Hydrol. Earth Syst. Sci. Discuss., 6, 4065–4105, 2009
www.hydrol-earth-syst-sci-discuss.net/6/4065/2009/

Hydrology and
Earth System
Sciences
Discussions

Uncertainty in the determination of soil hydraulic parameters and its influence on the performance of two hydrological models of different complexity

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Received: 12 May 2009 – Accepted: 22 May 2009 – Published: 4 June 2009

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Published by Copernicus Publications on behalf of the European Geosciences Union.

Abstract

Data of soil hydraulic properties forms often a limiting factor in unsaturated zone modelling, especially at the larger scales. Investigations for the hydraulic characterization of soils are time-consuming and costly, and the accuracy of the results obtained by the different methodologies is still debated. However, we may wonder how the uncertainty in soil hydraulic parameters relates to the uncertainty of the selected modelling approach.

We performed an intensive monitoring study during the cropping season of a 10 ha maize field in Northern Italy. These data were used to: i) compare different methods for determining soil hydraulic parameters and ii) evaluate the effect of the uncertainty in these parameters on different outputs (i.e. evapotranspiration, water content in the root zone, fluxes through the bottom boundary of the root zone) of two hydrological models with different complexity: SWAP, a widely used model of soil moisture dynamics in unsaturated soils based on Richards equation, and ALHyMUS, a conceptual model of the same dynamics based on a reservoir cascade scheme. We employed five direct and indirect methods to determine soil hydraulic parameters for each horizon of the experimental field. Two methods were based on a parameter optimization of: a) laboratory measured retention and hydraulic conductivity data and b) field measured retention and hydraulic conductivity data. Three methods were based on the application of widely used Pedo-Transfer Functions: c) Rawls and Brakensiek; d) HYPRES; and e) ROSETTA. Simulations were performed using meteorological, irrigation and crop data measured at the experimental site during the period June–October 2006.

Results showed a wide range of soil hydraulic parameter values evaluated with the different methods, especially for the saturated hydraulic conductivity K_{sat} and the shape parameter α of the Van Genuchten curve. This is reflected in a variability of the modeling results which is, as expected, different for each model. The variability of the simulated water content in the root zone and of the fluxes at the root zone bottom for different soil hydraulic parameter sets is found to be often larger than the difference be-

tween modeling results of the two models using the same soil hydraulic parameter set. Also we found that a good agreement in simulated soil moisture patterns may occur even if evapotranspiration and percolation fluxes are significantly different. Therefore multiple output variables should be considered to test the performances of methods and models.

1 Introduction

Water retention and hydraulic conductivity curves are crucial input parameters in any modelling study on water flow and solute transport. Computed water balances are very sensitive to soil hydraulic parameters and therefore their accurate determination is essential to model hydrological processes (Jhorar et al., 2004). Moreover, at most sites soil hydraulic parameters are characterized by a strong variability in both vertical and horizontal directions. Therefore a large number of data are required to properly describe the hydraulic properties of an area.

Due to these facts, over the last decades many studies have been devoted to the development of methods for estimating soil hydraulic parameters. In general, two categories of methods can be distinguished: (1) measurement techniques and (2) predictive methods (Haverkamp et al., 2006).

The first techniques rely on precise experimental procedures that can be categorized as being either laboratory- or field-based. Laboratory methods are based on the accurate measurement of flow processes, but they are generally performed on small soil samples and as a result their representativeness of field conditions can be questioned. In addition, the presence of stones, fissures, fractures, tension cracks, root holes, as commonly encountered in unsaturated soil profiles, is difficult to be captured in small-scale laboratory samples. Field techniques can be more difficult to manage and control, but they have the advantage of estimating more representative soil hydraulic properties.

However, despite the progress that has been achieved, the measurement techniques remain time consuming and costly, especially when data are needed for large areas (Wösten et al., 2001). For this reason the definition of reliable methods for estimating soil hydraulic properties in areas where the amount of available information is limited remains a key issue. This explains why 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 and van Lanen, 1987; Bouma, 1989), are particularly enticing as they are very well suited for large scale applications.

In general these relationships are based on statistical regression (Gupta and Larson, 1979; Rawls and Brakensiek, 1989; Cosby et al., 1984; Vereecken et al., 1989; Wösten et al., 1999; Saxton and Rawls, 2006, among the others), although some authors tried to develop more physically-based relationships (for instance: D'Urso and Basile, 1997). More recently some authors developed empirical relationships by using artificial neural networks (Minansi and McBratney, 2002; Schaap et al., 2001) or group methods of data handling (Pachepsky and Rawls, 1999); the advantage with these methods is that the identification of an a priori relation between input and output data is not needed.

In spite of the wide application of these methodologies, the reliability of the results obtained is still under discussion (see for instance: Tietje and Hennings, 1996; Romano, 1999). In most cases the methods are evaluated by comparing the values of selected soil hydraulic parameters obtained by the measurement techniques – supposed to be more accurate – with the indirectly estimated parameter values (Tietje and Tapkenhinrichs, 1993; Bastet et al., 1999; Nemes et al., 2003; Ungaro et al., 2005). These comparisons show that good performances can be obtained with predictive methods, but generally the results are site-specific. Therefore it is not possible to draw general conclusions about which methods are the best for a certain modeling purpose.

The direct comparison of parameter values does not provide information about their actual performance when used for specific applications, such as the simulation of soil moisture dynamics in agricultural fields. Therefore, rather than focussing on the direct comparison of parameter values, Wösten et al. (1986) proposed to use “functional criteria” directly related to specific applications. The basis for the identification of differences in hydraulic properties is 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). Islam et al. (2006) compared a set of measured soil water content values with three different sets of simulated values, computed by the spatial distributed MIKE SHE model with three different sets of hydraulic parameters. They showed that the model provides reasonable estimates only if the soil hydraulic parameters are estimated by using PTFs developed for the soils of the area. However, they pointed out that the best estimation method is yet to be identified because none of the considered methods can simulate soil water content data with a sufficient accuracy. In Gijsman et al. (2003) eight methods for estimating hydraulic parameters were compared using the functional approach for the prediction of crop yield by the CROPGRO-Soybean model. The authors showed that the discrepancy between estimations is so high that it is hard to make recommendations on which methods to use for which soils.

Cresswell and Paydar (2000) used the SWIM model with six different sets of hydraulic parameters. They showed that the error due to inaccurate hydraulic parameters tends not to be reflected in predicted soil water storage but instead in predicted drainage and evapotranspiration fluxes. This important result underlines that the use of profile water storage as the sole basis for functional comparison of methods may lead to misleading conclusions and that other water balance terms should also be into account. Vereecken et al. (1992) show that the uncertainty in hydraulic parameters results in a considerable variation of simulated soil moisture supply capacity and of the downward flux below the root zone. Soil variance component analysis indicated that about 90% of the variability of the moisture supply capacity for a map unit is due to the estimated hydraulic parameters. This variability was larger than the with-in map-unit variability of soil properties. Similar results were shown by Christiaens and Fejen (2001). Also Workmann and Skaggs (1994) used two hydrological models of different complexity and considered uncertainty in the parameters sets. The results pointed out that model concept uncertainty is less important than input parameter uncertainty.

