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Infiltration Processes and Soil Moisture Dynamics

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ABSTRACT: The description of soil moisture dynamics is a challenging problem for the hydrological community, as it is governed by complex interactions between climate, soil and vegetation. Recent research has achieved significant advances in the description of temporal dynamics of soil water balance through the use of a stochastic differential equation proposed by Laio *et al.* (2001). The assumptions of this model simplify the mathematical form of the soil water loss functions and the infiltration process. In this model, runoff occurs only for saturation excess that represents an excellent mathematical approximation producing a simple expression for the probability density function of the infiltration, but does not account for limited infiltration capacity of soil. In the present work, such a characteristic has been incorporated in the soil moisture model with the aim to understand the consequences of such hypothesis on the soil water balance dynamics. The comparison between the two models (the original version and the modified one) have been carried out via numerical simulations. Results show that limited infiltration capacity may influence the soil moisture Probability Density Function (PDF) reducing its mean and variance and increasing the skewness. Major changes in the PDFs have been found for climate characterized by storms of short duration and high rainfall intensity, in humid climates, and in the cases where soil have a low permeability.

INTRODUCTION

Soil moisture is a key variable for hydrological and ecohydrological modeling (e.g., Eagleson, 1982; Neilson, 1995; Rodrìguez-Iturbe *et al.*, 2000). Its evolution in time and space is driven by different processes acting over a variety of scales (e.g., Albertson & Montaldo, 2003; Rodríguez-Iturbe *et al.*, 2006; Manfreda *et al.*, 2007). The severity and persistence of water stress in plants, the outcomes of ecological competition, and the sustainability of vegetation communities are examples of important ecological research questions in which soil moisture dynamic plays a dominant role (e.g., Scholes and Archer, 1997; Rodrìguez-Iturbe *et al.*, 2001; Porporato *et al.*, 2001; Caylor *et al.*, 2005; Sofo *et al.*, 2008). In particular, vegetation water stress is intimately related to relative soil moisture and the length of time that the soil moisture is below a given threshold. The crossing properties of the soil moisture levels are controlled by the drying process and the infiltration inputs into the soil matrix. This last varies from soil to soil according to the texture and the permeability.

Recent research has achieved significant progress in the description of soil moisture dynamics through the development of a steady-state probability density function of soil moisture within the growing season (Rodrìguez-Iturbe *et al.*, 1999; Laio *et al.*, 2001). This approach is based on the steady-state solution of the stochastic differential equation for the soil water balance in which the rainfall represents the stochastic forcing. Although this model contains necessary assumptions that simplify the mathematical form of the stochastic differential equation used to derive the soil moisture PDF, it represents the most innovative method to describe, with a physically-based approach, the soil moisture dynamics.

In the present work, the focus is on the scheme adopted to describe the infiltration process. Most of the assumptions proposed by Laio *et al.* (2001) have been preserved, including in the scheme the additional hypothesis that the runoff production is limited by the infiltration capacity of soil. The saturation excess mechanism is adequate for the evaluation of the runoff production in some environments, but when the infiltration capacity of the soil becomes relevant respect to the rainfall intensity, infiltration excess should be taken into account.

Soil water content variations are simulated using a bucket model where the infiltration capacity is determined according to Philip's equation (Philip, 1960). In this scheme, infiltration depends on the rainfall occurrence, intensity, and also duration. Consequently, rainfall is described as a Poisson process of rainfall pulses with random total depths and durations. Both the rainfall total depth and its duration are assumed exponentially distributed and statistically independent. Assuming rainfall events described by rectangular pulses allows for the derivation of an analytical solution of the total infiltration over the rainfall duration that is particularly useful within the simulation framework.

We aim to investigate the main differences between the original model proposed by Laio *et al.* (2001) and the modified model proposed herein (Infiltration and Saturation Excess model). The probability distributions of the soil moisture derived with the two proposed models are compared to determine the effects of the infiltration process schemes on the soil water balance assuming: (1) saturation excess runoff, and (2) infiltration and saturation excess runoff production. It is necessary to point out that the two processes are not mutually exclusive and the second model includes also the possibility to produce runoff for saturation excess. The mean, the standard deviation, and the skewness of the soil moisture obtained with these two different approaches are compared for different climates and soil characteristics. Infiltration may not influence the soil moisture dynamics in soils with high permeability, while less permeable soil are more sensitive to the proposed modification.

In the following text, the conceptual model used by Laio *et al.* (2001) to derive analytically the soil moisture PDF is briefly described. The modifications introduced to account for storm duration and non linearity in the infiltration process are also introduced. The statistics obtained using these two different infiltration schemes are compared and the implications of the surface control on the soil moisture dynamics are discussed.

SOIL MOISTURE MODEL PROPOSED BY LAIO *et al.* (2001)

Soil water balance may be described through the use of a bucket scheme as first suggested by Manabe (1969). Many others have used the same idea with different aims (e.g., Milly, 1994; Kim *et al.*, 1996; Farmer *et al.*, 2003; Porporato *et al.*, 2004). This interpretation is extremely useful because it allows the use of water balance equation with a finite control volume generally represented by the root zone. Such assumption is at the core of the model proposed by Laio *et al.* (2001), which is based on the following equation,

$$nZ_r \frac{ds}{dt} = I - ET - L \qquad \dots (1)$$

where s is the relative saturation of the soil given by the ratio of the volumetric soil moisture θ [dimensionless] and the soil porosity n [dimensionless], Z_r is the root zone depth [L], I represents the infiltration rate [L T^{-1}], ET the actual evapotranspiration and L the leakage rates [L T^{-1}].

