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JOURNAL OF WATER AND LAND DEVELOPMENT
ISSN 1429–7426, e-ISSN 2083-4535

Polish Academy of Sciences (PAN), Committee on Agronomic Sciences
Section of Land Reclamation and Environmental Engineering in Agriculture
Institute of Technology and Life Sciences (ITP)

JOURNAL OF WATER AND LAND DEVELOPMENT
2020, No. 45 (IV–VI): 179–184
https://DOI.org/10.24425/jwld.2020.133492

Available (PDF): http://www.itp.edu.pl/wydawnictwo/journal; http://journals.pan.pl/jwld

Received 27.09.2019
Reviewed 12.02.2020
Accepted 18.02.2020

Results of water balance measurements in a sandy and silty-loam soil profile using lysimeters

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For citation: Tall A., Pavelková D. 2020. Results of water balance measurements in a sandy and silty-loam soil profile using lysimeters. Journal of Water and Land Development. No. 45 (IV–VI) p. 179–184. DOI: 10.24425/jwld.2020.133492.

Abstract

Lysimeters represent the ideal tool for direct measurement of soil water balance components in soil profiles. Changes in the water content in a soil monolith can be measured with sufficient accuracy by the precise lysimeter weighing system. Water content changes in soil monolith as derived from lysimeter mass represent one of the basic water balance component. This paper deals with the development and comparison of individual soil water balance components in two different soil profiles from the Easter-Slovakian-Lowland. Two lysimeter vessels were filled monolithically with two different soil profiles covered with grass: one sandy soil profile from locality Poľany and one silty-loam soil profile from locality Vysoká nad Uhom. A constant groundwater level of 1 m below ground level was maintained in both soil profiles. Under the same meteorological conditions, all differences in the development of water balance components were caused only by the differences in soil profiles. The actual evapotranspiration and water flows at the bottom of the soil profiles were compared. Sandy soils are generally considered to be more prone to drought than silty-loam soils. Under the specific conditions of this experiment (maintaining a constant groundwater level) the opposite was shown, when the silty-loam soil profile was more prone to drought than sandy soil profile. Sandy soil profile from Poľany reacted more quickly to precipitation (or evaporation). Due to the higher hydraulic conductivity of the sandy soil compared to the silty-loamy soil, the groundwater level response to external stimuli was much faster.

Key words: *evapotranspiration, lysimeter study, precipitation, water balance*

INTRODUCTION

Modern weighing lysimeters allow accurate measurement of the individual components of the soil water balance in the soil profile. The precise weighing system of the lysimeter allows to measure the changes in the water content of the soil monolith with sufficient accuracy. The change in water content (ΔW) in a known soil volume over a known time is equal to the flow at its upper and lower boundaries. In general, the equation of lysimeter soil water balance can be written in the following form [NOLZ *et al.* 2016; NOLZ, RODNÝ 2019]:

$$\Delta W = P + I - ET_a - SW + CR \tag{1}$$

At the upper boundary, between the soil surface, plant cover and atmosphere, water infiltrates from precipitation (P) or irrigation (I) and evaporates into the atmosphere in form of actual evapotranspiration (ET_a). At the lower boundary, due to gravity, the water enters the groundwater (SW = seepage water) or capillary forces rise from the groundwater upwards into the unsaturated zone (CR = capillary rise). The increase of lysimeter mass is mainly caused by precipitation, but also the weight of the adsorbed vapour in the form of dew formation cannot be neglected [KOHFAHL *et al.* 2019; NOLZ *et al.* 2014]. Water supplies within the defined horizon of the unsaturated zone are permanently influenced by water flows across its demarcated boundaries. Taking into account the entire thickness of the soil aeration zone, the soil surface is its upper and the groundwater level is the lower boundary. The unsaturated zone of soil profile reacts to water inflows and outflows through its upper and lower boundaries by changing its water content [KANDRA, GOMBOŠ 2008; MATI *et al.* 2011; ŠOLTÉSZ *et al.* 2016; VITKOVÁ *et al.* 2017]. Potential sources of inaccuracy in the measurement of soil water balance components using lysimeters result from the fact that lysimeter mass measurements are exposed to external influences (wind force, friction at the edges of the lysimeters caused by snow, animals passing over the surface, etc.) [NOLZ *et al*. 2013]. With increasing weighing accuracy of modern lysimeters, these small disturbances become visible in form of noise [RAMIER *et al*. 2014]. This noise has to be separated from signals using a filter routine [PETERS *et al*. 2014; VAUGHAN *et al*. 2007]. Inaccuracies may also be caused by rainfall measurements with rainfall gauges. Although the rain gauge is located in the immediate vicinity of the lysimeter, due to wind turbulences, different measurement heights, or different measurement areas, etc., the rain gauge data is often inaccurate [NOLZ *et al*. 2014].