In order to further explore these issues, in this study data collected in an intensive monitoring campaign were used to: i) compare five direct and indirect methods for deriving the values of soil hydraulic parameters and ii) evaluate the effect of the uncertainty in the determination of these parameters with respect to the resulting uncertainty in the outputs of two hydrological models of different complexity: SWAP (Kroes and van Dam, 2003) based on the numerical solution of the Richards equation, and ALHyMUS (Facchi et al., 2004; Gandolfi et al., 2006) based on a reservoir cascade scheme. Simulations were run for each model and each parameter set using inputs and crop parameters measured in a 10 ha maize field. Daily measurements of evapotranspiration, mean soil moisture content in the root zone and soil water flux at the root zone bottom monitored in the field were used to test the performances of the methods to determine soil hydraulic parameters and the effects of their use in the two hydrological models.

2 Materials and methods

2.1 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), in the experimental farm A. Menozzi of the Agricultural Faculty of the State University of Milan (45°19′ N, 9°15′ E, 88 m a.s.l.).

Instruments for detailed monitoring of water and energy fluxes were installed in the experimental field in 2005. A micrometeorological eddy-correlation (EC) based station was located in the centre of the field. The station was equipped with: a 4-component radiometer (Kipp & Zonen CNR-1), an infrared gas analyzer (LI-COR 7500) and a 3-D sonic anemometer (RM-81000V Young). Soil heat flux monitoring with heat flux plates (Hukseflux HFP01) and soil thermocouples (ELSI) allowed to close the surface energy balance.

A vertical trench was dug close to the tower site to characterize the soil profile and to collect samples for standard soil analyses and undisturbed samples for laboratory retention and hydraulic conductivity determinations. After that, in order to monitor the soil water dynamics, time-domain reflectrometry (TDR) sensors (CS616 Campbell Sci.) and tensiometers (SKYE) were installed in the profile at the depths of 5, 20, 35, 50 and 70 cm and 20, 35 and 70 cm, respectively. Due to the presence of a shallow water table 90–120 cm below the soil surface, a shallow piezometer with a pressure transducer device (STS) was installed as well. Standard meteorological devices and PAR sensors completed the equipment. Spatially distributed measures of Leaf Area Index LAI (–), crop height h_c (m), and rooting depth D_r (m), were conducted periodically to characterize the crop in the field. Moreover, saturated hydraulic conductivity K_{sat} (cm h^{-1}) was determined at depths of 20, 35 and 70 cm by means of a Guelph permeameter.

During the cropping season 2006 there were two irrigation treatments: the first one on 8 June with the sprinkler method to promote crop emergence, and the second one on 14 July with the border method. At the first irrigation, the amount was estimated by the increase of the measured soil moisture, yielding an irrigation amount of 20 mm. At the second irrigation, the canal water discharge was monitored by an electromagnetic flow sensor (Nautilus – OTT), yielding an irrigation amount of 140 mm. The run-off was negligible in the entire monitoring period. A summary of the main data collected at the monitoring site is shown in Table 1. Texture and organic matter measurements for the horizons identified in the soil profile are reported in Table 2.

2.2 SWAP model

The soil-water-atmosphere-plant (SWAP) model 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:

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

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) is subjected 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 were used (Van Genuchten, 1980; Mualem, 1976):

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

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

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}), n (–), and m are empirical shape factors, 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.

Canopy interception is calculated according to Braden (1985) as a function of the Leaf Area Index (LAI). SWAP includes both a simple and detailed crop growth module. We used the simple crop module, in which crop growth is prescribed by LAI, crop height and rooting depth as functions of crop development stage. The potential evapotranspiration rate ET_p (mm d^{-1}) is estimated by the Penman-Monteith equation (Monteith, 1965; Allen et al., 1998). In field conditions where crops partly cover the soil, 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).

2.3 ALHyMUS model

The soil water 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 represents the upper part of the soil profile in which infiltration, evaporation and percolation to the subsequent reservoir take place; the second reservoir 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) may vary in time, depending on the fluctuations of phreatic levels.

Canopy interception is evaluated by the Braden formula (Braden, 1985). Evaporative and transpirative rates are computed using the FAO-56 dual crop coefficient method (Allen et al., 1998). A one-dimensional 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, similar to those used in other conceptual models (see e.g. ANSWERS2000 – Bouraoui et al., 1997; EPIC – Williams et al., 1984), which considers a Darcian-type gravity flow; the relationship between the unsaturated hydraulic conductivity and the water content is modelled by Eq. (3). The influence of a shallow groundwater table is accounted for by the formula proposed by Liu et al. (2006), which gives the capillary rise G_c (mm d^{-1}) from the groundwater surface to the transpirative reservoir as a function of the water content in the reservoir θ_v (–), the rate of potential evapotranspiration ET_p (mm d^{-1}), and the groundwater depth D (cm). Finally, all these terms are included in the daily water balance equations of the reservoirs, which are solved by an implicit iterative procedure.

2.4 Soil hydraulic parameters

Five different methods were used to estimate the soil hydraulic parameters θ_s, θ_r, α, n, L and K_{sat}: parameter optimisation of retention and hydraulic conductivity data measured both in laboratory and in the field, and three well-known Pedo-Transfer Functions applied to commonly available field measurements of chemical-physical soil properties: Rawls and Braekensiek (1989), HYPRES (Wösten et al., 1999), ROSETTA (Schaap et al., 2001). The methods are coded in the text as LAB, f, RB, H and Ro respectively.

2.4.1 Laboratory measurements

Laboratory measurements were performed on undisturbed soil cores with diameter d=7.5 cm and height h=5 cm taken from each soil horizon (two replicates). For each soil core, saturated hydraulic conductivity K_{sat} (cm h^{-1}) was determined by the standard constant head technique (Reynolds et al., 2002); water contents θ corresponding to pressure head values ranging from −5 to −15 000 cm were determined by a hanging water column apparatus (Burke et al., 1986) for pressure heads higher than −1000 cm and a pressure plate apparatus (Dane and Hopmans, 2002) for lower pressure heads. The water retention function of Van Genuchten (1980) was fitted to the measured θ-h values using the RETC code (van Genuchten et al., 1991). The unsaturated hydraulic conductivity relationship was determined by using the water retention parameters plus the measured saturated hydraulic conductivity, according to the Mualem-Van Genuchten model (van Genuchten, 1980).

2.4.2 Field measurements

Simultaneous field measurements of soil moisture by TDR and pressure head by tensiometers were collected in the experimental site at the depths of 20, 35 and 70 cm. The water retention function of Van Genuchten (1980) was fitted to the field measured θ-h values using the RETC code (van Genuchten et al., 1991). Saturated hydraulic conductivity K_{sat} (cm h^{-1}) was measured by a Guelph permeameter at the same depths as the monitored θ-h values. As in the case of the laboratory measurements, the unsaturated hydraulic conductivity relationship was determined by using the water retention parameters plus the saturated hydraulic conductivity, according to the Mualem-Van Genuchten model (van Genuchten, 1980).