Infiltration, I [L T^{-1}], is interpreted with a simplified scheme particularly useful for analytical purposes. It is assumed equal to the daily rainfall depth, h, if the water deficit $nZ_r(1-s)$ is greater than h and $nZ_r(1-s)$ otherwise. Infiltration assumes the following form,

$$I = \begin{cases} h & h \le nZ_r(1-s) \\ nZ_r(1-s) & h > nZ_r(1-s) \end{cases} \qquad \dots (2)$$

where nZ_r [L] represents the soil water content at saturation and h [L] is the rainfall depth. This representation allows for an immediate definition of the infiltration PDF that assumes the same distribution of the rainfall depth (exponential distribution) with an atom probability at the value $nZ_r(1-s)$.

The soil water loss function accounts for two phenomena: evapotranspiration and leakage. Both are described though a deterministic function that depends on the actual value of s. In particular, evapotranspiration assumes four different behaviors conditional to the relative state of the soil moisture,

$$ET(s) = \begin{cases} 0 & s \le s_h \\ \dfrac{s - s_h}{s_w - s_h} E_w & s_h \le s \le s_w \\ E_w + \dfrac{s - s_w}{s^* - s_w}\left(E_{\max} - E_w\right) & s_w \le s \le s^* \\ E_{\max} & s \ge s^* \end{cases} \qquad \dots (3)$$

where E_w is the evapotranspiration at the wilting point s_w, E_{max} is the evapotranspiration at the initial stomata closure s^*, s_h is the soil water content at which the ET reaches the zero.

The leakage function can be described by,

$$L(s) = \begin{cases} 0 & s \le s_{fc} \\ K_s s^c & s > s_{fc} \end{cases} \quad \dots (4)$$

where K_s is the soil permeability at saturation, s_{fc} is the soil moisture content at the field capacity, $c = (2 + 3m)/m$ is the pore disconnectedness index and m is the pore-size distribution index. For analytical purposes, Laio *et al.* (2001) modified Eqn. 4 using an exponential approximation.

An example of the soil water loss function, $\chi(s) = ET(s) + L(s)$, is given in Figure 1 for two specific soil textures. Soil parameters are taken from Table 1, E_w is 0.01 cm/day and E_{max} is equal 0.45 cm/day.

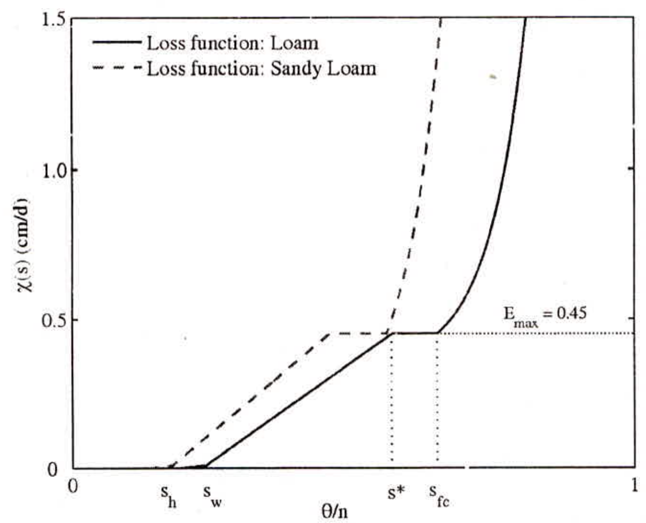

Fig. 1: The water loss function given by the sum of evapotranspiration and leakage: $\chi(s) = ET(s) + L(s)$

INCLUDING THE INFILTRATION EXCESS PROCESS IN THE SOIL WATER BALANCE

The previous model has been modified to include a different infiltration mechanism that accounts for the limited infiltration capacity of soil, and also for the effect of rainfall duration in order to provide a more accurate estimation of the soil moisture dynamics. The infiltration is considered as a daily input in the soil matrix, but it is computed as the integral of the Philp's equation over the rainfall duration. This introduces an additional random variable into the soil moisture model represented by the duration of storm events. As it will be further addressed in the next paragraphs, the soil moisture distribution seems to be particularly sensitive to this last parameter.

Rainfall Forcing

Rainfall is considered as a Poisson process of daily occurrences, where the storm depths are generated according to an exponential distribution $p(h) = 1/\alpha \exp(-h/\alpha)$, where α [L] represents the mean rainfall depth. Similarly, the rainfall arrivals are randomly generated with parameter λ [T^{-1}] representing the mean storms arrivals (Eagleson, 1978). These two parameters are representative of the local climate and together define the total amount of rainfall during a wet season.

In the second model, each rainfall pulse is associated to a storm duration that is also exponentially distributed with mean duration δ. Rainfall pulse is constituted by two components that are both relevant: the rainfall depth and its duration. These variables may be considered independent.

The characteristics of the modeled rainfall process is illustrated in Figure 2, where a sequence of pulses is shown. Rainfall may have different behavior moving from one region to one another according to the local climate.

