielding a laboratory data point for each soil sample (N = 32 locations × 6 values of h = 192 experimental values of θ), to consider the same number of data points for each pressure head.

Table 2. Considered scenarios to apply the BEST procedure and valid sampling points, i.e. yielding valid estimates of soil sorptivity and saturated soil hydraulic conductivity (sampled points = 32)

Progressive number	Scenario ID	Algorithm	Shape parameter estimation	β	γ	Valid sampling points, N
1	1	SLOPE	FIT	0.6	0.75	32
2	2	SLOPE	FIT	0.1	0.61	32
3	3	SLOPE	FIT	0.1	0.7	32
4	4	SLOPE	FIT	0.1	0.79	32
5	5	SLOPE	FIT	1.0	0.61	32
6	6	SLOPE	FIT	1.0	0.7	32
7	7	SLOPE	FIT	1.0	0.79	32
8	8	SLOPE	FIT	1.9	0.61	32
9	9	SLOPE	FIT	1.9	0.7	32
10	10	SLOPE	FIT	1.9	0.79	32
11	11	SLOPE	MM	0.6	0.75	32
12	12	SLOPE	MM	0.1	0.61	32
13	13	SLOPE	MM	0.1	0.7	32
14	14	SLOPE	MM	0.1	0.79	32
15	15	SLOPE	MM	1.0	0.61	32
16	16	SLOPE	MM	1.0	0.7	32
17	17	SLOPE	MM	1.0	0.79	32
18	18	SLOPE	MM	1.9	0.61	32
19	19	SLOPE	MM	1.9	0.7	32
20	20	SLOPE	MM	1.9	0.79	32
21	21	INTERCEPT	FIT	0.6	0.75	31
22	22	INTERCEPT	FIT	0.1	0.61	28
23	23	INTERCEPT	FIT	0.1	0.7	31
24	24	INTERCEPT	FIT	0.1	0.79	31
25	28	INTERCEPT	FIT	1.9	0.61	28
26	29	INTERCEPT	FIT	1.9	0.7	28
27	30	INTERCEPT	FIT	1.9	0.79	28
28	31	INTERCEPT	MM	0.6	0.75	31
29	32	INTERCEPT	MM	0.1	0.61	28
30	33	INTERCEPT	MM	0.1	0.7	31
31	34	INTERCEPT	MM	0.1	0.79	31
32	38	INTERCEPT	MM	1.9	0.61	28
33	39	INTERCEPT	MM	1.9	0.7	28
34	40	INTERCEPT	MM	1.9	0.79	28

In the field, a BEST infiltration test (Lassabatère et al., 2006) was carried out at each sampling point (N = 32) in spring-summer 2012. The Beerkan method used in this study is a simple three-dimensional infiltration test under positive head conditions, using a cylinder having an inner diameter of 0.30 m. The procedure was carried out in consecutive steps as follows. The surface vegetation was removed over an area slightly larger than the cylinder diameter, while the roots remained in situ. The cylinder was positioned at the soil surface and inserted to a depth of 0.01 m to prevent lateral losses of water. A fixed volume of water (800 mL, corresponding to a water depth of 11.3 mm) was poured into the cylinder at time zero, and the time required for infiltration of the known volume of water was measured. As soon as the first volume had completely infiltrated, another equal volume of water was added to the cylinder and the time was recorded for this volume to infiltrate (cumulative time). The procedure was repeated until the test reached nearly steady-state conditions, i.e. three identical consecutive infiltration times. In this way, a cumulative infiltration, I (L), versus time, t (T) relationship, including N_i discrete points (t_i, I_i) was determined.

Two alternative approaches were applied to estimate the shape parameters of the soil hydraulic characteristic curves on the basis of the measured textural fractions. In particular, the parameters of the BEST model for PSD were estimated by fitting this model to the percentages by mass of particles lower than 2, 50 and 2000 μm, respectively (FIT approach). This choice was forced, since only *cl*, *si* and *sa* content was available, but it was partially supported by the results of an investigation carried out by Bagarello et al. (2009) on Burundian soils. The n shape parameter of eq.(1a) was also estimated with eq.(18) by Minasny and McBratney (2007), that is an empirical pedotransfer function specifically developed for use in the BEST method (MM approach). Both the BEST-slope (Lassabatère et al., 2006) and BEST-intercept (Yilmaz et al., 2010) algorithms were applied to determine soil sorptivity, S, and saturated soil hydraulic conductivity, K_s, at a sampling point since both algorithms presuppose a fitting of the transient infiltration model to the data. According to other investigations, a poor representation of the transient infiltration process is a possible occurrence but the impact of the fitting quality of the infiltration model to the data on the reliability of the soil water retention and hydraulic conductivity predictions is still unknown (Xu et al., 2012; Bagarello et al., 2014a). According to other investigations, θ_s was assumed to coincide with soil porosity, ϕ (Mubarak et al., 2009a, 2010; Xu et al., 2009; Yilmaz et al., 2010; Bagarello et al., 2011). Both in BEST-slope and BEST-intercept algorithms, β = 0.6 and γ = 0.75 are used, but Nasta et al. (2012) suggested that the Beerkan method can be applied with $0 < \beta < 2$ and $0.6 < \gamma < 0.8$. Therefore, calculations were repeated by assuming β = 0.1, 1.0 and 1.9, and γ = 0.61, 0.7 and 0.79. A total of 20 scenarios (2 approaches for the estimation of the shape parameters × 10 pairs of β and γ values) were considered for BEST-slope but 14 scenarios were considered for BEST-intercept since $\beta = 1$ is not allowed for this algorithm (**Table 2**). The workbook by Di Prima (2013) was applied to automatically analyze the infiltration data collected for this investigation.

The method 2 by Wu et al. (1999) was also applied to calculate K_s for each BEST infiltration run. This choice was made because this method is based on a generalized solution for single ring infiltrometers that also works when the ponded depth of water on the soil surface is close to zero (Wu and Pan, 1997), as was the case for the BEST runs. The calculation procedure by Wu et al. (1999) makes use of the steady state phase of the infiltration process and it needs an estimate of the so-called α^* (L^{-1}) parameter, equal to the ratio between K_s and the field-saturated soil matric flux potential. Commonly, α^* is estimated on the basis of the soil textural and structural characteristics (e.g., Elrick and Reynolds, 1992a). In this investigation, α^* was determined at each sampling point with the following relationship:

$$\alpha^* = \frac{1}{\int_{h_i}^{0} \left[\left(1 + \left(\frac{h}{h_g} \right)^n \right)^{-m} \right]^{\eta} dh} \qquad (4)$$

using the fitted parameters of the vG model to the data and calculating the η parameter of the Brooks and Corey (1964) hydraulic conductivity function according to BEST.

The SFH technique (Bagarello et al., 2004) was also applied at the 32 sites. In all cases, the 0.30 m inner diameter ring was inserted 0.12 m into the soil at a distance of approximately 0.15-0.20 m from the ring used for the BEST run. Ring insertion was conducted using a rubber hammer, ensuring that the upper rim of the ring remained horizontal during the insertion process. The soil cores collected a few days before applying the SFH infiltration test allowed to determine the soil water content at the time of the run. This value and the saturated soil water content, θ_s, estimated using the measured ρ_b and considering a soil particle density of 2.65 Mg m^{-3} (Bagarello et al., 2004), were used to establish the volume of water to be used for the SFH test. In practice, a common water volume of 2 L was used at each sampling point to ensure one-dimensional flow in all cases. The K_s values were determined by the measured time, t_a (T), from the application of the known volume of water to the instant at which it had completely infiltrated. The choice of using the SFH technique to obtain independent K_s data was made since the relative performances of the two techniques (BEST, SFH) have been tested in other recent investigations (Bagarello et al., 2014a,b) and this circumstance assisted in the interpretation of the method comparison. The calculated α^* parameter by eq.(4) was also used to determine K_s with the SFH equation.

The BEST and SFH runs differed by the ring insertion depth since the infiltration process has to be three-dimensional in the former case (Lassabatère et al., 2006) and one-dimensional in the latter one (Bagarello et al., 2004). However, this last difference was not considered to represent a limitation of the established comparison because rings determine downward flow and ring infiltrometers are expected to essentially measure vertical soil water transmission parameters (Reynolds and Elrick, 2005). The choice not to describe in detail the methods and procedures used in this investigation was made for brevity reasons and also because an unavoidably synthetic method description would not be enough to allow a reader to reproduce the experiment.

To assess the performances of BEST for predicting soil water retention, it was considered that this procedure assumes aprioristically that the vG model is usable and it does not offer any other alternative. Therefore, the assessment of BEST was carried out in terms of the fitted (θ_{vG}) soil water content values against the corresponding values estimated by BEST (θ_B). For a comparison between two datasets, the paired differences, i.e. $\theta_{vG} - \theta_B$ for given sampling point and pressure head, were calculated and the hypothesis of normality of these differences was checked by the Lilliefors (1967) test. Then, a two-tailed, paired t-test was used to compare the means (Helsel and Hirsch, 1992). A linear regression analysis between θ_B and θ_{vG} was also carried out and the statistical significance of the correlation coefficient, R, was established by a one-tailed t test. The normality of the residuals was tested and the confidence intervals for both the intercept and the slope of the linear regression line were calculated. Similar comparisons were also carried out with reference to the K_s values obtained with BEST, method 2 by Wu et al. (1999) and the SFH technique. Statistical significance was assessed at a $P = 0.05$ probability level and the 95% confidence intervals for the intercept and the slope were calculated, unless otherwise specified.

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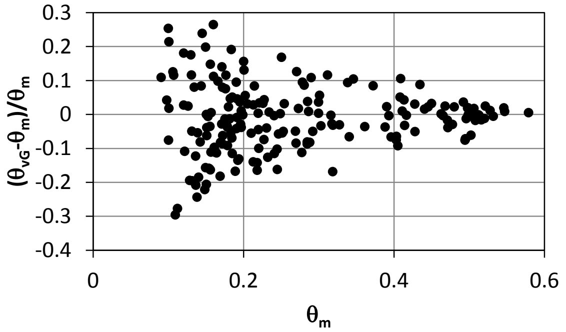
Figure 1. Relative differences between the volumetric soil water content predicted by fitting the van Genuchten (1980) model to the data, θ_{vG} (m^3m^{-3}), and the measured soil water content, θ_m (m^3m^{-3}), plotted against θ_m (sample size, N = 192)



RESULTS AND DISCUSSION

Fitting the water retention model to the data

Fitting the vG model to the water retention data yielded Er varying with the sample from 2.4% to 11.6% (mean = 6.3%; median = 6.0%). The Er did not exceed 5% for 11 samples, i.e. for 34% of the total soil samples. The $Me(\Delta\theta_i)$ values varied with h from -0.014 to 0.008 and the relationship between these two variables was not statistically significant (N = 6, R^2 = 0.041). The relationship between $\sigma(\Delta\theta_i)$ ($0.015 \leq \sigma(\Delta\theta_i) \leq 0.024$) and h also was non-significant (R^2 = 0.007). The difference between the predicted (θ_{vG}) and the measured (θ_m) θ values did not vary significantly with θ_m (R^2 = 0.001) but the relative differences, i.e. $(\theta_{vG}-\theta_m)/\theta_m$, approached zero as θ_m increased (**Fig.1**). A significant relationship between θ_{vG} and θ_m (N = 192, R^2 = 0.979) was obtained. Moreover, the residuals were normally distributed and the linear regression line was not significantly different from the identity line, since the confidence intervals for the intercept and the slope were equal to -0.0105 – 0.0022 and 0.984 – 1.026, respectively.

Table 3. Summary statistics of the porosity, ϕ (m^3m^{-3}), and the fitted saturated soil water content, $\theta_{s,vG}$ (m^3m^{-3}), and parameters of the linear regression of ϕ against $\theta_{s,vG}$

Statistic	ϕ	$\theta_{s,vG}$
Sample size	32	32
Mean	0.527	0.511
Coefficient of variation (%)	5.5	5.6
Intercept	0.207	
Slope	0.627	
Coefficient of determination, R^2	0.386	
99.5% confidence interval for the intercept	-0.017-0.431	
99.5% confidence interval for the slope	0.190-1.064	

The means were significantly different at P = 0.05 according to a two-tailed, paired t test. The coefficient of correlation, R, was significantly higher than zero at P = 0.05 according to an one-tailed t test.

According to the Er criterion, the vG model yielded, on average, unsatisfactory results. This result, that was obtained in a soil locally having a clay content not exceeding 19.6% (**Table 1**), was not surprising because, in another investigation carried out in Sicily, the risk of a weak performance of the vG water retention model used by BEST occurred for soils with a cl content not exceeding 44% (Bagarello and Iovino, 2012). The performances were generally poorer for lower θ values, and this also was an expected result since Haverkamp et al. (2005) evidenced that the vG equation provides a relatively poor description of retention data for dry conditions. According to these authors, using all five parameters in the optimization may improve data description by eq.(1a), but this approach was not tested in this investigation because of the constraints on both θ_r and the relationship between m and n in the BEST procedure. However, there were signs of a generally good predictive ability of the model, as denoted by the high R^2 value and the similarity between the θ_{vG} vs. θ_m regression line and the identity line. This last result, suggesting that θ_{vG} was a reasonably good estimate of the measured value, gave additional justification to the choice to compare θ_B with θ_{vG}.

The fitted saturated soil water content, $\theta_{s,vG}$, was lower than ϕ at the 75% of the sampling points and the means of $\theta_{s,vG}$, and ϕ were significantly different (**Table 3**). However, the ratio between these means was equal to 0.97, the regression of ϕ against $\theta_{s,vG}$ was statistically significant (N = 32, R^2 = 0.39) and a coincidence between the ϕ vs. $\theta_{s,vG}$ linear regression line and the identity line was plausible, although only according to the 99.5% confidence intervals for the intercept and the slope (**Table 3**). Therefore, the choice of assuming $\theta_s = \phi$ for the BEST calculations was reasonable taking into account that $\theta_{s,vG}$ was not very different from ϕ.

Soil hydraulic characterization by BEST

A total of 34 comparisons were carried out between θ_B and θ_{vG} (**Table 4**) since 34 different scenarios were considered for BEST application (**Table 2**). The hypothesis of a normal distribution of the paired differences between the two estimates of θ was never rejected. In all cases, R > 0 was obtained for the linear correlation between θ_B and θ_{vG}, and the hypothesis of a normal distribution of the residuals was not rejected (at P

Table 4. Comparison between the experimentally determined soil water content values, θ_{vG}, and the corresponding estimates obtained with the BEST procedure, θ_B

Scenario ID	N	θ_{vG} (m^3m^{-3})		θ_B (m^3m^{-3})		b_0	b_1	R^2	95% confidence intervals	
		Me	CV	Me	CV				Intercept	Slope
1	192	0.268	50.5	0.242	56.6	-0.022	0.983	0.945	-0.032 – -0.012	0.949 – 1.018
2	192	0.268	50.5	0.227	58.1	-0.021	0.926	0.902	-0.034 – -0.008	0.882 – 0.969
3	192	0.268	50.5	0.230	57.9	-0.026	0.954	0.939	-0.036 – -0.015	0.919 – 0.989
4	192	0.268	50.5	0.231	57.8	-0.025	0.957	0.938	-0.036 – -0.015	0.922 – 0.993
5	192	0.268	50.5	0.247	55.8	-0.019	0.996	0.950	-0.029 – -0.010	0.963 – 1.029
6	192	0.268	50.5	0.248	55.7	-0.019	0.997	0.949	-0.029 – -0.009	0.964 – 1.030
7	192	0.268	50.5	0.249	55.6	-0.018	0.999	0.948	-0.028 – -0.008	0.965 – 1.032
8	192	0.268	50.5	0.261	53.8	-0.011	1.015	0.956	-0.021 – -0.002	0.984 – 1.046
9	192	0.268	50.5	0.262	53.7	-0.011	1.015	0.955	-0.020 – -0.001	0.984 – 1.047
10	192	0.268	50.5	0.262	53.6	-0.010	1.016	0.954	-0.019 – 0	0.984 – 1.048
11	192	0.268	50.5	0.202	72.6	-0.078	1.048	0.928	-0.091 – -0.066	1.006 – 1.089
12	192	0.268	50.5	0.189	74.6	-0.079	0.998	0.921	-0.091 – -0.066	0.957 – 1.040
13	192	0.268	50.5	0.190	74.4	-0.079	1.004	0.921	-0.091 – -0.066	0.961 – 1.046
14	192	0.268	50.5	0.192	74.2	-0.079	1.009	0.920	-0.091 – -0.066	0.966 – 1.052
15	192	0.268	50.5	0.209	71.6	-0.077	1.066	0.934	-0.089 – -0.065	1.026 – 1.107
16	192	0.268	50.5	0.210	71.4	-0.077	1.069	0.934	-0.089 – -0.065	1.028 – 1.110
17	192	0.268	50.5	0.211	71.2	-0.076	1.071	0.933	-0.089 – -0.064	1.030 – 1.112
18	192	0.268	50.5	0.222	68.7	-0.072	1.098	0.943	-0.083 – -0.060	1.059 – 1.137
19	192	0.268	50.5	0.223	68.6	-0.071	1.099	0.942	-0.083 – -0.060	1.060 – 1.138
20	192	0.268	50.5	0.224	68.4	-0.071	1.100	0.942	-0.082 – -0.059	1.061 – 1.139
21	186	0.269	49.9	0.222	58.2	-0.030	0.935	0.945	-0.039 – -0.020	0.903 – 0.968
22	168	0.269	50.4	0.198	59.2	-0.028	0.836	0.939	-0.037 – -0.018	0.803 – 0.868
23	186	0.269	49.9	0.195	59.6	-0.030	0.836	0.937	-0.040 – -0.021	0.804 – 0.868
24	186	0.269	49.9	0.195	59.6	-0.030	0.836	0.937	-0.040 – -0.021	0.804 – 0.868
28	168	0.269	50.4	0.249	55.4	-0.019	0.994	0.955	-0.029 – -0.009	0.960 – 1.027
29	168	0.269	50.4	0.249	55.4	-0.019	0.994	0.955	-0.029 – -0.009	0.960 – 1.027
30	168	0.269	50.4	0.249	55.4	-0.019	0.994	0.955	-0.029 – -0.009	0.960 – 1.027
31	186	0.269	49.9	0.182	74.9	-0.081	0.975	0.925	-0.093 – -0.069	0.935 – 1.016
32	168	0.269	50.4	0.155	76.2	-0.070	0.837	0.921	-0.081 – -0.059	0.799 – 0.874
33	186	0.269	49.9	0.153	76.6	-0.072	0.837	0.920	-0.083 – -0.061	0.801 – 0.873
34	186	0.269	49.9	0.153	76.6	-0.072	0.837	0.920	-0.083 – -0.061	0.801 – 0.873
38	168	0.269	50.4	0.209	71.2	-0.077	1.062	0.936	-0.090 – -0.064	1.020 – 1.105
39	168	0.269	50.4	0.209	71.2	-0.077	1.062	0.936	-0.090 – -0.064	1.020 – 1.105
40	168	0.269	50.4	0.209	71.2	-0.077	1.062	0.936	-0.090 – -0.064	1.020 – 1.105

N = number of points included in the comparison; *Me* = mean value; *CV* = coefficient of variation; b_0, b_1 and R^2 = intercept, slope and coefficient of determination, respectively, of the linear regression line of θ_B against θ_{vG}. According to a two-tailed, paired t test, the means of θ were not significantly different at $P = 0.01$ only with reference to scenario no.10. For each scenario, the correlation coefficient, *R*, was significantly greater than zero at $P = 0.05$ according to an one-tailed t test.

= 0.01 in a single case). Note that the sample sizes were not the same for all considered scenarios (**Table 4**) because at some sampling points the infiltration run did not yield valid estimates of S and K_s on the basis of the t_{max} calculations, t_{max} being the maximum time for which transient expressions can be considered valid (Lassabatère et al., 2006; Yilmaz et al., 2010, **Table 2**). In particular, 168, 186 and 192 data points were considered for those scenarios yielding successful S and K_s results at 28, 31 and 32 sampling points, respectively.

In a recent analysis of approximately 400 infiltration runs carried out by setting the infiltration constants at the originally suggested values (Lassabatère et al., 2006; Yilmaz et al., 2010), BEST-intercept yielded successful results, i.e. positive S and K_s values, more frequently than BEST-slope (Bagarello et al., 2014c). However, the probability of failure of the calculations was higher with the former algorithm than the latter one when the intercept, $b_{+\infty}^{end}$, of the straight line describing steady-state conditions on the I vs. t plot was low, i.e. it fell in the 0.3 to 18 mm range. With reference to the scenarios of this investigation using β and γ at their original values (nos. 1, 11, 21 and 31, **Table 2**), BEST-slope was always successful and BEST-intercept failed for the run yielding the lowest $b_{+\infty}^{end}$ value, equal to 20.1 mm ($b_{+\infty}^{end} \geq 25.6$ mm in the other cases). An intercept of 20 mm is close to the threshold value of $b_{+\infty}^{end}$ discriminating between success and possibility of failure of BEST-intercept according to Bagarello et al. (2014c). Therefore, this investigation was in line with the findings by these Authors. In addition, the choice of β and γ within their feasible limits influenced the success of an analysis carried out with BEST-intercept but it was irrelevant for BEST-slope.

In general, BEST yielded lower values of θ than the experimental ones. Moreover, lower and slightly more variable predictions of θ were obtained with the MM procedure for shape

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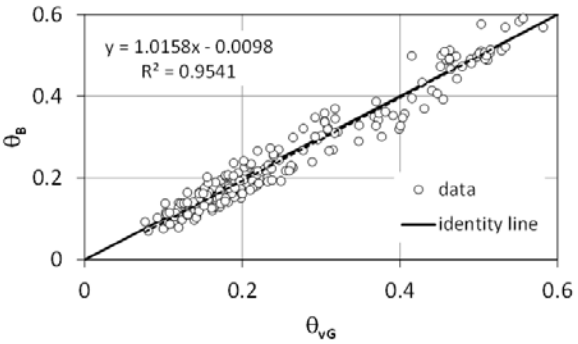
parameter estimation as compared with the FIT procedure. However, a scenario yielding satisfactory results, i.e. suggesting a good correspondence between θ_B and θ_{vG}, was detected. In particular, for the scenario no. 10, the means of θ_B and θ_{vG} were not significantly different at P = 0.01 and the confidence interval calculations suggested that the θ_B vs. θ_{vG} regression line coincided with the identity line (**Table 4**). The goodness of the predictions was also visually detectable (**Fig.2**). Therefore, using the BEST-slope algorithm, the FIT procedure for shape parameter estimation, and assuming β = 1.9 and γ = 0.79 yielded predictions of soil water content close to the values obtained experimentally. The *Er* of the transient infiltration model, calculated with eq.(26) of Lassabatère et al. (2006), was equal to 3.5% on average and it did not exceed 4.6% at an individual sampling point. Taking into account that an *Er* ≤ 5.5% denotes an acceptable error, the fitting quality was always satisfactory.

Figure 2. Regression of the volumetric soil water content predicted with the BEST procedure of soil hydraulic characterization (scenario no.10), θ_B (m^3m^{-3}), against the soil water content predicted by fitting the van Genuchten (1980) model to the data, θ_{vG} (m^3m^{-3}) (sample size, N = 192)



The optimal β and γ values among the tested ones were different from those originally proposed by Lassabatère et al. (2006), equal to 0.6 and 0.75 respectively, but feasible values of these two constants (Haverkamp et al., 1994; Lassabatère et al., 2009; Nasta et al., 2012) yielded reliable predictions of θ in this investigation. An attempt to establish the relative impact of β and γ within their feasible ranges on the predictions of θ was therefore carried out by considering the scenarios nos.1 to 10, since i) these scenarios were homogeneous in terms of algorithm (BEST-slope) and n estimating procedure (FIT), i.e. they only differed by the values of the two constants, and ii) they included the scenario yielding the best results (scenario no.10). The mean value of θ, $Me(\theta)$, increased with both β and γ (**Fig.3a**) but, in general, $Me(\theta)$ was more sensitive to β than to γ. In particular, an increase of γ from 0.61 to 0.79 determined an increase of $Me(\theta)$ varying from 0.6% for β = 1.9 to 2.1% for β = 0.1. On the other hand, an increase of β from 0.1 to 1.9 determined an increase in $Me(\theta)$ varying from 13.4% for γ = 0.79 to 15.0% for γ = 0.61. Therefore, the sensitivity of the estimates of $Me(\theta)$ to γ was higher for low values of β and the sensitivity of these estimates to β increased with a decrease in γ. The choice of the two infiltration constants also affected the estimated relative variability of θ, although the coefficients of variation of θ, $CV(\theta)$, varied in a relatively narrow range, i.e. from 53.6% to 58.1% (**Fig.3b**). The $CV(\theta)$ values decreased with an increase of both β and γ but the former constant affected $CV(\theta)$ more than the latter one. According to Nasta et al. (2012), β and γ have a large impact on the BEST estimation procedure and both constants should be calibrated as a function of the soil type. This investigation, carried out on a sandy loam soil, suggested that the choice of β has a larger impact on the estimates of θ as compared with the choice of γ within feasible values of these two constants. Therefore, calibration is particularly important for β, i.e. to adjust the relation between the water diffusivity and the unsaturated hydraulic conductivity (Nasta et al., 2012).

Figure 3. Mean, *Me* (a), and coefficient of variation, *CV* (b), of the estimated soil water content for different values of the β and γ constants

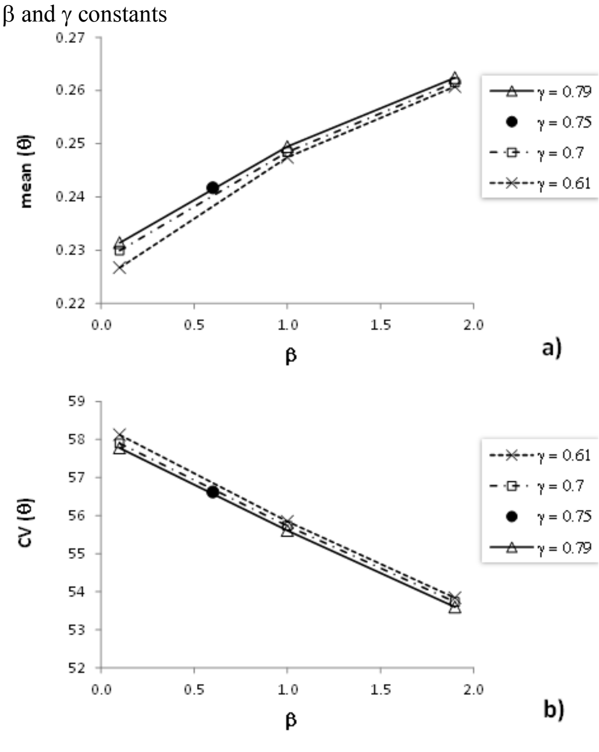


Table 5. Summary statistics of the saturated soil hydraulic conductivity, K_s (mm s^{-1}), estimated with the BEST procedure (scenario no.10), method 2 by Wu et al. (1999) (WU in the table) and the SFH technique (SFH in the table), and parameters of the linear regression of the former estimate of K_s (BEST) against the latter ones (WU, SFH) (sample size, N = 32)

Statistic	BEST	WU	SFH
Minimum	0.0023	0.0039	0.0170
Maximum	0.0130	0.0168	0.0418
Mean	0.0058ab	0.0067a	0.0267b
Median	0.0048	0.0058	0.0282
Coefficient of variation (%)	46.2	50.2	25.2
Intercept		0.0008	-0.0021
Slope		0.754	0.295
Coefficient of determination, R^2		0.879	0.546
99.5% confidence interval for the intercept		-0.0004 – 0.0019	-0.006 -0.002
99.5% confidence interval for the slope		0.599 – 0.908	0.146-0.443

The means followed by the same letter were compared and they were found to be significantly different at P = 0.05 according to a two-tailed, paired t test. The coefficients of correlation, R, were significantly higher than zero at P = 0.05 according to an one-tailed t test.

The α* values calculated by eq.(4) varied from 0.0016 to 0.370 mm^{-1} (N = 32). Excluding two values of α* > 0.1 mm^{-1}, that were considered unreliable being expected in gravels and very coarse sands with negligible amounts of finer soil particles (Reynolds and Lewis, 2012), the median of α* was equal to 0.0067 mm^{-1} and this value was used to calculate K_s with method 2 by Wu et al. (1999). This method yielded significantly higher K_s values than BEST (**Table 5** and **Fig.4**). The two estimates of K_s were significantly correlated but the linear regression line did not coincide with the identity line according to the calculated 99.5% confidence intervals for the intercept and the slope. However, the mean and the median of K_s obtained with method 2 by Wu et al. (1999) were higher than the corresponding values obtained with BEST by not more than 21%. With reference to the individual sampling points, the two estimates of K_s differed by a factor never exceeding 2.1 and <1.5 in the 97% of the cases (i.e. 31 out of 32). An uncertainty in the estimate of K_s by a factor of two or three can often be considered practically negligible since K_s ranges from 10^{-9} m s^{-1} for tight clays to 10^{-4} m s^{-1} for coarse sands and given the extreme spatial variability of K_s found in the field (Elrick and Reynolds, 1992a). Therefore, the differences between the two estimates of K_s obtained in this investigation were statistically significant but not substantial and, reasonably, they were negligible from a practical point of view. In other terms, the scenario no.10, allowing a good prediction of θ, also yielded plausible estimates of K_s, i.e. relatively close to the ones obtained by an alternative method of analysis of the same infiltration run, i.e. method 2 by Wu et al. (1999).

The SFH technique yielded significantly and substantially higher K_s values than BEST (**Table 5** and **Fig.5**). In particular, the mean and the median of K_s obtained with the former technique were 4.6-5.9 times higher than the corresponding values obtained with BEST. The relative variability of K_s was appreciably lower with the SFH technique than with BEST. The two estimates of K_s were significantly correlated but the linear regression line did not coincide with the identity line according to the calculated 99.5% confidence intervals for the intercept and the slope. The factor of discrepancy between the two estimates of K_s at a sampling point, i.e. the ratio between the K_s values obtained with the SFH technique and the BEST procedure, clearly decreased as the saturated soil hydraulic conductivity measured with this last procedure

Figure 4. Comparison between the saturated soil hydraulic conductivity, K_s, values estimated with the BEST procedure (scenario no.10) and method 2 by Wu et al. (1999) (WU in the figure)

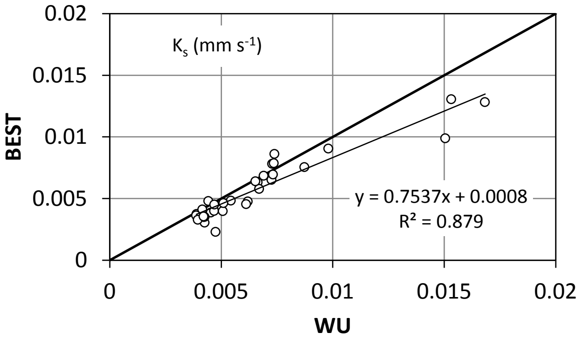


Figure 5. Comparison between the saturated soil hydraulic conductivity, K_s, values estimated with the BEST procedure (scenario no.10) and the SFH technique (SFH in the figure)

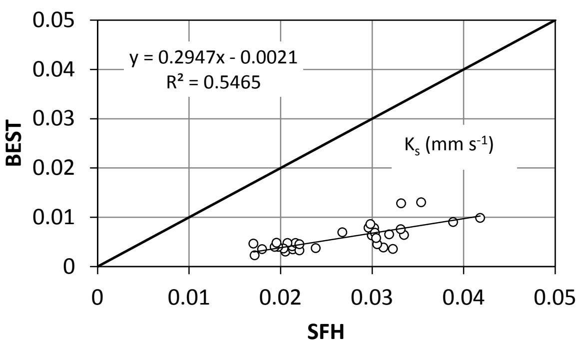


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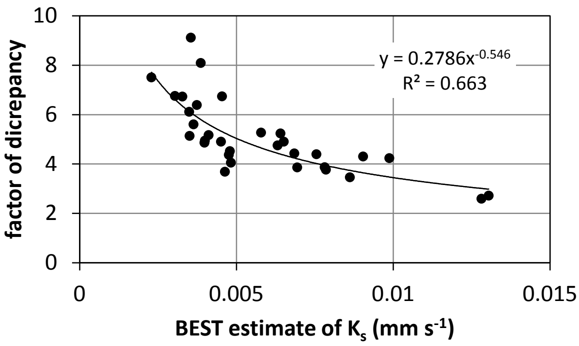
Figure 6. Factor of discrepancy, i.e. ratio between the saturated soil hydraulic conductivity, K_s (mm s^{-1}), obtained with the SFH technique and the BEST procedure, plotted against the estimate of K_s obtained with BEST



increased (**Fig.6**). The significant correlation between the two estimates of K_s can be viewed as a sign of the fact that a similar pore network was sampled at each location with the two techniques, notwithstanding that the BEST and SFH infiltration runs were carried out at a small distance each other. This result was plausible given that large diameter rings, allowing more representative measurements than small and commonly used rings (Lai et al., 2010; Wuest, 2005; Youngs, 1987), were used in both cases. A tendency of the SFH technique to yield higher K_s values than BEST was detected in other investigations (Bagarello et al., 2014a,b), and it was attributed to soil disturbance and air entrapment during the repeated water application necessary to run BEST since there were more opportunities to alter the soil surface with BEST than the SFH technique. The fact that the differences between the two techniques were more noticeable when BEST yielded lower K_s results is consistent with this interpretation since, in this case, pores are more sensitive to perturbing agents, determining for example clogging phenomena, being smaller, more tortuous and less interconnected. Probably for this reason, the differences between the two techniques were higher with reference to the lowest measured values of K_s, differing by a factor of 7.4, than the highest values, differing by 3.2 times. Therefore, the occurrence of the suggested perturbing effects also determined an increase of the relative variability of K_s with BEST. In addition, the BEST infiltration runs were approximately thirty times longer than the SFH runs. Probably, there were more opportunities to activate short-term soil swelling phenomena with the former technique, reducing macroporosity and hence determining a decrease in the measured conductivity, taking into account that these phenomena have also been documented for soils with a relatively low clay content (Bagarello and Sgroi, 2007; Bagarello et al., 2012). Therefore, this investigation confirmed that, from a hydrological point of view, the SFH technique appears more appropriate to characterize the soil at the beginning of a rainfall event yielding surface runoff whereas the BEST run appears more suitable to characterize the soil later during a rainfall event (Bagarello et al., 2014a,b).

