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Coupling Surface And Ground Water Processes For Water Resources Simulation In Irrigated Alluvial Basins

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Abstract:

Understanding the interaction between soil, vegetation and atmosphere processes and groundwater dynamics is of paramount importance in water resources planning and management in many practical applications. This is the case, for example, of the most important agricultural and industrial area in Italy, the Padana Plain, where intensive exploitation of groundwater for domestic and industrial supply coexists with massive diversions from surface water bodies, providing abundant irrigation to one of the most productive agricultural districts in Europe. Hydrological models of such complex systems need to include a number of components and should therefore seek a balance between capturing all relevant processes and maintaining data requirement and computing time at an affordable level. Water transfer through the unsaturated zone is a key hydrological process, at the interface between surface and ground water. The paper focuses on the analysis of the modelling approaches that are generally used to describe the soil water dynamics in hydrological models of water resources systems. A physically based approach, using numerical solutions of Richards equation, and two conceptual models, based on reservoirs cascade schemes, are compared. The analysis is part of a comprehensive modelling study of water resources in a 700 km^2 irrigation district in northern Italy. Simulations are carried out using ten years of rainfall data and a number of soil profiles that are representative of the pedological characteristics of the study area. Based on the analysis of results, showing significant differences in the simulated patterns of output variables, a number of remarks are drawn.

Keywords: Unsaturated zone; Richards equation; reservoir cascade; SWAT; SWRRB

1. INTRODUCTION

Integrated modelling approaches have a great potential for application to water resources planning and management. This is especially true for densely settled irrigated plains, where the interaction between surface and ground waters plays a dominant role. In the case of the Padana Plain (Northern Italy), for example, water supply for irrigation is based on surface water diversions, while domestic and industrial supply is provided by groundwater abstractions. A significant portion of the total recharge to the aquifers is due to the percolation of water used for irrigation, which is mostly performed with traditional, low efficiency methods.

A number of modelling tools have been proposed in the last decades, often including quite different representations of the individual hydrological processes. Water transfer through the unsaturated zone is one of the key process, as it determines evapotranspiration rates and, eventually, crop water stress on one side, and recharge to the aquifers on the other. Two main approaches are widely used for the mathematica representation of water flow in the unsaturated zone: numerical solutions of the Richards equation and reservoir cascade schemes.

Conceptual, reservoir cascade schemes are included in many hydrological models, both at the field and basin scale [CREAMS, Knisel, 1980; ANSWERS, Beasley and Huggins, 1981; SWRRB, Williams et al., 1985; GLEAMS, Leonard et al., 1987; AGNPS, Young et al., 1987; KINEROS, Woolhiser et al., 1990; EPIC, Sharpley and Williams, 1990; WEPP, Flanagan et al., 1995; SWAT, Neitsch et al., 1999; among the others].

On the other hand, physically based approaches, using numerical solutions of Richards equations, first adopted at the local scale, have been also incorporated into basin scale hydrological models [HYDRUS, Simunek et al., 1998; SWAP, Van Dam et al., 1997; SWIF, Bouten, 1992; SOIL, Johnson and Jansson, 1991; SHE, Abbott et al., 1986; ONZAT, Van Drecht, 1983]..

The objective of this paper is to present and discuss the results of the comparison of three different unsaturated flow models in view of the implementation of an integrated model of water resources in a large irrigation district (the 700 km^2 Muzza district) in northern Italy [Facchi et al., 2004].

2. UNSATURATED FLOW MODELS

Three models of water flow in unsaturated soil were considered: SWAP [Van Dam et al., 1997] and the two conceptual, reservoir-type components included in SWRRB [Williams et al., 1985] and ALHyMUS [Facchi, 2004].

