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FIELD MEASUREMENTS BASED MODEL FOR SURFACE IRRIGATION EFFICIENCY ASSESSMENT

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Abstract

Within scenarios of water scarcity, the irrigation efficiency plays an increasingly strategic role. In this paper, a method that uses an advance-infiltration model based on four field measurements and the soil particle size distribution is proposed to estimate border-irrigation efficiencies. This method was applied to fifteen irrigation events and the application, storage and distribution efficiencies were estimated. The advance-infiltration model was validated against soil moisture measurements. The field-scale saturated hydraulic conductivity was estimated by model fitting to the measured depth of water infiltration. The sensitivity of the modelled irrigation efficiency to the operational surface irrigation parameters was evaluated by simulating seven irrigation scenarios based on field-collected data.

The infiltration profiles obtained by the proposed method were in agreement with the soil moisture measurements. The maximum difference between simulated and measured infiltration depth was 0.018 m . The field-scale saturated hydraulic conductivity values were in agreement with the infiltrometer tests results. The analysis of both simulated scenarios and monitored irrigation events highlighted the need for farmers to reduce the flow rates and increase the duration of irrigation events, in order to improve the irrigation efficiencies.

Keywords: agricultural hydrology; surface irrigation; irrigation efficiency; irrigation modelling.

1 Introduction

Because of the ever-increasing demand for water, analyses of irrigation efficiency have assumed an important role in Italy and throughout the entire Mediterranean area (Chohin-Kuper et al., 2003; Fereres and Soriano, 2007; Inglesias et al., 2007). Additionally, climate change is expected to increase water scarcity (Arnell, 1999; Inglesias et al., 2007).

On the western Po River Plain (Piedmont, northern Italy), where corn (*Zea mays* L.) is the most widely grown crop, surface irrigation systems are primarily used. Thus, for water resource management programmes (for which it is necessary to evaluate and reach a compromise between the constraints imposed by water scarcity and the production requirements) the analysis of the irrigation efficiencies of surface irrigation systems has become an essential tool.

To calculate the dependence of irrigation efficiency on irrigation parameters, three different strategies may be adopted: i) a detailed simulation of infiltration (e.g., Manzini and Ferraris, 2004; Ferraris et al., 2012); ii) a detailed simulation of infiltration coupled with the surface advance of water (e.g., Gandolfi and Savi, 2000); and iii) an analytical solution to the Lewis and Milne (1938) integral equation (Philip and Farrell, 1964).

Because the latter strategy requires a low number of parameters, it is suitable for providing a field-scale description of the rates of water advance and infiltration for practical uses (such as managing irrigation performance). In particular, when related to an infiltration function such as that of Philip (1957), which considers the saturated hydraulic conductivity, the Philip and Farrell analytical solution solves the advance-infiltration problem.

Although the Philip and Farrell analytical solution is only valid for short irrigation durations and cannot accurately predict long-term behaviour (Knight, 1980), this solution has been employed by several authors to successfully describe the advance-infiltration problem for surface irrigation management (e.g., Collis-George and Freebairn, 1979; Or and Silva, 1996).

The Philip (1957) infiltration function, used in the Philip and Farrell (1964) analytical solution, requires knowledge of soil hydraulic parameters to estimate the soil infiltration dynamics. Several authors have indicated that the Beerkan Estimation of Soil pedoTransfer (BEST) infiltration test

proposed by Lassabatère et al. (2006) is an effective method for the hydraulic characterisation of soils directly in the field (e.g., Mubarak et al., 2009; Xu et al., 2009; Bagarello et al., 2011).

Bagarello et al. (2011) investigated the possibility of simplifying the particle size distribution curve (PSD) fitting by including only three points (the clay, silt and sand contents) instead of fourteen points. These authors found the simplified PSD to be a reliable alternative to the normal procedure.

Other methods have been recently developed for irrigation and management purposes (e.g.: Bautista et al., 2009; Strelkoff et al., 2009), which use surface water depth and mass balance methods to estimate the infiltration. Also, an interesting new analytical solution has been developed (Cook et al., 2013). However, it is beyond the scope of this paper to compare different analytical solutions.

The proposed method is based on the direct measurement of the infiltration depth to calibrate the infiltration advance model, and to estimate the saturated hydraulic conductivity at the field scale. Within the context of ~~this~~ the above mentioned simplification, this study aims to propose a method for the calculation of border-irrigation efficiencies by using an advance-infiltration model and four simple field measurements: i) the inflow rate; ii) the irrigation duration; iii) the water head imposed on the field surface during an irrigation event and iv) the monitoring of the soil water content at only one point in the field at only the beginning and the end of the irrigation process. The second objective of this study was to use the proposed method to evaluate the surface irrigation efficiency of irrigation events based on the actual practices adopted by farmers. Hence, this method can provide a simulation tool that is able to analyse the effects of differences in management practices on irrigation efficiency.

2 Methodology

2.1 Advance-infiltration models

Irrigation efficiencies depend on the volume of water infiltrated during the irrigation event and on the distribution of the infiltrated water across the field. To compute the infiltrated volume of water and assess its distribution, it is necessary to determine the infiltration profile across the field. This

77 infiltration profile can be obtained from the solution of the infiltration advance across the field. The
78 infiltration advance is calculated from the simultaneous solution of two equations: the analytical
79 solution to the Lewis-Milne (1938) differential equation proposed by Philip and Farrell (1964) to
80 describe the advance of the water front and the infiltration equation of Philip (1957). These two
81 equations are written as:

82 $$\frac{x}{q}=\frac{1}{C}\left[1-exp\left(\frac{4C^2t}{\pi\cdot S^2}\right)erfc\frac{2Ct^{1/2}}{\pi^{1/2}S}\right], \text{ and} \quad (1)$$

83 $$I=S\sqrt{t}+Ct, \quad (2)$$

84 where, x (L) is the horizontal spatial coordinate of the water advance front; q (L^2 T^{-1}) is the inflow
85 rate per unit of width; C (L T^{-1}) is a parameter related to the saturated hydraulic conductivity K_S (L
86 T^{-1}) according to the relation proposed by Haverkamp et al. (1988):

87 $$\frac{1}{3}K_S\le C\le\frac{2}{3}K_S, \quad (3)$$

88 which depends on the initial soil water content; t (T) is the time; S (L $T^{-1/2}$) is the sorptivity; I (L) is
89 the cumulative infiltration at any chosen value of x.
90 In this study, the parameter C was considered as constant and equal to $K_S/2$, as suggested by
91 Parlange (1977). Such an assumption is valid because C is only slightly dependent on the initial
92 water content (Philip 1957), and for most practical purposes, any change in C may be neglected.
93 This assumption is not made because C does not change, but the changes in C are relevant for long-
94 term infiltration rates, which are not considered in this work, and may be caused by changes in the
95 saturated hydraulic conductivity (Samani and Yitayew 1989; Silva 1995) in association with
96 changes in the near-surface soil porosity. Because long-term infiltration rates are not considered in
97 this work, the Philip and Farrel analytical solution can be applied. In fact, the Philip and Farrell
98 analytical solution should only be considered valid for short irrigation durations and should not be
99 applied to accurately predict long-term behaviour (Knight, 1980). The method proposed by Knight

100 (1980) to verify short-duration conditions has been adopted in this work and is presented in the
101 following section.
102 Sorptivity is defined as a function of the scale parameters of the water retention and hydraulic
103 conductivity curves according to the relationship proposed by Parlange (1975):

104 $$S^2 = \int_{\theta_i}^{\theta_S} (\theta_S + \theta - 2\theta_i) K \frac{dh}{d\theta} d\theta \quad (4)$$

105 where, θ_S ($L^3\ L^{-3}$) is the soil water content at saturation; θ ($L^3\ L^{-3}$) is the actual soil water content; θ_i
106 ($L^3\ L^{-3}$) is the initial soil water content; K ($L\ T^{-1}$) is the soil hydraulic conductivity at θ; h (-L) is the
107 actual matric potential.
108 In this study, the van Genuchten (1980) equation and the Brooks and Corey (1964) relationship
109 were chosen as the models for calculating the water retention and hydraulic conductivity,
110 respectively. The effect of hysteresis on the water retention curve was neglected, but it can be
111 incorporated by including a hysteresis model, as suggested by Canone et al., 2008.
112 Hence, by integrating Eq. (4) within the water content range, one obtains:

113 $$S^2(\theta_i, \theta_S) = -C_p \theta_S K_S h_g \left(1 - \frac{\theta_i}{\theta_S}\right)\left[1 - \left(\frac{\theta_i}{\theta_S}\right)^{\eta}\right] \quad (5)$$

114 Where, h_g (-L) is the matric potential scale parameter of the van Genuchten (1980) equation; K_S (L
115 T^{-1}) and η (L) are the scale parameter and shape parameter of the Brooks and Corey (1964)
116 equation; C_p (-) is a soil-dependent constant (Haverkamp et al., 2006) depending on the shape
117 parameters m and n of the van Genuchten (1980) equation.
118 Equation (1) is a function of S, K_S and q, and equation (2) is function of S and K_S. Since the method
119 was applied to estimate the irrigation efficiency of border irrigation, the flow rate was measured at
120 the inlet of a bay located at the centre of the field. The flow rate (q) was assessed by measurement
121 of the cross-sectional area and the measurement of the current velocity. The latter was determined
122 with a propeller flow meter OTT C2 (OTT Hydromet, Kempten, Germany, UE), which was