In a test of the original BEST-slope procedure on other Sicilian soils, satisfactory predictions of θ and plausible K_s data were obtained with relatively short infiltration runs, an estimate of *n* based on the *sa* and *cl* content (Minasny and McBratney, 2007), and a θ_s value equal to 0.93ϕ (Bagarello et al., 2014b). This investigation gave an additional support to the usability of BEST-slope for estimating soil hydraulic properties, but it also suggested that a preliminary comparison with independently measured data for the site of interest should be carried out to establish the best way to obtain good predictions of these properties with BEST. From a conceptual point of view, this suggestion agrees with the conclusion by Nasta et al. (2012) about the opportunity to calibrate the infiltration constants as a function of the soil type.

In this investigation, the most appropriate scenario was selected on the basis of a comparison carried out in terms of soil water retention values because more data were available for θ than for K_s (168-192 against 32). Moreover, θ was measured with a standard laboratory technique whereas method 2 by Wu et al. (1999) and the SFH technique by Bagarello et al. (2004) cannot be considered standard and commonly accepted methods for measuring K_s. According to different authors, standard measurement techniques of this last soil hydraulic property cannot be identified but just appropriate methods for a specific application could be individuated (Reynolds et al., 2000; Verbist et al., 2013; Bagarello et al., 2014a). Therefore, additional comparisons are obviously advisable in other soils, taking into account that, especially for K_s, the statistical tools alone cannot be enough to establish the reliability of the BEST results, but the explicit consideration of what information is contained in a particular measurement of this variable is also necessary to make evaluations and judgments. The comparison between BEST and the SFH technique was made taking into account that comparing different techniques for measuring K_s provides one of the few sources of information that practitioners can draw upon to select K_s

methods that are appropriate for their circumstances (Reynolds et al., 2000). The K_s comparison carried out by applying different procedures to analyze the same infiltration run allowed to exclude, in the interpretation of the results, possible effects of spatial variability, that is known to be particularly noticeable for this soil hydraulic property (Mallants et al., 1996, 1997; Warrick, 1998). Maybe, the combined approach used in this investigation (alternative techniques to determine K_s in the field, alternative methods to analyze the infiltration run) could also be applied in other circumstances to concretely carry out the conclusion by Reynolds et al. (2000) that work is still necessary for determining the most appropriate methods for both the soil conditions and the specific application of the K_s data.

CONCLUSIONS

In this investigation, the applicability of the BEST procedure for soil hydraulic characterization was tested in a sandy loam soil. With this aim, a comparison between the predicted and the laboratory measured water retention data was established. The saturated soil hydraulic conductivity, K_s, obtained with BEST, method 2 by Wu et al. (1999) applied to the BEST infiltration run and the Simplified Falling Head (SFH) technique were also compared.

The water retention model used by BEST reproduced satisfactorily the experimental data and the choice to assume a saturated soil water content coinciding with soil porosity, frequently made in several BEST applications, was reasonable because the two parameters were not very different for the investigated soil.

A good correspondence between the predicted and the experimental water retention was detected when the original BEST-slope algorithm was applied with the infiltration constants set at $\beta = 1.9$ and $\gamma = 0.79$. In this case, BEST also yielded plausible K_s values, i.e. differing by not more than a factor of two from the corresponding estimates obtained by applying the Wu et al. (1999) solution for single ring infiltrometers to the steady-state part of the measured infiltration process. The SFH technique yielded K_s values approximately five times higher than those of BEST, probably because with the former technique soil disturbance during water application, swelling and air entrapment phenomena had a less noticeable impact on the measured infiltration.

In conclusion, BEST is promising to simply characterize a soil but the application methodology of this procedure has to be adapted to the particular situation under consideration. Therefore, additional investigations should be carried out in other soils physically similar to that of this investigation, with the objective to understand if the developed methodology can be generalized for the sandy loam soils. Other similar investigation should be carried out on different soils with the aim to develop more general procedures for BEST application. Furthermore, data may contain unpredictable uncertainties that could influence the interpretation of a comparison. In other terms, differences detected between measured and predicted soil hydraulic properties can be due to approximations in the modeling approach, but also to errors in both the input data to run the model and the data used to establish a comparison with the predictions. Very accurate experimental procedures and large sample sizes, averaging errors, are therefore particularly important to establish and possibly improve the applicability of BEST with reference to specific soils. More investigations should also be carried out to establish which information is contained in the soil hydraulic characterization carried out through a particular experimental method, including BEST. In this view, a practical support to the choice of the most appropriate measurement method could be given by functional evaluation, that involves comparing an experimentally measured hydrological process (i.e., surface runoff at the base of a plot) with the corresponding process simulated with mechanistic models and the measured soil hydraulic properties.

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Appendix H: Determining hydraulic properties of a loam soil by alternative infiltrometer techniques

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ABSTRACT

Testing infiltrometer techniques to determine soil hydraulic properties is necessary for specific soils. For a loam soil, the water retention and hydraulic conductivity predicted by the BEST (Beerkan Estimation of Soil Transfer parameters) procedure of soil hydraulic characterization was compared with data collected by more standard laboratory and field techniques. Six infiltrometer techniques were also compared in terms of saturated soil hydraulic conductivity, K_s. BEST yielded water retention values statistically similar to those obtained in the laboratory and K_s values practically coinciding with those determined in the field with the pressure infiltrometer (PI). The unsaturated soil hydraulic conductivity measured with the tension infiltrometer (TI) was reproduced satisfactorily by BEST only close to saturation. BEST, the PI, one-potential experiments with both the TI and the mini disk infiltrometer (MDI), the simplified falling head (SFH) technique and the bottomless bucket (BB) method yielded statistically similar estimates of K_s, differing at the most by a factor of three. Smaller values were obtained with longer and more soil-disturbing infiltration runs. Any of the tested infiltration techniques appears usable to obtain the order of magnitude of K_s at the field site but the BEST, BB and PI data appear more appropriate to characterize the soil at some stage during a rainfall event. Additional investigations on both similar and different soils would allow development of more general procedures to apply infiltrometer techniques for soil hydraulic characterization.

Keywords: BEST (Beerkan Estimation of Soil Transfer parameters) procedure; Soil water retention; Soil hydraulic conductivity; Infiltrometer technique.

INTRODUCTION

The soil hydraulic properties are key information for understanding and simulating the hydrological processes (Assouline and Mualem, 2002; Wainwright and Parsons, 2002). Loam soils are particularly important to be characterized properly because they generally exhibit a good balance between large and small pores. Therefore, they have high economic interest since movement of water and air is easy and water retention is adequate (Hillel, 1998). Field infiltrometer techniques are becoming very popular for soil hydraulic characterization because the experiments are relatively easy, rapid and inexpensive.

Infiltrometer data are generally analyzed by assuming that the sampled porous medium is rigid, homogeneous, isotropic and uniformly unsaturated before the run (e.g., Reynolds and Elrick, 1990; Lassabatère et al., 2006). However, this is an approximate way to represent field soils (Reynolds and Elrick, 2002), and it is practically impossible to verify these assumptions under field conditions (Verbist et al., 2010). In addition, soil hydraulic properties generally exhibit a dynamic nature and even water application during the infiltrometer run can influence the measured infiltration rates (e.g., Bagarello et al., 2014b; Verbist et al., 2010) since flow is dominated by unstable structural macropores (Jarvis et al., 2013). Therefore, a given infiltrometer method cannot be suggested for general use and improving our knowledge of the potential of these methods is advisable for practical purposes.

Lassabatère et al. (2006) proposed the Beerkan Estimation of Soil Transfer parameters (BEST) procedure to estimate the soil water retention and hydraulic conductivity curves. Due to its simplicity and the physical soundness of the employed relationships and procedures, BEST is receiving increasing attention by the scientific community to tackle specific problems (Mubarak et al., 2009a,b, 2010; Lassabatère et al., 2010; Gonzalez-Sosa et al., 2010; Yilmaz et al., 2010; Bagarello et al., 2011) and to test and possibly improve or simplify specific experimental and analytical procedures (Minasny and McBratney, 2007; Bagarello et al., 2009, 2011, 2014c; Yilmaz et al., 2010; Xu et al., 2012; Bagarello and Iovino, 2012; Nasta et al., 2012). However, only a few comparisons of the predicted soil properties with data collected by other experimental methods can still be found in the literature (Yilmaz et al., 2010; Aiello et al., 2014; Bagarello et al., 2014a). The signs of a promising ability of the BEST procedure to yield a reasonably reliable soil hydraulic characterization can be found but these signs are not enough to suggest conclusions of general validity.

Among the soil hydraulic properties, saturated hydraulic conductivity, K_s, is particularly important since it controls many soil hydrological processes such as infiltration. Given that K_s depends strongly on soil structure, many measurements have to be repeated over time to characterize its spatial and temporal variability (Lauren et al., 1988; Logsdon and Jaynes, 1996; Prieksat et al., 1994).Especially for structured soils, K_s should be measured directly in the field to minimize disturbance of the sampled soil and to maintain its functional connection with the surrounding soil (Bouma, 1982). Many methods have been developed over time for measurement of K_s but different methods often yield substantially dissimilar K_s values since this parameter is extremely sensitive to sample size, flow geometry, sample collection procedures and various soil physical-hydrological characteristics (Reynolds et al., 2000). Comparing methodologically similar techniques can help to better establish what happens when a measurement of K_s is carried out because, in this case, factors determining the relative performances of alternative techniques can be determined with more confidence. Comparison among methods allows to better establish what kind of information is contained in a measurement of K_s carried out with a particular method.

Infiltration experiments into an initially unsaturated soil through a circular source of a generally small diameter have become very common to determine K_s in the field and a wide variety of methods and calculation techniques are now available. For example, K_s can be determined with BEST, the pressure infiltrometer (PI) (Reynolds and Elrick, 1990), the simplified falling head (SFH) technique (Bagarello et al., 2004), the tension infiltrometer (TI) (Perroux and White, 1988; Ankeny et al., 1991), the mini disk infiltrometer (MDI) (Dohnal et al., 2010), and the bottomless bucket (BB) method (Nimmo et al., 2009).

Much is known about these methods. The PI is one of the most frequently applied infiltrometer methods (e.g., Angulo-Jaramillo et al., 2000; Bagarello et al., 2000; Mertens et al., 2002; Vauclin et al., 1994) and comparisons between this and other methods have been carried out (e.g., Reynolds et al., 2000; Verbist et al., 2009, 2013; Bagarello et al., 2013b), allowing for example to conclude that the PI data could be uncertain in cracking clay loam soils and that some soil disturbance can occur with particular devices and applicative procedures. The SFH technique is less applied than the PI technique although these two techniques should be expected to yield similar results in relatively rigid porous media (Bagarello et al., 2013b). Recently, the TI method was found to be a good candidate to become a reference method for determining the saturated hydraulic conductivity of stony soils among other alternative methods (Verbist et al., 2013).

However, there are also poorly understood issues. For example, the usability, for K_s determination, of a device developed for measuring unsaturated soil hydraulic conductivity is still uncertain. Comparing the TI with other infiltrometer devices specifically developed for determination of K_s may help to address this issue. A reason of particular interest for this type of investigation is that the TI allows to minimize soil surface disturbance during the run, that can influence the measured conductivity (e.g. Bagarello et al., 2014b). Another point deserving developments is the usability of the MDI, that is a particular type of TI. The former device samples an appreciably smaller surface than the latter one and it is well known that determination of soil hydraulic conductivity at or close to saturation is strongly affected by the soil volume or the area sampled by an individual measurement (e.g., Lauren et al., 1988; Vepraskas and Williams, 1995; Lai and Ren, 2007). However, the relative performances of these two devices for a measurement of soil hydraulic conductivity are still unknown. Developing this issue is necessary also because there are examples in the literature that combine a measurement of K_s carried out with a relatively large ring with a measurement of conductivity very close to saturation (i.e., more or less the saturated hydraulic conductivity of the soil matrix) carried out with the MDI (Gonzalez-Sosa et al., 2010). In other terms, it should be established if the TI and the MDI yield similar results when they are applied with the same established pressure head, especially at or close to saturation. The performances of BEST in comparison with other infiltrometer methods to determine K_s are still largely unknown since only a few investigations have been carried out. A reason of interest for a comparison including the BB method is that it has so far received little field testing or comparison with other methods.

The general objective of this investigation was to assess usability of infiltrometer techniques for determining the soil hydraulic properties of a loam soil. In particular, the soil hydraulic properties predicted by the BEST procedure were compared with independent measurements of these properties. Six infiltration techniques to determine the saturated soil hydraulic conductivity were then compared.

MATERIALS AND METHODS

Field site and experimental procedures

The study site is located at the Department of Agricultural and Forestry Sciences of the Palermo University (13°21'6" E, 38°6'25" N) in western Sicily, Italy. The climate of the area is semi-arid Mediterranean, with a mean annual air temperature of 18.3°C and an annual rainfall of 855 mm in the period 1971-2000. The area, with a spontaneous, sparse herbaceous vegetation, is rectangular, nearly flat, and extends for approximately 150 m^2.

The following six infiltrometer methods were applied in this investigation to characterize the soil: Beerkan Estimation of Soil Transfer parameters (BEST) procedure, single-ring pressure infiltrometer (PI), tension infiltrometer (TI), mini disk infiltrometer (MDI), simplified falling head technique, and bottomless bucket (BB) method. All these methods make use of a circular source to establish an infiltration process into an initially unsaturated porous medium but they differ by many aspects including measured soil hydraulic properties, boundary conditions on the infiltration surface, flow field characteristics, stage of the infiltration process used for the analysis, field equipment and difficulty of the experiment.

In particular, a complete soil hydraulic characterization can be obtained with BEST, the saturated soil hydraulic conductivity, K_s, and an estimate of the soil hydraulic conductivity function is given by the PI, and hydraulic conductivity, K, points at saturation or near saturation are obtained with the other techniques.

Boundary conditions vary between positive (PI) and negative but close to zero (TI, MDI) pressure heads on the infiltration surface and between constant (PI, TI, MDI) and variable (BEST, SFH, BB) water pressure heads during the run. Therefore, different factors, including changes in soil structure upon wetting, hydraulic contact between the device and the sampled soil and air entrapment, can influence the relative performances of the tested methods.

All methods but the SFH technique establish a three-dimensional flow field. One-dimensional flow required by the SFH technique implies a relatively deep insertion of the ring into the soil and hence the risk of compaction or shattering of the sampled soil volume with this technique. Moreover, soil's anisotropy could determine differences between the K_s values obtained with the SFH and the other methods, although ring infiltrometers are essentially expected to measure vertical soil water transmission parameters since rings establish downward flow (Reynolds and Elrick, 2005).

Steady infiltration data are used with the PI, TI (multi-potential experiment) and BB methods. The initial stage of the infiltration process is considered by the SFH technique and the information collected during both the transient and the steady-state stage of the run is used with the BEST, TI (one-potential) and MDI methods. Different durations of the field run are expected to determine different soil alteration phenomena (e.g., weakening of particle bonds) during the method application. Possible uncertainties in the

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attainment of steady flow conditions during the run cannot be excluded, and they could affect the results obtained with some of the tested methods.

Finally, minimum experimental equipment and simple field runs are required for some methods (BEST, SFH, BB) whereas specific devices and more complicated runs are necessary with other methods (PI, TI, MDI). With some devices, the experiment can be expected to be particularly accurate. For example, with the TI, the pressure head to be established on the infiltration surface can accurately be calibrated in the laboratory. However, more complicated devices and/or runs also imply more opportunities for errors or uncertainties of experimental nature.

Soil sampling and field experiments were carried out during the months from May to early October in 2013. The choice of the exact dates of the sampling campaign was made taking into account the opportunity to sample a soil with similar antecedent soil water content and bulk density conditions. At this aim, the gravimetric soil water content, w (g g^{-1}), and the dry soil bulk density, ρ_b (Mg m^{-3}), were checked periodically during the experimental period. In particular, a total of 36 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. These cores were used to determine ρ_b and w, and hence the soil water content at the beginning of an infiltration experiment, θ_i (m^{3}m^{-3}), and the soil porosity, ϕ (m^{3}m^{-3}), assuming a soil particle density of 2.65 Mg m^{-3}. Other 20 disturbed soil samples were collected during the sampling period for determining w. All samples were taken at randomly selected points and the same criterion was applied for all infiltrometer techniques.

Ten disturbed soil samples (0-0.10 m depth) were used to determine the particle size distribution (PSD), using conventional methods (Gee and Bauder, 1986). Fine size fractions were determined by the hydrometer method, whereas the coarse fractions were obtained by mechanical dry sieving. The clay (cl), silt (si), and sand (sa) percentages were determined according to the USDA standards (Gee and Bauder, 1986).

Following Dane and Hopmans (2002), the water retention curve at high pressure heads ($h \geq$ -1.5 m) was determined by hanging water columns on soil cores collected in stainless steel cylinders (inner diameter = 0.08 m, height = 0.05 m) at ten points. Given that soil water retention at low pressure heads is mostly influenced by adsorptive forces, repacked soil samples and the pressure plate apparatus were used for $h \leq$ -3 m. In particular, for each sampling point, the dried soil from the undisturbed core was crushed and sieved at 2 mm, and then it was packed into rings having an inside diameter of 0.05 m and a height of 0.01 m. Two replicated samples were used for each sampling point and applied pressure head. Volumetric water retention data were obtained for h values of -0.05, -0.1, -0.2, -0.4, -0.7, -1.2, -3.37, -10.2, -30.6 and -153.0 m.

Ten infiltration runs of the BEST (Lassabatère et al., 2006) type were carried out using a ring with an inner diameter of 0.15 m, inserted to a depth of about 0.01 m, and individual water volumes of 150 mL. An experimental cumulative infiltration, I (L), vs. time, t (L), relationship including N_{tot} discrete points, N_{tot} being the number of collected (t, I) data points (9 $\leq N_{tot} \leq$ 20, depending on the run; mean = 14), was then deduced.

Ten single-ring pressure infiltrometer (PI) tests were conducted using a device similar to the one by Ciollaro and Lamaddalena (1998). A ring with an inner diameter of 0.15 m was inserted to a depth d = 0.12 m. Water was carefully poured on the soil surface to a small depth before opening the infiltrometer reservoir. A constant depth of ponding, H_1 = 0.053 m, was established on the soil surface, and flow rate was monitored until attainment of quasi steady-state conditions. A constant depth of ponding, H_2 = 0.11 m, was then established, and flow rate was monitored until another quasi steady-state condition was detected. Apparent steady-state flow rates (Q_{s1} and Q_{s2}) corresponding to the two applied H levels (H_1 and H_2, respectively) were estimated from the flow rate versus time plot.

A tension infiltrometer (TI) with a 0.24 m diameter base plate unit and a separated water supply unit was used. A 10 mm thick layer of contact material (Reynolds and Zebchuk, 1996; Bagarello et al., 2001; Reynolds, 2006) was placed over the surface and the pressure head offset determined by the contact material layer was considered in establishing the pressure head on the TI membrane (Reynolds, 2006). Ten multi-potential experiments were carried out applying an ascending sequence of pressure heads, h_0 (L), at the soil surface (-120, -60, -30, and -10 mm), to exclude the effects of hysteresis on the measured soil hydraulic conductivity (Reynolds and Elrick, 1991; Bagarello et al., 2005, 2007). The apparent steady-state infiltration rate was determined for each applied pressure head.

One-potential (h_0 = 0) TI runs were carried out at other ten sampling points, and twenty one-potential (h_0 = 0) experiments were carried out with the mini disk infiltrometer (MDI) (Madsen and Chandler, 2007; Dohnal et al., 2010). More runs were carried out with the MDI than with all other techniques since the former device samples a small area (approximately 15 cm^2).

Ten points were sampled to determine K_s by the simplified falling head (SFH) technique (Bagarello et al., 2004) using 0.15 m diameter rings inserted to a depth of 0.12 m. Undisturbed soil cores collected two or three days before the SFH test allowed to estimate the soil water content at the time of sampling, θ_i (m^3m^{-3}), that was used, with the estimated porosity, to determine the volume of water to be applied for the one-dimensional infiltration test. The initial depth of ponding for the SFH runs was 40 mm. The time, t_a (T), from the application of water to the instant at which the surface area was no longer covered by water was measured.

Finally, ten infiltration runs of the bottomless bucket (BB) type were carried out (Nimmo et al., 2009). A 0.15 m inner diameter ring was inserted into the soil to a depth of about 0.05 m. Water was poured on the confined infiltration surface to establish an initial depth of water of 0.1 m. The time from this application to the instant at which the surface area was covered by 0.02 m of water was measured and another volume of water was poured immediately into the ring to re-establish a ponded depth of water of 0.1 m. This procedure was repeated until the rate of decline of the falling head was nearly constant. Five to ten volumes of water were used, depending on the sampling point.

Calculation of soil hydraulic properties

The BEST procedure (Lassabatère et al., 2006) was applied to determine the parameters of the van Genuchten (1980) relationship (vG) for the water retention curve with the Burdine (1953) condition and the Brooks and Corey (1964) relationship for hydraulic conductivity. The Beerkan infiltration run was analyzed by the BEST-slope (Lassabatère et al., 2006), BEST-intercept (Yilmaz et al., 2010) and BEST-steady (Bagarello et al., 2014c) algorithms. Taking into account the small size of the sampled area and the random sampling for textural characterization, a representative PSD was obtained by averaging the ten individual PSDs. A mean value of both the antecedent soil water content, θ_i, and the dry soil bulk density, ρ_b, was similarly used to apply BEST. Therefore, the field site was assumed to be homogeneous in terms of PSD, θ_i, ρ_b, and hence estimated soil porosity, ϕ, but location-dependent water retention curve and hydraulic conductivity function were obtained (Bagarello et al., 2014a).

The two-level PI runs were analyzed with the Two-Ponding-Depth (TPD) approach by Reynolds and Elrick (1990) to obtain an estimate of both K_s and the so-called α^* parameter at each sampling point.

The multi-potential TI runs were analyzed according to Ankeny et al. (1991) to estimate the soil hydraulic conductivity at pressure heads of -10 (K_{10}), -30 (K_{30}), -60 (K_{60}) and -120 mm (K_{120}).

The BEST-steady algorithm was also applied to estimate K_s for the one-potential experiments carried out with both the TI and the MDI.

Eq.(15) by Bagarello et al. (2004) was used to determine K_s for the SFH infiltration runs, by assuming an α^* parameter of 4 m^{-1} (Elrick and Reynolds, 1992).

Finally, eq.(10) by Nimmo et al. (2009) was used to estimate K_s for each applied water volume during the BB experiment, assuming λ_c = $1/\alpha^*$ = 0.25 m. The last two determinations of K_s were averaged to obtain an estimate of K_s at a given sampling point.

Testing BEST against independent soil data

The hydraulic properties predicted with BEST were compared with independent measurements of water retention, saturated soil hydraulic conductivity, K_s, and unsaturated soil hydraulic conductivity, K. The water retention data were obtained by standard laboratory techniques (Dane and Hopmans, 2002). The K_s and K data were collected in the field by the PI and the TI (multi-potential experiment), respectively, considering that these techniques have become in the last 25 years near-standard approaches for field measurement of soil hydraulic conductivity (Angulo-Jaramillo et al., 2000; Bagarello et al., 2000; Reynolds et al., 2000; Verbist et al., 2013).

For each established pressure head in the laboratory, a mean value of θ was calculated using the valid laboratory data to obtain a single experimental water retention curve for the sampled site, and the vG model with the Burdine condition and θ_r = 0 was fitted to the mean (θ, h) data pairs. The fitting was performed by minimizing the sum of the squared residuals between the model and the data.

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Taking into account that the fitted saturated soil water content, θ_s, was appreciably lower than the porosity, ϕ, determined from the bulk density measurements (fitted θ_s = 0.3996 m^3m^{-3}, i.e. 76% of ϕ), the three BEST algorithms, i.e. BEST-slope, BEST-intercept and BEST-steady, were applied with both $\theta_s = \phi$ (BSL-ϕ, BIN-ϕ, and BST-ϕ, respectively) and θ_s equal to the fitted value (BSL-fit, BIN-fit, and BST-fit, respectively). The hydraulic parameters estimated with BEST were used to calculate θ at the experimentally imposed pressure heads for each sampling point and a mean value of θ was obtained for each h value by averaging the valid results with BEST. The θ values predicted with BEST were then compared with the measured θ values by linear regression analysis techniques.

The K_s values obtained with BEST were compared with the K_s data collected by the PI with the TPD approach since these calculations do not need any subjective estimation of soil parameters, that could affect the comparison between datasets. At first, the normality of the distribution of both the untransformed and the ln-transformed K_s data was tested by the Lilliefors (1967) test. Then, a two-tailed t test was applied to compare the K_s data obtained with the PI and the BEST procedure. This comparison was made for each applied BEST algorithm.

Another test of the K_s data obtained with BEST was carried out by establishing a comparison with the unsaturated soil hydraulic conductivity, K, measured with the TI. According to Bagarello et al. (2014a), this comparison can allow to discriminate between possible ($K_s > K$ at the highest pressure head, equal to -10 mm in this investigation) and physically impossible ($K_s < K_{10}$) situations. Also for the TI measurements, the normality of the distribution of both the untransformed and the ln-transformed K values was preliminarily tested.

Finally, for each established pressure head in the field by the TI, a mean value of K was calculated by using the individual K values obtained at each sampling point with this device to obtain a single experimental hydraulic conductivity function for the sampled site. The hydraulic parameters estimated with the six BEST algorithms were used to calculate K at the experimentally imposed pressure heads for each sampling point and a mean value of K was obtained for each h value by averaging the valid results with BEST. The K values predicted by BEST were then compared with the K values obtained with the TI.

Comparing methods to determine saturated soil hydraulic conductivity

A comparison among the K_s values obtained with different infiltrometer techniques was carried out. In particular, six independent sets of K_s data were obtained with the following techniques and procedures: 1) PI with the TPD approach (PI dataset); 2) BST-ϕ algorithm (BEST); 3) one-potential TI experiment, i.e. h = 0, steady algorithm, $\theta_s = \phi$ (TI); 4) MDI experiment, h = 0, steady algorithm, $\theta_s = \phi$ (MDI); 5) simplified falling head technique (SFH); and 6) bottomless bucket method (BB). The normality of the distribution of both the untransformed and the ln-transformed K_s data was tested. Then, the Tukey Honestly Significant Difference test was applied to compare the six datasets.

The choices to assume $\theta_s = \phi$ to analyze the BEST, SFH, TI and MDI data and to apply the steady algorithm for the analysis of the BEST, TI and MDI infiltration runs were made for the following reasons: i) assuming $\theta_s = \phi$ allowed to include the SFH experiment in the comparison. With θ_s set at the fitted value by the vG model, the hypothesis of 1D flow could be violated and the wetting front could be expected to go beyond the bottom of the cylinder as infiltration proceeded; ii) with $\theta_s = \phi$, the steady algorithm yielded K_s data for seven TI runs and for all MDI and BEST runs (sample sizes, N_s = 20 for the MDI and 10 for BEST), but lower success rates were obtained with both the slope (N_s = 7 for the TI, 20 for the MDI and 9 for BEST) and the intercept (N_s = 3, 18 and 10, respectively) algorithms. Therefore, the steady algorithm allowed to establish the K_s comparison by considering the highest possible number of runs; iii) from a practical point of view, simple approaches are obviously desirable. The steady algorithm is simpler to apply than the slope and intercept algorithms, and porosity determination is simpler than the determination of the soil water content at exactly the end of the infiltration run; iv) in any case, there was no certainty that the θ_s value obtained by fitting the vG model to the laboratory water retention data was really representative of the volumetric soil water content at the end of the infiltration runs because of the possible disturbance of soil structure during soil core collection; and v) the sensitivity of the K_s

values obtained with BEST and different estimates of θ_s ($\theta_s = \phi$ or fitted θ_s value) was small according to the existing criteria of evaluation (Elrick and Reynolds, 1992), with differences between means, not exceeding a factor of 1.6, that were particularly small for the intercept and steady algorithms (factor of difference $\leq$ 1.35).

The two K_s comparisons between BEST and the PI carried out in this investigation differed from a methodological point of view (comparison between two independent datasets; multiple comparison among six independent datasets) since they had different objectives and particularly i) testing the BEST performances against the most established and accepted infiltration technique for measuring K_s, and ii) assessing the relative performances of six infiltration techniques varying from a near-standard technique (PI) to an almost never tested technique (BB method).

RESULTS AND DISCUSSION

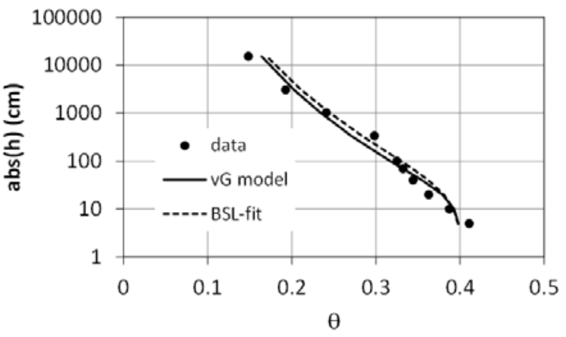
Texture and soil characteristics during the sampling period

The soil was loam at eight sampling points and clay-loam at other two locations (**Table 1**). The dry bulk density ranged from 1.21 to 1.36 Mg m^{-3} during the sampling period, and it varied over an appreciably smaller range (1.21-1.26 Mg m^{-3}) for all but one sampling dates, suggesting that changes in ρ_b were generally small. All field runs were carried out at an antecedent soil water content of $\leq$ 0.19 m^{3}m^{-3}.

Table 1. Sample size, N_s, minimum, *Min*, maximum, *Max*, mean and coefficient of variation, *CV*, of the clay, *cl*, silt, *si*, and sand, *sa*, percentages, gravimetric soil water content, *w*, and dry soil bulk density, ρ_b, sampled at the field site.

Variable	Sampling date	N_s	Min	Max	Mean	CV (%)
cl (%)	15/04/2013	10	21.6	31.3	24.9	12.7
si (%)		10	29.4	42.2	37.4	10.5
sa (%)		10	35.6	40.7	37.7	5.1
w (g g^{-1})	15/04/2013	20	0.11	0.27	0.15	24.1
	29/04/2013	3	0.18	0.19	0.18	1.9
	18/05/2013	3	0.10	0.13	0.11	13.8
	27/05/2013	3	0.10	0.13	0.12	16.2
	08/07/2013	20	0.03	0.08	0.05	23.9
	24/09/2013	2	0.12	0.14	0.13	14.8
	3/10/2013	5	0.07	0.09	0.08	12.1
ρ_b (Mg m^{-3})	15/04/2013	20	1.11	1.57	1.25	10.0
	29/04/2013	3	1.13	1.29	1.21	6.7
	18/05/2013	3	1.17	1.32	1.26	6.1
	27/05/2013	3	1.21	1.53	1.36	12.1
	24/09/2013	2	1.16	1.34	1.25	9.8
	3/10/2013	5	1.15	1.50	1.26	11.2

Figure 1. Measured water retention values, fitted van Genuchten's (1980) model to the measured data points and predicted soil water retention curve with the BSL-fit algorithm.



Testing BEST against independent soil data

Because of a malfunctioning of the laboratory equipment, seven experimentally determined water retention curves were usable. Depending on the pressure head, the coefficient of variation, *CV*, of θ varied from 2.7 to 7.5%. These values were small and consistent with those reported in the literature (e.g., Shouse et al., 1995; Hillel, 1998), supporting the choice to test the BEST procedure against the laboratory measured water retention data.

