Hydrol. Earth Syst. Sci., 19, 969–980, 2015
www.hydrol-earth-syst-sci.net/19/969/2015/
doi:10.5194/hess-19-969-2015

Hydrology and Earth System Sciences
Open Access

Development and evaluation of an efficient soil-atmosphere model (FHAVeT) based on the Ross fast solution of the Richards equation for bare soil conditions

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Received: 2 July 2014 – Published in Hydrol. Earth Syst. Sci. Discuss.: 25 July 2014
Revised: 29 January 2015 – Accepted: 29 January 2015 – Published: 20 February 2015

Abstract. In agricultural management, a good timing in operations, such as irrigation or sowing, is essential to enhance both economical and environmental performance. To improve such timing, predictive software are of particular interest. Optimal decision-software would require process modules which provide robust, efficient and accurate predictions while being based on a minimal amount of parameters easily available. The objective of this study is to assess the accuracy of a physically based model with high efficiency. To this aim, this paper develops a coupled model with climatic forcing based on the Ross fast solution for Richards' equation, heat transfer and detailed surface energy balance. The present study is limited to bare soil, but the impact of vegetation can be easily included. The developed model, FHAVeT (Fast Hydro Atmosphere Vegetation Temperature), is evaluated against the coupled model based on the Philip and De Vries (1957) description, TEC. The two models were compared for different climatic and soil conditions. Moreover, the model allows using various pedotransfer functions. The FHAVeT model showed better performance in regards to mass balance, mostly below 0.002 m, and generally improved computation time. In order to allow for a more precise comparison, six time windows were selected. The study demonstrated that the FHAVeT behaviour is quite similar to the TEC behaviour except under some dry conditions. The ability of the models to detect the occurrence of soil intermediate water content thresholds with a 1 day tolerance was also evaluated. Both models agreed in more than 90 % of the cases.

1 Introduction

In agriculture a good timing of management operations such as tillage, sowing, irrigation and harvesting is an important issue for both economical and environmental points of view. Inappropriate irrigation scheduling may lead to water and/or crop losses, whereas using heavy engines on wet soil condition may compact soils, which reduces oxygen and water flows. The decision-making is multifactorial, involving work organization, meteorological forecast or soil water content. Even if progresses have been made in soil water content probe development (Evett and Parkin, 2005), their implementation remains difficult in the operational context, such as for capturing the spatial soil variability (Evett et al., 2009) or handling in situ probes together with management operation. Modelling the soil water content dynamic is therefore an alternative to support decisions, and fast computing is an important issue to obtain real-time information and address the spatial variability through a 3-D or distributed 1-D model.

As explained in the review on decision-making by Ascough et al. (2008), an optimal decision-making software would require process modules which provide robust, efficient and accurate predictions while being based on a minimal amount of easily available parameters. Moreover, a decision-making software should allow for the representation of the major processes occurring in the studied object. In regards to decisions based on soil water content for agricultural management, some important processes are the water transfers in the soil/plant system and the energy fluxes in the soil and at the surface, the latter being important to determine top boundary conditions from standard climatic data. To represent such processes, characterisation of soil hydraulic properties is a critical point since they are rarely measured at the location of interest and have a strong impact on the simulations. The alternative is then to use pedotransfer functions that link those characteristics to commonly measured quantities such as the soil textural fractions.

For agricultural management purposes, capacity-based models are generally used (Bergez et al., 2001; Chopart et al., 2007; Lozano and Mateos, 2008). Such conceptual models represent soil through its water storage capacity and vertical fluxes that are governed by an overflow of a compartment towards the one just below. In general, additional processes are required to better represent infiltration and upwards flux involving empirical parameters that are site specific and need to be calibrated since they are not measurable and thus difficult to address through pedotransfer functions. Moreover, in her work, Blyth (2002) compared a conceptual model to a physically based model. The physically based model showed better performance and more versatility than the conceptual model. It should be noted, however, that the accuracy of a physically based model is dependent on the modeller's choice, for instance in regards to parameterisation or chosen processes (Holländer et al., 2014). Therefore, the development of a versatile, physically based model is of importance to allow for a non-site-specific decision tool.

In the unsaturated zone, a well-known physically based description of the mass balance, in regards to water flow, is the Richards equation. The Richards equation allows for a detailed description of soil water content distribution evolution as well as water fluxes inside the soil domain. Its solution is based on measurable physical parameters such as the water retention and the hydraulic conductivity, which may be obtained through experimentation. Moreover, pedotransfer functions are widely developed (Cosby et al., 1984; Rawls and Brakensiek, 1989; Wosten et al., 2001; Schaap et al., 2001) and allow describing of the parameters necessary for the resolution of the Richards equation using soil characteristics such as the soil texture and bulk density. Chanzy et al. (2008) demonstrated that pedotransfer functions may allow for a good approximation for agricultural soil water representation even though the adequacy of pedotransfer functions close to the surface is still under discussion (Jarvis et al., 2013), especially for wet conditions when preferential flow occurs.

The Richards equation is highly nonlinear leading to time-consuming numerical resolution and stability issues under some conditions such as the wetting of an initially dry medium. Numerous studies focused on the improvement of the numerical schemes (Short et al., 1995; Zhang et al., 2002; Caviedes-Voullieme et al., 2013) but it should be noted that computing codes based on Richards' equation are rarely used for decision-making software.

Ross (2003) proposed in his paper a fast solution of the Richards equation. This method demonstrated an accurate, robust and efficient behaviour on a variety of case studies. The solution developed by Ross (2003) has been used in different situations in recent years, proving its efficiency against models based on the classic numerical resolution of the Richards equation and analytical solutions. Varado et al. (2006a) tested the solution to evaluate its efficiency and demonstrated that the model shows improved robustness and accuracy compared to analytical solutions and the model SiSPAT (Braud et al., 1995). In their work, Crevoisier et al. (2009) proposed a comparison of the solution with the Hydrus software (Simunek et al., 2008) in unfavourable conditions, demonstrating an improvement in computing time efficiency and robustness.

Thanks to its efficiency and robustness a model based on Ross' solution is an interesting choice to develop a decision tool based on soil water content estimation. However, it is important to drive the model with a climate forcing and to be able to have a wide range of soil hydraulic functions (retention curve and soil hydraulic conductivity) in order to profit from the existing pedotransfer functions.

In most of the models based on Ross' solution, the introduction of climatic forcing is made through an empirical approach where the top water flux is the minimum of the potential evaporation and the maximum water flux through the top layer. Introduction of climate forcing through the surface energy balance is more straightforward and physically sound. This requires, however, representing soil heat transfer, which may be done with a soil energy balance. Tightly coupled equations developed by Philip and De Vries (1957) may be used. In such a tightly coupled model, water flow in its liquid and vapour phases is strongly related to heat transfers. Haverd and Cuntz (2010) actually coupled the Ross solution with an energy and vapour transport equation based on those coupled equations. Such a development increases the number of parameters,such as those related to soil vapour diffusion, and a more complex problem resolution is required. Another possibility is to consider a loosely coupled model. In such a model, the different balances (surface energy, heat transport and water transfers) are evaluated sequentially and vapour transport is neglected. To keep a limited amount of input parameters, we prefer to develop a model based on the original Ross approach, which was widely tested in a large range of soil and water flow conditions.

