SIMWASER model as a tool for the assessment of soil water balance

M. Šťastná[1], E. Stenitzer[2]

[1]*Mendel University of Agriculture and Forestry in Brno, Czech Republic*
[2]*Institute of Land and Water Management, Petzenkirchen, Austria*

ABSTRACT

The objectives of our study were to apply, test and to present the ability of the deterministic simulation model SIMWASER computing soil-water balance components. Two case studies for the assessment of percolation losses from irrigated carrots to deep groundwater at Obersiebenbrunn in the Marchfeld (Austria) and ground water recharge and capillary rise from shallow groundwater in grass lysimeters at Berlin-Dahlem (Germany) are presented to demonstrate the performance of the model by a comparison between measured and simulated results from the field experiments. At Obersiebenbrunn, simulated percolation and evapotranspiration were 183 and 629 mm, while the respective measured values amounted to 198 and 635 mm. In Berlin-Dahlem simulated capillary rise and evapotranspiration were –122 and 458 mm, whereas the measurement showed –155 and 454 mm. These results showed the SIMWASER method as a good applicable tool to demonstrate and study plant – soil – water relationships as well as influence of land use, especially on ground water recharge.

Keywords: SIMWASER model; soil water balance; ground water recharge

The modelling of interactions between plant – soil – water is one of the important steps of how to improve crop management strategies. Soil water balance of cropping systems, involving detailed experimental field monitoring and simulation modelling already assists agronomists to offer improved management options for greater production, profitability and minimize risks to environmental degradation (e.g. dryland, salinity, soil erosion). Soil water balance means the regular inter-action between precipitation and evaporation, run-off and storage-change in an area. Within the soil it means a temporal change of the water content of the soil due to resorption, storage and release of water. These are important factors for different uses, like water management (drinking water, etc.), planning of handling agricultural land or reflecting the effect of irrigation management strategies to the yield (Colaizzi et al. 2003).

According to that, the simulation of water movement in agricultural soils has become a very valuable tool in estimating the amount of natural ground water recharge, which must be known for effective ground water use (Lilly et al. 2003) as well as for the quantification of ground water pollution by fertilizers and pesticides. The respective models must be tested extensively, taking into account the different climatic conditions together with variable soil conditions and they also should be able to run at least for the most important agricultural crops, in order to get realistic simulation results (Šťastná and Žalud 1999, Xie et al. 2001). Long time periods and intensive field measurements of the soil water balance at different places are therefore very important to gather the data needed for model calibration and verification (Mills 2000).

The aim of this study was to present the SIMWASER model (Stenitzer and Murer 2003, Moreno et al. 2003) and to demonstrate its ability to simulate percolation to a deep groundwater and capillary rise from shallow groundwater. A similar field study was designed three years ago in Washington (USA) to compare estimates of groundwater recharge against directly measured values in a closed lysimeter, and to identify sources of uncertainty (e.g., measurement uncertainty and conceptual-model uncertainty) by Timlin et al. 2001.

Supported by ÖAD-Aktion Scholarship and by the Ministry of Agriculture of the Czech Republic, Project No. QF 3100.

MATERIAL AND METHODS

Model description

The functional and deterministic model SIMWASER was developed to describe one-dimensional, vertical flow of water in a soil profile. Inter-flow and preferential flow was neglected. Water balance and plant growth are linked together by the physiological interaction of assimilation and transpiration. The increase of dry matter production depends on the absorption of carbon dioxide from the air via the stomata, during which process water vapour is lost from inside of the plant to the unsaturated air. As long as the delivery of water to the stomata can satisfy potential transpiration, potential assimilation and potential plant growth take place, otherwise stomata will close and dry matter accumulation will be restricted. All the above-mentioned processes are influenced by the respective development phase of the plant, e.g. the partition of the daily-assimilated plant dry matter between leaves, stem and roots. SIMWASER defines the current development stage as a quotient of the current accumulated growing degree-days, divided by the sum of growing degree-days necessary for plant growth from sowing to ripeness. A growing degree-day is defined by the mean of daily air temperature minus a base temperature typically for the respective crop.

