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Optimum soil water content sensors placement for surface drip irrigation scheduling in layered soils

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ABSTRACT

Efficient irrigation management requires a sound information basis; therefore, various environmental measurements are currently used in irrigation scheduling. Among other technics, the recent progress in electromagnetic sensors technologies promoted the development of automated irrigation scheduling systems based on soil water content sensors with very promising results in terms of water savings. However, a key factor for the adequate performance of such systems is proper placement of soil moisture sensors. Up to now, sensor placement guidelines are fragmentary or empirically determined from site and crop specific experiments. This study aims to extend the findings of previous studies investigating the issue of proper positioning of water content sensors in drip irrigation scheduling systems in uniform soils for the case of layered soils. In this context the representativeness of soil water content sensors' readings and the existence of Time Stable Representative Positions (TSRP) are investigated using a specially developed mathematical model. The use of soil water content probes that are able to monitor soil water content at various depths is also evaluated. It was found that in contrast to the previous findings concerning uniform soils, in the case of layered soils it is not possible to precisely monitor the average soil water content temporal variation in the root zone using a single sensor; however, it is feasible to achieve this using a pair of sensors. Furthermore, common optimum positions for a pair of sensors providing representative soil water content readings independently from the prevailing conditions and the irrigation system configuration can be identified. It was also found that soil water content probes covering the average rooting depth and penetrating both soil layers are also able to provide representative soil water content readings during the whole duration of the irrigation cycle. The above results represent a further step towards the development of general guidelines for sensor placement in soil water content based surface drip irrigation scheduling systems.

1. Introduction

Among the most promising current strategies to increase irrigation water use efficiency is the improvement of irrigation management by applying the right amount of water to the crops at the right time. However, efficient irrigation management is challenging, because of the many factors that should be considered, for instance irrigation system characteristics, climate conditions, soil characteristics, crop species, etc. (Dabach et al., 2013). For this reason, several irrigation scheduling methods have been developed over the years such as soil water content or matric head monitoring, plant stress monitoring, water balance, computer models or charts (Lozoya et al., 2016; Cahn and Johnson, 2017). Nevertheless, irrespective of the method used, adequate irrigation management requires a sound information basis; therefore, various environmental measurements such as evapotranspiration, soil water content, or plant stress are used in modern irrigation scheduling (Nolz, 2016; Soulis and Elmaloglou, 2016; Nuñez-Olivieri et al., 2017). Recent progress in electromagnetic (EM) sensors technologies (e.g. low cost, ability to be easily automated, low maintenance needs), promoted the development of automated irrigation scheduling systems based on EM soil water content sensors (Blonquist et al., 2006; Kargas and Soulis, 2012, 2015; Paris et al., 2018). The use of similar systems may result in significant water savings. For example, savings as high as 60% are reported by Dukes et al. (2007) and Kim et al. (2009).

The key advantage of directly monitoring water content temporal variation in the root zone is the possibility to precisely manage agricultural water preventing waste of water and leaching of soluble chemicals. However, several important problems are still hampering the development of operational precision irrigation scheduling systems based on real time soil water content sensors data (Wang et al., 2012;

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Soulis et al., 2015; Dabach et al., 2016; Soulis and Elmaloglou, 2016). Soil water content patterns in the root zone are dynamic and influenced by many parameters such as soil hydraulic properties and their spatial heterogeneity, crop characteristics (e.g. rooting patterns), and irrigation system parameters. In the case of drip irrigation, the local application of irrigation water results in even higher spatial variability in the soil water content patterns formed under the emitters (Elmaloglou et al., 2013; Elmaloglou and Soulis, 2013).

Accordingly, proper soil moisture sensors placement is a key factor for the adequate performance of soil water content based drip irrigation scheduling systems (Coelho and Or, 1996; Dabach et al.,2013; Soulis et al., 2015; Soulis and Elmaloglou, 2016; Nolz et al., 2016). However, sensor placement guidelines are fragmentary or empirically determined from site and crop specific experiments (Coelho and Or, 1996; Wang et al., 2012; Soulis et al., 2015; Nolz et al., 2016). Specifically, Soulis et al. (2015) observed 20% reduction of irrigation efficiency in various scenarios of soil water content sensors placement. In a follow-up study, Soulis and Elmaloglou (2016) introduced the novel concept of Time Stable Representative Positions (TSRP) in irrigation scheduling systems based on soil water content sensors. TSRP are specific locations in the soil profile, where soil water content measurements can provide good estimates of the mean soil water content of the entire soil profile during the whole duration of the irrigation cycle. Accordingly, the identification of TSRPs for mean soil water content estimation may significantly facilitate efficient irrigation water management. The results of Soulis and Elmaloglou (2016) indicated that sensors' representativeness considerably varies according to the sensor position, the existing conditions (meteorological conditions, soil hydraulic properties, etc.), and the irrigation systems characteristics. However, in all the examined cases considering three homogenous soil profiles, at least one (or more) TSRP can be identified. Based on the obtained results, recommendations for the optimum sensor placement were provided. Based on Soulis and Elmaloglou (2016) results, Silva et al. (2018) investigated soil water sensors positioning for the various development stages of banana crop using experimental data.

