Water Balance Study of a
Groundwater-dependent Oak Forest

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Abstract – The objectives of this study were (1) to estimate the water balance components of an oak stand by calibrating a Hydrus 1-D model, (2) to determine the groundwater consumption by the water table fluctuation method and (3) to compare the results of the modelling with a remote-sensing based estimation.

Model simulation described the observed soil moisture and groundwater level relatively well, the root mean square errors varied between 12.0 and 14.9% for the soil moisture measurements and 5.0% for the groundwater level. Groundwater consumption was estimated also by the water table fluctuation method, which provided slightly different groundwater consumption rates than estimated by the Hydrus model simulation. The simulated evapotranspiration was compared with results of a remote-sensing based estimation using the surface temperature database of MODIS.

According to the Hydrus model, the estimated evapotranspiration resulted from transpiration (73%), interception loss (23%) and soil surface evaporation (4%) in the two-year study period. The proportion of groundwater consumption was 58% of the total transpiration. During the dry growing season of 2007 the groundwater consumption was significant with 66% of the total transpiration. Water supply from groundwater was found to be less important in the wet growing season of 2008 with 50%. The remote-sensing based estimation of evapotranspiration was about 4% lower than the model based results of nearby comparable sites.

groundwater / evapotranspiration / hydrus 1-D

Kivonat – Egy tölgyes vízforgalmi vizsgálata. A jelen tanulmány célja (1) egy kocsányos tölgyes állomány vízforgalmi komponenseinek becslése egy numerikus modell (Hydrus 1-D) alkalmazásával (2) a két felszín talajvízfogyasztásának becslése a talajvíz fluktuáció módszerének segítségével és (3) a modellezett evapotranszspiráció összehasonlítása egy távérzékelési módszeren alapuló párolgás eredményével.

A modell szimuláció jól követte a megfigyelt talajnedvesség- és talajvízszint értékeket. A talajnedvesség átlagos négyzetes gyök eltérése (RMSE) 12.0 és 14.9% között változott, míg a talajvízszint esetén 5.0% körüli érték volt jellemző. A talajvíz-fluktuáció módszerével becsült talajvíz-fogyasztás kissé eltérő értékeket szolgáltatott a Hydrus modell eredményénél. A vegetációs idejű evapotranszspiráció összegeket összehasonlítottam a MODIS felszínhőmérsékleti adatbázis felhasználásával becsült párolgás értékeivel.

A modell eredmények szerint a teljes vizsgált időszakban (2007.04.01–2009.03.31.) az evapotranszspiráció mintegy 73%-a származott növényi párologtatásból, 23%-a intercepciós párolgásból és mindössze 4%-a talajfelszín párolgásból. A talajvíz-fogyasztás a teljes transzspiráció 58%-a volt. A 2008-as vegetációs időszakban a talajvíz-fogyasztás aránya (50%) lényegesen kisebb volt a 2007-ben becsültnek (66%), mivel a csapadékos időszakokban az intercepciós veszteség és a telítetlen zóna párolgása dominált. A modell által becsült evapotranszspiráció 4%-kal volt kisebb a hasonló mintaterületeken – MODIS felszínhőmérséklet alapján – becsült értéknél.

talajvíz / párolgás / hydrus 1-D

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1 INTRODUCTION

In recent years, knowledge about the amount of recharge to the groundwater has become an important issue because groundwater has become a scarce resource in some areas. Changes of the vegetation cover, e.g. afforestation may be one of the factors, influencing the long-term changes of groundwater levels e.g. in the Hungarian Great Plain.

The vegetation cover influences significantly the interception loss, the transpiration and consequently the groundwater recharge. Interception loss is considerably higher at forested sites, compared to herbaceous vegetation due to higher leaf area index and much higher atmospheric conductance over forests (McMillan – Burgy 1960).

Evapotranspiration from forest is considerably larger than from any other crop or grassland and the amount of water left for groundwater recharge is relatively low. Gácsi (2000) found that deep recharge was significantly greater under bare soil than under a scotch pine forest on sandy soil in Hungarian Great Plain. Local studies of water balance of forests and other vegetation covers have found mainly that the forests have higher water consumption (Major 1990, Ladekarl et al. 2005, Nachabe et al. 2005, Schilling 2007), whilst some studies have demonstrated little difference in water consumption of different vegetation covers (Járó – Sitkey 1995, Roberts – Rosier 2005).

The present study intends to determine the water balance components of an oak stand on sandy soil in North-East Hungary to obtain actual evapotranspiration, calibrated with a Hydrus 1-D model by soil moisture and groundwater level measurements. Groundwater consumption was estimated also by the water table fluctuation method. The simulated evapotranspiration was compared with results of a remote-sensing based estimation using the surface temperature database of MODIS.

2 MATERIALS AND METHODS

2.1 Study area

The study area is located in the North-East part of the Hungarian Great Plain *(Figure 1),* characterized by sand dunes, built up from river deposits during the early Pleistocene (Borsy et al. 1981).
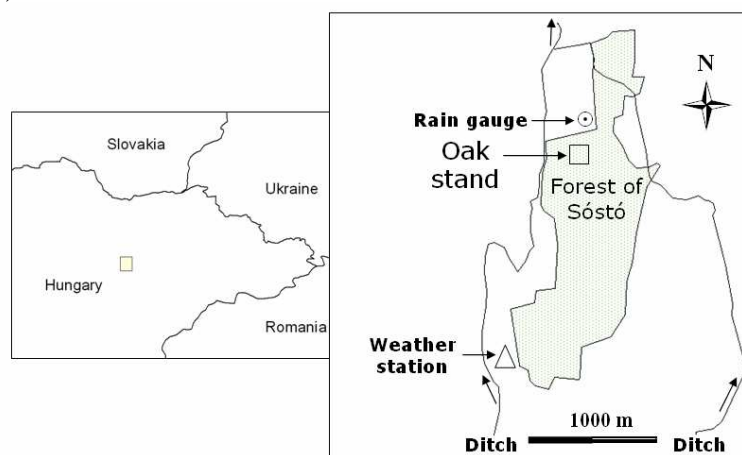

Figure 1. Location of the study site

The climate is continental, the mean annual precipitation (1951–2000) is approximately 520 mm and mean monthly temperature (1951–2000) ranges from –2.4°C in January to 20.5°C in July. The original vegetation was dominated by pedunculate oak (*Quercus robur*).

Much of these forests have been cleared and transformed into pasture and agricultural fields. The stand has a slope of less than 2‰ with no sign of surface runoff.

The stand is located at the discharge part of the local groundwater flow system, characterized by shallow groundwater depth and groundwater inflow. The groundwater level apparently did not responded to the water table changes of the nearby (distance: 300 m) ditches.