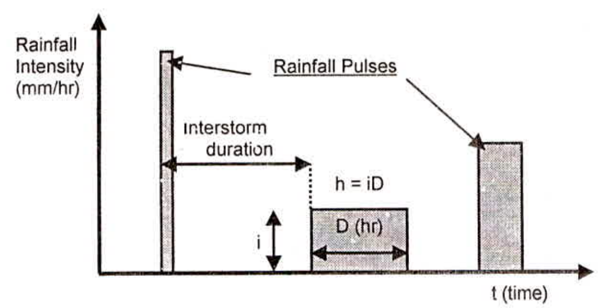

Fig. 2: Rainfall scheme of random pulses with durations and depths exponentially distributed

In the case of arid climates, the rare rainy storm tends to be extremely short in time and likely with high intensity. Such a condition may inhibit the infiltration process and, at the same time, may increase runoff production while being interpreted as a loss in the soil water budget. It is not clear to what extent soil type mediates the soil moisture budget as a consequence of this process.

In Figure 3(A) and (B), the probability distributions of the storm durations are drawn for two different rain stations located in arid areas in two different continents. Figure 3(A) refers to 10 years of hourly rainfall records of station 44 of the Sevillata research area (http://sevilleta.unm.edu/) in New Mexico (see Caylor *et al.*, 2005), while Figure 3(B) refers to a similar dataset recorded at the rain gauge station of Matera (Italy). The probability distributions of both the records follow an exponential distribution with mean equal to 1.7 hours and 2.3 hours, respectively. These examples are useful to describe or to give an idea of possible distribution of storm durations in arid climates. These two examples confirm that the storm durations may be very short in time and this aspect becomes more and more critical during the growing season.

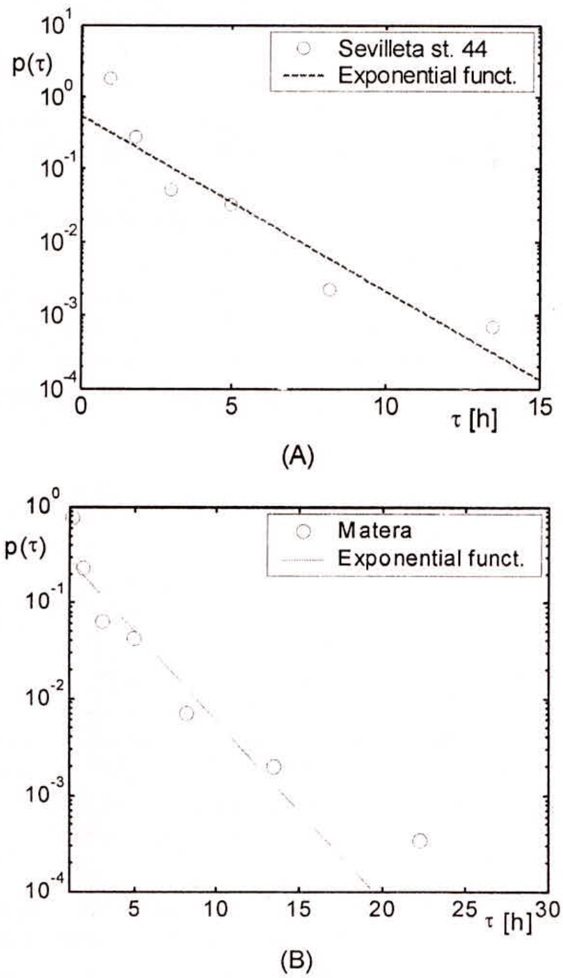

Fig. 3: (A) Probability distribution of the rainfall storm durations (circles) at the station 44 of the Sevilleta research area (USA) and exponential distribution with mean equal 1.7 hours (dashed line) in semilog plot. (B) Similarly, for the station of Matera (Italy) where the mean of the storm duration is equal 2.3 hours

The Limited Infiltration Capacity of the Soil

The method used to calculate the potential and actual infiltration rates are based on Philip's equation (Philip, 1960). This equation requires supplementary information about soil characteristics such as matrix potential curve, pore size distribution index, sorptivity and permeability.

The relationship between matrix potential and relative soil saturation is described by using results of Burdine (1958) and Brooks and Corey (1966): $K(s) = K_s s^c$ and $\psi(s) = \psi(1)s^{-1/m}$; where $K(s)$ [L T^{-1}]is the soil permeability, $\psi(s)$ [L] is the matrix potential, while c and m are empirical parameters.

The infiltration capacity of the soil using the Philip's equation is,

$$F_i(t) \approx \frac{1}{2} S_i t^{-1/2} + A_i \qquad \ldots (5)$$

where the parameters S_i infiltration sorptivity and A_i gravitational infiltration are respectively defined as $A_i = \frac{1}{2}[K_S - K(s_i)]$ and $S_i = 2n(1-s_i)\sqrt{\frac{\overline{D}}{\pi}}$, where s_i is the relative soil moisture at time i; $\overline{D}$ is the effective diffusivity of soil.

According to Eagleson (1978) parameters A_i and S_i can be expressed as a function of the hydraulic soil parameters and the initial soil moisture condition,

$$A_i = \frac{1}{2} K(1)(1 - s^c) \qquad \ldots (6)$$

$$S_i = 2(1 - s_i)\left(\frac{5nK_S\psi(1)\phi_i(m,s_i)}{3m\pi}\right)^{1/2} \qquad \ldots (7)$$

where m is the pore size distribution index, c is the pore disconnectedness index, $\phi_i(m, s_i)$ dimensionless effective diffusivity.

