Comparison of CGMS-WOFOST and HYDRUS-1D Simulation Results for One Cell of CGMS-GRID50

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Abstract: CGMS (Crop Growth Monitoring System) developed by JRC is an integrated system to monitor crop behaviour and quantitative crop yield forecast that operates on a European scale. To simulate water balance in the root zone the simulation model CGMS-WOFOST (Supit & van der Goot 2003) is used that is based on water storage routing. This study was performed to assess a possible impact of simplifications of the water storage routing based model on simulated water regime in the soil profile. Results of CGMS-WOFOST are compared with results of a more precise Richards' equation based model HYDRUS-1D (Šimůnek *et al.* 2005). 16 scenarios are simulated using HYDRUS-1D. Each scenario represents a single soil profile presented in the selected cell of GRID50 in the Czech Republic. Geometry of the soil profiles, material (texture) definition, root distributions, measured daily rainfall, calculated daily evaporation from the bare soil surface and transpiration of crop canopy were defined similarly to CGMS-WOFOST inputs according to the data stored in the SGDBE40 database. The soil hydraulic properties corresponding to each soil layer were defined using the class transfer rules (Wösten *et al.* 1999). The bottom boundary conditions were defined either similarly to CGMS-WOFOST bottom boundary condition as a free drainage or as a constant water level 250 cm below the soil surface to demonstrate a ground water impact on the soil profile water balance. The relative soil moisture (RSM) in the root zone during the vegetation period was calculated to be compared with the similar output from CGMS. The RSM values obtained using HYDRUS-1D are higher than those obtained using CGMS-WOFOST mostly due to higher retention ability of HYDRUS-1D. The reasonably higher RSM values were obtained at the end of simulated period using the HYDRUS-1D for the constant water level 250 cm below the soil surface.

Keywords: GRID50; capacity based model; WOFOST; Richards' equation based model; HYDRUS-1D; Crop Growth Monitoring System (CGMS); soil profile water balance; relative soil moisture

Many models of different complexity and dimensionality have been developed during the last several decades to quantify the basic physical and chemical processes affecting water flow and pollutant transport in the unsaturated zone. Methods describing these processes and model complexity depend on model application in water management, agricultural management, soil and groundwater pollution assessment and other environmental fields of activity. Different approaches may be used for a detailed description of processes on a small scale and in a short term compared to a description of processes on a large scale and in a long term. The main simulated process is a numerical simulation of

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the water regime. In general, there are two major approaches to water flow simulation. The simplest types of soil water flow models are based on water storage routing (capacity based models). Such models act as tipping buckets. Examples are WOFOST (Boogaard *et al.* 1998), EPIC (Williams 1999), CREAMS (Knisel 1980), GLEAMS (Knisel 1993; Knisel & Davis 2000), and CROPWAT (Smith 1992). These models are usually used for the solution of a particular problem such as irrigation scheduling, prediction of crop production, climate modelling or eco-hydrological modelling on a larger scale and in a longer term. The physically based approach uses Richards' equation that is based on Darcy's law and continuity equation. These models are generally applicable. They can be used for a precise description of water regime in an unsaturated and saturated soil profile and may be applied in fundamental research as well as in water management. Examples are HYDRUS-1D (Šimůnek *et al.* 2005), TOUGH2 (Pruess *et al.* 1999), UNSAT-H (Fayer 2000), SHAW2.3 (Flerchinger 2000), LEACHM (Hutson 2003) and SWAP (Kroes & van Dam 2003).

CGMS (Crop Growth Monitoring System) developed by JRC is an integrated system to monitor crop behaviour and quantitative crop yield forecast that operates on a European scale. To simulate water balance in the root zone the simulation model CGMS-WOFOST (Supit & van der Goot 2003) is used that is based on water storage routing. In this study we show an impact of simplifications of the water storage routing based model on a simulated water regime in the soil profile. Results of CGMS-WOFOST obtained for the selected cell of GRID50 in the Czech Republic are compared with results of a more precise Richards' equation based model HYDRUS-1D (Šimůnek *et al.* 2005).