The aim of this paper is to compare the development of individual soil water balance components in two identically constructed lysimeters and filled with two different soil profiles from the Eastern-Slovakian-Lowland (ESL) under the same meteorological conditions. Two different soil profiles were examined in identical lysimeters: sandy and silty-loam. A constant groundwater level (GWL) of 1 m below ground was maintained in both soil profiles. The changes in the water content of the soil profiles as well as the flows at their upper boundary (precipitation, evapotranspiration) and flows at the bottom boundary (capillary inflow/ percolation outflow) were compared. The hypothesis of the authors is as follows: in identical lysimeters, at constant GWL and under the same meteorological conditions, all differences in the development of water balance components are caused only by different hydrophysical properties of soil profiles. The originality of this research lies in the unique design of the lysimeters, which allow to maintain the selected groundwater level. Maintaining a constant GWL level is conditioned by constant refilling or draining of water at the bottom of the lysimeter. Therefore, flows at the lower boundary of the unsaturated soil zone in form of capillary rise and percolation can be directly quantified.

MATERIALS AND METHODS

PLACE AND TIME OF THE EXPERIMENT

The utilized lysimeters are part of the Lysimeter Station in Petrovce nad Laborcom (48°47.540´ N, 21°53.175´ E; 117 m a.s.l.) – Figure 1, which belongs to the Institute of Hydrology of the Slovak Academy of Sciences and is located in the Easter-Slovakian-Lowland in the eastern part of Slovakia. According to the Slovak Hydrometeorological Institute (Sk. Slovenský hydrometeorologický ústav) [SHMI 2015], it is a warm, moderately humid area with a mild winter (average annual air temperature of 10°C; average annual precipitation of 600–700 mm). Most of the territory of the ESL is used for agricultural purposes.

The period from 19.05.2018 to 26.11.2018 was studied, which represents 192 days. The late start of the study period in May was due to the general maintenance of the lysimeter station (spring 2018). The end of the investigated period corresponded to the end of the vegetation activity of the grass cover at the lysimeters.

Fig. 1. Lysimeter station in Petrovce nad Laborcom; source: own elaboration, phot. *A. Tall*

CHARACTERISTICS OF THE LYSIMETER STATION

The lysimeter station was built in 2014. It was put into full operation in spring 2015. It consists of five weighable lysimeters, installed in two plastic containers, a weather station, a hydrological well and solar panels. The lysimeters contain undisturbed soil monoliths, which are imported from five different places of the ESL. The soil monolith from first utilized lysimeter was imported from the locality Poľany (48°28.237´ N, 21°58.326´ E). The soil monolith was extracted from a site with the remains of an old eolic sand dune. The second utilized lysimeter monolith is from the locality Vysoká nad Uhom (48°36.854´ N, 22°06.914´ E). The surface of the lysimeters and their surroundings is made up of grass, trimmed to a height of ≈ 12 cm. Lysimeters are cylindrical, with internal diameter = 1.128 m and height = 2.5 m (surface area = 1 m^2, cylinder volume = 2.5 m^3, weight ≈ 5300 kg). The lysimeters are mounted on a three-point electronic weighing system. According to the manufacturer of the lysimeter station, the weighing precision is 10 g. The GWL was maintained at 1 m below the ground level throughout the experimental period. The lysimeters have a groundwater control system based on the principle of communicating vessels. Changes in the water level are monitored by a pressure sensor. If the water level deviates from the maintained level, it will be rebalanced by a pump system. Irrigation was not applied.