2.4.3 Pedo-Transfer functions

Three widely used Pedo-Transfer Functions were applied to the texture and organic matter measurements available for the experimental profile (Table 2). The first one is the PTF of Rawls and Braekensiek (1989), based on non-linear multiple regression equations. Ungaro and Calzolari (2001) showed that these PTFs, even if based on US soils data base, have a good performance also for soils of the Central Padana Plain (Northern Italy).

The second PTF used is the so-called HYPRES (Wösten et al., 1999), derived by multiple regression techniques as well, but using European data base of soils (although no data on soils of Northern Italy are included).

The third PTF set used is ROSETTA (Schaap et al., 2001), developed by the United States Salinity Laboratory using a neural network, and based on US soil data.

The bulk density ρ_b (g cm^{-3}) used in the PTFs was estimated from the organic matter OM (%) values (Table 2) by the relationship proposed by Jeffrey et al. (1970) which showed to provide good results for the soils data of the area (ERSAL, 2001).

2.5 Models inputs and parameters

The models were run with the different sets of soil parameters and other input data for the period 6 June–10 October 2006. Measured meteorological and irrigation data were used for the simulations. Daily patterns of crop height h_c (m), Leaf Area Index LAI (–) and rooting depth D_r (m) were obtained by linear interpolation of the field data collected during the cropping season (Fig. 1). The daily pattern of K_{cb} (–) (basal crop coefficient, see Allen et al., 1998), used by ALHyMUS to compute the transpiration rate T_p (cm d^{-1}), was estimated on the basis of literature values (Allen et al., 1998; Huygen et al., 1997; Borgarello et al., 1993) and adapted to the cropping stages observed in the field (Fig. 1). Table 3 shows the additional crop parameters needed 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 stress due to wet condition which was not taken into account, whereas the canopy resistance 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) from the Total Available Water (TAW) (Allen et al., 1998) are those proposed in literature for maize.

For the SWAP model the soil profile was schematized in five horizons, having the main characteristics reported in Table 2. Soil hydraulic parameters for each horizon were determined using the five methods illustrated above. For the method based on the field measurements, there's no a strict correspondence between measured values and horizons (see Fig. 2); for that case the retention and unsaturated conductivity curves obtained for the depth of 20 cm were also used for the 1st layer (0–10 cm) and those obtained for the depth of 70 cm were also used for the 3rd layer (40–55 cm).

Soil moisture at field capacity θ_{FC} (–) and at wilting point θ_{WP} (–) used by ALHyMUS to evaluate the Total Available Water (TAW) and the Total Evaporable Water (TEW) (Allen at al., 1998) were obtained for each horizon with Eq. (3), using pressure head values of −100 cm and −8000 cm, respectively.

Soil hydraulic parameters for the ALHyMUS reservoirs were computed from those determined for each horizon: in particular, for each reservoir, the arithmetic mean of the values of the soil hydraulic parameters of the horizons belonging to the reservoir, weighted by their thickness, was calculated. This approach was adopted for all the parameters except for the saturated hydraulic conductivity, for which the geometric mean was computed.

In both models the initial moisture conditions were fixed at the measured profile values at the beginning of the simulation period and the bottom boundary condition was prescribed according to daily measurements of groundwater levels.

2.6 Performance evaluation

SWAP and ALHyMUS were implemented with the five different sets of soil hydraulic parameters described above resulting in a total of ten model-data sets, as summarized in Table 4. Daily measurements of evapotranspiration, mean soil moisture in the root zone and flux at the bottom of the root zone collected in the field were used to test the performance of the five methods and of the two models. The statistical evaluation was carried out using the normalized root mean square error (NRMSE) and the mean error (ME) calculated from simulated and observed daily values for the period 6 June to 10 October 2006 respectively as:

$$\mathrm{NRMSE} = \frac{\mathrm{RMSE}}{\sigma} = \sqrt{\frac{\sum_{i=1}^{N}(s_i - m_i)^2}{\sum_{i=1}^{N}(m_i - \bar{m})^2}} \tag{4}$$

$$\mathrm{ME} = \frac{1}{N}\sum_{i=1}^{N}(s_i - m_i) \tag{5}$$

where m_i are the measured values, $\bar{m}$ and σ their mean and standard deviation, s_i the simulated values, and N is the number of data points.

Simulation is perfect (i.e. $m_i = s_i$) if NRMSE is zero; predictions are worse than using the mean of observed values if NRMSE is greater than one. Simulation shows a systematic over estimation if ME is positive and a systematic under estimation if ME is negative.

The same indices were also used to compare pairs of simulations obtained running either the same model with two different parameters sets, or the two models with the same parameters set; in these cases m_i and $\bar{m}$ were simulated values as well.

3 Results

3.1 Comparison of soil hydraulic parameters

Figure 2 illustrates the retention and the hydraulic conductivity functions at different depth obtained by introducing soil hydraulic parameters into the equations of Van Genuchten (1980) and Mualem (1976), respectively. Table 5 shows mean and variation coefficient for the parameters determined using the five methods.

The results confirm the existence of a wide range of variation for the parameter values in the different sets, remarkably in the case of saturated 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 (e.g. Jhorar et al., 2004).

Concerning the retention curves, PTFs RB in most of cases predict larger θ_s than the other methods. Due to relatively high α and n values, causing a steep decline in the curve, the method nevertheless provides comparable soil water contents θ for high suction values. Similar observations apply to K_{sat} and to the unsaturated conductivity curve; also in that case, due to the steepness of the curve, $K(\theta)$ values at lower water contents are comparable with those obtained by the other methods.

The PTF H results in lower θ_s and K_{sat} than PTF RB at almost all the different depths, but the overall patterns of retention and unsaturated conductivity curves are similar to those predicted by the latter method; the retention curves generally show a more moderate and prolonged decline of water content with suction.

The retention curves provided by PTF Ro are generally characterized by lower values of θ_s and a shape similar to the curves predicted by PTF H. The unsaturated conductivity curve is characterised by low values of K_{sat} and θ_s but, due to the shape parameters, the $K(h)$ values are often higher than those obtained with the other indirect methods.

The retention derived from laboratory measurements of h-θ show smaller θ_s values than those given by other methods, but generally show a more moderate and prolonged decline of water content with suction. The unsaturated conductivity curves are characterised by smaller values of K_{sat} except for the 4th layer for which the value is considerably higher. However, in all the layers the values of $K(h)$ at high suction values are generally higher then those obtained with the other methods.

The retention curves derived from field measurements of h-θ show values of θ_s within the range of those obtained with the other methods but the behaviour of the curve is quite different. In the 2nd horizon, at the higher h values, $\theta(h)$ values tend to become higher than those derived by applying the other methods, while for the 4th horizon the opposite occurs.

The unsaturated conductivity based on field measurements are characterised by smaller values of K_{sat} in comparison with the curves obtained by the other methods. For surface horizons the values of $K(h)$ remain lower than those predicted with the other methods for the whole range of h; for the 4th horizon $K(h)$ increases at higher suctions in comparison for example to PTFs RB. It is important to stress that since the soil water content in the field was always relatively high during the monitoring period – and this was particularly true for deeper layers due to the presence of the shallow groundwater table – at higher suctions the representativeness of the two curves obtained with these values can be questioned.

