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Analysis of the performances of methods for the evaluation of soil hydraulic parameters and of their application in two hydrological models

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Abstract. Daily measurements of evapotranspiration, mean soil moisture in the root zone and percolation out of the root zone collected in a cropped maize field in Northern Italy (Landriano-PV) were used to test the performances of two models: SWAP, a widely used hydrological model based on Richards equation, and ALHyMUS, a conceptual model based on a reservoir cascade scheme.

Each model was implemented with three different sets of hydraulic parameters values, derived by applying three well-known Pedo-Transfer Functions to the texture and organic matter measurements collected at the experimental site. Simulations were run using meteorological data measured at the site for the time period June - October 2006.

The results confirm the existence of a wide range of variation of the parameter values in the different sets, remarkably in the case of hydraulic conductivity. This is reflected in a high variability of the output variables of each model, which often is larger than the difference between the same outputs for the two models. Finally, the comparison shows that a good agreement of soil moisture patterns may occur even if evapotranspiration and percolation fluxes are significantly different; therefore multiple output variables shall be considered to test the performances of methods and models.

Keywords. Unsaturated zone – Hydrologic model – Pedo-transfer functions.

Analyse de performance des méthodes d'évaluation des paramètres hydrauliques du sol et leur application dans deux modèles hydrologiques

Résumé. *Des mesures journalières de l'évapotranspiration, de l'humidité moyenne du sol dans la zone racinaire et de la percolation, collectées dans un champ de mais au Nord de l'Italie, ont été utilisées pour tester la performance de deux modèles : SWAP, un modèle hydrologique très utilisé basé sur l'équation de Richards, et ALHyMUS, un modèle conceptuel basé sur un réservoir système cascade. Chaque modèle a été exécuté pour trois séries de paramètres hydrauliques à valeurs diverses, dérivées de trois fonctions de pédotransfert bien connues, qui ont été appliquées aux mesures de la texture et de la matière organique du champ expérimental. Les simulations ont été élaborées en utilisant des données météorologiques mesurées sur le site pour la période juin-octobre 2006. Les résultats confirment l'existence d'une grande variabilité des valeurs des paramètres hydrauliques pour les trois séries, en particulier la conductivité hydraulique. Cela entraine une grande variabilité des résultats de chaque modèle, qui est souvent plus grande que la différence entre les résultats des deux modèles obtenus à partir des mêmes paramètres. Enfin, la comparaison montre que les valeurs d'humidité du sol peuvent être en accord, même si les flux d'évapotranspiration et de percolation sont significativement différents; par conséquence plusieurs variables de sortie devraient être prises en compte afin de tester les performances des méthodes et des modèles.*

Mots-Clés. *Zone insaturée – Modèle hydrologique – Fonctions de pédotransfert.*

I – Introduction

Water retention and hydraulic conductivity curves are crucial input parameters in any modelling study on water flow and solute transport. Computed water balance is in fact sensitive to soil hydraulic parameters and therefore their accurate determination is essential to model hydrological processes (Jhorar *et al.*, 2004).

Direct methods for estimating soil hydraulic parameters, either laboratory- or field-based, remain relatively time consuming and costly, especially when data are needed for large areas (Wösten *et al.*, 2001). For these reasons many attempts have been made at estimating soil hydraulic parameters by means of empirical relationships based on readily available soil data, such as textural soil properties and bulk density. These relationships, commonly referred as Pedo-Transfer Functions (PTFs) (Bouma, 1989), are particularly enticing as they are very well suited for large scales applications. In spite of the wide diffusion of these methods, the reliability of the results obtained is still under discussion (see for instance: Tietje and Hennings, 1996; Romano, 1999; Tietje and Tapkenhinrichs, 1993; Bastet *et al.*, 1999; Nemes *et al.*, 2003; Ungaro *et al.*, 2005). These works show that good performances can be obtained also with predictive methods, but in general the evaluations are site specific and therefore it is not possible to draw general conclusions.

To evaluate and compare different methods for the estimation of the soil hydraulic properties, Wösten *et al.* (1986) proposed the use of functional criteria that are directly related to applications, rather then to the direct comparisons of parameters. The basis for the identification of differences in hydraulic properties will therefore be determined by the accuracy with which the functional criteria are predicted and not by the accuracy with which hydraulic properties are characterized (Vereecken *et al.*, 1992).