DATA FROM LYSIMETERS

The measured data from the lysimeter station are stored in dataloggers and from there are wirelessly transferred to a server once a day. All data from the lysimeter station are processed with a time step of 1 h. For the purpose of this study, the following data were used:

- W = lysimeter mass (kg); since the surface area of the lysimeter is 1 m^2, each change in lysimeter weight by 1 kg represents a water content (ΔW) change of 1 mm; raw mass data were smoothed using a Savitzky–Golay filter [SAVITZKY, GOLAY 1964; TALL *et al*. 2018];

smoothing was performed by using a 2nd order polynomial and 7 data points;
- *BF* = bottom fluxes (mm); these are the water flows at the bottom of the lysimeter; if the water flows into the lysimeter, it has a positive value, and when leaving the lysimeter, it has a negative value; since GWL was maintained at a constant level, positive values of *BF* represent capillary rise compensation and negative values of *BF* represent gravitational flows to GW;
- θ_{10} = water content (–); volumetric soil moisture in 10 cm under the surface measured by sensor UMP-1 (combined soil humidity, conductivity and temperature sensor).

BALANCE EQUATION

For balancing of individual components of the water balance in lysimeters the balance Equation (1) has been adjusted to the following form:

$$\Delta W = P_{lys} + D - ET_a \pm BF \tag{2}$$

Where: ΔW is the change in water content of the lysimeter, P_{lys} is the precipitation reaching the lysimeter, D is the vapour adsorption (dew) on the surface, ET_a is the actual evapotranspiration and BF are flows at the lower boundary of the lysimeter. All terms of the equation (2) are expressed in units of length (mm).

The data processing is governed by the following procedure:

If $(\Delta W \pm BF) < 0$ then $ET_a = \Delta W$ and $P_{lys} + D = 0$
If $(\Delta W \pm BF) > 0$ then $ET_a = 0$ and $P_{lys} + D = \Delta W$ (3)

The weight loss of the lysimeter $((\Delta W \pm BF) < 0)$ is due to evapotranspiration (ET_a) and the weight gain $((\Delta W \pm BF) > 0)$ is due to either precipitation (P_{lys}) or dew formation (D). If a precipitation event on the rain gauge in weather station is recorded when the weight of the lysimeter is increased, then the weight increase is assigned to the precipitation (P_{lys}). Otherwise, the weight gain is attributed to the vapour adsorption on surface (D).

CALCULATION OF REFERENCE EVAPOTRANSPIRATION

Hourly totals of the reference evapotranspiration (ET_{ref}) were calculated from the measured values from the weather station, which is part of the lysimeter station. The procedure for calculating the ET_{ref} was described by ALLEN *et al.* [2005]. The equation has the following form:

$$ET_{\mathrm{ref}} = \frac{0.408\Delta\,(R_n - G) + \gamma \frac{C_n}{T_{hr}+273} u_2\,(e_s - e_a)}{\Delta + \gamma\,(1 + C_d\,u_2)} \tag{4}$$

Where: R_n = net radiation at the crop surface (MJ·m^{-2}·h^{-1}), G = soil heat flux density at the soil surface (MJ·m^{-2}·h^{-1}), T_{hr} = mean hourly air temperature (°C), u_2 = mean hourly wind speed (m·s^{-1}), e_s = saturation vapour pressure (kPa), e_a = mean actual vapour pressure (kPa), Δ = slope of the saturation vapour pressure–temperature curve (kPa·°C^{-1}), γ = psychrometric constant (kPa·°C^{-1}), C_n and C_d are constants that change with reference type and calculation time step.