The stand is situated in the northern part of a native forested area, which was naturally regenerated in the 50s of the last century. The forest is a mixed stand of pedunculate oak (*Quercus robur*), sycamore maple (*Acer pseudoplatanus*) and black locust (*Robinia pseudoacacia*). The trees are 20–25 m high and the stand density is about 270 trees/ha.

The vertical distribution of the root density was determined by taking three replicate volumetric soil core samples from six different depths (0–0.2 m, 0.2–0.4 m, 0.4–0.6 m, 0.6–0.8 m, 0.8–1.0 m and 1.0–1.2 m). Fine roots (diameter < 2 mm), responsible for most of the water uptake, were separated by sieving the soil core samples. Fine root length decreased approximately linearly with depth and below 1 m of soil depth only little amount of fine roots were found. Root depth was estimated approximately 1.5 m, considering deeper penetrating roots below the trunks.

The particle size distribution of the soil profiles was determined by sieving and hydrometer analyses of samples, taken at 0.2 m intervals down to 3 meter depth. The soil texture is dominated by compacted fine sand (0.02–0.2 mm) near the surface and varies between 85–99%. The clay and silt fractions increased significantly with depth and reach 35 and 20% respectively, which corresponded to the sandy clay loam texture class (Dingman 2001). Three replicate samples for the determination of water retention were taken at 0.1, 0.3, 0.5, 0.7, 0.9 and 1.2 m by cylinders of 100 cm^3.

The saturated hydraulic conductivity was not measured in the upper soil horizon, but it was obtained from measured water retention curves and soil texture data by the Rosetta lite 1.1 pedotransfer software (Schaap et al. 2001). Below the deepest measured horizon the saturated hydraulic conductivities were estimated by slug tests. Saturated hydraulic conductivity was used for model calibration *(Table 1)*.

Table 1. Main parameter values

Field measured parameters		
Maximum LAI	(m^2/ m^2)	3.9
Free throughfall coefficient	(%)	14
Root depth	(m)	1.5
Estimated parameters from literature and database		
Reference height	(m)	20.1
Albedo	(%)	10–16
Maximum leaf conductance	(mm/s)	6.3
Roughness length	(m)	0.9
Displacement height	(m)	15.12
Light coefficient of extinction	(–)	0.5
Stem flow ratio of precipitation	(%)	3
Calibrated parameters		
Canopy storage capacity	(mm)	
Vegetation season		1.17
Dormant season		0.5
Litter storage capacity	(mm)	0.5
Saturated hydraulic conductivity	(mm/day)	
Root-zone		$0.9 \times 10^3 - 2.9 \times 10^3$
Below the root zone		1.4×10^2
Specific yield		0.032

Maximum Leaf Area Index (LAI) was estimated from leaf litter and the seasonal change of LAI was described using remote sensing images.

During late autumn 2007 leaves were collected from five (1 m × 1 m) plots. The decomposition of leaves did not begin at the time of collection and the old leaves from previous years has already decomposed to an extent that it was easy to separate from new leaves by careful collection. The leaves were dried in an oven (105°C for 24 hours), then some of the leaves were scanned and the ratio of weight to leaf area was determined for this subset of leaves and subsequently for the whole sample. According to average of the five samples, the maximum LAI was 3.9 m^2/m^2.

The seasonal change of LAI was estimated using the 16-day Enhanced Vegetation Index (EVI) product of MODIS (Moderate Resolution Imaging Spectroradiometer). The 250 m resolution EVI was transformed to LAI by an empirical relationship (Wang et al. 2005). According to the satellite images, the maximum LAI was 4.2 m^2/m^2 in 2007, which was a about 8% higher than the results of the leaf litter collection. During the dormant season the images showed approximately 1.5 m^2/m^2 LAI, which may be accounted for the herbaceous vegetation below the forest canopy *(Figure 2)*.
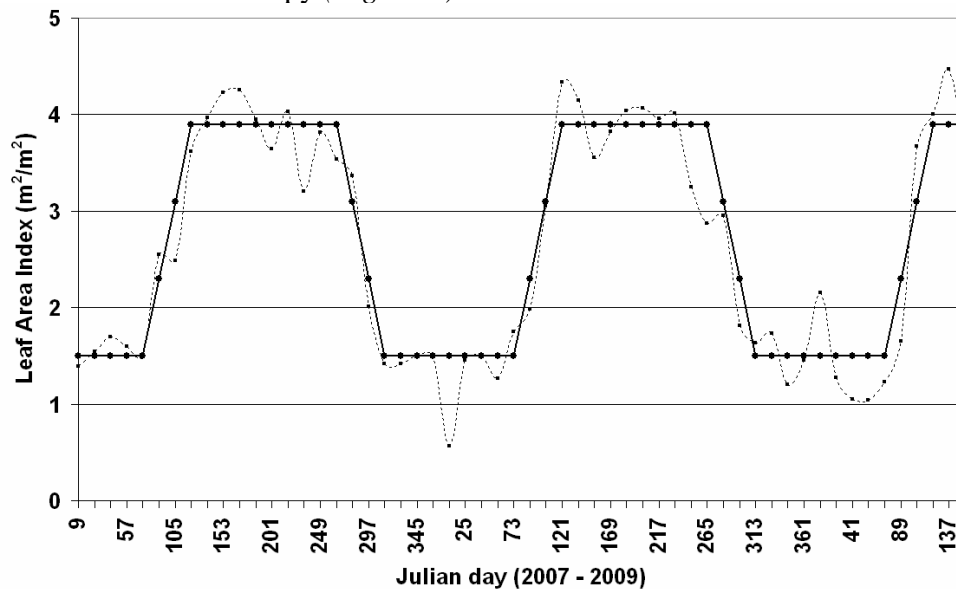

Figure 2. Seasonal change of LAI
(dashed line - MODIS data, solid line - applied in the model).

The seasonal change of albedo was estimated using the 500 m resolution images of MODIS. Daily albedo values were interpolated from the 16-day estimates and missing values were considered as snow cover. During these periods we used an albedo of 45% (Kondratiev 1969). During the vegetation period albedo had a value of 14–16%, while it decreased considerably in the dormant season.