The actual plant growth is calculated from the potential production rate as the proportion of actual transpiration to potential transpiration (eq. 1):

$$P_{act} = P_{pot} \times T_{act}/T_{pot} \qquad (1)$$

where: P_{act}, P_{pot} – actual and potential plant production (kg CH_2O/m^2, d); T_{act}, T_{pot} – actual and potential transpiration (mm/d)

Potential evapotranspiration PET is calculated according to the well known Penman-Monteith-formula (eq. 2):

$$\mathrm{PET} = (ft \times Q + 0.864\, H_0/R_{air})/(ft + 1 + R_{crop}/R_{air}) \qquad (2)$$

where: PET – potential evapotranspiration (mm/d); *ft* – weighing factor, depending on air temperature; Q – evaporation equivalent of available energy (mm/d); 0.864 – factor converting [(g H_2O/m^3)/(s/cm)] to (mm/d); H_0 – saturation deficit of air (g H_2O/m^3 air); R_{air} – aerodynamic resistance against water vapor exchange (s/cm); R_{crop} – crop resistance against water vapor exchange (s/cm)

Use of original formula requires variable dimensions not always strictly coinciding with the SI.

Both R_{air} and R_{crop} are variable, depending on the weather situation as well as on the current development stage of the crop. Potential transpiration T_{pot} is derived from PET proportionate to the energy absorbed by all leaves within the stand:

$$T_{pot} = \mathrm{PET}\ [1\times -\exp(-0.6 \times \mathrm{totlai})] \qquad (3)$$

where: totlai – total leaf area of the stand per unit soil surface (m^2/m^2); exp – exponent

The water balance on a daily base is made at the soil surface with precipitation and irrigation as input and evaporation and transpiration as output. Interception is also taken into account. The water movement within the soil is calculated according to Darcy's law and the continuity equation. The soil profile is divided into several soils layers (usually of 5–10 cm depth) down to a depth in which the plant roots may not have any direct influence on the water movement. In the case where capillary rise from shallow groundwater must be taken into account, the deepest soil layer must reach below the deepest groundwater level. In such case the boundary condition at the lower end of the model profile is given by the current groundwater level, otherwise the lower boundary condition is defined by the capillary conductivity of the deepest soil layer at the current water content. The normal time step of the model is the day, but water movement is calculated using variable time steps, which are limited by the condition, that the maximum change of water content within any of the soil layer during the time step is restricted to 0.001 cm^3/cm^3.

Input data

General information on the simulation scenario is given by the site name and by name with listing of the crop rotation to be simulated. The irrigation schedule includes the name of the site, number of irrigations and the date and amount of each irrigation.

Data representing soil profile by name of the site and its elevation must be given in meters above sea level. They content: name of the relevant weather station and (in case of a site influenced by ground water) name of the relevant ground water gauge (the elevation of it given in meters above sea level) and the difference in elevation between the ground water level at the gauging site and the simulation site given in meters.

For each of the different soil types within a soil profile the hydraulic parameters (soil water tension, soil water content, capillary conductivity, penetration resistance) must be given in tabulated form. This soil data may be directly derived from laboratory analyses of undisturbed soil samples or indirectly from field measurements. There also exist tables of the needed soil data for the whole

Table 1. Physical soil parameters of the Calcic Chernozem soil at Obersiebenbrunn

Depth (cm)	Soil class	Sand (%)	Silt (%)	Clay (%)	Humus (%)	pF 1.8 (vol %)	pF 2.5 (vol %)	pF 4.15 (vol %)	K_{sat} (mm/d)
0–30	Lu	22	55	24	2.50	35.9	32.9	16.3	330
30–45	Lu	21	53	26	2.70	34.3	31.3	16.6	370
45–90	Ut3	11	76	13	0.20	37.2	34.4	7.7	100
90–160	mSg5	89	8	3	0.10	5.0	3.9	3.1	9300

