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

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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-

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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