

Applications of Agro-Hydrological Sensors and Models for Sustainable Irrigation

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1. Introduction

In the last two decades, research on water resource monitoring and management has mainly been aimed at reducing irrigation water volume and energy consumption. At the same time, the effects of climate change and agricultural policies have also been major research interests. Therefore, there is an interest in focusing on the assessment of irrigation performance to improve water management and to increase the sustainability of irrigated agricultural territories.

Recent advances in optoelectronics, mechatronics, communication, and information technologies have allowed for the implementation of low cost, easy to operate, and virtual free maintenance of data acquisition systems to be used in soil-crop water status monitoring, as well as in smart irrigation systems. Agro-hydrological models have been recognized as an economic and simple tool to quantify crop water requirements in the decision-making processes for both farm and basin scales. They can simulate the mass and/or energy exchange processes in the soil-plant-atmosphere continuum under different spatial and temporal scales. In combination with new technologies such as sensors and remote sensing, these models are promising techniques that have accelerated spatial data collection substantially. Remote sensing and wireless sensor networks can cover scales from a single leaf to complete irrigation systems and can create data sets for large numbers of agricultural families and farming conditions.

Hence, the agro-hydrological sensor-model based approach must be properly chosen and calibrated to increase its use on larger commercial farms, even using remote sensing data.

This Special Issue consists of a collection of seven papers that cover a broad range of advances on modelling and partitioning evapotranspiration, modelling soil water and salt content, and modelling irrigation systems, with the aim to increase the sustainability of irrigation derived from the adoption of monitoring and optimum management practices.

2. Summary of This Special Issue

2.1. Evapotranspiration Modelling and Partitioning

Accurate determination of actual crop evapotranspiration ($ET_{c\ act}$) under field conditions is needed for the appropriate design and management of irrigation systems. The crop coefficient (K_c), which is required for computing $ET_{c\ act}$, is split into two coefficients to predict the specific effects of irrigation events on the crop coefficient. These coefficients are, namely, the basal crop coefficient (K_{cb}), which is related to crop transpiration, and the evaporation coefficient (K_e), which takes into account the soil evaporation. This approach is known as the dual crop coefficient procedure [1]. Although there are several methods for computing K_{cb} and K_e , the SIMDualKc model is the most suitable for perennial trees. Puig-Sirera et al. [2] successfully calibrated and validated the SIMDualKc model in an irrigated olive orchard using transpiration data acquired with sap-flow sensors. The authors



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obtained standard K_{cb} , but they observed that K_c was highly affected by rainfall variability. This paper also provided meaningful information about the evolution of the ratio of the evaporation vs. $ET_{c\text{act}}$ across the seasons. On the other hand, the authors also assessed the alternative A&P approach [3] for estimating K_{cb} and/or K_c by considering a density coefficient (K_d), which is based on the fraction of the ground shaded by plant canopy (f_c) and the crop height (h). The A&P approach gave reasonable results, but we believe it should be explored with more complete datasets. Both the SIMDualKc and A&P models should be further studied with the aim to develop a tool that could advise farmers to save water, enhance yields and fruit quality and, therefore, increase sustainability.

2.2. Soil Water and Salinity Modelling

The continuous development of sensors to monitor the soil water content allows for easier, quicker, and more accurate irrigation scheduling and management. The most common sensors usually measure some soil electromagnetic properties, which are closely related to the soil water content. This is the case for the Diviner 2000[®] capacitance probe, a frequency domain reflectometry (FDR) sensor that determines the apparent soil dielectric permittivity. However, each sensor requires a site-specific calibration since there are many factors that may affect its measurements. Provenzano et al. [4] suggested a new calibration equation to estimate the soil water content from readings of scaled frequency with the Diviner 2000[®] sensor. The model considered the changes of minimum bulk density with the gravimetric soil water content caused by the contraction process typical of shrinking/swelling clay soils. Thus, the new calibration equation estimates soil water content using the scaled frequency and the minimum bulk density as input parameters. The model was calibrated and successfully validated on repacked and undisturbed soil monoliths with different characteristics.

Subsurface drip irrigation (SDI) allows for more efficient water and nutrient application within the crop root zone over other irrigation systems when it is designed and installed properly and when the best management practices are adopted [5]. SDI is a promising alternative irrigation system for those crops with high water consumption, such as rice, in areas with limited water availability. However, the shallow rice roots are a challenge that should be addressed by selecting appropriate SDI dripline depths which allow suitable root wetting and reduced water losses by both deep drainage and evaporation. Arbat et al. [6] simulated and validated the soil water distribution for a rice crop with SDI using the HYDRUS-2D model [7], which is one of the most widely used software packages for simulating the movement of water, heat, and solutes under different soil and irrigation conditions. Then, they assessed the soil water content, deep drainage, and plant water extraction for two different dripline depths (0.15 m and 0.25 m), three soil textures (loam, sandy-loam, and silty-clay), and three irrigation frequencies (two irrigations per day, one daily irrigation, and one irrigation event every four days). They found that 0.15 m dripline depth coupled with one or two daily irrigation events maximized the water extraction by rice and reduced percolation under the studied conditions. In addition, the HYDRUS-2D model allowed for determining the most appropriate location of the soil water probes to efficiently manage the SDI in rice. This would avoid placing the soil water probes too close to the drip emitters, as there would be a risk to sub-irrigate the crop.

