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Comparison of deep seepage estimations of a virtual with a real lysimeter by means of TDR-measurements

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A b s t r a c t. The virtual lysimeter concept was tested in comparison with a real lysimeter and found to be suitable for quantifying effective deep seepage dynamics in sandy soils. Discharge measurements and calculation results agreed well. Preconditions are accurate water content and tension measurements with high temporal resolution below the zero flux plane and an error free water balance of the calibration period. The calibration procedure has resulted in an effective unsaturated hydraulic conductivity function which allows to perform deep seepage calculations based on the measured water content dynamics only. The assumption of the unit gradient produced adequate results in sandy soils. The calculation results are exponentially sensitive to errors of water content measurements and linearly sensitive to water balance errors. However, a single incorrect water content produces only a single incorrect deep seepage value, whereas the water balance error sums up. Therefore, the quality of the water balance estimation is of crucial importance.

K e y w o r d s: deep seepage, TDR measurements, lysimeter, hydraulic conductivity

INTRODUCTION

Quantifying deep seepage and solute leaching is necessary for addressing numerous economic and environmental problems such as the development of sustainable farm management systems with a view to providing non-polluted water for different users and determining safe yields of aquifers.

Soil hydrological field measurements using virtual lysimeters according to Kastanek (1995) allow to obtain information on the temporal variability of deep seepage and solute leaching (Kastanek, 1995; Rice, 1975). But measuring at various sites and with many sensors across the whole profile is expensive and not a feasible solution. A simplified method was devised and applied (Schindler *et al*., 1998). The method provides for the calculation of deep seepage based on water content and tension measurements only at one depth below the zero flux plane. The reliability of those deep seepage estimations was tested in comparison with real lysimeter measurements. The results are presented in the following.

MATERIALS AND METHODS

Concept of deep seepage estimation by virtual lysimeters

The method is feasible on sandy soils with a deep water table. Daily deep seepage rates (v) are calculated by DARCY (v = K i) based on water content measurements and an unsaturated hydraulic conductivity function K(wv) calibrated to the water balance and the hydraulic gradient below the zero flux plane. The assumption that a unit gradient of 1 is valid (Kutilek and Nielsen, 1994; Schindler and Müller, 1998) allows the simplification of Darcy's law to v = K (wv).

Procedure

Water content and tension measurements

Water contents are continually measured with TDR technique (Malicki and Skierucha, 1989; Malicki *et al*., 1994; Roth *et al*., 1992) at one, and tensions at two depths with a high temporal resolution, if possible below the zero flux plane with seepage conditions all the time. Usually these conditions are valid at most arable sites between 2 and 3 m and at forest sites approximately at 5 m depth.

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Predicting the relative unsaturated hydraulic conductivity function and derivation of relative deep seepage rates

The water retention function is fitted (van Genuchten, 1981) and the relative unsaturated hydraulic conductivity function (K_r(wv)) is predicted, in dependence on water content (Mualem, 1976). The hydraulic gradients (i) are calculated from the tensions between the two depths and allow to conclude on flow direction (positive - downwards, seepage; negative - upwards, capillary rise). The relative deep seepage rates (v_r) are calculated by the simplified Darcy equation (v_r = K_r) based on the water content dynamics, and the relative hydraulic conductivity function for periods with downward water movement. The unit gradient 1 is assumed.

Calibration to the water balance

The water balance at the soil hydrological plot is calculated for a calibration period. Usually preference is given to an autumn/winter period with negligible error for the estimation of the evapotranspiration (ET). In the NE German region, the evapotranspiration during the winter period is estimated according to Ivanov (Wendling *et al.*, 1991). The precipitation (P) is measured and the soil water storage difference (dΘ in the profile is calculated by means of water content measurements of the whole profile at the beginning and at the end of this period. The period should be as long as possible (2-4 months) and have a relevant precipitation (> 100 mm). At the start and end of the calibration period the soil profile should be free of frost.

The total discharge (V) results from V =P-ET+/-dΘ V is divided by V_r (total relative deep seepage of the calibration period) to get the matching factor (M=V/Vr) for transforming the relative hydraulic conductivity function into an effective level.

Lysimeter studies

One gravitational lysimeter (1x1m; 2 m depth) from the Dedelow lysimeter station (Uckermark) was used for the comparison of deep seepage estimations based on the virtual lysimeter concept with the measured real lysimeter discharge (Fig. 1). The soil stratification and soil properties of the lysimeter are given in Table 1. Winter wheat was grown in 2002.

Two tensiometers (Ψ) at 160 and 185 cm and one TDR-probe (Θ) at 185 cm depth were installed. The measurements were recorded at 8 h intervals. Additionally, the water contents were temporarily measured (Θ_t) with TDR-probes at 15, 30, 50, 70 90, 130 and 160 cm depth for the estimation of soil water storage and soil water storage differences in the profile. Weather data were recorded directly at the site.

