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Investigating the effects of soil moisture sensors positioning and accuracy on soil moisture based drip irrigation scheduling systems

Konstantinos X. Soulis*, Stamatios Elmaloglou, Nicholas Dercas

Division of Water Resources Management, Department of Natural Resources Management and Agricultural Engineering, Agricultural University of Athens, 75, Iera Odos str., 11855 Athens, Greece

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ABSTRACT

Recent advances in electromagnetic sensor technologies have made automated irrigation scheduling a reality using state-of-the-art soil moisture sensing devices. However, many of the available guidelines for sensor placement were empirically determined from site and crop specific experiments. Sensors accuracy could be also an important factor affecting irrigation efficiency. This study investigates how soil moisture sensors positioning and accuracy may affect the performance of soil moisture based surface drip irrigation scheduling systems under various conditions. For this purpose several numerical experiments were carried out using a mathematical model, incorporating a system-dependent boundary condition in order to simulate soil moisture based irrigation scheduling systems. The results of this study provided clear evidence that soil moisture sensors positioning and accuracy may considerably affect irrigation efficiency in soil moisture based drip irrigation scheduling systems. In specific cases the effect of soil moisture sensors positioning was as high as 16%; however, when nearby sensor positions were examined, the observed differences were generally low. The effect of sensors accuracy was even clearer. For the lower sensor's error level studied ($\pm 0.01\,cm^3\,cm^{-3}$) the effect on irrigation efficiency ranged between 2.5% and 6.4%, while for the higher error level ($\pm 0.03\,cm^3\,cm^{-3}$) the effect ranged between 10.2% and 18.7%. These results highlight the importance of a detailed study taking into account the characteristics of specific crops, irrigation, and scheduling systems as well as soil moisture sensors in order to provide a sound basis for improved irrigation scheduling. The need for soil specific calibration of the sensors used in such systems is highlighted as well. Lastly, a significant outcome of this study is the ability of computer models to serve as efficient tools for the detailed investigation of sensors positioning and accuracy, or other automated scheduling system characteristics.

1. Introduction

Water conservation in agriculture has recently received much attention in the light of increasing competition for fresh water resources between the various users, especially in semi-arid and arid regions facing limited water availability and at the same time increased water needs. Among the most promising current strategies to increase irrigation water use efficiency is the use of drip irrigation systems, which facilitate water management due to the highly localized application of water and nutrients, and the improvement of irrigation scheduling, i.e. by applying the right amount of water to cropland at the right time over the growing season.

Even though drip irrigation can be proven much more efficient than other irrigation systems since only the root zone of the cropped area is irrigated, improper management may lead to waste of water or leaching of soluble chemicals such as nitrate (Dukes et al., 2007; Zotarelli et al., 2011). However, efficient irrigation management is challenging, due to the many factors that should be considered, including climate, crop type, irrigation method, and system parameters (Dabach et al., 2013). The goal of irrigation scheduling is to make the most efficient use of water and energy by applying the right amount of water to cropland at the right time and in the right place, making sure water is available when the crop needs it (Tam, 2006). Scheduling maximizes irrigation efficiency by minimizing runoff and percolation losses. Proper irrigation management requires a sound basis for making irrigation decisions. Methods of irrigation scheduling can be classified as static or dynamic. According to the static approach the total amount of water for irrigation is allocated without specifying its temporal distribu-

* Corresponding author. Tel.: +30 2105294070.
E-mail addresses: soco@aua.gr, k.soulis@gmail.com (K.X. Soulis).

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tion along the growing season. By contrast, in the dynamic approach irrigation water is allocated at specific time steps along the growing season in order to achieve optimal soil water content conditions in the root zone at every growth stage (Shani and Dudley, 2001; Shani et al., 2004). Irrigation scheduling is normally based on environmental measurements such as evapotranspiration and soil water content or on monitoring plant stress.

Many researchers have investigated the automation of irrigation systems and the use of soil moisture sensing devices such as tensiometers, gypsum blocks, granular matrix sensors (GMS), and electromagnetic (EM) sensors. An automated irrigation scheduling system generally consists of soil moisture or matric head sensing devises, a control system, and the irrigation system components (Dukes and Scholberg, 2005). The use of switching tensiometers to automatically control irrigation events has been studied among others by Smajstrla and Koo (1986), Clark et al. (1994), Torre-Neto et al. (2000). In most of these studies, significant water savings were reported without a negative effect on crop yield. However, the use of tensiometers to initiate irrigation is associated with several problems, such as entrapped air in the tensiometers, organic growth on the ceramic cups, and need for recalibration (Smajstrla and Koo, 1986; Dukes and Scholberg, 2005). GMS require less maintenance and can be more easily integrated in automated irrigation systems. However, they are very sensitive in soil salinity and they often need recalibration. Muñoz-Carpena et al. (2005) found that GMS-based irrigation behaved erratically. The above issues of the available matric head sensing devises limited the extensive use of automated irrigation scheduling systems.

Recent advances in EM sensor technology, including their ability to be easily automated and the lower cost of recently developed capacitance and frequency EM sensors, have made automated irrigation scheduling a reality using state-of-the-art soil moisture sensing devices (Blonquist et al., 2006). Several studies investigated the use of EM sensors in novel automated irrigation management applications (Blonquist et al., 2006; Coates et al., 2006; Dukes et al., 2007; Kim et al., 2009; Kim and Evans, 2009; Miralles-Crespo and van Iersel, 2011). In these studies significant water savings in comparison with traditional irrigation scheduling approaches, as high as 60%, were reported.

However, a still unanswered question is how sensor positioning and accuracy may affect irrigation efficiency in soil moisture based automated irrigation scheduling systems. The wetting profile in the root zone of irrigated crops is dynamic and influenced by crop and irrigation system parameters such as soil hydraulic properties, irrigation system characteristics (e.g. emitter flow rate), root length and structure, and even mulch type when mulches are used. Especially in the case of drip irrigation, the non-uniform water distribution patterns about drippers make soil water sensor placement a key factor in the performance of soil moisture based drip irrigation scheduling schemes (Coelho and Or, 1996). More specifically, poor sensor positioning that is not representative of the soil moisture conditions in the root zone can result either in crop water stress, or in over-irrigation that negates the water saving capabilities of soil moisture scheduling (Stieber and Shock, 1995; Coelho and Or, 1996; Schroder et al., 2005; Wang et al., 2012). However, many of the available guidelines for sensor placement were empirically determined from site and crop specific experiments.

Soil moisture sensors accuracy could be also an important factor affecting the efficiency of soil moisture sensor based irrigation scheduling systems. Several recent studies on the performance of new electrical capacitance and frequency EM sensors extensively discuss issues of sensor-to-sensor variability and sensor accuracy (e.g. Seyfried and Murdock, 2004; Kargas and Kerkides, 2008; Kizito et al., 2008; Parsons and Bandaranayake, 2008; Kargas and Soulis, 2012). Regarding the sensor-to-sensor variability, variations as high as 0.04 $cm^3 cm^{-3}$ are being reported. In most cases the sensors accuracy when the factory calibration equations are used ranges between 0.03 $cm^3 cm^{-3}$ and 0.04 $cm^3 cm^{-3}$. However, using soil specific calibration the accuracy can be significantly improved, reaching 0.01 $cm^3 cm^{-3}$ or even better. It should be noted that the above general figures may vary among the various sensors technologies and models.