3.2 Performance evaluation

3.2.1 Evapotranspiration

In field conditions actual evapotranspiration rate is generally very close to the potential rate. In this specific situation the soil hydraulic parameters are not influencing significantly the evapotranspiration flux, therefore the model outputs obtained with the different sets of parameter values are very similar (Fig. 3). All the outputs fit rather well with the EC evapotranspiration measurements and in all the cases the values of NRMSE are smaller then one. However, with all the soil hydraulic parameters sets and for both models, a systematic overestimation is shown (i.e. positive ME values in Fig. 8).

More insight can be achieved by splitting the crop season into two periods: Fig. 4 shows the measured evapotranspiration values vs. the simulated values obtained with the two models implemented with the RB parameter-set; similar results were obtained implementing the models with the other sets of soil hydraulic parameters. In the first period when the crop is small and soil evaporation is more important than crop transpiration (approximately from the emergence to the beginning of July), the fitting is bad (NRMSE=1.46 and 1.41, respectively for SWAP and ALHyMUS). However, the systematic error in ALHyMUS is always positive but small (ME=0.14 mm d^{-1}); on the contrary, SWAP underestimates the process (ME=−0.88 mm d^{-1}). In this first period the soil characteristics of the upper portion of the profile (i.e. 10–15 cm) and the water availability play the most important role in the determination of the evapotranspirative flux. The poor performance is probably due to the presence of soil crusting and macroporosity, which were observed in the field but not accounted for in the two models. However, further research is needed to better investigate this issue.

In the second period (from the beginning of July to the harvest), the transpiration is the dominant process and the models performances are higher (NRMSE=0.76 and 0.59, respectively for SWAP and ALHyMUS); however, both models show a systematic overestimation of the evapotranspirative flux (ME=0.68 mm d^{-1} and 0.66 mm d^{-1}, respectively for SWAP and ALHyMUS). Different factors may have contributed to these results, among which the accuracy of crop parameters values and the actual environmental condition. Indeed, while nutrients limitation or soil salinization can be excluded, recent investigations in the area (e.g. Gerosa et al., 2003) showed that atmospheric pollution can inhibit the transpiration process.

A last consideration is related to the fact that, although the performances of the two models are generally good in the second period, SWAP tends to overestimate the evapotranspiration after intense rainfall or irrigation events (e.g. the days after the surface irrigation event: DoY=195 in Fig. 3); improvements could be obtained by calibrating the stress coefficients for wet conditions (i.e. setting non-zero values for the parameters $H_{\text{lim}}1$ and $H_{\text{lim}}2$ in Table 3).

3.2.2 Soil water content

The pattern of the simulated and measured values of the average soil moisture in the root zone and the corresponding efficiency indices are shown in Figs. 5 and 8, respectively. It can be noticed that both models show a high sensitivity to the different sets of hydraulic parameters in the simulation of the soil moisture content in the root zone. In some cases the performances are very good either for SWAP and for ALHyMUS: NRMSE of 0.53 and 0.44 and ME of −0.004 (m^3/m^3) and 0.011 (m^3/m^3) were found for the two models respectively with the parameters sets of RB and Lab. The ALHyMUS simulations show a good agreement with the observations also when H and RB parameters sets are used, while only Ro parameters provide model performances close to RB in the case of SWAP. The ranges of variation of the two performance indices is quite large and of the same order for the two models (NRMSE 0.53÷1.23 and ME −0.004÷0.064 for SWAP; NRMSE 0.43÷0.82 and ME −0.039÷0.034 for ALHyMUS). It is worth observing that the performances of parameters sets derived by PTFs are similar – or even better in the case of SWAP – to those of parameters sets obtained by direct methods.

The NRMSE and ME indices were computed also by coupling in all possible ways the different simulations of each of the two models (displayed in Fig. 5) and by comparing the pairs of simulations of the two models sharing the same set of parameters (of which Fig. 6 shows, as an example, the closest and most distant pairs). These results (Table 6) reveal that the range of within model variability, due to the choice of a different parameters set for a given model, is often wider than the range of intra-model variability, due to the choice of the model for a given parameter set.

3.2.3 Bottom flux

Figure 7 shows the comparison between the simulated and the "observed" values of the daily flow at the bottom of the root zone (whose depth increases from 30 to 70 cm during the crop growing stages, as shown in Fig. 1). The "observed" values of the flux are indeed obtained as residual terms of the daily hydrological balance computed by using the available measurements of soil water content and water inputs and outputs (i.e. rainfall, irrigation and evapotranspiration). Figure 8 shows the values of the efficiency indices calculated for the days in which the flow at the bottom of the root zone computed by the hydrological balance is available.

Flow is significantly influenced by the shallow water table and thus the monitoring period is characterized by an alternation of deep percolation and capillary rise. Although the number of observations of the bottom flux is rather limited, the results show clearly that both models succeed in capturing the daily pattern, but the overall performances are generally rather poor (i.e. NRMSE values between 0.5 and 1).

The best performances in terms of NRMSE are achieved in SWAP with the field parameters set and in ALHyMUS with Ro parameters set, although the fluxes are underestimated (negative ME values). For the SWAP model small ME values are obtained with RB parameters sets, although the estimated flux pattern turns out to be more delayed and smoothened. ALHyMUS performs reasonably well also with H and RB parameters sets, as it was the case for the soil water content in the root zone. The results provided by ALHyMUS also show that the empirical relation used for the capillary rise (Liu et al., 2006) can reproduce the process in a realistic way, even if the parameters were taken from literature and not calibrated.

The NRMSE and ME indices were computed also by coupling in all possible ways the different simulations of each of the two models (displayed in Fig. 8) and by comparing the pairs of simulations of the two models sharing the same set of parameters. These results (Table 7) confirm that, also in the case of the bottom flux, the range of within model variability, due to the choice of different parameter sets for a given model, is often wider than the range of intra-model variability, due to the choice of the model for a given parameter set.

4 Discussion and conclusions

The information collected during an intensive monitoring activity at a 10 ha maize field located in Northern Italy was 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 output of two hydrological models of different complexity: SWAP, a widely used model of soil moisture dynamics in unsaturated soils based on Richards equation, and ALHyMUS, a conceptual model of the same dynamics based on a reservoir cascade scheme.

Each model was implemented with five different sets of retention and unsaturated hydraulic conductivity curves, as determined by: i) parameter optimization using laboratory measured data; ii) parameter optimization using field measured data; iii) PTF of Rawls and Brakensiek (1989); iv) PTF of HYPRES (Wösten et al., 1999); and v) PTF of ROSETTA (Schaap et al., 2001). Simulations were run using meteorological, irrigation and crop data measured at the experimental site for the period June–October 2006. The comparison was focused on three output variables: evapotranspiration, water content in the root zone and flow at the bottom of the root zone.

The results show a high variability of the soil hydraulic parameter values in the different sets, especially in case of the saturated hydraulic conductivity K_{sat} (cm h^{-1}) and of the shape parameter α (cm^{-1}).