Lu = silty loam, mSg5 = medium sand with very high gravel, Ut3 = clayly silt; all soil classes according to DIN 4220

Table 2. Monthly weather parameters at the experimental field in Obersiebenbrunn during the simulation period

	March 2002	April 2002	May 2002	June 2002	July 2002	August 2002	September 2002
Temp (°C)	6.8	9.7	17.6	19.7	21.6	20.9	14.7
Humidity (%)	68	70	70	70	67	74	73
Wind (m/s)	1.9	1.5	1.1	0.9	1.0	1.0	0.9
Rain + irrigation (mm)	57	50 + 22	31 + 97	98	72 + 121	110 + 95	39 + 44
Global radiation (MJ/m²)	1141	1405	1933	2127	2147	1584	1311

range of soils, which are defined by particle size distribution, pore volume, humus content.

For each of the cropping elements to be simulated in the respective project typical physiological plant parameters must be given in tabulated format and may be derived by analyses of plant growth data or may be estimated from an existing table with the relevant data for about 30 different crop types.

Daily weather data include day length, maximum and minimum temperature, maximum and minimum relative humidity, wind velocity at 2 m height, amount and duration of precipitation, and global radiation. In case of ground water influence daily depths to groundwater (given in cm) must also be known.

Output data

Simulation results are given as daily values for each cropping element and include soil water storage, precipitation, evapotranspiration, deep percolation, capillary rise, surface runoff, leaf area index, total dry matter, root dry matter, water content and matric potential within each soil layer.

Case studies

The performance of the SIMWASER model in estimating percolation and/or capillary rise may be demonstrated by comparing measured and simu-

Table 3. Monthly water balance data at the experimental field in Obersiebenbrunn during the simulation period

	March 2002	April 2002	May 2002	June 2002	July 2002	August 2002	September 2002
Storage	356	358	368	343	319	359	339
Change	0	17	–36	–30	46	0	–33
Percolation	16	24	41	9	6	87	15
Evaporation	41	31	103	119	141	118	91
ETPOT	53	65	111	122	132	93	62

Storage = water storage within 160 cm depth (mm); change = change in water storage within each month (mm); percolation = percolation (mm); evaporation = rain – change – percolation (mm); ETPOT = potential reference evapotranspiration (mm)

Table 4. Physical soil parameters of the Podzol soil from Wildeshausen at the Berlin-Dahlem lysimeter station (Zenker 2003)

Depth (cm)	Soil class	Sand (%)	Silt (%)	Clay (%)	Humus (%)	pF 1.8 (vol %)	pF 2.5 (vol %)	pF 4.15 (vol %)	K_{sat} (mm/d)
0–40	Su2	81.50	14.90	3.60	4.00	23.00	16.50	5.00	1400
40–60	Su2	80.40	15.10	4.50	1.30	16.80	10.70	2.30	2210
60–50	Ss	87.50	9.00	3.50	0.50	25.30	16.60	4.30	490

Su2 = silty sand, Ss = sand; all soil classes according to DIN 4220

Table 5. Monthly weather parameters at the Berlin-Dahlem lysimeter station during the simulation period

	March 1997	April 1997	May 1997	June 1997	July 1997	August 1997	September 1997
Temp (°C)	5.3	6.5	13.4	17.1	18.9	21.5	14.4
Humidity (%)	68	62	67	64	67	65	66
Wind (m/s)	1.5	1.7	0.7	0.7	1.1	0.6	1.0
Rain (mm)	24	36	50	57	91	35	15
Global radiation (MJ/m^2)	920	1286	1725	1975	1799	1666	1118

lated results from field experiments and lysimeter studies. The following case studies are focussed on the assessment of percolation losses from irrigation to deep groundwater and on the estimation of capillary rise from shallow groundwater.

