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Modelling soil water and maize growth dynamics influenced by shallow groundwater conditions in the Sorraia Valley region, Portugal

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ABSTRACT

The southern European region faces increasing pressure on fresh water resources due to economic development and climate change. Integrative modelling operational tools capable of simulating the full soil-water-atmosphere transfer system are needed to improve agricultural water management at the plot scale. In this study, the MOHID-Land model was used to simulate soil water dynamics and maize growth in a plot located in the Sorraia Valley region, southern Portugal, during the 2014 and 2015 growing seasons. The simulated crop parameters included the leaf area index, canopy height, aboveground biomass, and maize yields. A system-dependent boundary condition that triggered irrigation when a certain threshold pressure head (h_t) was reached in the root zone domain was also implemented in MOHID-Land. This boundary condition was used to optimize the irrigation scheduling practices in scenarios with different groundwater depths and h_t values. MOHID-Land successfully simulated soil water contents and crop growth during the monitored crop seasons, producing acceptable errors of the estimates after normalization ($0.061 \leq$ NRMSE ≤ 0.390), and relatively high modelling efficiencies ($0.11 \leq$ EF ≤ 0.94). Model simulations further showed the importance of capillary rise (CR) to the soil water balance, and confirmed the inefficient water use of current irrigation practices. The analyses of the irrigation scenarios showed an increase of CR from 17.7 to 66.9% of the actual evapotranspiration values after optimizing the irrigation scheduling practices, and the contribution of the shallow groundwater to the root zone. Water productivity also increased up to 12% when compared with the farmer's standard irrigation practices. The MOHID-Land model proved to be an effective tool for irrigation water management in the Sorraia Valley region.

1. Introduction

In southern Europe, increasing water demand and withdrawals have been building up the pressure on fresh water resources, with agriculture accounting for more than half of the total water abstraction, rising to more than 80% in some regions (EEA, 2009). The problem has been enhanced by climate change, with climate projections showing a marked increase of summer temperatures and meteorological droughts (Kovats et al., 2014), and by economic development, with multiple economic activities (agriculture, energy production, industry, domestic use, tourism and recreation) competing for limited water resources. There is thus an immediate need for improving agricultural water management and for developing new strategies and management options to address water use, performance, and productivity of agricultural systems (Todorovic et al., 2014).

Although irrigation plays a decisive role in increasing agricultural productivity and production stability in southern Europe, erroneous irrigation practices may also promote environmental degradation of an already ecologically sensitive region. Therefore, the European Commission has given top priority to the protection of natural resources in the context of the Europe 2020 Strategy, including the sustainability of water resources (European Commission, 2011, 2012). Following these policies, southern European countries have established specific policy instruments for maximizing the effectiveness and efficiency of irrigation water use. For the case of Portugal, the established policy instrument (Portaria n° 50/2015) mandates the adoption of pressurized irrigation systems, the periodic inspection of irrigation systems, the precise quantification of irrigation pulses, and the definition of improved irrigation schedules based on soil water content status and crop water needs, i.e., based on the computation of the soil water balance

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at the plot scale. In this context, it seems essential the development of modern irrigation support tools to help farmers comply with legislation requirements and improve irrigation water management, including integrative modelling operational tools capable of simulating the full soil-water-atmosphere transfer system. These new modelling tools would not only help farmers improve irrigation water use at the plot scale, but could also serve as support tools for evaluating the effectiveness of the policy instruments implemented.

The Sorraia Valley region, located in southern Portugal, is part of one of the most important agricultural areas in the country. Maize (*Zea mays* L.) is a leading crop in the region, occupying 25.6–44.9% of the total area irrigated during 2004–2014 (ARBVS, 2015). Water scarcity and inappropriate land management practices have been some of the most critical constraints to the sustainable production of maize and other agricultural crops. Over the last decade, agronomical research has focused on studying soil water flow and solute transport processes in the region to improve irrigation water management and optimize water use and water productivity. Some of the most relevant studies included the relationships between maize production and irrigation strategies (Paredes et al., 2014a), evaluation of economic impacts of various irrigation management strategies (Paredes et al., 2014b), and the assessment of nutrient (Cameira et al., 2003, 2007) and pesticide (Azevedo et al., 2000) fate while considering farmers' agricultural practices. However, while these studies included detailed field experiments and numerical modelling, and contributed in identifying the best management practices to be performed at the plot scale, most have only addressed part of the soil-water-atmosphere transfer system (mainly the root water uptake process) or included models that are currently not suitable to run as operational tools.