Despite of this variability, the evapotranspiration fluxes simulated by the two models with the different sets of parameters are very similar. This is caused by the fact that when the actual evapotranspiration rate is close to the potential, as in the irrigated soil monitored in the study, soil hydraulic parameters play a minor role in the evapotranspiration process. Observing the results, the simulation period can be split in two subperiods. In the first one, when evaporation process is predominant over transpiration, the performance of both models is poor and they tend to underestimate the process. This is probably due to the occurrence of soil crusting, that was observed in the field but not accounted for in the two models. In the second period, when transpiration is predominant (i.e. high value of the soil cover fraction) the quality of the simulations improve, though both models show a systematic overestimation of the process, which might be due to non-optimal choice of crop parameters or to the occurrence of environmental stress factors (e.g. high ozone concentrations), which were not taken into account in the simulations.

Both models show an high sensitivity to the choice of the set of hydraulic parameters when the soil moisture content in the root zone is considered. The range of variation of the soil moisture values simulated with the different parameters sets is similar for the two models and it is generally larger than the range of variation of the soil moisture simulated by the two models with the same parameters set, for all the five sets. Both models replicate quite well the time pattern of observed soil moisture, though SWAP simulations show a systematic overestimation of soil moisture. The best performances are achieved either for SWAP and for ALHyMUS with sets of hydraulic parameters obtained with indirect methods (PTFs), even if not necessarily the same set for the two models. Good results for ALHyMUS are also achieved with the parameters set obtained from laboratory data.

When the flux at the bottom of the root zone is considered, both models show a fairly good capability to capture the influence of the shallow water table on the alternation of capillary rise and percolation fluxes at the bottom boundary over the simulation time, regardless of the parameters set. However, the accuracy of the simulated values is generally rather poor.

These results suggest that the wide range of variation in the soil hydraulic parameter values obtained with the five different methods is reflected in a high variability in the values of soil water content and flux at the bottom of the root zone predicted by SWAP and ALHyMUS. This variability is often larger than the difference between the values of the same output variables for the two models, demonstrating that, when looking at the

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soil moisture or at the bottom flux dynamics, the choice of the method for deriving the values of the soil hydraulic parameters may be more important than the choice of the model.

A further observation concerns the opportunity to consider multiple output variables in the evaluation of parameterization methods and of models performances. Indeed this evaluation is often based on the comparison of measured and computed soil moisture patterns (see e.g. Starks et al., 2003); however, this may lead to ambiguous conclusions because a good agreement of soil moisture patterns may occur even if evapotranspiration and flux at the bottom of the soil profile are badly simulated. This was already highlighted by Cresswell and Paydar (2000) and is confirmed also in our study: Fig. 8 proves that a good agreement between the computed and observed values of the daily average soil water content in the root zone is achieved by the simulations S-RB, S-Ro, A-Lab, A-H and A-RB; despite of this, the same figure shows that some of these simulations significantly overestimate evapotranspiration and underestimate fluxes at the bottom of the root zone. Clearly the errors in surface and bottom fluxes compensate each other, at least to a certain extent, and cannot be captured by looking just at soil moisture patterns. Therefore, multiple output variables should be considered for the evaluation of methods and models.

Finally, it is important to stress that when the models can not be calibrated with local measurements, soil hydraulic parameters obtained with direct methods do not necessarily guarantee the best performances. Indeed, for the specific case of the experimental profile, the use of PTFs based on site-specific texture and organic matter data did provide comparable results with both the tested models; in particular it emerged that the PTF of Rawls and Brakensiek (1989) give good performances in the simulation of all the outputs with both models, confirming previous observations of Ungaro and Calzolari (2001) for the soil data of Northern Italy.

Acknowledgements. The authors wish to thank Fondazione CARIPLO and MIUR for funding the research, respectively through the TwoLe grant and PRIN-2006 grant.

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Table 1. Summary of the main data collected at the monitoring site (3 June–10 October 2006).

Cumulative rain	429 mm
Mean temperature	21°C
Crop	Zea Maize
Emergence	6 Jun 2006 (DoY=157)
Harvesting	10 Oct 2006 (DoY=283)
$\mathrm{LAI}_{\mathrm{max}}$	4.2
Crop $\mathrm{height}_{\mathrm{max}}$	3.00 m
Rooting $\mathrm{depth}_{\mathrm{max}}$	0.70 m
Sprinkler irrigation event	8 Jun 2006 (DoY=159); 20 mm
Surface irrigation event	14 July 2006 (DoY=195); 140 mm
Water table depth	0.90–1.20 m

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

Depth (cm)	0–10	10–40	40–55	55–90
Horizons (USDA classif.)	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

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Table 3. Crop parameters values used by SWAP and ALHyMUS models (variables are explained in the text).

SWAP						SWAP and 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

Table 4. Summary of the simulations for the performance analysis.

Code	Description
M	Measured values
S-L	SWAP with parameters from laboratory measurements
S-f	SWAP with parameters from field measurements
S-H	SWAP with parameters from the application of PTFs HYPRES
S-RB	SWAP with parameters from the application of PTFs of R&B
S-Ro	SWAP with parameters from the application of PTFs Rosetta
A-L	ALHyMUS with parameters from laboratory measurements
A-f	ALHyMUS with parameters from field measurements
A-H	ALHyMUS with parameters from the application of PTFs HYPRES
A-RB	ALHyMUS with parameters from the application of PTFs of R&B
A-Ro	ALHyMUS with parameters from the application of PTFs Rosetta

Table 5. Statistics for the soil hydraulic parameters determined using the five methods.

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	0.28	0.07	0.03	1.402	0.050	5.8	−0.187
	CV	*12%*	*16%*	*18%*	*10%*	*3%*	*72%*	*89%*	*−341%*
10–40	mean	0.45	0.28	0.09	0.03	1.351	0.057	5.5	0.162
	CV	*12%*	*14%*	*28%*	*7%*	*7%*	*91%*	*77%*	*338%*
40–55	mean	0.42	0.29	0.08	0.03	1.448	0.029	2.6	0.049
	CV	*18%*	*12%*	*14%*	*9%*	*7%*	*98%*	*79%*	*1080%*
55–90	mean	0.38	0.31	0.12	0.05	1.448	0.019	0.4	−0.336
	CV	*8%*	*12%*	*38%*	*46%*	*16%*	*63%*	*89%*	*−386%*

Table 6. NRMSE and ME for soil water content in the root zone (simulated vs. simulated values).