MATERIAL AND METHODS

Simulation model WOFOST in CGMS

WOFOST (Boogaard *et al.* 1998) is a water storage routing based model. Water balance in the soil profile is solved using three different soil water sub-models. The first and most simple soil water balance applies to a potential production situation. Assuming the continuously moist soil, crop water requirements are quantified as the sum of crop transpiration and evaporation from the shaded soil under the canopy.

The second water balance in a water limited production situation applies to the freely draining soil where groundwater is so deep that it cannot have an influence on the soil moisture content in the rooting zone. The soil profile is divided into two compartments, the rooted zone and the lower zone between actual rooting depth and maximum rooting depth. The subsoil below the rooting depth is not defined. The second zone merges gradually with the first zone as the roots grow deeper. The principle of this soil water balance is a cascade (overflowing bucket). The rainfall infiltrates, a part may be temporarily stored above the surface or runs off. Evaporation loss is calculated. The infiltrated water that exceeds the retention capacity of a soil compartment percolates downward. There is no capillary rise.

WOFOST also allows to solve the influence of shallow groundwater using the third sub-model. However, this sub-model is not included in the CGMS. The principles are similar to the freely draining situation. A difference is that the soil moisture retention capacity is determined by the depth of the groundwater as is the percolation rate. There is a capillary rise if the rooted soil dries out. The groundwater level can be controlled by artificial drainage and the moisture content within the root zone does not vary with depth.

The daily evaporation from the bare soil surface and daily transpiration are calculated using Penman formula (Penman 1948) that was described in detail by van der Goot and Orlandi (2003):

$$E0 = \frac{(\Delta R_{na} + \gamma EA)}{\Delta + \gamma} \tag{1}$$

where:

$E0$ – evapotranspiration (L/T)

R_{na} – net absorbed radiation (L/T)

EA – evaporative demand (L/T)

Δ – slope of the saturation vapour pressure curve (M/L/T^2/K)

γ – Psychrometric constant (M/L/T^2/K) (0.067 kPa°C^{-1})

The actual water uptake is described using the water stress response function proposed by Feddes *et al.* (1978). See equation (3) below. However, in this case this relationship is expressed as a function of soil water contents defining θ_{wp}, θ_{cr}, θ_{fc} and θ_{st} that represent the water content of the soil at wilting point, critical point for potential transpiration, field capacity and saturation, respectively.

Simulation model HYDRUS-1D

HYDRUS-1D (Šimůnek *et al.* 2005) is a simulation model based on the numerical solution of Richards' equation using the Galerkin-type linear finite element method. Richards' equation, in this case describing the flow in a variably saturated anisotropic homogeneous rigid porous medium for one-dimensional isothermal Darcian flow, can be written in the following simplified form:

$$\frac{\partial\theta}{\partial t}=\frac{\partial}{\partial z}\left[K\left(\frac{\partial h}{\partial z}+\cos\beta\right)\right]-S \qquad (2)$$

where:
z – positive upward vertical coordinate (L)
t – time (T)
θ – volumetric water content (L^3/L^3)
h – pressure head (L)
K – unsaturated hydraulic conductivity function (L/T)
S – sink term (T^{-1})
β – angle between the flow direction and the vertical axis

The sink term, S, is defined as the volume of water removed from a unit volume of soil per unit time due to plant water uptake. Feddes *et al.* (1978) defined S as:

$$S(h) = \alpha(h)S_p \qquad (3)$$

where:
$\alpha(h)$ – root-water uptake water stress response function (–)
S_p – potential water uptake rate (T^{-1})

The potential water uptake rate is defined using the following equation:

$$S_p = b(z)\,T_p \qquad (4)$$

where:
T_p – potential transpiration rate (L/T)
$b(z)$ – normalized water uptake distribution (L^{-1})

The function $b(z)$ may be constant with depth (equal distribution within the root zone), linear (Feddes *et al.* 1978), constant to the specified depth and linear below that (van Genuchten 1987), or an exponential function with its maximum at the soil surface (Raats 1974). The potential transpiration rate must be defined or calculated.

