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Comparison of Groundwater Uptake and Salt Dynamics of an Oak Forest and of a Pasture on the Hungarian Great Plain

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Abstract – The forest area in Hungary has increased during the last century from 1.1 to 2.0 million ha. The European Union supports further afforestation so roughly 15 –18 000 hectares might be planted each year, mostly on the Hungarian Great Plain. Water uptake of forests from groundwater can be significant in shallow groundwater areas of the Hungarian Great Plain especially in drought periods. Therefore forests can induce water table depression and subsurface salt accumulation above saline water table in areas with a negative water balance.

The impact of forests was examined by a systematic study on the Hungarian Great Plain. An oak forest and a pasture groundwater uptake and salt accumulation effect were compared at the stand scale. Under the forest the water table levels were roughly 0.5 m lower than under the pasture, and the groundwater uptake of the oak plot was more than twice as great. Larger forest groundwater use is not followed by a higher salt uptake. Therefore slight salt accumulation was measured both in the soil and also in the groundwater. Higher groundwater uptake may cause more significant salt accumulation under pronounced drought conditions of a warmer climate.

evapotranspiration / shallow groundwater / diurnal fluctuation / salt accumulation / forest

Kivonat – Egy alföldi kocsányos tölgyes és egy szomszédos gyepterület talajvízfelvételének és sódinamikájának összehasonlítása. Magyarország erdősültsége a 20. század folyamán 1.1 millió ha-ról 2.0 millió hektárra nőtt. Az Európai Unió támogatja az erdősítést, így évente megközelítőleg 15–18 000 hektár nagyrészt mezőgazdasági területet erdősítenek be az Alföldön. A felszínközeli talajvízszinttel rendelkező területeken, így a Nagyalföld jelentős részén is, az erdők talajvízfelvétele, főként a száraz periódusokban, igen nagymértékű lehet. Előbbiek miatt az erdők a talajvízszint süllyedését és egyes helyeken esetlegesen só akkumulációt idézhetnek elő a talajvízben és a talajvízszint fölötti talajrétegekben az erősen negatív vízmérlegű területeken.

Egy nagyalföldi mintavételi pontokat tartalmazó szisztematikus vizsgálat keretében kezdtük el keresni a fenti kérdésekre a választ. Jelen cikkben egy kocsányos tölgyes és egy szomszédos legelő talajvíz-felhasználását és só-felhalmozódásra gyakorolt hatását hasonlítjuk össze. A vizsgálatok szerint az erdő durván fél méterrel csökkenti a talajvízszintet és több, mint kétszeres a talajvízből történő vízfelvétele, mint a gyepvegetációnak. Az erdő nagyobb talajvíz-felhasználása viszont nincs arányban a sófelvételével, így mind a talajban, mind a talajvízben kismértékű só-akkumuláció tapasztalható. A

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klímaváltozás kapcsán a hosszabb száraz periódusokban előálló nagyobb párolgási kényszer (és nagyobb talajvízfelvétel) a mértnél sokkal jelentősebb sófelhalmozódást okozhat.

evapotranszspiráció / sekély talajvíz / napi ingadozás / só akkumuláció / erdők

1 INTRODUCTION

Significant afforestration is planned in Hungary (700 000 ha), and this plan is also supported by the EU (Andrasevits et al., 2005). The areas available for afforestration are generally less profitable for field crop production. Based on the analysis of the soil types of the formerly forested areas, Führer and Járó (2005) stated that the Hungarian Great Plain can be the most important region for afforestration. However the hydrological and climatic role of the forest is most critical in the Hungarian Great Plain. From a hydrological viewpoint, two basic situations are encountered:

- When the water table is deeper than the root zone (these are very critical sites for afforestration), and
- when groundwater can be a source of transpiration. In the later situation groundwater uptake of a forest is the most frequent theme of this research.