123 installed before any irrigation monitoring and removed at the end of it. S and K_S are not directly
124 measurable. In the proposed approach, the sorptivity is computed by solving equation (5), which
125 requires the values of θ_S, θ_i, K_S, h_g, η, m and n.
126 The soil water content at saturation and the initial soil water content were measured at a time
127 domain reflectometry (TDR) station located at one point in the field. The matric potential scale
128 parameter (h_g) was calculated using the soil-independent conceptual model proposed by
129 Vanclooster et al. (2011) to predict the soil water retention curve from the cumulative particle size
130 distribution (PSD) curve and the void ratio.
131 In this study, the shape parameters m, n and η were determined from the PSD curve as suggested by
132 Haverkamp et al., 2002. The PSD curve was fitted to five points obtained from the analysis of soil
133 samples collected at an upstream, a centre and a downstream position along the bay under study.
134 The particle size analysis was performed according to the pipette method, which is based on the
135 difference in sedimentation speed between small and large soil particles. As demonstrated by
136 Bagarello et al. (2011), the use of five points to fit a cumulative particle size distribution curve is
137 sufficient for determining soil hydraulic parameters.
138 In the proposed approach, the saturated hydraulic conductivity ~~is~~ was the only parameter that cannot
139 be measured. The field-equivalent value (K_{Seq}) ~~is~~ was determined by model fitting. Equations (1)
140 and (2) were fitted to the depth of water infiltration at the end of an irrigation event. In Eqs. (1) and
141 (2) C was considered equal to $0.5K_{Seq}$ and S was replaced by Eq. (5), so that only K_{Seq} was obtained
142 by model fitting. The depth of water infiltration ~~is~~ was calculated from the water content data
143 measured at the TDR station at the start and at the end of the irrigation event, following the
144 methodology presented in section 2.5. The advance-infiltration model was validated against four
145 depths of water infiltration at four times in-between the start and the end of the irrigation event.
146 The differences between the simulated (I_s) and measured (I_m) infiltration depth were compared to
147 Cook et al. (2013) results employing the square root of the Nash-Sutcliffe efficiency coefficient
148 (Nash and Sutcliffe, 1970), given by the following relation:

149 $$RSR = \frac{\sqrt{\sum_{i=1}^{N}\left(I_m(t_i) - I_s(t_i)\right)^2}}{\sqrt{\sum_{i=1}^{N}(I_m(t_i) - \bar{I}_m)^2}}, \quad (6)$$

150 where N is the number of simulated and measured infiltration depths and t is time (s).

151 Following the procedure explained above, the field equivalent sorptivity and the saturated
152 hydraulic conductivity were determined once per year at each surveyed farm. These estimated field-
153 equivalent parameters were used to calculate the advance-infiltration profiles for each irrigation
154 event performed by the farmers and monitored within the study period.

155 Each saturated hydraulic conductivity value estimated using the proposed approach was compared
156 to three values of saturated hydraulic conductivity estimated by BEST tests performed at the same
157 location where the soil samples were collected, as explained in section 2.3. For the sake of
158 comparison, the K_S values were also determined by seven pedotransfer functions based on particle
159 size distribution data and θs (namely, Brakensiek et al., 1984; Cosby et al., 1984; Puckett et al.,
160 1985; Saxton et al., 1986; Campbell and Shiozawa, 1994; Dane and Puckett, 1994; Ferrer-Julià et
161 al., 2004).

162 *2.2 Verification of the assumption of short irrigation duration*

163 According to the limitations of the advance-infiltration model proposed by Philip and Farrell (1964)
164 for predicting long-term infiltration processes, the short irrigation duration assumption has to be
165 verified to employ this advance-infiltration model. In the proposed approach, the verification of the
166 assumption is performed according to the methodology proposed by Knight (1980), which requires
167 three variables. The first is a dimensionless time variable defined as:

168 $$\tau_k = K_S^2 t / S^2 . \quad (7)$$

169 The second is a dimensionless variable for the head on the soil surface given by:

170 $$C_k = K_S h_{surf} / S^2 , \quad (8)$$

171 where, h_{surf} (L) is the water head imposed on the field surface during the irrigation process.

The third is a dimensionless advancement variable given by the "linear" soil function proposed by Philip (1966, 1969), which, at small times, is given by the following equation when $C \neq 0$:

$$x_k = \frac{\tau}{C_k} - \frac{2\tau^{3/2}}{3C_k^2} - \frac{\left(2C_k - \pi\right)\tau^2}{8C_k} - \frac{\left(2C_k^2 - 4C_k\pi + \pi^2\right)\tau^{5/2}}{15\pi C_k^4}. \quad (9)$$

The dimensionless advancement is calculated by employing the linear soil function (Eq. 9) proposed by Philip (1966, 1969). Both the dimensionless advancement and time variables are compared to their maximum values (τ_{max} = 1.4 and x_{max} = 0.4), which are the limits of the area of a τ-x_k plot for which the time can be considered short. Because the Philip and Farrell advance-infiltration model behaves as the linear soil function, proposed by Philip (1966, 1969), for any values of C_k within the range between 0 and 2 (Knight, 1980), the short duration assumption is verified for τ_k and x_k values lower than τ_{max} and x_{max}, respectively.

2.3 Saturated hydraulic conductivity validation

In this study, the BEST infiltration test (Lassabatère et al., 2006) was employed to obtain an estimation of K_S that is independent from the advance-infiltration model and the soil water content measured by the TDR station. These independent values of K_S were determined once a year at the same locations where the soil samples were collected. They were compared to the K_{Seq} values estimated following the methodology presented in section 2.1 to validate the latter.

In the BEST procedure, the scale parameter for the residual water content (θ_r) was assumed to be zero, and the initial soil water content and the soil water content at field saturation (θ_S) were estimated using the TDR measurements collected before and after the infiltration tests. The values of K_S and S were determined by fitting the experimental infiltration data to the set of equations proposed by Lassabatère et al. (2006). Finally, the scale parameter for the matric potential (h_g) for the water retention curve of van Genuchten (1980) was obtained using Eq. (5).

2.4 Farm descriptions

Three farms, characterized by their analogous soil conditions were selected as testing sites. All farms performed border irrigation on corn (*Zea mays* L.) crops. These farms are located in the

Cuneo district (namely: farm 1, Ceresole d'Alba, Lat. 44° 48' 37", Lon. 7° 46' 45"; farm 2, Fossano, Lat. 44° 34' 40", Lon. 7° 42' 06"; farm 3, Sommariva del Bosco, Lat. 44° 44' 21", Lon. 7° 43' 33") in north-western Italy. The soil of the three farms, were analysed according to the USDA Keys to Soil Taxonomy (Soil Survey Staff, 2010), and belong to the following families: farm 1, Fluventic Dystrudept, coarse-loamy, mixed, nonacid, mesic; farm 2, Acquic Haplustept, coarse-loamy over loamy-skeletal, mixed, nonacid, mesic; farm 3, Acquic Haplustept, loamy-skeletal,mixed,nonacid,mesic.

Despite the fact that the soils belonged to similar textural classes (i.e., loam and silty loam), the soils exhibited differences in their hydraulic properties (e.g., the soil water content at saturation conditions and the field capacity, listed in Table 1) primarily because of the differences in tillage practices and the varying percentages of stones in the fields. The percentages of sand, clay, and silt (defined according to the USDA Classification System (Soil Survey Laboratory Staff, 1992)) are included in Table 2 and were calculated from the average of the laboratory analysis of four samples collected at four different depths (between 0.05 m and 0.6 m). The percentages of stones were determined from the analysis of two vertical soil profiles for each field. These analyses were performed during the 2007 irrigation season.

During the three-year period (2006-2008), the farmers executed thirty irrigation events, and fifteen were monitored with specific measurement campaigns. In such a period, the border sizes of these farms changed (Table 3) because the farmers autonomously followed their normal habits regarding cultivation management and irrigation practices. However, the practices of the farmers are crucial for the study because monitoring real-world agriculture was one of the study's main objectives. All farmers cultivated the corn (*Zea mays* L.) on bays composed by multiple rows (10 rows per bay at farm 1, 13 rows per bay at farm 2, and 8 rows per bay at farm 3) with interrow spacing of 0.75 m. The rows were oriented along the maximum field length. At the end of the field a small canal to collect surface runoff was seasonally dug.

2.5 TDR stations

Time Domain Reflectometry is a well-known technique that is commonly accepted for the assessment of water content and other physical properties of porous media by permittivity measurements (Topp et al., 1980; Robinson et al., 2003; Canone et al., 2009; Baudena et al., 2012; Previati et al., 2012). Soil permittivity measurements were carried out using a device composed by one TDR cable tester (Tektronix Metallic Cable Tester 1502C manufactured by Tektronix Inc., Beaverton, OR, USA) connected to a notebook and a multiplexer. The system allowed automatic measurements of soil permittivity at eight points along the soil profile. The TDR signals were sampled and acquired using the WinTDR software (Or et al., 2004) and stored in the hard disk of a notebook. The soil bulk permittivity was monitored from the beginning to the end of the irrigation events at a time interval of 3 minutes, and the volumetric soil water content was computed using the composite dielectric approach described by Roth et al. (1990).

The installed TDR probes were 150 mm long and were composed of three stainless steel rods held together by a nylon spacer. All of the probes were calibrated according to the method proposed by Heimovaara (1993). All of the connections were made using RG58 50 Ω coaxial cables. Each of the 10 probes was horizontally inserted into the soil. The probes were arranged in two vertical profiles at the depths of 0.05 m, 0.15 m, 0.30 m, 0.45 m, and 0.65 m to monitor the entire root zone. In one of the fifteen examined cases, a layer of stones prevented the 0.65 m depth measurement (Fig. 1). The TDR stations were located at approximately one-third of the field length along a bay situated at the centre of the field.

Each volumetric water content measurement was then associated with and weighted in relation to its specific corresponding volume of soil (equivalent to the thickness of each monitored layer). In other words, the value obtained by the probe placed at a depth of 0.05 m was considered representative of the soil layer between 0 m and 0.10 m depth, whilst the soil water content value obtained by the 0.15 m depth probe was considered representative of the soil layer between 0.10 m and 0.225 m of depth, and thus forth for the deeper probes. Thus, the volumes of water that infiltrated the soil and

248 the evolution of the water content profiles over time during the irrigation process (Fig. 2) were
249 obtained for the three farms.