Equation (4) was used to calculate a standardized reference evapotranspiration for the "short crop", which is similar to clipped grass at 12 cm (C_n = 37; C_d = 0.24 during daytime or C_d = 0.96 during night time); ET_{ref} values were calculated with an hourly time step.

SOIL ANALYSIS

Soil samples were taken from open pits during the soil monoliths excavation. The results of the particle-size analysis according to the hydrometer measurement method are shown in Figure 2. Soil horizons are shown to the depth of 1 m at 10 cm intervals. The soil profile from the site of Poľany is formed on the surface by sandy loam, which in the deeper horizons passes through the loamy sand to the pure sand. The soil profile from the locality Vysoká nad Uhom is relatively homogeneous and consists of silt loam.

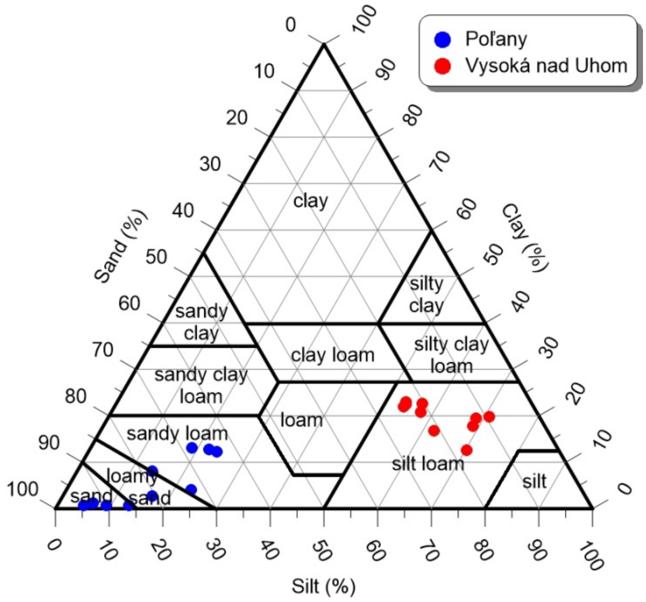

Fig. 2. Distribution of soil textures in the USDA textural triangle; source: own results

Soil water retention curves were determined in the laboratory using pressure plate extractor. Six undisturbed samples (100 cm^3 sampling rings) were taken at three depth intervals (0–0.1, 0.5–0.6 and 0.9–1.0 m). A soil water retention curves were expressed using van Genuchten equation [VAN GENUCHTEN 1980]. The measured water retention curves are presented in Figure 3.

The courses of retention curves show significantly different hydrophysical parameters of soil profiles in two investigated localities. The sandy soil profile from the Poľany site also shows greater heterogeneity compared to the profile from Vysoká nad Uhom.

Saturated hydraulic conductivity was measured on the same samples. Measured values at three depths (0–0.1, 0.5–0.6 and 0.9–1.0 m) were as follows: 12, 430 and 470 cm·day^{-1} for the Poľany soil profile and 10, 35 and 32 cm·day^{-1} for the soil profile Vysoká nad Uhom, respectively.

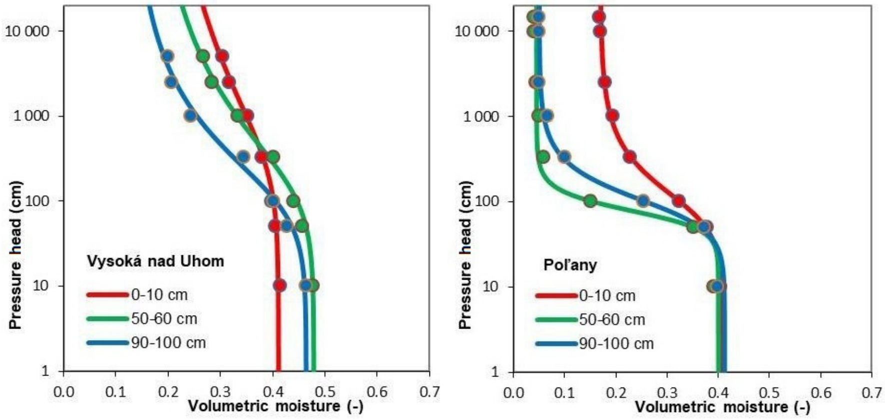

Fig. 3. Fitted soil water retention curves according to van Genuchten equation for measured laboratory data; source: own results