Percolation losses from irrigated carrots at Obersiebenbrunn in the Marchfeld (Austria)

The experimental field in Obersiebenbrunn is situated at 48°15'N and 16°41'E about 151 m above sea level with mean air temperature of 10.1°C and 510 mm rainfall. The soil is a Chernozem [Calcic Chernozem according to ISSS 1994 (Spaargaren 1994)] of about 90 cm depth, covering a gravely aquifer with ground water surface at about 250 cm below soil surface: therefore no capillary rise to the rooted soil horizons will take place. The measuring site was instrumented systematically at 10 cm distance down to 160 cm with TDR-sensors (TRASE system) to measure soil water content, and with calibrated resistance blocks (BECKMAN gypsum blocks and WATERMARK granular matrix sensors) to measure soil water suction. Soil temperature was also measured systematically at different depth for the correction of the resistance block readings. Physical soil parameters (pF- and Ku-curves) were determined by undisturbed soil samples in the laboratory. Additionally field-pF-curves were established by analysing concurrent measurements of water content and suction at the measuring site. The combination of both, laboratory and field pF-curves, was used for the simulation. Measured

Table 6. Monthly water balance data at the Berlin-Dahlem lysimeter station during the simulation period

	March 1997	April 1997	May 1997	June 1997	July 1997	August 1997	September 1997
Storage	291	287	280	269	272	261	272
Change	–3	1	–7	–6	–4	10	–11
Perc/Rise	15	–3	–19	–27	–3	–56	–24
Evaporation	12	38	78	90	98	81	50
ETPOT	40	60	86	104	108	97	56

Storage = water storage within 150 cm depth (mm); change = change in water storage within each month (mm); Perc/Rise = percolation (+) or capillary rise (–) (mm); evaporation = rain – change – (Perc/Rise) (mm)

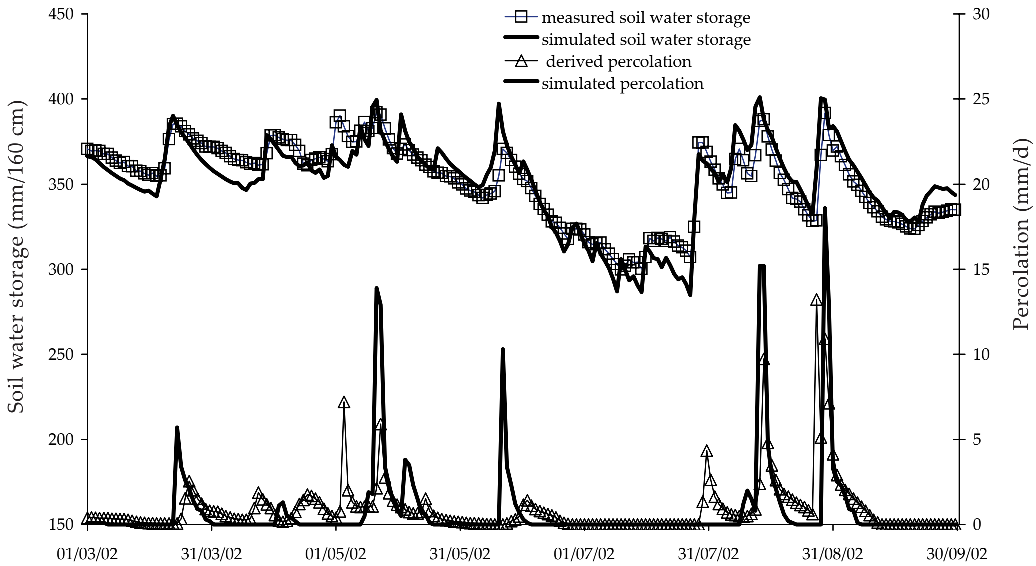

Figure 1. Comparison of measured soil water storage and percolation flux, derived from measured water content and suction gradient with water storage and percolation flux at Obersiebenbrunn simulated by the model SIMWASER

capillary conductivity was extrapolated according to the shape of the resulting pF-curve by the method of Millington and Quirk (Klute 1986).