The root depth, L_R, can be either constant or variable during the simulation. For annual vegetation the growth model is required to simulate a change in the rooting depth with time. HYDRUS-1D assumes that the actual root depth is the product of maximum rooting depth, L_m (L), and root growth coefficient, $f_r(t)$ (Šimůnek & Suarez 1993):

$$L_R(t) = L_m f_r(t) \qquad (5)$$

For the root growth coefficient, $f_r(t)$, the Verhulst-Pearl logistic growth function is used:

$$f_r(t)=\frac{L_0}{L_0+(L_m-L_0)e^{-rt}} \qquad (6)$$

where:
L_0 – initial value of the rooting depth at the beginning of the growing season (L)
r – growth rate (T^{-1})

The growth rate is calculated either from the assumption that 50% of the rooting depth will be reached after 50% of the growing season has elapsed, or from the given data.

The soil hydraulic properties, e.g. the soil water content retention curve, $\theta(h)$, and the hydraulic conductivity curve, $K(\theta)$, may be descried using the van Genuchten (1980) analytical functions:

$$\theta_e=\frac{\theta(h)-\theta_r}{\theta_s-\theta_r}=\frac{1}{\left(1+|\alpha h|^n\right)^m} \qquad h<0 \qquad (7)$$

$\theta_e = 1,\ h \geq 0$

and

$$K(\theta) = K_s\,\theta_e^l\,[1-(1-\theta_e^{l/m})^m]^2 \qquad h < 0 \qquad (8)$$

where:
θ_e – effective soil water content (–)
θ_r, θ_s – residual and saturated soil water content (L^3/L^3)
K_s – saturated hydraulic conductivity (L/T)
α (L^{-1}), n (–), m (–) – empirical parameters
l – pore-connectivity parameter (–)

Model comparison using the relative soil moisture (RSM) values

The relative soil moisture (RSM) in the root zone during the vegetation period was calculated for HYDRUS-1D simulation data to be compared with a similar output from CGMS-WOFOST according to the following equation:

$$\mathrm{RMS}(t)=\frac{\theta-\theta_{wp}}{\theta_{fc}-\theta_{wp}}\,100 \qquad (9)$$

where:
θ_{wp} – wilting point (L^3/L^3) (soil water content for the pressure head of –1500 kPa)
θ_{fc} – field capacity (L^3/L^3) (soil water content for the pressure head of –10 to –33 kPa)

Table 1. Definition of simulated soil profiles

STU	No. of STU	Area (ha)	TEXT_SRF_D	TEXT_SUB_D	TEXT_DEP_C	ROOT_DEPTH
4210001	1	13426	2	2	4	7
4210005	1	3642	9	2	4	7
4210011	4	27653	1	1	5	7
4210019	1	10104	2	2	5	7
4210026	1	4794	2	3	2	7
4210033	1	67	4	4	5	7
4210037	3	44166	4	4	5	8
4210041	1	5388	2	3	2	6
4210044	3	13399	4	4	3	5
4210048	1	1223	2	2	4	8
4210054	1	10078	4	4	3	8
4210150	3	16697	0	0	0	6
4210068	1	326	1	1	5	6
4210073	1	463	2	3	4	8
4210078	1	1853	2	2	4	8
4210106	2	61931	2	3	1	8
4210114	2	2024	2	3	2	6
4210121	1	13498	2	3	2	4
4210143	2	25263	1	1	5	4

Scenario definition

One cell of GRID50 (57066) in SGDBE40 database was selected to compare CGMS-WOFOST and HYDRUS-1D simulation results. 19 soil profiles are defined in this region as shown in Table 1 and Figure 1. STU identifies soil typological unit, TEXT-SRF-DOM and TEXT-SUB-DOM specify dominant texture of surface and subsurface layer, respectively, TEXT-DEPTH defines depth of textural change, ROOT-DEPTH defines maximal root depth. Geometry of the two layer soil profiles was characterized as follows. The maximum depth of the soil profile was 200 cm. The depth of textural change was set as an average value of a range shown in Table 2. The soil hydraulic properties (Tables 3 and 4) corresponding to each soil layer were defined using the class transfer rules (Wösten *et al.* 1999) as was proposed in SINFO project (Boogaard *et al.* 2005). Since two pairs of STU were identical and one STU was not predefined, only 16 soil profiles were generated.

