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Modeling irrigation in a farm in Portugal

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SUMMARY – Irrigation is a major environmental problem due to water consumption and pollution. Therefore, it is desirable to use the minimum amount of irrigation water necessary to keep crops at their optimum producing level. Here, a model that simulates soil water balance, using several factors including crop and soil characteristics and meteorological data is presented. The soil water balance is modelled, for a farm, for June 2001. For instance, maize requires 50 mm of water every 13 days and wheat requires 22 mm of water every 5 days. A sensitivity analysis to irrigation frequency is also performed showing that a higher frequency represents, for example, an 11% decrease in water consumption for wheat in June 2001. A comparison between irrigation needs in different types of soil shows the potential of this model as a tool to help planning farm land use.

Key words: Irrigation modelling, soil water balance, evapotranspiration, irrigation frequency.

RÉSUMÉ – *"Modélisation de l'irrigation dans une ferme au Portugal". L'irrigation est un problème environnemental dû à la dégradation et au gaspillage de l'eau. Par conséquence, il est désirable d'utiliser le minimum d'eau qui maintienne le niveau de production optimal des cultures. Ici est présenté un modèle qui calcule le bilan d'eau du sol, en utilisant les caractéristiques du sol et de la culture et des données météorologiques. Le modèle est appliqué à une ferme, en juin 2001. Par exemple, pour le maïs, il faut une moyenne de 50 mm d'eau tous les 13 jours et pour le blé, 22 mm tous les 5 jours. La sensibilité au regard de la fréquence d'irrigation est analysée. Une fréquence plus haute d'irrigation représente, par exemple, une diminution de 11% de l'eau pour le blé. La comparaison entre les besoins hydriques pour deux types de sol démontre le potentiel de ce modèle pour la planification de l'usage du sol.*

Mots-clés : Modèle d'irrigation, bilan hydrique du sol, évapotranspiration, periodicité d'irrigation.

Introduction

We have built a model to simulate the soil water balance that will be used by farmers in a Portuguese agricultural project named "Integrated Management of Soil and Water for the Lezíria Grande in Vila Franca de Xira". The model uses weather data recorded by meteorological stations located on the farms and soil and crop characteristics. Farmers will use this model to visualise soil water balance, for each of their crops, allowing them to adjust the irrigation schedule and amounts. In this paper we present the model and some preliminary results obtained for a farm, Quinta da França, for June 2001.

Model

The model has four main components: (i) calculation of soil water deficit; (ii) calculation of daily reference potential evapotranspiration using observational data; (iii) calculation of real crop evapotranspiration, taking into account crop cover and soil water content; and (iv) scheduling the timing and amount of the next irrigation. Each of these components is described briefly below.

The soil water content, θ (volume of water per volume of soil), is distributed uniformly through the soil thickness because hydrologic properties are considered constant with depth. The field capacity, θ_{FC}, is the amount of water that a well-drained soil should hold against gravitational forces. Chen and Dudhia (2001) state that this is 75% of the maximum capacity and present values for maximum capacity for each soil type.

The root zone soil water deficit, D_r, is the deficit of soil water with respect to field capacity. If soil water content in the root zone exceeds or equals the field capacity, D_r becomes zero; when soil water decreases due to evapotranspiration, the root zone soil water content decreases and D_r, becomes positive.

The root zone soil water deficit at hour i, $D_{r,i}$, is obtained through the soil water balance, $D_{r,i} = D_{r,i\text{-}1} - (Pp+I)_i + ET_{c,i}$, where i-1 stands for the previous hour, Pp_i is the total accumulated precipitation, I_i is the total irrigation amount that infiltrates the soil and $ET_{c,i}$ is the total crop evapotranspiration. Percolation and runoff are considered negligible until the soil reaches or surpasses its field capacity, which may occur following heavy rain or irrigation; whenever this happens, it is assumed that the soil water content becomes equal to θ_{FC} almost immediately. The amount of water transported upwards by capillarity from the saturation zone to the root zone is considered to be negligible because the water table is considered to be more than one meter deeper than the bottom of the root zone.