		S-Lab	S-f	S-H	S-RB	S-Ro	A-Lab	A-f	A-H	A-RB	A-Ro
S-Lab	NRMSE		0.45	0.83	1.12	0.92	1.17				
	ME		*−0.002*	*0.036*	*0.063*	*0.040*	*0.050*				
S-f	NRMSE	0.63		0.62	0.98	1.03		0.57			
	ME	*0.002*		*0.038*	*0.066*	*0.042*		*0.028*			
S-H	NRMSE	1.55	0.84		0.42	1.14			0.47		
	ME	*−0.036*	*-0.038*		*0.027*	*0.004*			*0.013*		
S-RB	NRMSE	1.79	1.13	0.36		1.05				0.16	
	ME	*−0.063*	*−0.066*	*−0.027*		*−0.023*				*0.001*	
S-Ro	NRMSE	0.92	0.74	0.61	0.65						1.40
	ME	*−0.040*	*−0.042*	*−0.004*	*0.023*						*0.058*
A-Lab	NRMSE	1.33						0.43	0.21	0.40	0.62
	ME	*−0.050*						*−0.024*	*−0.001*	*0.015*	*0.048*
A-f	NRMSE		0.64				0.59		0.39	0.56	0.89
	ME		*−0.028*				*0.024*		*0.023*	*0.038*	*0.072*
A-H	NRMSE			0.34			0.25	0.35		0.29	0.45
	ME			*−0.013*			*0.001*	*−0.023*		*0.015*	*0.049*
A-RB	NRMSE				0.15		0.53	0.55	0.32		1.03
	ME				*−0.001*		*−0.015*	*−0.038*	*−0.015*		*0.033*
A-Ro	NRMSE					1.35	0.95	1.08	0.84	0.65	
	ME					*−0.058*	*−0.048*	*−0.072*	*−0.049*	*−0.033*	

Table 7. NRMSE and ME for flux at the bottom of the root zone (simulated vs. simulated values).

		S-Lab	S-f	S-H	S-RB	S-Ro	A-Lab	A-f	A-H	A-RB	A-Ro
S-Lab	NRMSE		0.92	3.01	3.48	1.11	1.49				
	ME		*0.220*	*−0.290*	*0.132*	*−0.017*	*0.170*				
S-f	NRMSE	0.61		1.86	2.10	0.67		2.02			
	ME	*−0.220*		*−0.510*	*−0.088*	*−0.237*		*−0.268*			
S-H	NRMSE	0.92	0.86		1.10	0.35			0.96		
	ME	*0.290*	*0.510*		*0.422*	*0.273*			*0.424*		
S-RB	NRMSE	1.01	0.91	1.04		1.02				1.56	
	ME	*−0.132*	*0.088*	*−0.422*		*−0.149*				*−0.146*	
S-Ro	NRMSE	0.52	0.80	2.75	3.19						1.70
	ME	*0.017*	*0.237*	*−0.273*	*0.149*						*0.532*
A-Lab	NRMSE	0.78						1.35	1.34	3.16	0.67
	ME	*−0.170*						*−0.218*	*−0.036*	*−0.184*	*0.345*
A-f	NRMSE		0.79				0.67		0.23	0.99	0.62
	ME		*0.268*				*0.218*		*0.182*	*0.034*	*0.563*
A-H	NRMSE			0.86			0.70	0.25		1.09	0.54
	ME			*−0.424*			*0.036*	*−0.182*		*−0.148*	*0.381*
A-RB	NRMSE				0.78		0.88	0.55	0.58		0.83
	ME				*0.146*		*0.184*	*−0.034*	*0.148*		*0.529*
A-Ro	NRMSE					0.86	0.59	1.10	0.91	2.64	
	ME					*−0.532*	*−0.345*	*−0.563*	*−0.381*	*−0.529*	

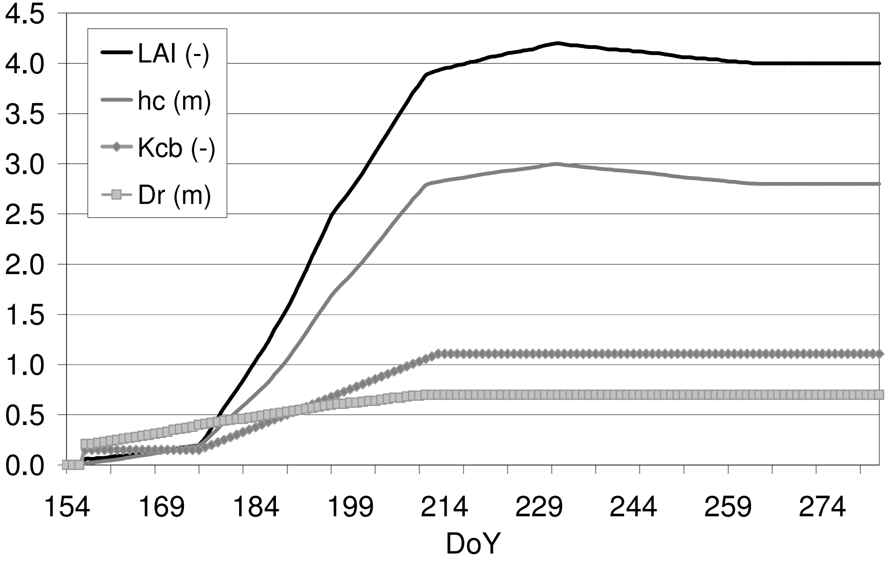

Fig. 1. Daily patterns of the following crop parameters for maize at the monitoring site: LAI ($\mathrm{m}^2\,\mathrm{m}^{-2}$), D_r (m), h_c (m) and K_{cb} (–).

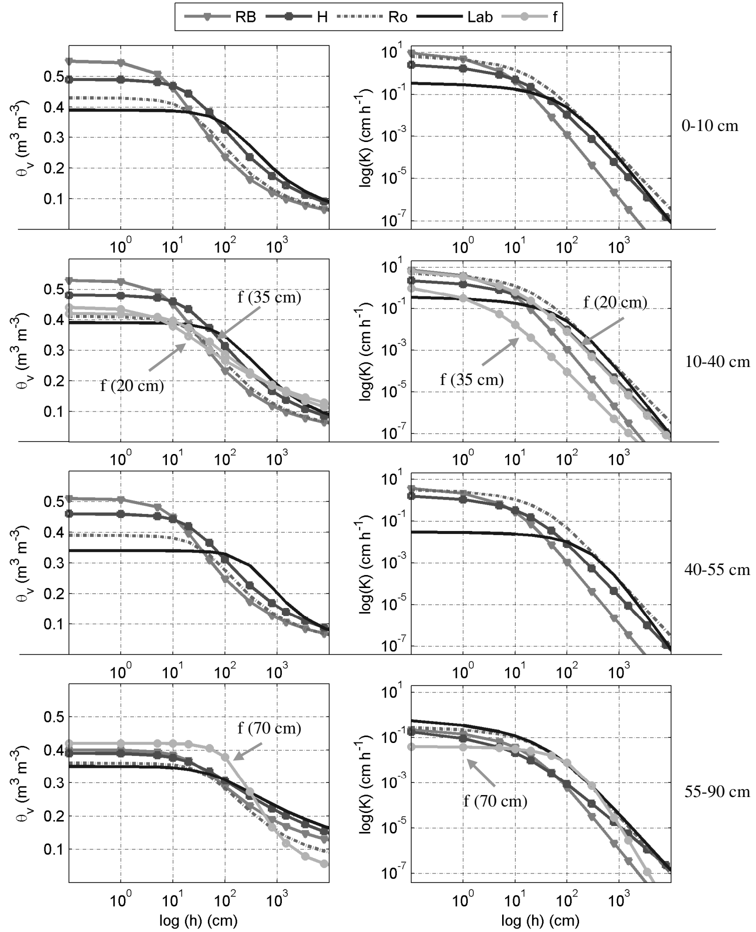

Fig. 2. Retention curves and hydraulic conductivity curves determined by using the five methods at the soil depths: 0–10 cm, 10–40 cm, 40–55 cm, 55–90 cm.