One of the most important aspects of studying soil moisture based drip irrigation scheduling schemes in the case of drip irrigation systems, is the determination of the soil moisture patterns formed under the emitter. Wetting patterns can be obtained either experimentally, which are case specific, or by simulation using suitable mathematical models. In most of these models, the Richards equation is used to simulate soil water matric potential or water content distribution during drip irrigation. Both numerical and analytical methods are used to solve the Richards flow equation (Elmaloglou et al., 2013). Several analytical solutions have been developed for the linearized form of the flow equation (Lomen and Warrick, 1974; Warrick and Lomen, 1976; Ben-Asher et al., 1978). Chen et al. (2009) obtained a series of closed-form analytical solutions for the water content distribution during trickle irrigation under either a single line source flux or multiple line sources. However, the application of analytical solutions is limited given the various assumptions needed (Coelho and Or, 1996). Therefore, numerical simulation models are used more often to analyze soil water dynamics under surface drip irrigation (e.g. Šimůnek et al., 1999; Vrugt et al., 2001; Elmaloglou and Malamos, 2005; Šimůnek et al., 2006; Elmaloglou and Diamantopoulos, 2008a, 2008b; Diamantopoulos and Elmaloglou, 2012; Elmaloglou et al., 2013; Elmaloglou and Soulis, 2013). In a recent study Dabach et al. (2013) investigated irrigation scheduling by combining the results of HYDRUS 2D/3D simulations with experimental data for the case of matric head triggered drip irrigation systems in order to optimize their main operational parameters, i.e. irrigation thresholds and water amounts. In their study the merits of using numerical simulation models in studying sensor based irrigation management were highlighted as well.

In this context the main objective of this study is to investigate how soil moisture sensors positioning and accuracy may affect the performance of soil moisture based surface drip irrigation scheduling systems under various conditions (soil types, potential evapotranspiration rates, discharge rates, irrigation depths, drip line spacing). For this purpose several numerical experiments were carried out using a mathematical model, which incorporates hysteresis in the soil water characteristic curve, evaporation from the soil surface, and water extraction by roots (Elmaloglou and Diamantopoulos, 2008a; Elmaloglou et al., 2013). Furthermore, a system-dependent boundary condition was implemented into the mathematical model considering changing conditions in specific locations of the flow domain in order to simulate soil moisture based automated drip irrigation scheduling systems.

2. Materials and methods

2.1. The mathematical model

In order to study how soil moisture sensor positioning and accuracy affects the performance of soil moisture based surface drip irrigation scheduling systems, the soil moisture patterns formed under the emitters for various conditions and various configurations of the studied system were determined using the mathematical model presented by Elmaloglou et al. (2013), which simulates soil water dynamics under surface drip irrigation from equidistance line sources. This mathematical model incorporates hysteresis in the soil water characteristic curve, evaporation from the soil surface, and water extraction by roots. Furthermore, due to the fact that the code of the model was developed in-house, it was possible to implement a system-dependent boundary condition considering changing conditions in specific locations of the flow domain, which correspond to the soil moisture sensors positions. In this manner it was made possible to simulate the operation of an automated soil moisture based drip irrigation scheduling system for several irrigation cycles.

In Fig. 1a graphical representation of the three-dimensional physical model is illustrated. As it can be seen, surface drip irrigation is applied from horizontal line sources, of width $2x_0$. In the same figure, the laterals spacing, which in this study was selected equal to 60 cm and 80 cm, the crop rows, and the two-dimensional spatial distribution of the active root zone, are also shown. The width of the plant root system is minimal on the surface and increases with depth up to 20 cm, where it acquires its maximum width. Then the width is reduced up to 60 cm, which is equal to the root zone depth. The spatial distribution of the active root zone was selected to represent a normal rooting pattern for various crops suited by drip irrigation systems (e.g. beans, tomato, potato, cucumber, and other vegetable crops) (FAO, 1989, 1998; Machado and Oliveira, 2005).

The plane flow symmetry allows for the physical model to be examined in one of the infinite vertical planes, which are perpendicular to the length of the line sources, and are determined from the x and z axes. In Fig. 1b, the discretization of the computational domain, which corresponds to the rectangle ABFE of Fig. 1a, is illustrated. The space steps Δx, Δz that were used for the numerical solution of the mathematical model were taken equal to 2 cm.

The phenomenon of hysteresis in the soil water characteristic curve is incorporated in the mathematical model with the simplification made by Kool and Parker (1987) for the empirical model of Scott et al. (1983). More specifically, it was assumed that $\alpha_d = \alpha_w/2$, where a_w and a_d are the values of the a parameter in the relationship of van Genuchten (1980) for the main wetting and drying curve, as proposed by Kool and Parker (1987).

Lastly, the mathematical model was successfully validated against an existing analytical solution and the Hydrus 2D numerical model as described in detail by Elmaloglou et al. (2013).

2.2. Simulation inputs

In this study, the cases of two homogenous soil profiles consisting of loamy sand (LS) and silt (Si), respectively, were examined. The hydraulic properties of these soils were taken from the Rosetta database (Schaap and Leij, 1998).

The soil hydraulic properties are modeled using the van Genuchten–Mualem constitutive relationships (Mualem, 1976; van Genuchten, 1980) as follows:

$$\Theta(H) = \Theta_r + \frac{\Theta_s - \Theta_r}{\left(1 + (a \times H)^n\right)^m}, \quad m = 1 - \frac{1}{n} \tag{1}$$

and

$$K(Se) = K_s Se^{0.5}\left(1 - \left[1 - Se^{n/(n-1)}\right]^m\right)^2$$
$$\text{where } Se = \frac{\Theta(H) - \Theta_r}{\Theta_s - \Theta_r} \tag{2}$$

where Θ_s is the saturated water content ($L^3\,L^{-3}$); Θ_r is the residual water content ($L^3\,L^{-3}$); K_s is the saturated hydraulic conductivity ($L\,T^{-1}$); and α (L^{-1}), n (–), and m (–) are shape parameters. The Se is the effective saturation (dimensionless) ($0 < Se < 1$). The values of the parameters included in the van Genuchten equations are summarized in Table 1. The unique $K(\Theta)$ relation for each soil type always follows from the parameter set (n, Θ_s, Θ_r, K_s) according to Eq. (2) (Kroes et al., 2008). The values of the initial volumetric water content Θ_i are 0.164 cm^3 cm^{-3} for the loamy sand and 0.198 cm^3 cm^{-3} for the silt soil, respectively. The above values were chosen so that for time $t = 0$, both soils had the same value of effective saturation ($Se = 33.7\%$). This Se value corresponds to initial hydraulic conductivity values small enough to minimize redistribution due to gravity. The corresponding pressure head values (−120 cm for the loamy sand and −756 cm for the silt soil) are well above the wilting point and are not related to significant crop water stress (water stress response according to Feddes et al. (1978), $a(H) \approx 1$). More details can be found in Elmaloglou et al. (2013).