The vG model fitted well to the data since the coefficient of determination, R^2, was equal to 0.973 and the relative error, *Er*, expressing the quality of the fit (Lassabatère et al., 2006), was of 4.2% (**Figure 1**). The fitted saturated soil water content, θ_s, equal to 0.3996 m^{3}m^{-3}, was lower than the calculated porosity, ϕ, equal to 0.5280 m^{3}m^{-3}. Different investigations have suggested that θ_s should be approximately 85-95% of ϕ (Somaratne and Smettem, 1993; Dane and Hopmans, 2002; Mubarak et al., 2009b; Verbist et al., 2013) but this indication has not a general validity since, for example, Gonzalez-Sosa et al. (2010) determined a mean θ_s/ϕ ratio of 0.7 using θ_s values measured in the field. Therefore, θ_s/ϕ = 0.76 was plausible.

Regardless of the estimate of θ_s (ϕ, fitted value), the BIN and BST algorithms were successful at each sampling point (N_s = 10). The BSL algorithm yielded unacceptable results in a few cases, impeding soil hydraulic characterization at one (with BSL-ϕ) or three (BSL-fit) locations.

In the comparison between the predicted and the measured water retention values, the three BEST algorithms (BSL, BIN and BST) applied with the same θ_s value (ϕ or the fitted value) showed similar performances and, in particular, the BIN and BST algorithms yielded identical

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Table 2. Results of the linear regression analysis between the volumetric soil water content predicted by different BEST approaches for 10 pressure head values, h ($-153 \leq h \leq -0.05$ m), and the laboratory measured volumetric soil water content.

Predictive approach	Regression coefficients			95% confidence intervals		Relative error (%)
	Intercept	Slope	R^2	Intercept	Slope	
BSL-ϕ	0.0029	1.2619	0.9752	–0.05 - 0.05	1.10 - 1.43	27.6
BIN-ϕ and BST-ϕ	–0.0276	1.2522	0.9588	–0.09 - 0.04	1.04 - 1.46	18.2
BSL-fit	0.0278	0.9325	0.9791	–0.01 - 0.06	0.82 - 1.04	4.5
BIN-fit and BST-fit	–0.0127	0.9701	0.9660	–0.06 - 0.03	0.82 - 1.12	8.4

R^2 = coefficient of determination. All R values were > 0 according to a one-tailed t test (P = 0.05).

results since the estimates of θ did not vary between these two algorithms (**Table 2**). This last result was due to the dependence of the h_g scale parameter of the water retention curve on the S^2/K_s ratio, S being the soil sorptivity, that is expected to be the same for both the BIN and BST algorithms (Lassabatère et al., 2006; Bagarello et al., 2014c). All regressions were statistically significant (P = 0.05). With $\theta_s = \phi$, the linear regression line between the predicted and the experimental values was different from the identity line according to the calculated 95% confidence intervals for the intercept and the slope, and high E_r values (18.2-27.6%) were obtained. With θ_s set at the fitted value, all algorithms yielded a linear regression line between the predicted θ values and the data that did not differ from the identity line, and the relative errors were much smaller (Er = 4.5-8.4%).

Therefore, it was possible to detect a satisfactory correspondence of the predicted soil water retention values with the experimental data, and the choice of θ_s was more important than the applied algorithm to reproduce the laboratory measured θ values since signs of a good predictive ability of BEST were only detected when θ_s was set at the indirectly determined experimental value. This last result might represent another support to the robustness of the BEST procedure because a ponding infiltration process, such as the one established with the Beerkan experiment, implies that some air can be entrapped in the sampled soil volume (Reynolds, 1993), physically determining $\theta_s < \phi$. With θ_s = fitted value, the three BEST algorithms showed similar, and consistently acceptable, predictive performances since all algorithms yielded regression lines statistically coinciding with the identity line. However, the BSL algorithm performed slightly better than the other two algorithms since a higher R^2 value and a lower Er value were obtained in the former case. In addition, the water retention curve predicted with BSL was very similar to that obtained by fitting the vG model to the data (**Figure 1**).

The statistical frequency distribution of the K_s data was assumed to be ln-normal, since the normality hypothesis was not rejected for all tested datasets only with reference to the ln-transformed K_s data (**Table 3**). Therefore, geometric means and associated coefficients of variations, CVs, were calculated to summarize the data using the appropriate ln-normal equations (Lee et al., 1985).

From a statistical point of view, the K_s values obtained with BEST and the PI were similar regardless of the applied algorithm (**Table 3**). However, the highest, and almost perfect, similarity between the PI and BEST estimates of K_s was detected with the BIN-fit algorithm, since the means and the associated CVs of K_s differed by 1.9% and 1.6 percentage units, respectively. The largest differences were detected with the BSL-fit algorithm, with means and CVs of K_s differing by 64.0% and 122.1 percentage units, respectively. Therefore, even the K_s comparison allowed to find a good correspondence between the BEST predictions and independent data obtained with a near-standard measurement

Table 3. Results of the normality test and geometric mean and associated coefficient of variation of the saturated soil hydraulic conductivity values, K_s, obtained with the pressure infiltrometer with the TPD approach (PI) and with different applicative scenarios of the BEST procedure of soil hydraulic characterization.

Method	Sample size	Normality test		Mean	Coefficient of variation (%)
		N	LN		
PI	10	yes	yes	97.6a,b,c,d,e,f	113.4
BSL-ϕ	9	no	yes	56.2a	185.9
BIN-ϕ	10	no	yes	133.8b	113.0
BST-ϕ	10	no	yes	111.5c	114.3
BSL-fit	7	yes	yes	35.1d	235.5
BIN-fit	10	no	yes	99.5e	111.8
BST-fit	10	no	yes	82.5f	113.9

N = normality of the untransformed K_s data; LN normality of the ln-transformed K_s data; yes = the normality hypothesis was not rejected at P = 0.05; no = the normality hypothesis was rejected.

Mean values followed by the same letter were compared and the differences were not significant according to a two-tailed t test (P = 0.05).

technique. The appropriateness of using $\theta_s < \phi$ was confirmed but the BEST algorithm allowing a good reproduction of the PI data was not the one best predicting the laboratory measured water retention values. In particular, the algorithm performing best in terms of water retention predictions performed worst with reference to K_s.

The BST-ϕ algorithm yielded practically equivalent K_s values to the BIN-fit algorithm since the means and the *CV*s differed by a negligible 12% and 2.5 percentage units, respectively. This last result reinforced the choice to apply the simplest approach for the K_s comparison among different infiltrometer techniques.

The estimates of a mean K_s obtained with the three BEST algorithms differed at the most by a factor of 2.4-2.8, depending on the assumed θ_s value (**Table 3**), and they decreased with the passage from the BIN algorithm to the BSL one, confirming previous findings (Bagarello et al., 2014c). These levels of difference could be negligible for some practical purposes taking into account that K_s is expected to vary by several orders of magnitude in the field (Elrick and Reynolds, 1992). However the three algorithms also differed in terms of relative variability of the predicted K_s values (*CV*s differing by 1.6-2.1 times, depending on θ_s) and BSL showed a tendency to yield particularly high *CV* values. Therefore, the choice of the BEST algorithm should be expected to have an appreciable impact on the predicted variability of K_s. On the basis of the established comparison with the PI data, the BIN and BST algorithms appear to yield more reliable variability predictions than BSL.

The statistical frequency distribution of the K_{10}, K_{30}, K_{60} and K_{120} data was assumed to be ln-normal, since the normality hypothesis was never rejected for all tested datasets with reference to both the untransformed and the ln-transformed data. This choice allowed to establish a comparison between the geometric mean values of the measured saturated and unsaturated hydraulic conductivities. On the basis of this comparison, a physically impossible K_s value was only detected with reference to the BSL-fit algorithm since K_s = 35.1 mm h^{-1} and K_{10} = 42.5 mm h^{-1} was obtained (**Figure 2**). Therefore, the suspect that the BSL-fit algorithm yielded unreliable K_s values was reinforced by this independent test. The K_s values obtained with both the other BEST procedures and the PI were considered more plausible than those obtained with the BSL-fit algorithm since they were all greater than K_{10}. However, some question about the information contained in the K_s data was legitimate because the $K(h)$ relationship in the pressure head range from 0 to -10 mm appeared to be flatter than expected on the basis of its detected slope in the -10 to -30 mm range.

Figure 2. Soil hydraulic conductivity, *K*, vs. pressure head, *h*, relationship obtained with the Tension Infiltrometer (TI) and comparison with the saturated soil hydraulic conductivity (*h* = 0) obtained with the Pressure Infiltrometer (PI) and different applicative scenarios of the BEST procedure of soil hydraulic characterization. BSL: BEST-slope; BIN: BEST-intercept; BST: BEST-steady; por: saturated soil water content, θ_s, assumed to be equal to the soil porosity; fit: θ_s equal to the fitted value on the basis of the laboratory soil water retention measurements.

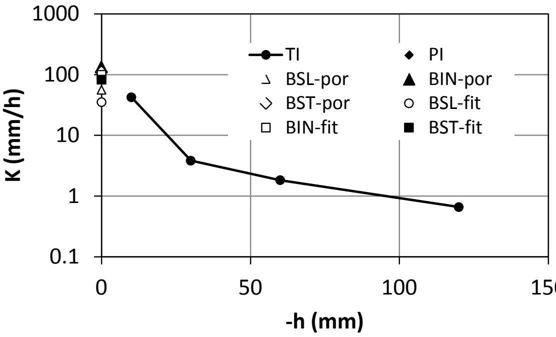
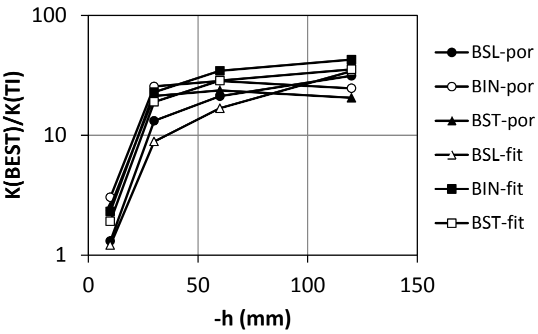


Figure 3. Ratio between the unsaturated soil hydraulic conductivity predicted with different applicative scenarios of the BEST procedure of soil hydraulic characterization, *K*(BEST), and the measured conductivity with the Tension Infiltrometer, *K*(TI), for different pressure head, *h*, values. BSL: BEST-slope; BIN: BEST-intercept; BST: BEST-steady; por: saturated soil water content, θ_s, assumed to be equal to the soil porosity; fit: θ_s equal to the fitted value on the basis of the laboratory soil water retention measurements.



The geometric means of *K* at a given pressure head from -10 to -120 mm were always higher with BEST than the TI, regardless of the applied BEST algorithm and the considered pressure head (**Figure 3**). Differences between the two experimental methods were particularly noticeable for $h \leq$ -30 mm, since BEST yielded *K* values higher by a factor of 9 to 35 than the TI, depending on both the algorithm and *h*. The differences were considerably smaller (i.e., by a factor of 1.2-3.0, depending on the algorithm),

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Table 4. Results of the normality test and geometric mean and associated coefficient of variation of the saturated soil hydraulic conductivity values, K_s (mm h^{-1}), obtained with the Tension Infiltrometer (TI), the Mini Disk tension Infiltrometer (MDI), the Simplified Falling Head technique (SFH), the Bottomless Bucket method (BB), the BEST procedure of soil hydraulic characterization (BEST) and the Pressure infiltrometer (PI).

Method	Sample size	Normality test		Mean	Coefficient of variation (%)
		N	LN		
TI	7	yes	yes	284.3	95.3
MDI	20	yes	yes	236.9	36.1
SFH	10	yes	yes	170.9	122.1
BB	10	no	yes	131.6	98.7
BEST	10	no	yes	111.5	114.3
PI	10	yes	yes	97.6	113.4

All differences between two mean values were not statistically significant according to the Tukey Honestly Significant Difference test (P = 0.05).

and maybe negligible in practice, for the highest pressure head (h = -10 mm). Moreover, these differences were slightly smaller with the algorithms using the fitted θ_s (1.2-2.3) than those setting θ_s at ϕ (1.3-3.0). Therefore, this check confirmed the recent finding by Bagarello et al. (2014a) that the BEST- and the TI-predicted unsaturated soil hydraulic conductivities can be expected to be relatively similar only very close to saturation, probably because the assumed hydraulic conductivity function in BEST does not reproduce satisfactorily the changes in the pore system of a real soil for h < -10 mm. In any case, even this test confirmed that setting θ_s at the fitted value was more appropriate than assuming $\theta_s = \phi$.

In summary, the BIN-fit algorithm performed best among the tested ones for the following reasons: i) relatively good prediction of laboratory measured water retention values; ii) almost perfect correspondence with saturated soil hydraulic conductivity measured with the PI; iii) plausible K_s values, although slightly lower than those expected on the basis of the TI experiment; and iv) ability to reproduce the TI-measured unsaturated soil hydraulic conductivity, but only close to saturation. The BSL-fit algorithm allowed to improve water retention prediction but it was not a good choice for soil hydraulic conductivity prediction.

This investigation was in line with the conclusion by Aiello et al. (2014) that the applicative methodology of the BEST procedure has to be adapted to the particular situation under consideration. Additional developments can be thought, including the choice of the constants of the infiltration model, since Nasta et al. (2012) suggested that a proper choice of these constants should be expected to improve the soil hydraulic parameters estimated with BEST. However, estimation procedures of the constants as a function of soil type have still to be developed. Another point deserving consideration is the representation of the soil as a single-permeability system in the current BEST procedure. This representation could be responsible of the poor matching between predicted and measured unsaturated soil hydraulic conductivity. An extension of the infiltration model used in BEST (Haverkamp et al., 1994) for cumulative infiltration into dual-permeability soils has recently been developed (Lassabatère et al., 2014). Further work should be carried out to derive an adapted BEST method for dual-permeability soils. Then, it should be established if this adaption improves prediction of soil hydraulic conductivity.

Comparing methods to determine saturated soil hydraulic conductivity

Geometric means and associated *CV*s were calculated to summarize the K_s data obtained with the six infiltration techniques since the normality hypothesis was not rejected for all tested datasets only with reference to the ln-transformed K_s data (**Table 4**). The means of K_s varied within a relatively narrow range (98 to 284 mm h^{-1}, i.e by a factor of not more than 2.9) and the relative variability of the K_s data was similar for all tested methods but the MDI one (CV = 36% for the MDI and 95-122% for the other methods). Differences between methods were not statistically significant at P = 0.05 according to the THSD test. This last result, and the suggestion by Elrick and Reynolds (1992) that a difference in K_s by a factor of two or three can be considered negligible for different practical purposes, indicated that the tested methods yielded a similar information on the mean K_s for the sampled area. This was an encouraging result from a practical point of view since it suggested that one of the factors that are known to influence the experimental determination of K_s, i.e. the applied measurement technique, had no more than a reduced impact on K_s determination.

However, an effect of the applied measurement method on the estimated values of K_s was also sensed. The reason was that K_s was highest for the TI and the MDI methods, intermediate for the SFH technique and lowest for the BB, BEST and PI methods, and a difference between these three groups of methods was thought to be possible considering the probability to alter the infiltration surface during the run. In particular, the TI and the MDI were the less perturbing methods since water was applied with a reasonably negligible kinetic energy. With the SFH technique, free water was applied on the soil surface only once. Water was repeatedly applied within the ring with the BB and BEST methods, and a constant head of water was maintained for the PI method with a device making use of the Mariotte bottle principle to supply repeatedly water to the infiltration surface. Therefore, the data suggested that the non-significant decrease of K_s from 284 to 98 mm h^{-1} was due, at least in part, to soil changes during the run. A partial support to this suggestion was given by Bagarello et al. (2012, 2013b), who concluded that a more noticeable disturbance of the infiltration surface should be expected with the PI device than with the SFH technique. Another support was found in an investigation by Assouline and Mualem (2002), which suggested that the distribution of steady-state infiltration rates can be expected to be normal in an unsealed, i.e. undisturbed, soil and log-normal in a sealed, i.e. more or less disturbed, soil. In this investigation, the normal distribution hypothesis of the untransformed K_s data was only rejected with reference to the BB and BEST datasets (**Table 4**), both obtained by a repeated application of a given water volume. In other terms, also the normality test was more or less in line with the suggested interpretation. A practical implication of this investigation is that the tested techniques can be used indifferently to obtain at least an estimate of the order of magnitude of K_s for the sampled soil, but also that using different techniques may allow an improved interpretation and/or simulation of hydrological processes such as rainfall partition into infiltration and rainfall excess (Bagarello et al., 2012, 2013b). The soil initial condition, i.e. before occurrence of rainfall, can be described with the TI, the MDI and maybe the SFH technique because the infiltration run is expected to alter only minimally the infiltration surface. A long and intense rainfall event can disturb appreciably the soil surface and this circumstance can be taken into account in terms of measured K_s, at least approximately, by carrying out a run with a PI device similar to the one used in this investigation or also with the BEST and BB techniques.

Another factor potentially affecting the detected differences between the applied methods to determine K_s was thought to be an incorrect choice of the α^* and λ_c parameters for the calculation of K_s with the SFH technique and the BB method, respectively. However, the choice of $\alpha^* = 4$ m^{-1} ($\lambda_c = 0.25$ m) was found to be appropriate for the sampled field soil since the two-level PI experiment yielded a geometric mean value of α^* equal to 5 m^{-1}, very close to the assumed value for this parameter.

The duration of the infiltration run was another possible factor affecting the observed differences because a longer run can determine more appreciable swelling phenomena, resulting in a decrease of K_s (Bagarello et al., 2012, 2013b). The mean duration of the TI, MDI and SFH test ranged from 4 to 25 min whereas it was of 25 to 112 min for the BB, BEST and PI runs, with the longest runs performed with this last technique. However, the duration was similar (25 min) for the TI and BEST runs. Therefore, lower K_s values were generally obtained with longer runs, although with some exception, suggesting that the run duration was a contributing factor to the observed differences.

Another point to be considered is the appreciably lower variability of the K_s data obtained with the MDI as compared with the other methods. An effect of soil disturbance due to the run cannot be suggested in this case because an appreciably higher *CV* was detected with the TI, similar to the MDI in terms of water application procedure at the infiltration surface. Some soil heterogeneity, such as macropores, likely occurred at the sampled site since even the lowest mean of K_s (98 mm h^{-1}) was approximately an order of magnitude higher than the expected K_s for a soil with a similar loam texture (10.4 mm h^{-1}, Carsel and Parrish, 1988). Therefore, a smaller soil volume was found to be more homogeneous than a larger volume probably because, as suggested by Lai and Ren (2007), the probability to sample only a part of the range of K_s values increases with a smaller source. As a matter of fact, a relatively few runs with the TI yielded K_s values ranging from 57 to 636 mm h^{-1} whereas an appreciably larger number of runs with the MDI yielded a smaller range of K_s values, varying from 127 to 405 mm h^{-1}. An implication of this interpretation is that a larger ring or disc was more appropriate to represent field soil heterogeneity (Bagarello et al., 2013a; Youngs, 1987). Moreover, a source having a diameter of 0.15-0.24 m was enough to give a representation of this variability because all randomly conducted experiments with sources of this size yielded similar *CV* values.

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The measured conductivity with both the TI and the MDI was considered to be the field-saturated soil hydraulic conductivity or very close to K_s for the following reasons: i) a null pressure head was established on the porous plate of the two devices; ii) the contact material layer was thin (i.e, 2-3 mm) for the MDI or the pressure head offset between the membrane of the TI and the soil was explicitly accounted for in setting the pressure head at the soil surface; iii) the data analysis procedure was sound from a theoretical point of view since it was based on a three-dimensional infiltration model (Haverkamp et al., 1994) that is valid for the case of a null pressure head on the infiltration surface; and iv) the "ex-post" check of the data supported the validity of the experimental and theoretical assumptions and procedures because, with the TI, $K_s = 6.7\times K_{10}$ was obtained on average. Therefore, a very small increase of h (from -10 mm to zero or nearly zero) determined much larger conductivities, which is a plausible result in terms of macropore effects on flow transport processes under near-saturated conditions. Moreover, the TI and MDI techniques yielded the highest K_s values among the tested infiltrometer techniques, suggesting that macropores were not excluded from the flow process established with these two devices.

The fact that the same order of magnitude of K_s was obtained with the six tested approaches can be viewed as a sign of robustness of the infiltrometer methods for determining this hydrodynamic parameter. This investigation also confirmed that the intended use of the data has to be taken into account in the choice of the most appropriate measurement method (Verbist et al., 2013; Bagarello et al., 2014b). This topic should further be developed also because some investigations questioned the usability of the infiltrometer data, at least in some circumstances (van de Giesen et al., 2000). Probably, more comparisons should be carried out between experimentally measured hydrological processes (e.g., surface runoff at the base of a plot) and the corresponding processes simulated with mechanistic models and the measured soil hydraulic properties (Aiello et al., 2014; Vandervaere et al., 1998). Another implication of the approximate similarity of the K_s results is that simple methods can be viewed as a good substitute of more demanding methods. This is a promising result since the importance of intensively sampling the soil to obtain a reliable characterization of the porous medium is known (Gómez et al., 2005; Bagarello et al., 2010; 2013c; Verbist et al., 2010) and simple approaches, requiring practically sustainable efforts, appear usable at this aim.

CONCLUSIONS

Comparing different techniques to estimate soil hydraulic properties is frequent in the scientific literature and uncertainties in the data interpretation are more or less unavoidable since reference values of these properties cannot generally be established. However, these comparisons help to understand the information contained in a particular measurement. What we are measuring with a particular method and a specific procedure remains a point to be further developed to improve interpretation and/or simulation of hydrological processes on the basis of the measured soil hydraulic properties.

In this investigation, carried out on a loam soil, the BEST-intercept algorithm with a saturated soil water content, θ_s, appreciably lower than the soil porosity was found to be the best choice, among the tested alternatives, to obtain a reasonably good prediction of laboratory measured water retention values, an almost perfect correspondence with the saturated soil hydraulic conductivity measured with the pressure infiltrometer (PI), plausible K_s values, although slightly lower than those expected on the basis of a multi-potential tension infiltrometer (TI) experiment, and a relatively good reproduction of the unsaturated soil hydraulic conductivity measured with the TI, but only very close to saturation. The θ_s value used for the BEST calculations was obtained in the laboratory and there was no proof that it did coincide with the saturated soil water content at the end of the field infiltration run. Notwithstanding this, sampling the soil confined by the ring at the end of this run to obtain an experimental value of θ_s appears a step of the application procedure of the BEST experiment that could yield a more reliable estimation of soil hydraulic properties in comparison with that obtained with the assumption of coincidence between θ_s and the soil porosity.

BEST, the PI, one-potential experiments with both the TI and the mini disk infiltrometer (MDI), the simplified falling head (SFH) technique and the bottomless bucket (BB) method yielded statistically similar estimates of K_s for the sampled area. However, the methods were not perfectly equivalent probably because they differed by the run duration and determined different levels of soil disturbance at the infiltration surface during the run. The conclusion was that any of the tested technique appears usable to obtain the order of magnitude of K_s at the field site. However, the TI, MDI and SFH data should be considered more appropriate to characterize the soil before wetting by a rainfall event. The BEST, BB and PI data seem more appropriate to characterize a soil at some later stage during a rainfall event.

In conclusion, BEST is promising to simply characterize a soil but additional investigations should be carried out in other soils texturally similar to the sampled soil to understand if the methodology performing reasonably well in this investigation can be suggested for a general use in loam soils. Another point deserving consideration is an improved representation of the unsaturated soil hydraulic conductivity function in the BEST procedure. This investigation suggested that, in general, soil stability upon wetting influences the relative performances of the considered infiltrometer methods to determine K_s. This suggestion could be tested by replicating the experiment in a more stable (or unstable) soil than the loam soil of this investigation. A practical support to the choice of the most appropriate measurement method could also be given by functional evaluation, that involves comparing an experimentally measured hydrological process (i.e., surface runoff at the base of a plot) with the corresponding process simulated with mechanistic models and the measured soil hydraulic properties.

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Appendix I: Soil hydraulic properties determined by infiltration experiments and different heights of water pouring

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ABSTRACT

Establishing the dependence of the soil hydraulic characterization carried out by an infiltration experiment on the procedure used to apply water on the confined soil surface may help to better interpret the collected data and also to develop more accurate strategies for soil hydraulic characterization. Soil was sampled at four Sicilian sites with both the Simplified Falling Head (SFH) technique and the Beerkan Estimation of Soil Transfer parameters (BEST) procedure and two heights of water application (0.03 and 1.5 m). The most appropriate BEST algorithm to analyze the data was determined and the effect of the height of water pouring on the measured soil hydraulic properties was evaluated. The two BEST algorithms, i.e. BEST-slope and BEST-intercept, differed substantially given that 19 and 76 runs out of 80 were successful in the former and the latter case, respectively, and only BEST-intercept was usable for low steady state infiltration rates (i_s < 0.038 mm s^{-1}). The height of water pouring did not affect significantly and/or appreciably the field saturated soil hydraulic conductivity, K_{fs}, measured with the SFH technique (differences between means varying with the site by a factor of 1.2-1.9) but it had an appreciable impact with BEST since low runs yielded higher means than the high ones by a factor of 11.5-35.2. The SFH and BEST techniques showed similarities at most of the sampled sites for a low height of water application (differences by a factor of 1.2-9.3, not exceeding 1.5 at three sites). With a great height of pouring, BEST yielded lower K_{fs} values than the SFH technique by a factor of 12.6-80.8. In conclusion, BEST-intercept is a practical improvement of the original BEST-slope methodology. Water height effects can be appreciable for a given soil and they vary with the applied measurement technique. The relationship between the water pouring height and the measured soil hydraulic properties should also be established for other soils and unsaturated soil water content values.

Keywords: Soil hydraulic properties; SFH technique; BEST procedure; water application

INTRODUCTION

Establishing more or less instantaneously a ponded depth of water on the soil surface is common to many laboratory and field procedures for measuring saturated (K_s) and field saturated (K_{fs}) soil hydraulic conductivity.

Water application procedures can influence measurement of both K_s and K_{fs} due to hydrodynamic shearing determining particle removal and rapid self-filtration of soil particles (Dikinya et al., 2008). A high turbulence at the soil surface promotes detachment of soil particles that become available for sealing the soil surface or for transport by flow, increasing the potential to clog water conducting pores (Assouline, 2004; Bedaiwy, 2008). Therefore, minimizing turbulence at the surface of the soil sample is expected to improve the reliability of the collected data (Lado et al., 2004; Ben-Hur et al., 2009).

The dependence of the measured conductivity on the water application procedure was tested in several laboratory investigations. For a clayey soil, for example, applying the constant head method on a surface protected with coarse sand yielded K_s values that were two times higher than those measured with a non protected surface (Arya et al., 1998). In the experiment by Ramos et al. (2000), the K_s values measured with a simulated rainfall from a height of 2.5 m were lower than those obtained without drop impact by a factor varying with the sampled soil from 47 to 291. For a sandy loam soil, the measured conductivity showed a less pronounced tendency to decrease with time when the ponded depth of water was established by a siphon than a mariotte bottle, determining more turbulence at the surface of the sample (Bagarello et al., 2011a). More specifically, the ratio between the K_s values obtained with a long (6 h) and a short (0.5 h) run was of 0.65-0.88 in the former case and of 0.29-0.47 in the latter one.

To our knowledge, the impact of the water application procedure on the K_{fs} values measured by a field infiltration experiment involving establishment of a ponded depth of water has not been established, although infiltration in an initially unsaturated soil is largely used to characterize soil (e.g., Reynolds and Elrick, 1987, 1990; Bagarello et al., 2004, 2012a; Lassabatère et al., 2006; Nimmo et al., 2009). However, a dependence of the reliability of the field data on the water application procedure is expected, so that several suggestions have been formulated to minimize this impact, including using backfill material, slowly raising the air tube of the device, applying water from a small height, carefully pouring water on the soil surface to a given depth before opening the infiltrometer reservoir, and dissipating the energy of the water on the fingers of the hand or a wire net suspended at a small distance from the infiltration surface, depending on the circumstances (e.g., Reynolds, 1993; Bagarello and Sgroi, 2004).

The Simplified Falling Head (SFH) technique for determining K_{fs} (Bagarello et al., 2004) and the Beerkan Estimation of Soil Transfer parameters (BEST) procedure of complete soil hydraulic characterization (Lassabatère et al., 2006) make use of a field infiltration experiment and they are attractive for practical use since they are reasonably rapid and easy. With the SFH technique, a given, small water volume is applied on the soil surface and the time from the water application to the instant at which all water has infiltrated is used to determine K_{fs}. With BEST, a given, small volume of water is poured in the cylinder at the start of the measurement and the elapsed time during the infiltration is measured. When the amount of water has completely infiltrated, an identical amount of water is poured into the cylinder, and the time needed for the water to infiltrate is logged. The procedure is repeated until the difference in infiltration time between consecutive trials become negligible, signaling a practically steady state infiltration. The interest for these two techniques is evident in the scientific literature. For example, the SFH technique has been applied to monitor temporal changes in K_{fs}, intensively characterize a clay soil at the plot scale, establish comparisons between pasture and forest soils, and detect low yielding zones in agricultural Swedish fields (Bagarello and Sgroi, 2007; Bagarello et al., 2010, 2012b; Agnese et al., 2011; Keller et al., 2012). BEST, allowing a complete hydraulic characterization of unsaturated soil, has been used to characterize temporal variability of soil hydraulic properties under high-frequency drip irrigation, review the soil hydraulic properties of a field sampled in the past, study the effect of sediment accumulation on the water infiltration capacity of two urban infiltration basins, document the spatial variability of the water retention and soil hydraulic conductivity curves in a small watershed, and determine the hydraulic properties of soils that are practically difficult to characterize with other laboratory and field experimental procedures (Mubarak et al., 2009, 2010; Lassabatère et al., 2010; Gonzalez-Sosa et al., 2010; Bagarello et al., 2011b). According to Yilmaz et al. (2010), the original BEST algorithm, named BEST-slope, may lead to erroneous values of K_{fs} especially when a very high level of precision relative to the steady state infiltration rate cannot be obtained. These authors introduced a revised version of BEST (BEST-intercept) to avoid obtaining negative K_{fs} estimates. Xu et al. (2012) suggested that BEST-intercept performs better than BEST-slope but additional testing of these two algorithms is advisable.

Therefore, establishing the effect of the water application procedure on soil hydraulic characterization performed with the SFH technique and the BEST procedure has practical interest. Considering simultaneously these two techniques has the additional advantage that water application effects can be assessed with reference to different field infiltration experiments, involving a single (SFH) and a repeated (BEST) water application. A simple means to test effects of water application on the measured soil hydraulic properties with both techniques is using different heights of water application, since applying water at a relatively long distance from the soil surface is expected to have the potential of altering the infiltration surface more than applying water at a short distance. In any case, water application effects should be established for different soils since porous media differ by their susceptibility to external alteration phenomena (e.g., Ben-Hur et al., 1985; Shainberg and Singer, 1988; Ramos et al., 2000).

The general objective of this investigation was to determine the effect of the height of water application on the hydraulic properties obtained with the SFH technique and the BEST procedure of soil hydraulic characterization at four Sicilian sites. At first, both BEST-slope and BEST-intercept were applied to determine the most appropriate algorithm with reference to the sampled sites. Then, the effect of the height of water application on the field saturated soil hydraulic conductivity obtained with both the SFH technique and the BEST procedure was determined. Finally, this effect was explored with reference to the water retention curve and the hydraulic conductivity function estimated with BEST.

Table 1. Coordinates, land use, management practices, clay (*cl* in %), silt (*si* in %), and sand (*sa* in %) content (USDA classification system) in the 0-0.1 m depth range, soil textural classification, soil organic matter (*OM* in %) content, dry soil bulk density (ρ_b in kg m^{-3}), and initial volumetric soil water content (θ_0 in m^{3}m^{-3}), for the sampled soils at the AR (Palermo), VIL (Villabate), ORL (Palermo) and SPA (Sparacia) sites. Standard deviations are indicated in parentheses

Variable	AR	VIL	ORL	SPA
Coordinates	33S 355511 E 4218990 N	33S 361309 E 4216047 N	33S 355341 E 4219012 N	33S 391172 E 4166165 N
Land use	Citrus orchard	Citrus orchard	Bare soil	Bare soil
Management practices	Conventional tillage	Conventional tillage	Cultivated fallow	Cultivated fallow
cl	17.6(1.9)	14.5(3.3)	29.9(2.8)	71.5(1.8)
si	29.8(2.8)	22.7(2.0)	34.1(1.8)	23.6(1.4)
sa	52.6(4.7)	62.8(1.8)	36.0(1.2)	4.9(0.8)
Textural classification	Sandy loam	Sandy loam	Clay loam	Clay
OM	3.9(0.7)	2.0(0.3)	2.3(0.1)	1.1(0.6)
ρ_b	1127(47.3)	1315(105.3)	1119(61.1)	1076(67.4)
θ_0	0.118(0.01)	0.139(0.02)	0.189(0.02)	0.251(0.05)

MATERIALS AND METHOS

Four Sicilian soils with different physical properties were considered in this study (**Table 1**). According to the USDA classification, a structured sandy loam soil (AR site) and an unstructured clay loam soil (ORL site) were located at the Faculty of Agriculture of the Palermo University. A clay soil (SPA site) was located at the experimental station for soil erosion measurement Sparacia of the University of Palermo, approximately 100 km south of Palermo. A sandy loam soil with a low degree of surface structure (VIL site) was located near Villabate, about 10 km southeast of Palermo. Land use and management practices at each site were summarized in **Table 1**. An area of approximately 150 m^2 was selected at each site and the sampled soil surface was gently levelled and smoothed. At the AR site, the superficial herbaceous vegetation was cut with a knife while the roots remained in situ. Bare areas prevailed at the other sites.