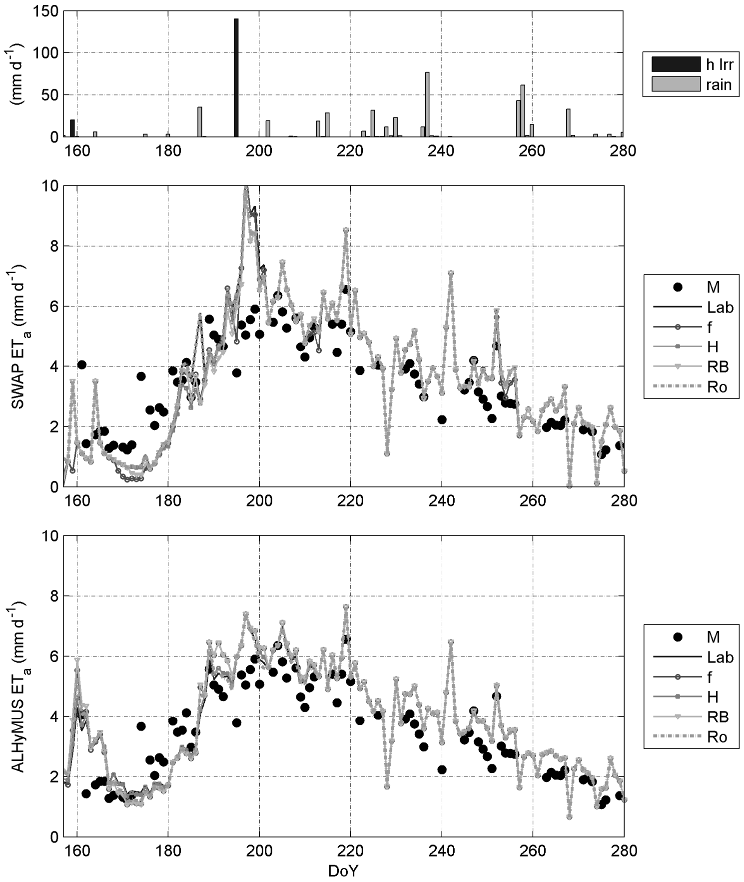

Fig. 3. Water inputs (1) and evapotranspiration simulated and measured by EC (2), (3).

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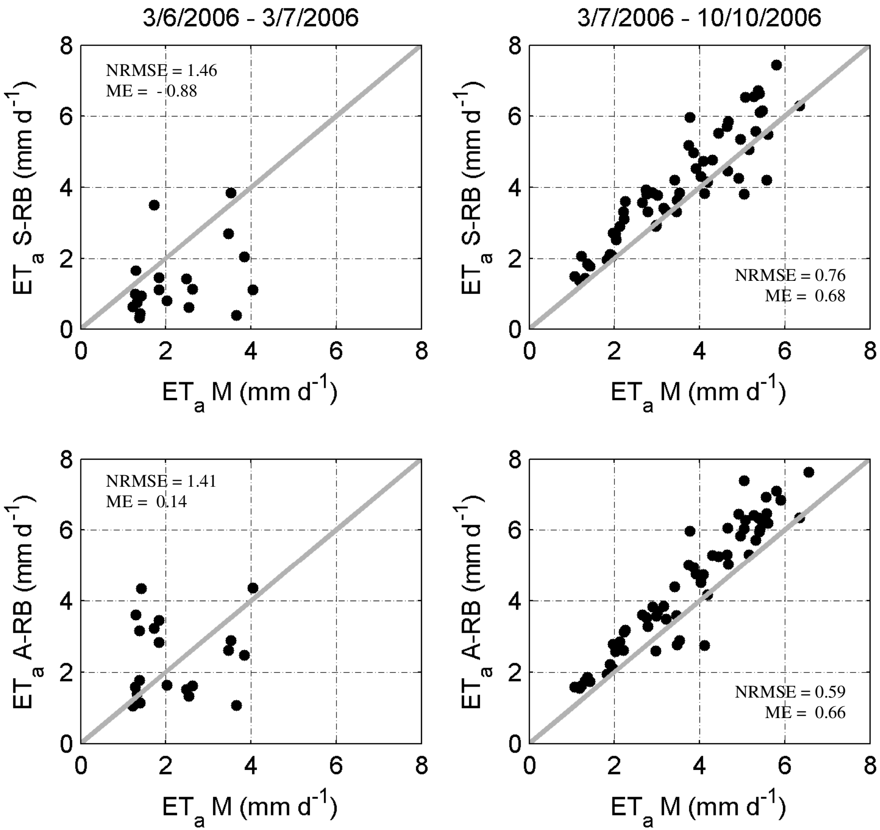

Fig. 4. Evapotranspiration measured by EC versus A-RB and S-RB simulations for the period 3 June–3 July and 3 July–10 October 2006.

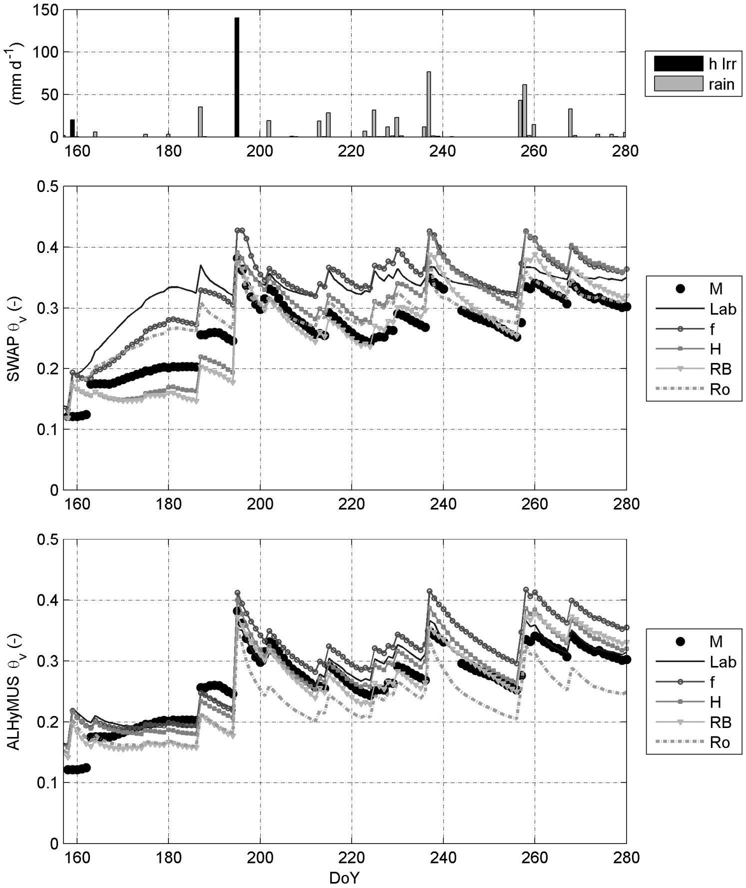

Fig. 5. Water inputs (1) and average soil water content in the root zone simulated and measured (2), (3).