Each irrigation cycle was initiated when the soil moisture value at the respective sensor position reached the initial soil moisture value. Dabach et al. (2013) demonstrated the effect of irrigation thresholds on the irrigation efficiency of matric head triggered irrigation systems. Therefore, test simulations with different Se values were also performed. These tests provided similar results, at least as related to the effect of sensor positioning and accuracy, which are the main topics of this study.

The potential evapotranspiration rate at any time point (mm h^{-1}) ET_r, is calculated by distributing the daily potential evapotranspiration ET_p (mm day^{-1}) over a 24-h period (Vellidis and Smajstrla, 1992). A sinusoidal type distribution is used:

$$ET_r = \frac{ET_p}{T_{\text{cycle}}}\left[1 + \sin\left[\frac{2\pi T_{\text{day}}}{T_{\text{cycle}}} - \frac{\pi}{2}\right]\right] \tag{3}$$

where T_{cycle} is the period of the cycle (h), in this case 24 h, and T_{day} is the current time on the 24-h clock minus the beginning time of the cycle (h).

Early in the growing season, soil evaporation is the highest part of the total evapotranspiration, but it gradually decreases as the plants grow and the canopy closes. However, even under a fully closed canopy, some soil evaporation occurs. In fully developed crops, transpiration is the dominant part of the total evapotranspiration, ranging between 80% and 90% of the latter (Bufon et al., 2012). The actual transpiration rate of a given crop is influenced by many factors, including crop type, soil and plant management practices, irrigation regime, climatic conditions, plant growth stage, plant genetic characteristics, leaf orientation, leaf age, etc. Accordingly, the daily potential evapotranspiration ET_p was partitioned into daily potential evaporation E_p and daily potential transpiration T_p, so that the ratio E_p/ET_p have a value around 0.14, which corresponds to average real conditions for a fully developed crop in semi-arid regions.

In this study, two different potential evapotranspiration rates were investigated. The higher rate was selected to be equal to 8.4 mm day^{-1}, which is an acceptable value for a fully developed crop in the dry period and in semi-arid regions. The lower value was selected to be equal to 4.2 mm day^{-1} in order to test the effect of soil moisture sensors positioning and accuracy under intermediate conditions in comparison to the more extreme case of the higher potential evapotranspiration rate.

2.3. Numerical experiments

As it was previously stated, recent progress in EM sensor technology promoted the broader application of automated irrigation scheduling using soil moisture sensing devices (Blonquist et al., 2006). Considering also the problems of matric head sensors that limited the wider application of automated irrigation scheduling up to now (Smajstrla and Koo, 1986; Dukes and Scholberg, 2005; Muñoz-Carpena et al., 2005), the case of soil moisture based automated irrigation scheduling is examined in this study. Furthermore, soil moisture triggered drip irrigation systems can be more consistently modelled through the implementation of a

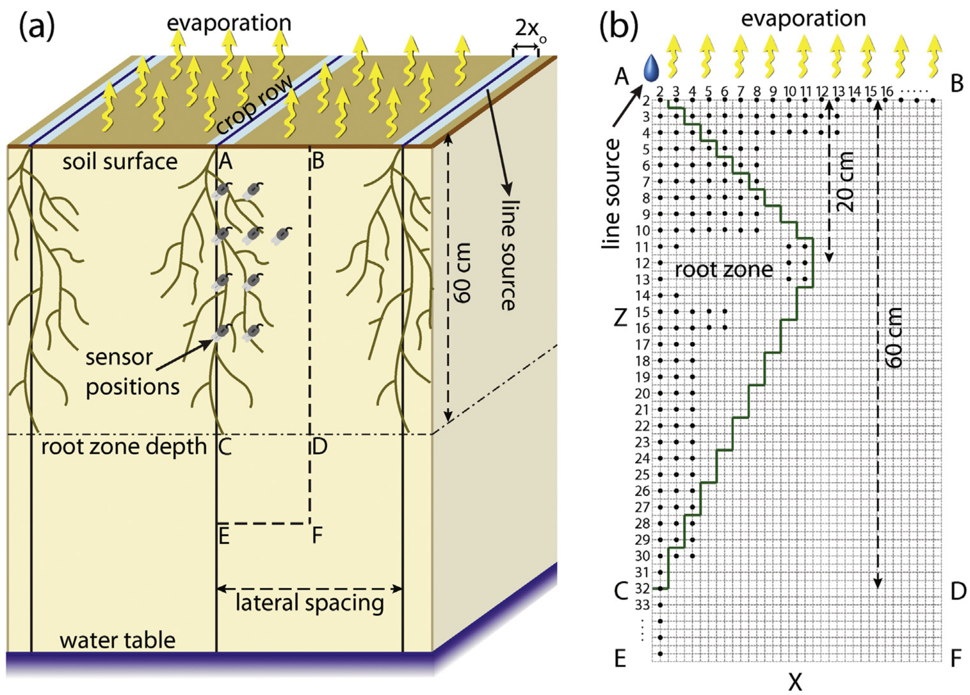

Fig. 1. The three dimensional physical model (a), and the discretization of the computational domain, which corresponds to the rectangle ABFE (b). This figure was created based on the corresponding figure presented by Elmaloglou et al. (2013).

system-dependent boundary condition when hysteresis in the soil water characteristic curve is considered. In the case of matric head triggered drip irrigation systems the triggering matric head value corresponds to different soil moisture values in the drying and the wetting curves due to the phenomenon of hysteresis in the soil water characteristic curve, thus complicating the modelling of such systems.

Soil water distribution under drip irrigation is mainly affected by the hydraulic properties of the soil, the drip lines discharge rate, the irrigation depth, the drip lines spacing and the root water uptake spatial and temporal distribution. As it was already mentioned above, two soil types (loamy sand and silt) and two potential evapotranspiration rates (8.4 and 4.2 mm day^{-1}) were investigated. Furthermore, the effect of soil moisture sensors positioning and accuracy was investigated for two discharge rates (2 and 4 l m^{-1} h^{-1}), for two irrigation depths (30 and 40 mm), and for two laterals spacings (60 cm and 80 cm). Usually, soil moisture sensing devices were used to initiate a preset timed irrigation event; therefore, the irrigation event was stopped after a preprogrammed irrigation time (corresponding to a specific irrigation depth) rather than after specific soil moisture conditions were met (Phene and Howell, 1984; Smajstrla and Koo, 1986; Clark et al., 1994; Torre-Neto et al., 2000; Dukes and Scholberg, 2005).