SWRRB belongs to the suite of USDA models, including among others EPIC, CREAMS, WEPP, which use the same basic approach to represent water flow in the unsaturated zone. This consists of a non-linear reservoirs cascade; the time constant of each reservoir is inversely proportional to the unsaturated hydraulic conductivity K, which is expressed by equation:

$$K(\theta) = K_{sat}\left(\frac{\theta}{\theta_{sat}}\right)^{\beta} \tag{1a}$$

where θ_{sat} [L^{3}L^{-3}] is the water content at saturation, K_{sat} [LT^{-1}] is the corresponding hydraulic conductivity, and β is a shape coefficient given by

$$\beta = \frac{-2.655}{\log \frac{\theta_{FC}}{\theta_{sat}}} \tag{1b}$$

θ_{FC} [L^{3}L^{-3}] being the water content at field capacity. This ensures that K=0.002 K_{sat} at θ=θ_{FC}. Outflow from each reservoir decreases with decreasing θ and is assumed to be null for $\theta \le \theta_{FC}$.

The unsaturated flow component of ALHyMUS is also based on a non linear reservoir cascade scheme, including two reservoirs in the root-zone and one additional reservoir from the root-zone to the groundwater table. Outflow from each reservoir is proportional to hydraulic conductivity K, as expressed by Brooks & Corey equation

$$K(\theta) = K_{sat}\left(\frac{\theta - \theta_r}{\theta_{sat} - \theta_r}\right)^{n} \tag{2}$$

where θ_r [L^{3}L^{-3}] is the residual water content and n a shape coefficient.

Finally, SWAP is a widely applied and well documented model, based on a finite difference solution of Richards equation. Van Genuchten and Brooks & Corey equations were used here to describe water retention and conductivity curves, respectively.

3. MATERIALS AND METHODS

Four different soils were considered in the tests, covering a wide range of hydraulic characteristics (see Table 1): BSC, BLV, RAM, SCH, respectively characterised by silty loam; loam; sandy loam and sandy textures. For each soil three different homogeneous profiles were considered with depths of the groundwater table from the ground surface of 1, 2 and 10 m.

Table 1. Hydraulic parameters of the test soils

Soil	**θ_{sat}** (m^3 m^{-3})	**θ_r** (m^3 m^{-3})	**K_{sat}** (cm h^{-1})	**n** (-)	**θ_{FC}** (m^3 m^{-3})
BSC	0.52	0.02	1.85	8.65	0.30
BLV	0.50	0.07	1.43	8.85	0.29
RAM	0.44	0.05	7.03	7.73	0.23
SCH	0.42	0.04	35.18	6.96	0.16

Inputs to the top of the profile are rainfall plus irrigation. A ten year (1993-2002) series of daily rainfall was used; comparison with historical data shows that dry (<Q_{10}), average (Q_{50}) and wet (>Q_{90}) years are well represented. A number of irrigations, ranging from three to five per year depending on weather conditions, was also supplied, according to the normal irrigation practices in the area.

No interception, evapotranspiration and surface runoff are assumed to take place, the focus being only on the water accumulation and transport processes into the unsaturated profile.

4. RESULTS

Simulation results are compared in terms of:

- water content in the top soil (i.e. the first 1 m of each profile);
- water flow at the bottom of the profile, i.e. the recharge to the saturated groundwater layer.

The former is the key variable for determining evapotranspiration rate and crop water stress, while the latter is crucial for the analysis and modelling of surface–ground water interactions.

4.1 Soil water content in the root zone

A first observation is that the influence of the saturated surface depth (i.e. of the boundary condition at the bottom of the profile) cannot be captured by reservoir cascade models. Unless a specific component for capillary rise is included in these models (which however implies increasing the number of parameters) it does not make any difference wether the profile is 1, 2 or 10 m deep.