Percolation was deduced from systematic measurements of soil water content and soil suction according to DARCY's law:

$$\text{perc} = K(w) \times I \tag{4}$$

where: perc – percolation flux (mm/d); $K(w)$ – capillary conductivity at water content (w) at 140 cm depth; I – suction gradient at 140 cm depth

For the case study presented here deep percolation from irrigated carrots in the year 2002 is investigated. Soil and weather data characterising the simulated site are given in Tables 1 and 2.

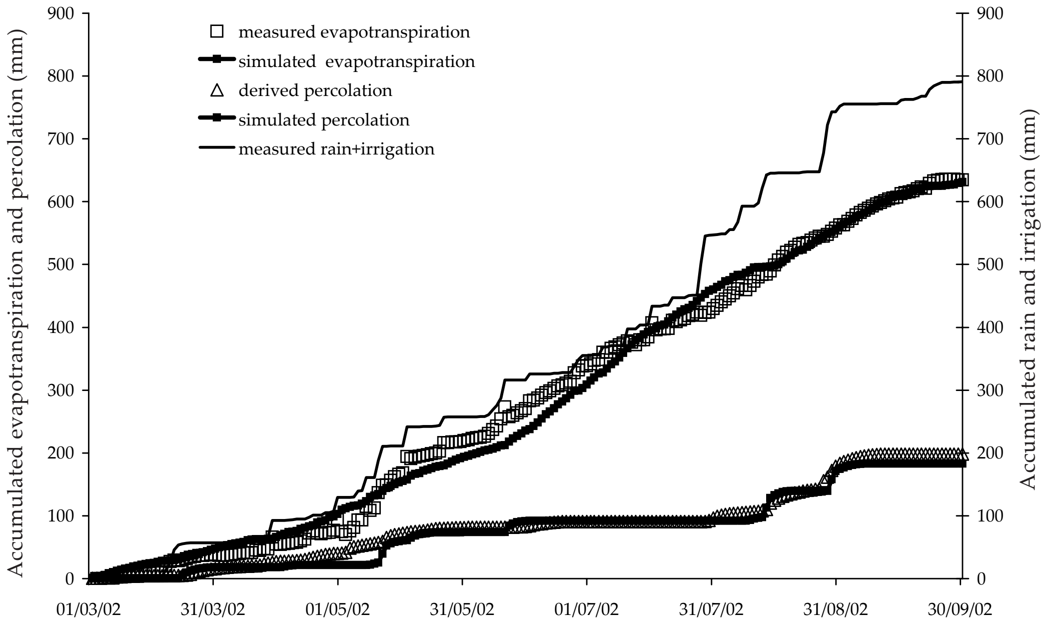

Figure 2. Comparison of accumulated deep percolation derived from measured water content and suction gradient and of accumulated evapotranspiration calculated from soil water balance with ground water recharge and evapotranspiration at Obersiebenbrunn simulated by the model SIMWASER

