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A distributed parameters model for soil water content: Spatial and temporal variability analysis

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ABSTRACT

Soil water content is the main limiting factor for plant development under arid or semi-arid climates. Furthermore, it is a key factor in the physical, chemical and biological processes that occur in the soil-plant-atmosphere system; acting as a vector between these components. A distributed parameters model is proposed in order to describe the spatiotemporal variability of soil water content, linking the soil water content with the system inputs, such as rain or irrigation water, and the system outputs: evaporation, transpiration and percolation losses. Adding the lateral exchanges and the surface runoff makes it possible to take into account the terrain orography and tessellation. An experimental plot in SW Spain was used, where Soil Water Content was monitored with frequency-domain reflectometry sensors in several points, whereas the plot was divided into rectangular sectors. The rainfall was measured by a nearby agro-climatic station. A simulation environment was developed, using it to identify the model terms with experimental measurements and run other simulations for different climatic conditions.

1. Introduction

A correct measurement of the Soil Water Content (SWC) is critical for the water and energy balance estimation. SWC is also the main communication vector between the elements in the complete Soil-Plant-Atmosphere system, therefore it is necessary to understand the biological and chemical processes in the aforementioned process. It determines how much of the water supply (either as rainfall or as irrigation) infiltrates, which part is surface-flooded or lost by runoff and deep percolation; also how it will be returned to the atmosphere, through evaporation and transpiration, thereby affecting the energy distribution at the surface.

In arid or demi-arid climates, SWC is the first limiting factor for the vegetal growth and the biomass production. Therefore, it can be considered as the nexus of the global water, energy and carbon cycles that govern the interaction between climate, soil and vegetation. That is the founding stone of the eco-hydrology, developed by Rodriguez-Iturbe (2000) parting from the seminal works of Eagleson (1978, 2002): a framework for the integrated analysis of ecological and geophysical processes that determine the water balance in an area.

The first works about SWC modelling were developed by Thornthwaite (1948) and Thornthwaite and Mather (1955), evidencing the influence of the SW behavior over the infiltration, evapotranspiration and recharge through non-linear interactions. Taking into account the occurrence and the total volume of rainfall as stochastic processes, the equation of water balance becomes a stochastic differential equation in S, where S is the Soil Water Content (SWC). For that differential equation, Rodriguez-Iturbe (2000) proposed an analytical solution for different surface flow conditions, thus allowing the study of the dynamic interaction between climate, soil and vegetation under different circumstances. The cases of limited water availability, where SWC conditions the vegetation distribution, are of special interest (Rodriguez-Iturbe et al., 2001; Porporato et al., 2002).

Recent studies on the global hydrological cycle acceleration (Gedney et al., 2006), on continental-scale global runoff patterns (Milly et al., 2005) and on feedback processes on the atmosphere (Koster et al., 2004), renew the interest on the SWC dynamic and its influence over the Soil-Plant-Atmosphere interaction at different scales. The U.S. Global Change Research Program (Anthes and Moore, 2007) describes the SWC as the “most important parameter in the interaction between key components in hydrological and bio-geochemical processes”. In that line, there is no lack of recent studies (Flint et al., 2013; Cuthbert et al., 2013) trying to characterize the hydrological models.

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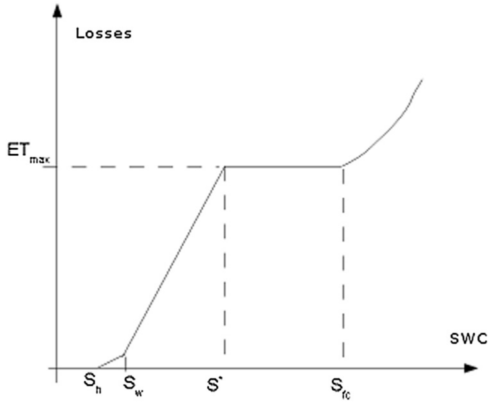

Fig. 1. Losses effect depending on SWC level.

As reflected by Kizito et al. (2008), the accurate measurement of SWC is critical for the water and energy balances estimation, as much as to understand the biological and chemical processes in the soil-plant system. A review of sensing procedures can be found in Hopmans and Simunek (1999), including geophysical and remote probing techniques. For the experiments performed, a Time-Domain Reflectometry electromagnetic probe (Robinson et al., 2003) was used.

In this paper, a distributed parameters model for the soil water content behavior in the Soil-Plant-Atmosphere system is proposed. After the model parameter identification, several simulations were conducted to evaluate its performance under different climatic conditions. The objective is to set a different approach to the SWC modelling problem, making possible simulations under different environmental and soil conditions with a simple yet comprehensive model, thus allowing the analysis both in the spatial and the temporal coordinates. With a proven model, new techniques for management and control of the agricultural water use can be designed.

The remainder of the paper is organized as follows: a description of the proposed model and a simulator are exposed in Section 2. In Section 3, several results from identification, real data and simulation with stochastic input are presented. Finally, the major conclusions to be drawn are given in Section 4.