For each site, a total of ten 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 in five randomly chosen sampling points. These cores were used to determine the dry soil bulk density, ρ_b, and the soil water content at the time of sampling, θ_0. The soil porosity, *f*, was calculated from the ρ_b data, assuming a soil particle density of 2650 kg m^{-3}. According to other investigations, the field saturated soil water content, θ_{fs}, was assumed to coincide with *f* (Mubarak et al., 2009; Bagarello et al., 2011b). A disturbed soil sample was also collected from the upper 0.10 m of soil to determine the soil particle size distribution (PSD) and the soil organic carbon content, *OC* (%). The PSD was determined using conventional methods following H_2O_2 pre-treatment to eliminate organic matter and clay deflocculation using sodium hexametaphosphate and mechanical agitation (Gee and Bauder, 1986). The *OC* content, determined by the Walkley-Black method, was used to obtain an estimate of the soil organic matter content, *OM* (%), using the conversion factor of 1.724. **Table 1** summarizes the measured soil properties at each site.

For a given site, the SFH technique was applied at 20 randomly selected points and the infiltration run of the BEST procedure was carried out at other 20 randomly selected points. A ring was inserted to a depth of 0.11 m for the SFH experiment and of 0.01 m for the BEST experiment. A single (SFH technique) or several

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Figure 1. Device used to ensure flow verticality and to prevent wind effects during the runs with a height of water application of 1.5 m

(BEST procedure) volumes of water were then poured on the confined infiltration surface. In particular, 200 or 250 mL of water, depending on the site, were used to apply the SFH technique. This difference was related to the θ_0 and θ_{fs} values for the site, considering that the wetting front should not emerge from the bottom of the confined soil volume (Bagarello et al., 2004). A total of 15 water volumes, each of 64 mL, were poured to apply BEST. The diameter of the rings used in this investigation was particularly small, i.e. equal to 0.085 m for both the SFH and BEST measurements, to more clearly detect possible effects of soil disturbance due to water application. Ring insertion was conducted by gently using a rubber hammer and ensuring that the upper rim of the ring remained horizontal during insertion. The apparent inconsistency between an infiltration run with small, but positive, pressure heads and the zero ponded infiltration model used in BEST was considered negligible by Lassabatère et al. (2006), and this assumption was supported by numerical tests carried out by Touma et al. (2007).

At a given site, 10 SFH runs and 10 BEST runs were carried out by applying water at a small distance from the infiltration surface, i.e. approximately at a height, h_w, of 0.03 m, and dissipating its energy on the fingers of the hand, in an attempt to minimize soil disturbance due to water application (low, L, runs), as is commonly suggested in practical application of an infiltration method (Reynolds, 1993). Water was applied from h_w = 1.5 m at the other 10 sampling points for a given measurement technique (high, H, runs). The soil surface was not shielded in this case to maximize possible damaging effects of water impact. To ensure flow verticality and to prevent wind effects, the device shown in **Figure 1** was used. This device consists of a transparent plexiglass tube with a funnel located in the upper part, supported by an adjustable tripod. A rigid plastic mesh was applied at the bottom of the funnel, in order to disperse water on the infiltration surface, i.e. to reduce the possibility that water converged to a single point or a small area of the sampled surface. The verticality of the pipe was established with a level and the relative distance between the soil surface and the funnel (1.5 m) was verified by a wood folding ruler. All infiltration runs at a site were carried out within one day to exclude any effect of temporal variability on the measured infiltration rates. All data were collected between the spring and summer of 2012, in initially dry or relatively dry conditions (**Table 1**), given that both the SFH technique and the BEST procedure have to be applied on initially unsaturated soil. However, no cracks were visible at the time of the measurements. A site was considered homogeneous in terms of PSD, ρ_b, f, θ_0 and θ_{fs} values. The representative ρ_b, f, θ_0 and θ_{fs} values for a site were obtained by averaging the individual determinations of each variable.

The calculation of K_{fs} for the SFH runs was carried out by assuming an α^* parameter equal to 12 m^{-1}, which is the value of first approximation for most field soils (Elrick and Reynolds, 1992). The acronyms SFH/L (L = low) and SFH/H (H = high) were used to denote the experiments carried out with the SFH technique and h_w = 0.03 m and 1.5 m, respectively. Both BEST-slope (Lassabatère et al., 2006) and BEST-intercept (Yilmaz et al., 2010) algorithms were applied to estimate the soil water retention curve and the hydraulic conductivity function. The acronyms BEST/L and BEST/H were used to denote the experiments carried out with the BEST procedure and h_w = 0.03 m and 1.5 m, respectively.

Data sets were summarized by calculating the mean, M, and the associated coefficient of variation, CV. In particular, the arithmetic mean and the associated CV were calculated for cl, si, sa, OM, ρ_b, θ_0 and θ_{fs}. For K_{fs}, the statistical frequency distribution of the data was assumed to be log-normal, as is common for this variable (e.g. Mohanty et al., 1994; Warrick, 1998), and geometric means and associated *CV*s were calculated using the appropriate “log-normal equations” (Lee et al., 1985).

At first, a comparison between BEST-slope and BEST-intercept was carried out, in terms of both successful runs and quality of the fitting of the experimental data to the transient infiltration model, to choose the most appropriate algorithm with the considered dataset, given that they are expected to differ, especially when a very high level of precision relative to steady state infiltration rate cannot be obtained (Yilmaz et al., 2010). Taking into account that the SFH technique only allows estimating K_{fs}, the effect of the water application on the field saturated soil hydraulic conductivity obtained at the four sites with the two measurement technique, i.e. SFH and BEST, was then assessed. Finally, a comparison between the soil hydraulic characteristic curves obtained with BEST and the two heights of water application was carried out for each site. For a given height of water application, a mean water retention curve was obtained by calculating, for a set of pre-established pressure heads, the arithmetic mean of the estimated soil water content at each sampling point. A similar procedure was applied for the soil hydraulic conductivity curve. In this case, however, geometric means were calculated for a set of pre-established θ values.

RESULTS AND DISCUSSION

BEST-intercept vs. BEST-slope

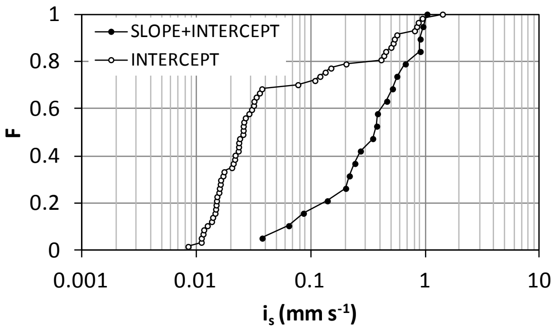
The two BEST algorithms, i.e. BEST-slope (Lassabatère et al., 2006) and BEST-intercept (Yilmaz et al., 2010), differed substantially given that 19 and 76 runs out of 80 were successful, i.e. yielded physically possible estimates of soil hydraulic properties, in the former and the latter case, respectively (**Table 2**). The difference between the two algorithms was particularly noticeable for the H (h_w = 1.5 m) runs since BEST-slope failed in all cases but one while BEST-intercept was always successful. A total of 19 runs were found to be analyzable with both versions of BEST but 57 runs were only analyzable with BEST-intercept and four runs were not analyzable with any version of BEST.

BEST-slope was suggested to be an inappropriate approach when a measured term, i.e. the steady state infiltration rate, i_s, approaches a calculated term, i.e. AS^2, where A is a coefficient and S is the soil sorptivity that varies with the applied algorithm, although marginally (Yilmaz et al., 2010). Therefore, it is practically useful establishing if the applicability of the two algorithms can only be predicted on the basis of i_s. Of the 41 runs with $i_s \geq 0.038$ mm s^{-1}, 19 runs were analyzable with both algorithms, 18 were only analyzable with BEST-intercept (**Figure 2**) and four runs were not analyzable. However, only BEST-intercept was usable for $i_s < 0.038$ mm s^{-1}. Therefore, i_s was usable to make a preliminary choice of the algorithm to be applied. In particular, both algorithms should be tested for relatively high i_s values but only BEST-intercept is expected to be usable for low steady state infiltration rates.

Table 2. Number of successful runs with the two algorithms to analyze the BEST experiment for each site and water application height (N = 10 runs for a given height at a site)

Site	Height (m)	BEST-slope Lassabatère et al. (2006)	BEST-intercept Yilmaz et al. (2010)
AR	0.03	7	7
	1.5	0	10
VIL	0.03	1	10
	1.5	1	10
ORL	0.03	4	10
	1.5	0	10
SPA	0.03	6	9
	1.5	0	10

Figure 2. Cumulative empirical frequency distribution of the steady state infiltration rate, i_s, values for the runs allowing a complete soil hydraulic characterization with both the BEST-slope and BEST-intercept algorithms and only with BEST-intercept



A preliminary evaluation of the expected reliability of a soil hydraulic characterization performed with BEST can be carried out by calculating the relative error, E_r (%), with eq.(26) by Lasabatère et al. (2006) to express the quality of the data fitting on the transient cumulative infiltration model. Large errors may occur, for example, if the assumed infiltration model is not appropriate for the sampled soils or the data have a poor quality (Bagarello et al., 2011b). With BEST-intercept, the E_r values were higher for the H runs ($7.3 \leq E_r \leq 36.1\%$, M = 21.0%, median, Md = 19.3%) than the L ones ($1.6 \leq E_r \leq 26.7\%$,

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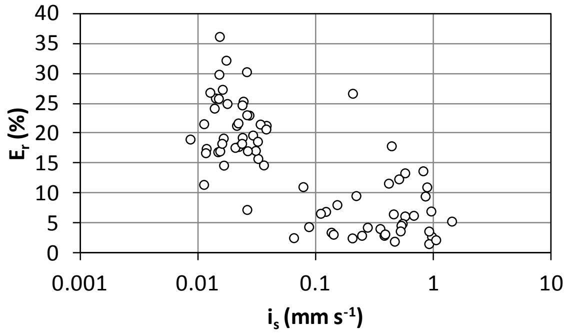
Figure 3. Relative error of the fitting of the infiltration model to the data, E_r, against steady state infiltration rate, i_s



M = 7.1%, Md = 5.4%) but they were generally higher than the threshold value (E_r = 3.5%) used to discriminate between a good and a poor fitting of the data (Lassabatère et al., 2006), particularly in soils with low i_s values **(Figure 3**). A possible factor determining this result was that, in low permeability conditions, establishing the exact application time of the new volume of water was not easy because ponding conditions did not disappear uniformly from the infiltration surface. Due to this circumstance, some uncertain in the measured cumulative infiltration curve was unavoidable. Another possible reason of the relatively poor fitting was that a small diameter ring was used. A repeated perturbation of a small soil surface can be expected to determine a greater departure of the sampled porous medium from the ideal one assumed by the theory. For 15 (or 79%) of the 19 runs that were analyzable with both algorithms, BEST-intercept yielded a higher E_r value than BEST-slope, with a mean and a median of the ratio between corresponding E_r values equal to 1.21 and 1.11, respectively. Higher errors (50-60%) than the ones obtained in this investigation have been reported in the literature for both BEST-intercept and BEST-slope (Xu et al., 2012).

On the basis of the existing criteria, soil hydraulic characterization performed with BEST-intercept should be considered uncertain for most runs, since high E_r values were generally obtained. However, the impact of the relative error on the reliability of the soil water retention and hydraulic conductivity predictions is still unknown. In other words, there is no proof that a high E_r value implies a poor soil hydraulic characterization, although it appears a plausible assumption. Moreover, BEST-intercept performed slightly worse than BEST-slope in terms of fitting quality. Notwithstanding this, the adapted BEST method by Yilmaz et al. (2010) was considered to be a practically important improvement of the methodology originally proposed by Lassabatère et al. (2006), since it was the only algorithm usable to analyze almost all infiltration runs and to characterize soils with a very small steady state infiltration rate. Therefore, the BEST-intercept results were considered for the subsequent analysis.

Field saturated soil hydraulic conductivity

The mean K_{fs} values obtained at a site with the SFH and BEST techniques and two heights of water application (0.03 and 1.5 m) varied by 17 to 106 times, depending on the site (**Table 3**). Changes in $M(K_{fs})$ were lower for the relatively coarse textured soils (maximum factor of difference $\leq$ 35, AR and VIL sites) than the finer ones (maximum factor of difference $\geq$ 81, ORL and SPA sites). Therefore, the applied K_{fs} measurement technique and the height of water application had a noticeable impact on the measured conductivity, especially in the soils with a fine or relatively fine texture.

The height of water pouring did not have a statistically detectable effect on the K_{fs} values obtained with the SFH technique at three (i.e. AR, ORL and SPA) of the four sampled sites (**Table 3**). At the VIL site, the SFH/L runs yielded higher K_{fs} values than the SFH/H ones by a significant factor of 1.9. In the passage from h_w = 0.03 m to h_w = 1.5 m, $CV(K_{fs})$ did not change appreciably at the two sites established on sandy loam soils (AR, VIL) and it clearly decreased in the finer textured soils. On the other hand, the height of water application affected the K_{fs} values obtained with BEST at all sampled sites (**Table 3**), with the low runs yielding higher means than the high ones by a factor of 11.5-35.2, depending on the site. In the passage from low to high runs, $CV(K_{fs})$ decreased at all sites, although this decrease varied with the site, being small at the SPA site and particularly noticeable (i.e. by approximately three times) at the ORL site. With h_w = 0.03 m, the SFH and BEST techniques yielded not significantly different K_{fs} values at the AR and SPA sites. The differences were significant at the VIL site, with BEST yielding a 1.5 times higher $M(K_{fs})$ value as compared with the SFH technique, and at the ORL site, where the SFH technique overestimated $M(K_{fs})$ by a factor of 9.3 as compared with BEST. With h_w = 1.5 m, the SFH technique yielded significantly higher K_{fs} values as compared with BEST, with differences between the two techniques by a factor varying with the site from 12.6 to 80.8.

Table 3. Sample size (*N*), minimum (*Min*), maximum (*Max*), mean, and coefficient of variation (*CV*, in %) of the field saturated soil hydraulic conductivity, K_{fs} (mm h^{-1}), values obtained with the SFH and BEST experiments by pouring water into the cylinder from two different heights

Experiment	Height (m)	Statistic	Site			
			AR	**VIL**	**ORL**	**SPA**
SFH	0.03	N	10	10	10	10
		Min	252.2	352.3	270.1	15.2
		Max	509.8	993.8	4140.9	4473.0
		Mean	432.7 a c	555.6 A C	1256.9 a C	819.9 a c
		CV	21.5	32.9	126.9	631.6
	1.5	N	10	10	10	10
		Min	243.1	130.5	358.3	124.3
		Max	557.7	461.4	1490.7	4025.7
		Mean	374.2 a D	296.8 A D	665.1 a D	1300.9 a D
		CV	27.6	41.3	47.1	132.6
BEST	0.03	N	7	9	10	10
		Min	297.5	452.9	68.0	182.7
		Max	783.0	1139.3	438.5	1151.6
		Mean	504.8 B c	827.9 B C	135.3 B C	471.4 B c
		CV	35.7	33.0	67.2	63.8
	1.5	N	10	10	10	10
		Min	21.3	16.6	7.9	12.0
		Max	36.9	34.0	16.3	61.9
		Mean	29.0 B D	23.5 B D	11.8 B D	16.1 B D
		CV	17.9	21.2	23.0	52.5

Within-site statistical comparisons were carried out. For a given site (i.e., within a column), the values followed by the same upper case letter were significantly different according to a two tailed t test (P = 0.05). The values followed by the same lower case letter were not significantly different.

Taking into account that a difference between K_{fs} values by a factor of two or three can be considered negligible for most practical applications (Elrick and Reynolds, 1992), this investigation suggested that the height of pouring did not affect significantly and/or appreciably the measured conductivities with the SFH technique. On the other hand, the height of water application influenced significantly and substantially the measured conductivities with BEST. The SFH and BEST techniques showed similarities (not significant differences, significant but practically negligible differences) at most of the sampled sites when the height of water application was low. With a great height of pouring, the BEST technique yielded substantially lower K_{fs} values than the SFH technique.

Different flow dimensionality between the two techniques (1D for SFH, 3D for BEST) could be thought to be a source of method discrepancy, especially in anisotropic soils. However, this should not be more than a minor factor affecting the method comparison because it has been established that ring infiltrometers measure mainly vertical soil water transmission parameters (Reynolds and Elrick, 2005). A support to this statement can be found in Touma et al. (2007) who used rings driven 0.4-0.5 cm into the soil for determining soil hydraulic properties usable in the prediction of vertical infiltration.

Some discrepancies between the SFH and BEST techniques could also be attributed to an incorrect choice of the α^* parameter for the SFH calculations. For the soils at the ORL and SPA sites, in particular, an α^* of 4 m^{-1} could be considered more appropriate than 12 m^{-1} on the basis of soil textural considerations (Elrick and Reynolds, 1992; Reynolds, 1993). However, this last value was used in this investigation for the following reasons: i) in the numerical simulations of a ponding infiltration process carried out by Reynolds and Elrick (1990), an α^* of 4 m^{-1} was considered representative of a porous medium with K_{fs} = 0.036 mm h^{-1}, and higher α^* values were associated with more permeable soils. In this investigation, the independent BEST experiment yielded means of K_{fs} not lower than 12 mm h^{-1}, suggesting that α^* = 4 m^{-1} was too low for the SFH calculations; ii) Reynolds et al. (1992) concluded that α^* = 10-12 m^{-1} should be appropriate for most field soils on the basis of a dataset including fine textured and weakly structured soils; iii) the first approximation α^* value was successfully used in other fine textured soils characterized by lower K_{fs} values than the ones obtained in this investigation (Reynolds and Zebchuk, 1996), and iv) the sensitivity of the K_{fs} calculations to the α^* parameter is not expected to be substantial (Bagarello et al., 2004).

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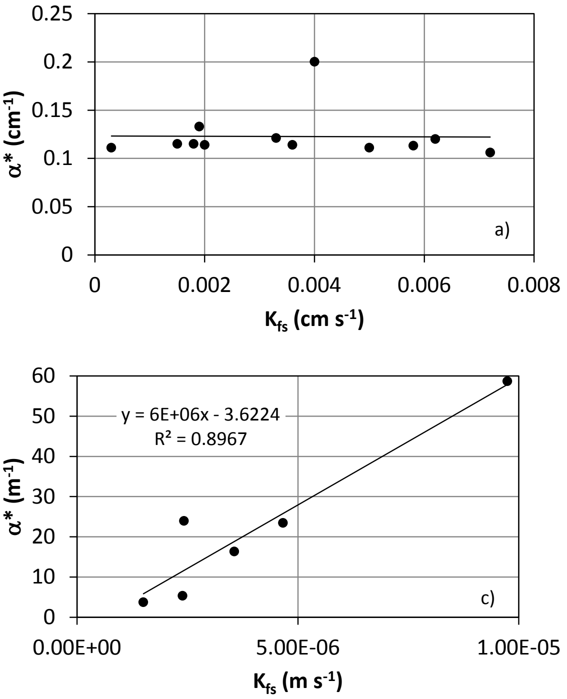
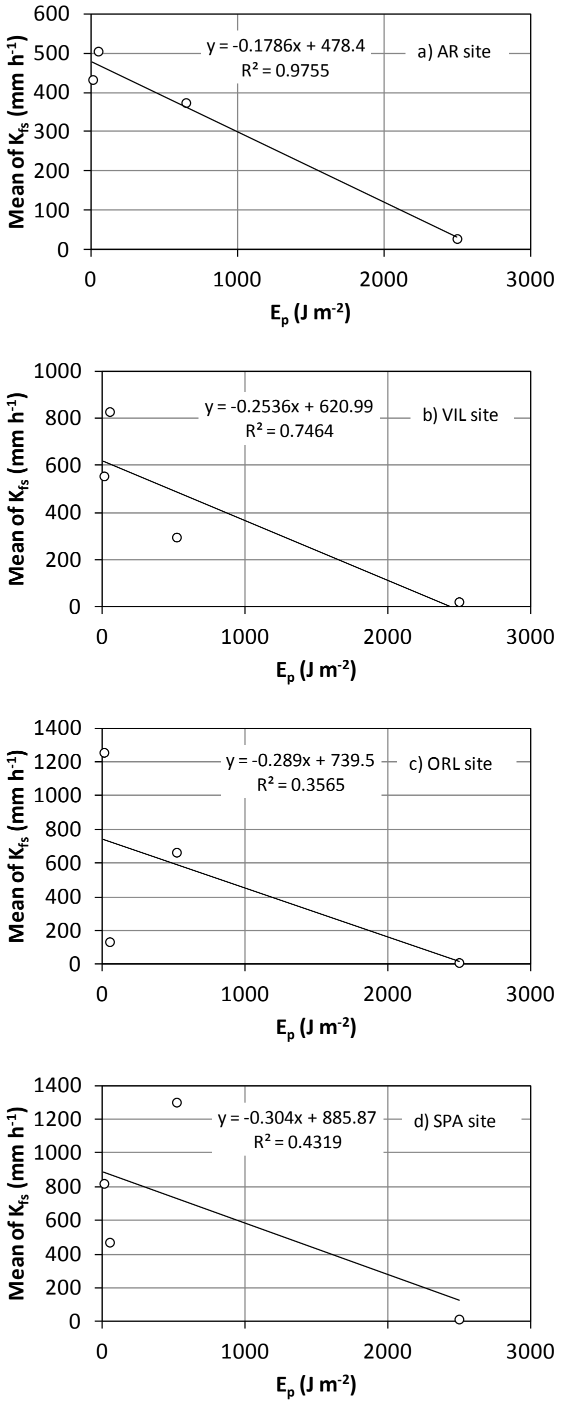
Figure 4. Relationship between the α* parameter and the field saturated soil hydraulic conductivity, K_{fs}, obtained by using a) the Guelph permeameter (GP) data published by Paige and Hillel (1993) in their Tables 1 and 2; b) the GP data listed by Reynolds and Elrick (1985) in their Table 3 (well radius = 0.02 m); c) the GP data listed by Reynolds and Elrick (1985) in their Table 4 (well radius = 0.03 m); and d) the single ring pressure infiltrometer data obtained by Bagarello et al. (2013) in several Sicilian soils



The link between α* and K_{fs} (first reason) necessitates a specific discussion. From a theoretical point of view, the α* parameter, which is indicative of the relative importance of the field-saturated and capillarity components of steady flow (Reynolds et al., 1992), is not functionally related to K_{fs}. Reynolds (2011) stated that α* is independent of the K_{fs} value when the $K(h)$ function has K_{fs} as a multiplier, which is the case of the van Genuchten's (1980) model (Reynolds, 2011) but also of the Gardner's (1958) relationship. Experimental data indicating that α* is independent of K_{fs} can be found in the literature. For example, **Figure 4a** shows the relationship between these two variables obtained with the data published by Paige and Hillel (1993, their Tables 1 and 2). Low α* values are typical of soils where the proportion of steady flow due to capillarity is relatively high whereas high α* values occur in soils where this proportion is relatively small. The relative importance of the two components of steady flow is expected to depend on soil texture and structure (Elrick and Reynolds, 1992). A link between α* and K_{fs} can be expected because K_{fs} also depends on soil textural and structural characteristics. According to Reynolds and Elrick (1990), α* increases monotonically from 1 to 36 m^{-1} as K_{fs} increases from 1×10^{-9} (clay cap/liner) to 1×10^{-4} m s^{-1} (sand soil). This relationship appears logical from a physical point of view. Soils with a low capillarity (high α*) include "coarse and gravelly sands; may also include some highly structured soils with large and/or numerous cracks and biopores" (e.g. Table 1 by Reynolds, 2010). In addition, a high α* value corresponds to an initially steep $K(h)$ relationship (Reynolds, 1994), that is a signal of the fact that a small decrease in pressure head is enough to determine a substantial pore emptying. This phenomenon can only occur if the pores are large or relatively large. Therefore, soils with high α* values have high K_{fs} values, as clearly stated by White and Sully (1992). On the other hand, soils with a high capillarity (low α*) include "porous materials that are both fine textured and massive; includes unstructured clayey and silty soils, as well as very fine to fine structureless sandy materials". In addition, a small α* value corresponds to an initially flat $K(h)$ relationship, that is a signal of a less appreciable pore emptying as the pressure head decreases. This can occur when pores are small. Therefore, small α* values are associated with fine textured, fine structured or compacted soils (Reynolds, 2011) that are expected to have small K_{fs} values. Using the valid K_{fs} and ϕ_m calculations obtained by Reynolds and Elrick (1985, Table 3, well radius = 0.02 m), a clear relationship between α* and K_{fs} was not detected (**Figure 4b**). However, α* $\leq$ 5.5 m^{-1} was obtained for low K_{fs} values ($\leq 4.92\times10^{-7}$ m s^{-1}) whereas α* varying between 22 and 82 m^{-1} was obtained for high K_{fs} values ($\geq 1.26\times10^{-6}$ m s^{-1}). Using the data published in Table 4 of the above mentioned article (well radius = 0.03 m, **Figure 4c**), an increasing relationship between the two variables was found. Figure 2 by Reynolds et al. (1992) shows a plot of α* versus $\log_{10} K_{fs}$ for four different soils. According to these Authors, α* was essentially constant for a structureless loamy sand soil, and it increased, mildly or substantially (in a single case), with K_{fs} for the other soils. Therefore, an increasing relationship was the most common result in that investigation. Finally, **Figure 4d** shows the α* vs. K_{fs} relationship obtained by considering single ring pressure infiltrometer data collected in several Sicilian soils (Bagarello et al., 2013). The fitted line suggests an increasing relationship between the two variables. Perhaps, a more scientifically exhaustive assessment of α* should be carried in the near future, also considering that this parameter i) seems to be directly comparable with parameters of the water retention curve (i.e., Mubarak et al., 2010), and ii) has a noticeable practical interest since it is included in many equations allowing rapid calculations of K_{fs} (Elrick and Reynolds, 1992; Reynolds and Elrick, 1990; Bagarello et al., 2004, 2012a; Nimmo et al., 2009; Wu et al., 1999).

Figure 5. Relationship between the mean field saturated soil hydraulic conductivity, K_{fs}, values and the gravitational potential energy, E_p, of the water for the four sampled sites



The larger influence of the height of water application on the measured conductivity for BEST than the SFH technique was consistent with the fact that water was repeatedly applied on the exposed soil surface in the former case while water was applied only once in the latter case. In other terms, there were more opportunities to alter the soil surface with BEST than the SFH technique.

Droplet impact during a rainfall event can modify surface soil hydraulic conductivity (Somaratne and Smettem, 1993; Assouline and Mualem, 1997), and models of transient soil surface sealing and infiltration establish that, for a given soil, the final saturated conductivity depends on the cumulative energy of the applied water (e.g., Brakensiek and Rawls, 1983; Shainberg and Singer, 1988; Mualem et al., 1990; King and Bjorneberg, 2012). In this investigation, the gravitational potential energy, E_p, of the water used for a run was calculated taking into account that both the mass of water and the height of fall were known. The highest and the lowest values of E_p were obtained for the BEST/H (E_p = 2500 J m^{-2}) and SFH/L (E_p = 10-13 J m^{-2}, depending on the sampled site) experiments, because a relatively large water volume was applied at a considerable distance from the soil in the former case whereas a relatively small water volume was applied at a short distance from the soil surface in the latter one. The BEST/L and SFH/H experiments were characterized by intermediate E_p values equal to 50 J m^{-2} and 520-650 J m^{-2}, respectively. Changes in $M(K_{fs})$ at a sampled site were explained by E_p (**Figure 5**) at the AR site (R^2 = 0.98, R > 0, P = 0.95) and, less satisfactorily, at the VIL one (R^2 = 0.75, R > 0, P = 0.90). The means of K_{fs} were not significantly correlated with E_p at the ORL (R^2 = 0.36) and SPA (R^2 = 0.43) sites. Several investigations have suggested that soil disturbance due to establishment of a ponded head at the soil surface is a dynamic phenomenon (Dikinya et al., 2008; Bagarello et al., 2011a). Therefore, for a given water volume and a fixed height of application (i.e., for a given E_p value), the soil surface can be expected to be more disturbed if water is applied by different amounts poured in succession rather than in a single application. To test this possibility, the BEST/L and BEST/H experiments were considered and the mean infiltration times for both h_w = 0.03 m, Δt_L, and h_w = 1.5 m, Δt_H, were calculated for each applied water volume. The $\Delta t_H/\Delta t_L$ ratio was found to

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increase with the number of the applied volumes of water, N_v, for all soils (**Figure 6**). Therefore, Δt_H increased more than Δt_L at each successive water application, supporting the hypothesis of a progressive deterioration of the infiltration surface with the repeated application of a given volume from a great height. For the relatively coarse textured soils at the AR and VIL sites, $\Delta t_H/\Delta t_L$ increased with N_v until the end of the run, suggesting that soil deterioration phenomena were not completed by the application of 15 water volumes. For the relatively fine textured soils at the ORL and SPA sites, a plateau was approximately detectable on the $\Delta t_H/\Delta t_L$ vs. N_v plot after having applied 9-10 water volumes, suggesting that soil deterioration was practically completed, or it became independent of *h*, before concluding the infiltration run. Therefore, each water application generally contributed to alter the soil surface and the energy of the applied water was a more appropriate predictor of the expected changes in K_{fs} when soil deterioration was not completed in the early stage of the infiltration run.

For the SFH technique, a linear regression analysis of the ratio between the mean Kfs values obtained with low and high runs, $K_{fsL/H}$, against the mean *cl*, *si*, *sa*, *OM* and ρ_b values of each soil

Figure 6. Ratio between the mean infiltration time for a water application height of 1.5 (Δt_H) and 0.03 (Δt_L) m during the BEST runs plotted against the number of the applied volumes of water for the four sampled sites

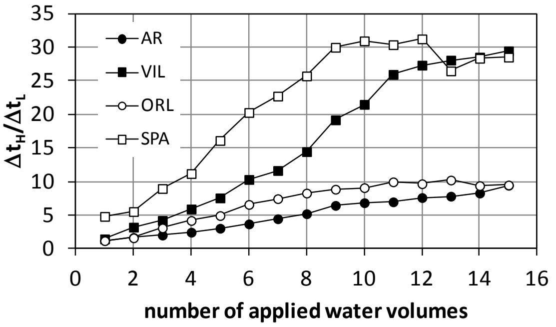
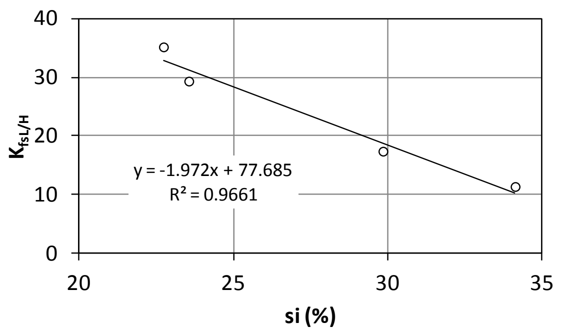


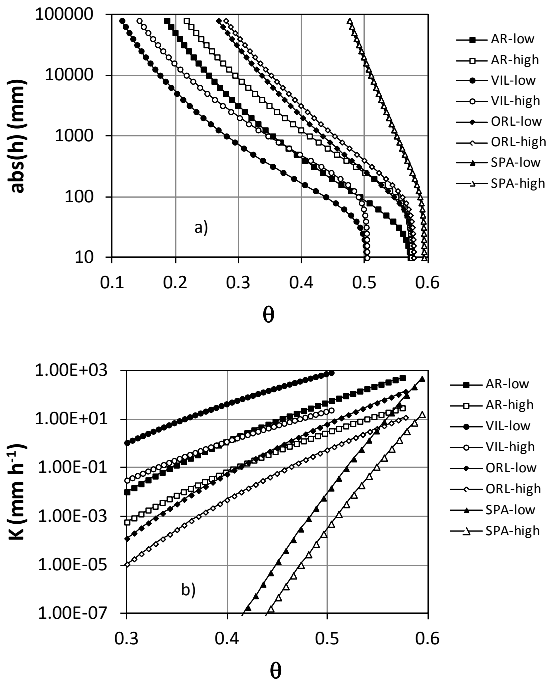
Figure 7. Ratio between the mean K_{fs} values obtained with low and high runs by the BEST procedure, $K_{fsL/H}$, against the mean silt, *si*, content of the soil



did not allow to detect statistically significant relationships since the coefficients of determination, R^2, did not exceed 0.57 (N = 4). This result was not surprising taking into account that the height of water application did not affect appreciably the K_{fs} values obtained with the SFH technique. Repeating the same analysis with the BEST results allowed to find a single statistically significant relationship showing a decrease of the $K_{fsL/H}$ ratio with an increase of the silt content (**Figure 7**). According to the fitted relationship, the height of water application had a lower impact on soils with a high silt percentage. An inverse relationship between saturated soil hydraulic conductivity and silt content can be expected (Ramos et al., 2000) and the soils with high silt content are known to have a low aggregate stability (Wischmeier et al., 1971). Therefore, $K_{fsL/H}$ decreased with *si* probably because even the BEST/L run was enough to alter a soil with a relatively high silt content. The comparison between the BEST/L and SFH/L experiments supported this interpretation because it suggested that even a relatively small perturbing action was enough to reduce the field saturated hydraulic conductivity of the soil with the highest silt content (ORL site) by approximately an order of magnitude.