The aim of this paper is to present and evaluate the improvements made on the model developed in Crevoisier et al. (2009) with the introduction of new soil hydraulic function formalisms as well as new processes (soil heat transfer and surface energy balance). At longer term, the interest would be to enlarge the scope of the soil water and heat transfer model to other processes such as root uptake, solute transport, biogeochemical reaction and soil property dynamics. It was found that the main challenge in implementing a physically based model to estimate soil water content is the evaluation of soil hydraulic properties, requiring the development of estimation strategies such as using pedotransfer functions (PTF) and assimilation techniques (Witono and Bruckler, 1989; Zhu and Mohanty, 2004; Medina et al., 2014). Our work focuses on the innovation made in the FHAVeT (Fast Hydro Atmosphere Vegetation Temperature) model and does not consider those strategies that are already addressed in other studies (Chanzy et al., 2008). Therefore, to evaluate the FHAVeT model, we used a data set simulated by the TEC model (Chanzy et al., 2008) as our reference. It is based on the DeVries approach, which is physically sound to represent water transfers in the soil and at the soil–atmosphere interface. Moreover, Chanzy et al. (2008) have shown the potential of such a model for operational applications by developing an implementation strategy with limited soil characterisation. The question is then to evaluate to which extent the gain in computing efficiency and robustness brought by the Ross method, together with the physical simplification on heat and water coupling, affect the results in comparison to the TEC model that presents a stronger physical background.

In this paper, the work is limited to bare soils in order to focus on the impacts of the innovations included in FHAVeT, which are limited to the soil compartment including the interface with the atmosphere. Moreover, the very dry conditions encountered near the surface on bare soil are the worst conditions in to test the lack of soil water vapour assumption. Bare soil is also an important phase in the crop cycle during which important decisions have to be taken by farmers such as crop installation (soil tillage, sowing).

2 Model description

The model FHAVeT consists in the coupling of a surface energy balance, a soil energy balance and a soil mass balance module. Models development and simulations were performed using the INRA Virtual Soil[1] platform. This platform provides an easy way to use and couple numerical modules representing processes occurring in soils. A scheme of the model is presented in Fig. 1. The model consists of three main modules computed sequentially in the following order: surface energy balance – soil water transfer – soil heat transfer.

[1]All information about the platform and how to use it and contribute can be found in the dedicated web site: http://www.inra.fr/sol_virtuel.

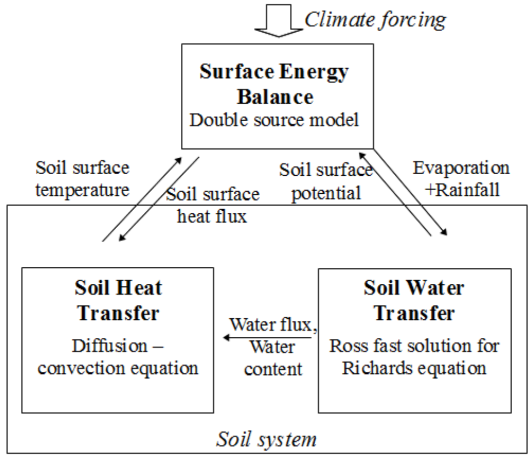


Figure 1. The FHAVeT model coupling scheme.

As shown in Fig. 1 the surface energy balance is driven by climatic forcing, soil surface temperature and soil surface water potential, and it computes evaporation and soil surface heat flux. The soil water transfer module is driven by evaporation/rainfall and computes soil water potential, water flux and water content. Finally, the soil heat transfer module depends on water flux, water content and surface heat flux and computes soil temperature.

2.1 Surface energy balance

An equation of energy budget (Eq. 1) at the soil surface is used to obtain the soil surface heat flux G ($\mathrm{W\,m^{-2}}$) and the soil evaporation flux E_g ($\mathrm{kg\,m^{-2}\ s^{-1}}$).

$$\mathrm{Rn_g} = H_\mathrm{g} + L_\mathrm{v}(T_\mathrm{s})\,E_\mathrm{g} + G \tag{1}$$

$$= -\rho_\mathrm{a} c_\mathrm{p} \frac{(T_\mathrm{a} - T_\mathrm{s})}{R_\mathrm{aH}} - L_\mathrm{v}(T_\mathrm{s}) \frac{\rho_\mathrm{a}(h_\mathrm{a} - h_\mathrm{s})}{R_\mathrm{av}} + G \tag{2}$$

In these equations, $\mathrm{Rn_g}$ ($\mathrm{W\,m^{-2}}$) is the net radiation, L_v ($\mathrm{J\,kg^{-1}}$) is the latent heat of vaporisation and H_g ($\mathrm{W\,m^{-2}}$) is the sensible heat flux. The aerodynamic resistances for heat and vapour R_aH ($\mathrm{s\,m^{-1}}$) and R_av ($\mathrm{s\,m^{-1}}$) are calculated using the formulation by Taconet et al. (1986). T corresponds to the temperature and h to the specific humidity (mass of water in air over mass of humid air), subscript "a" relates to the air and subscript "s" to the soil surface level. Moreover, ρ_a ($\mathrm{kg\,m^{-3}}$) is the air density and c_p the specific heat at constant pressure. Solving Eq. (1) requires climatic observation parameters, as well as the soil surface temperature and soil surface water potential calculated from the soil heat and water transfers at the previous time step and input parameters as described in Table 2.

2.2 Soil mass balance

Ross' fast solution for the Richards equation is described in Ross (2003) and Fast Hydro, the upgraded implementation

Table 1. Hydraulic property curves available in the FHAVeT and Kirchhoff potential calculation methods.