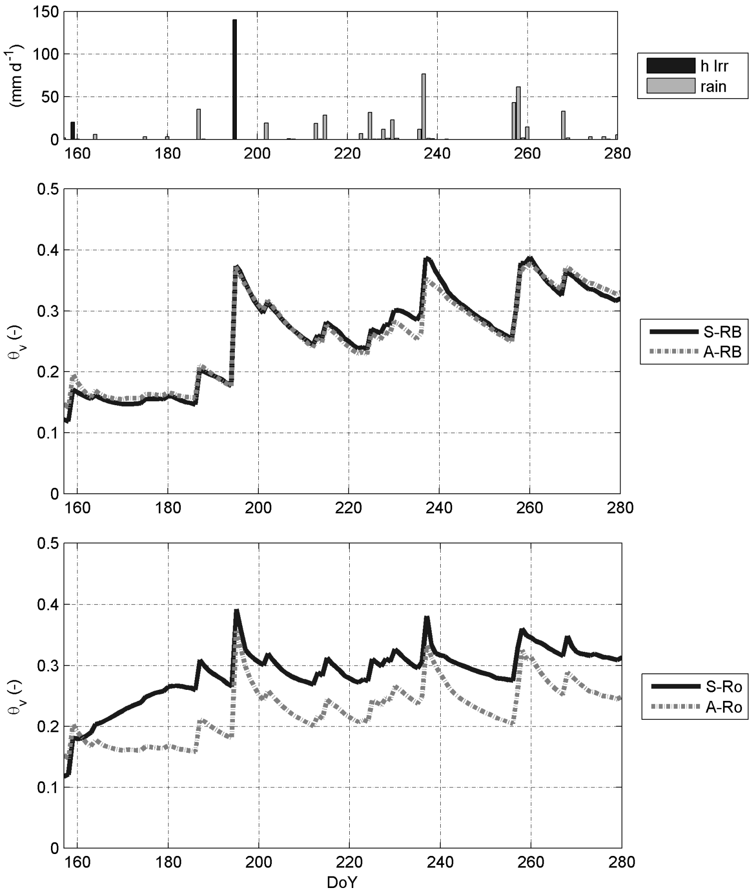

Fig. 6. Water inputs (1) and average soil water content in the root zone simulated by SWAP and ALHyMUS with the RB and Ro parameters sets.

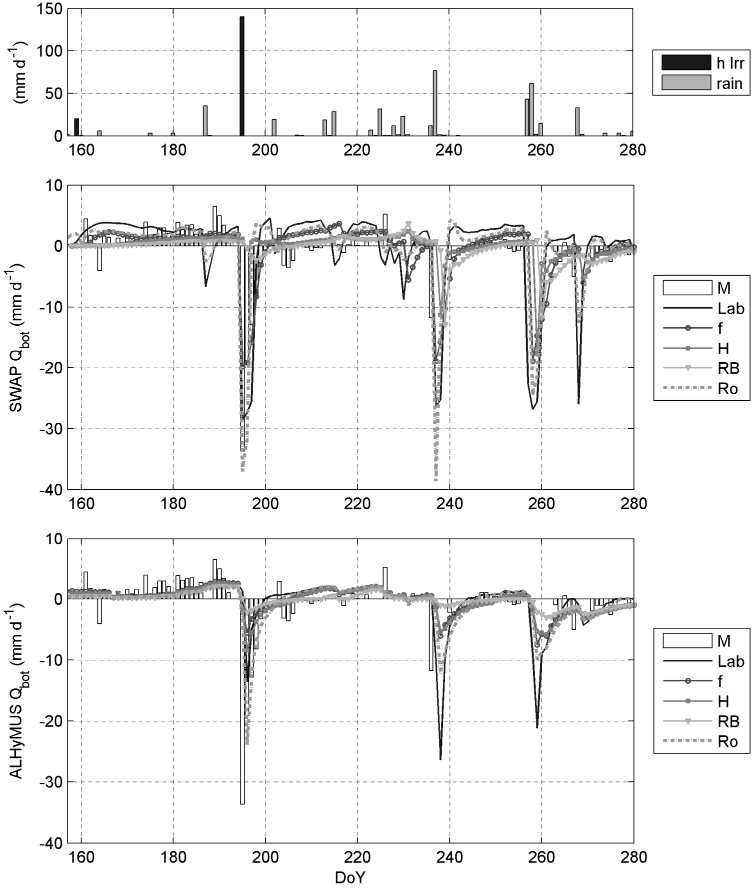

Fig. 7. Water inputs (1) and flow at the bottom of the root zone simulated and estimated by hydrological balance (2), (3).

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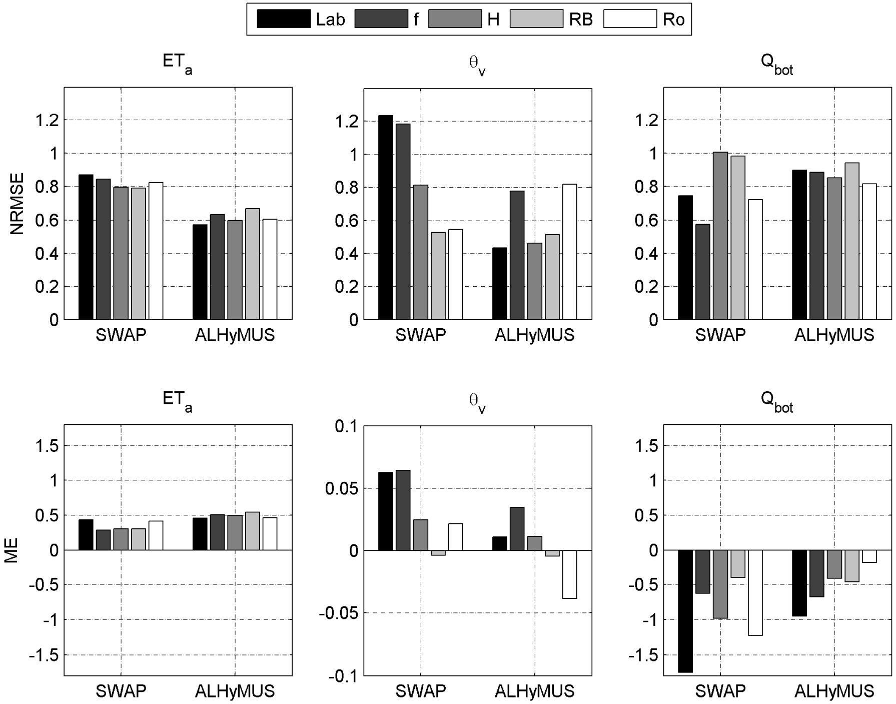

Fig. 8. NRMSE and ME for evapotranspiration, soil moisture and bottom flux outputs (simulated vs. measured values).