The water regime in the soil profile was simulated for the year 2004 using a single set of daily rainfall, daily evaporation from the bare soil surface and daily transpiration of winter wheat that is stored in GRID_WEATHER (Figure 2). Values of daily rainfall were measured. The daily evaporation from the bare soil surface and daily transpiration are calculated using Penman formula (van der Goot

Table 2. Definition of textural change depth classes

Class	Depth (cm)	Range (cm)
0	no information	
1	40	20–40
2	60	40–60
3	80	60–80
4	120	80–120
5		< 120
6	60	20–60
7	120	60–120

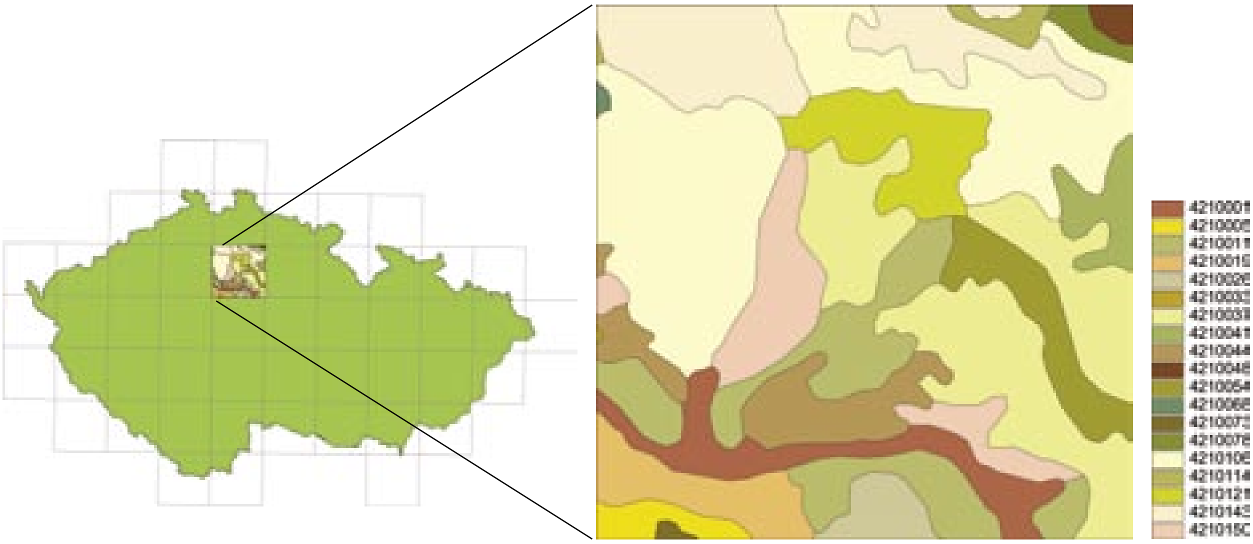

Figure 1. Selected cell of GRID50 in SGDBE40 database with specified soil typological units (STU)

& Orlandi 2003). The snow melt was not assumed in this study since the temperature (Figure 3) was not significantly below limits (HYDRUS-1D assumes the snow form for an air temperature below –2°C, the liquid form for an air temperature above +2°C and a linear transition between the limits). The root zone for winter wheat was specified assuming root growth and the root distribution function proposed by van Genuchten (1987). The depth of the roots at the beginning of simulation was 20 cm. The maximum depth of roots was specified as an average value of a range shown in Table 5. The variable root depth, L_R, during the vegetation period was simulated assuming that 50% of the rooting depth will be reached after 50% of the growing season has elapsed. The plant water stress response function, $\alpha(h)$, proposed by Feddes *et al.* (1978) with coefficient stored in the HYDRUS-1D database for wheat was applied to simulate the actual transpiration rate.