The saturated soil hydraulic conductivity could be considered an objectively and rigorously measurable soil property, according to the Darcy's law. If it is accepted that the permeability of a saturated soil represents an intrinsic property of the porous medium, then an obvious implication is that the best measurement process is a process that does not alter, neither minimally, the measured body. However, an unbounded literature shows that this parameter is extremely sensitive to many factors, including sample size, flow geometry, sample collection procedures, and various soil physical-hydrological characteristics (e.g., Bouma, 1983; Bagarello, 1997; Reynolds et al., 2000). Therefore, different measurement methods and application procedures often yield substantially dissimilar data. Moreover, the measured conductivities could be considered equivalent values, since they represent the conductivity of a hypothetical (i.e., rigid, homogeneous, isotropic) porous medium characterized by the actually measured flow process on a real soil (Nimmo et al., 2009; Bagarello et al., 2010). Therefore, attempting to find a single reference or standard method, i.e. equally appropriate for all applications, soil types and soil conditions, appears pointless in practice because this method does not seem to exist (Bouma, 1983). Instead, it is important to improve our ability to interpret the conductivity data with the objective to find the most appropriate measurement method and application procedure of a particular method for both the soil conditions and the intended application of the survey (Reynolds et al., 2000). In other words, more efforts should be centered around establishing what information is contained in a particular point measurement, with the obvious premise that it does not contain uncertainties of methodological or analytical nature, to find the "suite" of methods appropriate for a particular field program (Reynolds and Elrick, 2005). Many contributions can be set in this frame. Only to give an example, it is by now commonly accepted that K_{fs} is more appropriate than the hydraulic conductivity of a completely saturated soil (K_s) when natural and man-made infiltration processes have to be interpreted or simulated (Reynolds, 1993). However, it is also known that small changes in the entrapped air content may have an appreciable impact on the measured conductivity (Sakaguchi et al., 2005). Therefore, K_{fs} is still a more vaguely defined parameter than K_s. Assessing experimental methods and procedures is complicated by the fact that the measurement process itself can have an influence on the measurement outcome, through effects such as particle re-arrangement and other structural changes (e.g., Dikinya et al., 2008; Nimmo et al., 2009; Bagarello et al., 2011a). Notwithstanding this, comparisons between alternative methods and application procedures provide one of the few sources of information that practitioners can draw upon to select methods and procedures appropriate for their circumstances (Reynolds et al., 2000). A method comparison is unavoidably difficult to interpret because differences are expressive of a global effect that could theoretically be attributed to different, and perhaps many, factors. On the other hand, an experiment in which a single factor of the measurement procedure is allowed to vary appears an effective strategy to improve our knowledge of the information contained in a given data point, at least if possible effects of spatial variability are removed or minimized by choosing an appropriate number of replicated measurements (Warrick, 1998). An example is the investigation by Youngs (1987), where infiltration measurements were carried out with rings of different diameters to establish the ring size effects on the measured conductivity. With this perspective, a low run with the SFH technique appears more appropriate to characterize the soil at the beginning of a rainfall event yielding surface runoff. A low BEST run could also be used, with the possible exception of the more silty soils, whereas a high BEST run appears more suitable to characterize the soil after a prolonged and intense rainfall. Another way to look at the results of this investigation is that they are expressive of what can happen with a rough application of a measurement method. In particular, the SFH technique is appreciably less sensitive to inaccuracies of experimental nature as compared with the BEST procedure.

Figure 8. Soil characteristic curves predicted by BEST at the four sampled sites with different heights of water application: a) water retention curves, and b) soil hydraulic conductivity functions



Soil water retention curve and hydraulic conductivity function

In general, increasing the height of water application altered the estimated soil water retention curve (van Genuchten, 1980; Burdine, 1953), since the water content, θ, corresponding to a given pressure head, h, increased (**Figure 8**). This effect was more appreciable for the VIL soil, with a maximum (*max*) percentage difference between the two θ predictions for a given h of 23.7% (M = 17.5%), and the AR one (*max* = 16.5%, M = 13.0%). The difference between the two water retention curves was less noticeable for the ORL soil (*max* = 4.4%, M = 3.3%), and it was

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negligible for the SPA soil (max = 0.14%, M = 0.10%). According to the assumed soil hydraulic conductivity model (Brooks and Corey, 1964), the hydraulic conductivity curves for a soil differed by a constant factor, equal to the ratio between the K_{fs} values obtained with the L and the H runs. Therefore, this investigation suggested that the height of water application affected both soil characteristic curves in the relatively coarse textured soils but only the hydraulic conductivity function in the fine textured soil.

The comparison established in this investigation in terms of soil characteristic curves was approximate, because a possible influence of the height of water application on the dry soil bulk density, affecting calculation of the shape parameters, and the saturated soil volumetric water content, influencing both characteristic curves, was not taken into account. However, all predicted changes were consistent with a pore size reduction, that was considered plausible since pore clogging and compaction phenomena are expected consequences of raindrop impact (Somaratne and Smettem, 1993), approached by a high run in this investigation. In other words, BEST allowed to obtain a reasonably reliable picture of what happens in terms of soil hydraulic characteristic curves with a change in the applied forces at the soil surface, notwithstanding that the effect of the water application height was only considered with reference to the infiltration experiment.

In this investigation, the soil at a site was sampled once and in a short period of time, to avoid temporal variability effects on the measured soil hydraulic properties. However, soil alteration phenomena due to rapid wetting of an initially unsaturated soil can be expected to depend on the soil water content at the time of sampling because, according to different Authors, initially moist soil aggregates can be more stable than initially dry aggregates (e.g., Boix-Fayos et al., 1998; Cerdà, 1998; Salvador-Sanchis et al., 2008). Establishing a ponded flow process through an initially very dry soil sample may promote particular soil structure alteration due to aggregate disintegration induced by different mechanisms and processes (e.g., swelling, aggregate explosion caused by rapid compression of entrapped air) that add to the ones due to the mechanical action of the moving water. Therefore, the relationship between the water application procedure and the estimated soil hydraulic properties should be established in the future with reference to a range of unsaturated soil water conditions.

SUMMARY AND CONCLUSIONS

Soil was sampled at four Sicilian sites with both the SFH technique and the BEST procedure of soil hydraulic characterization and two heights of water application (0.03 and 1.5 m). The most appropriate BEST algorithm to analyze the data was determined and the effect of the height of water pouring on the measured soil hydraulic properties was assessed.

BEST-intercept was found to represent a practically important improvement as compared with the original BEST-slope algorithm since characterization of soils with a very small steady state infiltration rate was only possible with the former approach. This characterization was expected to be rather approximate because the fitting quality of the infiltration model to the data was satisfactory only in a few cases. However, the relationship between the reliability of the estimated soil hydraulic properties and the fitting performance of the infiltration model to the data needs specific assessment, since it is still unknown.

The height of pouring did not affect significantly and/or appreciably the measured conductivities with the SFH technique. On the other hand, the height of water application influenced significantly and substantially the measured conductivities with BEST, with the low runs yielding higher means than the high ones by a factor of 11-35, depending on the site. The SFH and BEST techniques showed similarities at most of the sampled sites when the height of water application was low. With a great height of pouring, the BEST technique yielded substantially lower K_{fs} values than the SFH technique. The different sensitivity of the two techniques to water application height was attributed to the fact that water was applied once with the SFH technique and several times with the BEST procedure. Each water application generally contributed to alter the soil surface, and total energy of the applied water was a more appropriate predictor of the changes in K_{fs} when soil deterioration was not completed before concluding the infiltration run. Water height effects detected with a given technique cannot be considered of general validity, i.e. independent of the K_{fs} measurement technique, for a particular soil.

The height of water application affected both the water retention curve and the hydraulic conductivity function in the relatively coarse textured soils, since high runs determined an increase in the stored water and a reduced ability to transmit water. Only the hydraulic conductivity function changed in the fine textured soil. All predicted changes were consistent with a pore size reduction, that was considered plausible since pore clogging and compaction phenomena are expected consequences of a high run.

According to this investigation, the choice of the methodology to be applied (SFH, BEST) and the height of water application (low, high) should vary with the intended use of the K_{fs} data. If the objective of the field campaign is to obtain data usable to explain surface runoff generation phenomena during intense rainfall events, the most appropriate choice among the tested ones should be BEST with a high run, to mimic relatively prolonged rainfall effects on the soil surface. A low run is more appropriate to determine the saturated conductivity of a soil that is not directly impacted by rainfall, due for example to the presence of a mulching on the soil surface. In this case, the SFH and BEST techniques appear to yield relatively equivalent results in sandy loam and clay soils, which suggests that the more rapid SFH technique should be applied if only K_{fs} is the variable of interest. This technique should also be preferred in the more silty soils, where there were signs that a repeated water application promoted some soil disturbance decreasing K_{fs} also with a low application height.

In the future, the relationship between the water pouring height and the measured conductivity should be established with reference to other soils and a range of unsaturated soil water conditions. Soils in their natural status, i.e. not altered by smoothing and leveling actions before applying the infiltrometer, should also be considered in an attempt to generalize the detected water height effects.

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Appendix J: Testing infiltration run effects on the water transmission properties of a sandy-loam soil

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ABSTRACT

Testing factors influencing determination of soil water transmission properties by an infiltrometer method helps to better interpret the collected data and allows to develop appropriate sampling strategies for the intended use of the data. These factors include the soil water content at the start of the experiment, the height from which water is poured onto the soil surface, and the duration of the infiltration run. A sandy-loam soil was sampled with the BEST (Beerkan Estimation of Soil Transfer parameters) procedure of soil hydraulic characterization and two heights of pouring of water (0.03 and 1.5 m) on three dates differing by the initial soil water content, θ_i ($0.12 \leq \theta_i \leq 0.20$ m^3m^{-3}). According to the BEST guidelines, relatively short infiltration runs (average run duration $\leq$ 1.5 hours, depending on both the date and the height from which water was poured) were carried out. However, three long infiltration runs (10 hours) were also carried out when θ_i was of 0.075 m^3m^{-3}. The saturated soil hydraulic conductivity, K_s, and the soil sorptivity, S, were estimated for each infiltration run with the BEST-steady algorithm. The means of K_s varied with the height of pouring of water and the date from 13 to 496 mm h^{-1}, and low runs yielded 13 to 27 times higher means than the high runs, depending on the sampling date. An inverse relationship between K_s and θ_i was clearer with the low runs than the high ones. The mean conductivity obtained with the long runs (15 mm h^{-1}) was close to the means of K_s obtained with the high and shorter runs (13-19 mm h^{-1}, depending on the date). The means of S varied from 35 to 126 mm $h^{-0.5}$, with the low runs yielding 2.3 to 2.8 times higher means than the high runs. The high sorptivity obtained with the long runs (160 mm $h^{-0.5}$) was in line with the low initial soil water content. In conclusion, the water application procedure and the duration of the infiltration run can have a noticeable effect on the estimated soil water transmission properties. High or long runs appear more appropriate than low runs to obtain data usable to explain surface runoff generation phenomena during intense rainfall events, especially when the soil is relatively dry at the time of sampling. In the future, the effects of both the height from which water is poured and the run duration on the measured water transmission properties with BEST should be tested for different initial soil water conditions in other soils. The usability of the height from which water is poured onto the soil surface as a parameter to mimic high intensity rain should also be investigated specifically.

Keywords: Soil hydraulic properties; beerkan infiltration run; BEST procedure; height of water application; run duration

INTRODUCTION

Measuring soil hydraulic properties is necessary for interpreting and simulating many hydrological processes having environmental and economic importance, such as rainfall partition into infiltration and runoff. Especially for the soil water transmission properties, that depend strongly on soil structure, field measurement techniques should be used to minimize disturbance of the sampled soil volume and to maintain its functional connection with the surrounding soil (Bouma, 1982). Many replicated measurements of these properties have to be carried out to characterize an area of interest since they are known to vary widely both in space and time (e.g., Prieksat et al., 1994; Logsdon and Jaynes, 1996). Therefore, the technique to be applied at the near point scale should be simple and rapid.

Reasons for using ponding infiltrometer techniques to determine soil water transmission properties in the field include robust theory, simple devices, relatively small volumes of water, generally rapid experiment, extensive testing, and possibility to determine different water transmission properties, such as saturated soil hydraulic conductivity, K_s, and sorptivity, S (Reynolds, 2008a,b). Infiltrometer runs were also included in simplified methodologies for a complete soil hydraulic characterization. In particular, in the BEST (Beerkan Estimation of Soil Transfer parameters) procedure of soil hydraulic characterization (Lassabatère et al., 2006; Yilmaz et al., 2010; Bagarello et al., 2014a), the shape parameters of certain analytic formulae for the hydraulic characteristic curves are estimated from particle-size analysis whereas the structure dependent scale parameters are obtained by a three-dimensional field infiltration experiment at theoretically zero pressure head, using the infiltration model by Haverkamp et al. (1994).

Generally, the analysis of the infiltration data is based on an idealized representation of the sampled soil that is assumed to be rigid, homogeneous, isotropic and uniformly unsaturated before the run (e.g., Reynolds and Elrick, 1990; Lassabatère et al., 2006). However, structure dependent soil properties have a dynamic nature and they can vary appreciably upon wetting due to different phenomena, such as aggregate breakdown promoted by raindrop impact or weakening of interparticle bonds (Collis-George and Laryea, 1971; Assouline and Mualem, 2002, 2006; Chen et al., 2013). Therefore, using infiltrometers to characterize initially unsaturated real soils needs assessing the usability of a measurement carried out with a particular technique and under specific experimental conditions. This is still an open issue although some investigations developing this topic can be found in the literature. For example, K_s under rainfall conditions appears to be better represented by the tension infiltrometer than ponded head infiltrometers in stony soils (Verbist et al., 2013) but the opposite was suggested for other soils (Alagna et al., 2015; Bagarello et al., 2012, 2014b).

Although BEST appears attractive for a simple, rapid and complete soil hydraulic characterization, little is known about the dependence of the calculated soil water transmission properties on the applied experimental procedure in the field. Bagarello et al. (2014c) suggested that the K_s values determined by applying water at a relatively large distance from the soil surface could be more appropriate than those obtained with a low height of pouring of water to explain surface runoff generation phenomena during intense rainfall events. However, it should be established if, for a given soil, the effect of the height from which water is poured on the calculated soil water transmission properties varies with the initial soil water content since changes in soil structure due to wetting depend on the antecedent wetness conditions (e.g., Le Bissonnais, 1996; Cerdà, 1998). Another factor needing consideration is the duration of the infiltration run, that is often chosen quite subjectively. BEST calculations need measurement of steady-state infiltration rate but relatively short runs are generally carried out in the field. Although the measured infiltration rates generally suggest rapid attainment of quasi steady-state conditions (Reynolds et al., 2000; Lassabatère et al., 2006), a long run could be expected to yield more robust estimates of steady-state infiltration rates than a short run (e.g. Elrick et al., 1990). However, a long run may also imply more time and opportunities for altering the sampled soil volume due, for example, to swelling and weakening of particle bonds (Hillel and Mottes, 1966; Talsma and Lelij, 1976). Therefore, long runs could not be a valid alternative to short runs in any case. Even in this case, it is necessary to establish what happens in the field with runs of different duration to make an appropriate use of the calculated soil parameters. In addition, repeatedly pouring water on the surface of an initially dry soil, according to the BEST original procedure, implies a possible effect of air entrapment in the sampled soil volume on the measured infiltration rates. This factor has to be considered because even small changes in the entrapped air content may have a noticeable effect on the experimentally determined K_s values (Faybishenko, 1995; Reynolds, 2008a,b; Sakaguchi et al., 2005).

The relationship between the applied experimental approach and the measured parameter is not totally clear for sandy-loam soils.

For example, similar estimates of K_s were obtained with a transient and a steady-state technique differing by the expected soil disturbance effects (Bagarello and Sgroi, 2007), but this similarity was only partially confirmed in a subsequent investigation (Bagarello et al., 2014b). Moreover, a noticeable dependence of K_s on the height from which water was poured was detected for BEST but not for the Simplified Falling Head technique (Bagarello et al., 2004, 2014c). The high percentage of coarse particles in these soils could suggest a certain rigidity of the porous medium, and hence a reduced sensitivity to disturbance due to wetting. However, the limited content in clay particles could also imply weak soil aggregation and hence the possibility that water application determines particle detachment and clogging of the largest pores. Moreover, soil swelling during the infiltration run cannot be completely excluded due to the clay that is present in the soil. The importance to establish factors specifically influencing measurement of K_s of sandy-loam soils was also acknowledged by other Authors (Somaratne and Smettem, 1993; Lado et al., 2004).

The objective of this investigation was to test, for a sandy-loam soil, the effect of the height from which water was poured for the BEST infiltration experiment on the estimated saturated soil hydraulic conductivity and sorptivity for different initial soil water contents. The dependence of the K_s and S estimates on the duration of the infiltration run was also tested.

MATERIALS AND METHOS

The study was performed at the Department of Agriculture and Forestry Sciences of the Palermo's (Italy) University, in a citrus orchard with trees spaced 4 m × 4 m apart. The soil (Typic Rhodoxeralf), having a relatively high gravel content and an organic matter content in the 0-0.1 depth range of 3.9% (Bagarello et al., 2014c), was classified as sandy-loam (**Table 1**). The soil surface was gently levelled and smoothed before sampling. The superficial herbaceous vegetation was cut with a knife while the roots remained in situ.

Height of pouring of water

An area of approximately 150 m^2, already used for an earlier investigation (Bagarello et al., 2014c), was sampled on May 2014 and January 2015.

Table 1. Coordinates, land use, management practices, clay (%), silt (%) and sand (%) content (USDA classification system) in the 0–0.1 m depth range and soil textural classification. Standard deviations are indicated in parentheses

Variable	Site characteristic
Coordinates	33S 355511E - 4218990N
Land use	Citrus orchard
Management practices	Conventional tillage
clay	17.6 (1.9)
silt	29.8 (2.8)
sand	52.6 (4.7)
Textural classification	Sandy-loam

On a sampling date, a total of 20 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 in randomly chosen sampling points. These cores were used to determine the dry soil bulk density, ρ_b, and the soil water content at the time of the experiment, θ_i. The soil porosity, f, was calculated from the ρ_b data, assuming a soil particle density of 2.65 Mg m^{-3}. According to other investigations, the field saturated soil water content, θ_s, was assumed to coincide with f (Mubarak et al., 2009; Bagarello et al., 2011, 2014c).

Small diameter (i.e., 0.08 m) rings inserted to a depth of 0.01 m were used for the beerkan infiltration runs (Lassabatère et al., 2006). Ring insertion was conducted by gently using a rubber hammer and ensuring that the upper rim of the ring remained horizontal during insertion. The rings were particularly small to more clearly detect possible effects of soil disturbance due to water application. A total of 20 runs were carried out at randomly selected locations on a sampling date. Following the existing guidelines (Lassabatère et al., 2006), for each run 15 water volumes, each of 57 mL, were successively poured in 3-5 s on the confined infiltration surface. Ten runs were carried out by applying water at a small distance from the infiltration surface, i.e. approximately at a height, h_w, of 0.03 m, and dissipating its energy on the fingers of the hand, in an attempt to minimize soil disturbance due to water application (low, L, runs), as is commonly suggested in practical application of a ponding infiltration method (Reynolds, 2008a). Water was applied from h_w = 1.5 m at the other 10 sampling points (high, H, runs). The soil surface was not shielded in this case to maximize possible damaging effects of water impact. To ensure flow verticality and prevent wind effects, the device developed by Bagarello et al. (2014c) was used. The mean infiltration time of each applied water volume was calculated for both the low, Δt_L (T), and the high, Δt_H (T), runs.

The BEST procedure (Lassabatère et al., 2006) was applied to estimate the whole set of parameters for the water retention (van Genuchten, 1980; Burdine, 1953) and hydraulic conductivity (Brooks and Corey, 1964) curves. According to this procedure, residual water content is supposed to be zero and shape parameters of these curves are estimated from particle size distribution and porosity, using specific pedo-transfer functions. With the BEST-steady algorithm (Bagarello et al., 2014a), calculation of soil sorptivity, S (L T$^{-0.5}$), and saturated soil hydraulic conductivity, K_s (L T^{-1}), makes use of the intercept, b_s^{exp} (L), and the slope, i_s^{exp} (L T^{-1}), of the straight line fitted to the data describing steady-state conditions on the cumulative infiltration, I (L), vs. time, t (T), plot. The following relationships are used to calculate S and K_s:

$$S = \sqrt{\frac{i_s^{exp}}{A + \frac{C}{b_s^{exp}}}} \quad (1)$$

$$K_s = \frac{C\, i_s^{exp}}{A\, b_s^{exp} + C} \quad (2)$$

where A (L^{-1}) and C are constants in the steady-state expansion of the infiltration model by Haverkamp et al. (1994). The scale parameter for water pressure is finally estimated from S and K_s. For each infiltration run, a linear regression line was therefore fitted to the last data points, describing the near steady-state conditions, in order to estimate b_s^{exp} and i_s^{exp} on the I vs. t plot. Eqs.(1) and (2) were then applied to estimate S and K_s, respectively. For these calculations, the site was considered homogeneous in terms of particle-size distribution (PSD) and ρ_b, f, θ_i and θ_s values. The mean PSD determined by Bagarello et al. (2014c) was also used in this investigation. The representative ρ_b, f, θ_i and θ_s values were obtained by averaging the individual determinations of each variable obtained from the undisturbed soil cores on a given sampling date.

BEST-steady was applied because it allows a simple calculation of S and K_s and also because it was expected to yield a higher success percentage of the infiltration runs, implying more experimental information, as compared with other possible algorithms. In particular, Di Prima et al. (2015) showed that the BEST-slope (Lassabatère et al., 2006) and BEST-intercept (Yilmaz et al., 2010) algorithms can fail when the transient phase of the infiltration process is too short or it is described by a too small number of data points. Failure of these two algorithms was considered possible because a rapid attainment of near steady flow conditions was expected for this relatively coarse textured soil.

The hypothesis of normality was checked by the Lillefors (1967) test for both the untransformed and the ln-transformed S and K_s data. Then, for a given height of pouring of water, the data were summarized by calculating the mean, M, and the associated coefficient of variation, CV.

Two different sampling campaigns were carried out in this investigation but a third dataset was developed by re-analyzing with the BEST-steady algorithm the data collected on June 2012 at the same field site (Bagarello et al., 2014c). On 2012, a different number of cores were collected to determine θ_i and ρ_b (10 instead of 20), the ring was slightly larger (inner diameter = 0.085 m instead of 0.08 m), and more water was applied with each pouring (64 mL instead of 57 mL). However, the experimental differences between the earlier (2012) and later (2014, 2015) sampling campaigns were considered to be practically negligible and inconsequential, and this circumstance made it possible to consider three different sampling dates for testing effects of the height from which water was poured.

Attempting to check soundness of the estimated sorptivities, it was considered that, according to Reynolds and Elrick (2002), S can be approximated by:

$$S = \left[\gamma_w \left(\theta_s - \theta_i\right) \phi_m\right]^{1/2} \quad (3)$$

where γ_w is a dimensionless constant (White and Sully, 1987) related to the shape of the wetting (or drainage) front and ϕ_m (L^{2}T^{-1}) is the matric flux potential, defined by (Gardner, 1958):

$$\phi_m = \int_{h_i}^{0} K(h)\, dh = \frac{K_s - K_i}{\alpha} \qquad h_i \leq h \leq 0 \quad (4)$$

where h (L) is the soil water pressure head, h_i (L) is the initial value of h, K (L T^{-1}) is the soil hydraulic conductivity ($K_i = K(h_i)$), and α (L^{-1}) is the slope of ln K versus h. Substituting eq.(4) into eq.(3) and assuming $K_i = 0$ yields:

$$S = \left[\gamma_w \left(\theta_s - \theta_i\right) \frac{K_s}{\alpha}\right]^{1/2} \quad (5)$$

Duration of the infiltration run

On July 2014, three long duration (10 hours) infiltration runs were carried out at randomly chosen points of the selected field site by using rings with an inner diameter of 0.15 m inserted to a depth of 0.01 m into the soil. From seven to 10 water volumes of 150 mL, depending on the run, were poured in succession on the confined infiltration surface to monitor the initial, transient stage of the process with the common procedure for a beerkan experiment (Lassabatère et al., 2006). Then, to continue the run for a long period of time, a large Mariotte bottle was connected to the ring by a pipe immediately after infiltration of the last applied volume of water, and a small constant head (i.e., ~ 5 mm) was established until the end of the run. The bottle consisted of a graduated, transparent cylinder with an inner diameter of 0.144 m and a height of 1.9 m (**Fig. 1**). The large capacity (~ 30 L) of this reservoir avoided the need of frequent refilling. The time interval between visual readings at the reservoir was of 1 to 15 min. A total of six undisturbed soil cores were also collected to determine θ_i and ρ_b at the 0-0.05 m and 0.05-0.10 m sampling depths.

Each run was repeatedly analysed to detect possible changes in the calculated S and K_s values with the duration of the run. In particular, for a given number of collected (I, t) data, the last five points were assumed to represent the steady-state phase of the process and S and K_s were calculated with BEST-steady. Calculations were repeated by assuming a variable number of collected data points, ranging from a minimum of eight (Lassabatère et al., 2006) to a maximum of 78-93, depending on the run, corresponding to an infiltration process of 10 hours.

For each assumed run duration, the gravity time, t_{grav} (T), was calculated (Philip, 1969):

$$t_{grav} = \left(\frac{S}{K_s}\right)^2 \tag{6}$$

The fractional influence of gravity on cumulative three-dimensional infiltration, ε, was also determined as a function of time by the following relationship (Smettem et al., 1995):

$$I(1-\varepsilon) = St^{1/2} + \frac{\gamma S^2}{r(\theta_s - \theta_i)} t \tag{7}$$

Figure 1. Mariotte bottle used for the long duration infiltration runs

RESULTS AND DISCUSSION

Height of pouring of water

__Initial conditions__

The antecedent soil water content differed appreciably among the three sampling dates ($0.118 \le \theta_i \le 0.202$ m^{3}m^{-3}, **Table 2**) but the dry soil bulk density ($1.126 < \rho_b < 1.144$ Mg m^{-3}) and, hence, the estimated saturated soil water content ($0.568 \le \theta_s \le 0.575$ m^{3}m^{-3}) remained practically constant (i.e., differences by not more than 1.6%; $0.20 \le \theta_i/\theta_s \le 0.35$).

__Duration of the infiltration process__

The initial check of the field data suggested that the height from which water was poured influenced the infiltration process on all sampling dates since the mean duration of the H runs, varying with the date from 3500 s to 5400 s, was 4.0 to 5.4 times longer than the mean duration of the L runs (640 - 1020 s). In all cases, $\Delta t_H/\Delta t_L$ ($1.2 \le \Delta t_H/\Delta t_L \le 9.5$) increased with the number of the applied volumes of water, N_v (**Fig. 2**), indicating that Δt_H increased more than Δt_L during the run. Differences between the three $\Delta t_H/\Delta t_L$ vs. N_v relationships started to become clear after infiltration of six volumes of water, and relatively dry initial soil conditions ($\theta_i \le 0.16$ m^{3}m^{-3}) yielded similar $\Delta t_H/\Delta t_L$ ratios, higher than those

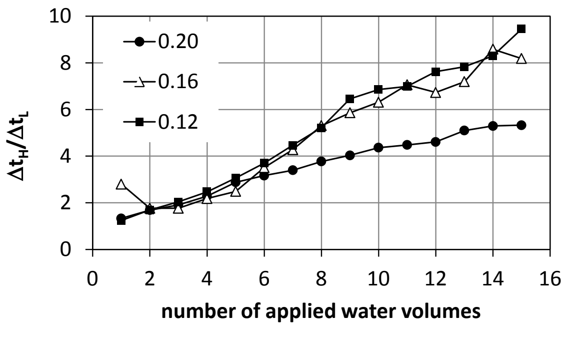
Table 2. Sample size (*N*), minimum (*Min*), maximum (*Max*), mean, and coefficient of variation (*CV*, in %) of the soil water content at the time of sampling, θ_i (m^3m^{-3}), dry soil bulk density, ρ_b (Mg m^{-3}), and saturated soil hydraulic conductivity, K_s (mm h^{-1}), and sorptivity, *S* (mm $h^{-0.5}$), values obtained on different years with the BEST experiment by pouring water into the cylinder from two different heights

Variable	Height of water pouring (m)	Statistic	June 2012	May 2014	January 2015
θ_i		N	10	20	20
		Min	0.103	0.094	0.155
		Max	0.132	0.201	0.239
		Mean	0.118	0.158	0.202
		CV	9.1	17.4	10
ρ_b		N	10	20	20
		Min	1.054	1.039	1.002
		Max	1.194	1.302	1.249
		Mean	1.127	1.144	1.126
		CV	4.2	6.3	4.4
K_s	0.03	N	10	9	10
		Min	169.2	97.7	36.6
		Max	854.7	958.1	457.6
		Mean	496.4 a A	299.2 a AB	168.8 a B
		CV	43.5	95.2	74.3
	1.5	N	10	10	9
		Min	13.1	3.2	5.4
		Max	23.8	45.0	22.0
		Mean	18.1 b A	18.9 b A	12.8 b A
		CV	22.8	77.5	44.1
S	0.03	N	10	9	10
		Min	54.7	63.3	48.6
		Max	181.8	117.6	116.1
		Mean	126.3 a A	84.8 a B	83.1 a B
		CV	31.8	23.7	28.3
	1.5	N	10	10	9
		Min	39.5	24.0	24.6
		Max	52.3	54.9	49.3
		Mean	45.7 b A	37.3 b AB	34.8 b B
		CV	9.3	30.4	23.0

For a given variable, the values in a column followed by a different lower case letter were significantly different according to a two tailed t test (*P* = 0.05). The values in a row followed by the same upper case letter were not significantly different according to the Tukey Honestly Significant Difference test (*P* = 0.05). The values followed by a different upper case letter were significantly different.

detected for the wetter soil. The H and L runs differed only by the height from which water was poured since averaging 10 runs for a given height should be appropriate to obtain representative values for the field site (Reynolds et al., 2002; Verbist et al., 2010). Therefore, the differences between Δt_H and Δt_L were expressive of a progressive deterioration of the infiltration surface with the repeated application of a given amount of water from a great height. Disturbance occurred soon, since $\Delta t_H/\Delta t_L$ was systematically greater than one even in the early stages of the infiltration run, and it increased with a prolonged exposure of the soil surface to water. For a small number of applied water volumes, $\Delta t_H/\Delta t_L$ was independent of the soil water content at the time of the experiment. However, an initially wet soil condition reduced the effect of the height from which water was poured for relatively large infiltrated water volumes.

Figure 2. Ratio between the mean infiltration time for a water application height of 1.5 (Δt_H) and 0.03 (Δt_L) m during the BEST runs plotted against the number of the applied volumes of water for different values of the initial soil water content, θ_i, ranging from 0.12 to 0.20 m^3m^{-3}



<u>*Statistical distribution of the data*</u>

According to the Lilliefors (1967) test, the hypothesis of a normal distribution for both the untransformed and the ln-transformed K_s and *S* data was never rejected (*P* = 0.05) for the 12 tested datasets, developed by considering a given initial soil water content and a height of pouring of water. However, the largest difference between the empirical cumulative distribution function and the corresponding theoretical function was generally smaller with reference to the

Table 3. Results of the Lillefors (1967) test for each developed dataset

Variable	Sampling date	Type of run	Sample size	D_{max} N	D_{max} LN	D_{crit}
K_s	June 2012	L	10	0.1209	0.1159	0.258
		H	10	0.1458	0.1464	0.258
	May 2014	L	9	0.2326	0.1553	0.271
		H	10	0.1582	0.1822	0.258
	January 2015	L	10	0.1055	0.1601	0.258
		H	9	0.1299	0.1478	0.271
S	June 2012	L	10	0.0999	0.1637	0.258
		H	10	0.1132	0.1228	0.258
	May 2014	L	9	0.1358	0.1485	0.271
		H	10	0.1262	0.1299	0.258
	January 2015	L	10	0.1381	0.1858	0.258
		H	9	0.1173	0.1145	0.271

K_s = saturated soil hydraulic conductivity; S = soil sorptivity; L = low (height of water application = 0.03 m); H = high (height of water application = 1.50 m); D_{max} = largest difference between the empirical cumulative distribution function and the corresponding theoretical function; D_{crit} = critical value of D_{max}; N = normal; LN = log-normal.

untransformed data (**Table 3**). Therefore, K_s and S were assumed to be normally distributed, and the data were summarized by calculating the arithmetic mean and the associated coefficient of variation.