On the other hand, however, the results show that this influence of the lower boundary condition is significant only for shallow profiles and fine textured soils. In practice, only for soil BSC and profile depths up to very few meters the water content in the top soil changes significantly. Figure 1 shows that the difference in water content values is large between the 1 m and the 2 m profile, while it's much smaller (soil BSC) or negligible (for coarser soils) between the latter and the 10 m profile. When the lower boundary condition is not influential, both SWRRB and ALHyMUS generally show a good agreement with SWAP. For coarser soils, however, water contents lower than field capacity are often computed by SWAP and ALHyMUS, while no flux underneath field capacity is allowed by SWRRB (Figure 2). This assumption apparently limits the flexibility of SWRRB in simulating soil water dynamics at low water contents. These observations are confirmed by Table 2, which reports values of some statistical and fitting indices

Table 2. Average values and coefficient of variation for the simulation runs. Nash-Sutcliffe fitting index was computed using SWAP simulations as reference series

	BSC	**BLV**	**RAM**	**SCH**
Average value (m^3 m^{-3})				
SWAP-10m	0.350	0.319	0.213	0.155
ALHyMUS	0.345	0.318	0.214	0.156
SWRRB	0.342	0.329	0.239	0.169
CV (%)				
SWAP-10m	9.143	7.577	10.017	11.664
ALHyMUS	9.484	7.188	10.247	11.670
SWRRB	9.493	6.722	8.604	11.384
Nash-Sutcliffe index (-)				
ALHyMUS	0.630	0.660	0.567	0.485
SWRRB	0.568	0.587	-1.209	-0.757

4.2 Outflow from the profile

Figure 3 shows the outflow at the bottom of the profile for the loamy soil BLV. At increasing profile deptht, the effects of smoothing and delaying of the input signal caused by increased soil depths can be seen very clearly. Both effects are magnified in finer textured soils, while for coarse soils the depth of the profile has a smaller influence on the output signal.

Non linear behaviour is also very clear and can only partly be captured by reservoir cascade schemes (see Figure 4 and Table 3). Both SWRRB and ALHyMUS overestimate the smoothing effect when the thinner (1 m) soil profiles are considered, with a much more pronounced attenuation of peaks compared to SWAP, especially in the case of finer soils. On the contrary, when thicker profiles are analysed, the amplitude of the signal is reasonably well captured, but the phase is poorly described.

Special attention should be paid when using SWRRB with coarse soils, due to possible undesired effects of the discontinuity in the hydraulic conductivity function at water content equal to the field capacity. For example, the sandy soil SCH drops from a relatively high K=16.9 mm/d at field capacity (Eq. 1) to zero at lower water contents. This abrupt change in conductivity produces a typical pulsating pattern of recharge, which does not seem to have any physical reason.

The agreement between SWAP and ALHyMUS or SWRRB can be improved if the number of reservoir in the cascade is allowed to vary with changing profile depth, as illustrated in Figure 5, where ALHyMUS has been run for the 10 m profile, using up to five reservoirs for the percolation layer underlying the root zone (for which always two reservoirs were used). However, no well established and scientifically sound rule for fixing the reservoir number is available, and only empirical indications can be found in literature (see, e.g. Besbes and De Marsily, 1984).

Since the comparison is carried out in view of coupling unsaturated zone model with a regional groundwater flow model, it was deemed important to check to which extent the differences in recharge are mitigated by considering longer simulation time steps, which are generally used in the latter models. As it could be expected the differences become smaller as the time step increases. Figure 6 and Table 3 show, for example, the results aggregated at three months time step, which is the stress period used for groundwater simulation in the Muzza case study.

Table 3. Nash-Sutcliffe indices for the daily and three-monthly recharge patterns for all the selected scenarios

	daily		*three-monthly*	
	ALHyMUS	SWRRB	ALHyMUS	SWRRB
1m-BSC	0.627	0.501	0.889	0.939
1m-BLV	0.419	0.689	0.938	0.935
1m-RAM	0.678	0.917	0.956	0.998
1m-SCH	0.717	0.817	0.973	0.996
2m-BSC	0.491	0.561	0.831	0.878
2m-BLV	0.735	0.749	0.939	0.942
2m-RAM	0.674	0.616	0.964	0.938
2m-SCH	0.753	-0.206	0.979	0.925
10m-BSC	0.494	0.473	0.669	0.652
10m-BLV	0.227	0.219	0.674	0.611
10m-RAM	0.221	-3.304	0.721	-0.640
10m-SCH	0.219	-11.154	0.726	-0.833