To further explore this issue, an intensive monitoring activity was conducted in 2006 in a 10 ha maize cropped field located in Northern Italy (Landriano – PV). The information collected has been used in this research: *i)* to compare different methods for deriving the values of the soil hydraulic parameters and *ii)* to evaluate the effect of the uncertainty in the determination of these parameters on the outputs of two hydrological models of different complexity: SWAP (Kroes and van Dam, 2003), a widely used model of soil moisture dynamics in unsaturated soils based on Richards equation, and ALHyMUS (Facchi *et al.*, 2004), a conceptual model of the same dynamics based on a reservoir cascade scheme.

Each model has been implemented with three different set of parameters obtained applying three widely used Pedo-Transfer Functions to the texture and organic matter measurements collected for each horizon of the experimental profile at the monitoring site: *i)* Rawls and Brakensiek (1989); *ii)* HYPRES (Wösten *et al.*, 1999); and *iii)* ROSETTA (Schaap *et al.*, 2001). Simulations have been run with each model and each parameters set using meteorological inputs measured at the site for the time period June - October 2006. The comparison has been focused on three output variables: evapotranspiration, water content in the root zone and outflow at the bottom of the root zone.

II – Materials and methods

1. Experimental field site

The monitoring activities were conducted in 2006 during the cropping season of a 10 ha maize field, located in Northern Italy (Landriano – PV; 45°19’ North, 9°15’ East, 88 m a.s.l.). Instruments for the detailed monitoring of water and energy fluxes have been installed in the experimental field since 2005. A micrometeorological eddy-correlation (EC) based station was located in the centre of the field. A vertical sided trench was opened close to the tower site with the purpose of characterizing the profile and collecting samples from each horizon for standard soil analyses. TDR devices (CS616 Campbell Sci.) and tensiometers (SKYE) were installed in the profile respectively at the depth of 5, 20, 35, 50 and 70 cm and 20, 35 and 70 cm. Due to the presence of a shallow water table (90-120 cm below the topographic surface) a shallow piezometer with a pressure transducer device (STS) was installed as well. Standard meteorological devices and PAR sensors completed the installation. Spatially distributed measures of Leaf Area Index LAI (-), crop height h_c (m) and rooting depth D_r (m) to characterize the crop in the field were conducted periodically. Moreover, saturated hydraulic conductivity K_{sat} (cm h^{-1}) was measured at the different soil depth through a Guelph permeameter.

During the cropping season 2006 there were two irrigation treatments: the first one in date June 8th (Day of the Year, DoY = 159) by sprinkler irrigation to allow the crop emergence, and the second one, in date July 14th (DoY = 195) by surface irrigation. The irrigation depths were estimated through the variation of the measured soil moisture in the profile in the first case and through the measure of the water discharge in the irrigation channel by an electromagnetic flow sensor (Nautilus - OTT) in the second one. The values of the irrigation depths were found to be 20 mm and 140 mm respectively. Due to the field condition (i.e. flat field) the run-off was negligible in the whole monitoring period. A summary of the data collected at the monitoring site is shown in Table 1.

Table 1. Summary of meteo and crop data collected at the monitoring site (3 June – 10 October)

Cumulative rain	**429 mm**
Mean temperature	21 (°C)
Crop	Zea Maize
Emergence	6 June 2006 (DoY = 157)
Harvesting	10 October 2006 (DoY = 283)
LAI_{max}	4.2 (-)
Crop height $_{max}$	3.00 (m)
Rooting depth $_{max}$	0.70 (m)
sprinkler irrigation	8 June 2006 (DoY = 159); 20 mm
surface irrigation	14 July 2006 (DoY = 195); 140 mm

2. SWAP model

The soil–water–atmosphere–plant (SWAP) is a widely applied and well documented model, based on a finite difference solution of the Richards equation (Van Dam *et al.*, 1997). It simulates the vertical soil water flow and solute transport in close interaction with crop growth. Richards equation (Richards, 1931) is applied to compute transient soil water flow:

$$C(h)\frac{\partial h}{\partial t} = \frac{\partial}{\partial z}\left[K(h)\left(\frac{\partial h}{\partial z}+1\right)\right] - S_a \tag{1}$$