250 *2.6 The measurements of irrigation parameters*

251 Field measurements were performed to acquire the following data for each monitored irrigation
252 event: i) the duration of the irrigation event, t_{ir} (T); ii) the irrigation inflow rate, F_r (L^3 T^{-1}); iii) the
253 volume of water delivered during the irrigation event, V_d (L^3), and average volume of water
254 delivered per unit area, (L^3 L^{-2}); and iv) the water head imposed on the field surface during the
255 irrigation event, h_{surf} (L), which was measured by a water level staff gauge (marked at every
256 millimetre) under steady flow conditions at the upstream position. We also recorded the occurrence
257 of surface runoff, the time at which the surface runoff was eventually starting. The volume of
258 surface runoff and deep percolation were not measured. They were calculated from the partition of
259 the applied water volume determined from infiltration profiles as explained in the following section.
260 Furthermore, the number of irrigation events initiated during the season by each farmer, the
261 irrigation parameters and the infiltration advance profiles were used to partition the applied water
262 volumes.

263 *2.7 Partitioning of the applied water volume*

264 The volume of storable water at field capacity V_{fc} (L^3) was calculated by multiplying the water
265 content at field capacity by the volume of soil in the root layer. The soil water content at field
266 capacity was calculated as the soil water content value given by the van Genuchten (1980) equation
267 for the matric potential value of -3.3 m. Using the infiltration advance profiles and the scheme given
268 in Figure 3, the volume of water applied to the field was partitioned as follows: i) the total volume
269 of water stored in the soil V_{st} (L^3), which was calculated by subtracting the water volume lost
270 through deep percolation from the total infiltrated volume and then adding the volume stored on the
271 surface; ii) the volume stored at the surface V_s (L^3), which is the volume of water on the surface of
272 the field after the completion of the water application; iii) the volume of water lost by surface runoff

273 V_r (L^3), which was calculated as the sum of the infiltrated water volume and the volume of water
274 stored on the land surface beyond the end of the field (when the irrigation ended); and iv) the
275 volume lost through deep percolation below the root layer V_{dp} (L^3). The volume of water stored on
276 the surface (V_s) was divided into two parts. The amount of the V_s that remained on the portion of the
277 field where deep percolation occurred was considered lost. The remaining volume was added to the
278 stored volume. The errors introduced by such assumptions are small because V_s never exceeded
279 10% of the stored volume (Table 4).
280 The volumes of water lost by surface runoff and deep percolation were not measured. They were
281 calculated from the infiltration profiles given by the infiltration advance model. Considering that the
282 model was validated on the infiltrated water depth at the locations of the TDR stations (as shown in
283 section 3.1) and the aim of the work was to employ simple measurement techniques, we choose not
284 to measure the volume of water lost by runoff and deep percolation. Such measurements were not
285 necessary for the validation of the model and their acquisition would have severely complicated the
286 field measurement campaigns.
287 All calculated water volumes were used to compute the application efficiency (E_a), the storage
288 efficiency (E_s), and the distribution efficiency (E_d) terms for the field-equivalent parameters. For
289 further comparison, the efficiency terms were also calculated for the three sets of parameters
290 determined by the infiltration BEST tests. Finally, the proposed model was used to simulate the
291 effects of changes in various irrigation parameters, namely, the flow rate (F_r), the irrigation event
292 duration (t_{ir}), the volume of water delivered (V_d) and the initial soil moisture θ_i.

293 *2.8 Irrigation efficiencies*

294 The application efficiency (E_a) quantifies the volume of water actually stored in the root layer in
295 relation to the volume of water delivered. The storage efficiency (E_s) quantifies the recovery of the
296 field water deficit. The distribution efficiency (E_d) quantifies the homogeneity of water storage
297 along the field. The combination of these three efficiency terms provides the global efficiency of the

298 irrigation process. Additionally, by employing the proposed method, the choice of the best irrigation
299 practice may be achieved.
300 The water application and storage efficiencies are given according to the relationships proposed by
301 Kruse et al. (1990):

302 $$E_a = \frac{V_{st}}{V_d}, \quad (10)$$

303 $$E_s = \frac{V_{st}}{V_{fc}}, \quad (11)$$

304 The distribution efficiency is determined using the relationship proposed by Burt et al. (1997):

305 $$E_d = \frac{V_{lq}}{V_{fq}}, \quad (12)$$

306 where, V_{lq} is the volume of water stored in the last quarter of the field (L^3), whilst V_{fq} is the volume
307 stored in the first quarter of the field (L^3).

308 *2.9 Predictive simulations*
309 After the irrigation efficiencies of the monitored events were calculated, and the model was
310 employed to predict the irrigation efficiencies of simulated irrigation events. In particular, the
311 irrigation simulations were performed using seven different combinations of the irrigation
312 parameters (i.e., V_d, F_r and θ_i) to determine their influence on irrigation efficiency. The values of
313 the irrigation parameters are presented and discussed in section 3.4.

314 **3 Results and Discussion**
315 *3.1 Model validation*
316 The first step of the model validation was the confirmation of the short duration assumption. For the
317 measured irrigation times used in this study, the calculated values of x_k and τ_k, as proposed by
318 Knight (1980), corresponded to a short-duration behaviour. These parameter values are given in
319 Table 5. The dimensionless time and advancement variables never exceeded the maximum values
320 (τ_{max} = 1.4 and x_{max} = 0.4) proposed by Knight (1980). According to Knight (1980), employing this

321 combination of values ensures that the behaviour of the Philip and Farrell analytical solution
322 matches the actual advance-infiltration processes.
323 Using the proposed method, the field-equivalent saturated conductivity (K_{Seq}) values, obtained by
324 fitting of Eqs. (1,2 and 5) as explained in section 2.1, were close to the three sets of values
325 estimated by the BEST infiltration tests (Tables 6 and 7). The differences among the K_{Seq} values and
326 the results of the corresponding BEST tests were almost always lower than 16% of the K_S values
327 obtained from BEST tests. Only two differences exceeded that range. Both values were recorded at
328 Farm 2, one in the year 2007 (36.7%) and the other in the year 2008 (-40.9%), as shown in Table 7.
329 The results of the BEST tests indicated low K_S variability across the fields of Farm 1 and Farm 3, as
330 shown by the standard deviation of K_S values (Table 6) and by the three K_S values measured at each
331 field, and among the three-year period (Table 7). The low variability of K_S was probably attributed
332 to the tillage practices: each year, the soil structure was effectively destroyed by the rototilling
333 practices performed prior to sowing. In any case, for further comparison, the root mean square error
334 (RMSE) between the results of seven different pedotransfer functions applied for the estimation of
335 K_S and the K_{Seq} values were evaluated. The RMSE between the results of the BEST tests and the
336 K_{Seq} values were also evaluated. The K_S values are depicted in Figure 4 and the RMSE are listed in
337 Table 8. Only one of the seven pedotransfer functions (Puckett et al., 1985) produced results that
338 are in agreement with the estimated K_{Seq} values.
339 The infiltration depths of water were then compared with the infiltration profiles, which were
340 calculated using the fitted K_{Seq} values (Table 6), the K_S values obtained by the BEST tests, and the
341 irrigation parameters chosen by the farmers. The infiltration depths were obtained from the TDR
342 soil water content measurements. Finally, the differences between the infiltration profiles and the
343 infiltrated depth of water were assessed. The infiltration model outputs were always in good
344 agreement with the measured infiltration depths (Fig. 5), as shown by the differences between
345 simulated and measured infiltration depths reported in Table 9. The highest and the lowest
346 differences recorded during the fifteen monitored events were 0.018 m and 0.002 m. The SRS

calculated to evaluate the performance of the proposed method on the monitored irrigation events was 0.22 at Farm 1, 0.07 at Farm 2 and 0.05 at Farm 3. Cook et al. (2013) found SRS values between 0.29 and 6.83 for the Philip and Farrel (1964) infiltration-advance solution for short-term duration. The low SRS obtained in our experiments is due to the direct measurement of the infiltration depth. Cook et al. (2013) employed infiltration depths estimated by Taylor (1981) using the mass balance method of Finkel and Nir (1960). The highest difference between the simulated and measured data observed during the first irrigation event performed by farm 1 in 2007 was 0.013 m. This difference was recorded at a station located 30 m from the beginning of the field at 720 s and 913 s (t_{ir}) after the start of irrigation. The simulated infiltration depths were 0.178 m and 0.203 m, respectively, and the measured depths were 0.191 m and 0.216 m, respectively. The minimum difference occurred during the same irrigation event, was recorded at 360 s after the start of irrigation, at a station located 32 m from the beginning of the field. The simulated infiltration depth was 0.116 m and the measured depth was 0.114.

3.2 Irrigation efficiencies vs. hydraulic parameters

As expected from Eqs. 1, 2 and 5, the analysis of the influence of the initial water content on the volume of water that might infiltrate the soil demonstrates the relationship between θ_i and the irrigation efficiency. The analysis of irrigation events performed at the constant values of K_S and F_l, and similar values of F_r, indicate that a high θ_i results in low E_a values because of the low infiltration rate and, consequently, high surface runoff. Moreover, high θ_i values indicate a low soil retention capacity, which results in deep percolation losses even during low infiltration events.

The K_{Seq} values and the three K_S values estimated by the BEST infiltration tests were used to calculate four sets of efficiency values. The analysis of the application and storage efficiency values indicates that K_S has only a minor influence on the results (Figs. 6a and 6b) because the variability in K_S was very low. The low variability in K_S values could only transform deep percolation losses into runoff losses when there was little change in the volume of water stored in the root layer. Thus,

372 the distribution efficiency is more highly influenced by K_S than the other two efficiencies (Fig. 6c)
373 because it depends on the shape of the infiltration profile and can be modified by small variations in
374 K_S. The variation among the E_a values of the irrigation events was negligible (below 0.05) in almost
375 all cases. As indicated in Figure 6a, we observed the highest variation of E_a in the first irrigation
376 performed on farm 3 in 2006 (0.06). The variation among the E_s values was also negligible in
377 almost all cases; the highest value was also observed for the first irrigation performed on farm 3 in
378 2006 (0.07), as shown in Figure 6b. The variation among E_d values was negligible for six of the
379 fifteen irrigation events monitored; the highest E_d value was again observed for the first irrigation
380 performed on farm 3 in 2006, as shown in Figure 6c, but this value was much higher (0.27) than the
381 values found for E_a and E_s.