RESULTS AND DISCUSSION

SOIL WATER CONTENT

The course of the volumetric soil moisture content in the top layer of both soil profiles during the monitored period is shown in Figure 4.

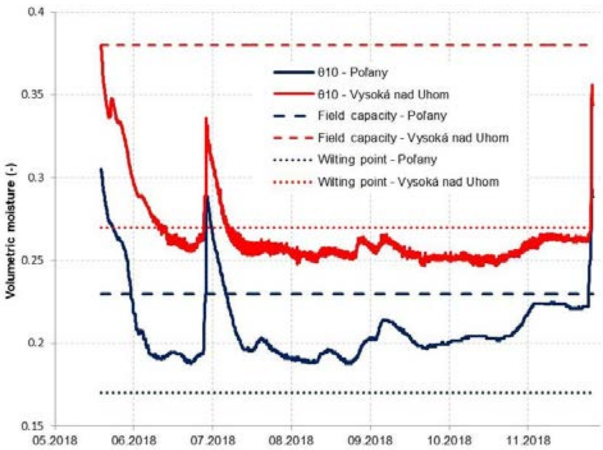

Fig. 4. The course of the volumetric soil water content in the top layer (10 cm under the surface) of the both soil profiles during the monitored period; θ_{10} = water content (–); volumetric soil moisture in 10 cm under the surface measured by sensor UMP-1 (combined soil humidity, conductivity and temperature sensor); source: own results

The volumetric moisture content (θ_{10}) in the upper layer of both profiles were comparatively high at the beginning of the study period. In the soil profile from locality Vysoká nad Uhom, θ_{10} value reached the level of the field capacity and in the soil profile from locality Poľany field capacity was even exceeded. Subsequent decline in θ_{10} values was significantly affected only by heavy precipitation at the end of June and at the end of the study period in November. During the whole study period θ_{10} values were higher in soil profile from Vysoká nad Uhom compared to soil profile from Poľany. The θ_{10} values in the soil profile from Poľany were never lower than the wilting point value. In the soil profile from the locality Vysoká nad Uhom, θ_{10} values fell below the wilting point value for a longer time.

DEVELOPMENT OF THE WATER BALANCE COMPONENTS

The development of the water balance components of the two examined soil profiles is summarized in Figure 5 and in Table 1. Regarding precipitation quantity, the study period in 2018 was significantly below the long-term average with exception of June. Compared to the long-term