For the above combinations corresponding to various conditions and irrigation system configurations, the effect of soil moisture sensors positioning was investigated by simulating the operation of an automated soil moisture based scheduling system and by calculating the corresponding irrigation efficiency for different sensor positions. The simulated sensor positions are illustrated in Fig. 1a. The various positions were selected to represent a wide range of possible sensor placement options including the most commonly used practices (Stieber and Shock, 1995; Coelho and Or, 1996; Schroder et al., 2005; Wang et al., 2012).

As it was already mentioned, soil moisture sensors accuracy may also be an important factor affecting the efficiency of soil moisture sensor based irrigation scheduling systems. Therefore, in order to investigate the magnitude of sensors accuracy impact a final set of numerical experiments was carried out. In these numerical experiments two levels of sensor errors were examined. A higher error level was selected equal to ± 0.03 cm^3 cm^{-3} so as to correspond to the accuracy of most EM sensors using the factory calibration equations under normal conditions, while the lower error level was selected equal to ± 0.01 cm^3 cm^{-3} so as to correspond to the accuracy of most EM sensors using the soil specific calibration equations (Seyfried and Murdock, 2004; Kargas and Kerkides, 2008; Kizito et al., 2008; Parsons and Bandaranayake, 2008; Kargas and Soulis, 2012). In this approach the previously described combinations of conditions and irrigation system configurations were simulated supposing a systematic error of +0.03, −0.03, +0.01, and −0.01 cm^3 cm^{-3}.

In total more than 200 numerical experiments were carried out. The main combinations investigated are presented in Table 2.

Finally, it should be mentioned that for each case investigated, a period corresponding to eight irrigation cycles was simulated in order to diminish the influence of the initial conditions on the result obtained. The length of each irrigation cycle varied according to the

Table 1
Values of the shape parameter (n), the saturated (Θ_s), residual (Θ_r) water contents, the saturated hydraulic conductivity (K_s) and the scaling factors (a_w) and (a_d) for the main wetting and drying curve, respectively.

Soil type	a_w (cm^{-1})	a_d (cm^{-1})	n (–)	Θ_s (cm^3 cm^{-3})	Θ_r (cm^3 cm^{-3})	K_s (cm h^{-1})
Loamy sand	0.03467	0.017335	1.7378	0.390	0.049	4.383
Silt	0.00661	0.003305	1.6596	0.489	0.050	1.819

Table 2
The main simulated cases for the investigated characteristics in the performed numerical experiments.

Characteristic	Simulated cases
Soil (type)	LS; Si
Discharge rate ($l\,t\,m^{-1}\,h^{-1}$)	2; 4
Irrigation depth (mm)	30; 40
Drip line spacing (cm)	60; 80
Sensors error level ($cm^3\,cm^{-3}$)	±0.01; ±0.03
Sensor position (X cm, Z cm)	1, 10; 11, 10; 1, 20; 11, 20; 19, 20; 1, 30; 11, 30; 1, 40; 11, 40

various conditions (soil types, potential evapotranspiration rates, discharge rates, irrigation depths, drip line spacings) and the various sensor positions and accuracy values simulated and it ranged between 72 h and 120 h for ET_p = 8.4 mm day^{-1} and between 140 h and 232 h for ET_p = 4.2 mm day^{-1}.

3. Results and discussion

3.1. Suitable sensor positions

The main parameters characterizing irrigation performance such as deep percolation, irrigation efficiency in terms of actual transpiration, and actual evaporation were calculated for each case investigated. In this process the variation of soil moisture below 60 cm plus the water drained out from the bottom boundary are considered as deep percolation. Furthermore, the irrigation efficiency is defined as the ratio of the depth of irrigation water that is beneficially used by the plants to the depth of irrigation water applied (On Farm Irrigation Committee, 1978; Irmak et al., 2011).

The main results of the numerical experiments considering the high potential evapotranspiration rate of 8.4 mm day^{-1} and the high drip line discharge rate of 4 l m^{-1} h^{-1} are presented in Table 3, however, the following analysis is based on the results of all the numerical experiments described in Table 2. As it was expected, irrigation efficiency varies considerably according to the drip line spacing, the irrigation depth, and the soil type. More specifically, irrigation efficiency increases with decreasing drip line spacing (the observed difference ranges between about 2.7% and 8.8%) and with decreasing irrigation depth (the observed difference ranges between about 1.4% and 9.7%). As it can be also observed irrigation efficiency is lower for the coarse soil (loamy sand) in all cases studied due to the higher deep percolation losses. The above results are in agreement with results presented in other similar studies e.g. (Khan et al., 1996; Cote et al., 2003; Li et al., 2003; Souza and Matsura, 2003; Elmaloglou and Diamantopoulos, 2010; Selim et al., 2012; Elmaloglou et al., 2013). Furthermore, the observed differences in irrigation efficiency are more significant for the case of the coarse soil (loamy sand). By contrast, drip line discharge rate was found to have a limited effect on irrigation efficiency, therefore, only the results considering the high drip line discharge rate are presented in Table 3. Considering the main question of this study, which is related to the effect of soil moisture sensors positioning on irrigation efficiency, a notable variation of irrigation efficiency among the various positions investigated was observed. In many cases, this variation was greater than the variation among the various irrigation system configurations. As an example, the irrigation efficiency related to the various sensor positions in the case of the loamy sand soil, the 4 l m^{-1} h^{-1} discharge rate, the 30 mm irrigation depth, and the 60 cm drip line spacing ranged between 89.7% (sensor position X = 11 cm, Z = 10 cm) and 73% (sensor position X = 1 cm, Z = 30 cm), while the irrigation efficiency related to the various irrigation system configurations for the loamy sand soil and for the more suitable sensor position (X = 11 cm, Z = 10 cm) ranged between 89.7% and 77.9%. The corresponding irrigation efficiency values for the case of the silt soil ranged between 93.7% and 78.7% and 93.7% and 86.4%, respectively. This observation highlights the importance of the proper positioning of the soil moisture sensors driving automated irrigation scheduling systems. However, when nearby sensor positions are examined, the observed differences are lower and in some cases they are negligible.

The irrigation efficiency variations observed among the investigated sensor positions noticeably vary among the irrigation system configurations and soil types studied. In order to quantify this variability, the standard deviations of the irrigation efficiencies corresponding to the various sensor positions for each irrigation system configuration and soil type were calculated (Table 3). The calculated standard deviations ranged from 5.8% for the 4 l m^{-1} h^{-1} discharge rate, the 30 mm irrigation depth, the loamy sand soil, for both drip line spacings to 2.8% for the 2 l m^{-1} h^{-1} discharge rate, the 40 mm irrigation depth, for 60 cm drip line spacing, for both soils. The higher standard deviations are observed in the case of the coarse soil (loamy sand) and especially for the case of the higher discharge rate. These observations may be attributed to the variation of the representativeness of the sensor readings according to its position, which is examined in more detail in the next section. Furthermore, higher standard deviations are related to conditions favoring the vertical movement of the wetting front through the soil profile e.g. coarse soils (Khan et al., 1996; Cote et al., 2003; Li et al., 2003; Souza and Matsura, 2003; Elmaloglou and Malamos, 2005; Elmaloglou and Diamantopoulos, 2010; Elmaloglou et al., 2013).