382 *3.3 Irrigation efficiencies vs. irrigation parameters*

383 The irrigation parameters varied considerably during the study period. In fact, the farmers were
384 completely free to manage the irrigation events. Relying on their experience and on an empirical
385 evaluation of the soil water content, many farmers tried to limit the effect of the initial water content
386 by varying the volume of irrigation water and, in several cases, the flow rate (Table 10). Because of
387 farm management needs, the farmers also changed the lengths of several plots during the three-year
388 period.

389 The variations in the lengths of the plots, combined with a non-proportional variation in the flow
390 rate and the temporal variability of the field-scale saturated hydraulic conductivity, resulted in
391 variations in the time required for the water to reach the end of the field (t_{fl}). Additionally, this
392 variation caused i) a modification of the time required to impose a uniform hydraulic head over the
393 entire field surface and ii) a change in the volume of infiltrated water that, in some cases, was large
394 enough to mask the effects of the initial water content. To limit the effects of the farmers' choices
395 and to assess the real influence of t_{fl} and θ_i on irrigation efficiency, the analysis was conducted on
396 pairs of irrigation events in which the other parameters were maintained nearly as constants.

As indicated in Eqs. (1) and (5), the analysis of irrigation events performed with constant values of K_S and F_l and similar values of F_r indicate that the effect of t_{fl} on irrigation efficiency is inversely proportional to θ_i. High θ_i values are associated with low t_{fl} values, which result in low E_a values because of the high surface runoff. Low t_{fl} values are associated with the rapid imposition of a constant head over the bay, which causes high values of E_s and E_d (Figs. 6b, 6c). Only a few exceptions were found. In the examined pairs of irrigation events, the exceptions were explained by the differences in t_{ir} and F_r employed by the farmers.

By employing higher flow rates, each of the farms achieved higher distribution efficiency values. However, because of the surface runoff, the benefits of a higher E_d often did not compensate for the decrease in the application efficiency values. The irrigation time (t_{ir}) cannot be decrease to approach t_{fl} to avoid surface runoff because a low t_{ir} would cause a great difference in the time of infiltration between upstream and downstream areas, which would strongly reduce the distribution efficiency values. The best compromise was often achieved by modifying the flow rate. However, if the irrigation district is provided with a network of gully channels, the volumes of water lost as surface runoff should not be counted among the losses that affect the application efficiency (Clemmens et al., 2008).

In most cases, the volumes of water stored during the monitored irrigation events balanced the hydraulic deficit of the root layer. However, whilst the irrigations performed at farm 1 resulted in water storage efficiencies that were significantly lower than one, all of the irrigations performed at farm 2 and 3 resulted in higher E_s values, but with the disadvantage of high deep-percolation losses.

3.4 Scenario analysis and considerations for predictive settings

The infiltration profile across the entire field, which was simulated using the actual parameters of the first irrigation event that was performed at farm 1 in 2007 (Fig. 7a), was compared with the infiltration profiles produced by seven irrigation simulations. In the first three cases (Figs. 7b to 7d), the duration of the irrigation event and the flow rates were altered. The infiltration profiles

422 described by cases 4-7 (Fig. 7e to 7h) were produced with differing flow rates and initial water
423 contents. The values of the input parameters employed in the simulations are summarized in Table
424 11 in addition to the simulation results.
425 In the first case (Fig. 7b), the flow rate was reduced to a value of 0.04 (m^3 s^{-1}), whilst the duration
426 of the irrigation event was increased by approximately one-third (1200 s) (Table 11). In this case, an
427 E_a value of 0.95 was achieved because the water flowed only slightly past the end of the field and
428 slightly deeper than the bottom of the soil root layer; hence, there were only small amounts of
429 surface runoff and percolation losses. Although the watering volume of this first case was greater
430 than that of the real monitored case, the majority of the water was stored equally and the E_s was
431 slightly improved because of this level of storage. In contrast, there was a reduction in E_d that
432 caused a reduction in the overall irrigation efficiency.
433 In the second case (Fig. 7c), the flow rate was equal to the previous case (Table 11), but the
434 duration of the irrigation event was increased by one-third (1600 s). The results indicate an
435 improvement in the E_s and E_d and a decrease in the E_a value. The watering volume considered in
436 this case was higher than the two previous cases, which suggests that the necessary watering
437 volume was surely underestimated for the monitored case.
438 In the third case (Fig. 7d), the flow rate was the same as in the real irrigation event, whilst the event
439 duration was the same as in the second case, thus applying a watering volume that was almost twice
440 as large as the volume of the real irrigation event. In this case, both the E_s and E_d increased to a
441 value of 1, but the E_a value (0.64) was the lowest among all of the cases considered (Table 11).
442 In the fourth case (Fig. 7e), the flow rate was increased to a value of 0.06 (m^3 s^{-1}) but the irrigation
443 duration was maintained at the actual value used by the farmer (Table 11). Compared to the real
444 irrigation event, the results indicate an increase in the E_s (+0.04) and E_d (+0.10) and a decrease in
445 the E_a (-0.11). The E_a value was comparable to the value obtained in the second case, but the E_s and
446 E_d values were lower.

447 In the fifth case (Fig. 7f), the flow rate was increased to a value of 0.07 ($m^3 s^{-1}$), whilst the irrigation
448 event duration was maintained at the actual irrigation duration. Compared to the previous case, the
449 E_s and E_d increased slightly (+0.02 and +0.07, respectively). In this case, the E_a value was slightly
450 lower than in the second case, whilst the storage efficiency value decreased by 0.12.
451 In the sixth case (Fig. 7 g), the flow rate and the irrigation event duration values were the same as
452 the values from the real irrigation event (Table 11), but the initial soil water content was set to a
453 value of 0.05 ($m^3 m^{-3}$), which is lower than the measured value. Compared to the real event, the
454 results suggest an increase in the E_a (+0.05) because of the higher infiltration rate caused by the
455 high value of the matric potential, which is inversely proportional to the soil water content.
456 When compared to the real irrigation event, the results of the first six cases also indicate a reduction
457 in the E_s because the water deficit was higher in these simulations. Additionally, the results
458 demonstrate a reduction in the E_d because of the difference in the depth of water infiltration at the
459 beginning and at the end of the field during the time required to establish a uniform hydraulic head
460 over the field. The simulation results suggest that, when the irrigation is performed at a θ_i that is
461 lower than in the actual irrigation event considered, the flow rate should be increased.
462 Finally, in the seventh simulation (Fig. 7 h), the initial water content was assumed to be higher than
463 the real value and was set to a value of 0.15 ($m^3 m^{-3}$). However, the other parameters were the same
464 as in the real irrigation event (Table 11). As expected, the results were the opposite of the previous
465 case. Compared to the real event, the E_a decreased (-0.06) and both the E_s and E_d increased to +0.12
466 and +0.10, respectively.
467 According to the simulation results, the best E_a value was obtained for the sixth case, but the
468 corresponding E_s and E_d values were the lowest. This result suggests that this choice would
469 represent a misuse of water. In contrast, the best E_s and E_d values were registered in the third case,
470 but the E_a value was the lowest. The real irrigation event considered represents a compromise
471 between saving water and the best use of water for crop production. The second case is also a good
472 compromise because a slightly greater volume of water is employed to obtain a large increase in E_s

and E_d. A higher flow rate was not always the best solution. A comparison between the results of the fourth and fifth cases indicates that a high flow rate could be employed to increase the E_s and E_d values. However, this solution can only be applied in cases where the irrigation district is provided with a network of gully channels to avoid surface runoff losses and maintain high values of E_a.

For the monitored irrigation events, the flow rate employed by the farmer was suitable for the field conditions, whereas the watering volume was insufficient, as shown in the third simulation (Fig. 7d). Similar to the previous simulations, the sixth and seventh simulations (Fig. 7 g and 7 h) demonstrated the influence of the initial field conditions. These results suggest that farmers should apply larger watering volumes, but less frequently, to obtain higher irrigation efficiencies. Moreover, to avoid low E_s and E_d values, irrigation should not be performed when the soil water content is too low.

5 Conclusions

In this study, a method based on the Philip and Farrel (1964) advance-infiltration model was proposed for i) calculating the border irrigation efficiency from four simple field measurements (inflow rates, irrigation durations, and soil water content values monitored at only one point of the field at the beginning and at the end of the irrigation processes) and ii) for testing the sensitivity of irrigation efficiency to surface irrigation operational parameters.

The irrigation efficiency of 15 real irrigation events performed on three different farms during the growing seasons in 2006, 2007 and 2008 were analysed. Finally, a scenario analysis based on data collected during one of the surveyed events was also performed by altering the irrigation parameters that affect irrigation efficiency (namely, irrigation duration, flow rate, and initial soil water content). The proposed method proved to be capable of describing real irrigation practices. Moreover, the method was capable of evaluating the changes in irrigation efficiency as a consequence of variations in the operational irrigation parameters.

497 The results demonstrate that the equivalent saturated hydraulic conductivities estimated using the
498 proposed method is always in good agreement with the K_S values estimated using the infiltration
499 tests performed at three different positions in each field. Additionally, the irrigation efficiencies
500 calculated using both the proposed approach and using the parameters estimated by infiltration
501 measurements were in good agreement.
502 The efficiencies analysis (of the water application, storage, and distribution efficiencies) highlighted
503 the marked variability in the values among the monitored farms and within each farm. This level of
504 variability was associated with the variations in the watering volumes and flow rates. The influence
505 of the initial soil water content on the storage efficiency was clear, but some exceptions were
506 observed when irrigation durations was sufficiently long to mask the effects of the initial soil water
507 content.
508 The analysis of both the simulated scenarios and fifteen monitored irrigation events demonstrated
509 the need to irrigate these fields using lower flow rates and higher irrigation durations than those
510 currently used by the farmers. The scenario analysis also revealed that the irrigation efficiencies are
511 highly dependent on the initial soil water content.

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FIGURE CAPTIONS

Fig. 1 Example of volumetric soil water content data collected by a TDR station with probes inserted below a row. The represented survey was performed during the first irrigation event at farm 2 (in 2008). The vertical line indicates the end of the irrigation event. The 0.65 m depth data are missing because a layer of stones prevented the insertion of a TDR probe.