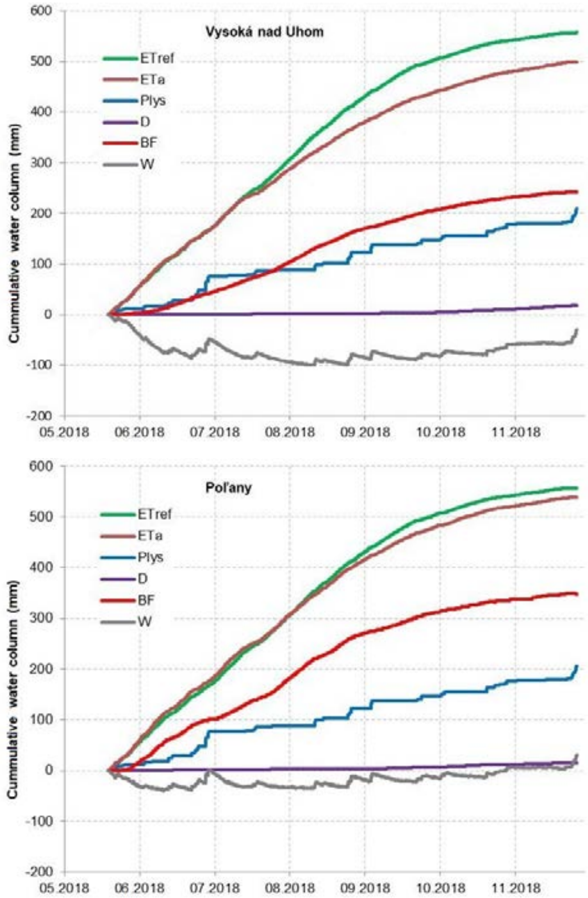

Fig. 5. Development of water balance components of two examined soil profiles: a) from Vysoká nad Uhom, b) Poľany; ET_{ref} = reference evapotranspiration, ET_a = actual evapotranspiration, D = vapour adsorption (dew) on the surface, BF = flows at the lower boundary of the lysimeter, W =lysimeter mass; source: own study

Table 1. Monthly sums of water balance components (mm)

Month[1)]	$P_{average}$[2)]	P_{lys}	*BF*	*W*	ET_{ref}	ET_a	*D*
Vysoká nad Uhom							
May	60–80	12.4	4.2	–41.0	57.5	57.5	0.2
June	60–80	63.6	40.6	–11.1	116.2	116.0	0.5
July	80–100	11.9	58.5	–41.5	131.8	113.3	1.0
August	60–80	34.9	66.7	9.0	125.4	93.6	1.0
September	60–80	25.1	37.7	3.0	75.4	61.7	2.0
October	40–60	30.9	24.8	23.8	36.0	38.1	6.3
November	40–60	30.8	10.1	29.1	14.8	18.8	7.0
Σ	400–540	209.5	242.5	–28.8	557.1	499.2	17.9
Poľany							
May	60–80	12.3	18.2	–30.4	57.5	61.3	0.4
June	60–80	63.7	83.2	25.8	116.2	121.9	0.9
July	80–100	11.5	79.8	–29.5	131.8	123.1	1.4
August	60–80	34.9	90.2	16.9	125.4	109.5	1.2
September	60–80	24.5	41.0	2.0	75.4	66.6	3.1
October	40–60	30.0	25.5	21.6	36.0	38.6	4.8
November	40–60	29.3	9.4	23.6	14.8	17.2	3.1
Σ	400–540	206.3	347.3	30.0	557.1	538.2	14.9

1) From 19.05.2018 to 26.11.2018.
2) Average totals over 30 years acc. to Slovak Hydrometeorological Institute [SHMI 2015].
Explanations: $P_{average}$ = long-term average precipitation totals, P_{lys} = precipitation reaching the lysimeter, *BF* = flows at the lower boundary of the lysimeter, *W* =lysimeter mass, ET_{ref} = reference evapotranspiration, ET_a = actual evapotranspiration, *D* = vapour adsorption (dew) on the surface.
Source: own study.

average, less than half of the average rainfall fell in the study period.

Obviously, the rainfall could not cover the need for evapotranspiration by far and therefore the water had to be replenished both by the GWL inflow and by the exhausting the unsaturated zone of the soil profile.

At the beginning of the year, both soil profiles were in a relatively saturated state after the winter and spring months. Saturated soil profiles initially provided a sufficient supply of water for the evapotranspiration demand without the need of extracting water from GWL (during May). However, since the beginning of June, the water demand for evapotranspiration had to be compensated by GWL inflows. At the end of June, due to heavy precipitation, the soil profiles were partially refilled. During the summer months, which were significantly short of precipitation, even the inflows from GWL, together with the exhausting of water supplies of soil profiles, could not cover the full need for evapotranspiration. An evapotranspiration deficit (ET_{ref} – ET_a) resulted in July, which reached its peak in August and lasted until September (Fig. 6). At the end of the study period, also a period with low precipitation, much lower *BF* inflows were sufficient to maintain a constant GWL, since the water consumption for evapotranspiration was already considerably lower in the autumn than in the summer months. The soil profiles were also gradually saturated. In percentage terms, the evapotranspiration deficit in the soil profile from Vysoká nad Uhom reached 10.4% and in the soil profile from the Poľany site 3.4% in the whole monitored period.