Dimensionless effective diffusivity can be written as a function of the pore-size distribution index and the initial soil moisture s_i (Bras, 1990),

$$\phi_i(m,s_i) = \frac{3\pi}{10(1-s_i)}\left(\frac{m}{1+4m} + \frac{m^2 s_i^{1/m+4}}{(1+4m)(1+3m)} - \frac{m^2 s_i}{1+3m}\right) \qquad \ldots (8)$$

The total infiltration during a storm event with duration D may be computed by dividing the rainfall pulse in two intervals according to the magnitude of the infiltration capacity with respect to the rainfall intensity, i. The two rates are equal when $t_0 = \frac{S_i^2}{4(i - A_i)^2}$, when $t < t_0$ all the rainfall infiltrates and after t_0 infiltration is limited by $F_i(t)$. In order to account for the surface saturation effect, Eagleson (1978) suggested that surface saturation takes place in a time duration comparable to t_0. Assuming that the ponding water reinfiltrate into the soil after the rainy event and that the storm has a duration D, it follows that the infiltration may be computed as,

$$I = \begin{cases} iD & D \le 2t_0 \\ 2it_0 + \int_{t_0}^{D-t_0} \left(\frac{1}{2} S_i t^{-1/2} + A_i \right) dt & D > 2t_0 \end{cases} \quad \ldots (9)$$

that leads to,

$$I = \begin{cases} iD & D > 2t_0 \\ 2it_0 + A_i(D - 2t_0) + S_i\sqrt{D - t_0} - S_i\sqrt{t_0} & D \le 2t_0 \end{cases} \quad \ldots (10)$$

The infiltration equation given above allows the derivation of the probability distribution of infiltration into the soil under the hypothesis of rainfall pulses of constant duration and total depths that are exponentially distributed. An example of these distributions is given in Figure 4 where one can appreciate how the PDF of the infiltration deviates from the original exponential function of the rainfall. The graphs describe the PDFs of the infiltration, I, assuming different soil moisture states (Figure 4A) and different storm durations (Figure 4B) for a loamy soil under a specific climate.

In the present work, the rainfall pulses are assumed to be characterized by random durations and depths. Consequently, a numerical approach was used in order to derive the PDFs of the soil moisture under several climatic conditions and soil types. The soil parameters adopted in the present work are taken from Cosby *et al.* (1984) and are summarized in Table 1.

The two models considered herein differ only in the description of the infiltration input in the soil matrix. In particular, the Infiltration and Saturation Excess model exploits Eqn. 10 to account for the limited infiltration capacity of soil. Nevertheless, saturation excess occasionally may occur also in this model given the limited storage capacity of the soil bucket.

Table 1: Soil Parameters Associated with Each of the Soil Textures Taken from Cosby *et al.* (1984). Parameters s_h, s_w, s^* and s_{fc} Correspond to a Soil Matric Potential of –10 MPa, –3 MPa, –0.09 MPa and –0.03 MPa

Soil Type	*ψ(1) (cm)*	*b*	*c*	*n*	*K_s (cm/d)*	s_h	s_w	s^*	s_{fc}
Sand	4.7	3.38	9.8	0.37	203.7	0.05	0.07	0.21	0.29
Sand loam	13.2	4.50	12.0	0.41	61.4	0.14	0.18	0.39	0.50
Loam	20.7	5.70	14.4	0.43	36.2	0.23	0.28	0.51	0.62
Clay	39.1	12.13	27.3	0.46	17.3	0.52	0.58	0.77	0.84