Evapotranspiration, $ET_{c,i}$, values are calculated using $ET_{c,i} = K_c\, K_s\, ET_{o,i}$, where K_c and K_s are dimensionless factors respectively called crop coefficient and water stress coefficient. The variable $ET_{o,i}$ represents the potential evapotranspiration for a given crop at instant i and is calculated using the Penman-Monteith equation (Monteith and Unsworth, 1990). The weather data needed (wind, solar radiation, temperature and humidity) to compute $ET_{o,i}$ is obtained from the meteorological station.

In general, for annual crops, the crop factor, K_c, begins with relatively small values at germination, increases with the intense development phase and attains the maximum value at the full development stage, maintains a high value during the maturation period and finally decreases (Allen *et al.*, 1998). We calculate K_c using two alternative methods. The first method is to use the values for K_c presented by (Allen *et al.*, 1998) for the different crops, according to the phase of development. The second method takes into account the irrigation frequency, by taking $K_c = K_{cb} + K_e$ (Allen *et al.*, 1998), where the basal crop coefficient, K_{cb}, is plant transpiration and K_e is the evaporation from the soil surface. Values for K_{cb} are listed for different crops in Allen *et al.* (1998). The parameter K_e is given by $K_e = K_r\,(K_{c\max} - K_{cb})$, where K_r is the dimensionless evaporation reduction coefficient, dependent on the cumulative amount of water evaporated from the topsoil. This value has its maximum value following irrigation or rain, and decreases with the dryness of the soil (Allen *et al.*, 1998). K_c can never exceed a maximum value, $K_{c\max}$, determined by the energy available for evapotranspiration at the soil surface. Both methods of computing K_c were used and compared for three different crops (wheat, maize and irrigated pasture), in two different kinds of soil (loamy sand and clay loam).

We determine the stress coefficient, K_s, by $K_s = TAW - D_{r,i} / TAW - RAW$, where TAW is the total available water and RAW is the readily available water. TAW is the amount of water that a crop can extract from its root zone, $TAW = (\theta_{FC} - \theta_{WP})\, Z_{root}$, where θ_{WP} is the wilting point, i.e. the threshold below which the crops are no longer able to extract water, and Z_{root} is the maximum rooting depth (a function of the development stage). RAW is the fraction of total available water that a crop can extract from the root zone without suffering water stress (Allen *et al.*, 1998).

Summing up, if the root zone soil water deficit, D_r, is less than RAW, evapotranspiration is equal to the product of K_c times ET_o, but if D_r exceeds RAW, evapotranspiration, ET_c, is reduced and must be computed taking into account K_s. If the water content reaches its minimum value, θ_{WP}, no water is left for evapotranspiration in the root zone, K_s becomes zero, and D_r reaches its maximum value, TAW. Hence, $0 < D_{r,i} < TAW$.

The estimation of the stress coefficient, K_s, requires a water balance computation, $D_{r,i}$, for the root zone. But because K_s itself is needed to determine the water balance, K_s is calculated using the soil water deficit of the previous hour because the hourly change in soil moisture is relatively small.

Initial conditions for the soil water deficit are either derived from a soil water content measurement or are assumed to be zero if following heavy rain or irrigation.The timing and the amount of irrigation is determined according to a maximum allowable soil water deficit. The choice of maximum allowable deficit is left to the operator.

Results and discussion

This model is applied to Quinta da França, a farm located in central Portugal, in June 2001. Irrigation needs are modelled considering that the soil is at field capacity at midnight of the first day and that crops are irrigated at midnight when the soil water deficit is higher than the *RAW*. The crops considered are wheat, maize and irrigated pasture, on loamy sand and clay loam soils.

Irrigation needs modelled with an average crop coefficient, K_c

The crop coefficients for each crop were obtained from Allen *et al.* (1998) and take into account the development phase in June (with maize in its initial development and wheat in its final development phase). The amount of irrigation water is computed so as to bring the soil water content to its field capacity minus 25% of *RAW*.