The calibration of the hydraulic conductivity function (effective function) was conducted in two different ways.

1. Matching to the lysimeter discharge
2. Matching to the estimated discharge based on the water balance.

The first procedure was applied with a view to getting an idea of the potential of the virtual lysimeter concept when exact calibration data (in this case, measured discharge data) are used. The second procedure was used to analyze the effect of calculations when exact water balance data for the calibration are not available.

The total period of comparison ranged from 1st November, 2001 to 22nd August, 2002. The calibration period went from 1st November, 2001 to 15th February, 2002. The validation occurred between 16th February and 22nd August, 2002.

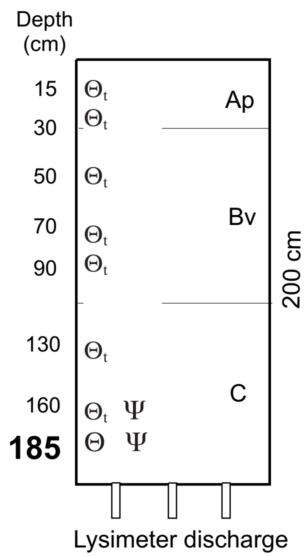

Fig. 1. Lysimeter construction, Θ - TDR recording, Θ_t - TDR probe for temporary measurements, Ψ - tension recording.

T a b l e 1. Stratification and soil properties of the lysimeter site

Horizon	Depth (cm)	$C_{org.}$ (%)	Bulk density (g cm^{-3})	Granulometric composition (%)		
				Clay	Silt	Sand
Ap	0-35	0.64	1.52	4	24	72
Bv	35-115	0.10	1.63	9	29	62
C	115-200	0.10	1.65	1	4	95

RESULTS

Water content and tension dynamics

Tensions and water contents were measured with a high temporal resolution and accuracy. Both values had comparable dynamics with regard to drainage and saturation processes (Fig. 2). Water contents were found to vary between minimum10.8 and maximum 18.9% vol. and tension values between minimum 19 and maximum 42 hPa. Tension and water content changes occurred continually and were strongly influenced by precipitation in winter time when soils had no storage deficits (Fig. 3). Till the end of January the increase of water contents and decrease of tensions occurred smoothly. Saturation processes of the soil profile were dominant. In February and March the soil hydrological dynamics increased markedly with a good response to precipitation. Starting in April, evapotranspiration became dominant, precipitation had no recognizable effect on soil water contents and tensions at 185 cm depth, and the soil below the zero flux plane drained.

Calibrating the hydraulic conductivity

From TDR- and tension measurements (Fig. 2) a typical water retention curve was fitted (Fig. 4). This figure contains data of both the calibration and the validation periods, as the analysis started with the calibration period in winter. Thus the range of the curve in the calibration period was too small. Figure 4 shows only typical data points and the fitted line. Based on the fitted water retention function (Fig. 4), the relative unsaturated hydraulic conductivity function (Kr) was derived and matched to the measured lysimeter discharge and the estimated discharge based on the water balance in the calibration period from 1st November, 2001 to 15th February, 2002 (Fig. 5).

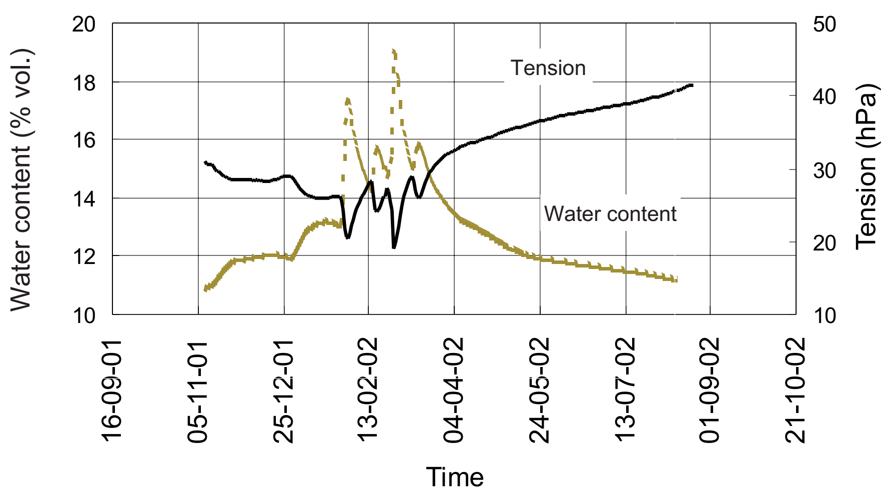

Fig. 2. Tension and water content dynamics, 185 cm depth (total period).