Retention curve	Hydraulic conductivity curve	Kirchhoff potential calculation
Brooks and Corey (1964) $S(h)=(\alpha_{BC}h)^{-\lambda}$	Corey $K=K_{sat}\,S^{\eta}$	Analytical (Ross, 2003)
Linear $S(h)=\exp\left(\alpha_G\,(h-h_e)\right)$	Linear $K=K_{sat}\,S$	Analytical (Crevoisier et al., 2009)
van Genuchten (1980) $S(h)=\left(1+\lvert\alpha_{VG}\,h\rvert^{n}\right)^{-m}$	Mualem (1976) $K=K_{sat}\,S^{\eta}\left[1-\left(1-S^{1/m}\right)^{m}\right]^{2}$	Numerical ($\eta=0.5$) (Crevoisier et al., 2009)[a] Beta functions ($\eta>-1$)[b] Numerical ($\eta\leq-1$)[b]
Modified van Genuchten (1980) $S(h)=\frac{1}{S_M}\left(1+\lvert\alpha_{VG}h\rvert^{n}\right)^{-m}$ $S_M=\left(1+\lvert\alpha_{VG}\,h_e\rvert^{n}\right)^{-m}$	Mualem (1976) $k_r=\frac{S_M\,S^{\eta}}{k_M}\left[1-\left(1-(S_M\,S)^{1/m}\right)^{m}\right]^{2}$ $k_M=S_M^{\eta}\left[1-\left(1-S_M^{1/m}\right)^{m}\right]^{2}$	Numerical ($\eta=0.5$) (Crevoisier et al., 2009)[b] Beta functions ($\eta>-1$)[b] Numerical ($\eta\leq-1$)[b]
van Genuchten (1980) $S(h)=\left(1+\lvert\alpha_{VG}h\rvert^{n}\right)^{-m}$	Corey $K=K_{sat}\,S^{\eta}$	Beta functions[b]

[a] Integration method upgraded and [b] new feature in the FHAVeT model.

of Ross' method used in this study is described in Crevoisier et al. (2009). It solves the Richards equation (Eq. 3) by a noniterative approach.

$$\frac{\partial\theta}{\partial t}=\nabla\cdot(K\nabla(\widetilde{h}-z)), \tag{3}$$

where θ ($\mathrm{m^3\,m^{-3}}$) is the soil water content, $\widetilde{h}$ (m) is the soil potential, K ($\mathrm{m\,s^{-1}}$) is the soil hydraulic conductivity and z (m) is the soil depth. A detailed description of the Ross solution may be found in Crevoisier et al. (2009). Similarly to the code developed in Crevoisier et al. (2009), a water surface layer and time step optimisation are used. The Ross solution is based on a linearisation of the mixed form of the Richards equation. The solution evaluates the effective saturation ($S=(\theta-\theta_r)/(\theta_s-\theta_r)$) under unsaturated conditions and Kirchhoff potential ($\phi(h)=\int_{-\infty}^{0}K(\widetilde{h})\,d\widetilde{h}$ in $\mathrm{m^2\,s^{-1}}$) under saturated conditions to allow for an exact calculation of the Darcian fluxes (Crevoisier et al., 2009). However, the integration of the hydraulic conductivity is not always straightforward. Ross (2003) used exclusively the Brooks and Corey formulation which is integrable analytically. Crevoisier et al. (2009) developed a numerical integration method for the use of the van Genuchten–Mualem hydraulic characteristics with $\eta=0.5$. However, some PTF, including commonly used PTF, require the use of other formulations. For instance, the PTF of Wosten et al. (2001) or Schaap et al. (2001) implies the use of van Genuchten–Mualem hydraulic characteristics with η potentially different from 0.5. To this end, a method using beta functions was developed for the integration of hydraulic conductivity as described by van Genuchten–Mualem. This method, however, is convergent only for $\eta>-1$. Therefore, a numerical iterative method was developed for the usability of the van Genuchten–Mualem description with $\eta\leq-1$. A summary of the hydraulic properties that may be used in FHAVeT is shown in Table 1.

2.3 Soil energy balance

The soil energy balance is modelled using a simple convection diffusion model (Eqs. 4–5) with convection being limited to the liquid phase.

$$(\rho C)_{eq}\frac{\partial T}{\partial t}+\rho_w C_w \boldsymbol{q}^{\sigma}\cdot\nabla T=\nabla\cdot(\lambda\nabla T), \tag{4}$$

$$(\rho C)_{eq}=\rho_h C_{eq}=\rho_w C_w\theta+\rho_s C_s\,(1-\theta_s)\,, \tag{5}$$

where ρ_s (ρ_w) ($\mathrm{kg\,m^{-3}}$) is density of solid (water), ρ_h ($\mathrm{kg\,m^{-3}}$) is the soil bulk density, θ_s ($\mathrm{m^3\,m^{-3}}$) is the saturated water content (assumed equal to the porosity), C_s (C_w) ($\mathrm{J\,kg^{-1}\,K^{-1}}$) is the specific heat of solid (water) and λ ($\mathrm{W\,m^{-1}\,K^{-1}}$) is the soil heat conductivity. The soil heat conductivity is assumed to have a linear dependence on soil water content following Eq. (6) (Van de Griend and O'Neill, 1986) where Λ_s ($\mathrm{J\,m^{-2}\,K^{-1}\,s^{-1/2}}$) is the thermal inertia at saturation.

$$\lambda=\left(1/0.654\,(\Lambda_s+2300\theta-1890)\right)/C_{eq} \tag{6}$$

Moreover, impact of the rain on fluid transport is considered as a working hypothesis with rain having a constant temperature of 283 K.

Table 2. Input climate forcing and parameters for the FHAVeT model.

Climatic forcing data		
Short-wave incoming radiation RG	$\mathrm{W\,m^{-2}}$	
Long-wave incoming radiation RA	$\mathrm{W\,m^{-2}}$	
Atmospheric temperature at reference height T_a	K	
Atmospheric pressure p_{atm}	Pa	
Air vapour content e_a	Pa	
Wind velocity at reference height U_a	$\mathrm{m\,s^{-1}}$	
General properties		
Water density ρ_w	$1000\,\mathrm{kg\,m^{-3}}$	
Air density ρ_a	$\mathrm{kg\,m^{-3}}$	Function of temperature and pressure
Latent heat of vaporisation L_v	$\mathrm{J\,kg^{-1}}$	Function of temperature
Specific heat of dry air at constant pressure c_p	$1004\,\mathrm{J\,kg^{-1}\,K^{-1}}$	
Specific heat of water C_w	$4181\,\mathrm{J\,kg^{-1}\,K^{-1}}$	
Surface energy properties		
Ground surface albedo α_g	0.20–0.30	Function of surface water content
Ground surface emissivity ε_g	0.96	
Roughness length for momentum z_{om}	0.002 m	
Roughness length for heat z_{oh}	m	Calculated with Brutsaert (1982) formula
Soil hydraulic properties		
Saturated volumetric water content θ_s	$\mathrm{m^3\,m^{-3}}$	
Residual volumetric water content θ_r	$\mathrm{m^3\,m^{-3}}$	
Water retention curve parameters		
Hydraulic conductivity curve parameters		
Soil thermal properties		
Soil heat conductivity λ	$\mathrm{W\,m^{-1}\,K^{-1}}$	Function of soil water content
Soil heat capacity C_λ	$\mathrm{J\,kg^{-1}\,K^{-1}}$	Function of soil bulk density

2.4 The reference model: TEC

The TEC model (Chanzy and Bruckler, 1993) is based on the heat and mass flow theory in unsaturated media (Philip and De Vries, 1957). The resulting nonlinear partial differential equation system is solved using a Galerkin finite element method. The model is driven by a climatic forcing in case of bare soil. The model was evaluated against various experimental conditions (Chanzy and Bruckler, 1993; Aboudare, 2000; Findeling et al., 2003; Sillon et al., 2003). The major differences between the models TEC and FHAVeT are as follows:

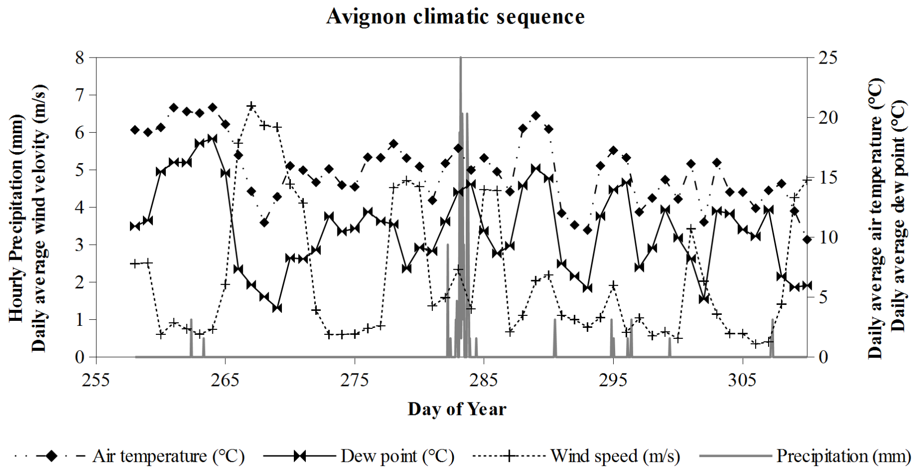
- TEC is based on a finite element method for resolution of the equations, while FHAVeT uses the Ross solution for solving mass balance, and the energy balance is solved through a finite difference method;

- the coupling of soil mass and energy balances is based on a tightly coupled Philip and De Vries (1957) approach in TEC while the FHAVeT model uses a loose coupling, neglecting the vapour transport.

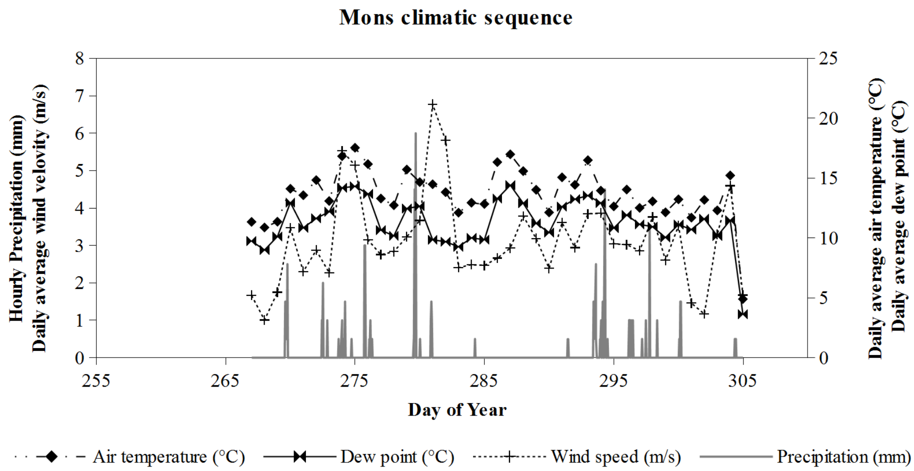
There are however others differences between the two models. The evolution of soil heat conductivity with soil water content and the aerodynamic resistances are calculated through different means. Moreover, the numerical spatial discretisations are different, with a coarser mesh for FHAVeT near the surface.

3 Model intercomparison

Understanding a location's soil water content profile is critical when it comes to agricultural management. Therefore, the prediction capacity in regards to soil water content of the FHAVeT model is going to be the major focus of the intercomparison. Chanzy et al. (2008) developed an implementation strategy under operational conditions when only limited information is available to describe the soil system. Their study was based on a large database covering contrasting climate regimes, a large range of soil textures and four PTFs. This data set was appropriate to analyse FHAVeT results under various pedoclimatic conditions and test different soil hydraulic functions.



(a) Avignon sequence



(b) Estree-Mons sequence

Figure 2. Climate forcing: precipitation, air temperature, dew point and wind velocity at 2 m height.

3.1 Climatic forcing

The cases studied were chosen so as to offer a variety of climatic and soil conditions that may occur in France and in an agronomic context. Two climatic sequences are used. The first one was measured at Avignon (southern France, 43.78° N, 4.73° E) and represents a Mediterranean climate with occasional heavy rains and long periods of dryness (Fig. 2a). Wind velocity also varies strongly. The second climatic sequence was measured at Estrées-Mons (northern France, 48.99° N, 2.99° E). It represents an oceanic climate with frequent light rainfalls and short dryness periods (Fig. 2b).

In order to study specific features of the two climatic sequences, six time windows (TWs) were selected (Table 3). TWs 1 and 2 are chosen within the first drying period of the Avignon sequence with TW 1 showing strong wind conditions and TW 2 weak wind conditions. Indeed, Chanzy and Bruckler (1993) demonstrated that wind has an influence on vapour transport, with lower vapour flow when the convective part of the climatic demand is stronger. TW 3 is selected during the heavy rain period of the Avignon sequence. TW 5 covers the drying conditions of the Estrées-Mons climate. Finally, TWs 4 and 6 were chosen during wet periods of the Estrées-Mons sequence, respectively, before and after the dry period. A summary of the averaged climatic conditions during the six time periods is shown in Table 3.

3.2 Soil types

Four soils from the sites of Estrées-Mons and Avignon with various textures, ranging from silty loam to silt clay loam (Table 4), were chosen for the study.

Table 3. Climatic forcing summary for the selected time windows (TWs).

Case	Site	Start date	End date	Duration	Temperature	Precipitation	Mean wind velocity
TW 1	Avignon	23 Sep 1997	30 Sep 1997	168 h	14.9 °C	0 mm	5.14 m s^{-1}
TW 2	Avignon	30 Sep 1997	5 Oct 1997	120 h	15.3 °C	0 mm	0.65 m s^{-1}
TW 3	Avignon	11 Oct 1997	12 Oct 1997	24 h	15.9 °C	55 mm	1.25 m s^{-1}
TW 4	Mons	4 Oct 2004	8 Oct 2004	91 h	15.9 °C	16 mm	4.08 m s^{-1}
TW 5	Mons	16 Oct 2004	25 Oct 2004	214 h	14.9 °C	1 mm	3.09 m s^{-1}
TW 6	Mons	26 Oct 2004	31 Oct 2004	120 h	12.9 °C	11 mm	3.06 m s^{-1}