MOHID-Land is a physically-based mechanistic model developed at the Instituto Superior Técnico (Trancoso et al., 2009; Brito et al., 2015; Simionesei et al., 2016a), capable of simulating the full soil-water-atmosphere transfer system at the plot scale, including root water uptake, the influence of groundwater on the soil water balance, and crop development. Although conceptually different, MOHID-Land has embedded some of the approaches used by state-of-the-art models, such the HYDRUS software package (Šimůnek et al., 2016) and the SWAP model (Kroes and van Dam, 2003), for describing physical processes at the plot scale. Recently, these reference models have been coupled with MODFLOW (Harbaugh et al., 2000) and are today capable of combining processes in the vadose zone and groundwater (Twarakavi et al., 2008; Xu et al., 2012). They have also been coupled with the EPIC model (Williams et al., 1989; Neitsch et al., 2011) and can further simulate plant growth under different soil moisture, salinity, and temperature conditions (Xu et al., 2013, 2015; Han et al., 2015; Wang et al., 2015). Lately, the MOHID-Land model has been integrated in the FIGARO decision support system (DSS) for supporting irrigation water management in the Sorraia Valley region at the plot scale (Simionesei et al., 2016b). The FIGARO DSS is a holistic and structured irrigation platform that offers farmers flexible, crop-tailored irrigation scheduling protocols for their specific fields. The FIGARO DSS is structured for data acquisition from monitoring devices (soil moisture sensors) and includes different forecasting meteorological and hydrological tools, enabling full decision support for end users at the plot scale (Linker et al., 2016). Nonetheless, a proper calibration/validation of the MOHID-Land model and the processes simulated at the plot scale were still missing, as well as the necessary developments for converting this model into an operational tool capable of optimizing irrigation scheduling and supporting irrigation water management practices.

Different soil-water balance models (Raes, 2002; Rosa et al., 2012; Vanuytrecht et al., 2014) are normally used for computing the irrigation scheduling for different crops, soils, and climate conditions. These models usually consider the soil domain simplistically, often defining it based on the notions of field capacity and the wilting point, with soil-water dynamics and irrigation scheduling being computed based on the soil-water storage capacity and atmospheric demands, as proposed by Allen et al. (1998), while other outputs such as percolation and capillary rise are defined using empirical or semi-empirical equations. Mechanistic models such as MOHID-Land are less commonly used for computing the irrigation scheduling as they require many parameters, including a full description of the soil hydraulic properties (i.e. the soil water retention and the unsaturated hydraulic conductivity curves), which measurements are complex and, thus, are not easily available for many regions of the world. Dabach et al. (2013) constitutes here a rare reference as these authors upgraded the HYDRUS-1D model for computing irrigation scheduling by considering soil pressure heads, target thresholds, and crop evapotranspiration. Nonetheless, mechanistic models are usually considered to provide superior predictions of soil water contents than simpler soil water balance models, offering also larger capabilities in terms of irrigation water management. Hence, these models are today used, for example, for optimizing water saving practices in arid regions with shallow groundwater conditions (Xu et al., 2013; Ren et al., 2016); improving irrigation management with poor quality waters (Ramos et al., 2011; Raij et al., 2016); and quantifying the fate of agro-chemical contaminants in different ecosystems (Ramos et al., 2012; Phogat et al., 2014).

The main objective of this study was to use the MOHID-Land model for simulating soil-water flow and crop development in a plot with maize located in the Sorraia Valley region. The specific objectives were: (i) to predict soil water contents and fluxes, and the evolution of different crop growth parameters, including the leaf area index, canopy height, biomass, and yield during the 2014 and 2015 maize growing seasons; (ii) to compute the soil water balance while considering the effect of the groundwater table on soil water and maize growth dynamics; (iii) to implement a system-dependent boundary condition for automatically triggering irrigation when a certain threshold was reached at the root zone; and (iv) to optimize ' irrigation scheduling practices by analysing different groundwater levels and threshold scenarios. The modelling approach will help us improve the model performance in the FIGARO DSS, and consequently irrigation water management practices at the plot scale, in the Sorraia Valley region.

2. Material and methods

2.1. Field experiment

This study was conducted at Herdade do Zambujeiro, located near Barrosa, Sorraia Valley, southern Portugal (38°58′0.97″N, 8°44′46.63″W), during the 2014 and 2015 growing seasons. The climate in the region is semi-arid to dry sub-humid, with hot dry summers and mild winters with irregular rainfall. Hourly weather data used in this study was taken from a meteorological station located nearby and included the average temperature (°C), wind speed ($m\,s^{-1}$), relative humidity (%), global solar radiation ($W\,m^{-2}$), and precipitation (mm). These data were then used to determine the hourly reference evapotranspiration (ET_0, mm d^{-1}) using the FAO Penman-Monteith method (Allen et al., 1998) (Fig. 1).

The soil was classified as Haplic Fluvisol (IUSS Working Group, 2014). The soil's main physical and chemical properties are presented in Table 1. The particle size distribution was obtained using the pipette method for particles having diameters <2 μm (clay fraction) and between 2 and 20 μm (silt), and by sieving for particles between 20 and 200 μm (fine sand) and between 200 and 2000 μm (coarse sand). These textural classes follow the