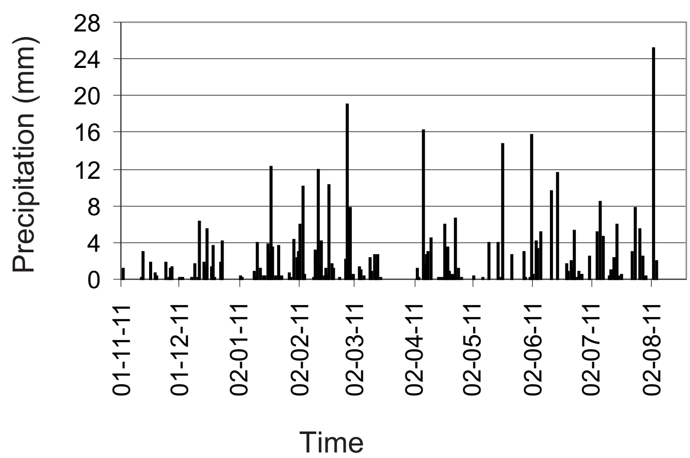

Fig. 3. Precipitation from November 11, 2001 to August 11, 2002.

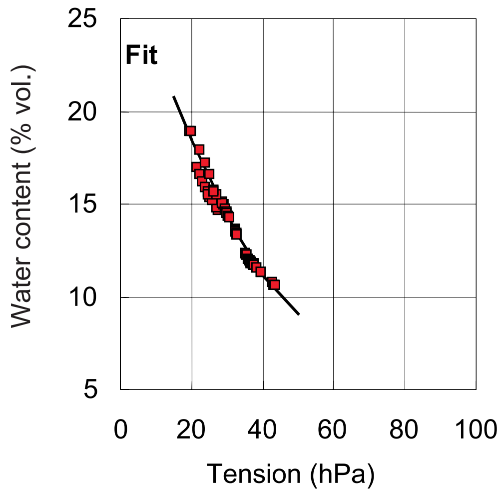

Fig. 4. Water retention curve, measured values and fit.

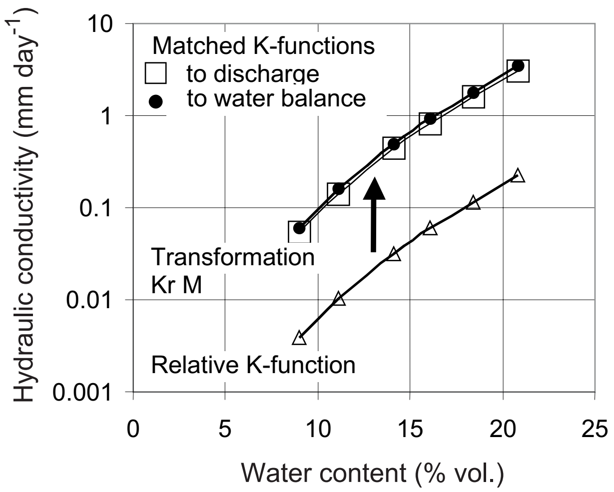

Fig. 5. Unsaturated hydraulic conductivity functions, relative and matched (effective) functions.

Water balance:

Precipitation	+135 mm
Evapotranspiration	- 32 mm
Soil water storage	- 34 mm

Discharge based on water balance +69 mm.

Comparison between real lysimeter discharge and discharge calculation

Figure 6 shows the results of the comparison between measurements and calculations when the measured discharge was used for calibration. Deep seepage calculations were found to agree well with lysimeter measurements and show the potential of the virtual lysimeter method when exact calibration data are available. Temporal dynamics of daily rates as well as total seepage differed only negligibly from measured discharge in the calibration (1st November, 2001 to 15th February, 2002) and validation period (16th February to 22nd August, 2002).

The calculation results changed when discharge estimated on water balance (69 mm) was used for calibration (Table 2). The differences between calculation 1 (calibration with measured discharge) and calculation 2 (calibration based on the water balance) were approximately 10.9%, exactly the same as the difference between lysimeter discharge and water balance (77.4 and 69 mm, difference 10.9%). The differences between calibration discharge values were linearly transformed into the calibration results.

CONCLUSIONS

1. The virtual lysimeter concept was tested and found to be suitable for quantifying effective deep seepage dynamics in sandy soils. Preconditions are accurate water content and tension measurements with high temporal resolution below the zero flux plane and an error free water balance of the calibration period.

2. The calibration procedure has resulted in an effective unsaturated hydraulic conductivity function which allows deep seepage calculations based on the measured water content dynamics only. The assumption of the unit gradient produced adequate results in sandy soils.

T a b l e 2. Measured and calculated discharge

Discharge values	Unit	Measured discharge	Calculation 1	Calculation 2
Medium daily discharge	mm day^{-1}	0.81	0.80	0.71
Maximum		9.60	9.91	8.84
Minimum		0.06	0.00	0.00
Total discharge	mm	239.2	234.6	209.2
Calibration period		77.4	77.4	69.0
Validation period		161.8	157.2	140.2

Calculation 1 - calibration to measured discharge, calculation 2 - calibration to discharge from the water balance.