Table 4. Soil characteristics for comparative study, from Chanzy et al. (2008),

Soil ID	Depth (m)	Texture	Clay (%)	Sand (%)	Bulk density (kg m^{-3})	Organic matter (%)
AL-SiL	0.00–0.10	Silt loam	17.00	34.30	1240	1.50
	0.10–0.40		17.00	29.20	1280	1.50
	0.40–0.80		17.00	29.20	1460	1.00
AL-SiCL	0.00–0.10	Silt clay loam	38.90	5.30	1300	2.50
	0.10–0.40		39.70	4.60	1350	2.50
	0.40–0.80		48.10	2.00	1600	1.00
MO-SiL	0.00–0.33	Silt loam	14.50	5.20	1280	2.10
	0.33–0.80		25.20	3.00	1520	0.90
PO-SiCL	0.00–0.10	Silt clay loam	27.20	11.00	1290	2.40
	0.00–0.25		27.20	11.00	1400	2.40
	0.25–0.80		27.20	11.00	1600	1.00

3.3 Soil hydraulic characteristics

To validate the versatility of the model, the three integration methods (Table 1) were solicited through the use of three different PTFs. The pedotransfer function developed by Cosby et al. (1984) offers parameters corresponding to a Brooks and Corey set of hydraulic properties and therefore requires the use of analytical integration in the software. The pedotransfer function developed in Rawls and Brakensiek (1989) allows deriving van Genuchten–Mualem hydraulic property parameters with the hypothesis of shape parameter, otherwise known as tortuosity, $\eta = 0.5$. Therefore, integration with beta functions may be used. Finally, the pedotransfer function of Wosten et al. (2001) also derives van Genuchten–Mualem parameters, but the shape parameters η obtained are usually below -1; therefore, numerical integration is necessary. All three functions require the same parameters, which are the textural characteristics of soils, summarised in Table 4.

3.4 Soil thermal characteristics

Thermal characteristics of the different soils were considered dependent on volumetric soil water content. The heat capacity is calculated as the mean of soil and water capacities weighed by relative volumes. In the FHAVeT model, the heat conductivity dependence on the soil water content is obtained through Eq. (6). The thermal inertia at saturation Λ_s has been tabulated against soil textures by Van de Griend and O'Neill (1986). In the TEC model, the evolution of heat conductivity is obtained through the De Vries (1963) description.

3.5 Model setup

The initial values for soil matric potential and soil temperature used in the FHAVeT model were the ones derived using the TEC model from a preliminary climatic sequence (Chanzy et al., 2008). Constant matric potential (-3.33 m) and temperature (293 K) are considered at the bottom of the studied domain for both models as used in Chanzy et al. (2008).

The one-dimensional mesh used in FHAVeT is homogeneous with a cell thickness of 2 cm and a total soil thickness of 80 cm while the mesh used in TEC is refined close to the surface with element thicknesses ranging from 0.6 to 5 cm. The number of cells is identical for both models.

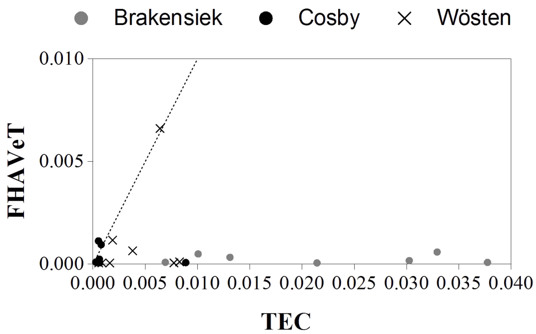


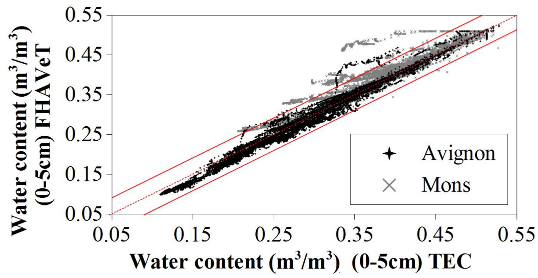
Figure 3. Maximum absolute error in mass balance (in cubic metres of water per unit of soil surface) – comparison between models. The dotted line corresponds to the 1 : 1 line.

4 Results and discussion

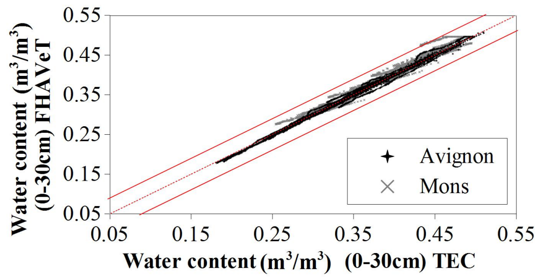
4.1 Models performances

A study on the efficiency of the Ross solution against the classic resolution of Richard's equation under various boundary conditions was done in Crevoisier et al. (2009). In their work, they demonstrated that Ross' solution allowed for a computation time of 5 times per grid cell faster (on average) compared to a regular solution of Richards' equation. Similar outcomes, (computation time of around a couple minutes with FHAVeT and a few tens of minutes with TEC) were observed in this study. It should be noted that in one case (AL-SiCL with the Wosten pedotransfer functions and under the Avignon climate) the computation time using FHAVeT remained in the same order of magnitude, as when using TEC.

To compare the numerical accuracy of both models, a calculation of mass balance was performed. The mass balance absolute error was computed as the absolute difference between cumulated inflow and outflow of the soil domain and the soil water storage evolution from initial state at each time step. The maximal value along time for the mass balance error is represented in Fig. 3. As shown in Fig. 3, the TEC mass balances are not always respected (error lower than 0.01 $m^3\,m^{-2}$) due to the strong water potential near the surface in dry conditions. FHAVeT offers improved results in regards to mass balance compared to the TEC model. In most cases the absolute mass balance error was below 0.002 $m^3\,m^{-2}$, with only one case being higher. In this particular point, corresponding to the soil AL-SiCL with the Wosten pedotransfer functions and under the Avignon climate, both the computing time and the mass balance (0.008 $m^3\,m^{-2}$) error were too large. As explained in the model description, the variables calculated are different when a cell is saturated (Kirchhoff potential) or unsaturated (effective saturation). Therefore, when a cell is going from unsaturated to saturated state (or reversely), the calculation undergoes an error. For the hydraulic conductivity curves from Wosten et al. (2001), there is a very steep nonlinear



(a) 0-5 cm layer



(b) 0-30 cm layer

Figure 4. Comparison of soil water content between models FHAVeT and TEC for all models every 2 h.

variation of permeability close to the saturation. This leads to a slow numerical calculation of the permeability close to saturation state as well as a strong discrepancy between the soil's saturated and slightly unsaturated state flow characteristics. All of these considerations lead to a heightened probability for an "oscillation" to occur between saturated and unsaturated states and the consequent error accumulation. An improvement of the numerical integration method should, however, improve the computation time and allow for the use of a more constraining numerical tolerance.

4.2 Water content evaluation

Figure 4 shows the comparison of all cases studied between soil water content of both models for the 0–5 and 0–30 cm soil layers. A tolerance of 0.04 $m^3\,m^{-3}$ is shown. The models show generally good agreement. For the 0–5 cm layer, only 1.55 % (6.76 %) of the results are out of the tolerance zone for the Avignon (Mons) climate. The results go down to 0 % (1.17 %) for the 0–30 cm layer under the Avignon (Mons) climate.