2.2 Monitoring at the field site

2.2.1 Meteorological measurements

Meteorological variables (air temperature, relative humidity, solar radiation, wind speed) were measured hourly at 2 meter height by an automatic weather station (iMETOS, Pessl Instruments, Austria), about 3 km distance from the oak stand *(Figure 3)*. Additionally, an automatic rain-gauge (Rainlog Data Logger, Rainwise, USA) was installed in 2007 at a distance of 500 m from the forest stand. Air temperature and relative humidity data, as

measured were applied above the forest canopy, which probably influenced the potential transpiration estimate to some extent. Interception loss was not measured.
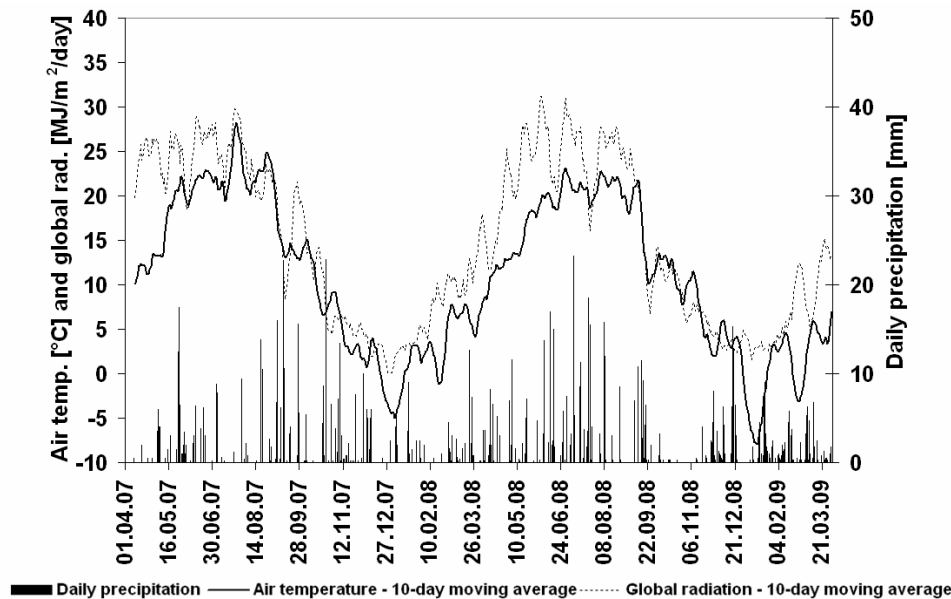

Figure 3. Meteorological conditions during the study period

The vegetation period (April to September) of the year 2007 was unusually dry with only 260.9 mm precipitation while 2008 was relatively wet with 401.4 mm rainfall. Air temperature was above average during almost the whole study period.

2.2.2 Soil water content in the root zone

The volumetric water content was measured by FDR (Frequency Domain Reflectometers) with Decagon EC-5 probes (Decagon Devices, Pullman, USA). The probes were inserted at 0.1, 0.3, 0.5, 0.7 m depth, respectively.

FDR measurements were verified by the gravimetric method using bulk density to convert gravimetric water content to volumetric. The accuracy of the FDR measurement was ±3.7%, which did not differ significantly from ±3%, given by the manufacturer (Decagon Devices, Pullman, USA).

2.2.3 Groundwater level

Shallow monitoring well was installed in spring 2007. Groundwater level was monitored by Dataqua DA-S-LRB 118 pressure transducer with an accuracy of 1 mm.

Besides the continuous monitoring, occasionally, groundwater level was measured also manually to check the reliability of the automatic groundwater monitoring.

2.3 Water balance modelling using Hydrus 1-D model

The Hydrus 1-D model (Simunek et al. 2005) was used for estimation of the water balance components *(Figure 4).* Hydrus 1-D 3.0 is a Windows-based modelling environment for analysis of water flow and solute transport in variably saturated porous media. Details can also be found at http://www.pc-progress.com/en/Default.aspx?HYDRUS-1D.

The base of the Hydrus 1-D model is the variable saturated vertical soil domain, where water flow is simulated.

The upper boundary condition (BC) was set to atmospheric BC with surface layer. The lower BC was set to variable flux, according to the groundwater supply (Q_{NET}), computed by the daily diurnal groundwater fluctuation method (Gribovszki et al. 2008b).

Input meteorological variables on the upper boundary of the 1-D model included the daily potential transpiration (T_P), the potential evaporation (E_P) and the effective precipitation (P_{EFF}).
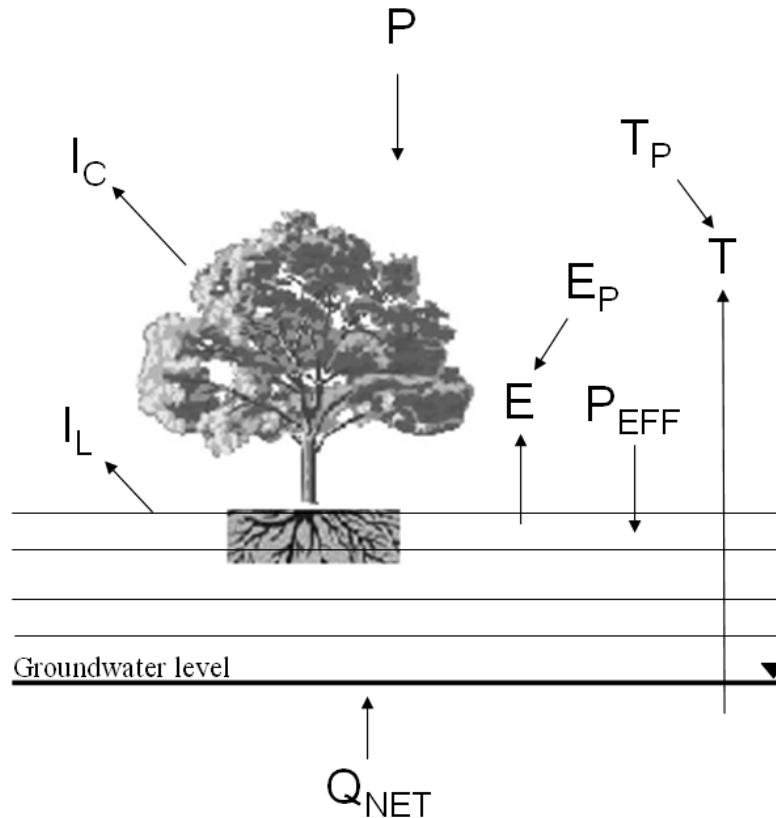
Figure 4. Water balance components of the numerical model
(P: gross precipitation, P_{EFF}: effective precipitation, I: interception loss,
I_C: canopy interception loss, I_L: litter interception loss, T_P: potential transpiration,
T: actual transpiration, E_P: potential soil surface evaporation,
E: actual soil surface evaporation, Q_{NET}: net groundwater supply.)