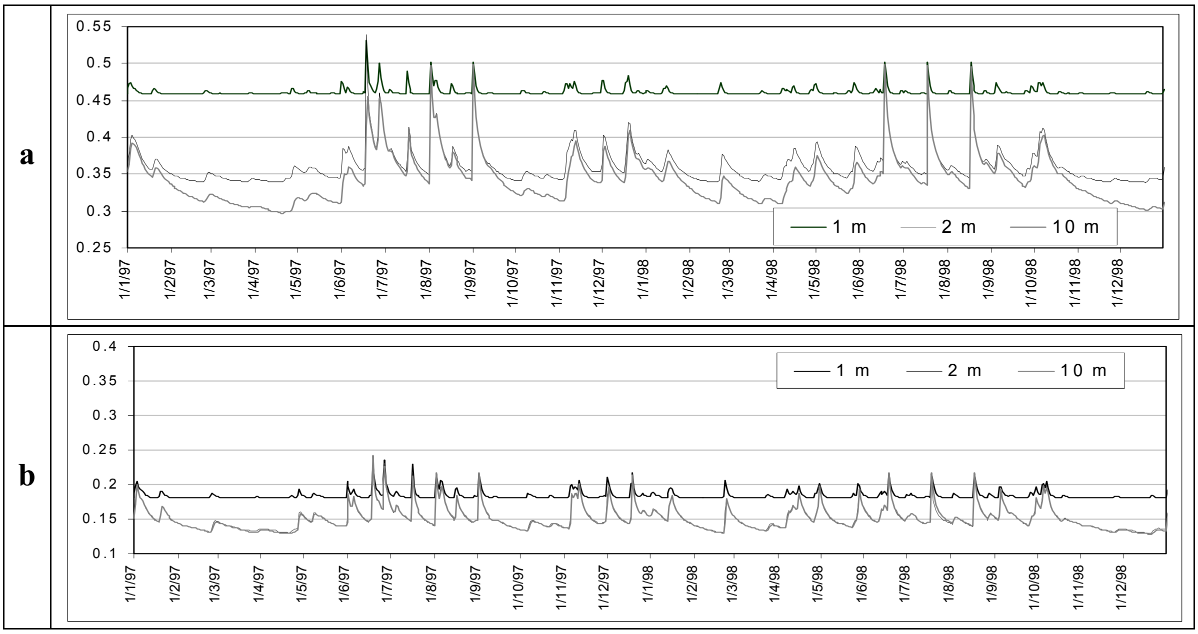

Figure 1. Daily patterns of soil water content $[L^3 L^{-3}]$ in the top soil, simulated with SWAP with water table depth of 1, 2, and 10 m; (a) soil BSC, (b) soil SCH; years years 1997-1998