The bottom boundary conditions were defined either as a free drainage (no specific input for HYDRUS-1D is necessary) or as a constant water level 250 cm below the soil surface (the constant water table elevation must be defined or variable pressure heads may also be used). While the boundary condition defined as a free drainage at the depth of 200 cm should not considerably influence the water regime in the top part of the soil profile, the boundary condition defined as a constant (or variable) water level should ensure a moderate water supply of the soil profile water storage from the groundwater.

Table 3: Definition of texture classes

Code	Description
0	no information
9	no texture (Histosols, etc.)
1	coarse (clay < 18% and sand > 65%)
2	medium (18% < clay < 35% and sand > 15%, or clay < 18% and 15% < sand < 65%)
3	medium fine (clay < 35% and sand < 15%)
4	fine (35% < clay < 60%)
5	very fine (clay > 60%)
6	medium (18% < clay < 35%, or clay < 18% and 15% < sand < 65%) (for use with the Digital Soil Map of the World only)
7	very fine (clay > 35%) (for use with the Digital Soil Map of the World only)

Table 4. van Genuchten – Mualem parameters for the fits on the geometric mean curves (Wösten *et al.* 1999)

	θ_r (cm³/cm³)	θ_s (cm³/cm³)	α (1/cm)	*n* (–)	*m* (–)	*l* (–)	K_s (cm/day)
Topsoil							
Coarse	0.025	0.403	0.038	1.377	0.274	1.25	60.00
Medium	0.010	0.439	0.031	1.180	0.153	–2.34	12.06
Medium Fine	0.010	0.430	0.008	1.254	0.203	–0.58	2.27
Fine	0.010	0.520	0.037	1.101	0.092	–1.97	24.80
Very Fine	0.010	0.614	0.026	1.103	0.094	2.50	15.00
Subsoil							
Coarse	0.025	0.366	0.043	1.521	0.342	1.25	70.00
Medium	0.010	0.392	0.025	1.169	0.144	–0.74	10.75
Medium Fine	0.010	0.412	0.008	1.218	0.179	0.50	4.00
Fine	0.010	0.481	0.020	1.086	0.079	–3.71	8.50
Very Fine	0.010	0.538	0.017	1.073	0.068	0.001	8.23
Organic*	0.010	0.766	0.013	1.204	0.169	0.40	8.00

*Within the organic soils no distinction is made in topsoils and subsoils

Table 5. Definition of rooting depth classes

Class	Depth (cm)	Range (cm)
1	10	< 10
2	20	10–20
3	40	20–40
4	60	40–60
5	80	60–80
6	100	80–100
7	120	100–120
8	150	120–150

The relative soil moisture (RSM) was calculated from soil water content distributions in the soil profile each 10th day of the vegetation period obtained using the HYDRUS-1D. The wilting points and the field capacities were defined as soil water contents for the pressure head of –1500 kPa and –20 kPa, respectively. The RSM values were calculated automatically using the WOFOST in CGMS selecting grid cell, year (2004) and crop (winter wheat). The wilting points and the field capacities as well as other soil water content limits differ from those applied in HYDRUS-1D since the data stored in CGMS database were used.