To study the conditions of the divergences between the two models, the evolution of soil water content with time for the surface layer and in one particular simulation is shown in Fig. 5. This figure shows that the most significant discrepancy between the two models seems to occur during TW 5, that is, during the drying period of the Mons climate.

In order to extend this analysis to all cases studied, Fig. 6 shows the histogram of the absolute difference distribution between the water content averaged over a defined soil depth

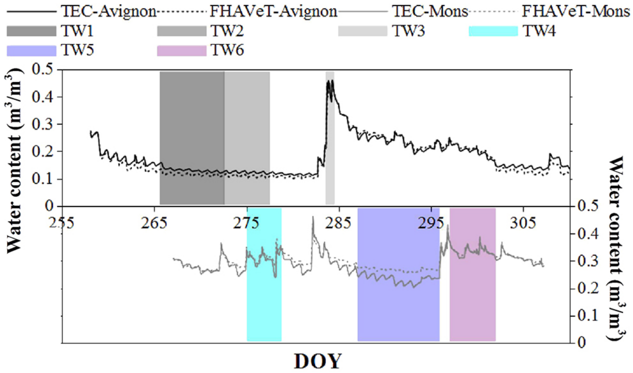
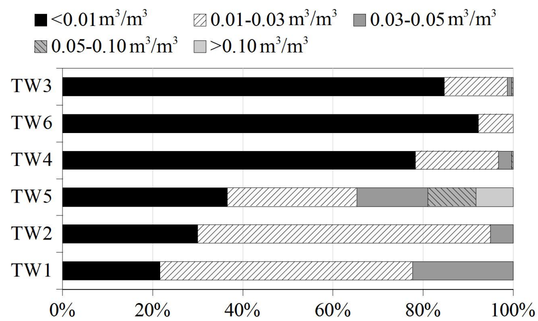
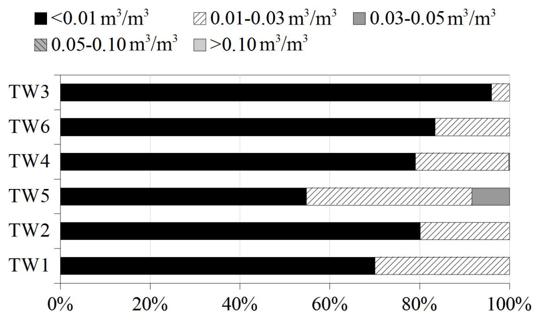


Figure 5. Soil water content evolution in time for the 0–5 cm layer; comparison between models – soil AL-SiL, PTF – Wosten. Avignon climate (top) and Mons climate (bottom).



(a) 0-5cm layer



(b) 0-30cm layer

Figure 6. Absolute water content difference distribution between the developed model and TEC for each climatic case study.

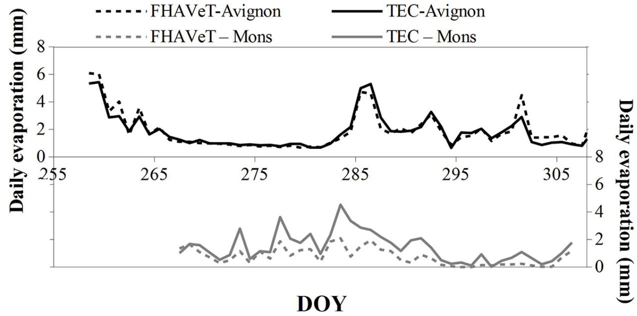


Figure 7. Daily evaporation (in mm) evolution in time; comparison between models – Soil AL-SiL, PTF – Wosten.

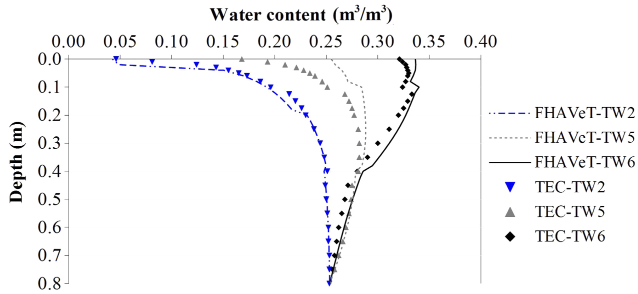


Figure 8. Water content profiles in TW 2 (dry conditions, Avignon climate, DOY (day of year) 275), TW 5 (dry conditions, Mons climate, DOY 292) and TW 6 (wet conditions, Mons climate, DOY 300) for soil AL-SiL, Wosten pedotransfer function.

(0–5 and 0–30 cm) for both models over each time window. The comparison takes into account all pedotransfer functions.

It can be clearly observed that under wet conditions (TWs 3, 4 and 6) the two models led to similar results with the absolute difference in averaged water content being lower than 0.01 $m^3\,m^{-3}$ for around 80 % of the time in the 0–5 cm soil layer and always below 0.03 $m^3\,m^{-3}$ in the 0–30 cm soil layer. However, under dry conditions (TWs 1, 2 and 5) the difference between the two models is more consequent. This is especially true in TW 5, where there is little rain for a long time (1.5 mm in 12 days), which leads to an absolute water content difference of over 0.1 $m^3\,m^{-3}$. Since the discrepancies between the models mostly occur during drying, the lack of vapour transport is likely to be a source of error. In order to investigate the role of vapour transport, the evaporated flux was plotted in Fig. 7 for one case. This case shows representative behaviour of all soils and climates studied where there is discrepancy between the two models (with the exception of the case showing numerical issues).

As shown in Fig. 7, the model FHAVeT tends to underestimate the evaporation of soil under Mons climate drying conditions and consequently leads to a higher soil water content in the observed soil layer. The errors are larger in the 0–5 cm layer than in the 0–30 cm layer which tends to demonstrate that the impact of vapour transport is most important close to the surface. Such considerations are further observed in Fig. 8. This figure compares three water content profiles for each model. Under dry conditions and Mons climate (during TW 5) the profiles are comparable below 30 cm and their discrepancy increases when depth decreases. Moreover, the water content simulated by the TEC model during the drying phase is significantly smaller than the one computed with the FHAVeT model. Therefore, the driest conditions at the soil surface must be balanced by vapour flow to produce greater evaporation rates. Under Avignon climate, both models led to similar evaporation rates even in very dry conditions and therefore the water content profiles (Fig. 8) are comparable even close to the surface. In such dry conditions, Chanzy (1991) showed that water vapour flows are much smaller than at the beginning of the drying phase. Therefore, intermediate water content conditions, such as the ones encountered under Mons climate, lead to the strongest discrepancies. After a rainy period, the profile almost seems to be recovered in TW 6. While the maximal error between the two models in water content is $0.087\,\mathrm{m^3\,m^{-3}}$ in the dry state (TW 5), it is $0.015\,\mathrm{m^3\,m^{-3}}$ 8 days later. This result shows that the local error generated during the drying is diluted along the soil profile. Moreover, the error in water amount of the whole domain is reduced by 27 % (from $0.0071\,\mathrm{m^3\,m^{-2}}$ in the dry state to $0.0052\,\mathrm{m^3\,m^{-2}}$), showing a partial recovery of soil water content.