Fig. 2 Example of soil water content profiles measured with the TDR technique every 5 minutes during the first irrigation event performed at farm 1 in 2006. The lines represent the water content profiles computed every 5 minutes from the beginning of the irrigation event, *t0*, until the end of the irrigation event. The vertical axis, *z*, indicates the soil depth.

Fig. 3 Diagram of an infiltration profile in which the whole water volume is subdivided into five portions. The horizontal black line represents the field surface, and the vertical line represents the end of the field. The data represent the real irrigation event performed on July 2008 at farm 3.

Fig. 4 Comparison of the saturated hydraulic conductivity values estimated by seven different well-known pedotransfer functions and the field-equivalent values estimated by the proposed method (Ks_eq). The tested pedotransfer functions are indicated as follows: Cosby et al. (1984) = (Ks_C); Saxton et al. (1986) = (Ks_S); Brakensiek et al. (1984) = (Ks_B); Ferrer-Julià et al. (2004) = (Ks_F); Campbell and Shiozawa (1994) = (Ks_CS); Puckett et al. (1985) = (Ks_P); and Dane and Puckett (1994)= (Ks_DP).

Fig. 5 Soil water infiltration profiles observed during the first irrigation event performed at farm 1 in 2007. The circles represent the depths of water infiltration that were measured using TDR probes. The curved lines represent the water content profiles calculated every 5 minutes from the beginning of the irrigation event (*t0*) until the end of the irrigation event (t_{ir}). The imposed hydraulic head

(dash-dotted line) corresponds to the volume of water stored on the field surface divided by the total surface. The vertical axis, *z*, indicates the soil depth.

Fig. 6 Application efficiencies (E_a) (a), storage efficiencies (E_s) (b) and distribution efficiencies (E_d) (c) calculated from the infiltration profiles obtained by using the field-equivalent saturated hydraulic conductivity values and the three sets of saturated hydraulic conductivity values estimated by the BEST infiltration tests. The irrigation events (*x* axis) are identified as farm: irrigation event: year.

Fig. 7 Infiltration-profile scenario analysis based on the data collected during the first irrigation event performed at farm 1 in 2007. The real case is depicted in box (a) whilst the simulated cases, obtained by modifying the soil and irrigation parameters, are shown in boxes (b to h). The values of the parameters for the scenarios are listed in each single box: initial soil water content (θ_i), watering volume (V_d), flow rate (F_r) and irrigation duration (t_{ir}).

(a) The circles represent the depths of water infiltration measured using the TDR technique. The dotted vertical line and dashed vertical line indicate the locations of the two TDR probe profiles, which were located at 30 m and 32 m from the beginning of the field, respectively.

TABLE CAPTIONS

Tab. 1 Saturated and field-capacity water content values of the examined soils.

Tab. 2 Soil texture and the percentages of stones in the three different farm soils monitored.

Tab. 3 Plot size variability during the three-year monitoring period.

Tab. 4 Relationship between the water volume stored on the surface (V_s) and the water volume stored in the root layer (V_{rt}) for the fifteen monitored irrigation events.

Tab. 5 Calculated values of the dimensionless parameters t_k (-), C_k (-), and x_k (-) for the Philip and Farrell analytical solution.

695 **Tab. 6** Field-equivalent saturated hydraulic conductivity values (cm h^{-1}) calculated for each farm
696 and each year during the period from 2006-2008.
697 **Tab. 7** Saturated hydraulic conductivity values (cm h^{-1}) estimated by means of the three BEST tests
698 for each farm and each year during the period from 2006-2008. Differences between estimated
699 saturated hydraulic conductivity and corresponding K_{Seq} values are given in brackets as percentage
700 of saturated hydraulic conductivity.
701 **Tab. 8** RMSE calculated between the K_{Seq} values and the K_S values estimated by pedotransfer
702 functions and BEST tests.
703 **Tab. 9** Differences between simulated and measured infiltration depths. The differences were
704 calculated at 180 s (t_1), 360 s (t_2), 540 s (t_3), 720 s (t_4) from the start of the irrigation events and at
705 the end of them (t_{ir}) at the locations of the TDR profiles (30 m - x_1 - and 32 m - x_2 - from the
706 beginning of the field).
707 **Tab. 10** Volumetric soil water content at the beginning of the irrigation event (θ_i), irrigation water
708 volume (V_d), flow rate (F_r), irrigation event duration (t_{ir}), time required for the water front to reach
709 the end of the field (t_f), field length (F_l), and values of the water application efficiency (E_a), water
710 storage efficiency (E_s), and water distribution efficiency (E_d) for each irrigation event monitored
711 during the period from 2006-2008.
712 **Tab. 11** Volumetric soil water content at the beginning of each irrigation event (θ_i), irrigation water
713 volume (V_d), flow rate (F_r), irrigation event duration (t_{ir}), field length (F_l), and values of the water
714 application efficiency (E_a), water storage efficiency (E_s), and water distribution efficiency (E_d) for
715 the first irrigation event performed at farm 1 in 2007 and the seven simulated scenarios.

716 **TABLES**

717

	Saturated soil water content (m^3 m^{-3})				Field capacity soil water content (m^3 m^{-3})			
	2006	**2007**	**2008**	**Average**	**2006**	**2007**	**2008**	**Average**
Farm 1	0.405	0.398	0.424	0.409	0.347	0.341	0.363	0.350
Farm 2	0.454	0.419	0.440	0.438	0.391	0.361	0.379	0.377
Farm 3	0.426	0.414	0.427	0.422	0.381	0.371	0.382	0.378

718 **Table 1**

719

720

Farm	**Sand (%)**	**Silt (%)**	**Clay (%)**	**Stones (%)**	**Texture**
					721
1	20.4	71.1	8.5	20	Silty Loam
2	42.1	48.8	9.1	30	Loam 722
3	46.8	42.2	11	25	Loam 723

724 **Table 2**

725

	2006		**2007**		**2008**	
Farm	**Length (m)**	**Width (m)**	**Length (m)**	**Width (m)**	**Length (m)**	**Width (m)**
1	130	35	88	35	88	35
2	134	120	134	120	229	11
3	600	96	600	96	600	96

726 **Table 3**

727

	Irrigation event - year	V_s/V_{rt} (m^3 m^{-3})
Farm 1	1 - 2006	0.10
	4 - 2006	0.04
	1 - 2007	0.06
	2 - 2007	0.09
	1 - 2008	0.09
Farm 2	2 - 2006	0.10
	3 - 2006	0.10
	1 - 2007	0.10
	1 - 2008	0.03
Farm 3	2 - 2006	0.04
	4 - 2006	0.05
	1 - 2007	0.05
	2 - 2007	0.10
	1 - 2008	0.08
	4 - 2008	0.10

Table 4

	Farm 1					**Farm 2**					**Farm 3**				
	2006		**2007**		**2008**	**2006**		**2007**		**2008**	**2006**		**2007**		**2008**
	1	**4**	**1**	**2**	**1**	**2**	**3**	**1**		**1**	**2**	**4**	**1**	**2**	**1**	**4**
τ_k	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.02		0.02	0.03	0.03	0.03	0.03	0.04	0.04
C_k	0.21	0.11	0.07	0.07	0.19	0.1	0.15	0.14		0.13	0.11	0.13	0.12	0.16	0.15	0.18
x_k	0.05	0.10	0.10	0.09	0.07	0.19	0.10	0.13		0.12	0.23	0.22	0.26	0.18	0.23	0.22

Table 5

	2006	**2007**	**2008**	**Average**	**Standard deviation**
Farm 1	2.47	2.38	2.51	2.45	0.12
Farm 2	4.64	5.02	1.76	3.81	1.17
Farm 3	2.28	2.52	2.85	2.55	0.30

Table 6

742

	BEST test 1			BEST test 2			BEST test 3		
	2006	**2007**	**2008**	**2006**	**2007**	**2008**	**2006**	**2007**	**2008**
Farm 1	2.34	2.31	2.25	2.41	2.44	2.48	2.63	2.52	2.57
	(5.3%)	(2.9%)	(10.4%)	(2.4%)	(-2.5%)	(1.2%)	(-6.5%)	(-7.1%)	(-2.4%)
Farm 2	3.96	3.18	1.61	4.35	4.28	1.87	4.66	4.91	2.48
	(14.7%)	(36.7%)	(8.5%)	(6.3%)	(14.7%)	(-6.3%)	(-0.4%)	(-40.9%)	(2.2%)
Farm 3	1.93	2.36	2.51	2.16	2.48	2.73	2.54	2.51	3.07
	(15.7%)	(7.8%)	(12.2%)	(5.7%)	(3.1%)	(4.5%)	(-10.9%)	(2.0%)	(-7.3%)

743 **Table 7**

744

	Ks_C	Ks_S	Ks_B	Ks_F	Ks_CS	Ks_P	Ks_DP	Ks_BEST #1	Ks_BEST #2	Ks_BEST #3
RMSE	1.54	2.73	3.06	2.49	3.00	0.62	6.10	0.69	0.28	0.28

745 **Table 8**

746

		t_1	t_2	t_3	t_4	t_{ir}
Farm 1 x_1	1 - 2006	0.012	0.009	0.005	-0.005	-0.012
	4 - 2006	0.006	0.007	0.006	0.003	-0.002
	1 - 2007	0.003	0.005	-0.009	-0.013	-0.013
	2 - 2007	0.006	-0.003	0.004	-0.004	-0.005
	1 - 2008	0.007	0.005	0.004	-0.007	-0.006
Farm 1 x_2	1 - 2006	0.008	0.006	0.007	-0.003	-0.093
	4 - 2006	0.003	0.008	0.007	0.004	-0.007
	1 - 2007	0.006	0.002	0.002	-0.005	-0.004
	2 - 2007	0.007	0.004	0.005	-0.004	0.003
	1 - 2008	0.011	0.01	0.012	0.009	0.004
Farm 2 x_1	2 - 2006	0.007	0.004	-0.005	0.006	0.01
	3 - 2006	0.006	0.006	0.007	-0.004	-0.018
	1 - 2007	0.011	0.018	0.004	-0.006	-0.004
	1 - 2008	0.01	0.007	0.005	-0.008	-0.005
Farm 2 x_2	2 - 2006	0.006	-0.003	-0.008	-0.009	-0.012
	3 - 2006	0.004	0.004	0.002	-0.003	-0.007
	1 - 2007	0.018	0.011	0.006	-0.003	-0.008
	1 - 2008	0.007	0.013	0.01	0.005	0.005
Farm 3 x_1	1 - 2006	0.003	0.003	0.005	-0.006	-0.008
	4 - 2006	0.009	0.008	0.01	-0.004	-0.005
	1 - 2007	0.004	0.007	0.011	0.008	-0.006
	2 - 2007	0.011	0.012	0.015	0.003	-0.01
	1 - 2008	-0.017	-0.018	-0.005	-0.003	0.012
	4 - 2008	-0.008	-0.007	-0.005	-0.011	0.007
Farm 3 x_2	1 - 2006	0.011	0.009	0.006	0.004	-0.009
	4 - 2006	0.007	0.012	0.008	-0.005	-0.004
	1 - 2007	-0.006	0.004	0.012	0.009	-0.009
	2 - 2007	0.012	0.011	0.009	0.004	-0.006
	1 - 2008	-0.01	-0.01	-0.006	-0.003	0.011
	4 - 2008	-0.007	-0.006	-0.003	-0.008	0.009