This study aims to extend the findings of the previews studies of Soulis et al. (2015) and Soulis and Elmaloglou (2016) for the case of layered soils. In this context the representativeness of soil water content sensors' readings and the existence of Time Stable Representative Positions (TSRP) according to Soulis and Elmaloglou (2016) is investigated for two cases of layered soil profiles; specifically, the case that a coarse soil layer lays over a fine soil layer and vice versa. The use of soil water content probes that are able to monitor soil water content at various depths is also evaluated. To this end, several numerical experiments are carried out for various drip irrigation system characteristics, and under various conditions using an adapted version of the mathematical model presented by Elmaloglou and Soulis (2013), incorporating a system-dependent boundary condition that allows for the simulation of soil water content based irrigation scheduling systems. By meeting the above objectives, this study will make a further step towards the development of general guidelines for sensor placement in soil water content based irrigation scheduling systems.

2. Materials and methods

The first step of this analysis was to examine the existence of Time Stable Representative Positions (TSRP) that could provide accurate water content readings regarding to the average soil water content in the root zone during the whole duration of the irrigation cycle for each examined case. To this end, the evolution of soil water distribution patterns during a set of irrigation cycles was analyzed in detail and the readings of virtual soil water content sensors located in each of the examined positions was compared with the corresponding average soil water content in the root zone as it is explained in detail below. Following, in order to investigate other possible solutions providing sufficiently representative readings for the case of layered soils, the readings of all the possible combinations of pairs of virtual sensors located at all the examined positions were evaluated in a similar way. As a final step of this analysis, the case of soil water content probes that are able to monitor soil water content at various depths was also investigated. These probes are available at various lengths and have sensors fixed at specific intervals in order to provide a more comprehensive picture of soil water content variation according to the soil depth. The representativeness of the probe readings according to its distance from the line source was investigated by comparing the time series of the average values of the readings of all the sensors integrated in each probe with the time series of the average soil water content in the root zone during the whole duration of the irrigation cycle for each examined case.

2.1. The physical and the mathematical model

The dynamic evolution of soil water content patterns can be monitored experimentally, which is very difficult and case specific, or they can be calculated with simulation models. In most studies, soil water content temporal and spatial distribution during drip irrigation is described with Richards' equation, which is solved using analytical or, more frequently, numerical methods (Coelho and Or, 1996; Šimůnek et al., 1999, 2006; Elmaloglou and Diamantopoulos, 2008a, 2008b, 2009; Diamantopoulos and Elmaloglou, 2012; Dabach et al., 2013; Elmaloglou et al., 2013; Elmaloglou and Soulis, 2013; Friedman et al., 2016).

Accordingly, in this study, the soil moisture patterns formed in the studied layered soil profiles for various irrigation system configurations and conditions were computed using a specially adapted version of the mathematical model presented by Elmaloglou and Soulis (2013), which simulates soil water dynamics for surface drip irrigation in layered soils. This model considers hysteresis in the soil water retention curve and is able to simulate root water extraction as well as evaporation from the soil surface. Additionally, the adapted model implements a system-dependent boundary condition especially developed to allow the modification of the boundary conditions (i.e. initiate irrigation) according to the soil water content value at a specified zone or position of the simulated soil profile. In this way, it was made possible to simulate the operation of an automated drip irrigation scheduling system based on soil water content readings for several irrigation cycles.

The physical model and the corresponding computational domain of the numerical model are illustrated in Fig. 1a and b respectively. As can be seen, drip irrigation line sources are located along the crop rows at the soil surface. The layered soil profile consists of two layers. Two general cases are simulated, (a) fine soil above coarse soil and (b) coarse soil above fine soil. The soil layers thickness, the width of the line sources, the laterals spacing, and the spatial distribution of the active root zone, can be seen in the same figure. Due to the existence of plane flow symmetry in the simulation of line sources, the three-dimensional (3D) physical model (Fig. 1a) can be examined in one of the infinite vertical planes, which are perpendicular to the line sources, and therefor simplified in a two-dimensional problem (Fig. 1b).

The water flow equation that describes the physical problem is:

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial x}\left(K(H)\frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial z}\left(K(H)\frac{\partial H}{\partial z}\right) - \frac{\partial K(H)}{\partial z} - S(H, z, t) \qquad (1)$$

where x, z are the Cartesian coordinates (L) with z positive downwards, H is the pressure head (L), K is the unsaturated hydraulic conductivity (L T^{-1}), θ is the volumetric water content of the soil (L^3 L^{-3}), t is time since the beginning of flow (T), S is a distributed sink function representing the water uptake by the roots (L^3 L^{-3} T^{-1}).

The initial and boundary conditions of the mathematical model can be found in Elmaloglou and Soulis (2013).