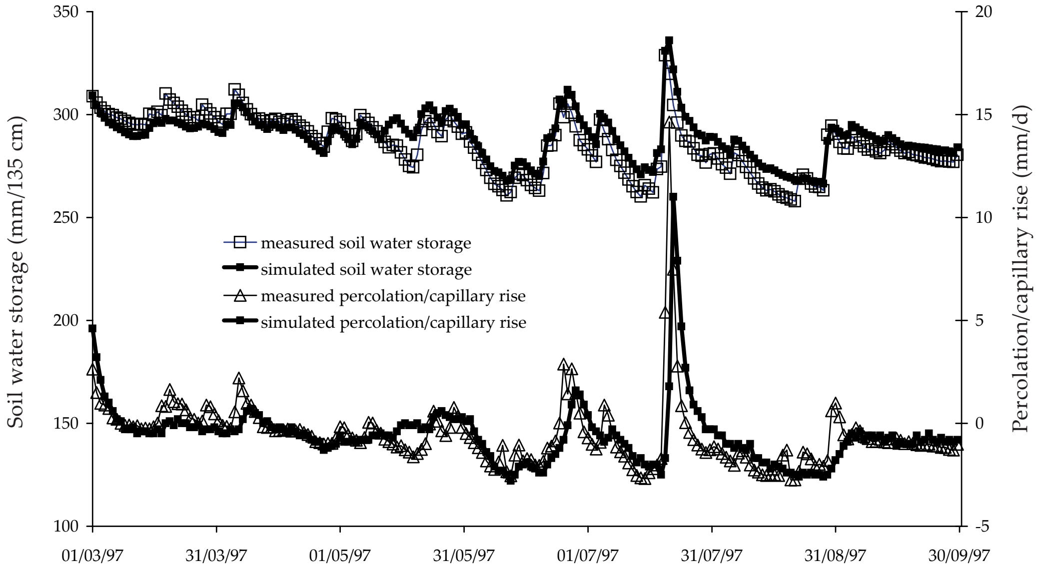

Figure 3. Comparison of measured and simulated soil water storage together with measured and simulated percolation/capillary rise

Monthly mean values of measured soil water storage and percolation at the experimental field as well as calculated evapotranspiration are given in Table 3.

Ground water recharge and capillary rise in grass lysimeters at Berlin-Dahlem (Germany)

The lysimeter station at Berlin-Dahlem consists of 12 weighable lysimeters, by which all components of the soil water balance may be measured (Zenker 2003). The station is situated at 52°28′N and 13°18′E about 51 m above sea level with mean air temperature of 9.3°C and 545 mm rainfall. The lysimeters have a surface of 1 m^2 and they are 150 cm deep; they contain three different types of undisturbed soil monoliths. All lysimeters were under grass from 1996 to 1999 and had a constant ground water level at either 210 cm (deep ground water) or 135 cm depth (shallow groundwater). For the case study presented here, the simulation was restricted to one growing season (April 1997 to March 1998) and only lysimeters No. 3 and 4 were investigated,