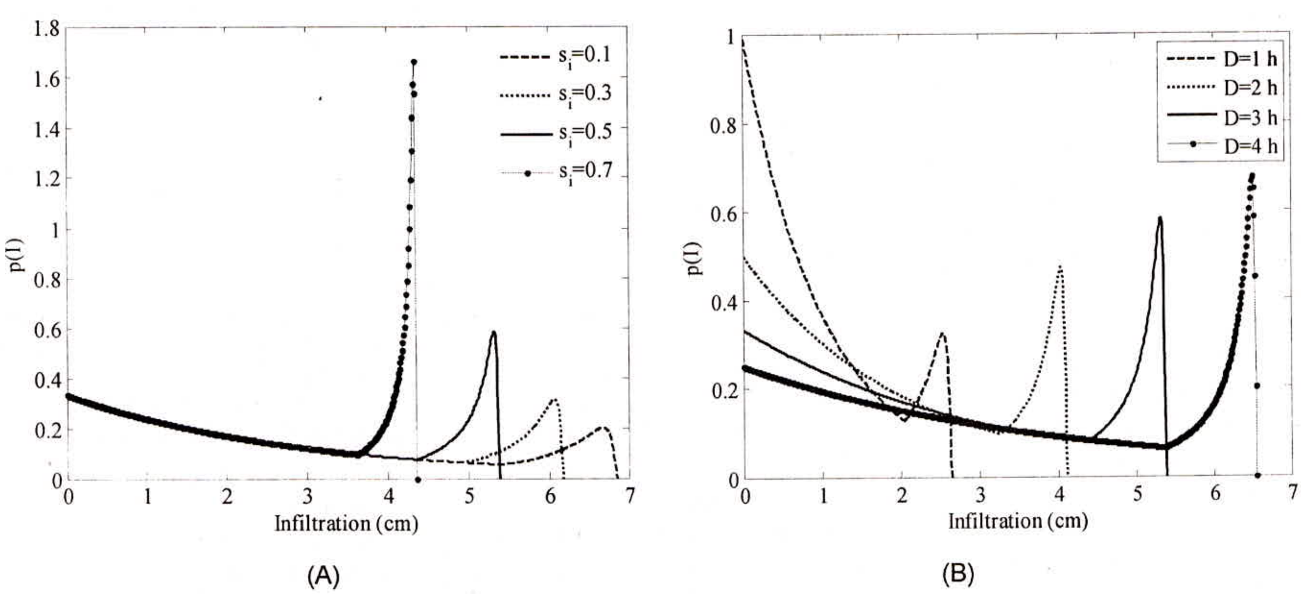

Fig. 4: Probability density function of the infiltration into the soil using the hypothesis of limited infiltration capacity for different values of initial soil moisture (A) and for different rainfall pulse durations (B). Parameters used are λ = 0.30 event/day, α = 1.0 cm/day, δ = 3 hours (only in A), s_i = 0.5 (only in B) and the soil texture is loam (see Table 1)

RESULTS AND DISCUSSION

Simulations are carried out over a wide range of climatic conditions using different soil textures whose characteristics are described in Table 1. For the sake of brevity, the graphs reported herein refer only to the four different soil textures that represent common soil types. The temporal window of simulation is 40 years in order to obtain sufficiently stable results. An example, of a two-year run is given in Figure 5, where the soil moisture evolution in time for the two proposed schemes is depicted. The paths of the two soil moisture models is almost the same. The Infiltration and Saturation Excess model slightly deviates from the path of the model based only on Saturation Excess mechanism when the relative saturation of the soil gets higher and especially when intense rainfall occurs.

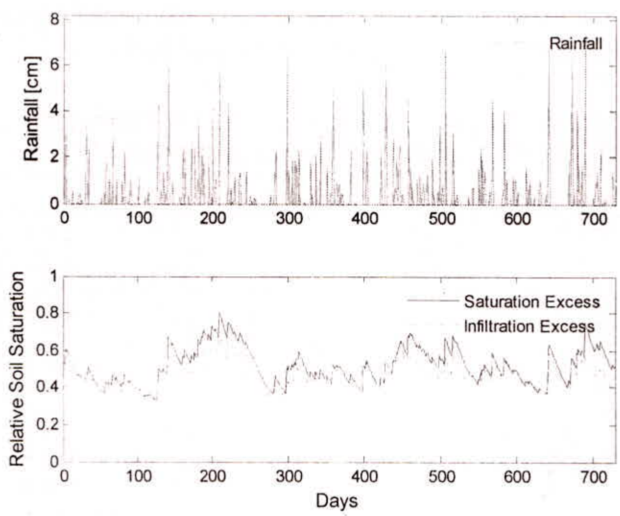

Fig. 5: An example of soil moisture dynamics driven by stochastic rainfall obtained using two schemes for the infiltration process. Parameters used for the simulation are λ = 0.30 event/day, α = 1.5 cm/day, δ = 3 hours, Z_r = 30 cm, E_w is 0.01 cm/day, E_{max} is equal 0.45 cm/day and the soil texture is loam (see Table 1)

In Figure 6, eight examples of PDFs referred to both the original model by Laio *et al.* (2001) and the model with Infiltration Excess are plotted in order to compare the soil moisture dynamics in two different rainfall regimes and for different soil textures. The two rainfall regimes refer to an arid climate with parameters α = 1.0 cm/day, λ = 0.1 event/day and δ = 3.0 hours and to a humid regime with rainfall parameters α = 1.5 cm/day, λ = 0.30 event/day, and δ = 3.0 hours. As a general remark, the differences between the two models were negligible in the case of sandy soil and obviously becomes more relevant for less permeable soils such as loam and clay (Figure 6(F) and (H)). In the arid climate (Figure 6(A), (C), (E), (H)), it is clear that the two distributions are practically identical in all the soil texture types; while in humid conditions (Figure 6(B), (D), (F), (G)), the differences between the two distributions are more significant especially with regard to the right tail of the probability distribution and for the less permeable soils like loam and clay.