Besides the above mentioned irrigation efficiency variability among the various cases studied, it was observed that the most suitable position was 11 cm from the drip line and 10 cm below the soil surface (X = 11 cm, Z = 10 cm) in all cases studied. Generally, sensor positions 20 cm from the soil surface or deeper are related to noticeably lower irrigation efficiencies. When the sensors are positioned more deeply in the soil profile soil evaporation is reduced; however, this reduction cannot balance the increased deep percolation values due to increased soil water content values at the lower part of the root zone (Table 3), leading to more frequent irrigations. A characteristic example is presented in Fig. 2, where the soil water content spatial distribution patterns for a shallower (X = 11 cm, Z = 10 cm) and a deeper (X = 11 cm, Z = 30 cm) sensor position for the case of the loamy sand soil, the 4 l m^{-1} h^{-1} discharge rate, the 30 mm irrigation depth, and the 60 cm drip line spacing, in three representative times (last irrigation cycle, t_i = end of irrigation, t_{end} just before irrigation, t_{mid} in-between time) are illustrated. Furthermore, it was observed that sensor positions directly under the emitters are also linked to lower efficiencies (Table 3). It should be noted that in tests carried out for positions further away from the drip line or deeper in the soil profile than the positions presented here, irrigation efficiency drops considerably.

The main conclusions obtained for the lower potential evapotranspiration rate of 4.2 mm day^{-1} were similar to that of the higher potential evapotranspiration rate analyzed above. However, irrigation efficiencies are generally lower in all cases due to higher deep percolation losses. As it was expected, soil evaporation is reduced due to the lower potential evapotranspiration rate; however these reductions are generally low. Finally, noticeable irrigation efficiency variations between the investigated sensor positions are still present, but the calculated standard deviation values are lower.

3.2. Representative sensor positions

At a second step of analysis, it was investigated how soil moisture sensors positioning influences the representativeness

Table 3
Sensor positions suitability: main numerical experiments results obtained for the high discharge rate of $4\,\mathrm{l\,m^{-1}\,h^{-1}}$ and the high potential evapotranspiration rate of $8.4\,\mathrm{mm\,day^{-1}}$.

Characteristics			Sensor position	Efficiency		Losses	
Soil	Irrigation depth	Drip line spacing		Transpiration		Deep Percolation	Soil evaporation
Type	mm	cm	X cm, Z cm	(%)	Std. Dev.	(%)	(%)
LS	30	60	1, 10	84.5	*	3.5	13.9
LS	30	60	1, 30	73.0		10.6	12.0
LS	30	60	1, 20	79.9	5.8	6.5	13.1
LS	30	60	11, 10	89.7		1.6	14.8
LS	30	60	11, 20	81.4		5.8	13.4
LS	30	60	11, 30	76.0		8.1	12.5
LS	30	80	1, 20	71.1	5.8	12.2	11.7
LS	30	80	11, 10	83.8		4.4	13.8
LS	30	80	11, 20	74.6		9.6	12.3
LS	30	80	11, 30	72.2		11.9	11.9
LS	40	60	1, 20	71.4	3.9	13.8	11.8
LS	40	60	11, 10	80.0		7.5	13.2
LS	40	60	11, 20	74.0		12.0	12.2
LS	40	60	11, 30	72.1		13.4	11.9
Si	30	60	1, 10	92.5	*	−3.0	15.1
Si	30	60	1, 30	78.7		3.1	12.7
Si	30	60	1, 20	85.0	5.3	1.1	13.8
Si	30	60	11, 10	93.7		−3.2	15.2
Si	30	60	11, 20	85.8		1.0	13.9
Si	30	60	11, 30	81.0		2.4	13.1
Si	30	80	1, 20	80.3	5.4	2.8	13.0
Si	30	80	11, 10	90.7		−1.9	14.8
Si	30	80	11, 20	82.7		2.1	13.4
Si	30	80	11, 30	78.3		3.6	12.7
Si	40	60	1, 20	81.5	3.8	3.0	13.1
Si	40	60	11, 10	88.3		0.1	14.2
Si	40	60	11, 20	82.7		2.6	13.4
Si	40	60	11, 30	79.4		4.3	12.8

* These values are not included in the standard deviation calculation so as to be compatible.

of their readings regarding to the average soil water content in the root zone. In this analysis the readings of hypothetical soil moisture sensors located in several positions in the root zone were compared with the corresponding average soil water content in the root zone. The results obtained for the case of the $4\,\mathrm{l\,m^{-1}\,h^{-1}}$ discharge rate, the 30 mm irrigation depth, and the 80 cm drip line spacing for both soils studied and for both ET_p rates are presented in Table 4. As it can be clearly seen in this table, there is a considerable variability in the sensors' representativeness according to their positioning. In the same table it can be seen that sensors' representativeness may vary according to the soil hydraulic properties or the meteorological conditions. Additional numerical experiments data indicated that sensors' representativeness may also vary according to the irrigation system configuration. This is an important finding as it highlights the significance of proper soil moisture sensors positioning according to each application's requirements. This information could be proven valuable in irrigation management or in other applications requiring the

Table 4
Sensor positions representativeness: results obtained for the case of the $4\,\mathrm{l\,m^{-1}\,h^{-1}}$ discharge rate, the 30 mm irrigation depth, and the 80 cm drip line spacing for both studied soils and for both ET_p rates.

$ET_p = 8.4\,\mathrm{mm\,day^{-1}}$				$ET_p = 4.2\,\mathrm{mm\,day^{-1}}$			
Soil	Sensor position	Estimators		Soil	Sensor position	Estimators	
		RMSE	R^2			RMSE	R^2
Type	X cm, Z cm	$\mathrm{cm^3\,cm^{-3}}$	–	Type	X cm, Z cm	$\mathrm{cm^3\,cm^{-3}}$	–
LS	1, 10	0.027	−1.15	LS	1, 10	0.016	−0.15
LS	11, 10	0.033	−2.37	LS	11, 10	0.017	−0.29
LS	1, 20	0.014	0.42	LS	1, 20	0.009	0.64
LS	11, 20	0.016	0.20	LS	11, 20	0.008	0.74
LS	19, 20	0.028	−1.35	LS	19, 20	0.012	0.31
LS	1, 30	0.020	−0.26	LS	1, 30	0.011	0.48
LS	11,30	0.007	0.85	LS	11,30	0.006	0.82
LS	1,40	0.045	−5.20	LS	1,40	0.018	−0.54
LS	11,40	0.013	0.47	LS	11,40	0.011	0.42
Si	1, 10	0.033	−2.40	Si	1, 10	0.021	−3.63
Si	11, 10	0.037	−3.36	Si	11, 10	0.022	−4.03
Si	1, 20	0.011	0.68	Si	1, 20	0.007	0.54
Si	11, 20	0.012	0.53	Si	11, 20	0.005	0.69
Si	19, 20	0.021	−0.49	Si	19, 20	0.009	0.26
Si	1, 30	0.026	−1.01	Si	1, 30	0.015	−1.29
Si	11,30	0.012	0.61	Si	11,30	0.010	0.06
Si	1,40	0.038	−3.58	Si	1,40	0.018	−2.13
Si	11,40	0.016	0.23	Si	11,40	0.012	−0.38