Potential transpiration and evaporation were calculated using the Penman-Monteith equation (Monteith 1965). The infiltrated rainfall into the mineral soil (effective precipitation) required the estimation of interception loss from canopy (I_C) and litter (I_L) from gross rainfall measurements (P).

The model simulated the presence of vegetation by root water uptake. Actual value of transpiration (T) was computed by the Hydrus 1-D model by water uptake reduction function. The S-shaped model for water uptake reduction was used, proposed by van Genuchten (1987). The actual value of soil surface evaporation (E) was estimated by the model, according to the moisture conditions at the topsoil.

Water retention variables and the saturated hydraulic conductivity functions were required to be specified for each soil horizons. The van Genuchten (1980) function was applied to describe the water retention of soil layers. The RETC software (van Genuchten et al. 1991) was used to fit the soil water retentíon curves.

2.3.1 Input data

The input data of the model is discussed separately as the upper and the lower boundary condition. Potential transpiration, potential evaporation and effective precipitation are discussed as the upper while variable bottom flux is analysed as the lower boundary condition.

Upper boundary condition

Potential transpiration was determined after Jarvis (1976) by estimating the leaf conductance C_{leaf} (mm/s).

$$C_{leaf} = g_{l\min} + f_T f_D f_R f_W f_C (g_{l\max} - g_{l\min}) \tag{1}$$

where g_{lmax} (mm/s) and g_{lmin} (mm/s) are the maximum and minimum leaf conductance respectively and f_T, f_D, f_R, f_W, f_C are reduction factors, varying between 0 and 1, that account for effects of temperature, vapour pressure deficit, radiation, leaf water stress and atmospheric carbon dioxide concentration respectively, on stomatal opening. Canopy conductance was computed by multiplying the leaf conductance with the leaf area index.

Potential evaporation from soil surface was also estimated by the Penman-Monteith equation, based on estimates of net radiation, aerodynamic and surface resistances applicable at the soil surface. Net radiation at the soil surface was computed using Beer's low, leaf area index and extinction coefficient.

Effective precipitation was calculated by the estimation of the interception loss. For herbaceous vegetation evaporation from canopy during and after rainfall events plays little importance (McMillan – Burgy 1960), thus solely the storage capacity can be used for estimation of interception loss. Conversely, due to the high atmospheric conductance above the forest canopy, the evaporation of intercepted rain cannot be neglected.

Canopy interception was estimated by the Gash model (Gash 1979). This model was chosen, because it yields accurate estimation and only needs a few parameters to describe interception (Dolman 1987). Gash considered rainfall to occur as a series of discrete events, each comprising of a period wetting up, a period of saturation and a period of drying out after the rainfall. The canopy has sufficient time to dry out between rainfall events. Canopy parameters (free throughfall coefficient, storage capacity of canopy, stem flow proportion) were based on literature values and field observations.

The value of storage capacity of canopy S (mm) was estimated by a logarithmic saturation curve (Wattenbach et al. 2005):

$$S = f[\log(1 + LAI)] \tag{2}$$

where f is a species-specific parameter, which was set to 1.5, thus the value of S was 1.17 mm at the LAI of 3.9. During the dormant season the storage capacity of stems and branches were assumed to be 0.5 mm (Larcher 1994).

Rainfall and evaporation intensities were computed as monthly averages from hourly meteorological variables, where the rainfall rate exceeded 0.5 mm/h (Gash 1979). The rainfall interception was calculated on a daily basis. The evaporation rate was computed by the Penman equation.

Beyond the vegetation period we used the daily interception method to estimate the daily interception loss I (mm), proposed by Menzel (1997):

$$I = S(1 - e^{(-cp_i)}) \tag{3}$$

where p_i (mm) is the daily precipitation amount and c (–) is species-specific parameter, which was set to 0.7 (Wattenbach et al. 2005).

Litter storage capacity was estimated to be 0.5 mm during the model calibration. The total storage capacity (canopy + litter) was 1.67 (1.17 + 0.5) mm during the vegetation period and 1.0 (0.5 + 0.5) mm in the dormant season.

Lower boundary condition

The lower boundary condition was set to variable flux, according to the groundwater inflow, calculated by the water table fluctuation method (Gribovszki et al. 2008b). Beyond the vegetation period the groundwater level responded apparently to significant rainfall events, however these responses were slow and gradual due to the relatively deep (1.5–2.3 m) groundwater level.

In general, the lower boundary variable flux was set to zero for the period without observable daily groundwater fluctuation.

2.3.2 Result variables

Reduction of potential to actual transpiration was calculated by the model for all soil layers, where the normalized root density was above zero (Simunek et al. 2005). The S-shaped function (van Genuchten 1987) was applied with recommended parameters to describe the water uptake stress response function.

Actual evaporation was estimated internally by the model from the prevailing soil moisture conditions near the soil surface.

2.4 Estimation of groundwater consumption by the water-table fluctuation method

Significant diurnal fluctuation of groundwater level and streamflow rate can be seen at shallow groundwater areas during periods with no rainfall (Bond et al. 2002, Gribovszki et al. 2008a). This fluctuation is caused mainly by the diurnal variation of transpiration, originated by the vegetation cover.

Groundwater consumption T_G (mm/day) was estimated from groundwater level readings. An empirical version of the technique, developed by Gribovszki et al. (2008b), was applied. Gribovszki et al. (2008b) upgraded the White-method (White 1932) based on the fundamental assumption that groundwater supply per unit area, Q_{net} (mm/day), exhibits a significant daily variation due to hydraulic gradient changes over the day. Groundwater consumption values were calculated as the difference between the net inflow rate and the storage change (Gribovszki et al. 2008b).

$$T_G = Q_{net} - S_y \frac{dh}{dt} \qquad (4)$$

where S_y (–) is the readily available specific yield was estimated from soil sediment texture data. According to the trilinear diagram of Loheide II et al. (2005), S_y varied from 0.03 to 0.10. Low specific yield values are further justified by the shape of the water retention curves of the lowest measured horizons and the low hydraulic gradient of the adjacent areas (Maidment 1993).

Days with less than 5 mm precipitation did not present any problem for the ET estimation, because these light rainfall events cannot produce any measureable groundwater recharge due to interception loss. Larger rainfall events (> 5 mm) can affect the estimation for up to 2 days, so those periods were excluded from the analyses (Gribovszki et al. 2008b). During the excluded periods the groundwater consumption can be considered negligible due to interception and evaporation loss from topsoil.

While this method aims to describe storage changes within the saturated zone only, implicitly it accounts (at least partially) for moisture withdrawal from the vadose zone as

well, depending on the depth of the water table. Consequently, this method shows water extraction amounts from variable soil profile height, according to the groundwater depth and capillary fringe.