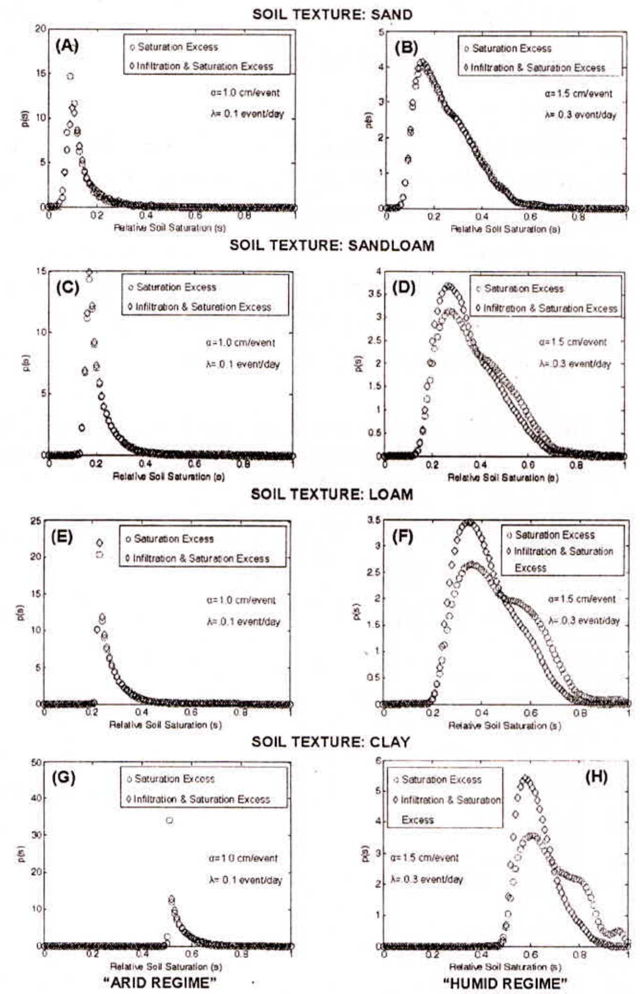

Fig. 6: Comparison of the soil moisture PDFs obtained with the two soil moisture models for two different climatic conditions (on the columns) and four different soil textures (on the rows). Soil parameters are taken from Table 1 and other parameters are the same of Figure 5

With the aim to provide a quantitative comparison between the two simulation schemes, the mean, the Standard Deviation (SD) and the skewness of the soil moisture have been estimated using different soil textures and different values of the rainfall parameters (α and λ). These parameters characterizes the local climate conditions that is assumed to vary from severe arid ($\alpha = 0.1$ and $\lambda = 0.1$) to extremely humid condition ($\alpha = 1.5$ and $\lambda = 0.4$). Furthermore, the comparison is carried out for three different values of the mean storm duration δ (1.5, 3.0, 5.0 hours). The differences between the resulting soil moisture PDF obtained by the two models are summarized in Figure 7, Figure 8 and Figure 9. In particular, the graphs describe the relative change in mean, standard deviation and skewness of the soil moisture obtained with the first model (Saturation Excess runoff mechanism) respect to the second one (Infiltration Excess and Saturation Excess runoff mechanism) expresses in percentage difference. This relative change, Δ, is generally positive for the mean and the Standard Deviation (SD) of the soil moisture that are overestimated by the first model; while the skewness is underestimated in most of the cases for the first model. The challenge is to understand when and where such over or underestimations are important. A first attempt to define this range is made here assuming a significant threshold value Δ = ±10%, this limit is depicted in the graphs with a continuous line.