where $C(h)$ (cm^{-1}) is the differential soil water capacity $(\partial\theta/\partial h)$, θ (-) is the volumetric water content, h (cm) the soil water pressure head, $K(h)$ (cm d^{-1}) the hydraulic conductivity, S_a (d^{-1}) the root water extraction rate, and z (cm) the vertical coordinate (positive upward). The numerical solution of Eq. (1) (Richards, 1931) is subject to specified initial and boundary conditions, and requires known relationships between the soil hydraulic variables moisture θ, pressure head h and hydraulic conductivity K. The following relations between these variables have been used (Van Genuchten, 1980; Mualem, 1976):

$$\theta(h)=\theta_r+\frac{\theta_s-\theta_r}{\left[1+|\alpha h|^n\right]^m} \tag{2}$$

$$K(\theta)=K_{sat}S_e^L\left[1-\left(1-S_e^{\frac{1}{m}}\right)^m\right]^2 \tag{3}$$

where θ_r (-) is the residual water content, θ_s (-) the saturated water content, $S_e = (\theta - \theta_r)/(\theta_s - \theta_r)$ (-) the relative saturation, α (cm^{-1}) an empirical shape factor, n (-) an empirical shape factor, K_{sat} (cm h^{-1}) the saturated hydraulic conductivity, and L (-) an empirical coefficient. The value of m is fixed as $m = 1-1/n$.

SWAP includes both a simple and detailed crop growth module. In the simple crop module used in this research, crop growth is described by *LAI* (-), crop height h_c (m) and rooting depth D_r (m) as functions of crop development stage. The potential evapotranspiration rate ET_p (mm d^{-1}) is estimated by the Penman–Monteith equation (Monteith, 1965). In field conditions where crops partly cover the soil, the ET_p is partitioned into the potential soil evaporation E_p (mm d^{-1}) and the potential crop transpiration T_p (mm d^{-1}) using the daily pattern of *LAI* (Goudriaan, 1977; Belmans *et al.*, 1983).

3. ALHyMUS model

The unsaturated flow model ALHyMUS (Facchi et al, 2004; Gandolfi *et al.*, 2006) is based on a non-linear reservoir cascade scheme, including two reservoirs in the root-zone and one (or more) additional reservoir(s) extending from the root-zone to the groundwater table. The first reservoir (evaporative) represents the upper part of the soil profile in which infiltration, evaporation and percolation to the subsequent reservoir take place; the second reservoir (transpirative) extends through the root zone having a thickness variable with the phenology of the crop and considers the processes of transpiration and percolation to the reservoir beneath; in the last reservoir(s) only percolation is taken into account. The thickness of the last reservoir(s) varies in time, due to the fluctuations of phreatic levels. Evaporative and transpirative rates are computed using the FAO-56 dual crop coefficient method (Allen *et al.*, 1998). A 1-D mathematical representation of the infiltration and percolation processes is adopted. The potential infiltration rate is estimated by the Green-Ampt equation (Green and Ampt, 1911). Drainage discharges from each reservoir are determined using a simplified scheme, which considers a Darcian-type gravity flow; the relation between the unsaturated hydraulic conductivity and the water content is modelled by Eq. (3). The water balance is computed by an implicit iterative procedure.

Due to the presence of a shallow groundwater table in the study field, for this research the ALHyMUS model was added with the empirical relation of Liu *et al.* (2006), which computes the capillary rise G_c (mm d^{-1}) from groundwater surface to the transpirative reservoir as a function of the moisture in the reservoir θ_v (-), the rate of potential evapotranspiration ET_p (mm d^{-1}) and the shallow groundwater depth D (m).

4. Soil hydraulic parameters

Three widely used Pedo-Transfer Functions have been applied to the texture and organic matter measurements collected at the profile of the experimental site (Table 2). The first one is the set of PTFs of Rawls and Braekensiek (1989), based on non-linear multiple regression equations. Calzolari *et al.* (2001) have shown that these PTFs, even if developed using USA soil data, have a good performance also for the soils of the central Padana Plain (Northern Italy). The second set of PTFs used is the so-called HYPRES (Wösten *et al.*, 1999), based on multiple regression equations as well, but developed using an European data-base of soils; it is important to underline that in this data-base no soils from Northern Italy are included. Finally, the last set is the one called ROSETTA (Schaap *et al.*, 2001) developed by the USSL (United States Salinity Laboratory) using a neural network model based on USA soil data. The values of the bulk density ρ_b (g cm^{-3}) necessary for the PTFs has been estimated by the relation proposed by Jeffrey *et al.* (1970), that proved to provide good results for the soil data of the area (ERSAL, 2001).