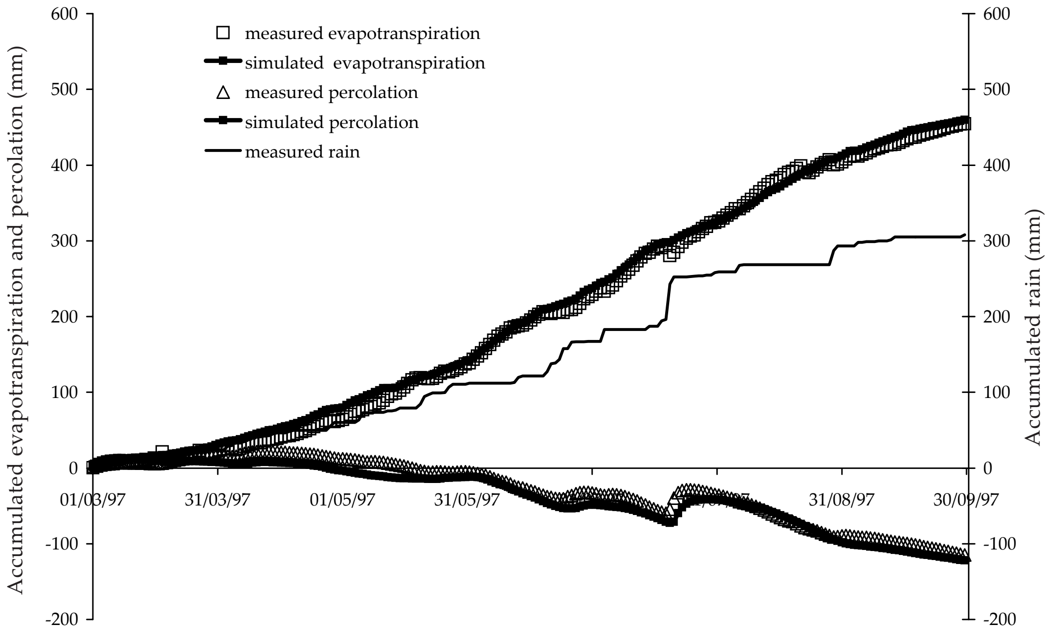

Figure 4. Measured and simulated evapotranspiration and percolation in comparison with observed rain

which represent a sandy Humic Podzol (ISSS 1986) from Wildeshausen (Lower Saxonia, Germany), with shallow ground water depth.

Soil and weather data characterising the simulated site are given in Tables 4 and 5. The monthly mean values of measured soil water storage and percolation or capillary rise of lysimeters 3 and 4, as well as calculated evapotranspiration are given in Table 6.

RESULTS AND DISCUSSION

Graphical comparison of measurements and simulation results from the SIMWASER model for both case studies are shown in Figures 1–4.

At the Obersiebenbrunn experimental field simulated soil water storage and simulated fluxes of evapotranspiration and percolation (Figures 1 and 2) are in good agreement with the measured values. Simulated accumulated percolation and evapotranspiration during the vegetation period amounted to 183 and 629 mm respectively, which is close to the measured values of 198 and 635 mm.

There were also measured and simulated soil water storage and fluxes of capillary rise and evapotranspiration at the Berlin-Dahlem, where lysimeters agreed with each other very well. Here the simulated accumulated percolation and evapotranspiration were during the vegetation period –122 and 458 mm, whereas measured values were –115 and 454 mm (Figures 3 and 4).

A significant observation from this work is the value of using an integrated and realistic model. Such model as SIMWASER may be used to integrate point measurements within a real-time basis for water content, pressure-head and water level changes. This study also identifies practical field instrumentation and analytical model for estimating ground-water recharge using real-time databases. It is able to demonstrate temporal relationships in subsurface water flow, water-content redistribution and evapotranspiration.

A graphical comparison of measurements and simulation results for both case studies (Figures 1–4) show that SIMWASER model was able to simulate the percolation and capillary rise with rather good accuracy. Thus proofing this model as a valuable tool in soil hydrology research at the field scale. We will focus on the evaluation of drought risk, soil water balance and soil processes in agricultural land use, crop growth and yield in the field study, which is going to be done in Zabcice experimental station (the Czech Republic) soon. In such case it is necessary to have a good assessment of soil water availability to predict yields more correctly as far as it is known, that soils water balance influences the crop during the growing period. The SIMWASER model will be used in the above-mentioned study to prove its eligibility to simulate the influence of water availability on crop yield.

Acknowledgements

The authors thank to Prof. Heiko Diestel and Dr. Thomas Zenker for making available the Berlin-Dahlem data, and Ing. Leopold Gassner for his measurements at the Obersiebenbrunn experimental field.

REFERENCES

Colaizzi P.D, Barnes E.M., Clarke T.R., Choi CH.Y., Waller P.M. (2003): Water stress detection under high frequency sprinkler irrigation with water deficit index. Journal of Irrigation and Drainage Engineering, *129*: 36–43.

DIN 4220 (1998): Pedologic site assessment – Designation, classification and deduction of soil parameters. Beuth Verlag GmbH, Berlin. (In German)

ISSS/FAO (1986): Soil map of Middle Europe 1: 1 000 000 – Explanatory text, International Society of Soil Science.