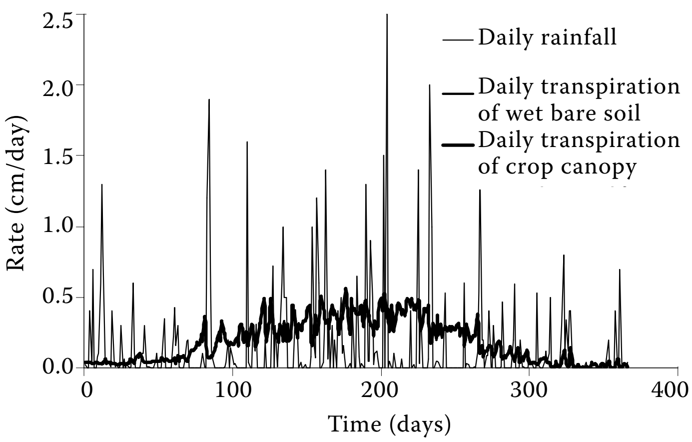

Figure 2. Daily rainfall, transpiration of wet bare soil and transpiration of crop canopy

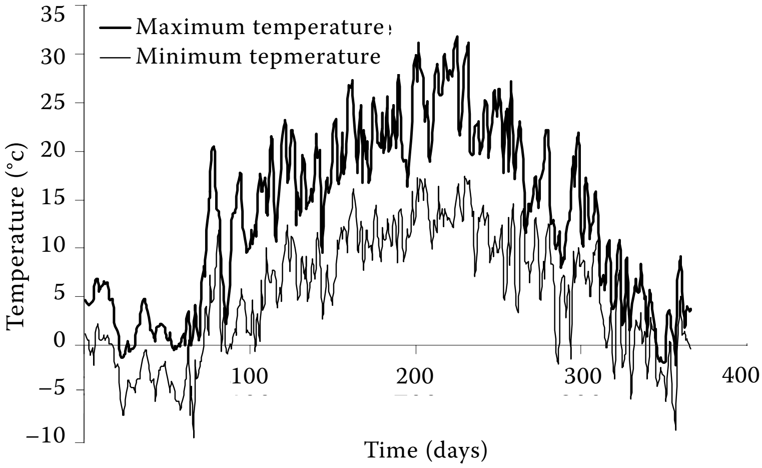

Figure 3. Daily maximum and minimum temperature

RESULTS AND DISCUSSION

The average RSM values in 2004 as well as the long-term average RSM values calculated with CGMS-WOFOST are shown in Figure 4. The RSM values for all soil profiles simulated with HYDRUS-1D for the free drainage boundary condition are shown in Figure 5a. The RSM values for different soil profiles are considerably different depending on the root depth and soil texture. The shallower root zone is calculated, the lower RSM values at the end of vegetation period are obtained. The lower RSM values at the end of the simulated period are obtained also for coarse texture soils (code 1) and for fine texture soils (code 4). Interestingly for STUs with higher RSM values at the beginning the lower RSM values were obtained at the end of the simulated period and reversely. The minimal difference between maximal and minimal RSM values was obtained for STU 4210005 with Histosol (code 9). The average RSM values that were calculated assuming the area of each soil typological units are plotted also in Figure 5a. The RSM values obtained using HYDRUS-1D are higher than those obtained using CGMS-WOFOST due to the following reasons. Firstly, the RSM values are dominantly influenced by θ_{fc} values that were defined as the soil water content for the pressure head of –20 kPa when calculated for HYDRUS-1D simulations. If the soil water contents for a higher pressure head were used, the lower values of RSM would be obtained. Secondly, the mathematical modelling with CGMS-WOFOST is based on an assumption of leakage from the simulated domain when the field capacity is exceeded. The water regime simulated with HYDRUS-1D depends on boundary conditions and simulated conditions within the soil profile. As a result, drainage from the examined root zone simulated with CGMS-WOFOST is higher than that simulated with HYDRUS-1D. On the other hand, in many real soil types a non-equilibrium