Table 2. Chemical-physical data for the horizons of the study profile

Depth (cm)	0-10	10-40	40-55	55-90
soil classification (USDA)	Ap1	Ap2	B	2Bt1
Sand (%)	67.0	65.0	56.0	44.5
Silty (%)	30.5	32.0	39.5	31.5
Clay (%)	2.5	3.0	4.5	24.0
Organic matter (%)	2.7	2.3	1.9	0.5

5. Model inputs and parameters

The models have been set up for the period 6 June – 10 October 2006. Measured meteorological and irrigation data have been used for the simulations. Daily pattern of crop height, h_c (m), Leaf Area Index, *LAI* (-) and rooting depth, D_r (m) have been obtained by linear interpolation from the data collected in the field during the cropping season. The daily pattern of K_{cb} (-) (basal crop coefficient, see Allen *et al.*, 1998), used by ALHyMUS to compute the transpiration rate T_p (mm d^{-1}), has been estimated on the basis of literature values (Allen *et al.*, 1998; Huygen *et al.*, 1997; Borgarello *et al.*, 1993) adapted to the cropping stages observed on the field. Table 3 shows the main additional crop parameters necessary for the implementation of the two models: the pressure head values H_{Lim} (cm) for the crop stress condition in SWAP are those proposed in Hupet *et al.* (2004) except for the wet stress condition not taken into account in this research, the canopy resistence r_c (s m^{-1}) for the SWAP Penman–Monteith equation, the interception model parameters *a* (mm d^{-1}) and *k* (-), and the *p* (-) parameter used by ALHyMUS to determine the fraction of Readly Avalilable Water (RAW) form the Total Available Water (TAW) (Allen *et al.*, 1998) are those proposed in literature for maize.

Table 3. Crop parameters values used by SWAP and ALHyMUS models

SWAP						*SWAP – ALHyMUS*		*ALHyMUS*
H_{LIM} 1 (cm)	H_{LIM} 2 (cm)	H_{LIM} 3 (cm)	H_{LIM} 4 (cm)	H_{LIM} 5 (cm)	r_c (s m^{-1})	*a* (mm d^{-1})	*k* (-)	p (-)
-	-	-325	-600	-8000	70	0.25	0.385	0.5

The soil hydraulic parameters have been determined using the three PTFs illustrated above for all the horizons of the study profile. The values of the soil moisture at the field capacity θ_{FC} (-) and at the wilting point θ_{WP} (-) used by ALHyMUS to evaluate the Total Available Water (*TAW*) and the Total Evaporable Water (*TEW*) (Allen at al., 1998) have been computed solving the retention curve equation (Eq. 2) for the pressure head of -100 cm and -8000 cm respectively.

The soil hydraulic parameter values for the ALHyMUS reservoirs have been computed from those determined for each horizon. In particular, for each reservoir, the arithmetic mean of the parameters of the horizons which fall in it, weighted by their thickness, is used for all the soil hydraulic parameters except for the saturated hydraulic conductivity, for which the geometric mean has been adopted.

The initial moisture conditions have been fixed in both models at the measured values and the bottom boundary condition has been prescribed according to the measurements of the groundwater levels, respectively using the daily data as input (Liu *et al.*, 2006) in ALHyMUS and using the data to calibrate the following relationship for estimating the bottom flux Q_{bot} (cm d^{-1}) in SWAP:

$$Q_{bot} = \frac{\phi_{acquif} - \phi_{avg}}{c_{conf}} \quad (4)$$

where ϕ_{acquif} is the hydraulic head in the semi-confined aquifer (cm), ϕ_{avg} is the average groundwater level measured in the field (cm), and c_{conf} is the semi-confining layer resistance (d).

III – Results and discussion

1. Comparison of soil hydraulic parameters

Table 4 shows mean and coefficient of variation (CV) for the parameters determined using the three PTFs for each soil layer. The results confirm the existence of a wide range of variation of the parameters values in the different sets, remarkably in the case of hydraulic conductivity K_{sat} (cm h^{-1}) and of the shape parameter α (cm^{-1}). The parameter *L* (-) also shows a high variability but it is demonstrated that hydrological models are less sensitive to its variations (Jhorar *et al.*, 2004).

Table 4. Statistics for the soil hydraulic parameters determined using the three PTFs.