Klute A: (1986): Methods of soil analysis. Part 1: Physical and mineralogical methods. 2nd ed. Agronomy Series No. 9 (Part 1). American Society of Agronomy, Madison, Wisconsin, USA.

Lilly A., Malcolm A., Reid D. (2003): A rationale for the development of a groundwater quality monitoring network for Scotland. Scottish Geographical Journal, *119*: 25–38.

Mills, G. (2000): Modelling the water budget of Ireland. Evapotranspiration and soil moisture. Irish Geography, *33*: 99–116.

Moreno F., Murer E.J., Stenitzer E., Fernández J.E., Girón I.F. (2003): Simulation of the impact of subsoil compaction on soil water balance and crop yield of irrigated maize on a loamy sand soil in SW Spain. Soil and Tillage Research, *73*: 31–41.

Spaargaren O.C. (ed.) (1994): World reference base for soil resources. ISSS/FAO. Wageningen/Rome.

Stenitzer E., Murer E. (2003): Impact of soil compaction upon soil water balance and maize yield estimated by the SIMWASER model. Soil and Tillage Research, *73*: 43–56.

Šťastná M., Žalud Z. (1999): Sensitivity analysis of soil hydrologic parameters for two crop growth simulation models. Soil and Tillage Research, *50*: 305–318.

Timlin D.J., Starr J.L., Cady R., Nicholson T.J. (2001): Field studies for estimating uncertainties in groundwater recharge using near-continuous piezometer data. NUREG/CR-6729, U.S. Nuclear Regulatory Commission, Washington, DC.

Xie Y., Kiniry J.R., Nedbalek V., Rosenthal W.D. (2001): Maize and sorghum simulations with CERES-maize, SORKAM, and ALMANAC under water-limiting conditions. Agronomy Journal, *93*: 1148–1155.

Zenker T. (2003): Evaporation resistances and reference evapotranspiration of grass. Lysimeter studies on the Penman-Monteith Formula in the Berlin area (in German). Dissertation D83 Technical University of Berlin. http://edocs.tu-berlin.de/diss/2003/zenker_thomas.pdf

Received on September 6, 2004

ABSTRAKT

Model SIMWASER jako nástroj hodnocení bilance vody v půdě

Cílem naší práce byla aplikace, testování a prezentace možností deterministického simulačního modelu SIMWASER vyhodnotit komponenty bilance vody v půdě. Jsou zde prezentovány dvě případové studie: 1. hodnocení ztrát průsakem do podzemní vody při závlaze mrkve v Obersiebenbrunnu v Marchfeldu (Rakousko) a 2. zásoba podzemní vody a kapilární vzlínání z podpovrchové vrstvy lyzimetrů se zatravněným povrchem na experimentální stanici v Berlíně-Dahlemu (Německo), aby demonstrovaly srovnání měřených a simulovaných výsledků z polních pokusů. Simulované hodnoty perkolace a evapotranspirace pro stanici v Obersiebenbrunnu dosáhly hodnot 183 a 629 mm v porovnání s naměřenými údaji 198 a 635 mm. Modelem simulované hodnoty kapilárního vzlínání a evapotranspirace pro stanici Berlín-Dahlem –122 a 458 mm zachycují stejně jako u předchozí stanice pouze nepatrnou odchylku v porovnání s naměřenými údaji –155 a 454 mm. Získané výsledky prokázaly, že model SIMWASER je vhodným nástrojem využitelným k demonstraci a studiu procesů probíhajících v systému rostlina – půda – voda. Stejně dobře zachycuje změny při využívání půdy především z pohledu zásoby podzemní vody.

Klíčová slova: SIMWASER model; vodní bilance půdy; dynamika podzemní vody

Corresponding author:

Dr. Ing. Milada Šťastná, Mendelova zemědělská a lesnická univerzita v Brně, Zemědělská 1, 613 00 Brno, Česká republika
phone: + 420 545 132 459; fax: + 420 545 132 459; e-mail: stastna@mendelu.cz