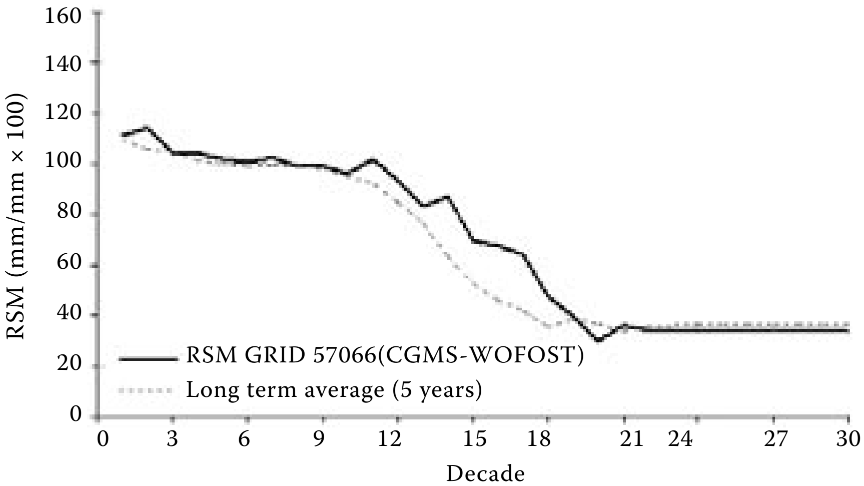

Figure 4. Relative soil moisture (RSM) in the root zone during the vegetation period calculated by CGMS -WOFOST