Depth (cm)		θ_s (-)	θ_{FC} (-)	θ_{WP} (-)	θ_r (-)	n (-)	α (cm^{-1})	K_{sat} (cm h^{-1})	L (-)
0-10	mean	0.49	0.27	0.07	0.03	1.401	0.050	7.7	-0.19
	CV	13%	17%	20%	14%	3%	72%	60%	-341%
10-40	mean	0.47	0.27	0.07	0.03	1.404	0.048	6.2	-0.18
	CV	13%	15%	16%	13%	2%	70%	56%	-360%
40-55	mean	0.45	0.28	0.08	0.03	1.404	0.038	3.4	-0.10
	CV	14%	11%	12%	17%	3%	72%	41%	-521%
55-90	mean	0.38	0.29	0.13	0.05	1.311	0.026	0.3	-0.89
	CV	5%	4%	23%	52%	9%	40%	17%	-166%

2. Performance evaluation

A. *Evapotranspiration*

The actual evapotranspiration rate at the experimental site is generally close to the potential. In this condition the hydraulic parameters don't play an important role and the output of the models obtained with the different sets of values are similar. The performance of both models is different in the first period (3 June - 2 July), when the crop is small and evaporation is the predominant process and in the second period (2 July – 10 October), when the crop grows and reaches the maximum LAI value. Figure 1 shows for example the simulation results obtained with the two models using the set of parameters obtained by the Rawls and Brakensiek PTFs (1989) vs. the EC measurements; the data have been split in the two periods. The results show that in the first period, the performance of both models is poor. This is probably due to processes (such as cracking or soil crusting) not accounted for in the models. In the second period the simulations performance improves, though the estimate values show a systematic overestimation (probably because the agronomic and environmental conditions of the crop are always considered optimal). Similar results have been obtained for the other sets of soil parameters.

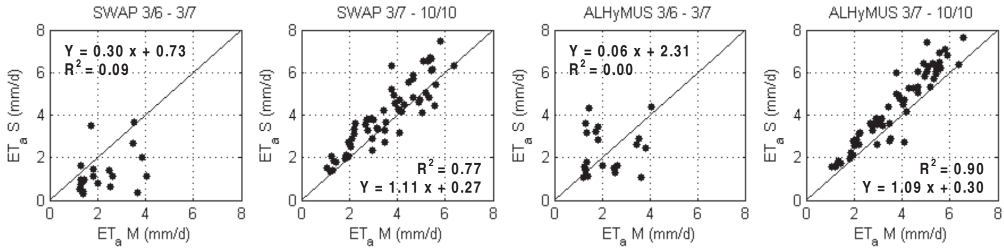

Figure 1. Evapotranspiration: measured values by EC technique (Et_a M) vs. simulated (Et_a S) by the two models using the PTFs of Rawls and Brakensiek (1989); periods 3/6/2006 - 3/7/2006 and 3/7/2006 - 10/10/2006.

B. Soil water content

The pattern of the soil moisture content in the root zone is very sensitive to the different sets of hydraulic parameters for both models. Figure 2 shows the simulated vs. measured values with the three sets. The best fit is very good for either SWAP and ALHyMUS and it is achieved with the set of parameters obtained applying the Rawls and Brakensiek PTFs (1989). On the contrary, the Rosetta set gives the worst performances for both models, but with these soil parameters SWAP systematically over-estimates soil moisture while ALHyMUS does the opposite. The behaviour of the models when the HYPRES set of parameters is adopted is similar, with a rather good performance and a general overestimation of the soil moisture values. These results demonstrate that when the soil water content in the root zone is considered, the choice of the method for deriving the soil hydraulic parameters may be more important than the choice of the model.