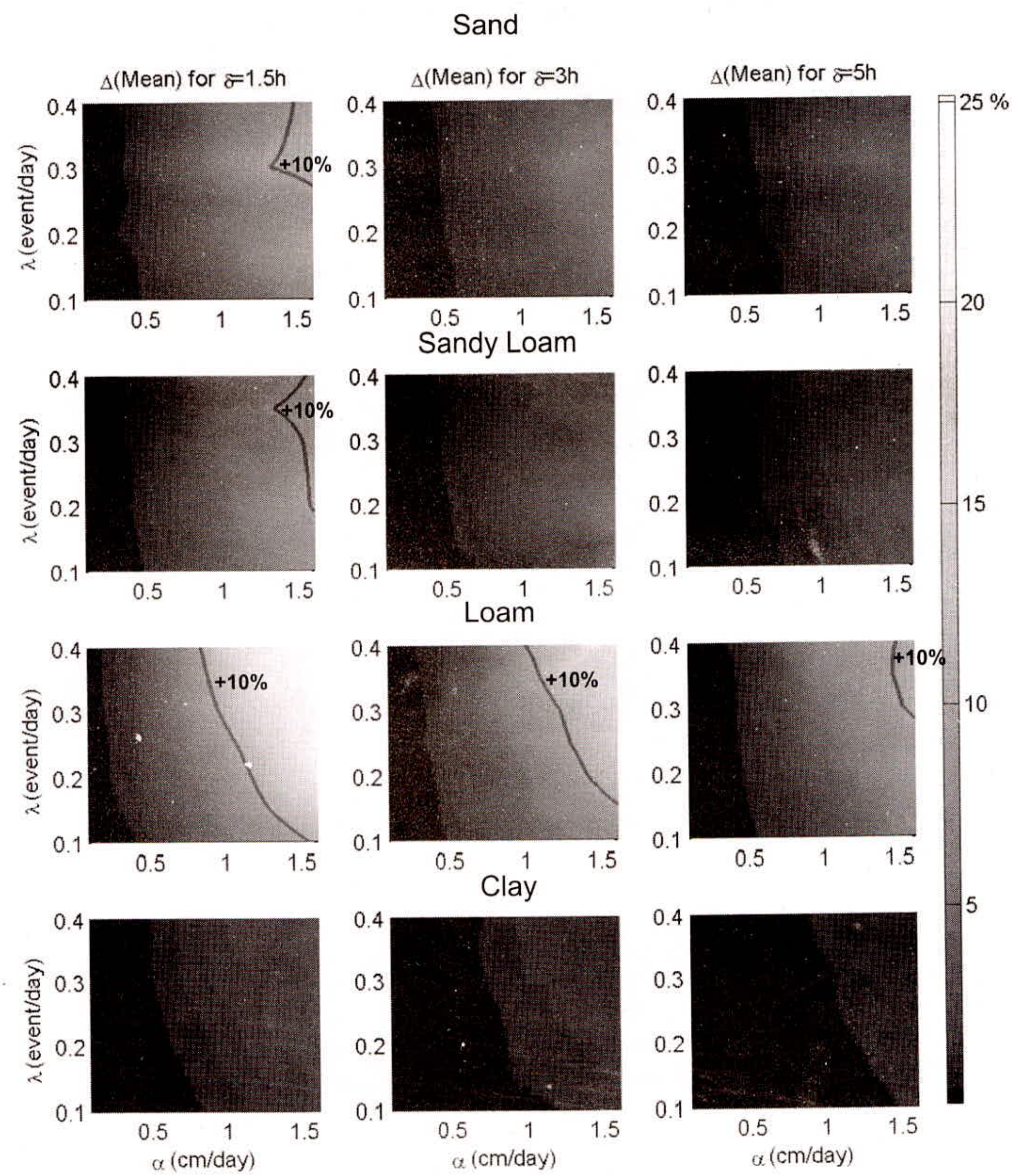

Fig. 7: Percentage differences (?) between the mean soil moisture obtained using the original model by Laio *et al.* (2001) and modified version with limited infiltration capacity. The Saturation Excess model provides an accurate estimate of the mean with errors always lower than the 18%, the errors decrease with the increase of the mean storm duration values *d*. From the left to the right the mean storm duration varies from 1.5, 3, and 5 hours. Adopted parameters for the simulations are the same of Figure 5 and the soil parameters for each texture are taken from Table 1

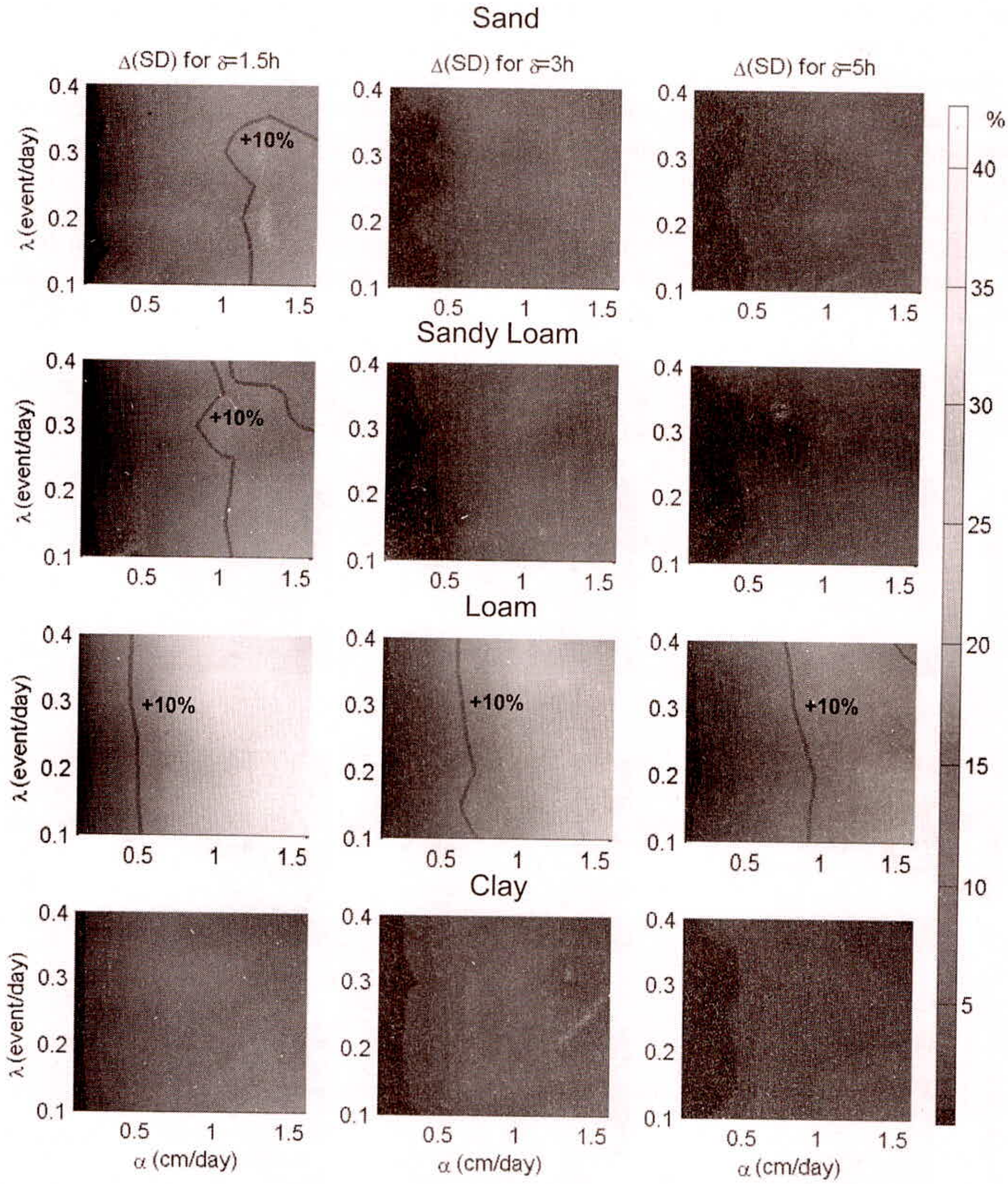

Fig. 8: Percentage differences (?) between the standard deviation of soil moisture obtained using the original model by Laio *et al.* (2001) and modified version with limited infiltration capacity. The graphs highlight the presence of large areas where the Saturation Excess scheme produces an overestimation of the Standard Deviation (SD) up to 40% for humid climates with short storm durations. Adopted parameters for the simulations are the same of Figure 5 and the soil parameters for each texture are taken from Table 1.