In Fig. 1 we see that maize is irrigated every 13 to 15 days with approx. 50 mm, wheat every 5 or 6 days with approx. 22 mm and irrigated pasture every 4 to 5 days with approx. 24 mm. The same crops in clay loam soils need more water more frequently, with irrigated pastures presenting the most striking example with approx. 32 mm every 3 days.

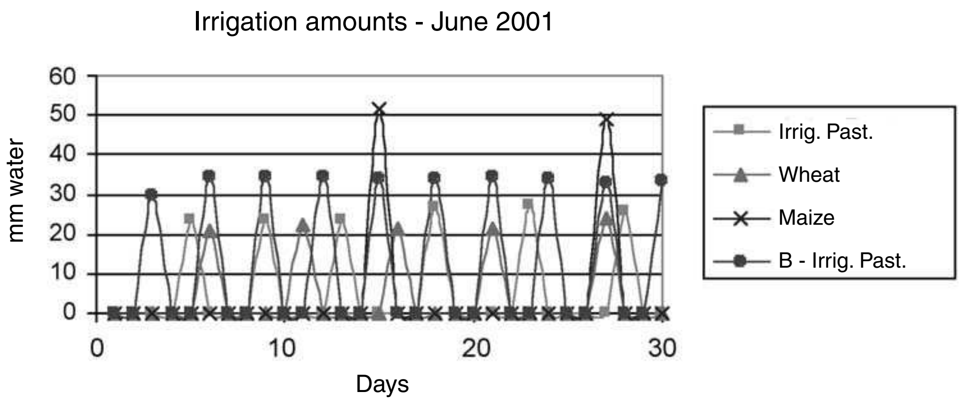

Fig. 1. Irrigation needs in mm for maize, wheat and irrigated pasture on loamy sand soils and irrigated pasture on clay loam soils (B).

Irrigation needs modelled with a crop coefficient modelled as $K_c = K_{cb} + K_e$

To analyse the model's sensitivity to irrigation frequency, we considered, for each of the previous crops, two different decision rules to determine the irrigation schedule. In the first rule, we consider that the amount of water is computed to bring the soil water content to its field capacity minus 25% of *RAW* (Fig. 2) and in the second case to its field capacity minus 50% of *RAW* (Fig. 3).

Comparing both figures we conclude that the second rule implies a higher frequency of irrigation, less amount of water in each irrigation event and a lower total amount of water. The irrigation water saved was approx. 5% for irrigation pasture and maize and 11.5% for wheat. However, if the model took into account the water evaporated during the irrigation process, these percentages would be lower.

Conclusions

We developed a model based on the guidelines provided by Allen *et al.* (1998) and used it to simulate the irrigation schedule and amount. We used two approaches for the calculation of the crop coefficient, also based on Allen *et al.* (1998). The most sophisticated approach makes this coefficient dependent on soil moisture and therefore is a function of irrigation frequency. This approach is

Fig. 2. Irrigation needs in mm for maize, wheat and irrigated pasture on loamy sand soils and irrigated pasture on clay loam soils (B). Irrigation brings soil content to its field capacity minus 25% of *RAW*.

Fig. 3. Irrigation needs in mm for maize, wheat and irrigated pasture on loamy sand soils and irrigated pasture on clay loam soils (B). Irrigation brings soil content to its field capacity minus 50% of *RAW*.

justified because lower amounts of irrigation water (higher frequencies) showed a significant decrease in water consumption. Simulations performed for different crops are in agreement with the irrigation practice on the farm. Simulations with two types of soil revealed the importance of this tool as an aid to plan land use.

As a future development we also want to improve this management tool by using meteorological forecast data to forecast the evolution of soil water balance for the following days. The model used will be a mesoscale meteorological model, MM5, developed by Grell *et al.* (1995) and implemented for Portugal, in Instituto Superior Técnico, with a 9-km resolution grid and with 3 day-forecasts and available at http://meteo.ist.utl.pt. This model is already validated for Portugal by Sousa (2003) and Palma *et al.* (pers. comm.), with good results.

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