4.3 Model ability for water content thresholds estimation

In decision-support software, soil water content thresholds can be applied as criteria for decisions on agronomic management, such as irrigation or tillage and harvesting, to prevent soil compaction (Saffih-Hdadi et al., 2009). Therefore, the ability of a model to accurately detect the day when the soil water content status reaches such thresholds is essential. Figure 9 shows the number of dates (considering TEC as a reference) in which a given saturation value (for the top 30 cm layer) was detected either from dry to wet conditions (wetting) or from wet to dry conditions (drying) as well as day detection with a 1 day tolerance.

Due to the small number of saturation condition cases below 50 %, the lowest threshold shown in Fig. 9 is 60 %. It can be observed that thresholds are detected on the same date in two-thirds of the cases at higher saturation (thresholds of 90 and 80 %) and in slightly over half of the cases for thresholds of 70 and 60 % during drying. The success rate is much higher during wetting. Moreover, the success in day detection with a 1 day tolerance is quite high in wet conditions (thresholds of 90 %).

Important day detection delays (or advance) of over 3 days have occurred in only 0.8 % of the cases and significant day detection misses (when the threshold is reached for more than three days) in 1.4 % of the cases. The day detection inaccuracy may have different causes. The case where mass balance error is high has lead to an early detection in the FHAVeT model. This is likely due to the numerical error as the discrepancy between soil water volume between the two models and the mass balance error in the FHAVeT model are quite similar. The other cause of day detection miss or delays could be the lack of vapour transport. Indeed, all other day detection misses or delay appear during the drying period and especially TW 5. As mentioned previously, this period corresponds to the intermediate water condition that led to the largest discrepancy in evaporation and thus soil moisture. Therefore, in a tightly coupled model such as TEC, the soil is allowed to dry at a higher pace, leading to earlier day detection than in a loosely coupled model such as FHAVeT.

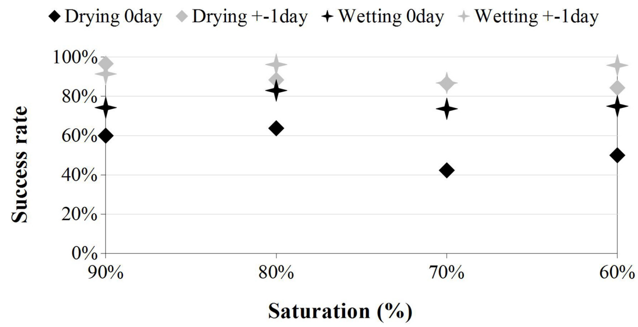


Figure 9. Day detection success rates. Drying 0day and wetting 0day show the number of identical day detection for both models during drying and wetting respectively. Drying ±1 day and wetting ±1 day show the success rate for day detection when there is less than 1 day difference between the two models.

5 Conclusions

FHAVeT extends the model developed by Ross (2003) and improved by Crevoisier et al. (2009) by introducing a coupling with the atmospheric conditions and by considering a wider range of soil hydraulic functions in order to profit from commonly used pedotransfer functions. The coupled model is based on existing process modules and uses the coupling technology offered by the soil virtual modelling platform to make the software development easier. As a consequence, a loose coupling between soil heat and mass flow is introduced leading, to neglect water vapour flows. Moreover, water and heat flow are computed sequentially. The model developed was compared to a reference model, TEC, under two climates typical of France and using four soil textures from different areas in France.

The model demonstrated good efficiency and improved mass balance conservation in comparison to the TEC model with the exception of one particular condition. In that case, the soil characteristic curves (soil water retention and relative permeability) are highly nonlinear and lead to an "oscillatory" behaviour between saturated and unsaturated states, accumulating numerical errors.

The loose coupling lead to little error in rainy conditions. Under dry conditions with the Avignon climate the error is larger, which was to be expected due the more important role of vapour transport. However, the simulated discrepancy is limited to the first centimetres and therefore concerns a rather limited volume of water.

Since the developed model is aimed at being a support for decision-making software, it is important that it accurately simulates threshold criteria. The FHAVeT and TEC models are in good agreement for about 90 % of the day detections with a 1 day tolerance. Considering the modelling parameters and initial condition uncertainties in field application, such a tolerance seems to be acceptable. Moreover, due to the lesser computing time (Crevoisier et al., 2009) required by the Ross solution, the FHAVeT model is a much better candidate than TEC for improvement techniques of parameter and initial condition descriptions such as data assimilation.

However, under drying conditions, the FHAVeT model may fail to correctly simulate the soil drying, especially close to the surface. In such conditions, wrong decisions may be taken even though the model allowed for a good recovery of the soil water content after a rainy period. It is consequently important to fully identify the specific climatic and soil history conditions that lead to an inaccurate description of the soil behaviour in regards to water content. To do so, a wider evaluation of the model, as well as a comparison with experimental field values, requires further work. Future improvements of the model include a better numerical integration method in order to deal with highly nonlinear soil characteristic functions and coupling with water transfers due to vegetation.

Acknowledgements. The project was funded by project ANR-11-EITC-001 (Agence Nationale de Recherche).

Edited by: N. Romano

References

Aboudare, A.: Stratégies de stockage et d'utilisation de l'eau pour le tournesol pluvial dans la région de Meknes, PhD thesis, Institut Agronomique et Vétérinaire Hassan II, Rabat, Maroc, 2000.

Ascough, J., Maier, H., Ravalico, J., and Strudley, M.: Future research challenges for incorporation of uncertainty in environmental and ecological decision-making, Ecol. Model., 219, 383–399, 2008.

Bergez, J.-E., Debaeke, P., Deumier, B., Lacroix, B., Leenhardt, D., Leroy, P., and Wallach, D.: MODERATO: an object-oriented decision tool for designing maize irrigation schedules, Ecol. Model., 137, 43–60, 2001.

Blyth, E.: Modelling soil moisture for a grassland and a woodland site in south-east England, Hydrol. Earth Syst. Sci., 6, 39–48, doi:10.5194/hess-6-39-2002, 2002.

Braud, I., Dantas-Antonino, A., Vauclin, M., Thony, J., and Ruelle, P.: A Simple Soil Plant Atmosphere Transfer model (SiSPAT), J. Hydrol., 166, 213–250, 1995.

Brooks, R. and Corey, A.: Hydraulic properties of porous media, Hydrology Paper 3, Colorado State Univ., Fort Collins, 27 pp., 1964.

Brutsaert, W.: Evaporation into the atmosphere: Theory, history and applications, D. Reidel Publishing Co., Dordrecht, 299 pp., 1982.

Caviedes-Voullieme, D., Garcia-Navarro, P., and Murillo, J.: Verification, conservation, stability and efficiency of a finite volume method for the 1D Richards equation, J. Hydrol., 480, 69–84, 2013.