The comparison of the two schemes allows to understand the implications that the choice of an infiltration scheme have on the soil moisture under different climatic conditions. The analyses provided the following results: (1) the errors in the estimation of the mean and the skewness of the first model depend on the mean rainfall rate ($\alpha\lambda$), while the standard deviation seems to be more markedly influenced by the rainfall intensity (controlled by the parameters α and δ); (2) the Saturation Excess scheme may produce significant overestimation of the soil moisture variance and underestimation of the skewness, while overestimation of the mean values are always minor; (3) the skewness is generally underestimated in most of the cases, with a reduced number of cases where a slightly overestimation takes place in arid climates; iv) the relative changes in the standard deviation and mean is most pronounced for a loam soil textures. This last result is due to the changes in s_h with the soil texture. In particular, this parameter represents a lower limit for the soil moisture that reduces its variance. In case of clay soils s_h assumes a particularly high value limiting the range of variability of the soil moisture and also the relative changes between the two simulation schemes. Under those conditions the relative changes for clay in the mean and the standard deviation of soil moisture are lower than those measured for loam.

The Saturation Excess scheme alone reproduces correctly the PDFs of soil moisture in the case of arid climate with small amount of rainfall. Nevertheless, increasing mean rainfall intensity may cause the inhibition of infiltration, thereby reducing accuracy of the first model even in arid conditions. Differences between the two schemes are essentially due to the overestimation of the infiltration term in the water balance equation. Limited infiltration capacity may reduce the mean soil moisture value, but its major effect is observed on the standard deviation and the skewness of the soil moisture. Of particular interest is the fact that the soil moisture is highly sensitive to the mean storm duration. In fact, its reduction strongly increases the runoff production and effecting the dynamics of soil moisture as one can clearly see from the panels of Figure 7, Figure 8 and Figure 9.

CONCLUSIONS

The model proposed by Laio *et al.* (2001) provides a reliable representation of the soil moisture dynamics over a wide range of climatic conditions. The infiltration process is well interpreted especially in the case of highly permeability soil such as sandy soils. It is necessary to remark that for less permeable soils the hypothesis to neglect the surface control on the infiltration capacity may produce a significant overestimation of the mean and variance of the soil moisture especially in climates characterized by storms of high intensity and short durations. In general, errors in the variance of the soil moisture as well as skewness are higher with respect to the changes observed in the mean soil moisture estimates. Significant differences in the variance of the soil moisture may produce change in the crossing properties of the soil moisture process also influencing the vegetation water stress with important implications for ecohydrological models.

The results of this paper need to be interpreted also considering that the analyses presented refer to a soil water balance at the point scale where redistribution mechanisms have been totally neglected. This hypothesis implies that the results of these models can be applied to flat landscapes or to arid climates where soil moisture redistribution does not take place. The rainfall regimes in arid climates tends to be characterized by storm of short duration producing events of high intensity. In those cases, the soil moisture scheme developed by Laio *et al.* (2001) is consistent when dealing with more permeable soils, while more attention have to be paid to the adopted infiltration scheme in less permeable soils and when the mean rainfall intensity in particularly high.

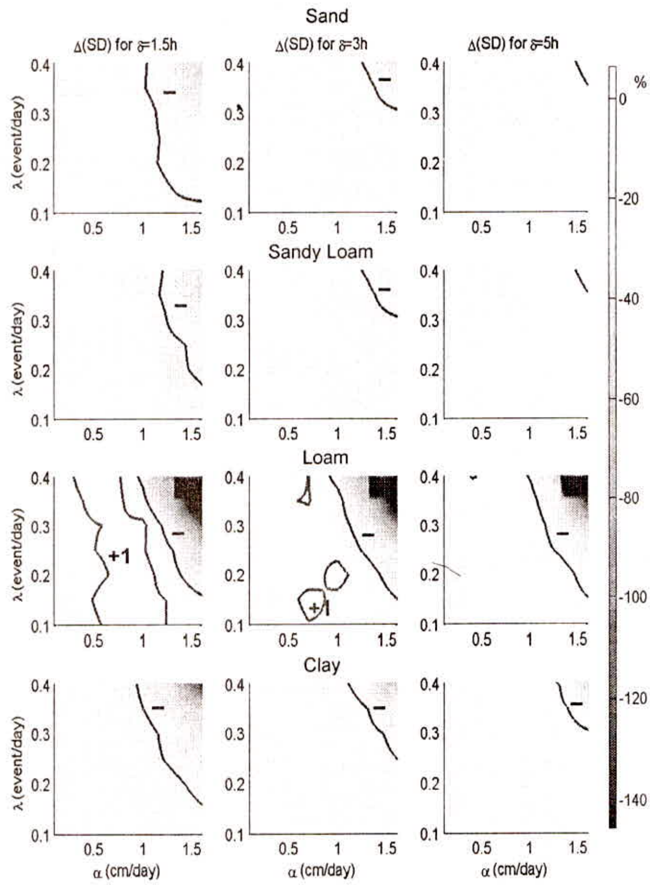

Fig. 9: Percentage differences (Δ) between the skewness of soil moisture obtained using the original model by Laio *et al.* (2001) and modified version with limited infiltration capacity. The graphs highlight that the Saturation Excess scheme produces a significant underestimation of the skewness up to −140% for humid climates with short storm durations. Adopted parameters for the simulations are the same of Figure 5 and the soil parameters for each texture are taken from Table 1

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