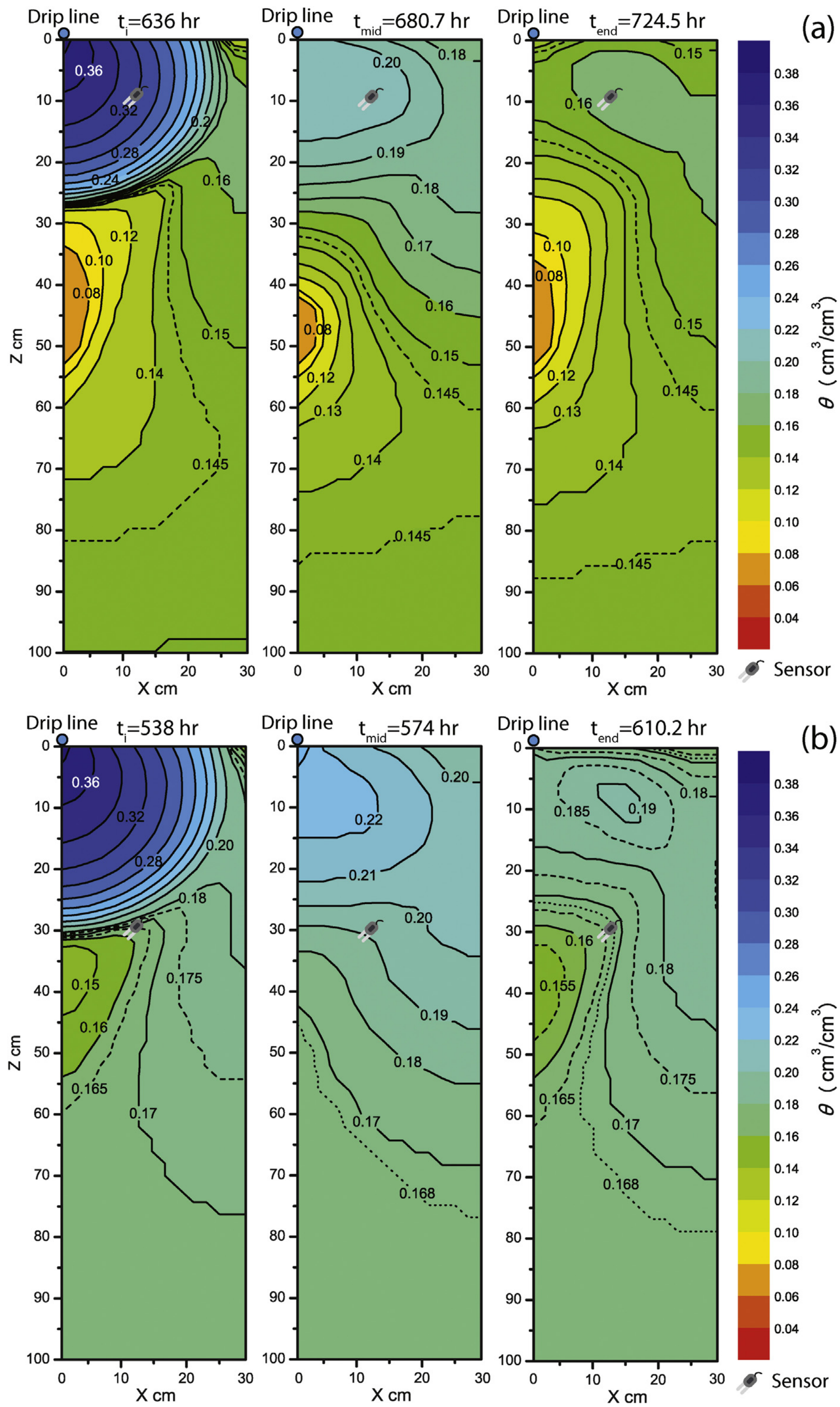

Fig. 2. Soil water content spatial distribution patterns for (a) a shallower and (b) a deeper sensor position for the case of the loamy sand soil, the 4 l m^{-1} h^{-1} discharge rate, the 30 mm irrigation depth, the 60 cm drip line spacing, and the high potential evapotranspiration rate of 8.4 mm day^{-1} in three representative times (last irrigation cycle, t_i = end of irrigation, t_{end} just before irrigation, t_{mid} in-between time).

monitoring of soil water content. The ability of computer models to serve as an efficient tool for the detailed investigation of sensors positioning schemes is a significant outcome as well.

A graphical representation of the above described comparison between the same hypothetical soil moisture sensors with the corresponding average soil water content in the root zone for the case of the 4 l m^{-1} h^{-1} discharge rate, the 30 mm irrigation depth, the 8.4 mm day^{-1} ET_p rate, and the 60 cm drip line spacing for both studied soils is provided in Fig. 3. As it can be observed, in the case of loamy sand soil the most representative position was 11 cm from the drip line and 30 cm below the soil surface (X = 11 cm, Z = 30 cm). As it can be also observed, the readings of shallower sensor positions are characterized by steep rises and drops as they are influenced more directly by the soil surface conditions (irrigation,

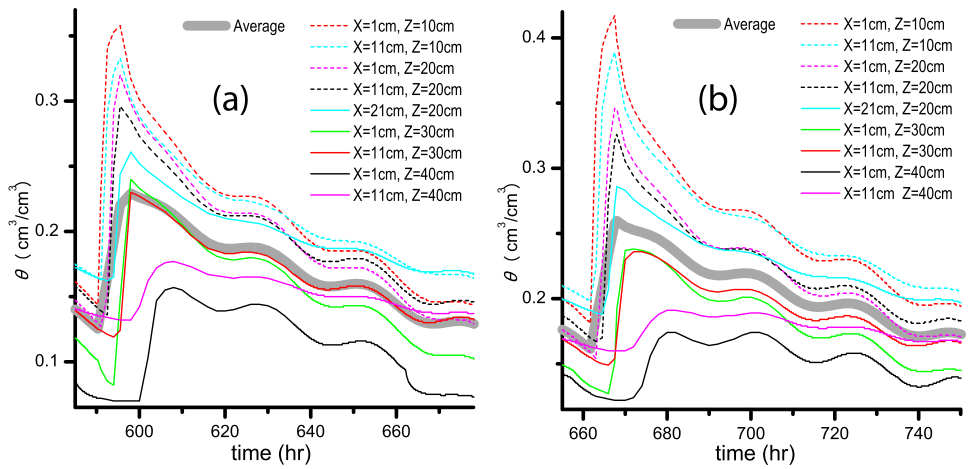

Fig. 3. Graphical representation of the comparison between the investigated hypothetical soil moisture sensors readings with the corresponding average soil water content in the root zone for the case of the 4 l m^{-1} h^{-1} discharge rate, the 30 mm irrigation depth, the 8.4 mm day^{-1} ET_p rate, and the 60 cm drip line spacing, for (a) the loamy sand soil, and (b) the silt soil (Only the last irrigation cycle is presented).