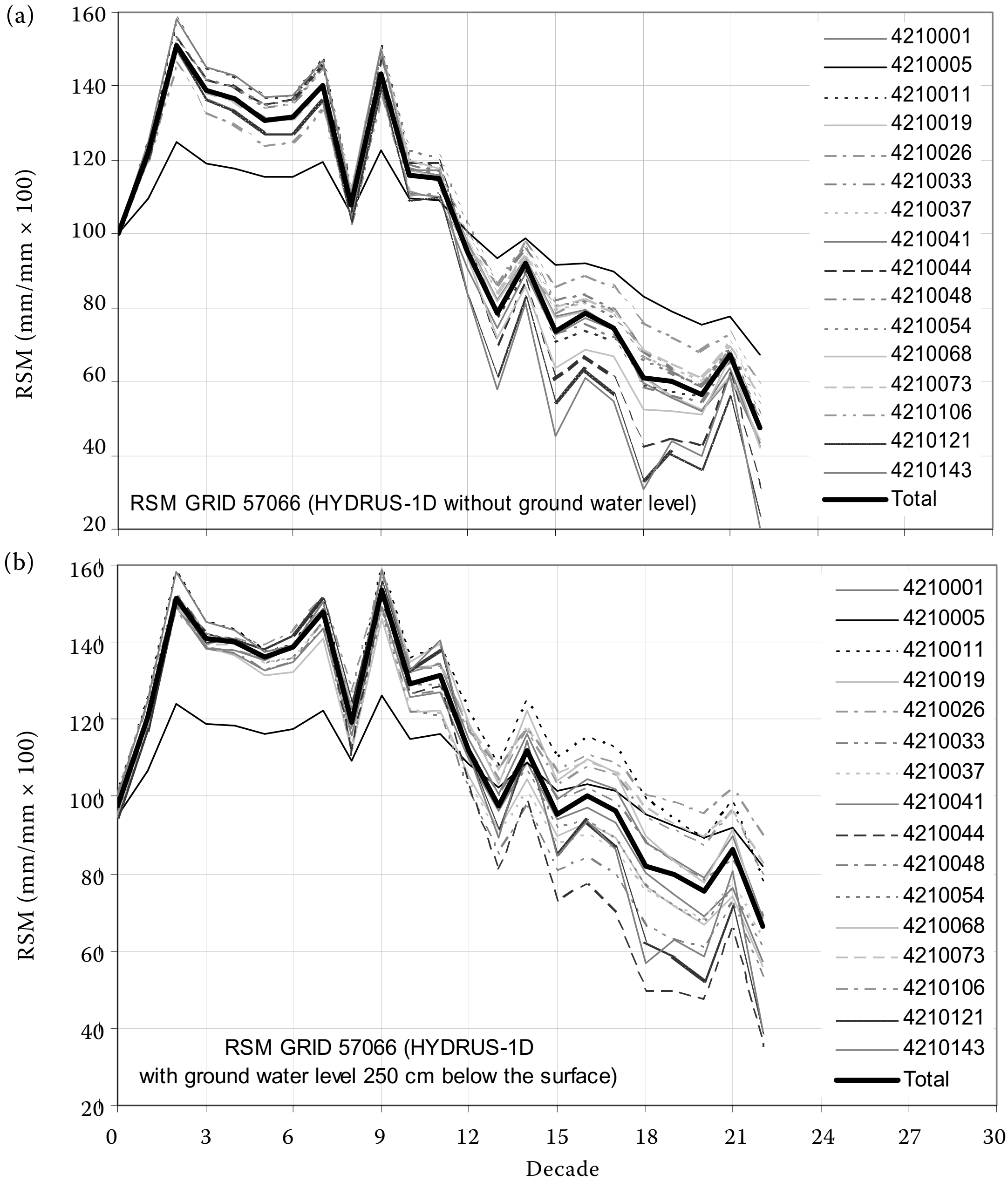

Figure 5. Relative soil moisture (RSM) in the root zone during the vegetation period calculated for HYDRUS-1D simulation results: a) soil profile not influenced by the groundwater level, b) soil profile with groundwater level 250 cm below the soil surface

water flow may appear that causes quicker water percolation through the soil profile, which is not described by the used version of HYDRUS-1D. A module simulating the non-equilibrium water flow (Šimůnek *et al.* 2003) would have to be used in this case. The impact of non-equilibrium water flow was shown for instance on ponded infiltration in clay soil in Kodešová *et al.* (2006) or on water and contaminant transport in Vogel *et al.* (2000), Köhne *et al.* (2006) and Kodešová *et al.* (2005). The average RSM values obtained using the HYDRUS-1D and CGMS-WOFOST results seem to be mutually shifted along the vertical axis having a similar difference between the maximal and minimal RSM values. The reasons are the identical precipitation and potential evapotranspiration which dominantly controlled the water storage in the root zone in both cases, and low sensitivity of wheat to plant water stress. Such a similarity occurred in spite of the fact that the calculation of actual transition in HYDRUS-1D is very different compared to that in CGMS-WOFOST. Transpiration in HYDRUS-1D depends on the root distribution in the soil profile described by the root distribution function and actual soil water content at the given element. CGMS-WOFOST assumes homogenous distribution and average soil water contents within the calculated root zone. Closer correspondence of root growth and coefficients describing the plant water stress between HYDRUS-1D and CGMS-WOFOST was not considered.

The Richards' equation based model allows for the simulation of groundwater table impact that may be very significant as is obvious from HYDRUS-1D simulations (Figure 5b). While the first bottom boundary defined as a free drainage did not considerably influence the water regime in the root zone, which was controlled mainly by atmospheric conditions, the second boundary condition defined as a constant water level of 250 cm below the soil surface caused higher water storage in the root zone. The impact of the groundwater table depends on soil texture and root depth again. The RSM values for coarser texture soils and shallower root zones were affected by the groundwater table to a larger extent.

HYDRUS-1D is a proper and precise tool for modelling the soil water regime within the soil profile. This precision may be too high taking into account the precision of CGMS-WOFOST. Firstly, a very simplified definition of the soil profiles causes very similar behaviour of some STUs. Secondly, RSM values are calculated as an average value of the wide range of RSM values for each soil typological unit. As was shown, the RSM values appeared to be shifted along the vertical axis that may be considered using the CGMS-WOFOST models. The precise estimates of soil water storage within the root zone are very important from the aspect of calculated crop transpiration that affects yield forecast in CGMS-WOFOST. The crop yield may be either underestimated (lower calculated soil water contents using the CGMS-WOFOST compared to HYDRUS-1D) or overestimated (impact of water table close to the surface and/or too high soil water content that is not assumed in CGMS-WOFOST). Therefore the improvement of CGMS-WOFOST model should be proposed and/or a possible application of any Richards' equation based models with some precisions/simplifications should be studied to obtain better estimates of water regime in the soil profiles.

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