Chanzy, A.: Modélisation simplifiée de l'évaporation d'un sol nu utilisant l'humidité et la température de surface accessible par télédétection, PhD thesis, Institut National Agronomique Paris-Grignon, Paris, France, 1991.

Chanzy, A. and Bruckler, L.: Significance of soil surface moisture with respect to daily bare soil evaporation, Water Resour. Res., 29, 1113–1125, 1993.

Chanzy, A., Mumen, M., and Richard, G.: Accuracy of top soil moisture simulation using a mechanistic model with limited soil characterization, Water Resour. Rese., 44, W03432.1–W03432.16, 2008.

Chopart, J., Mezino, M., Aure, F., Le Mezo, L., Mete, M., and Vauclin, M.: OSIRI: A simple decision-making tool for monitoring irrigation of small farms in heterogeneous environments, Agr. Water Manage., 87, 128–138, 2007.

Cosby, B., Hornberger, G., Clapp, R., and Ginn, T.: A statistical exploration of the relationship of soil moisture characteristics to the physical properties of soils, Water Resour. Res., 20, 682–690, 1984.

Crevoisier, D., Chanzy, A., and Voltz, M.: Evaluation of the Ross fast solution of Richards' equation in unfavourable conditions for standard finite element methods, Adv. Water Resour., 32, 936–947, 2009.

De Vries, D.: Physics of plant environment, in: chap. Thermal properties of soil, North-Holland Publishing Co., the Netherlands, 210–235, 1963.

Evett, S. and Parkin, G.: Advances in soil water content sensing: the continuing maturation of technology and theory, Vadose Zone J., 4, 986–991, 2005.

Evett, S., Schwartz, R., Tolk, J., and Howell, T.: Soil profile water content determination: Spatiotemporal variability and neutron probe sensors in access tubes, Vadose Zone J., 8, 926–941, 2009.

Findeling, A., Chanzy, A., and de Louvigny, N.: Modeling water and heat flows through a mulch allowing for radiative and long distance convective exchange in the mulch, Water Resour. Res., 39, 1244, doi:10.1029/2002WR001820, 2003.

Haverd, V. and Cuntz, M.: Soil-Litter-Iso: A one-dimensional model for coupled transport of heat, water and stable isotopes in soil with a litter layer and root extraction, J. Hydrol., 388, 438–455, 2010.

Holländer, H. M., Bormann, H., Blume, T., Buytaert, W., Chirico, G. B., Exbrayat, J.-F., Gustafsson, D., Hölzel, H., Krauße, T., Kraft, P., Stoll, S., Blöschl, G., and Flühler, H.: Impact of modellers' decisions on hydrological a priori predictions, Hydrol. Earth Syst. Sci., 18, 2065–2085, doi:10.5194/hess-18-2065-2014, 2014.

Jarvis, N., Koestel, J., Messing, I., Moeys, J., and Lindahl, A.: Influence of soil, land use and climatic factors on the hydraulic conductivity of soil, Hydrol. Earth Syst. Sci., 17, 5185–5195, doi:10.5194/hess-17-5185-2013, 2013.

Lozano, D. and Mateos, L.: Usefulness and limitations of decision support systems for improving irrigation scheme management, Agr. Water Manage., 95, 409–418, 2008.

Medina, H., Romano, N., and Chirico, G. B.: Kalman filters for assimilating near-surface observations into the Richards equation – Part 2: A dual filter approach for simultaneous retrieval of states and parameters, Hydrol. Earth Syst. Sci., 18, 2521–2541, doi:10.5194/hess-18-2521-2014, 2014.

Mualem, Y.: A new model predicting the hydraulic conductivity of unsaturated porous media, Water Resour. Res., 12, 513–522, 1976.

Philip, J. and De Vries, D.: Moisture movements in porous materials under temperature gradients, Eos Trans. Am. Geophys. Union, 38, 222–232, 1957.

Rawls, W. and Brakensiek, D.: Unsaturated flow in hydrologic modeling – Theory and practice, in: chap. Estimation of soil water retention and hydraulic properties, Kluwer Academic Publishing, Beltsville, USA, 275–300, 1989.

Ross, P.: Modeling soil water and solute transport – Fast, simplified numerical solutions, Agron. J., 95, 1352–1361, 2003.

Saffih-Hdadi, K., Defossez, P., Richard, G., Cui, Y.-J., Tang, A.-M., and Chaplain, V.: A method for predicting soil susceptibility to the compaction of surface layers as a function of water content and bulk density, Soil Till. Res., 105, 96–103, 2009.

Schaap, M., Leij, F., and van Genuchten, M.: ROSETTA: A computer program for estimating soil hydraulic parameters with hierarchical pedotransfer functions, J. Hydrol., 251, 163–176, 2001.

Short, D., Dawes, W., and White, I.: The practicability of using Richards' equation for general purpose soil-water dynamics models, Environ. Int., 21, 723–730, 1995.

Sillon, J.-F., Richard, G., and Cousin, I.: Tillage and traffic effect on soil hydraulic properties and evaporation, Geoderma, 116, 29–46, 2003.

Simunek, J., Sejna, M., Saito, H., Sakai, M., and van Genuchten, M. T.: The HYDRUS-1D software package for simulating the one-dimensional movement of water, heat, and multiple solutes in variably-saturated media, Department of Environmental Sciences, University of California Riverside, Riverside, California, 2008.

Taconet, O., Bernard, R., and Vidal-Madjar, D.: Evapotranspiration over an agricultural region using a surface flux/temperature model based on NOAA-AVHRR data, J. Clim. Appl. Meteorol., 25, 284–307, 1986.

Van de Griend, A. and O'Neill, P.: Discrimination of soil hydraulic properties by combined thermal infrared and microwave remote sensing, in: IGARSS' 86 Symposium, Zurich, 1986.

van Genuchten, M.: A closed-form equation for predicting the hydraulic conductivity of unsaturated soils, Soil Sci. Soc. Am. J., 3, 909–916, 1980.

Varado, N., Braud, I., Ross, P., and Haverkamp, R.: Assessment of an efficient numerical solution of the the 1D Richards' equation on bare soil, J. Hydrol., 323, 244–257, 2006a.

Witono, H. and Bruckler, L.: Use of remotely sensed soil moisture content as boundary conditions in soil-atmosphere water transport modeling, Water Resour. Res., 25, 2423–2435, 1989.

Wosten, J., Pachepsky, Y., and Rawls, W.: Pedotransfer functions: bridging the gap between available basic soil data and missing soil hydraulic characteristics, J. Hydrol., 251, 123–150, 2001.

Zhang, X., Bengough, A., Crawford, J., and Young, I.: Efficient methods for solving water flow in variably saturated soils under prescribed flux infiltration, J. Hydrol., 260, 75–87, 2002.

Zhu, J. and Mohanty, B.: Soil hydraulic parameter upscaling for steady-state flow with root water uptake, Vadose Zone J., 3, 1464–1470, 2004.