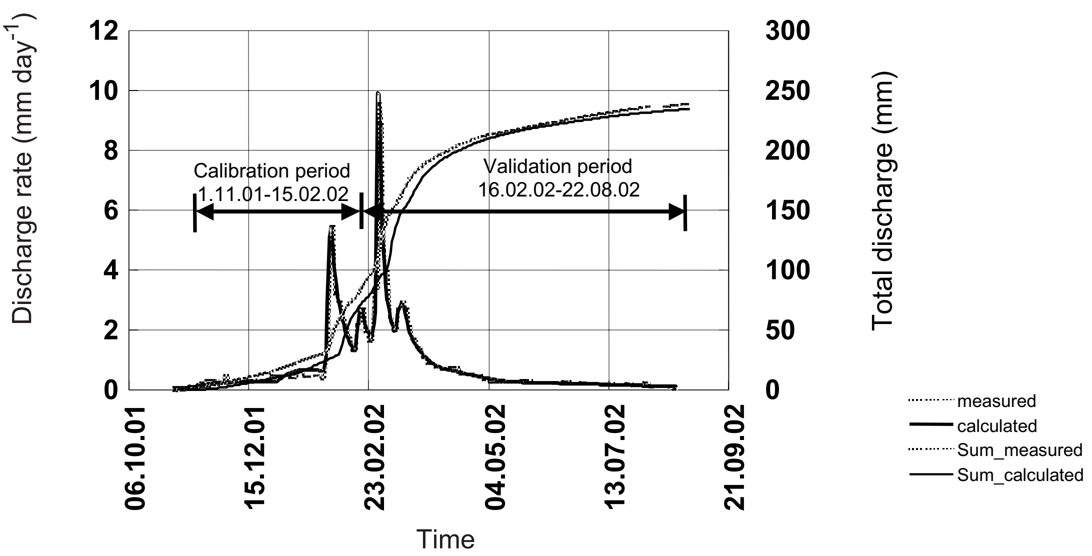

Fig. 6. Lysimeter discharge and deep seepage calculations, calibration to the discharge between 1st November, 2001 and 15th February, 2002.

3. More important than the accuracy of absolute water content proved to be the measuring accuracy and long-term reproducibility of water content changes.

4. The calculation results are exponentially sensitive to errors of water content measurements and linearly sensitive to water balance errors. However, one incorrect water content produces only one incorrect deep seepage value, whereas a water balance error sums up. The error of water balance estimation in the calibration period is linearly transformed into the discharge calculation error. Therefore, the quality of the water balance estimation proved to be of crucial importance.

REFERENCES

Kastanek F., 1995. Kritische Bemerkungen zur Verwendung von Lysimetern. 5. Gumpensteiner Lysimetertagung 'Stoff-transport und Stoffbilanz in der ungesättigten Zone'. BAL Gumpenstein 25.-26. April 1995. BAL-Bericht. 93-102.

Kutilek M. and Nielsen D.R., 1994. Soil Hydrology. GeoEcology textbook. Catena Verlag,Cremlingen-Destedt.

Malicki M.A., Plagge R., and Roth C.H., 1994. Influence of matrix on TDR soil moisture readings and its elimination. Proc. Symp. Time Domain Reflectometry in Environmental, Infrastructure, and Mining Applications, Evanston, IL, Sept 7-9, U.S. Bureau of Mines, Special Publication, 105-114.

Malicki M.A. and Skierucha W., 1989. A manually controlled TDR soil moisture meter operating with 300 ps rise time needle pulse. Irrig. Sci., 10, 153-163.

Mualem Y., 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. Water Resour. Res., 12(3), 513-522.

Rice R.A., 1975. Diurnal and seasonal soil water uptake and flux within a bermudagras root zone. Soil Sci. Soc. Amer. Proc., 39, 394-398.

Roth C.H., Malicki M.A., and Plagge R., 1992. Empirical evaluation of the relationship between soil dielectric constant and volumetric water content as the basis for calibrating soil moisture measurements by TDR. Soil Sci., 43, 1-13.

Schindler U. and Müller L., 1998. Calculating deep seepage from water content and tension measurements in the vadose zone at sandy and loamy soils in north-east Germany. Archives of Agronomy and Soil Science, 43, 233-243.

Van Genuchten M.Th., 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. Soil Sci. Soc. Am. J., 44, 892-898.

Wendling U., Schellin H.G., and Thomä M., 1991. Bereitstellung von täglichen Informationen zum Wasserhaushalt des Bodens für die Zwecke der agrarmeteorologischen Beratung,- Z. f. Meteorologie, 41, 6, 1-16.