Table 9

	Monitored irrigation event - year	θ_i ($m^3\ m^{-3}$)	V_d ($m^3\ ha^{-1}$)	F_r ($m^3\ s^{-1}$)	t_{ir} (*s*)	t_{fl} (*s*)	F_l (m)	E_a (-)	E_s (-)	E_d (-)
Farm 1	1 - 2006	0.08	838	0.054	1513	1505	130	1.00	0.67	0.47
	4 - 2006	0.12	741	0.048	1505	1505	130	1.00	0.63	0.46
	1 - 2007	0.12	706	0.051	913	594	88	0.92	0.81	0.70
	2 - 2007	0.08	706	0.051	913	675	88	0.95	0.59	0.64
	1 - 2008	0.14	1482	0.060	1630	467	88	0.67	0.87	0.89
Farm 2	2 - 2006	0.05	1772	0.125	1797	1034	130	0.72	0.99	0.97
	3 - 2006	0.13	1183	0.125	1200	843	130	0.81	0.96	0.86
	1 - 2007	0.12	1119	0.125	1135	898	130	0.72	0.98	0.92
	1 - 2008	0.13	1817	0.160	2925	784	229	0.53	1.00	1.00
Farm 3	2 - 2006	0.12	1352	0.123	3957	3825	600	0.79	0.93	0.72
	4 - 2006	0.16	1409	0.128	3963	3144	600	0.69	0.98	0.93
	1 - 2007	0.08	1829	0.138	4771	3727	600	0.69	0.98	0.94
	2 - 2007	0.13	1577	0.159	3571	2326	600	0.65	1.00	0.99
	1 - 2008	0.07	2249	0.156	5190	3543	600	0.59	1.00	1.00
	4 - 2008	0.18	1791	0.161	4005	2250	600	0.60	1.00	1.00

Table 10

	Irrigation event - year	θ_i ($m^3\ m^{-3}$)	V_d ($m^3\ ha^{-1}$)	F_r ($m^3\ s^{-1}$)	t (*s*)	F_l (m)	E_a (-)	E_s (-)	E_d (-)
Farm 1	2 - 2007 - real case	0.12	706	0.051	913	88	0.92	0.81	0.70
	2 - 2007 - case 1	0.12	727	0.040	1200	88	0.95	0.87	0.64
	2 - 2007 - case 2	0.12	970	0.040	1600	88	0.79	0.97	0.89
	2 - 2007 - case 3	0.12	1236	0.051	1600	88	0.64	1.00	1.00
	2 - 2007 - case 4	0.12	830	0.060	913	88	0.80	0.84	0.82
	2 - 2007 - case 5	0.12	968	0.070	913	88	0.71	0.86	0.89
	2 - 2007 - case 6	0.05	706	0.051	913	88	0.97	0.70	0.61
	2 - 2007 - case 7	0.15	706	0.051	913	88	0.86	0.92	0.79