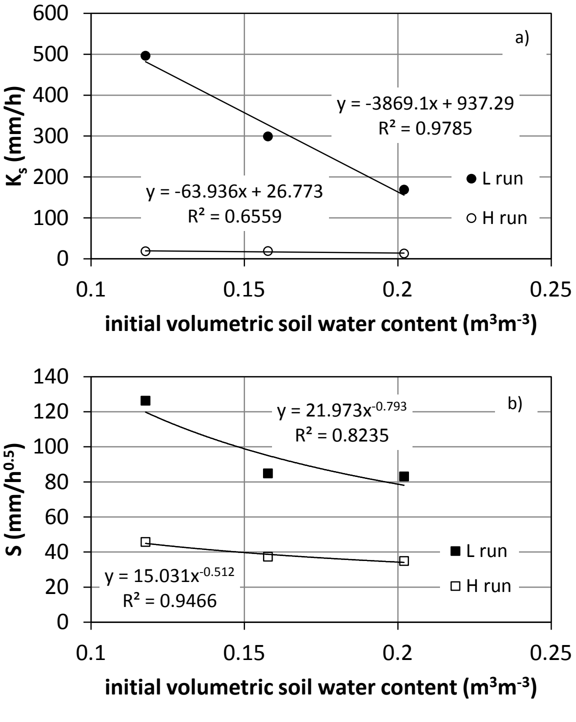
Saturated soil hydraulic conductivity

The means of K_s varied from 13 to 496 mm h^{-1} (difference by a factor of approximately 39) and the associated *CV*s ranged from 23% to 95% (**Table 2**). Soil macroporosity likely influenced the results of the L runs since a mean $K_s \geq 169$ mm h^{-1} was obtained and this value was higher than the expected saturated conductivity on the basis of the soil textural characteristics alone (e.g., K_s = 44.2 mm h^{-1} for a sandy-loam soil according to Carsel and Parrish, 1988). The effect of the height from which water was poured on K_s was statistically significant, and also noticeable, on all sampling dates because $M(K_{sL})$ (mean of K_s obtained with a low run) was 13 to 27 times higher than $M(K_{sH})$ (K_s for a high run), depending on the sampling date. The ratio between the two means decreased from the driest to the wettest soil conditions. Relative variability of K_s was larger with the low runs than the high ones. The $M(K_{sL})$ values differed at the most by a factor of three. Some differences were statistically significant according to the Tukey Honestly Significant Difference test (P = 0.05) and the means clearly decreased with an increase in the initial soil water content (**Fig.3**). The $M(K_{sH})$ values differed by not more than a factor of 1.5, the differences were not statistically significant and the inverse relationship between K_s and θ_i was less clear (**Fig.3**).

An inverse relationship between K_s and θ_i was expected for the sampled sandy-loam soil due to moderate swelling phenomena and weakening of the interparticle bonds reducing macropore volume in wet soil (Bagarello and Sgroi, 2007). Air entrapment did not explain this relationship since an initially higher soil water content should imply less opportunities for air entrapment during the infiltration run and hence higher K_s results (Reynolds, 2008a,b).

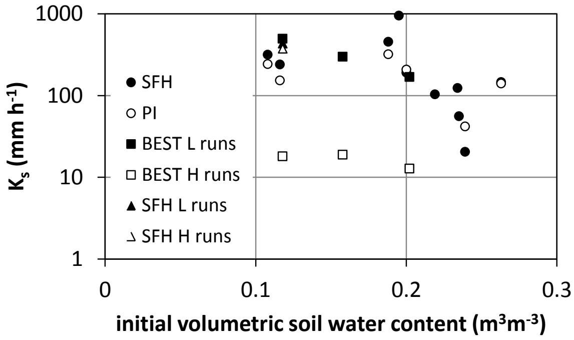
The more soil perturbing experiment (H infiltration runs) reduced the dependence of K_s on θ_i and a drier soil condition determined larger differences between K_{sL} and K_{sH}. Therefore, the applied experimental methodology had a noticeable effect on the measured conductivity under all antecedent conditions, but a dry soil was more sensitive to the height from which water was

Figure 3. Effect of the initial volumetric soil water content on the mean values of a) the saturated soil hydraulic conductivity, K_s, and b) the soil sorptivity, S, for both the low (L) and high (H) infiltration runs



Alagna, V., Bagarello, V., Di Prima, S., Giordano, G., Iovino, M. Testing infiltration run effects on the estimated water transmission properties of a sandy-loam soil. Submitted to Geoderma in 2015

Figure 4. Effect of the initial volumetric soil water content on the mean saturated soil hydraulic conductivity obtained at the field site in this and other investigations (Bagarello and Sgroi, 2007; Bagarello et al., 2014c) with different experimental methodologies



poured than a wet soil. Likely, a higher height from which water was poured implied more energy applied to the soil surface and therefore more opportunities for aggregate breakdown, compaction of the exposed soil surface and macropore obstruction, particularly in more macroporous conditions (lower θ_i, higher K_s).

The mean K_s values obtained with the BEST runs and a low height of water pouring were in line with the saturated conductivity previously measured at the same field site with the SFH and PI techniques (**Fig. 4**) (Bagarello and Sgroi, 2007; Bagarello et al., 2014c). The information collected by a high BEST run on a relatively dry soil was closer to that collected by less perturbative approaches (SFH, PI techniques) in relatively wet soil conditions.

Soil sorptivity

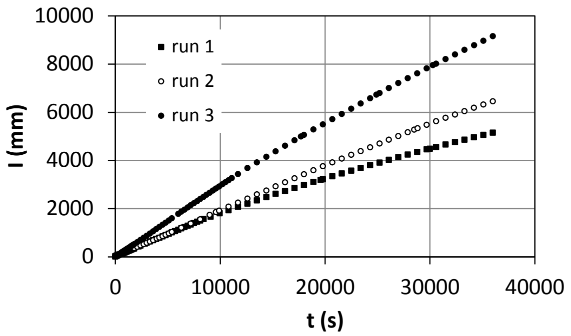
The means of S varied from 35 to 126 mm $h^{-0.5}$ (difference by a factor of 3.6) and the associated *CV*s ranged from 9% to 32% (**Table 2**). In all cases (initial soil water content, height from which water was poured), relative variability was smaller for S than for K_s. The effect of the height from which water was poured on S was statistically significant on all sampling dates and it varied only slightly for the three sampling campaigns because $M(S_L)$ (the mean of S obtained with a low run) was 2.3 to 2.8 times higher than $M(S_H)$ (S for a high run), depending on the period. The three $M(S_L)$ values differed at the most by a factor of 1.5 whereas $M(S_H)$ changed by not more than 1.3 times and some differences were statistically significant in both cases. This result and the plot of S against θ_i (**Fig. 3**) suggested a tendency of S to decrease with an increase of θ_i. The S data collected in this investigation were consistent with the expected effect of both θ_i and K_s on this soil property according to eq.(5). For a given θ_i (i.e., for a given sampling date), S decreased with a decrease in K_s and, for a given type of run (L or H), S showed a tendency to decrease as θ_i increased and K_s decreased.

Soil disturbance determined a reduced ability of the porous medium to adsorb water due to capillarity and, in the range of the tested θ_i values, this effect was more noticeable than that produced by an increase of θ_i. Even the fact that $CV(S) < CV(K_s)$ was always obtained was considered physically plausible. The reason was that K_s strongly depends on the highly variable soil structure, particularly influencing the largest pores and their hydraulic continuity (e.g., Somaratne and Smettem, 1993; Jarvis et al., 2013), whereas S is more expressive of the capillary forces exerted by the soil matrix, which is known not to vary much in space. Therefore, the estimates of S appeared plausible on the basis of the physical meaning of this variable. This results was not expected a priori because data were collected by a ponding infiltration experiment which is not the best choice to detect capillarity effects on the established flow process (Reynolds and Elrick, 1990). Perhaps, the fact that the ponding depth was small (i.e., close to zero) was an appropriate choice to obtain plausible S data.

Link between field soil data and hydrological processes

Establishing a conceptual link between the applied experimental methodology for characterizing the soil and the interpretable hydrological processes is important to understand the practical usefulness of a particular measurement. For example, Amezketa et al. (1996) and Le Bissonnais (1996) suggested that testing aggregate stability under fast wetting is appropriate to assess effects of heavy rain storms occurring in summer on the soil. Slow wetting experiments corresponds to a field condition of wetting under gentle rain. Liu et al. (2011) suggested that double ring infiltrometer experiments are usable to mimic effects of fast wetting of initially dry soil under high rainfall intensities. According to other investigations, however, K_s data collected by infiltrometer methods could be expected to be unusable for interpreting field hydrological processes, and particularly infiltration, for different reasons. For example, the high K_s values obtained by van de Giesen et al. (2000) with ring infiltrometers were

Figure 5. Cumulative infiltration, *I*, against time, *t*, for the long duration infiltration runs



not considered to be the actual values during rainstorms because they would have precluded occurrence of the measured runoff. To explain this inconsistency, van de Giesen et al. (2000) suggested that runoff producing events determined massive air inclusion in the soil and crust formation and associated particle sorting phenomena, decreasing overall permeability, that did not occur or were less noticeable when K_s was measured with the infiltrometer. Flow at saturation is dominated by structural macropores, that are known to be fragile (Jarvis et al., 2013). Moreover, runoff generation often presupposes development of a surface seal layer (Assouline and Mualem, 2006; Chen et al., 2013) but it can also happen that rainfall does not induce significant changes in K_s (Schiettecatte et al., 2005). A significant decrease of K_s can occur after an intense rainfall but not as a consequence of a light rain (Liu and Chen, 2015).

The methodology applied in this investigation, combining low and high infiltration runs, seems appropriate to test the effect of intense and prolonged rainfall events on the hydraulic characteristics of the surface soil layer, and it is also simpler than an approach involving soil characterization both before and after natural or simulated rainfall since it needs less equipment and field work.

The validity of the suggested method can also found some indirect support in the scientific literature, due to the correspondence of the results of this investigation with other results. For example, the fact that the height from which water was poured had a more noticeable effect on K_s than *S* was consistent with the results obtained by Somaratne and Smettem (1993) in another sandy-loam soil, since simulating intense rainfall in initially dry soil conditions determined a decrease of the average hydraulic conductivity whereas sorptivity remained unaffected. The homogenizing effect of the H runs on K_s was in line with the conclusion by Assouline and Mualem (2006) that the formation of soil surface seal apparently reduces the effect of the field areal variability on the steady infiltration rate.

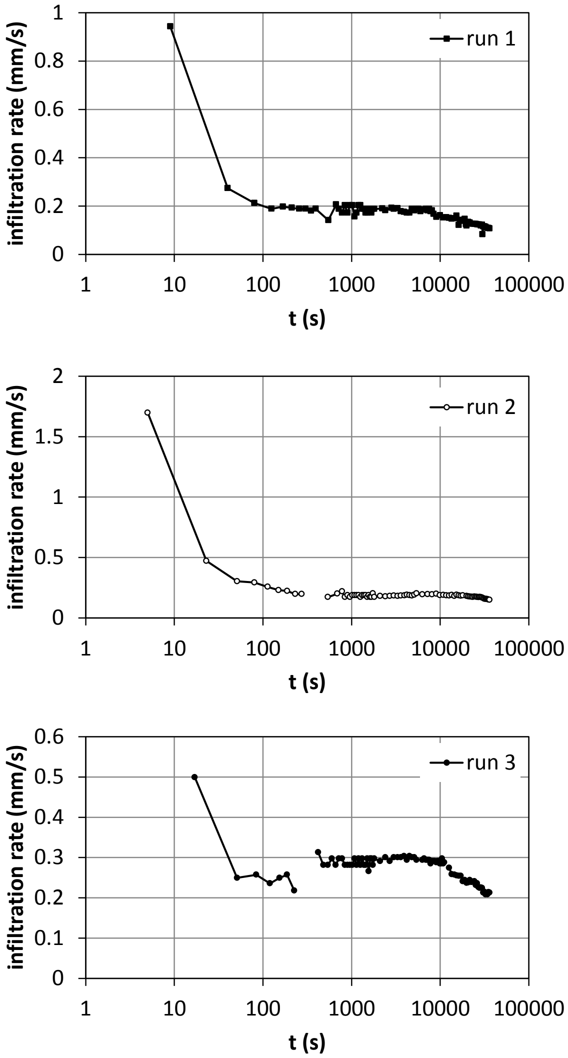
An intense and prolonged rainfall event has a soil surface perturbing effect that, reasonably, was better represented by the H runs than the L runs. Therefore, K_s can be expected to be high and highly variable, depending on the soil water content, before occurrence of high energy rainfall events. Rainfall determines a decrease of K_s in the upper soil layer, that assumes a value that does not depend strongly on the antecedent soil water content. Initially dry soil is particularly sensitive to changes in both *S* and K_s attributable to the energy of the applied water. A noticeable soil disturbance during wetting reduces in general infiltration and it also attenuates the effect of θ_i on this hydrological process.

Duration of the infiltration run

Field data and saturated soil hydraulic conductivity and soil sorptivity calculations

The experimentally measured cumulative infiltration curves appeared consistent with the theoretically expected curve (**Fig.5**). The small concavity was plausible since the soil had a relatively coarse texture (Lassabatère et al., 2009). For long runs 1 and 2, the infiltration rate, i_r, was initially high (**Fig.6**) but it soon decreased and approached a near steady value (i.e., approximately after less than 200 s). This near steady condition persisted for a relatively long period and it was more noisy in its early stages than at later times. At a later stage of the infiltration process (i.e., after more or less 8000 s), i_r started to decrease again until the end of the run. Long run 3 evolved as the other two runs but, in addition, i_r increased abruptly and permanently at the beginning of the near steady condition. For run durations of less than approximately 8000-10000 s, depending on the run, K_s was nearly independent of *t* but it showed appreciable oscillations, at least for two runs (**Fig.7a**). Then, K_s decreased progressively with *t*. Sorptivity did not vary systematically with *t* for both relatively short and long durations of the run but a long run yielded consistently higher *S* values than a short run (**Fig.7b**). Moreover, clear oscillations of *S* were only detected for relatively short durations of the run. The calculated final values of K_s and *S* were relatively similar for the three runs ($10.2 \leq$

Figure 6. Infiltration rate against time, *t*, for the long duration infiltration runs



$K_s \leq 19.4$ mm h^{-1}, mean = 14.7 mm h^{-1}; $134.8 \leq S \leq 186.2$ mm h$^{-0.5}$, mean = 159.9 mm h$^{-0.5}$).

Early stage of the infiltration run

Initially, K_s and S were relatively high and low, respectively, suggesting a significant role of macropores and other large voids on water transport processes in the soil. As a matter of fact, the lowest K_s value during this phase was 230 mm h^{-1} (**Fig.7**) that is appreciably higher than the expected saturated conductivity for a sandy-loam soil (Carsel and Parrish, 1988).

The oscillations of S and K_s were associated with oscillations in infiltration rates that can occur under air confining conditions (Jarrett and Fritton, 1978; Wang et al., 1998). According to Wang et al. (1998), in particular, when the air pressure ahead of the wetting front reaches an air-breaking value, soil air escapes from the surface, leading to an immediate decrease in the air pressure and an increase in the infiltration rate. When the air pressure falls below a certain air-closing value, air escape stops, the infiltration rate decreases again and the air pressure increases. In this investigation, air confining conditions could be considered unlikely or even impossible due to the absence of physical obstacles to air escape. However, air entrapment is common in three-dimensional ponding infiltration experiments (Reynolds, 2008a,b) and the experimental conditions likely favored entrapment of air in the sampled soil volume. In fact, ponding conditions were established on the surface of an initially very dry soil (θ_i = 0.075 m^{3}m^{-3}) and, in the early stages of the run, a new volume of water was applied after complete infiltration of the previously poured volume. Therefore, a cyclic infiltration process maybe occurred because much air was present in the soil at the beginning of the run and the experimental approach favored air entrapment during wetting. The attenuation of the phenomenon at later stages of the run probably occurred because a small positive head was steadily established on the soil surface at a certain moment and the opportunities for air entrapment decreased. Moreover, the i_r vs. t plot suggested a very rapid attainment of near steady conditions and, in these conditions, the field-saturated zone under the infiltration surface should remain essentially constant in size and

Figure 7. Estimated values of a) the saturated soil hydraulic conductivity, K_s, and b) the soil sorptivity for different assumed durations, *t*, of the three long duration infiltration runs

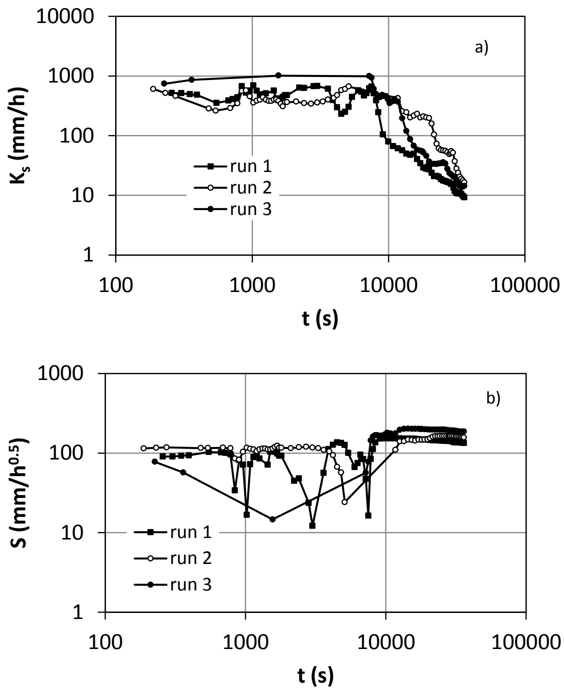
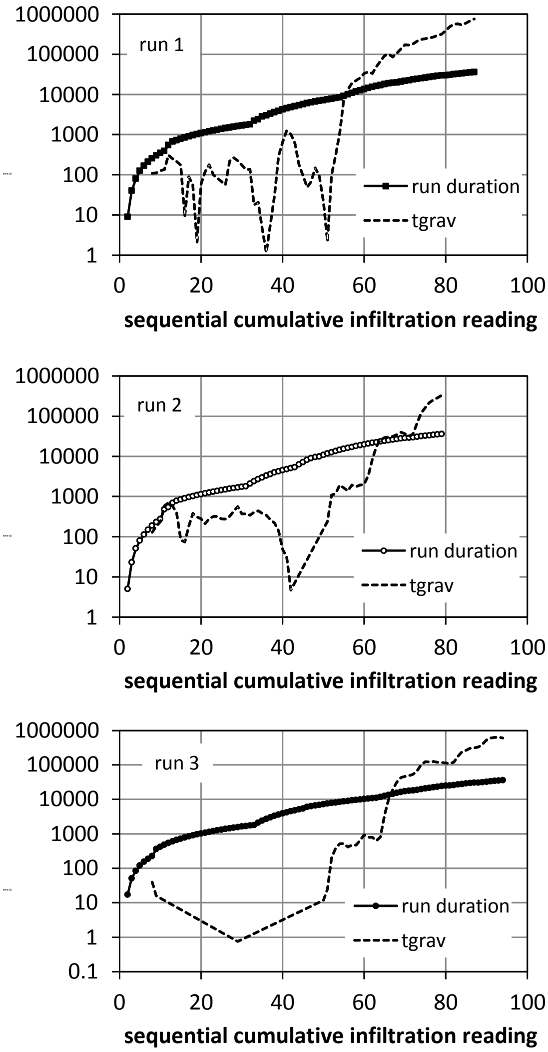


Figure 8. Comparison between the run duration and the gravity time, t_{grav}, for the three long duration infiltration runs



shape (Elrick and Reynolds, 1992). Therefore, as the run proceeded, there were more and more opportunities for a permanent removal of the entrapped air from the field-saturated bulb.

Probably, an effect of the entrapped air was not detected with the shorter L and H runs for the following reasons: i) limited number of water volumes used for the run and hence insufficient experimental information to detect a clear oscillating pattern in the measured infiltration rates, and ii) higher initial water content of the sampled soil as compared with the long duration infiltration runs, implying less opportunities for air entrapment during the run.

<u>*Late stage of the infiltration run*</u>

To explain the effect of time on K_s and S during the late phase of the infiltration process, the hypothesis that the infiltration process did not reach the necessary steady conditions required by BEST-steady was initially excluded. As a matter of fact, the decreasing stage in the i_r vs. t plot followed a long phase suggesting practically constant i_r values (**Fig.6**). Moreover, the comparison between the considered run duration for the calculation of S and K_s and the corresponding gravity time, t_{grav} (T) (**Fig.8**), suggested that the choice to analyze the infiltration process by BEST-steady (i.e., assuming that a near steady-state condition was reached) was appropriate even for relatively short duration runs. At later times, $t < t_{grav}$ was detected and a change from $t > t_{grav}$ to $t < t_{grav}$ with longer infiltration times suggested that the sampled soil was not ideal as required by theory (Haverkamp et al., 1994). Moreover, the depth of soil sampling was presumably thick since a large amount of water infiltrated the soil before i_r started to decrease permanently (**Figs. 5** and **6**). Therefore, an effect of non-homogeneous subsurface soil characteristics (wetter conditions, less permeable layer) on the measured infiltration rates was not totally excluded.

Alteration phenomena occurring at or close to the soil surface were considered to be at least a concomitant cause of the late time decreasing infiltration rates since the soil remained saturated for several hours before the infiltration rates started to decrease. There was time for some macropore narrowing promoted by swelling, that maybe was moderate due to the relatively low clay content of the soil, but it certainly occurred given that the water outlet tip of the device needed to be raised by a few mm during the run not to obstruct water discharge from the reservoir. Moreover, due to the long wetting period, weakening of the particle bonds likely occurred. Water was applied by a Mariotte bottle as subsequent impulses and, after each impulse, a few soil particles were noted to float in the established water ponding layer until they were deposited on the soil surface, possibly clogging exposed pores. The long duration of this phase of the infiltration process (decreasing i_r vs. t relationship) implied a long available time for the occurrence of these phenomena and revealed that they were continuous until the end of the run. A test of this last interpretation was made in the laboratory on an undisturbed soil core (diameter = 8 cm, height = 5 cm) that was saturated from the bottom to reproduce more or less the soil condition at the beginning of the late time i_r vs. t relationship for the field experiment (wetted soil). Then, flux densities were measured under a constant head of 1 cm for several hours. Flux

Figure 9. Flux density against time for a constant head laboratory experiment

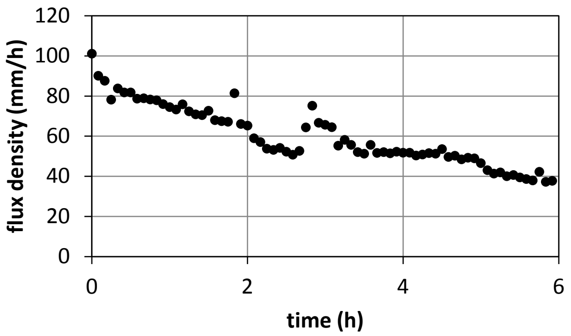
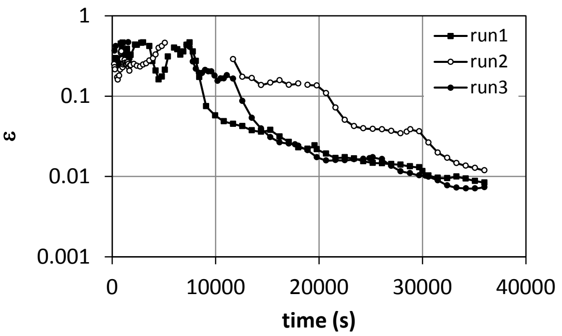


Figure 10. Fractional influence of gravity on cumulative 3D infiltration, ε, as a function of time for the three long duration infiltration runs



densities decreased with time (**Fig.9**), supporting the suggestion that physical soil deterioration phenomena occurring at or close to the soil surface were a possibility not to be excluded. In the field, soil alteration determined a progressive decrease of K_s but it left S practically unchanged, which is reasonable taking into account that sorptivity is more expressive of capillary effects, that mainly depend on soil matrix.

For the three long runs, gravity contributed appreciably to the infiltration process in the early stages of the run (**Fig.10**), which was in line with other findings on field soils (Smettem et al., 1998). Disturbance phenomena had the effect to substantially decrease this contribution.

Comparison between long and high runs

The results of the long and the high, but shorter, runs were compared taking into account that both experiments determined some kind of soil alteration. This comparison suggested that the two perturbation factors (height from which water was poured, duration of the run) had a similar impact on the measured parameters. In particular, the mean value of K_s obtained with the long runs was within the range, not particularly wide (maximum/minimum = 1.5), of the mean K_s values obtained with the H runs. The sorptivity calculated with the long runs was appreciably higher (i.e., by a factor of 3.5) than the highest S value obtained with the H runs. Even this result was considered to be plausible since the long runs were carried out in an initially drier soil than the H runs.

Comparison with literature data

Finally, a numerical correspondence was noted between the mean K_s values obtained in this investigation (L runs: 170-496 mm h^{-1}; H and long duration runs: 10-19 mm h^{-1}) and those reported by Lado et al. (2004) for another sandy-loam soil (183-412 mm h^{-1} and 8-13 mm h^{-1} for samples constituted by aggregates of 2-4 mm and < 2 mm, respectively). These Authors attributed the detected differences to the larger pore volume in the former samples than the latter ones and they also showed that soil structure alteration phenomena occurring during the run determined a decrease of the measured conductivity. Although the applied experimental methods differed by many aspects between the two investigations and the numerical correspondence could be fortuitous, the data by Lado et al. (2004) reinforced the suggestion that a decrease of the measured conductivity by more than an order of magnitude should be considered an expected consequence of structure alteration phenomena promoted by the experimental run in sandy-loam soils.

Possible experimental improvements in future research

This investigation improved our knowledge of the factors affecting measurement of water transmission properties by an infiltrometer method and also allowed us to recognize what experimental improvements could be advisable to give independent support to suggested interpretations of the field data. In particular, X-ray tomography could be used to experimentally assess the reasons for the dependence of the K_s measurements on θ_i and height from which water is applied (Luo et al., 2008; Peth et al., 2010). A direct measurement of θ_s at the end of the infiltration run should also be made to check the impact of the assumed coincidence between saturated soil water content and porosity on the S and K_s calculations (Luo et al., 2008; Koestel and Larsbo, 2014; Snehota et al., 2015; Alagna et al., 2015). Finally, water temperature should be measured during the long infiltration runs taking into account that production of air bubbles and changes in water viscosity are expected consequences of water temperature changes (Clancy and Alba, 2011).

CONCLUSIONS

The height from which water was poured onto the infiltration surface influenced significantly measurement of saturated soil hydraulic conductivity, K_s, and soil sorptivity, S, with the low runs yielding higher means than the high runs. Height of pouring of water effects were particularly noticeable for K_s probably because this property depends strongly on soil structure that was altered by pouring water from a great height. Sorptivity was less affected by the height of pouring of water since this property depends more than K_s on soil matrix, which does not change with the water application procedure. The height from which water was poured had more appreciable effects on K_s in the initially drier soil conditions, and a more soil perturbing experiment (high infiltration runs) reduced the dependence of K_s on θ_i detected with the low and less perturbing runs. High runs also had a homogenizing effect on the measured conductivity. With the long duration runs, the estimated mean conductivity was close to the means of K_s obtained with the high, but shorter, runs.

In conclusion, the application procedure of a given experimental method has to be considered a source of variability of the measured soil properties.

The results of this investigation may allow to better explain the infiltration process at the field site and also provide suggestions on how to sample the soil depending on the intended use of the data. If water application does not perturb appreciably the exposed soil surface, initially wetter soil conditions determine less infiltration due to the reduced ability of the soil to adsorb water but also because a wet soil is less permeable to water than a dry soil. Water application determining a noticeable disturbance of the soil surface reduces in general infiltration and it also attenuates the effect of θ_i on this process. If the objective of the field campaign is to obtain data usable to explain surface runoff generation phenomena during intense rainfall events, the most appropriate choice should be a high run, to mimic relatively prolonged rainfall effects on the soil surface. A low run is more appropriate to determine the saturated conductivity of a soil that is not directly impacted by rainfall, due for example to the presence of a mulching on the soil surface. In any case, the height from which water is poured has a reduced impact on the measured soil properties in relatively wet soil conditions. Moreover, a high and relatively short run seems usable to test what happens, in terms of estimated saturated conductivity, when a ponding water condition is maintained on the soil surface for a long time.

In the future, the effects of the height of pouring of water and the run duration on the measured water transmission properties should be tested for different initial soil water conditions in other soils. More in general, establishing the information contained in the measured soil properties, with particular reference to those that strongly depend on soil structural characteristics, appears necessary to understand the practical usability of the collected data and hence to improve our ability to interpret and simulate hydrological processes.

The hypothesis that the height from which water is poured onto the soil surface is a parameter usable in infiltration experiments to mimic the effect of high intensity rain on the soil hydraulic properties needs specific experimental testing. At this aim, comparisons could be established between infiltration rates measured by applying water at a relatively large distance from the soil surface and those obtained by rainfall simulation experiments.

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Appendix K: Estimating field-saturated soil hydraulic conductivity by a simplified Beerkan infiltration experiment

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ABSTRACT

Field-saturated soil hydraulic conductivity, K_{fs}, is highly variable. Therefore, interpreting and simulating hydrological processes, such as rainfall excess generation, need a large number of K_{fs} data even at the plot scale. Simple and reasonably rapid experiments should be carried out in the field. In this investigation, a simple infiltration experiment with a ring inserted shortly into the soil and the estimation of the so-called α* parameter allowed to obtain an approximate measurement of K_{fs}. The theoretical approach was tested with reference to 149 sampling points established on Burundian soils. The estimated K_{fs} with the value of first approximation of α* for most agricultural field soils (α* = 0.012 mm^{-1}) differed by a practically negligible maximum factor of two from the saturated conductivity obtained by the complete BEST (Beerkan Estimation of Soil Transfer parameters) procedure for soil hydraulic characterization. The measured infiltration curve contained the necessary information to obtain a site-specific prediction of α*. The empirically derived α* relationship gave similar results for K_{fs} (mean = 0.085 mm s^{-1}; coefficient of variation, *CV* = 71%) to those obtained with BEST (mean = 0.086 mm s^{-1}; *CV* = 67%), and it was also successfully tested with reference to a few Sicilian sampling points, since it yielded a mean and a *CV* of K_{fs} (0.0094 mm s^{-1} and 102%, respectively) close to the values obtained with BEST (mean = 0.0092 mm s^{-1}; *CV* = 113%). The developed method appears attractive due to the extreme simplicity of the experiment.

Keywords: Hydrological processes; Soil hydraulic properties; Measurement methods.

INTRODUCTION

Interpreting and simulating different hydrological processes, including rainfall partitions into infiltration and runoff, need measuring field-saturated soil hydraulic conductivity, K_{fs}, that is a highly variable soil property. Therefore, a reliable soil characterization needs a large number of spatially distributed determinations of K_{fs} (e.g. Warrick, 1998; Bagarello et al., 2012). These data should be collected in the field to maintain the functional connection between the sampled soil volume and the surrounding soil (Bouma, 1982) and hence to prevent preferential flow phenomena that can occur when detached soil columns are used in the laboratory (Lauren et al., 1988). Using small volumes of water, easily transportable equipment, and conducting short-duration experiments is desirable to determine K_{fs} at a great number of locations over a large area and with a realistic use of resources in terms of time and costs.