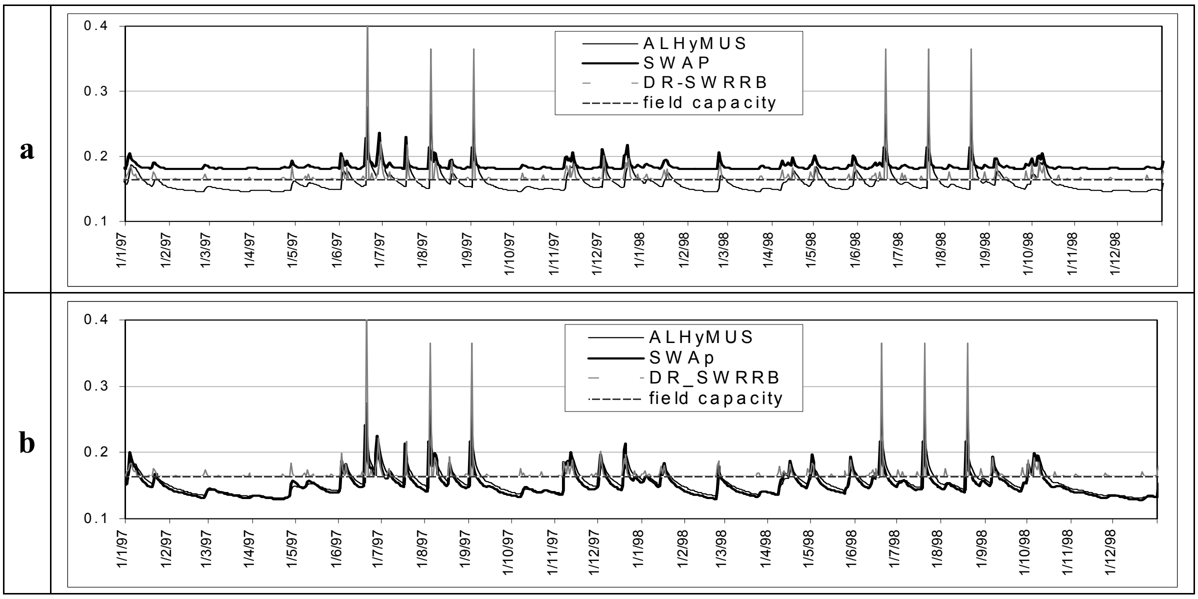

Figure 2. Daily patterns of soil water content $[L^3 L^{-3}]$ in the top soil, simulated with SWAP, ALHyMUS and SWRRB for soil SCH and water table depth at (a) 1 m and (b) 10 m; years years 1997-1998

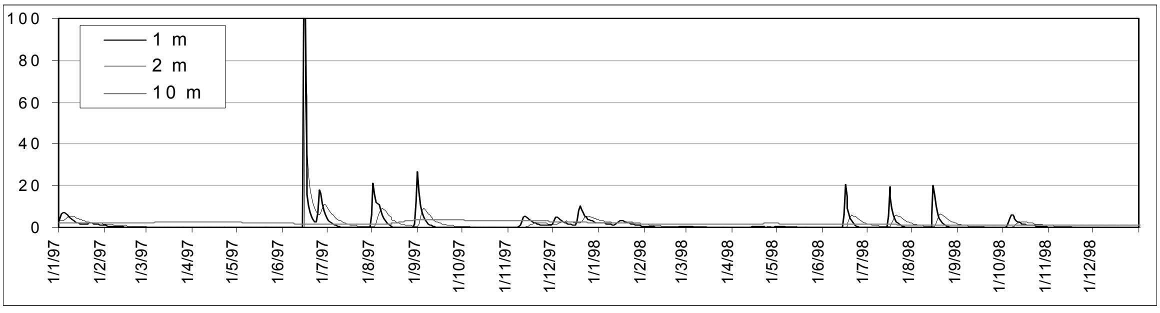

Figure 3. Daily patterns of the outflow at the bottom of the profile (mm d^{-1}) simulated with SWAP with water table depth of 1, 2, and 10 m; soil BSC; years 1997-1998