Table 11

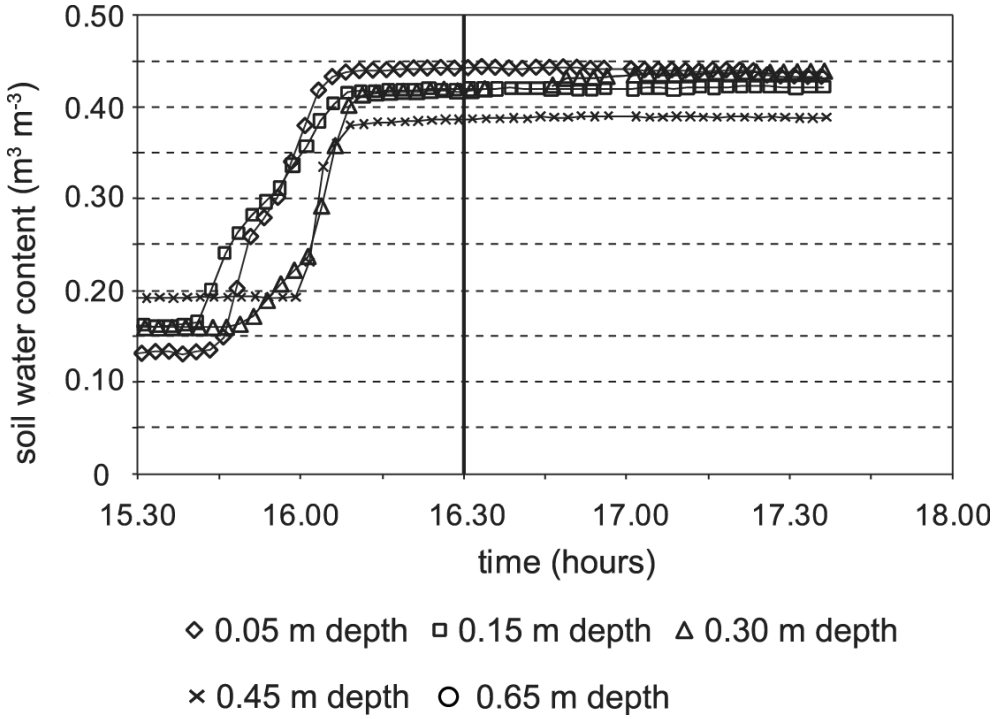

Figure 1

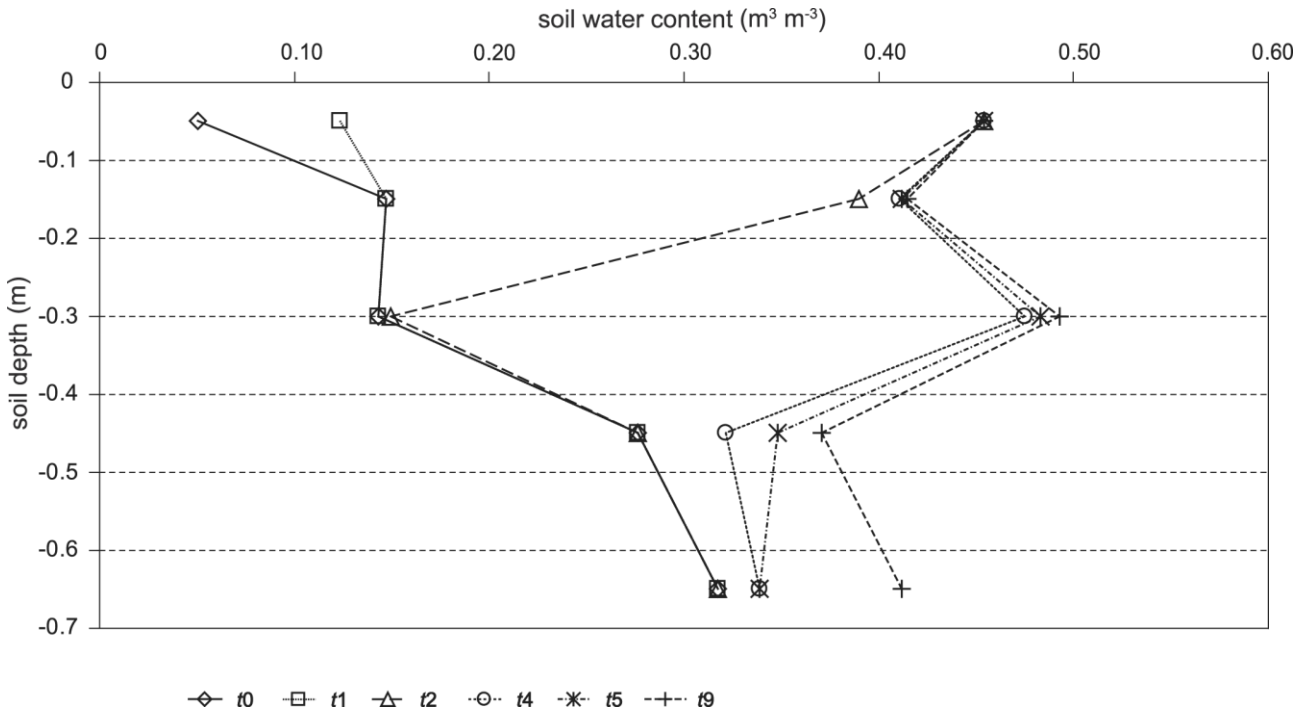

Figure 2

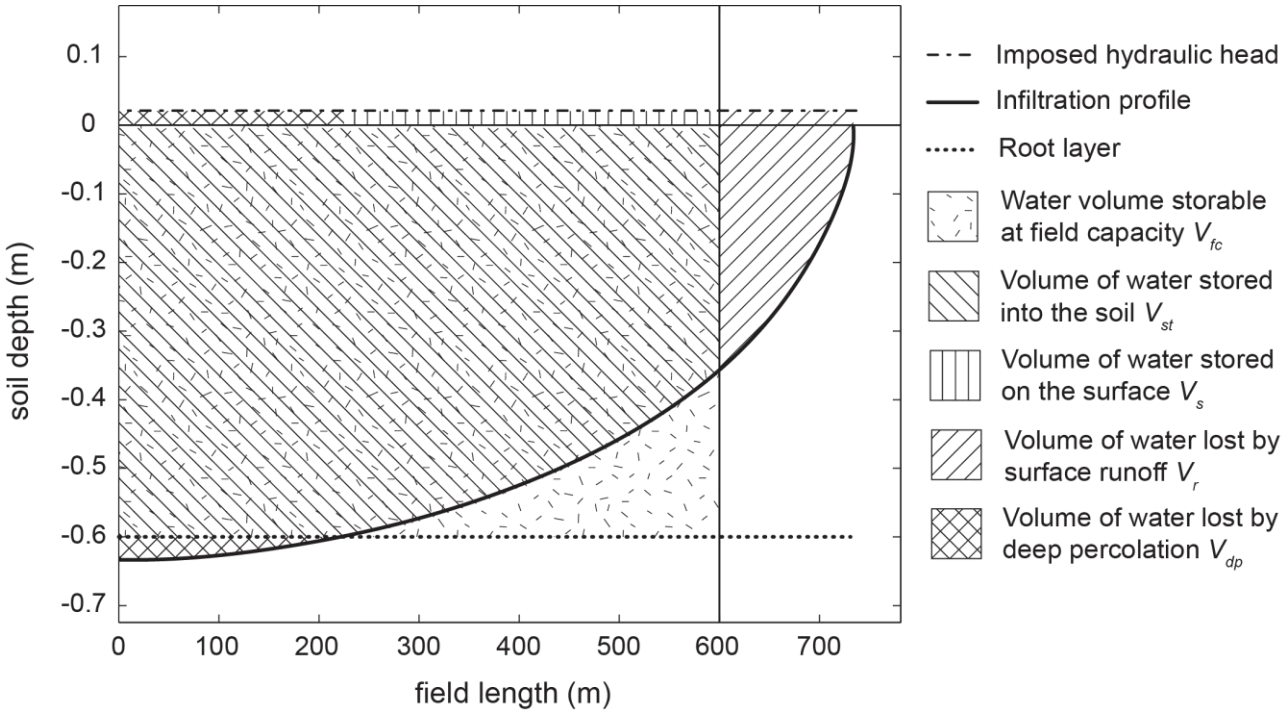
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
-0.7
soil depth (m)
0
100
200
300
400
500
600
700
field length (m)
Imposed hydraulic head
Infiltration profile
Root layer
Water volume storable at field capacity V_{fc}
Volume of water stored into the soil V_{st}
Volume of water stored on the surface V_s
Volume of water lost by surface runoff V_r
Volume of water lost by deep percolation V_{dp}

Figure 3

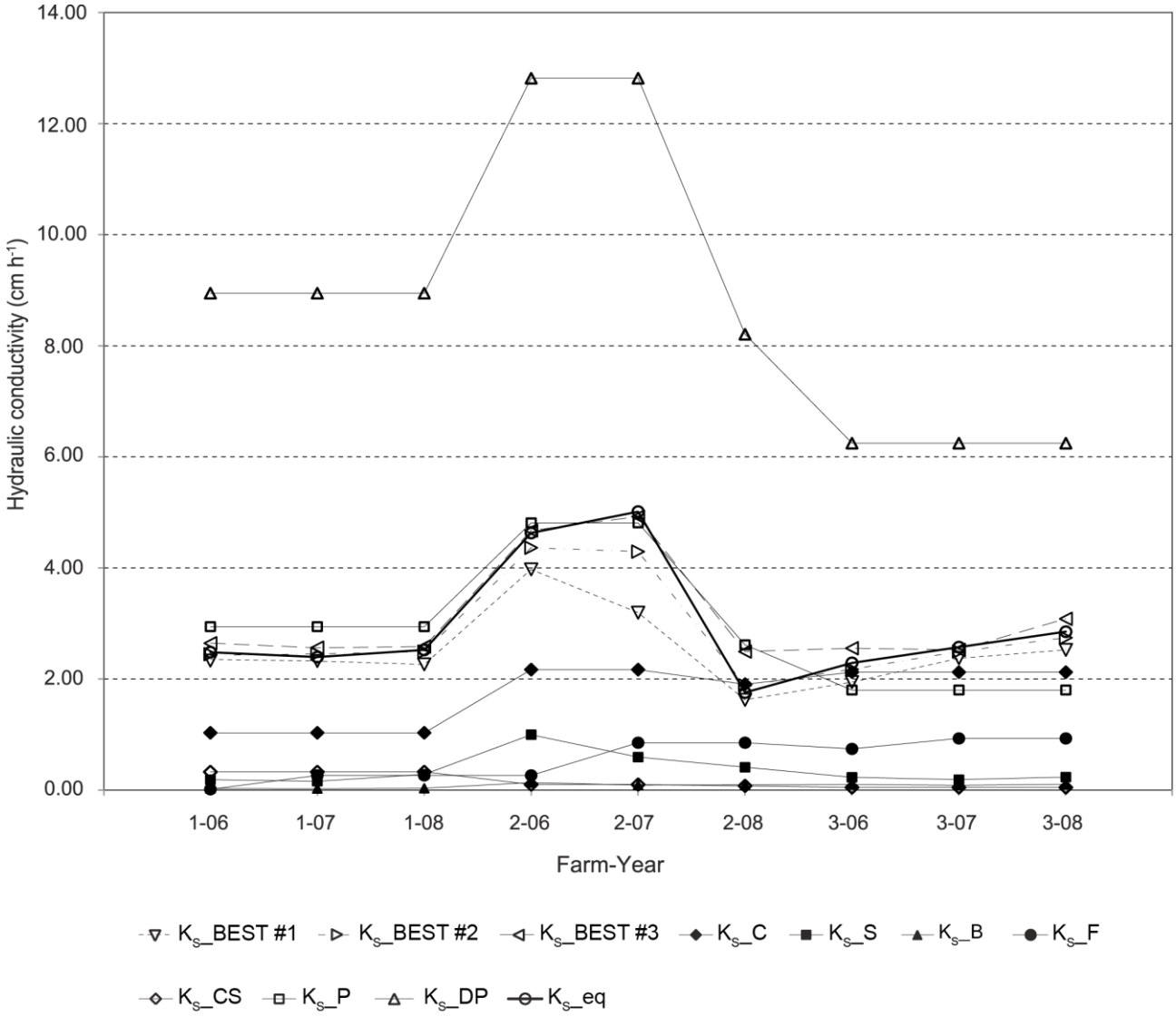
14.00
12.00
10.00
8.00
6.00
4.00
2.00
0.00
Hydraulic conductivity (cm h-1)
1-06
1-07
1-08
2-06
2-07
2-08
3-06
3-07
3-08
Farm-Year
KS_BEST #1
KS_BEST #2
KS_BEST #3
KS_C
KS_S
KS_B
KS_F
KS_CS
KS_P
KS_DP
KS_eq

Figure 4

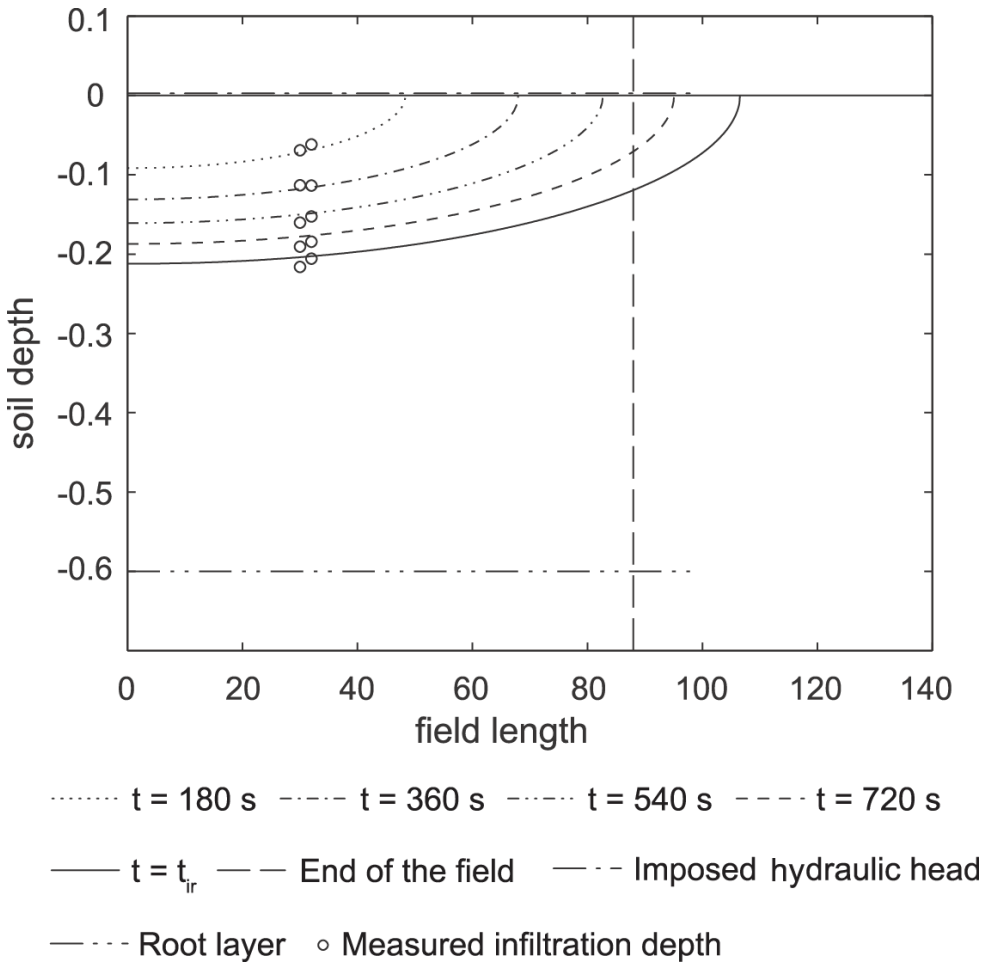
0.1
0
-0.1
-0.2
-0.3
-0.4
-0.5
-0.6
soil depth
0
20
40
60
80
100
120
140
field length
t = 180 s
t = 360 s
t = 540 s
t = 720 s
t = t_ir
End of the field
Imposed hydraulic head
Root layer
Measured infiltration depth