evapotranspiration), while conditions at the readings of deeper sensor positions are generally smoother. A similar behavior can be observed for the case of silt soil; however, in this case the most representative position was between the positions located 1 cm from the drip line and 20 cm below the soil surface and 11 cm from the drip line and 30 cm below the soil surface. Taking also into account the results for both soils presented in Table 4, it can be presumed that in conditions favoring slower water movement in the soil profile (e.g. finer soils or more uniform soil water content patterns) the most representative sensor positions are located nearer to the soil surface and to the plane of symmetry AE defined by the emitter (Fig. 1). A general observation considering the above results and the results regarding irrigation efficiency presented in the previous section is that in some cases the most representative sensor position is not necessarily linked to the best irrigation efficiency. As it was described in the previous section, deeper sensor positions are related to increased soil water content values at the lower part of the root zone. Therefore, in some cases that deep percolation is the most significant loss, the best irrigation efficiency is achieved for sensor positions a little higher than the most representative sensor position. On the other hand, irrigation efficiency is not the only decision parameter. As an example, crop stress as well as excessive irrigation may cause yield decreases relative to optimum irrigation amounts. Therefore, more representative sensor readings facilitate irrigation management as they provide more accurate information about the average conditions at the root zone. This observation highlights the complexity of the studied issue and the need for a detailed investigation for each particular application considering the specific conditions (e.g. soil, crop, irrigation system characteristics) and in relation to the applied irrigation management practices.

In practice a great variety of soil moisture sensor types with different characteristics (e.g. volume of influence, measurement range, accuracy) and configurations (e.g. number of sensors, placement) are used (Stieber and Shock, 1995; Coelho and Or, 1996; Schroder et al., 2005; Dukes et al., 2007; Kim et al., 2009; Zotarelli et al., 2011; Wang et al., 2012; Miller et al., 2014). However, the above results highlight the need for a more detailed study for each specific case. Numerical modelling can be proven an additional valuable tool in this effort.

3.3. Sensor accuracy

In order to investigate the sensors accuracy effect on the efficiency of soil moisture sensor based irrigation scheduling systems a set of numerical experiments was carried out assuming two levels of sensor errors as it was described in Section 2.3. The obtained results concerning the lower error level ($\pm$0.01 cm^3 cm^{-3}) indicated that there is a noticeable but generally limited effect. More specifically, the effect of this error level on irrigation efficiency ranged between 4.5% and 6.4% for the loamy sand soil and between 2.5% and 4.5% for the silt soil for the cases investigated. Similar results were obtained for the deep percolation and the evaporation losses.

By contrast, more significant effects were observed in the case of the higher error level ($\pm$0.03 cm^3 cm^{-3}). More specifically, in the numerical experiments where the sensors underestimated soil water content by 0.03 cm^3 cm^{-3} (i.e. the actual soil water contents were 0.03 cm^3 cm^{-3} higher than the sensor readings), irrigation efficiency decrease varied between 15.7% and 18.7% for the loamy sand soil and between 10.2% and 12.9% for the silt soil for the cases investigated. On the contrary, in the numerical experiments where the sensors overestimated soil water content by 0.03 cm^3 cm^{-3} (i.e. the actual soil water contents were 0.03 cm^3 cm^{-3} lower than the sensor readings) deep percolation and soil evaporation losses dropped due to the lower soil water content values in the soil profile with positive results on irrigation efficiency. However, in this case, crop stress increased considerably (actual evapotranspiration to potential evapotranspiration ratios dropped) having as a possible effect serious crop production losses. Likewise, excessive irrigation may as well cause yield decreases relative to optimum irrigation amounts (Locascio et al., 1989; Sezen et al., 2006; Ngouajio et al., 2007).

As an example, the soil water content spatial distribution patterns at the end of the final irrigation cycle for the case of the 4 l m^{-1} h^{-1} discharge rate, the 40 mm irrigation depth, the 60 cm drip line spacing, and the 8.4 mm day^{-1} ET_p rate, for both soils studied are presented in Fig. 4 supposing a systematic error of +0.02 cm^3 cm^{-3} (the actual soil water contents are 0.02 cm^3 cm^{-3} higher than the sensor readings) and −0.02 cm^3 cm^{-3} (the actual soil water contents are 0.02 cm^3 cm^{-3} lower than the sensor readings), which lies in-between the examined cases, in comparison to the standard case (no error).

It should be noted that error levels of about $\pm$0.03 cm^3 cm^{-3} are generally optimistic for many EM sensors using the factory calibration equations under normal conditions and in specific cases it may even be as high as $\pm$0.05 cm^3 cm^{-3} (Seyfried and Murdock, 2004; Kargas and Kerkides, 2008; Kizito et al., 2008; Parsons and Bandaranayake, 2008; Kargas and Soulis, 2012). Therefore, taking also into consideration the above results, it can be concluded that soil specific calibration of the EM sensors used in soil moisture