When comparing both profiles, it is obvious that under the same meteorological conditions and with constant GWL, the soil profile from Vysoká nad Uhom was more prone to dryness (evapotranspiration deficit was three times higher). Sandy soil profile from Poľany reacted much more quickly to precipitation (or evapotranspiration).

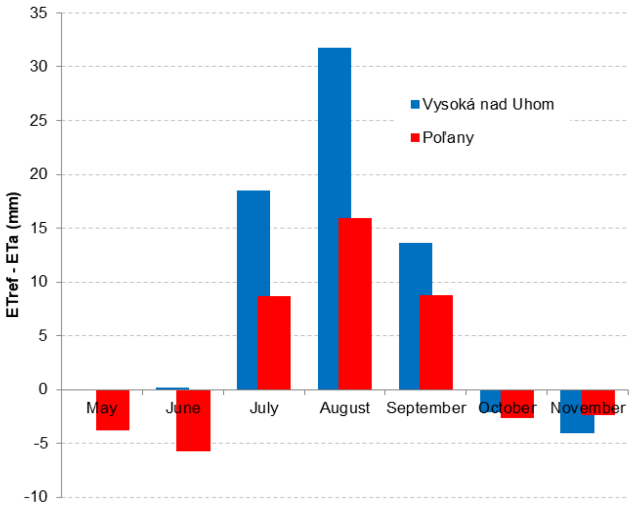

Fig. 6. Development of evapotranspiration deficit in studied soil profiles; ET_{ref} = reference evapotranspiration, ET_a = actual evapotranspiration; source: own study

Due to the higher hydraulic conductivity of the sandy soil compared to the silt loamy soil, the GWL response to external stimuli was much faster. Hence, a higher inflow of water (*BF*) in the sandy (347.3 mm) than in the silt loamy soil profile (242.5 mm) was necessary to maintain a constant GWL. Otherwise, it is clear that if the GWL is not kept constant, the sandy soil water supply would be exhausted much faster and the soil drought would occur earlier due to the faster water movement in the sandy profile.

CONCLUSIONS

With the use of weighing lysimeters, the development of water balance components of two different soil profiles from the Eastern Slovakian lowland was compared: silty loam (from the locality Vysoká nad Uhom) and sandy (from the locality Poľany). In two identically constructed lysimeters, with the same meteorological conditions and a constant GWL, all differences in the development of water balance components were due to different hydrophysical parameters of the soil profiles. Using values of saturated hydraulic conductivity and the course of the water retention curves, different hydrophysical parameters of both soil profiles were detected. The study period was significantly below the long-term average in terms of precipitation. In both soil profiles, in addition to insufficient precipitation, water inflows from GWL as well as water supplies from unsaturated zones were required for evapotranspiration needs. The evapotranspiration deficit was greater in the silty-loam soil profile (10.4% vs. 3.4%). The higher hydraulic conductivity of the unsaturated zone of the sandy soil profile (as compared with silty-loam) resulted in more intense water flows at its lower boundary.

The replenishment of water towards the unsaturated soil zone from the constantly maintained GWL is therefore more intense in this profile. Sandy soils are generally considered to be more prone to drought than silty-loam soils. However, in the case of this experiment, this statement has not been confirmed. The sandy soil profile was less prone to drought than the silty-loam soil profile. A specific condition (maintained groundwater level) has caused that the water inflows from the groundwater level were more intensive in the case of sandy soil profile due to higher hydraulic conductivity.

FUNDING

Scientific Grant Agency of the Ministry of Education, Science, Research and Sport of the Slovak Republic: (project VEGA: 2/0044/20).

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