Figure 5

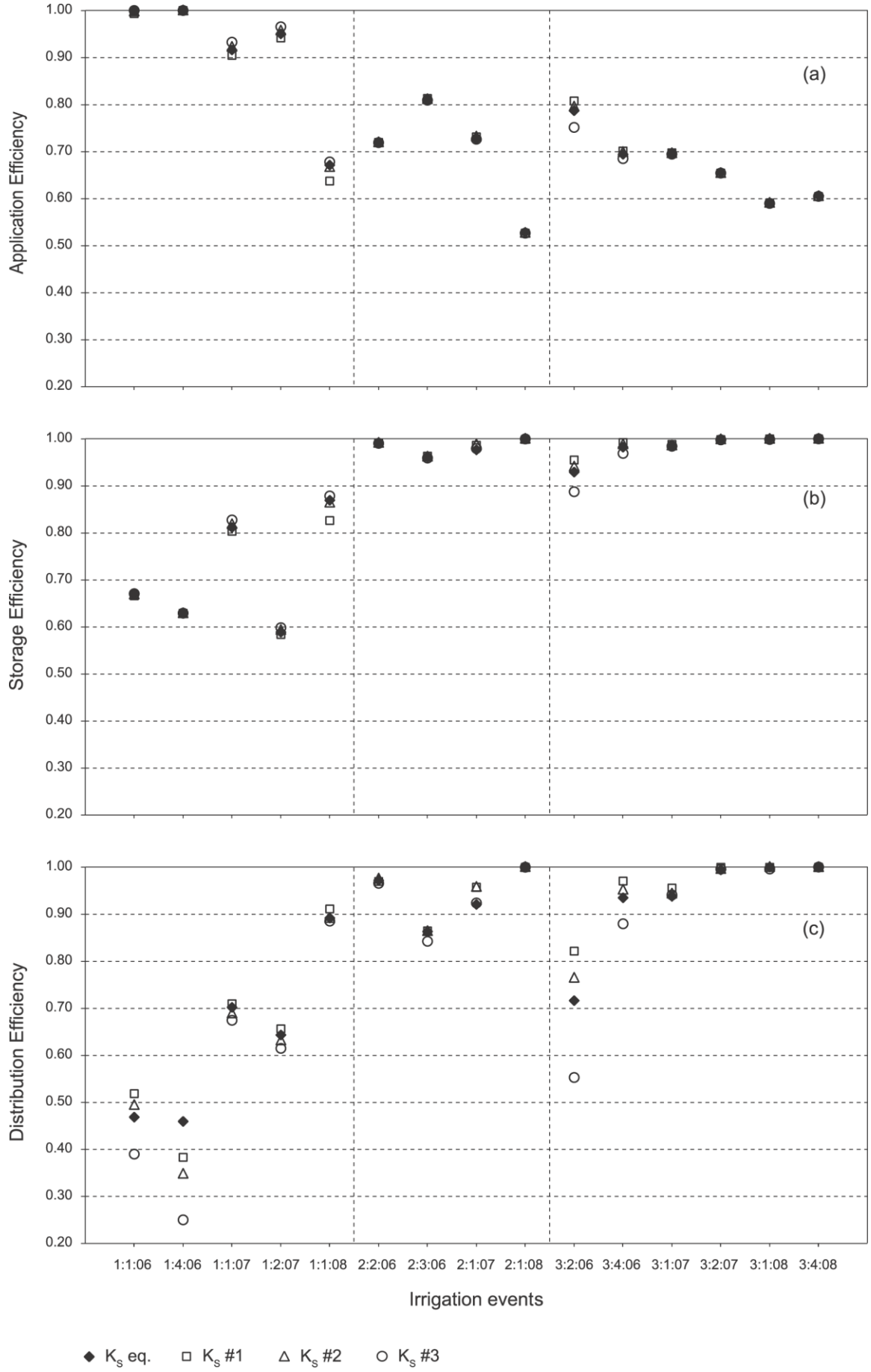
Application Efficiency
Storage Efficiency
Distribution Efficiency
(a)
(b)
(c)
1.00
0.90
0.80
0.70
0.60
0.50
0.40
0.30
0.20
1:1:06
1:4:06
1:1:07
1:2:07
1:1:08
2:2:06
2:3:06
2:1:07
2:1:08
3:2:06
3:4:06
3:1:07
3:2:07
3:1:08
3:4:08
Irrigation events
Ks eq.
Ks #1
Ks #2
Ks #3

Figure 6

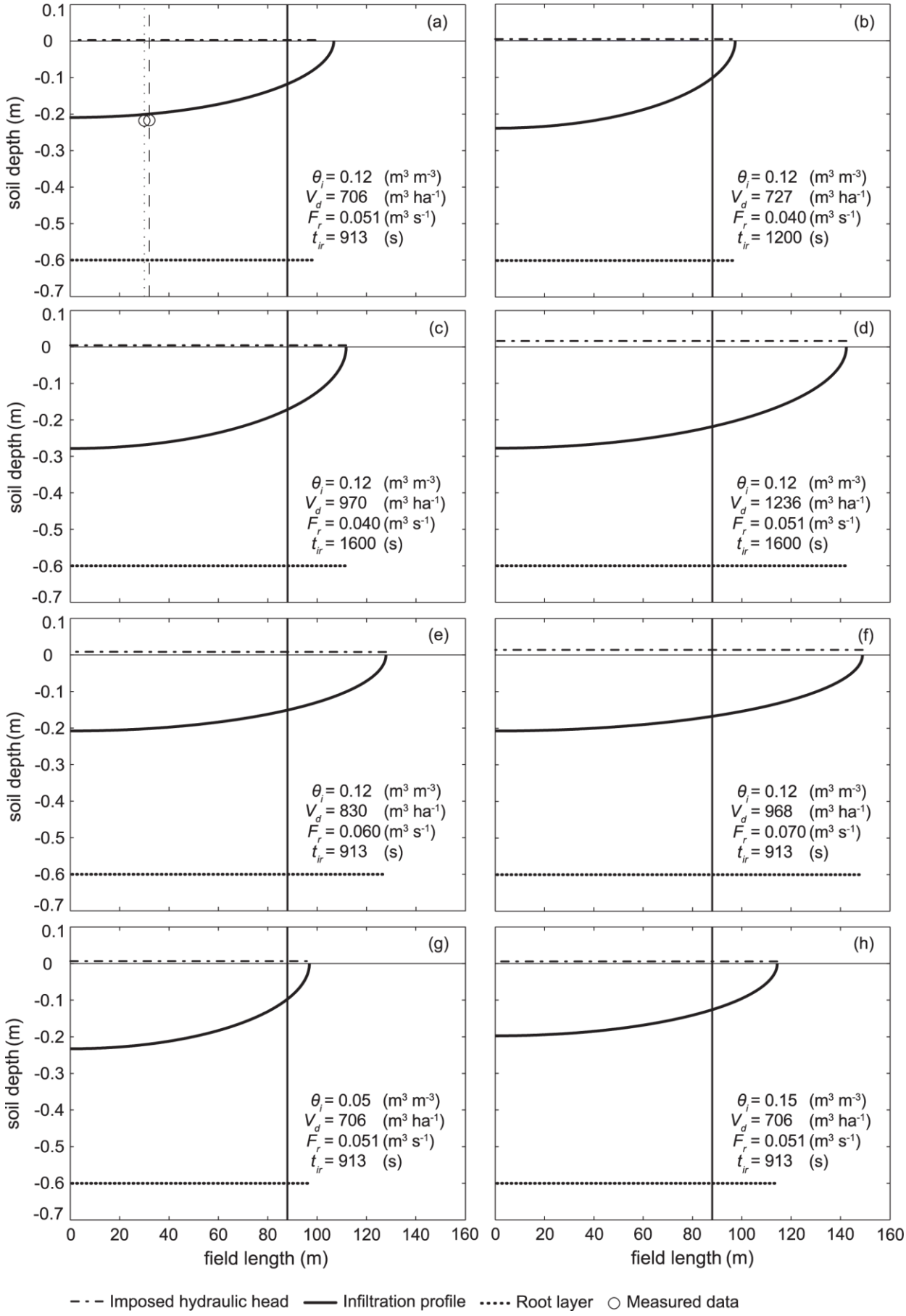
(a)
θ_i = 0.12 (m³ m⁻³)
V_d = 706 (m³ ha⁻¹)
F_r = 0.051 (m³ s⁻¹)
t_{ir} = 913 (s)
(b)
θ_i = 0.12 (m³ m⁻³)
V_d = 727 (m³ ha⁻¹)
F_r = 0.040 (m³ s⁻¹)
t_{ir} = 1200 (s)
(c)
θ_i = 0.12 (m³ m⁻³)
V_d = 970 (m³ ha⁻¹)
F_r = 0.040 (m³ s⁻¹)
t_{ir} = 1600 (s)
(d)
θ_i = 0.12 (m³ m⁻³)
V_d = 1236 (m³ ha⁻¹)
F_r = 0.051 (m³ s⁻¹)
t_{ir} = 1600 (s)
(e)
θ_i = 0.12 (m³ m⁻³)
V_d = 830 (m³ ha⁻¹)
F_r = 0.060 (m³ s⁻¹)
t_{ir} = 913 (s)
(f)
θ_i = 0.12 (m³ m⁻³)
V_d = 968 (m³ ha⁻¹)
F_r = 0.070 (m³ s⁻¹)
t_{ir} = 913 (s)
(g)
θ_i = 0.05 (m³ m⁻³)
V_d = 706 (m³ ha⁻¹)
F_r = 0.051 (m³ s⁻¹)
t_{ir} = 913 (s)
(h)
θ_i = 0.15 (m³ m⁻³)
V_d = 706 (m³ ha⁻¹)
F_r = 0.051 (m³ s⁻¹)
t_{ir} = 913 (s)
soil depth (m)
field length (m)
Imposed hydraulic head
Infiltration profile
Root layer
Measured data

Figure 7