2.5 Comparison of the simulated local evapotranspiration data with ET results based on remote-sensing

Recently several remote-sensing based estimations of areal actual evapotranspiration (ET) were developed (Gowda et al. 2008). Szilagyi – Kovacs (2010) recently presented an ET estimation method based on the daytime land surface temperature of MODIS. Areal evapotranspiration rates were achieved by a linear transformation of the MODIS daytime land surface temperature employing the complementary relationship of evaporation.

The method was validated in the USA (Szilagyi – Józsa, 2009) and also in Hungary. The spatially distributed ET rates corresponded well with soil/aquifer properties and the resulting land use type. Validation of the ET rates has been performed at three sites in Hungary by Eddy-covariance measurements.

Monthly actual ET rates for 2000-2008 were mapped for Hungary at a spatial scale of about 1 km. Various meteorological data (sunshine duration, air temperature and humidity) and the daytime land surface temperature of MODIS was used for the estimation of ET.

A comparison of the model estimated ET of the oak plot with the remote-sensing based estimation has been carried out. Since the horizontal coverage of the oak plot (where the estimated ET values were valid) is smaller than 1 km, the direct, pixel-based comparison was not possible. For the comparison we have chosen suitable sites, (shallow groundwater table and similar leaf area index) in the vicinity.

2.6 Testing of the model performance

To test the performance of the model, time series of simulated soil water contents and groundwater levels were compared with observed values. Three performance criteria were used to quantitatively examine model performance: the coefficient of determination (R^2), the root mean square error (*RMSE*) and the Nash–Sutcliffe modelling efficiency (*ME*).

3   RESULTS AND DISCUSSION

3.1 Calibration of the Hydrus model

Measured soil moisture and groundwater level were used to calibrate the Hydrus model. Soil water measurements showed a cyclic variation seasonally, drying began in April, wetting started usually in September. Very dry conditions prevailed during late summer in 2007, soil water content dropped close to wilting point in the upper layers. Soil frost caused significant drop in soil water content during January of 2008 and 2009.

In *Figure 5* the soil moisture measurements and model predictions are shown.

Soil moisture measurements and model simulation generally compare well both in the dry (2007) and wet year (2008). However, there was a slight overprediction of the water contents in summer 2008. Unfortunately, the model, applied for daily time-resolution was not able to simulate accurately the transpiration on days with short and high-intensity rainfalls.
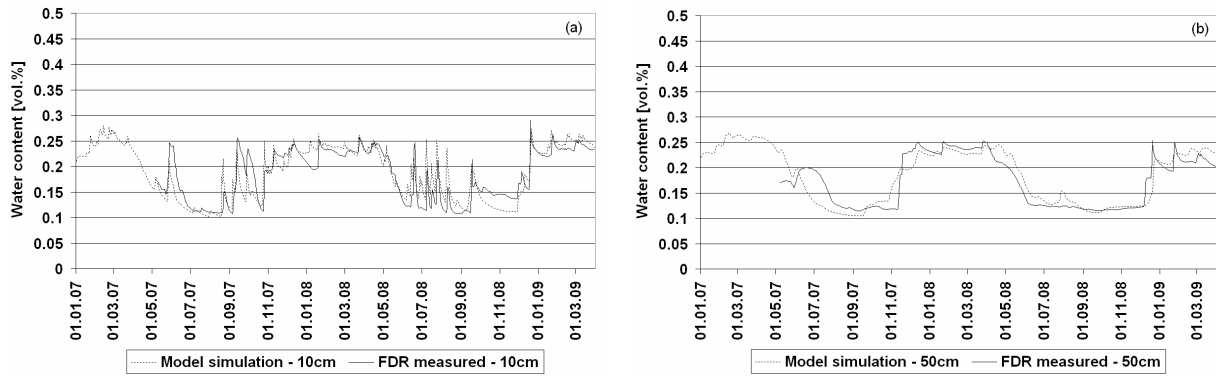
Figure 5. Comparison of measured and simulated water content for 10 cm (a) and 50 cm (b)

Groundwater levels showed also a cyclic seasonal variation during the study period and dropped deeper in the growing season of 2007 than in 2008 due to dry weather conditions in 2007. During the growing season groundwater levels showed a diurnal fluctuation, which is caused mainly by the diurnal variation of transpiration *(Figure 6)*.
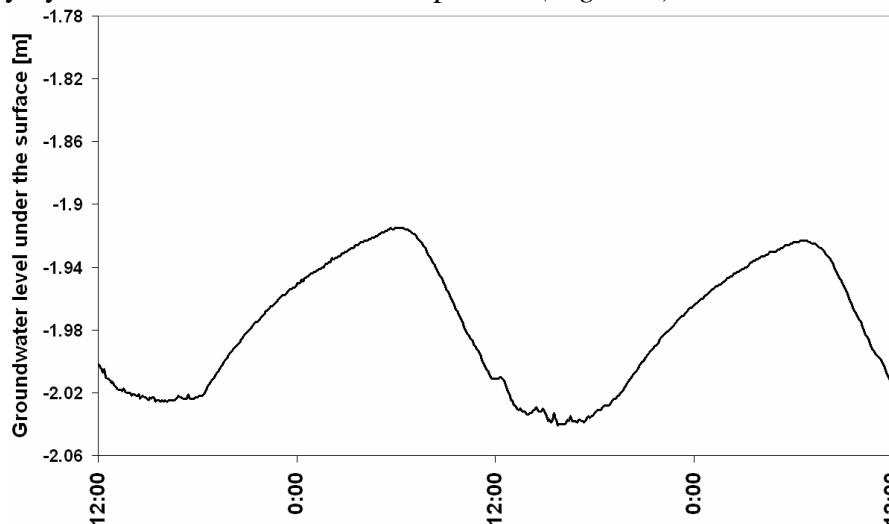

Figure 6. Diurnal fluctuations in groundwater level between 27.06.2007 and 29.06.2007.

Model simulations of groundwater levels compared fairly well with observations *(Figure 7)*. We observed a significant divergence during early autumn, namely simulated groundwater level was lower than the measured levels. Percolating rainwater could not explain the abrupt rise of groundwater, because it took months for the wetting front to reach groundwater at 2 meter depth. Macropores might also caused similar effect, but water level rose from 4th to 24th September 2007, while precipitation event already ended on 12th September. This behaviour was not typical for preferential flow. The estimated groundwater consumption was only 19 mm in September and 11 mm in October 2007, therefore it could not be the cause of the divergence.