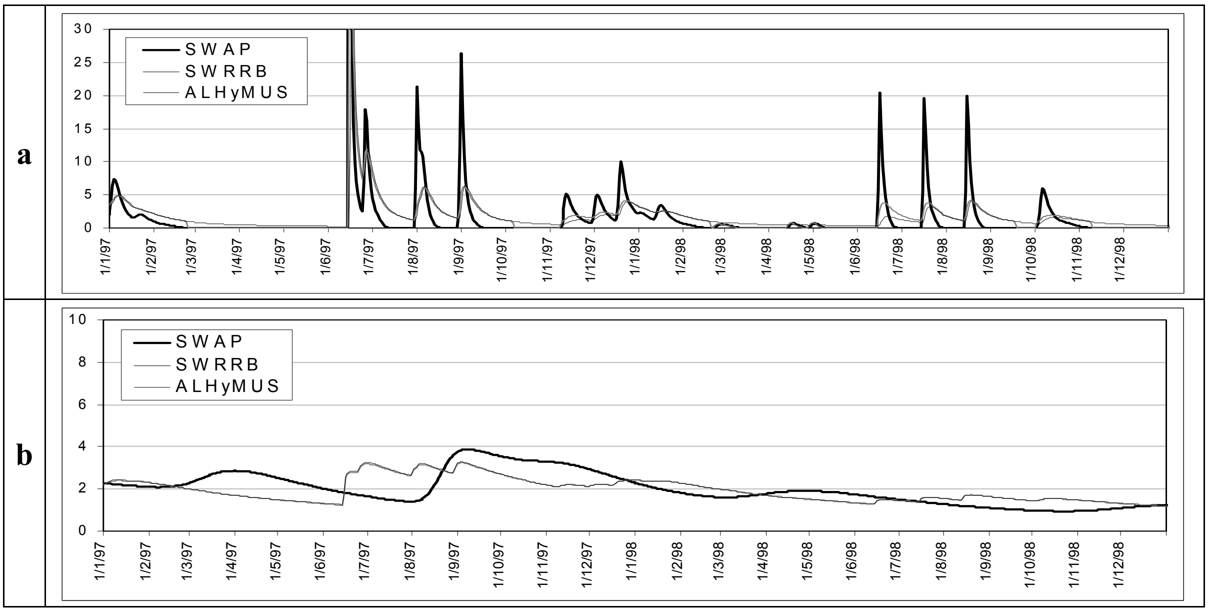

Figure 4. Daily patterns of the outflow at the bottom of the profile (mm d^{-1}) simulated with SWAP with water table depth of 1 and 10 m; soil BSC; years 1997-1998

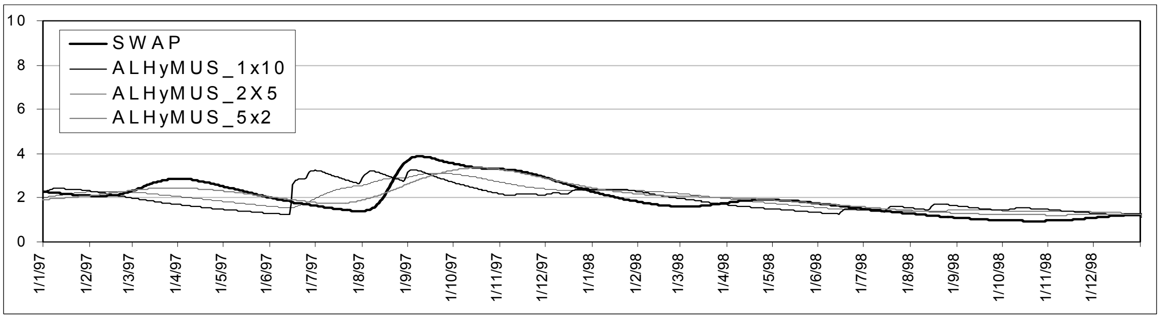

Figure 5. Daily outflow from a 10 m profile, BSC soil, simulated by SWAP and ALHyMUS, at changing of the reservoir number in the cascade; years 1997-1998