On the other hand, the HYDRUS-3D model simultaneously solves transport problems in the soil volume and provides more realistic calculations of the soil water distribution around the drip emitter. Domínguez-Niño et al. [8] configured, calibrated, and validated the HYDRUS-3D software to simulate three-dimensional soil water movement in a drip-irrigated apple orchard using measurements with neutron probes and tensiometers, which were located at different positions and depths over two different growing seasons. Their work is mainly focused on analyzing the effect of the estimation of soil hydraulic parameters (i.e., residual water content, saturated water content, saturated hydraulic conductivity, and the three van Genuchten shape parameters) on the performance of the model. The use of the Rosetta pedotransfer function software [9] yielded less accurate results than the site-specific

determination of the soil hydraulic parameters in the laboratory using the HYPROP and WP4C systems [10,11]. Moreover, empirical calibration of the n-van Genuchten shape parameter based on field measurements improved the fitness of simulations for both daily values at the seasonal scale, and hourly values over several days. Overall, HYDRUS-3D simulations adjusted better in the soil area affected by the emitter, which is important for achieving an efficient and sustainable irrigation management.

Besides water availability in the soil, crop yields depend on other factors such as soil salinity. Trying to cope with this issue, Wu et al. [12] used the Jensen [13] modified model that takes into account the effect of water and salinity on cotton yield at different growth stages. Then, they optimized both soil water and salinity thresholds for maximizing cotton yield, considering the water and salt balances in the root zone, the irrigation amount, and several boundary condition constraints. A total of 480 different scenarios were analyzed to obtain the threshold values of soil water and salinity at different growth stages as well as the salt accumulation amount during the irrigation season. They concluded that soil water and salinity must be specially controlled during the flowering-ball stage since it is the most critical for the cotton growth. Following the procedures highlighted in this paper, the threshold levels at the different cotton growth stages can be found for different production areas. Thus, the model would allow for determining those regions where actions for reducing salt content in the root zone should be carried out in order to assure sustainable agriculture.

2.3. Irrigation System Performance Modelling

Proper performance of drip irrigation systems is the key to achieving high water and energy use efficiencies. Sharu and Ab Razak [14] analyzed the hydraulic performance of a small greenhouse surface drip irrigation facility with pressure-compensating emitters. According to the field measurements carried out at four different pressures, water distribution uniformity was very good. The authors also successfully modeled both discharges and pressures of the drip irrigation system using the EPANET software [15]. The modelling of the drip irrigation system revealed that the operating pressure could be reduced by using a pump with 23% less power, therefore increasing both energy efficiency and farmers' economic profit. Any action that reduces energy consumption should be promoted in the context of high energy prices and with the adoption of renewable energy sources, such as photovoltaics, that currently can supply less energy than conventional electricity generation.

Pressurized sand media filters are commonly used in drip irrigation systems to avoid emitter clogging. The head losses produced in this system component increase pressure requirements and, consequently, energy consumption. In addition, the small open area available at the slots of the underdrains of these filters causes local flow conditions which may conflict with those accepted as valid for common pressure drop-flow rate correlations suggested for packed beds. Graciano-Uribe et al. [16] used computational fluid dynamics (CFD) for assessing five different pressure loss equations (i.e., Darcy, Kozeny-Carman, Darcy-Forchheimer, Ergun, and a power function to superficial velocity) in three porous media (microspheres and two sizes of silica sand) and two bed heights (117 mm and 137 mm) with a laboratory filter scaled from a commercial one. All of the equations predicted the total filter pressure drops within the experimental uncertainty range for superficial velocities below 38.3 m/h, but the Ergun equation performed the best above this velocity for silica sand. Simulations also revealed that up to 40% of the pressure drop was due to the sharp edge found at the beginning of the underdrain outlet pipe and the high velocity reached at this point. This highlights the relevance of correctly designing the water drainage to maximize the flow uniformity within the porous media. With the aim of helping in the filter design, an analytical model that includes this non-uniform flow region within the packed bed was developed, matching their results with those obtained by CFD.

3. Conclusions

This Special Issue included inspiring pieces of research where different sensors were used to calibrate and validate specific models that allow for computing evapotranspiration, soil water content, soil salinity, or the performance of the equipment of irrigation systems. The joint use of sensors and models provides for better knowledge of the main phenomena involved with irrigation. This is the basis for adopting accurate irrigation water management practices and, therefore, increasing both water and energy use efficiencies. Highly efficient and sustainable irrigation systems are mandatory for assuring the world's food security, especially considering growing constraints due to the climate change and also to geopolitical issues.

The continuous development of more reliable, robust, and economic sensors, as well as more user-friendly and accurate models and their integration through the Internet of Things (IoT), suggests magnificent advances that would allow for smarter and more sustainable irrigation. However, further research, and especially knowledge transfer to stakeholders and final users, would be needed to successfully achieve this goal around the world. This is the commitment behind all of the papers published in this Special Issue.

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