Possible explanation of the divergence is that during late summer, groundwater is significantly lowered under the forest stand, compared to the neighbouring landcovers. At late summer evaporation forcing and transpiration usually cease abruptly and the groundwater depression disappears quite quickly due to groundwater supply from background. During this early autumn period the background groundwater supply was estimated from the mean of the smallest time-rate of change in the predawn hours. This time-rate of change was decreased linearly by the time of equilibrium groundwater level.
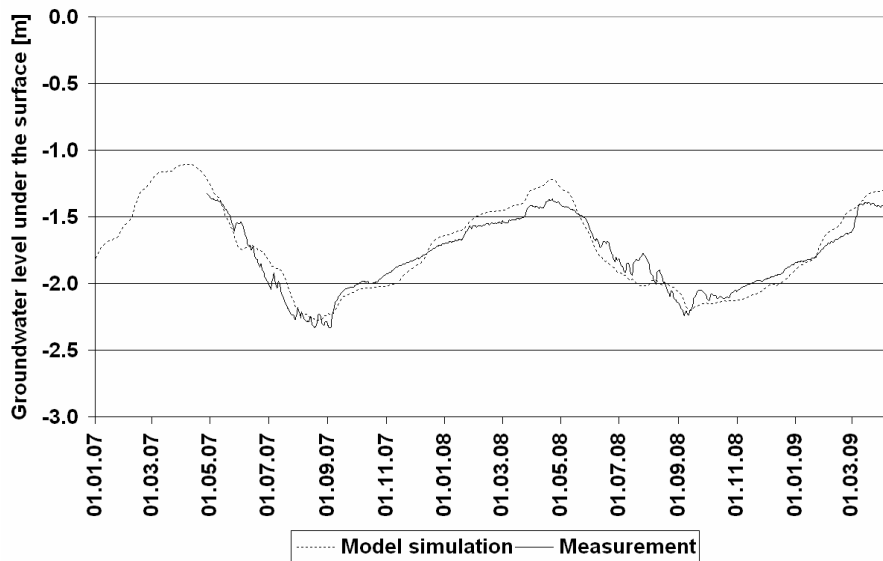
Figure 7. Comparison of measured and simulated groundwater level

Table 2 gives an overview of the obtained performance criteria.

Table 2. Various model performance criteria

Oak site	R^2	RMSE%	ME
Soil moisture (10cm)	0.73	14.91	0.69
Soil moisture (30cm)	0.83	11.95	0.80
Soil moisture (50cm)	0.79	13.52	0.77
Groundwater	0.92	5.03	0.88

Day-by-day comparison was used to analyse the deviations between the observed and simulated soil moistures and groundwater levels. We found no systematic deviation of the simulation from the observed values. The average deviation was –0.008 vol% for the soil water content and 0.009 m for the groundwater level.

Model calibration was accomplished primarily by trial-and-error adjustment of the storage capacity of vegetation and soil hydraulic parameters to minimize the root mean-squared error and optimize graphical fit between simulated and observed soil moisture content of each layer and groundwater level.

The storage capacity determined interception loss to a considerable extent. The value of *f* *(Equation 6)* was changed between 1.0 and 3.0 and finally was set to 1.5, opposed to the suggested 2.0 (Wattenbach et al. 2005). The storage capacity of canopy was 1.17 mm at *LAI* of 3.9, which was in good agreement with other study results. In Andre et al. (2008) the interception capacity of an oak dominated stand was 1.19 mm with *LAI* of 3.8. Rutter et al. (1975) and Dolman (1987) suggested 0.8 mm for oak stands. In the dormant season the storage capacity of stems and branches were not changed from the initial value of 0.5 mm, suggested by Larcher (1994). The value of the storage capacity of litter has been decreased during the calibration from 1.1 mm to 0.5 mm.

The α and n shape parameters of the soil water retention curves were slightly adjusted during the calibration.

Initially, the saturated hydraulic conductivity (K_S), estimated by the Rosetta Lite 1.1 software, was used for the root-zone (< 1.5 m) of the soil profile. Below the root-zone the mean of the results of the slug tests was used.

The calibrated K_S values varied between 2.9×10^3 mm/day in the upper most horizon and 0.9×10^3 mm/day at about 1 m depth. In the saturated zone the calibrated K_S value differed only slightly from the measured value.

Specific yield was used for estimating the bottom boundary flux in the Hydrus models via the water table fluctuation method. It was used for model calibration, since the magnitude of the bottom boundary flux was quite sensitive to the specific yield. The diagram of Loheide II. et al. (2005) suggested specific yield in the range of 0.03–0.10, based on the soil texture. During the calibration process the best fit with groundwater levels were achieved by lower values of specific yield. Finally, the calibrated value was 0.032.

3.2 Water balance components

3.2.1 Interception loss

According to the model, canopy interception was 27.7% and litter interception 7.6% of the rainfall amount during the study period, which was in good agreement with other study results (Führer 1994). The effect of evaporation during and after rainfall events raised the interception loss rapidly *(Figure 8)*.
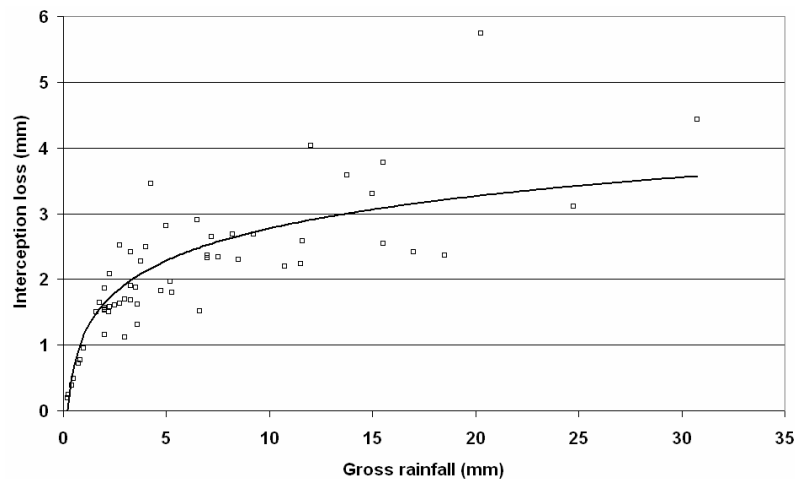

Figure 8. Relationship between gross rainfall and interception loss in the growing season of 2008

Although the amount of interception loss was larger in the growing season of 2008 (128 mm), than in 2007 (98 mm), the relative interception loss (% of precipitation) was slightly larger in 2007 (37.6%) than in 2008 (33.3%) due to occurrence of more frequent rainfall events in 2007 with low amount.