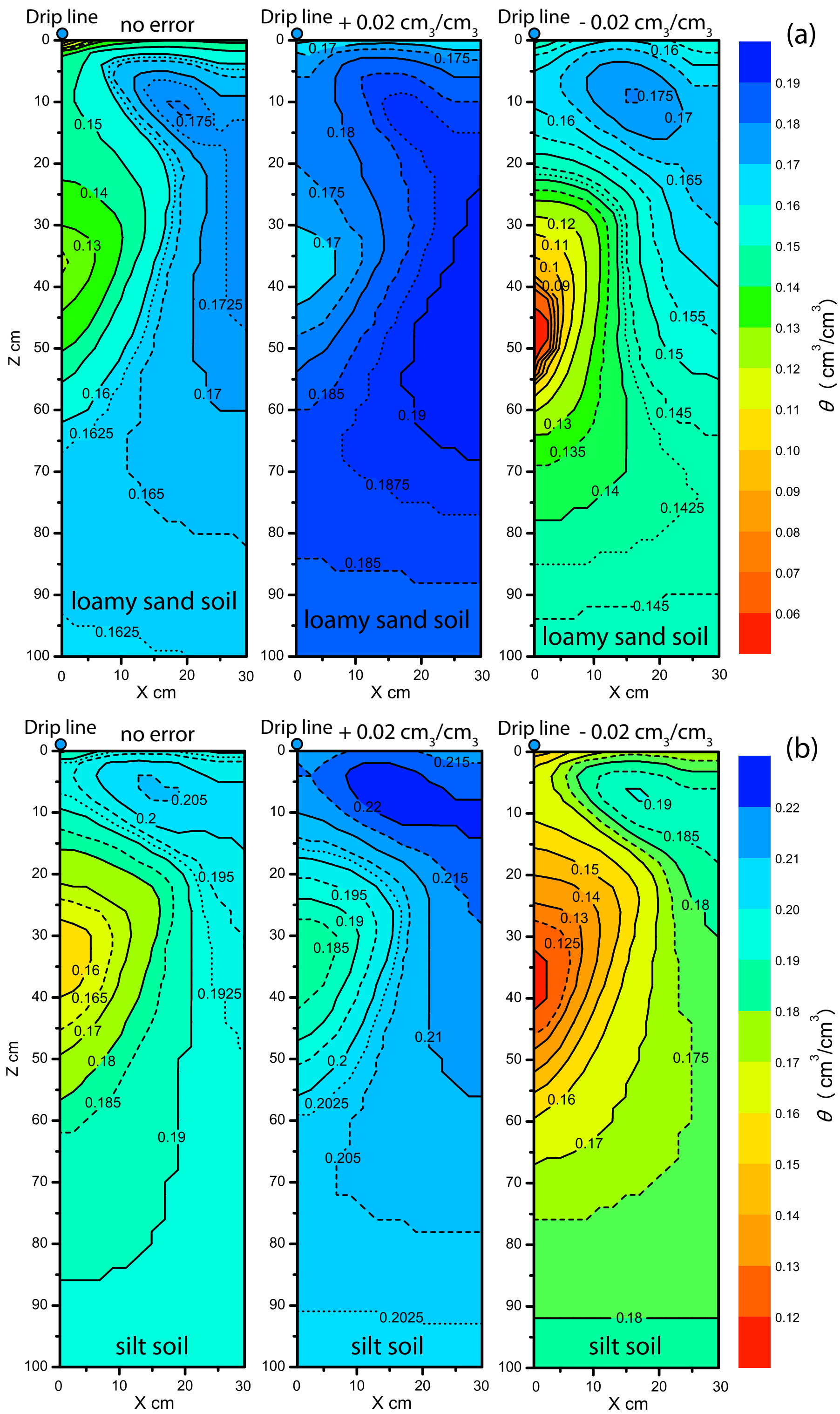

Fig. 4. Illustration of the soil water content spatial distribution patterns at the end of the final irrigation cycle for the case of the 4 l m^{-1} h^{-1} discharge rate, the 40 mm irrigation depth, the 60 cm drip line spacing, and the 8.4 mm day^{-1} ET_p rate, for (a) the loamy sand soil, and (b) the silt soil, supposing a systematic error of +0.02 cm^3 cm^{-3} and −0.02 cm^3 cm^{-3} in comparison to the standard case (no error).

based surface drip irrigation scheduling systems is a fundamental requirement.

4. Summary and conclusions

In this study the effect of soil moisture sensors positioning and accuracy on the performance of soil moisture based surface drip irrigation scheduling systems under various conditions (soil types, potential evapotranspiration rates, discharge rates, irrigation depths) was investigated using a mathematical model, which incorporates hysteresis in the soil water characteristic curve, evaporation from the soil surface, and water extraction by roots.

The use of a custom-made mathematical model allows the comparison of the obtained results with those of other similar models. Therefore, more reliable conclusions about important design and operation parameters of drip irrigation systems can be made. In addition, there is increased flexibility in the approach of the various irrigation problems due to the fact that the code of the model was developed in-house and therefore there is possibility for further development including the implementation of a system-dependent boundary condition into the mathematical model considering changing conditions in specific locations of the flow domain in order to be able to simulate soil moisture sensors based drip irrigation scheduling and to achieve the main goals of this study. The model was successfully validated against an existing analytical solution and the state of the art Hydrus 2D numerical model.

The effect of soil moisture sensors positioning was investigated by simulating the operation of an automated soil moisture based scheduling system for a coarser and a finer soil, for a high and a low potential evapotranspiration rate, for two discharge rates, and for two irrigation depths. Furthermore, the effect of sensors accuracy was investigated for the same combinations of conditions and irrigation system configurations for two sensors accuracy levels.

The results of the numerical experiments considering the effect of soil moisture sensors positioning on irrigation efficiency indicate that in many cases irrigation efficiency varies considerably among the different positions investigated. Furthermore, it was observed that in many cases, this variation was greater than the variation among the various irrigation system configurations. However, the observed irrigation efficiency variations for the investigated sensor positions noticeably differ for the irrigation system configurations and soil types studied. Generally, it was found that higher variations were related to conditions favoring the vertical movement of the wetting front through the soil profile.

The above conclusions were valid for both potential evapotranspiration rates studied. However, irrigation efficiencies were generally lower in the case of the low potential evapotranspiration rate due to higher deep percolation losses. Furthermore, noticeable irrigation efficiency variations among the investigated sensor positions were observed for both potential evapotranspiration rates, but the variability is lower in the case of the low potential evapotranspiration rate. The above results highlight the significance of the proper positioning of the soil moisture sensors driving automated irrigation scheduling systems. Besides the above mentioned irrigation efficiency variability among the various cases studied, it was observed that the most suitable position was 11 cm from the drip line and 10 cm below the soil surface. Generally, sensor positions 20 cm from the soil surface or deeper were related to noticeably lower irrigation efficiencies. However, it should be noted that when nearby sensor positions were examined, the observed differences were generally low and in some cases negligible.

When the influence of soil moisture sensors positioning on the representativeness of their readings regarding to the average soil water content in the root zone was considered, a clear effect was observed. It was also found that the effect of sensors positioning varies according to the soil hydraulic properties, the meteorological conditions, and the irrigation system configuration. These results further support the importance of proper soil moisture sensors positioning according to each application requirements (e.g. irrigation management or other applications requiring the monitoring of soil water content).

Finally, concerning the effect of sensors accuracy on the efficiency of soil moisture sensor based irrigation scheduling systems, it was found that while the lower error level ($\pm 0.01\,cm^3\,cm^{-3}$) had an obvious but generally limited effect (between 2.5% and 6.4%), the higher error level ($\pm 0.03\,cm^3\,cm^{-3}$) had a critical effect (between 10.2% and 18.7%). Considering that error levels of about $\pm 0.03\,cm^3\,cm^{-3}$ are generally optimistic for many EM sensors using the factory calibration equations, the need of soil specific calibration of the EM sensors used in soil moisture based surface drip irrigation scheduling systems is highlighted.

Concluding, the results of this study provide clear evidence that soil moisture sensors positioning and accuracy may considerably affect irrigation efficiency in soil moisture based drip irrigation scheduling systems. More importantly, it was found that sensor accuracy could be a critical factor for the successful implementation of soil moisture sensor based irrigation scheduling systems. It should be also noted that in this study the effects of sensor positioning and accuracy were separately investigated. Therefore, even in cases that the observed errors for each of these two factors were not important, the synergistic effect of both factors could be more important.

It was also found that a detailed study taking into account the characteristics of specific crops, irrigation systems, scheduling systems, as well as soil moisture sensors will provide a sound basis for improved irrigation scheduling. Lastly, the ability of computer models to serve as an efficient tool for the detailed investigation of sensors positioning schemes or other automated scheduling system characteristics is a significant outcome of this study as well.

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