Most field techniques, such as the well permeameter and single-ring infiltrometer constant-head techniques (Reynolds and Elrick, 1986, 1990) rely on the attainment of a steady-state flow rate of water into the soil. Waiting for flow steadiness can be a practical limit to the field use of these techniques since steady-state experiments with a reasonably short duration can be conducted only in relatively permeable soils (Elrick and Reynolds, 1992). According to the existing literature, a possible strategy to increase rapidity of an individual determination of K_{fs} is to use a single ponded depth of water and an estimate of the α^* parameter, equal to the ratio between K_{fs} and the field-saturated matric flux potential (Reynolds and Elrick, 1990; Elrick and Reynolds, 1992). The α^* parameter describes the relative importance of gravity and capillary flow for ponded infiltration and it increases as soil capillarity decreases from very strong to negligible. Even with a single ponded depth of water, however, a constant-head device must be used and transported throughout the area of measurements. A falling-head experiment should be preferred to determine K_{fs} in situ due its simplicity compared to the constant-head one (Philip, 1992). An example of falling-head procedure is the Simplified Falling Head (SFH) technique by Bagarello et al. (2004), based on a transient infiltration process. Field use of this technique can be complicated by the need to i) insert the ring to a relatively large depth into the soil (i.e., a dozen of cm), in order to establish a one-dimensional infiltration process, and ii) sample the soil before the infiltration run, to determine the antecedent and field-saturated soil water contents. Therefore, developing alternative methods to obtain K_{fs} data with minimal experimental efforts and theoretical constraints is desirable especially for areas of the world where resources for experimental soil research are scarce.

The BEST (Beerkan Estimation of Soil Transfer parameters) procedure by Lassabatère et al. (2006) is very attractive for practical use since it allows an estimation of both the soil water retention curve and the hydraulic conductivity function. With this procedure, data describing the transient phase of an infiltration process have to be collected. Lassabatère et al. (2006) suggested to measure the infiltration time of small volumes of water repeatedly poured on the soil surface confined by a ring inserted to a depth of about 1 cm into the soil. The BEST infiltration experiment is simple and it can be expected to yield reliable K_{fs} data because soil disturbance by ring insertion is minimal, due to the limited insertion depth. Moreover, soil surface alteration phenomena should not be appreciable because the water volumes are small and they are poured from a small distance (i.e., a few cm). However, the infiltration experiment alone is not enough to obtain an estimate of K_{fs} because, according to the BEST procedure, the soil particle size distribution and the initial and field-saturated soil water contents have also to be measured.

The objective of this investigation was to only use the infiltration data collected according to the BEST methodology to obtain an approximate determination of field-saturated soil hydraulic conductivity. The theoretical analysis was initially developed. The simplified measurement method of K_{fs} was then tested through the comparison with the corresponding K_{fs} values obtained by the original BEST procedure. Data collected in two very different areas of the world (Burundi and Sicily) were used to test the generality of the developed methodology.

THEORY

For an infiltration experiment with zero pressure on a circular surface of radius r (L) above a homogeneous soil with a uniform initial water content, θ_0, the BEST method by Lassabatère et al. (2006) approximates the three-dimensional cumulative infiltration, I (L), by the following explicit transient two-terms relationship:

$$I(t) = S\sqrt{t} + \left(A\,S^2 + B\,K_{fs}\right)t \qquad (1)$$

where t (T) is the time, S (L T$^{-1/2}$) is soil sorptivity, A (L^{-1}) and B are constants, and K_{fs} (L T^{-1}) is the field-saturated soil hydraulic conductivity. BEST also assumes the hydraulic conductivity, K (L T^{-1}), vs. volumetric soil water content, θ (L^{3}L^{-3}), relationship proposed by Brooks and Corey (1964) with a residual soil water content equal to zero:

$$\frac{K(\theta)}{K_{fs}} = \left(\frac{\theta}{\theta_s}\right)^{\eta} \qquad (2)$$

where η is a shape parameter and θ_s (L^{3}L^{-3}) is the saturated soil water content. For the Brooks and Corey equation, the A and B constants are defined as:

$$A = \frac{\gamma}{r\,(\theta_s - \theta_0)} \qquad (3a)$$

$$B = \frac{2-\beta}{3}\left[1-\left(\frac{\theta_0}{\theta_s}\right)^{\eta}\right] + \left(\frac{\theta_0}{\theta_s}\right)^{\eta} \qquad (3b)$$

where β and γ are coefficients equal to 0.6 and 0.75, respectively, for $\theta_0 < 0.25\ \theta_s$ (Smettem et al., 1994; Haverkamp et al., 1994).

If the soil is relatively dry at the begin of the experiment, $(\theta_0/\theta_s)^\eta$ is approximately equal to zero (i.e., $K(\theta_0) << K_{fs}$) and B is equal to 0.467. Dividing both sides of eq.(1) by $\sqrt{t}$ (Vandervaere et al., 2000) and introducing eq.(3) in the infiltration equation, the following linear relationship between $I/\sqrt{t}$ and $\sqrt{t}$ is obtained:

$$\frac{I(t)}{\sqrt{t}} = S + \left[\frac{0.75\,S^2}{r(\theta_s - \theta_0)} + 0.467\,K_{fs}\right]\sqrt{t} = S + b_1\sqrt{t} \tag{4}$$

Therefore, the slope, b_1, of eq.(4), equal to:

$$b_1 = \frac{0.75\,S^2}{r(\theta_s - \theta_0)} + 0.467\,K_{fs} \tag{5}$$

can be estimated by a linear regression analysis of the ($I/\sqrt{t}$, $\sqrt{t}$) data.

Reynolds and Elrick (1990) and Elrick and Reynolds (1992) proposed to express the relative importance of gravity and capillary forces during a ponding infiltration process by the following α^* (L^{-1}) parameter:

$$\alpha^* = \frac{K_{fs}}{\phi_m} \tag{6}$$

where ϕ_m (L^2T^{-1}) is the matric flux potential, defined as (Reynolds and Elrick, 1990):

$$\phi_m = \int_{h_i}^{0} K(h)\,dh \tag{7}$$

where h_i is the initial pore water pressure head and $K(h)$ is the hydraulic conductivity – pressure head relationship. The ϕ_m parameter is an indicator of the capillary pull exerted by the unsaturated porous medium on the water during an infiltration or drainage process (Reynolds and Elrick, 2002a).

The relationship between S and ϕ_m can be written as (Philip, 1957; Reynolds and Elrick, 2002a):

$$S = [\gamma_w(\theta_s - \theta_0)\phi_m]^{1/2} \tag{8}$$

where γ_w is a dimensionless constant (White and Sully, 1987) related to the shape of the wetting or drainage front. Eq.(8) with γ_w = 1.818 (i.e., the value for a wetting front) was considered by Reynolds and Elrick (2002b) suitable to estimate sorptivity with a ponded infiltration experiment from a single ring. Combining eqs.(5), (6) and (8) and solving for K_{fs} gives:

$$K_{fs} = \frac{b_1}{0.467\left(\dfrac{2.92}{r\,\alpha^*} + 1\right)} \tag{9}$$

Therefore, a very simple infiltrometric experiment, identical to that performed with the BEST method, can provide an estimate of K_{fs} if α^* is known or it is properly evaluated. According to the literature, the α^* parameter can be estimated on the basis of a general description of soil textural and structural characteristics (Elrick and Reynolds, 1992). In particular, four α^* values (0.036, 0.012, 0.004 and 0.001 mm^{-1}) were suggested for practical use of permeameters and infiltrometers in soils varying from coarse sands to compacted clays. An α^* value of 0.012 mm^{-1} was considered to be the value of first approximation for most field soils (Reynolds et al., 2002). With the proposed eq.(9), additional field and laboratory measurements, such as initial and final soil water content, particle size distribution, or bulk density, are not strictly necessary. A theoretical limit is that eq.(1) is valid for the transient phase of the infiltration process (Lassabatère et al., 2006). In other words, theory establishes that this equation cannot be used whatever the number of poured water volumes is. From a practical point of view, however, the duration of the infiltration run in the field does not represent a crucial step of the data analysis procedure based on eq.(1) (Bagarello et al., 2011).

The effect of an erroneous choice of α^* on the predictions of K_{fs} with eq.(9) was explored for each of the four K_{fs}-α^* combinations used by Reynolds and Elrick (1990) to define representative porous media. In particular, eq.(9) was used to calculate the b_1 value corresponding to a particular K_{fs}-α^* combination. Then, K_{fs} was re-calculated with the true b_1 value and a value of α^* differing by plus or minus one category from the correct one, according to the values of α^* suggested by Elrick and Reynolds (1992). For example, 0.012 mm^{-1} was replaced by either 0.036 or 0.004 mm^{-1}, whereas 0.036 mm^{-1} was only replaced by 0.012 mm^{-1}. The relative error in K_{fs}, i.e. the difference between the erroneous and the true value, expressed as a percentage of this last value, and the corresponding factor of discrepancy, f_D (maximum K_{fs} between the erroneous and the true value/minimum K_{fs} between the erroneous and the true value), associated with an erroneous choice of α^* were determined. The f_D term was also considered because ratios are commonly calculated to express differences between K_{fs} values (e.g., Elrick and Reynolds, 1992). Calculations were carried out for r = 75 and 150 mm to assess the ring size effect on the results of this sensitivity analysis.

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Table 1. Relative error (i.e., difference between erroneous and true value, expressed as a percentage of the true value) and factor of discrepancy (maximum K_{fs} between the erroneous and the true value/minimum K_{fs} between the erroneous and the true value, in parenthesis) obtained by calculating the field-saturated soil hydraulic conductivity, K_{fs}, with eq.(9) and an erroneous choice of the α* parameter by a category, for two values of the ring radius, r

Porous medium	Erroneous α*(mm^{-1})	r = 75 mm	r = 150 mm
Sand soil (K_{fs} = 1.0 ×10^{-1} mm s^{-1}, α* = 0.036 mm^{-1})	0.012	-51.0 (2.04)	-41.2 (1.70)
Loam soil (K_{fs} = 1.0 ×10^{-3} mm s^{-1}, α* = 0.012 mm^{-1})	0.004	-60.5 (2.53)	-55.3 (2.24)
	0.036	103.9 (2.04)	70.2 (1.70)
Clay soil (K_{fs} = 1.0 ×10^{-5} mm s^{-1}, α* = 0.004 mm^{-1})	0.001	-73.1 (3.72)	-71.3 (3.49)
	0.012	152.9 (2.53)	123.7 (2.24)
Clay cap/liner (K_{fs} = 1.0 ×10^{-6} mm s^{-1}, α* = 0.001 mm^{-1})	0.004	272.0 (3.72)	248.9 (3.49)

The f_D values varied from 1.70 to 3.72 (**Table 1**), with higher values in low permeability soils. For a given porous medium, larger errors were associated to the underestimation of α* as compared with those due to the overestimation of this parameter. The errors were slightly lower with the larger ring. An error in K_{fs} by a factor of two or three has been considered acceptable given that K_{fs} ranges from 10^{-9} m s^{-1} for tight clays to 10^{-4} m s^{-1} for coarse sands and given the extremely high spatial variability of K_{fs} found in the field (Elrick and Reynolds, 1992). Assuming a factor of three or more as an important error, this analysis suggested that an erroneous choice of α* by a category should not be expected to substantially compromise the reliability of the K_{fs} prediction for most field soils. In any case, the risk to be in error decreases as the soil permeability to water increases. If a technician has a doubt on which α* value has to be chosen, it is preferable to use a relatively high value because the expected error is lower. Finally, the use of a large ring for the experiments should be preferred because this reduces the K_{fs} estimation error due to an improper selection of α*.

MATERIALS AND METHODS

Experimental data were collected at 34 Burundian sites (**Table 2**), i.e. small fields each having an area of approximately 7 m^2, where the BEST procedure of soil hydraulic characterization (Lassabatère et al., 2006) was applied. The sampling sites were chosen within cropped areas, on the basis of available lodging facilities and the need to move essentially by feet (Bagarello et al., 2011). In general, five infiltration runs were carried out at different sampling points for each site using a 0.075-m-radius ring inserted to a depth of about 0.01 m into the soil surface to avoid lateral loss of the ponded water.

In particular, 19 of the 34 sites used for this investigation were the sites established by Bagarello et al. (2011) in the areas of Kinyami (2°54’30” S, 29°49’06” E) and Nyamutobo (3°27’50” S, 30°15’40” E). According to the FAO classification, Rhodic Ferrasols prevail in the middle and the top of the hillslopes at Kinyami whereas Humic Cambisol soils are present in the valley bottom. Ferrasol Rhodique soils prevail in the Nyamutobo area. For this investigation, an additional group of 15 sites were sampled in the Nyamutobo area in summer 2011. Soil texture was clay at 59% of the 34 sites, clay loam (21%), and silty clay, silty clay loam and loam at the remaining sites. The experimental procedure described by Bagarello et al. (2011) was applied at all sites. Therefore, only a few details on the experiment will be repeated here for brevity reasons. For each site, a total of six 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 in three different sampling points. A disturbed soil sample (0-0.10 m depth) was also collected at the given site. As prescribed by the BEST experimental procedure (Lassabatère et al., 2006), a known volume of water (150 mL) was poured in the cylinder at the start of the measurement and the elapsed time during the infiltration was measured. When the amount of water had completely infiltrated, an identical amount of water was poured into the cylinder and the time needed for the water to infiltrate was logged. The procedure was repeated until the difference in infiltration time between three consecutive trials became negligible, suggesting a practically steady-state infiltration. An experimental cumulative infiltration, I (L), vs.

Table 2. Minimum, maximum, arithmetic mean, Me, and coefficient of variation, CV, of the measured soil properties (ρ_b = soil bulk density) for N = 34 Burundian sites

Variable	min	max	Me	CV (%)
clay (%)	22.7	62.6	44.5	26.1
silt (0.002-0.05 mm) (%)	17.4	49.7	34.2	29.8
sand (%)	12.3	32.9	21.3	23.1
ρ_b (Mg m^{-3})	0.82	1.03	0.91	5.1

time, t (T), relationship including N_{tot} discrete points, N_{tot} being the number of collected (t, I) data points, was then deduced. The undisturbed soil cores were used to determine the soil bulk density, ρ_b (Mg m^{-3}), at the time of sampling and the initial volumetric soil water content. Following Mubarak et al. (2009), the saturated soil water content was calculated as total soil porosity assuming the density of the soil particles equal to 2.65 Mg m^{-3}. The disturbed soil was used to determine the particle size distribution using conventional methods (Gee and Bauder, 1986). Representative values of soil bulk density, water content and particle size distribution for a site were obtained by averaging the individual determinations, since these properties show generally a low spatial variability.

The original BEST procedure by Lassabatère et al. (2006) was applied to obtain the value of the field-saturated soil hydraulic conductivity at each infiltration point. Such value of K_{fs}, denoted by the symbol $K_{fs,B}$, was considered to be the reference value for this investigation. Therefore, the experimental investigation was carried out with the aim to establish the ability of the simplified method based on eq.(9) to reproduce the K_{fs} results given by the BEST procedure. A description of the BEST procedure would be long and it was not considered necessary, being detailed in other recent papers (e.g. Lassabatère et al., 2006; Yilmaz et al., 2010; Bagarello et al., 2011).

For each infiltration run yielding a $K_{fs,B}$ value, a linear regression analysis of the ($I/\sqrt{t}$, $\sqrt{t}$) data was carried out to obtain b_1 of eq.(4). A simplified estimate of K_{fs}, denoted by the symbol $K_{fs,S}$, was obtained by eq.(9) with $\alpha^* = 0.012$ mm^{-1}, and a comparison between $K_{fs,S}$ and $K_{fs,B}$ was carried out. In particular, a two-tailed paired t test was used to establish statistical significance of the differences between the two datasets at $P = 0.05$. A linear regression analysis of $K_{fs,S}$ vs. $K_{fs,B}$ was also carried out. Statistical significance of the correlation coefficient, R, was assessed by an one-tailed t test ($P = 0.05$). The 95% confidence intervals for the intercept and the slope were also calculated to compare the regression line with the identity one.

The assumed value of α^* represented an obvious simplification for the K_{fs} estimation procedure. Assuming that an improved estimate of α^*, as compared with the value of first approximation, may give better K_{fs} estimates, a calibration procedure of this parameter was applied. In particular, alternative scenarios were considered, including a single α^* for the considered data set and an α^* parameter varying with the measured b_1. The reasons of these choices were that we did not find in the literature a specific support for using $\alpha^* = 0.012$ mm^{-1} as a first approximation value for tropical soils, and α^* is theoretically expected to vary from soil to soil (Elrick and Reynolds, 1992). In both cases, the SOLVER routine of Microsoft Excel software (Microsoft Company, Redmond, WA, USA) was used to find the α^* values that minimized an objective function defined as the sum of the squared differences between $K_{fs,S}$ and $K_{fs,B}$. However, the sum of the absolute relative differences between the two variables was also minimized for comparative purposes, taking into account that the percentage difference between the estimated and the true value of K_{fs} has generally more practical interest than the absolute error. For example, an absolute error of 2 mm h^{-1} is negligible for a true K_{fs} of 100 mm h^{-1} but it is substantial if K_{fs} is equal to 1 mm h^{-1}.

The developed relationship between α^* and b_1 was tested with reference to a few data collected in a completely different environment. In particular, the original BEST procedure was applied near Giampilieri (Eastern Sicily, Italy). A total of 11 points were sampled using a 0.075-m-radius ring inserted to a depth of about 0.01 m into the exposed soil surface, and applying 150 mL of water at each pouring. The experimental methods and the analytical procedures described by Bagarello et al. (2011) were used to determine $K_{fs,B}$.

In this investigation, the paired t test was used for statistical analysis because the differences between $K_{fs,S}$ and $K_{fs,B}$ were found to be normally distributed according to the test by Lilliefors (1967) at $P = 0.05$ for most considered scenarios. Linear regression analysis was carried out according to Nearing (1998), who used this approach to determine the relationship between the measurement and the corresponding prediction of a given variable (event soil loss) with reference to a set of data collected at different locations, independently of the data statistical distribution. This approach was considered appropriate because a “perfect” predictive method of K_{fs} yields exactly the same result as the BEST method within the entire range of the sampled $K_{fs,B}$ values and hence the linear regression line between $K_{fs,S}$ and $K_{fs,B}$ coincides with the identity line.

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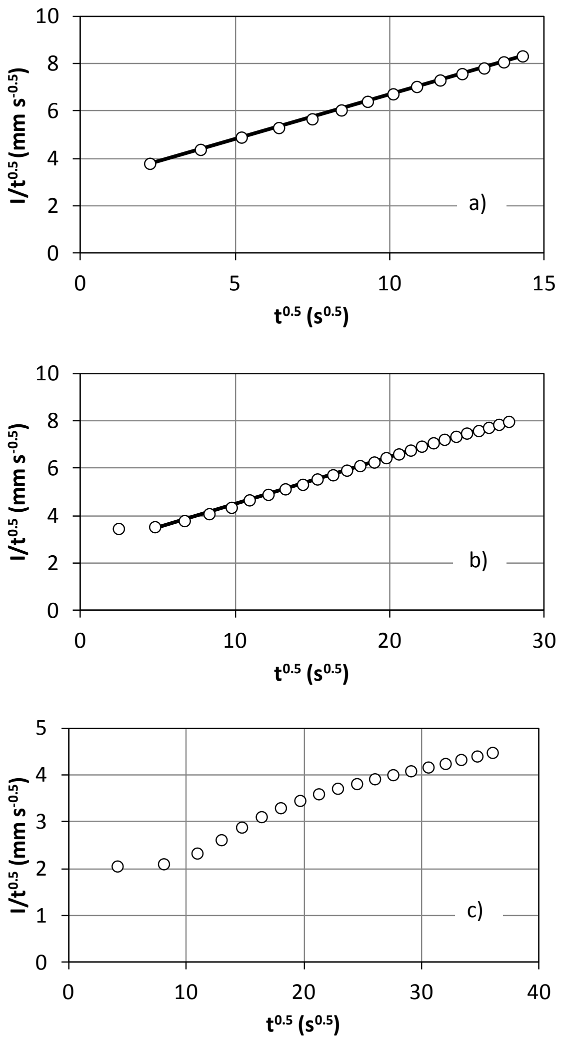
Fig.1. Values of the ratio between the cumulative infiltration, *I*, and the square root of time, *t*, plotted against the square root of *t*. Examples for a run a) showing the expected linear relationship between the two variables for the entire infiltration process; b) showing the linear relationship with the exclusion of the first data point; and c) with an undetectable linear relationship between the two variables



RESULTS

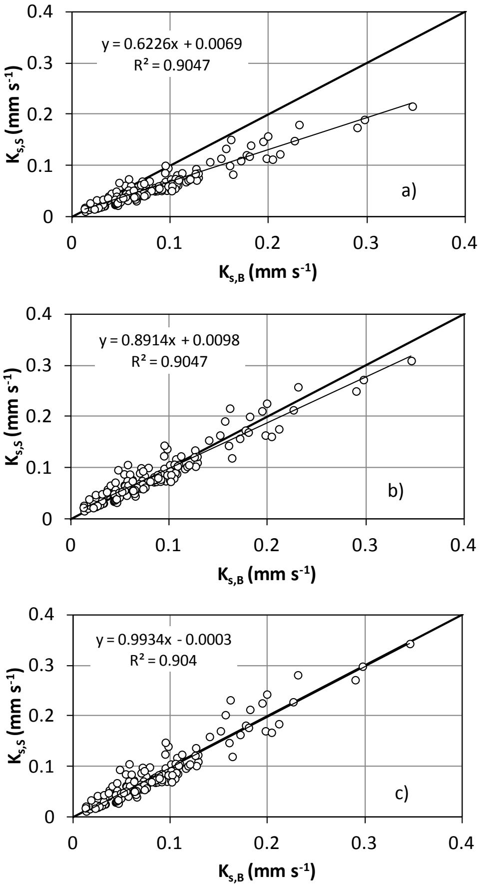
Burundi

The plot of $I/\sqrt{t}$ against $\sqrt{t}$ showed in general the expected linear relationship between the two variables for the entire infiltration run (**Fig.1a**) or with the exclusion of the first few points (generally one or two points and only occasionally more, **Fig.1b**). In some cases, however, a linear relationship between the two variables was undetectable (**Fig.1c**). A perturbation of the run in the early stage of the infiltration process has been detected in other investigations and removed in the fitting of the data to the selected model (e.g. Wu et al., 1999). Therefore, the initial phase of the run denoting an anomalous process was excluded from the fitting in this investigation. However, when the data did not allow to detect a linear relationship between the two variables, the infiltration run was excluded from the analysis since the two-terms infiltration model was not appropriate to describe the process. In most of the ten non linearizable cases, the $I/\sqrt{t}$ vs. $\sqrt{t}$ data showed a downward concavity, excluding the first one or two data points (**Fig.1c**), similar to the one detected by Vandervaere et al. (2000) when hydraulic contact was lost at a certain instant during a tension infiltrometer run (their Fig.1c). The results and the interpretation given by Vandervaere et al. (2000) suggested that the downward concavity is due to the fact that something determining an abrupt slowing down of the infiltration process occurs at a certain instant. With reference to the BEST-type runs, possible factors determining an abrupt slowing down of the infiltration process include soil layering and/or vertical soil water content gradients, with a subsoil less permeable and/or wetter than surface soil. Another possible reason is the occurrence of air entrapment and/or soil particle detachment phenomena, given that water is applied repeatedly on an exposed soil surface.

A total of 149 infiltration runs, yielding a relatively wide range of $K_{fs,B}$ results (maximum/minimum = 26.6, **Table 3**), were used for this investigation. The duration of these runs varied from 158 to 5128 s (mean, Me = 1055 s) and fitting the ($I/\sqrt{t}$, $\sqrt{t}$) data with a linear relationship yielded coefficients of determination, R^2, varying from 0.967 to 0.9997 (Me = 0.995).

Using the value of first approximation of α^* (α^* = 0.012 mm^{-1}) with eq.(9) yielded $K_{fs,S}$ values differing significantly from the corresponding $K_{fs,B}$, a significant correlation between the two variables, and a regression line differing from the identity one (**Fig.2a** and **Table 3**). The ratio between the two estimates of K_{fs} did not exceed a factor of two (i.e., $0.5 \leq K_{fs,S}/K_{fs,B} \leq 2.0$) for 147 of the 149 sampling points, i.e. in the 98.7% of cases, with a maximum error by a factor of 2.06. A prevalence of an underestimation of K_{fs} by eq.(9) was detected, since it occurred in the 87.9% of cases. Considering that, generally, errors in K_{fs} by a factor of two or three can be considered negligible (Elrick and Reynolds, 1992), this investigation suggested that the developed methodology (i.e., eq.(9) with α^* = 0.012 mm^{-1}) may be attractive from a practical point of view.

Fig.2. Comparison between the field-saturated soil hydraulic conductivity estimated with the BEST method ($K_{fs,B}$) and the corresponding values ($K_{fs,S}$) obtained by eq.(9) and an α* parameter a) equal to 0.012 mm^{-1}; b) equal to the optimized one (0.020 mm^{-1}); and c) estimated as a function of the measured b_1 value by eq.(10)



A possible reason of the observed differences between $K_{fs,S}$ and $K_{fs,B}$ was that α* = 0.012 mm^{-1} was not the best choice for the Burundian tropical soils. However, the single, alternative value of α* for the entire dataset obtained by using different objective functions (squared differences, absolute relative error) was not strongly different from the value initially assumed, since it was equal to 0.020 mm^{-1} (**Fig.2b**) or 0.018 mm^{-1}. Whatever α* was assumed, the regression line between $K_{fs,S}$ and $K_{fs,B}$ differed from the identity one (**Table 3**). An α* = 0.020 mm^{-1} was more appropriate than α* = 0.018 mm^{-1} considering that the differences between the two datasets were not statistically significant only in the former case. Moreover, the error did not exceed a factor of two in the 98.0% of cases, and the maximum discrepancy was by a factor of 2.16. Underestimation of K_{fs} by the simplified procedure was obtained in the 53.7% of cases. Therefore, the results obtained with the optimized α* were better than those associated with α* = 0.012 mm^{-1} since the number of the underestimations and the overestimations was similar and, on average, the two sets of data ($K_{fs,S}$, $K_{fs,B}$) did not show significant differences. However, a single α* parameter did not yield a regression line statistically coinciding with the identity line.

A possible strategy to improve the reliability of the $K_{fs,S}$ predictions was thought to use a variable α* with the considered sampling

Table 3. Minimum, maximum, mean, *Me*, and coefficient of variation, *CV*, of the field-saturated soil hydraulic conductivity, K_{fs} (mm s^{-1}), data obtained at N = 149 Burundian sampling points, and parameters of the linear regression line between $K_{fs,S}$ (simplified method) and $K_{fs,B}$ (original BEST procedure)

Variable	α* parameter	Objective function	minimum	maximum	Me	CV (%)	Intercept	Slope	R^2
$K_{fs,B}$			0.013	0.346	0.086 (a) b (c) d e f g h i	67.0			
$K_{fs,S}$	0.012 mm^{-1}		0.012	0.216	0.060 (a)	62.4	0.007 (0.003 - 0.010)	0.623 (0.590 - 0.656)	0.905
	Constant, 0.020 mm^{-1}	SQD	0.017	0.309	0.086 b	62.4	0.010 (0.005 - 0.015)	0.891 (0.844 - 0.939)	0.905
	Constant, 0.018 mm^{-1}	ARE	0.016	0.293	0.082 (c)	62.4	0.009 (0.005 - 0.014)	0.844 (0.800 - 0.889)	0.905
	α*=f(b_1), linear	SQD	0.016	0.317	0.086 d	64.0	0.008 (0.003 - 0.013)	0.908 (0.960 - 0.955)	0.905
	α*=f(b_1), linear	ARE	0.015	0.346	0.084 e	69.5	0.001 (-0.004 - 0.007)	0.969 (0.917 - 1.021)	0.904
	α*=f(b_1), power	SQD	0.016	0.314	0.086 f	63.7	0.008 (0.003 - 0.013)	0.905 (0.857 - 0.953)	0.905
	α*=f(b_1), power	ARE	0.013	0.341	0.085 g	69.9	0.0007 (-0.005 - 0.006)	0.983 (0.931 - 1.036)	0.904
	α*=f(b_1), logarithmic	SQD	0.016	0.314	0.086 h	63.7	0.008 (0.003 - 0.013)	0.905 (0.857 - 0.952)	0.905
	α*=f(b_1), logarithmic	ARE	0.012	0.343	0.085 i	70.7	-0.0003 (-0.006 - 0.005)	0.993 (0.941 - 1.046)	0.904

Means followed by the same lower case letter enclosed in parenthesis are significantly different according to a two-tailed, paired t test (P = 0.05). Means followed by the same lower case letter not enclosed in parenthesis are not significantly different. Values in parenthesis in the Intercept and Slope columns are the 95% confidence intervals for the two parameters. SQD: squared differences. ARE: absolute relative error.

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point, given that α* is expected to vary with the soil characteristics (Elrick and Reynolds, 1992).

On the basis of the experimental results, choosing α* according to soil textural characteristics was not expected to perform well. In fact, $\alpha^* < 0.012$ mm^{-1} should have been selected taking into account that most soils were fine-textured (Elrick and Reynolds, 1992), but $\alpha^* = 0.012$ mm^{-1} was found to be excessively low, since it yielded a clear prevalence of K_{fs} underestimations. However, α* is also expected to increase with K_{fs} (Reynolds and Elrick, 1990) and an increasing b_1 with K_{fs} is predicted by eq.(5). Therefore, α* should increase with b_1. In practice, different α* vs. b_1 relationships (linear, power, logarithmic) were considered and the two unknown parameters of a given relationship were determined by minimizing the sum of the differences between $K_{fs,S}$ and $K_{fs,B}$. Six scenarios were therefore considered, i.e. three shapes of the α* vs. b_1 relationship × two objective functions. The analysis showed that α* increased with b_1, as expected. The correlation between $K_{fs,S}$ and $K_{fs,B}$ was statistically significant and the two datasets did not show significant differences (**Table 3**). Defining the objective function in terms of relative error also yielded a linear regression line between $K_{fs,S}$ and $K_{fs,B}$ not significantly different from the identity one. The maximum closeness of the regression line between $K_{fs,S}$ and $K_{fs,B}$ to the identity one (**Fig.2c**) was detected for the following logarithmic relationship between α* and b_1:

$$\alpha^* = 0.0262 + 0.0035 \times ln(b_1) \qquad (10)$$

For the considered dataset ($0.023 \leq b_1 \leq 0.428$ mm s^{-1}), the calculated α* varied from 0.013 to 0.023 mm^{-1}. The ratio between the two estimates of K_{fs} did never exceed a factor of 1.98, and the $K_{fs,S} < K_{fs,B}$ result was obtained in the 59.1% of the cases. Therefore, using eqs.(9) and (10) was appropriate to obtain individual estimates of K_{fs} not statistically different from the corresponding values obtained with the complete BEST procedure.

Due to the practical difficulties of carrying out additional experiments in Burundi, developing a validation dataset was impossible, notwithstanding the awareness that testing the developed relationship with locally collected, independent data would represent a precious test to verify the generality of the proposed approach at least for Burundian soils. Splitting the available data in two datasets, one for calibration purposes and the other for validation, according to some criterion (e.g., first 19 sites and additional 15 sites) was not considered a good choice, and developing the most robust estimation procedure of α* with all available data was preferred.

Sicily

The measured clay, silt and sand percentages varied from 14.1 to 19.6%, 15.4 to 19.5% and 63.1 to 67.5%, respectively (sample size, N = 11), and the soil was classified as sandy loam. The dry soil bulk density, ρ_b, ranged between 1.26 and 1.81 Mg m^{-3} (N = 11). Therefore, the sampled soil in Sicily was very different from those considered in Burundi, suggesting that the considered validation dataset allowed a meaningful test of eq.(10), although with reference to a relatively small sample size. Two of the 11 infiltration runs were not linearizable on the ($I/\sqrt{t}$, $\sqrt{t}$) plot because the data suggested a practically horizontal relationship between the variables. These two runs were the slowest ones given that, for example, eight volumes of water infiltrated in 20000-34000 s, as compared with a maximum time of 15000 s for the other runs. When the run is very slow, the risk to make mistakes in the field increases because, for example, establishing the exact time to pour the new water volume is difficult or even impossible. In this case, therefore, the data have unavoidably a reduced quality. The mean $K_{fs,B}$ value for the nine valid runs was 0.0092 mm s^{-1} and the associated CV was equal to 113.5%. The measured b_1 values varied from 0.002 and 0.042 mm s^{-1} and eq.(10) yielded α* values varying between 0.004 and 0.015 mm^{-1}. Therefore, the considered dataset included b_1 data also falling outside the Burundian range. The mean of $K_{fs,S}$ and the associated CV were equal to 0.0094 mm s^{-1} and 102.2%, respectively, and the differences between $K_{fs,B}$ and $K_{fs,S}$ were not statistically significant. The maximum discrepancy was by a factor of 3.5, and seven discrepancies did not exceed a factor of approximately two. Therefore, the maximum factor of discrepancy was higher than, but very close to, the maximum acceptable error according to Elrick and Reynolds (1992) and others. Finally, the correlation between the variables was significant (R^2 = 0.80) and the regression line (intercept = 0.002, slope = 0.82) did not differ from the identity one (confidence intervals for the intercept and the slope equal to -0.003 – 0.007 and 0.45 – 1.19, respectively). These results were encouraging since they suggested that the proposed relationship was usable with some approximation in a very different environment compared to the calibration one.