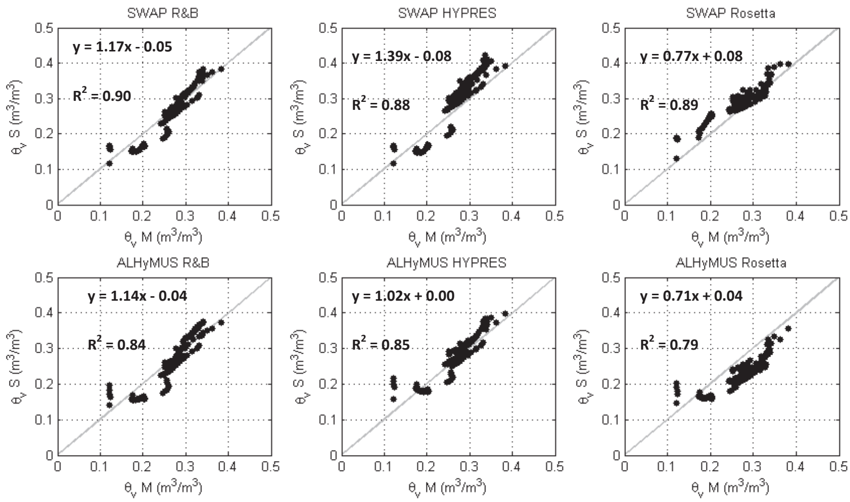

Figure 2. Soil moisture content in the root zone: measured values (θ_v M) vs simulated (θ_v S) by the two models implemented with the different sets of hydraulic parameters.

C. Bottom flux

Figure 3 shows the comparison between the simulated vs. the measured values of the daily flow at the bottom of the root zone which varies from 30 to 70 cm during the growing stages. The values simulated are the outputs of the two models implemented with the different sets of soil parameters. The values measured are obtained as residual terms of the daily hydrological balance by using the available measured values of soil water content and water inputs and outputs (i.e. rainfall, irrigation and evapotranspiration). Flows are significantly influenced by the very shallow water table and thus the monitoring period is characterized by an alternation of deep percolation (negative values in the figure) and capillary rise (positive values). The performance of both models is rather poor: in general the percolation flux is smoothed and delayed compared to the measured values and, especially in days immediately following intense precipitation or irrigation events, this flux are underestimated.

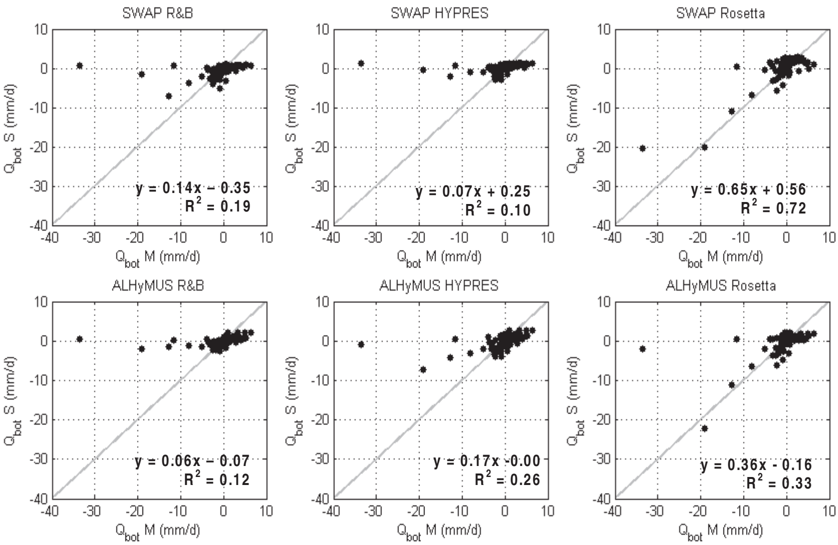

Figure 3. Bottom flux: measured values (Q_{bot} M) and simulated (Q_{bot} S) by the two models implemented with he different set of soil parameters.

IV – Conclusion

The results confirm the existence of a wide range of variation of the hydraulic parameter values obtained applying different PTFs. This is reflected in a high variability of SWAP and ALHyMUS output variables, which often is larger than the difference between the same output simulated by the two models adopting the same soil hydraulic parameters set.

The actual evapotranspiration rate at the experimental site is generally close to the potential. In this condition the hydraulic parameters don't play an important role and the output of the models obtained implementing the different sets of values are similar with a general overestimation of the evapotranspiration fluxes. Both models show a high sensitivity to the different sets of hydraulic parameters when the soil moisture content in the root zone is considered. The best performance is achieved with the PTFs of Rawls and Brakensiek (1989) for both models; these PTFs already proved to provide good results for the soil data of the central Padana plain (Calzolari *et al.*, 2001). When the flux at the bottom of the root zone is considered both models show to capture the influence of the shallow water table in terms of general pattern with each hydraulic parameters set. However, the accuracy of the simulated values is rather poor showing a general underestimation of the process. These general behaviour of overestimation of evapotranspiration and underestimation of the bottom flux suggest that a good agreement of soil moisture patterns may occur even if the performances of the models in the simulation of the fluxes are poor. Therefore multiple output variables shall be always considered to test the performances of methods and models.

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