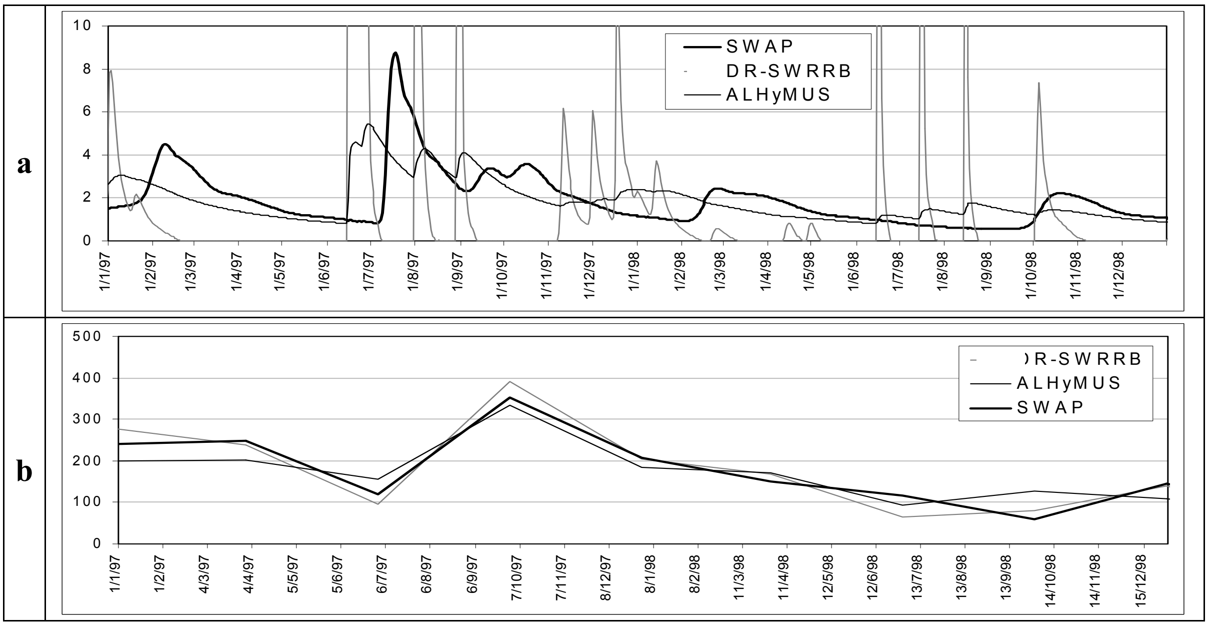

Figure 6. Daily (a) and three-monthly (b) patterns of of the outflow at the bottom of the profile, simulated with SWAP, ALHyMUS and SWRRB for soil SCH and water table depth of 10 m; years 1997-1998

5. CONCLUDING REMARKS

In the paper results of the comparison of a widely applied model based on Richards equation – SWAP – with two reservoir models – SWRRB and HALyMUS – were presented. The analysis was carried out in the framework of an comprehensive modelling study of water resources in a 700 km^2 irrigation district in northern Italy [Facchi et al., 2004]. A number of soil profiles, representative of the study area characteristics, were selected and simulations were carried out using 10 years of daily rainfall observation plus the normal irrigation supply, according to the current practices in the area. Soil types range from silty loam to sand and profile depths from 1 to 10 m.

The comparison was focused on two output variables, i.e. water content of the top soil (first 1 m) and outflow at the bottom of the profile.

A first observation is that reservoir models cannot capture the influence of water table depth on the soil water profile. This may extend to the top soil when the water table depth is small and soil texture is fine. A site-specific analysis needs therefore to be carried out: in the Muzza study area, for example, the water table effects turned out to be relevant only for the finest soil (BSC) and for water table depths of 3-4 m, which are not very common in the area. When the lower boundary is not influential the results of the three models are generally in good agreement. For coarser soils, however, while water contents computed by SWAP and ALHyMUS often drop below field capacity, SWRRB tends to overestimate the soil water content due to the assumption of no flux at water content lower than field capacity. This is reflected also in the pattern of the outflow from the profile, which may show a typical pulsating behaviour as a result of the sudden drop of hydraulic conductivity when field capacity is reached.

The ability of reservoir models to mimic the nonlinear effects on input-output transformation is rather poor. In general, both SWRRB and ALHyMUS may overestimate the smoothing effect when thin soil profiles are considered, with a more pronounced attenuation of peaks compared to SWAP. On the contrary, when thicker profiles are analysed, the amplitude of the signal is reasonably well captured, but the phase is poorly described. Only when outflow is aggregated over longer time intervals (e.g. months) the differences decrease significantly. This observation may be relevant in practical applications, when the unsaturated flow model is coupled with a regional aquifer model, providing recharge fluxes over the aquifer stress periods, which are often of the order of decades or months.

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