3.2.2 Actual transpiration and groundwater consumption

Actual transpiration was similar to the potential value in our experiment. This is not surprising, since the root system of the vegetation was in connection with the saturated zone via the capillary fringe throughout the year. Gazal et al. (2006) found the transpiration of a cottonwood forest was not limited at groundwater table depth of 1.5–1.8 m. Hence, transpiration of riparian vegetation responds less to changes in soil moisture because of their direct access to the groundwater table (Oren – Pataki 2001).

Groundwater consumption was determined by the simulated soil water content changes and capillary fringe dynamics of the Hydrus models. The depth of separation was the field capacity of the soil layer, containing the capillary fringe. According to the Hydrus model simulation, the groundwater consumption of vegetation was approximately 66% of the total simulated transpiration in the growing season of 2007 and 50% in 2008.

Relative extractable water (REW) was calculated for the upper 60 cm of the soil profile from soil hydraulic properties (Granier et al. 1999), namely water content at field capacity (W_{fc}), the actual water content (W) and permanent wilting point (W_{pwp}):

$$REW = \frac{W - W_{pwp}}{W_{fc} - W_{pwp}} \tag{5}$$

During the growing season of 2007 the REW declined almost continuously at the upper 60 cm of the soil profile, because of severe drought in summer. Accordingly, the proportion of groundwater consumption increased up to 90% for periods during late summer. In 2008 several rainfall events increased considerably the water content of the unsaturated zone, thus the groundwater consumption was less than in 2007 *(Figure 9)*.
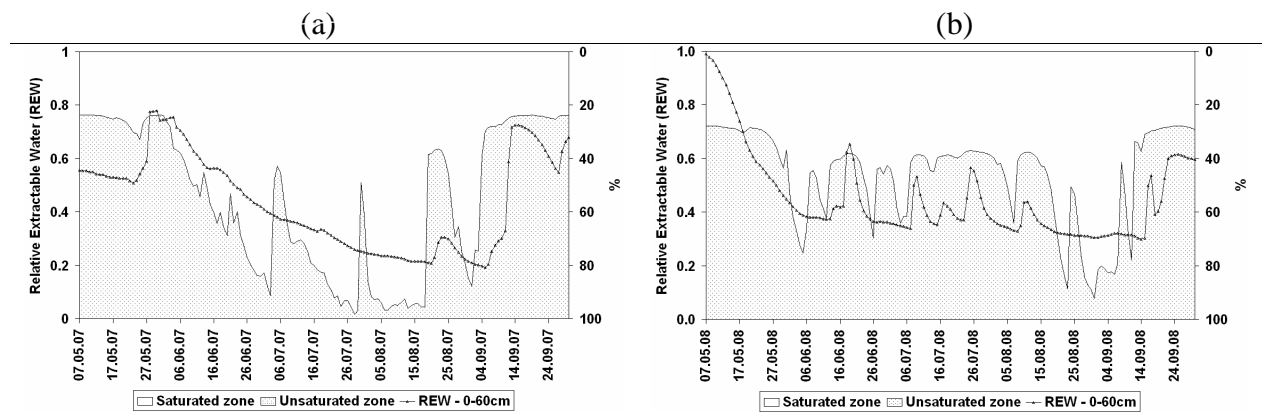
(a) (b)

Figure 9. Proportion of the modelled water uptake from the saturated and unsaturated zone and the relative extractable water (0-60 cm) during the growing season of 2007 and 2008

The groundwater fluctuation method showed that groundwater consumption was 69% of the total simulated transpiration in the growing season of 2007 and 44% in 2008. The daily groundwater consumption showed large fluctuation during the growing season and exceeded sometimes considerably even the daily potential transpiration *(Figure 10)*. Despite of the deeper groundwater level, groundwater consumption was higher in 2007 than in 2008. In 2008 large rainfall events interrupted often the continuous groundwater consumption of vegetation. The gaps in the groundwater consumption denoted the days with larger rainfall events.
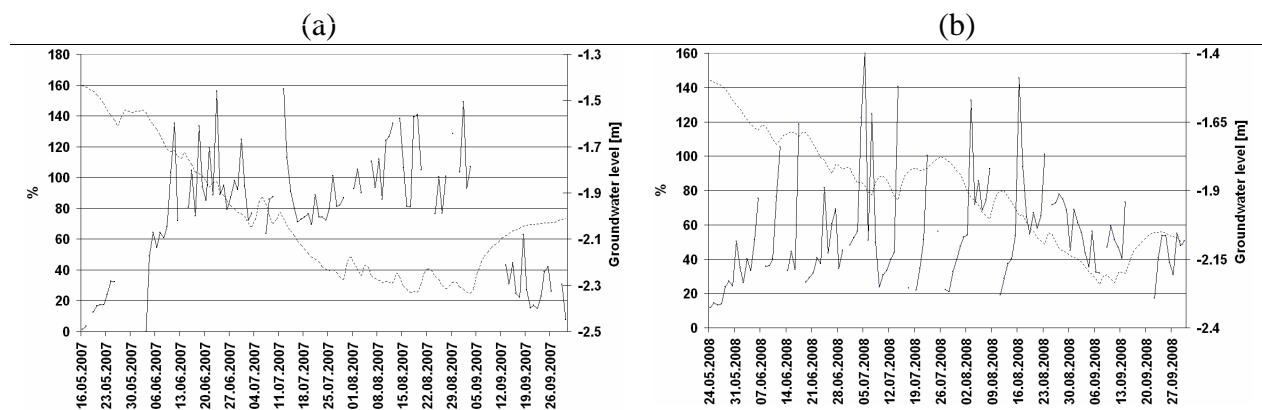
(a) (b)

Figure 10. Ratio of the groundwater consumption to the potential transpiration (solid line) and groundwater level (dotted line) in 2007 (a) and in 2008 (b)

The estimated groundwater consumptions of the groundwater fluctuation method were slightly different than the results of the Hydrus simulations. The differences between the approaches may be attributed to the slightly subjective determination of the minimum and maximum rate of groundwater supply in the groundwater fluctuation method. Namely, the values of Q_{net} are quite sensitive to atmospheric changes (e.g. clouds), which may have confounded the determination of the amount of groundwater supply. Besides, the water table daily net variation reflects the net variation of several fluxes (recharge, baseflow, evapotranspiration, subsurface flow), as a result, the estimated groundwater consumption probably includes some subsurface redistribution of water (Healy – Cook 2002). The determination of the daily groundwater consumptions from the soil water content profile of the Hydrus model simulations had also several uncertainties (e.g. position of the capillary fringe, root depth).