DISCUSSION

From a practical point of view, the K_{fs} measurement method developed in this investigation should be attractive because it suggests that a rapid or relatively rapid experiment carried out with a ring, a stopwatch and small volumes of water can allow an estimation of K_{fs}. This method has clear similarities with the well known One Ponding Depth (OPD) approach for the single-ring pressure infiltrometer method (Reynolds and Elrick, 1990) because a ring, a single measured infiltration process and an estimate of the α^* parameter are used in both cases to determine K_{fs}. Our method, using the transient phase of the infiltration process, is more rapid than the OPD approach since reaching steady state flow rate is necessary only in the latter case.

Eq.(9) is theoretically sound because it combines a physically based infiltration model with basic relationships between soil variables. Therefore, this equation should be considered of general validity.

On the other hand, eq.(10) was physically plausible but it was developed empirically for a particular data set and tested with another, small data set. Therefore, this equation needs additional testing with other data sets from both tropical and temperate soils. More in general, additional investigations on α^* should consider that a rough estimation of this parameter is not expected to compromise calculation of K_{fs} because the error did not exceed a factor of two both when a variable α^* was used in eq.(9) and with a fixed α^* (0.012 mm^{-1}), lower than the minimum value determined with eq.(10) (0.013 mm^{-1}). In other words, a generic estimate of α^* seems usable to obtain the order of magnitude of K_{fs}. On the other hand, the choice of this parameter should not be undervalued because only an improved estimating procedure allowed to detect a statistical coincidence (means and regression line) between $K_{fs,S}$ and $K_{fs,B}$.

The choice to use $K_{fs,B}$ as a benchmark needs some explanation. In principle, testing a new method to measure a soil parameter should imply a comparison with an independent measurement of that parameter, made with a well established method. A reason of our choice, important from a practical point of view but scientifically weak, was that measuring K_{fs} in Burundi by an alternative method was practically impossible due to the limitations in the available instrumentation and resources. More important is the fact that comparing techniques for measuring K_{fs} is known to be an imprecise and perhaps even dubious enterprise, and different measurement methods often yield substantially dissimilar values since K_{fs} is extremely sensitive to sample size, flow geometry, sample collection procedures, etc.. Differences can also be detected when different calculation techniques are applied to the same data set (Mertens et al., 2002), but the results can be interpreted more easily in this last case (Wu et al., 1999). Therefore, we used $K_{fs,B}$ as the benchmark because it was determined on the basis of exactly the same experimental information used to derive $K_{fs,S}$.

Additional investigations may help to more clearly define factors determining the observed departures of the $I/\sqrt{t}$ vs. $\sqrt{t}$ data from the expected linear behavior. From a practical point of view, these departures show that the method is not universally applicable. In any case, field data allow to make a prediction on the local applicability of the procedure (linearity of the data points).

CONCLUSIONS

The investigation showed that an approximate evaluation of field-saturated soil hydraulic conductivity, K_{fs}, can be carried out by a simple methodology needing minimal experimental effort. A cylinder is inserted to a short depth into the soil, so to produce a minimal disturbance of the medium, and the infiltration time of a few small volumes of water repeatedly applied at the surface of the confined soil is measured. Calculating K_{fs} needs to determine the slope of the linearized cumulative infiltration vs. time relationship, the ring radius and to estimate the α^* parameter.

An α^* = 0.012 mm^{-1}, suggested as the value of first approximation for most agricultural soils, was found to be usable in the agricultural tropical soils sampled in Burundi. In particular, this value of α^* allowed to obtain an estimate of K_{fs} differing at the most by a practically negligible factor of two from the K_{fs} values obtained by the complete BEST procedure of soil hydraulic characterization. The analysis also suggested that, for soils similar to those sampled in Burundi, the

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estimation of K_{fs} can be improved if a slightly higher value of α^* ($\alpha^* = 0.020$ mm^{-1}) is used.

A more important result was however the empirical detection of a physically plausible relationship between α^* and the slope of the linearized infiltration curve. The implication of this result was that the measured infiltration curve contained the necessary information to estimate α^*. The developed α^* predictive relationship allowed to reproduce accurately the K_{fs} values obtained by BEST in terms of means and individual predictions, and it should be robust enough to be used in soils similar to the sampled ones since it was obtained by considering a reasonably large dataset.

The relationship was successfully tested for a few Sicilian soils, but testing the developed procedure in other areas of the world is advisable.

The developed method is cheap, rapid and parsimonious in terms of both the devices that have to be transported and the measurements that have to be carried out in the field. Therefore, it is a good candidate method for intensively sampling an area of interest with a practically sustainable experimental effort and, hence, it could allow improved interpretation and simulation of soil hydrological processes, such as runoff generation.

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Appendix L: Testing a Simplified Approach to Determine Field Saturated Soil Hydraulic Conductivity

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ABSTRACT

Interpreting and simulating hydrological processes need a large number of field saturated soil hydraulic conductivity, K_{fs}, data that should be collected with simple and rapid field experiments. A Simplified method based on a Beerkan Infiltration run (SBI method) was recently developed and tested successfully on Burundian soils. With the SBI method, a cylinder is inserted to a short depth into the soil and the infiltration time of a few small volumes of water repeatedly applied at the surface of the confined soil is measured. Calculating K_{fs} needs the slope of the linearized cumulative infiltration vs. time relationship and an estimate of the so called α^* parameter. In this investigation, the SBI method was validated with reference to a larger dataset, also including different Sicilian soils. The α^* value of first approximation (0.012 mm^{-1}) yielded an estimate of K_{fs} differing in general by not more than a factor of three from the K_{fs} values obtained by the more complete and onerous BEST (Beerkan Estimation of Soil Transfer parameters) procedure of soil hydraulic characterization. The K_{fs} values obtained with SBI method were also very close (means differing by a factor of 1.01) to the ones determined with the One Ponding Depth relationship for the single ring pressure infiltrometer technique. Detection of physically plausible relationships between α^* and the slope of the linearized infiltration curve indicated that the measured infiltration process contains the necessary information to estimate α^*. Different α^* predictive relationships for Sicily and Burundi allowed to obtain estimates of K_{fs} never differing by more than a factor of three from the corresponding values obtained with BEST. The developed method is a good candidate method for intensively sampling an area of interest. Points needing developments include tests with other datasets, comparisons with independent measurements of both α^* and K_{fs}, and maybe development of an improved experimental methodology to obtain the infiltration data.

Keywords: Soil hydraulic properties; Measurement methods; BEST (Beerkan Estimation of Soil Transfer parameters) procedure; Single ring pressure infiltrometer.

INTRODUCTION

Interpreting and simulating different hydrological processes, including rainfall partition into infiltration and runoff, need a large number of spatially distributed determinations of field saturated soil hydraulic conductivity, K_{fs}, that is a highly variable soil property (e.g., Warrick, 1998). These data should be collected in the field to maintain the functional connection between the sampled soil volume and the surrounding soil (Bouma, 1982; Lauren et al., 1988). Using small volumes of water, easily transportable equipment, and conducting short duration experiments is desirable to determine K_{fs} at a great number of locations over a large area and with a realistic use of resources in terms of time and costs.

Most field techniques, such as the well permeameter and single ring infiltrometer constant head techniques (Reynolds and Elrick, 1986, 1990), rely on the attainment of a quasi steady state flow rate of water into the soil. The One Ponding Depth (OPD) approach is one of the simplest means to apply these techniques since a single ponded depth of water is established on the infiltration surface (Reynolds and Elrick, 1990). However, waiting for flow steadiness can be a practical limit to the field use of permeameters and infiltrometers since steady state experiments with a reasonably short duration can only be conducted in relatively permeable soils (Elrick and Reynolds, 1992).

On the basis of the BEST (Beerkan Estimation of Soil Transfer parameters) procedure of soil hydraulic characterization (Lassabatère et al., 2006), Bagarello et al. (2012a) suggested to determine K_{fs} by only a transient infiltration process through a soil surface confined by a ring and an estimate of the α^* parameter, expressing the relative importance of gravity and capillary forces during an infiltration process (Reynolds and Elrick, 1990). With reference to different Burundian soils having in most cases a clay or a clay loam texture, the estimates of K_{fs} obtained by the proposed method and the α^* value of first approximation for most field soils, i.e. $\alpha^* = 0.012$ mm^{-1} (Elrick and Reynolds, 1992), were significantly lower than the ones obtained by BEST. However, the ratio between these two K_{fs} estimates did not exceed a factor of two in the 99% of cases, with a maximum error by a factor of 2.1. Considering that, generally, errors in K_{fs} by a factor of two or three can be considered negligible (Elrick and Reynolds, 1992), Bagarello et al. (2012a) suggested that using the α^* value of first approximation may be attractive from a practical point of view. These authors also developed an empirical relationship to predict α^*, allowing to obtain statistically equivalent estimates of K_{fs} with BEST and the simplified method.

The general objective of this investigation was to validate the new method for determining Kfs with reference to a larger dataset, also including data from different Sicilian soils. The K_{fs} values obtained by the simplified method were compared with the ones determined by BEST and the OPD approach for the single ring pressure infiltrometer technique. An attempt to improve the α^* estimation for K_{fs} prediction was also carried out.

THE SIMPLIFIED METHOD FOR DETERMINING FIELD SATURATED SOIL HYDRAULIC CONDUCTIVITY

The simplified method developed by Bagarello et al. (2012a) to determine K_{fs} is based on a field infiltration experiment identical to the one used by the BEST procedure of soil hydraulic characterization (Lassabatère et al., 2006). A cylinder is inserted to a short depth into the soil, so to produce a minimal disturbance of the porous medium, and the infiltration time of a few small volumes of water repeatedly applied at the surface of the confined soil is measured. An experimental cumulative infiltration, I (L), vs. time, t (T), relationship including a given number of discrete points (8 to 15 according to Lassabatère et al., 2006) is then deduced and used to estimate K_{fs} (L T^{-1}) by the following relationship:

$$K_{fs} = \frac{b_1}{0.467\left(\frac{2.92}{r\,\alpha^*}+1\right)} \tag{1}$$

where b_1 (L T^{-1}) is the slope of the linearized cumulative infiltration curve, estimated by a linear regression analysis of the ($I/\sqrt{t}, \sqrt{t}$) data and r (L) is the radius of the ring. Therefore, a very simple infiltrometric experiment can provide an estimate of K_{fs} if the α^* (L^{-1}) parameter is known or it is properly evaluated. Additional field and laboratory measurements, such as initial and final soil water content, particle size distribution or bulk density, are not strictly necessary. The acronym SBI is suggested to denote the method, given that it is a Simplified method based on a Beerkan Infiltration run.

Eq.(1) is theoretically sound because it combines a physically based infiltration model (Lassabatère et al., 2006) with basic relationships between soil variables (Philip, 1957; Reynolds and Elrick, 1990, 2002a,b). A theoretical limit is that the infiltration model is valid for the transient phase of the infiltration process. From a practical point of view, however, the duration of the infiltration run in the field does not represent a crucial step of the data analysis procedure based on the infiltration equation by Lassabatère et al. (2006) (Bagarello et al., 2011).

According to the literature, the α^* parameter can be estimated on the basis of a general description of soil textural and structural characteristics (Elrick and Reynolds, 1992). Working with 149 infiltration curves collected on Burundian soils, Bagarello et al. (2012a) developed the following relationship between α^* (mm^{-1}) and b_1 ($mm\ s^{-1}$):

$$\alpha^* = 0.0262 + 0.0035 \times ln(b_1) \quad (2)$$

suggesting that the measured infiltration curve contains the necessary information to estimate α^*. Eq.(2) was positively tested with reference to a few sampling points (sample size, N = 9) located in the Giampilieri (Eastern Sicily) area, and an increasing relationship between α^* and b_1 was also detected with reference to this small dataset alone (Bagarello et al., 2012b). However, eq.(2) needs additional testing and possibly developments with other datasets.

MATERIALS AND METHODS

A relatively large dataset was considered in this investigation by supplementing the data already considered by Bagarello et al. (2012a,b) (Burundi, Giampilieri) with data collected at other Sicilian sites, mainly located close to Palermo. The complete BEST procedure was applied at a total of 241 sampling points, using the same methodology at each point to measure infiltration. In particular, a ring of radius r = 0.075 m was inserted to a depth, d, of about 0.01 m into the soil surface. A known volume of water (150 mL) was poured in the cylinder at the start of the measurement and the elapsed infiltration time was measured. When the amount of water had completely infiltrated, an identical amount of water was poured into the cylinder and the time needed for the water to infiltrate was logged. The procedure was repeated until the difference in infiltration time between three consecutive trials became negligible, suggesting a practically steady state infiltration. An experimental cumulative infiltration, I, vs. time, t, relationship including N_{tot} discrete points, N_{tot} being the number of collected (t, I) data, was then deduced. For each infiltration run yielding an estimate of K_{fs} with BEST, denoted by the symbol K_{fsB}, a linear regression analysis of the ($\sqrt{t}$, $I/\sqrt{t}$) data was carried out to obtain b_1 of eq.(1). The infiltration runs showing a linear $I/\sqrt{t}$ vs. $\sqrt{t}$ relationship, with the exception at the most of the first few data points (Bagarello et al., 2012a), were included in the considered dataset in this investigation.

At first, three estimates of K_{fs} for a sampling point were compared, i.e. K_{fsB}, K_{fsS} and K_{fsRE}, where K_{fsS} denotes the conductivity obtained with the SBI method and K_{fsRE} is the K_{fs} value calculated by the OPD relationship for the single ring pressure infiltrometer technique (Reynolds and Elrick, 1990). An estimate of quasi steady state infiltration rate, i_s ($L\ T^{-1}$), was available for each infiltration run, being also necessary to apply BEST. The ponded head of water on the infiltration surface, H (L), was not really constant during the run but it did not varied substantially, decreasing from a maximum of 0.011 m to zero. The average of these two extreme values was assumed for H in the K_{fsRE} calculation, also considering that numerical tests done with a variable head at the soil surface gave essentially the same results as those with the mean constant head (Touma et al., 2007). Eq.(36) by Reynolds and Elrick (1990) was used to calculate the shape factor, G, as a function of d/r. This equation was developed for $0.03 \le d \le 0.05$ m and $0.05 \le H \le 0.25$ m. Therefore, an uncertain G estimate cannot be excluded although other investigations suggested a wider validity of the equation (Youngs et al., 1993). The same value of α^*, equal to the first approximation value (i.e. α^* = 0.012 mm^{-1}), was used for the K_{fsS} and K_{fsRE} calculations. By this choice, differences between K_{fsS} and K_{fsRE} were not attributable to a different choice of α^* and the comparison allowed to establish what happens when a calculation approach using a rough estimate of α^* (K_{fsS}, K_{fsRE}) is used instead of a more complicated and theoretically robust procedure (K_{fsB}). A two tailed paired t test was used to establish the statistical significance of the differences between two datasets at P = 0.05. A linear regression analysis of two sets of K_{fs} data was also carried out. Statistical significance of the correlation coefficient, R, was assessed by an one tailed t test (P = 0.05). The 95% confidence intervals for the intercept and the slope were also calculated to compare the regression line with the identity one.

An attempt to improve estimation of the α^* parameter of eq.(1) was then carried out by applying the procedure described in greater detail by Bagarello et al. (2012a) to the Sicilian dataset. In particular, different α^* vs. b_1 relationships (linear, power, logarithmic) were considered and the SOLVER routine of the Microsoft Excel software (Microsoft Company, Redmond, WA, USA) was used to determine the two unknown parameters of a given $\alpha^* = f(b_1)$ relationship. The

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Table 1. Sample size (N), minimum (min), maximum (max), mean (M), median (Md) and coefficient of variation (CV in %) of the clay (cl), silt (si) and sand (sa) percentages, the dry soil bulk density (ρ_b), the duration of the infiltration process (d_i), the number of applied water volumes (N_v), the coefficient of determination (R^2) of the linear regression line between $I/\sqrt{t}$ and $\sqrt{t}$, I being the cumulative infiltration and t the time, and the slope (b_1) of the linearized cumulative infiltration curve for the Sicilian dataset.

Statistic	cl (%)	si (%)	sa (%)	ρ_b (g cm^{-3})	d_i (s)	N_v	R^2	b_1 (mm s^{-1})
N	34	34	34	37	43	43	43	43
min	14.1	15.4	14.2	0.865	155	9	0.911	0.0018
max	58.1	37.5	67.5	1.716	20031	20	0.999	0.669
M	26.6	26.1	47.2	1.076	1839	15.1	0.983	0.199
Md	18.7	27.3	53.1	1.074	573	15	0.991	0.173
CV	50.7	26.5	38.0	12.9	202.5	12.9	2.0	75.4

objective function to be minimized was defined as the sum of the squared differences between K_{fsS} and K_{fsB}. The sum of the absolute relative differences between the two variables was also minimized, taking into account that the percentage difference between the estimated and the true value of K_{fs} has generally more practical interest than the absolute error. Six scenarios were therefore considered, i.e. three shapes of the α^* vs. b_1 relationship × two objective functions.

RESULTS AND DISCUSSION

The Sicilian soils considered in this investigation differed appreciably by the clay, cl, silt, si, and sand, sa, percentages (USDA classification) and the dry soil bulk density, ρ_b (**Table 1**). The soil texture was clay loam, sandy loam and, in a few cases, clay. Therefore, the database was representative of different physical conditions and it was considered to be appropriate for reliably testing and developing the SBI method. The infiltration runs selected for this investigation were 192 (i.e. 80% of the total) since the BEST procedure failed or a linear relationship between $I/\sqrt{t}$ and $\sqrt{t}$ was undetectable for 49 runs. In particular, 149 and 43 valid runs were carried out in Burundi and in Sicily, respectively. For the valid runs carried out in Sicily, **Table 1** summarizes the run duration, d_i, the number of applied water volumes, N_v, the coefficient of determination, R^2, of the linear relationship of $I/\sqrt{t}$ vs. $\sqrt{t}$, and the slope of the linearized cumulative infiltration curve, b_1. Bagarello et al. (2012a) gave a similar information for the Burundian dataset. On average, the initial 1.7 (for Burundi) and 0.9 (for Sicily) points were excluded from the fitting of the data with the linearized infiltration model. The initial perturbation of the infiltration process under both saturated and unsaturated conditions has been attributed to several factors such as hydrophobicity, initial air entrapment in the soil, or turbulence of the applied water volumes (Carrick et al., 2011; Minasny and McBratney, 2000; Nimmo et al., 2009; Wu et al., 1999).

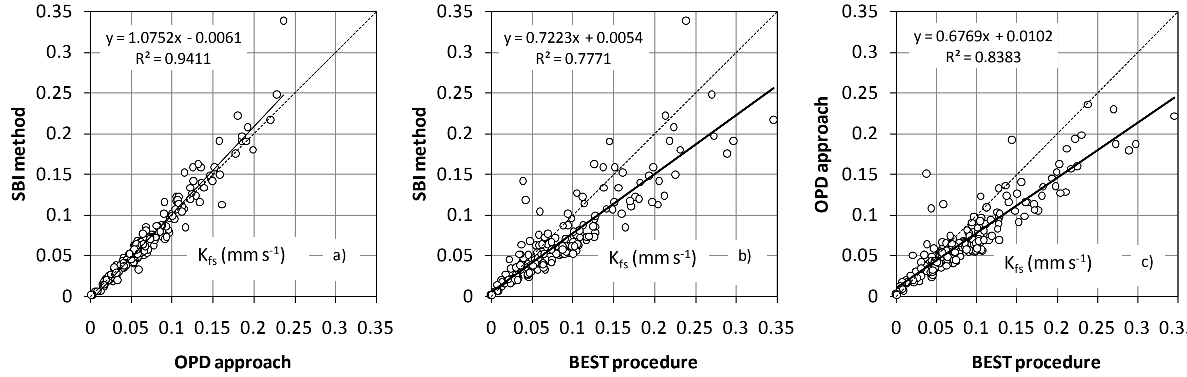
The mean K_{fsS} and K_{fsRE} values were very similar (i.e. differing by a negligible factor of 1.01) and not significantly different (**Table 2**). The medians also differed by a negligible factor of 1.07. The SBI method yielded more variable results than the OPD approach but the two coefficients of variation (CV = 66 and 74%) differed by a few percentage units. The K_{fsS} and K_{fsRE} values were significantly correlated (R^2 = 0.941) and the regression line was close to the identity line (**Figure 1**). However, the calculated 95% confidence intervals for the intercept and the slope varied from -0.009 to -0.003 and from 1.04 to 1.11, respectively, suggesting that the two lines did not coincide. A negative intercept of the regression line and a slope greater than one indicate a tendency of the SBI method to yield lower (higher) values than the OPD approach for

Table 2. Minimum (min), maximum (max), mean (M), median (Md), and coefficient of variation (CV, in %) of the field saturated soil hydraulic conductivity, K_{fs} (mm s^{-1}), values obtained with the BEST procedure of soil hydraulic characterization (K_{fsB}), the OPD approach (K_{fsRE}) and the SBI method (K_{fsS}) (sample size, N = 192).

Statistic	BEST procedure, K_{fsB}	OPD approach, K_{fsRE}	SBI method, K_{fsS}
min	0.0001	0.0013	0.0009
max	0.346	0.236	0.337
M	0.088 (a) (b)	0.070 (a) c	0.069 (b) c
Md	0.073	0.058	0.054
CV	70.8	66.1	74.1

The values in a row followed by the same lower case letter enclosed in parentheses were significantly different according to a paired two tailed t test (P = 0.05). The values followed by the same lower case letter not enclosed in parentheses were not significantly different.

Figure 1. Comparison between the field saturated soil hydraulic conductivity, K_{fs}, values obtained by the One Ponding Depth (OPD) approach, the BEST procedure of soil hydraulic characterization and the SBI method for the complete set of Sicilian and Burundian data (sample size, N = 192).



low (high) K_{fs} values. Taking into account that the two methods differ by the considered portion of the infiltration run (final data for the OPD approach, all data for the SBI method), possible factors determining this tendency might include overestimation of quasi steady flow rate in low permeability soils and changes in the soil particle arrangement at the infiltration surface due to the repeated pouring of water. In any case, the two estimates of K_{fs} at a sampling point differed at the most by a factor of 2.3 and this difference did not exceed a factor of 2 in the 99% of the cases. Therefore, the two calculation procedures of K_{fs} were very similar, supporting the soundness of the developed SBI method. On average, K_{fsB} was significantly greater than both K_{fsS} and K_{fsRE} (**Table 2**). A statistically significant correlation was detected between K_{fsB} and both K_{fsS} (R^2 = 0.777) and K_{fsRE} (R^2 = 0.838) but the regression lines (**Figure 1**) differed significantly from the identity line, given that the 95% confidence intervals for the intercept and the slope were equal to -0.0006 – 0.011 and 0.67 – 0.78, respectively, for the K_{fsS} vs. K_{fsB} relationship, and to 0.006 – 0.15 and 0.63 – 0.72, respectively, for the K_{fsRE} vs K_{fsB} relationship. For both simplified approaches (SBI, OPD), the difference between the K_{fs} estimate and K_{fsB} did not exceed a factor of two and three in the 96.4 and 98.4% of the cases, respectively. The maximum difference was by a factor of 13.4 for the OPD approach and of 6.4 for the SBI method. Therefore, the OPD data were better correlated with the BEST ones, but the results of the SBI method were closer to the data obtained with the complete BEST procedure. The fact that, for the majority of the sampling points, the difference between K_{fsB} and both K_{fsS} and K_{fsRE} did not exceed a factor of three suggested that both simplified methods with a rough estimation of α^* can be used to obtain at least a first approximation value of K_{fs}. The SBI method appears to be marginally preferable to the OPD approach since the maximum departure from the more complete method was lower in the former case.

For the Sicilian dataset, an increasing α^* vs. b_1 relationship, as expected (Bagarello et al., 2012a), was obtained for all considered shapes (linear, power, logarithmic) only when the objective function was defined in terms of absolute relative differences between K_{fsS} and K_{fsB}. With both the linear and the power relationship between α^* and b_1, i) the correlation of K_{fsS} against K_{fsB} was statistically significant, ii) the two datasets did not show significant differences, and iii) the linear regression line between K_{fsS} and K_{fsB} was not significantly different from the identity line (**Table 3**). The maximum difference between K_{fsS} and K_{fsB} was lower with the linear α^* vs. b_1 relationship (factor of 3.2) than the power one (factor of 5.8).

Table 3. Minimum (*min*), maximum (*max*), mean (*M*), and coefficient of variation (*CV* in %) of the field saturated soil hydraulic conductivity, K_{fs} (mm s^{-1}), data obtained at N = 43 Sicilian sampling points, and parameters of the linear regression line between K_{fsS} (SBI method) and K_{fsB} (original BEST procedure).

Variable	$\alpha^*=f(b_1)$ relationship	min	max	M	CV	Intercept	Slope	R^2	Error		
									Max	< 2	< 3
$K_{fs,B}$		0.00015	0.272	0.097 a b c	80.0						
$K_{fs,S}$	linear	0.00047	0.420	0.088 a	96.8	-0.003 (-0.025 – 0.019)	0.937 (0.759 – 1.114)	0.734	3.2	83.7	95.3
	power	0.00023	0.356	0.087 b	88.0	0.003 (-0.015 – 0.021)	0.865 (0.718 – 1.013)	0.773	5.8	86.0	95.3
	logarithmic	0.00015	0.328	0.087 c	83.2	0.007 (-0.010 – 0.023)	0.821 (0.686 – 0.956)	0.786	9.3	86.0	95.3

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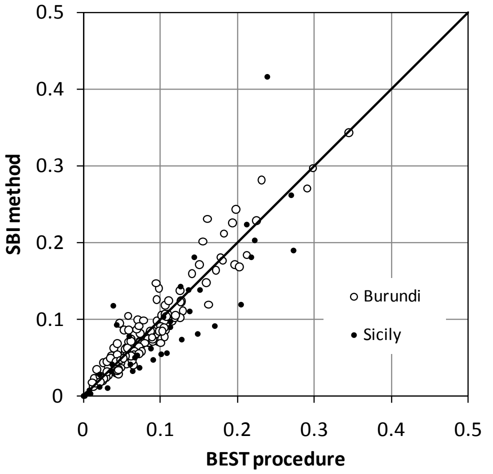
Figure 2. Comparison between the field saturated soil hydraulic conductivity, K_{fs} (mm s^{-1}), values obtained with the BEST procedure of soil hydraulic characterization and the SBI method with the α* parameter estimated as a function of the slope of the linearized cumulative infiltration curve (sample size, N = 149 for Burundian soils and N = 43 for Sicilian soils).



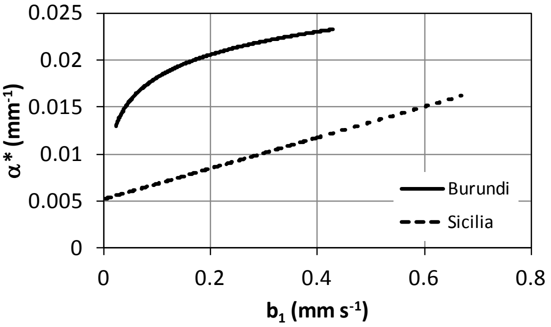
A factor of 3.2 is very close to the maximum factor of difference that can be considered negligible from a practical point of view (Elrick and Reynolds, 1992). Therefore, the following relationship was considered to yield satisfactory conductivity predictions for the considered Sicilian dataset according to the selected criteria:

$$\alpha^* = 0.0052 + 0.016 \times b_1 \quad (3)$$

Figure 2, comparing K_{fsB} with the corresponding values of K_{fsS} obtained by eqs.(2) (Burundi) and (3) (Sicily), suggests a satisfactory agreement between the two datasets.

Applying eq.(3) in the experimental range of b_1 ($0.0018 \leq b_1 \leq 0.669$ mm s^{-1}) yielded α* values varying from 0.0052 to 0.016 mm^{-1} (mean = 0.008 mm^{-1}). According to the textural characteristics of the sampled Sicilian soils, the value of α* to be chosen from the list by Elrick and Reynolds (1992) would be 0.004 or 0.012 mm^{-1}. These values were not very different from the ones obtained with the Sicilian dataset, which can be viewed as an independent support to the applicability of eq.(3) in soils of temperate climates.

Figure 3. Relationships between the α* parameter and the slope of the linearized cumulative infiltration curve, b_1, obtained for Burundian and Sicilian soils.



Eqs.(2) and (3) yielded clearly different α* estimates (**Figure 3**), with the former equation overestimating α* by a factor varying with b_1 ($0.002 \leq b_1 \leq 0.43$ mm s^{-1}) between 1.9 and 2.7. A difference between the α* relationships appears plausible since temperate and tropical soils show chemical and physical differences (Tomasella and Hodnett, 2004) including, for example, lower bulk densities for the tropical than the temperate soils (Hodnett and Tomasella, 2002). For both soil types, however, the measured infiltration curve contained the necessary information to estimate α*.

The assumed shape of the relationship between α* and the slope, b_1, of the linearized infiltration curve is reported in the "$\alpha^*=f(b_1)$ relationship" column. Means followed by the same lower case letter were not significantly different according to a two tailed, paired t test (P = 0.05). Values in parenthesis in the "Intercept" and "Slope" columns are the 95% confidence intervals for the two parameters. *Max* in the "Error" columns is the maximum factor of difference between the two estimates of K_{fs}. The percentage of cases with a factor of difference not exceeding two and three is given in the "< 2" and "< 3" columns, respectively.

This investigation confirmed that a rather generic estimate of the α* parameter (α* = 0.012 mm^{-1}) can be used to obtain a plausible estimate of K_{fs}. However, the choice of this parameter should not be undervalued because only an improved estimating procedure allowed to obtain K_{fsS} values that were not statistically different from the K_{fsB} ones. Moreover, only in this last case the maximum difference between the two variables did not exceed a practically negligible level.

In this investigation, the choice to use K_{fsB} as a benchmark was due to the fact that comparing K_{fs} measurement methods is uncertain (Reynolds et al., 2000) and K_{fsB} was determined on the basis of the same experimental information used to derive K_{fsS} and K_{fsRE}. Obviously, developing more confidence on the SBI method implies additional investigations that should be carried out with other datasets and also with independent measurements of both α* and K_{fs}. It would also be advisable to more clearly define factors determining the observed departures of the $I/\sqrt{t}$ vs. $\sqrt{t}$ data from the expected linear behavior. From a practical point of view, field data allow to make a prediction on the local applicability of the procedure, that can be evaluated by the linearity of the data points. The experimental procedure used to collect a set of (t, I) data at a given sampling point also needs testing and maybe developments. The reason is that BEST, the SBI method and the OPD approach theoretically assume that a constant pressure head ≥ 0 is maintained on the infiltration surface of a rigid porous medium. Pouring water when the previously applied amount had completely infiltrated may promote air entrapment phenomena in the sampled soil volume and may also favor soil structure alteration phenomena at the infiltration surface. Therefore, the impact of the suggested procedure, that has the obvious advantage of being very simple, on the soil hydraulic characterization should be specifically taken into account. At this aim, comparisons with infiltration runs carried out by steadily maintaining a small (i.e., close to zero) depth of water on the infiltration surface should be developed.

CONCLUSIONS

The investigation confirmed that an approximate evaluation of field saturated soil hydraulic conductivity, K_{fs}, can be carried out by a simple methodology needing a minimal experimental effort. A cylinder is inserted to a short depth into the soil and the infiltration time of a few small volumes of water repeatedly applied at the surface of the confined soil is measured. Calculating K_{fs} needs to determine the slope of the linearized cumulative infiltration vs. time relationship and to estimate the α^* parameter. The acronym SBI was used to denote the method, given that it is a Simplified method based on a Beerkan Infiltration run.

An $\alpha^* = 0.012$ mm^{-1}, suggested as the value of first approximation for most agricultural soils, was found to be usable in soils of both tropical and temperate climates to obtain an estimate of K_{fs} differing in general by less than a practically negligible factor of three from the K_{fs} values obtained by the complete BEST procedure of soil hydraulic characterization. Clear similarities were also detected between the SBI method and the One Ponding Depth procedure of analysis of single ring infiltration data.

Detecting physically plausible relationships between α^* and the slope of the linearized infiltration curve suggested that the infiltration data contained the necessary information to estimate α^*. The developed α^* predictive relationships, differing between tropical and temperate climate soils, allowed to reduce the maximum discrepancies between different K_{fs} estimates.

Additional data should be collected to improve the robustness of the α^* predictive relationship. Other points needing developments include comparisons with independent measurements of both α^* and K_{fs}, a more clear definition of the factors determining an anomalous behavior of the first part of the linearized cumulative infiltration curve, and maybe development of an improved experimental methodology to obtain an infiltration dataset, i.e. reducing the risk of air entrapment and soil disturbance phenomena. The developed method is cheap, rapid and parsimonious in terms of both the devices that have to be transported and the measurements that have to be carried out in the field. Therefore, it is a good candidate method for intensively sampling an area of interest with a practically sustainable experimental effort.

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