2. Matherial and methods

2.1. Model

This model was developed parting from a “leaky bucket” type model, as proposed by Rodríguez-Iturbe et al. (1999). It is a continuity equation (Eq. (1) where a water balance is established, stating that the soil water content has a lineal variation with the addition of several inputs and losses.

$$nZ_r\frac{dS(t)}{dt} = I(S,t) - L(S) - T(S) - E(S) \tag{1}$$

In this equation, n is the soil porosity, Z_r is the root zone depth, S the volumetric soil water content, I the water infiltration (rainfall and, if existing, irrigation, minus crop interception), L(S) the percolation losses, *T(S)* the plant transpiration and *E(S)* the evaporation losses. Fig. 1 shows the distribution of such losses (L, T and E) depending on S.

Five regions can be observed: in the first region, $S < S_h$, soil water content is so low that the soil is able to retain it completely, therefore negating evapotranspiration; in the second (very small) one, $S_h < S < S_w$, there is evaporation but not enough water content for the plant to transpirate; in the third one, $S < S < S^*$, both evaporation and transpiration reduce the SWC in the root zone with a linear dynamic; in the fourth region, $S^* < S < S_{fc}$, the evapotranspiration has reached its saturation bound, whereas percolation still has no discernible effect; and finally, in the fifth region, $S > S_{fc}$, percolation losses rapidly become the dominant factor in the dynamic.

The rainfall is modelled as a stochastic process, with the storm occurrence being modelled as a Poisson discrete random variable and its intensity (and therefore, the quantity of rainfall added to the system) as an exponential continuous random variable. Subtracting the interception due to vegetation and the non-saturated volume of the root zone, the infiltration results as shown in Eq. (2).

$$I(S,t) = \min\left[\mathrm{P}(\mathrm{t_i}), \mathrm{nZ_r}\left(1 - \mathrm{S}\left(\mathrm{t}_i^-\right)\right)\right] \tag{2}$$

Where P(t_i) are the precipitations volume (mm) in a time instant and t_i^- is the immediately earlier time instant.

Eqs. (3)–(5) show the values for the Evaporation (E), Transpiration (T) and percolation losses (L) as a function of the SWC.

$$E(S) = \begin{cases} 0, S \le S_h \\ E_{\max}\dfrac{S - S_h}{S^* - S_h}, S_h < S \le S^* \\ E_{\max}, S > S^* \end{cases} \tag{3}$$

$$T(S) = \begin{cases} 0, S \le S_w \\ T_{\max}\dfrac{S - S_w}{S^* - S_w}, S_w < S \le S^* \\ T_{\max}, S > S^* \end{cases} \tag{4}$$

$$L(S) = K_{sat}\frac{\exp\left[\beta\left(\mathrm{S} - \mathrm{S_{fc}}\right)\right] - 1}{\exp\left[\beta\left(1 - \mathrm{S_{fc}}\right)\right] - 1} \tag{5}$$

Where S^* is the saturation bound, where the plant cannot transpirate any further; S_w is the lower bound (residual soil moisture); S_h is the lower bound for evaporation; S_{fc} is the field capacity, the minimum point for the percolation to be a relevant factor; and $E_{\max}$ and $T_{\max}$ represent the maximum evaporation and transpiration rates. K_{sat} is the saturated hydraulic conductivity and β a soil parameter.

This model is commonly used at the point scale. The modelling of precipitation is as a stochastic process makes it possible to predict the long-term behaviour of the system variables (namely the SWC), typically one year. There is nothing in the model, however, that makes it unfit to be extended from the point to the field scale.

The distributed parameter model proposed was obtained by dividing the plot into rectangular sectors. Eq. (1) with its inputs and outputs was applied afterwards for each of them, adding the lateral flow effect: water will flow, guided by gravity, from the higher cells to the lower ones. To consider this, an additional variable was added to the system: sector mean altitude, $\mathrm{h_i}$. That made possible to obtain the inclination angle for two adjacent sectors (i,j), as shown in Eq. (6).

$$\theta_{ij} = \tan^{-1}(l)/\left(h_i - h_j\right) \tag{6}$$

Where l is the distance between the centers of both sectors. With these angles, and assuming a rectangular sector with a depth Z_r, it is possible to define a losses flow in three components: a vertical component (z) and two horizontal components (x and y).

Under these conditions, for a $l_x \times l_y$ cell, lateral flows (one per adjacent cell) can be obtained as shown in Eq. (7).

$$L_i = \begin{cases} \dfrac{L}{4}\dfrac{Z_r}{l_i}\sin\left(\theta_i\right), \mathrm{if}\theta_i > 0 \\ 0, if\theta_i \le 0 \end{cases} \tag{7}$$

At the same time, percolation losses can be obtained as shown in Eq. (8).

$$L_z = L - L_{x_1} - L_{x_2} - L_{y_1} - L_{y_2} \tag{8}$$

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