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According to the groundwater fluctuation method, the daily groundwater consumption varied between 0.8 and 5.8 mm, which is in good agreement with other study results. Bauer et al. (2004) obtained riparian ET rates of 0.06–4.3 mm/day (potential ET was between 150–200 mm) for different vegetation cover (trees, shrub, grass) and soil characteristics, where continuous groundwater level readings were used for the estimates (groundwater depths varied around 2 m from the surface). Schilling (2007) obtained transpiration rates in Iowa (USA) between 5.0 and 6.3 mm/day at a forest during mid July at groundwater depths between 0.9–1.2 m under the forest.

3.2.3 Actual soil surface evaporation

Model results showed that actual soil surface evaporation was only 3.7% of the evapotranspiration during the study period. The sum of the actual evaporation and the litter interception was 11.6% in our experiment. Forest floor evaporation, including litter interception, varied between 8 and 11% of the total evapotranspiration in deciduous forests during the growing season (Moore et al. 1996, Wilson et al. 2000).

During summer of 2007 actual evaporation was only 42% of the potential value due to the low water content of the upper soil layer, initiated by drought periods. During summer of 2008 the rainy weather allowed actual soil surface evaporation close to potential value.

3.2.4 Summary of the water balance analyses

The simulated water balance components for the vegetation periods between 2007.04.01–2007.09.30 and 2008.04.01–2008.09.30 are shown in *Table 3*. The intervals of uncertainties were determined by the root mean square errors, expressed in % of the mean observed variable.

Table 3. Estimated water balance components (mm) for vegetation periods of 2007 and 2008

Vegetation period	P	T_p	ET_a	I	T_a	E_a	Q_{net}	ΔS
2007	261	659	730±83	98±11	609±69	23±3	289±33	−180±20
2008	383	551	678±77	128±15	513±58	37±4	184±21	−111±13

P: precipitation, T_p: potential transpiration, ET_a: actual evapotranspiration,
I: interception, T_a: actual transpiration, E_a: actual soil surface evaporation,
Q_{net}: net groundwater inflow, ΔS: soil water storage change

3.2.5 Comparison of the results of the modelled and remote-sensing based evapotranspiration

Two large forest areas (E1 and E2) along the river Tisza were chosen for comparison with ET results of Hydrus simulation *(Figure 11)*.
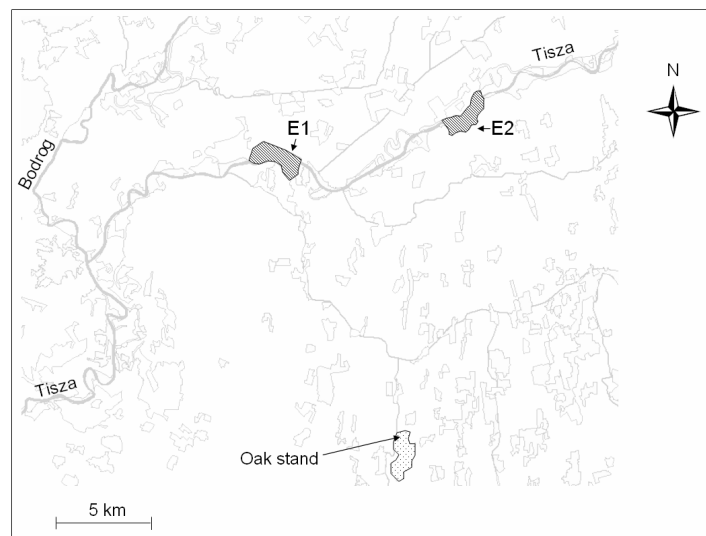

Figure 11: Location of the study plot and the chosen sites for comparison (E1, E2)

The E1 and E2 forest areas are located close to the river Tisza, characterized by shallow (1-–2 meter deep) and fluctuating groundwater level. We have selected the pixels, where the leaf area index was closest to the maximal value of the oak stand. ET of the vegetation period was compared with 4 and 5 pixels, respectively *(Table 4)*.

Table 4. The evapotranspiration and the average maximal leaf area index of chosen pixels of the two sample areas, compared to the model

Area	E1			E2		
	ET		LAI	ET		LAI
Growing season	2007	2008		2007	2008	
Pixel1	717	684	5.0	673	657	3.9
Pixel2	727	688	5.1	682	662	4.0
Pixel3	681	667	4.1	699	657	4.5
Pixel4	713	685	4.5	688	667	3.7
Pixel5	709	676	4.7	–	–	–
Average of pixels	709	686	4.7	680	661	4.0
Hydrus model	730	678	3.9	730	678	3.9

Evapotranspiration results of the Hydrus simulation were closer to the higher values of the remote-sensing based ET estimation. The deviation from the results of the remote-sensed based estimation was not larger than 4% from the mean of the sample area.

4 CONCLUSIONS

In this study, the water balance components of an oak stand was estimated for a two-year period (Spring 2007 – Spring 2009). The study site was located at the discharge part of the local groundwater flow system, characterized by shallow groundwater depth and groundwater inflow.

Water balance components were estimated by calibrating the Hydrus 1-D model to fit measured soil moisture and groundwater level. Groundwater supply from background – estimated by the water table fluctuation method – was applied as the lower boundary condition in the Hydrus models. Model simulation described the observed soil moisture and groundwater level relatively well, the root mean square errors RMSE varied between 11.95% and 14.91% for the soil moisture measurements and 5.03% for the groundwater level.

According to the Hydrus model, the estimated evapotranspiration resulted from transpiration (73%), interception loss (23%) and soil surface evaporation (4%) in the two-year study period. Canopy interception loss was 27.7%, while litter interception loss reached 7.6% of the precipitation. Actual transpiration was similar to the potential values, which was not surprising, since the root system of the vegetation was in connection with the saturated zone via the capillary fringe throughout the year. Soil surface evaporation was not significant.

The proportion of groundwater consumption was 58% of the total transpiration. During the dry growing season of 2007 the groundwater consumptions were significant with 66% of the total transpiration. Water supply from groundwater was found to be less important in the wet growing season of 2008 with 50%. Climate change projections predict that summer temperature may increase by up to four degrees by the end of this century in Hungary (Gálos et al. 2007). Increasing temperatures may raise the evapotranspiration demand, thus groundwater consumption of forests can be expected greater due to increased ET as long as the groundwater is available for roots for water uptake.

Groundwater consumption was computed also by the water table fluctuation method. We found that the groundwater fluctuation method provided slightly different groundwater consumption rates by 8,5%, than estimated from the Hydrus model simulations. The cause of the difference may be originated from the uncertain estimation of the groundwater supply from background, but probably also from the Hydrus model simulations (e.g. position of the capillary fringe, root depth). The remote-sensing based estimation of evapotranspiration was approximately 4% lower than the model based result of nearby similar sites.

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