In the shallow water table areas, forest vegetation can change the water and salt balance of the soil (Nosetto et al., 2007) and these effects are manifested in the lowering of the water table (Major, 2002) and increase of salt concentration in certain soil and subsoil layers (Jobbágy and Jackson, 2004; Nosetto et al., 2007; Nosetto et al., 2008). In a shallow groundwater environment, the impact of a forest on groundwater and salt dynamics are reviewed by Szabó et al. (2012) specially focusing on the processes going on in the Hungarian Great Plain *(Figure 1).*

Forest evapotranspiration (sum of transpiration and interception) is generally higher than the evapotranspiration of neighbouring grasslands, because of the increased LAI (leaf area index) and root depth of the woody vegetation (Calder, 1998; Nosetto et al., 2005). These properties of a forest are especially true in the Great Plain with a subhumid climate, where the precipitation is less than the water demand of woody vegetation, so trees can survive arid periods if they can use groundwater resources as well (Ijjász, 1939; Magyar, 1961).

Móricz et al. (2012) compared the water balance of different land uses in Nyírség (Northeast part of the Hungarian Great Plain), and found that a common oak forest has approximately 30% more evapotranspiration (758 mm a^{-1}) than a neighbouring fallow land (623 mm a^{-1}). The difference is more significant (3 fold) in groundwater use of different vegetation types (oak: 243 mm a^{-1}, fallow: 85 mm a^{-1}). The groundwater consumption was close to 60% of the total transpiration in the oak forest and approximately 30% on the fallow plot. Groundwater consumption was approximately 40% less in the wetter vegetation period of 2008 than in the drier growing season of 2007, despite the fact that the groundwater level was deeper during the drier summer. Thus, during the drier period both vegetation covers relied considerably on the available groundwater resources.

Magyar (1961) analyzed the root growth of seedlings in a saline environment and found that in a moderately saline soil environment, roots of seedlings can reach 3.5 m down to the water table in three years, but roots of elms can be detected 5.15 m deep two years after planting.

Under a forest, the water table can be detected deeper than under grassland if the trees are able to reach it. The difference of the water table level is larger in the growing season (Ijjász, 1939). Jobbágy and Jackson (2004) stated that the groundwater level can be 75 cm deeper under a forest. On the basis of their measurements in shallow groundwater areas of Kiskunság, the researchers Szodfridt and Faragó (1968) found that forest vegetation generally lowers a water table 50–60 cm compared to herbaceous vegetation. But they also stated that on the sites where groundwater levels (in April) are found deeper than 2.5 m, only sparse herbaceous vegetation can survive under natural conditions. Major (2002) observed that under a coniferous forest compartment in Kiskunság, the water table can be 0.8–1.1 m deeper than under the neighbouring non-forested areas.

Szilágyi et al. (2012) analysed the evapotranspiration (determined by linear transformation of the MODIS daytime land surface temperature) in the Danube-Tisza Sand Plateau of the Hungarian Great Plain. According to land cover, the largest ET (about 505 mm a^{-1}) was found over deciduous forests where the regional annual precipitation was 550 mm. On some locations ET is estimated to be larger than precipitation. These groundwater discharge areas in many locations overlap with forest cover. Often the dense and deep root system of forests can tap the shallow groundwater level (if it exists), thus leading to a high ET rate, frequently exceeding the rate of precipitation which the area receives. In the groundwater discharge areas, the average annual ET for the forests is 620 mm a^{-1}, which is about 70–80 mm more than the mean annual precipitation rate of the region. This negative water balance can be maintained if forests create a local depression in the water table so as to induce groundwater flow directed toward them (*Figure 1*).

Detailed investigation of the afforestation in the Hungarian Great Plain is being carried out through the systematic study of all affecting factors, like climatic water balance, water table depth and salinity, tree species, subsoil layering and stand age (in the frame of the OTKA NN 79835 project). The aim of this paper is to describe the complex interrelation of these factors in such a way that the effect of planned new afforestations could be predicted.

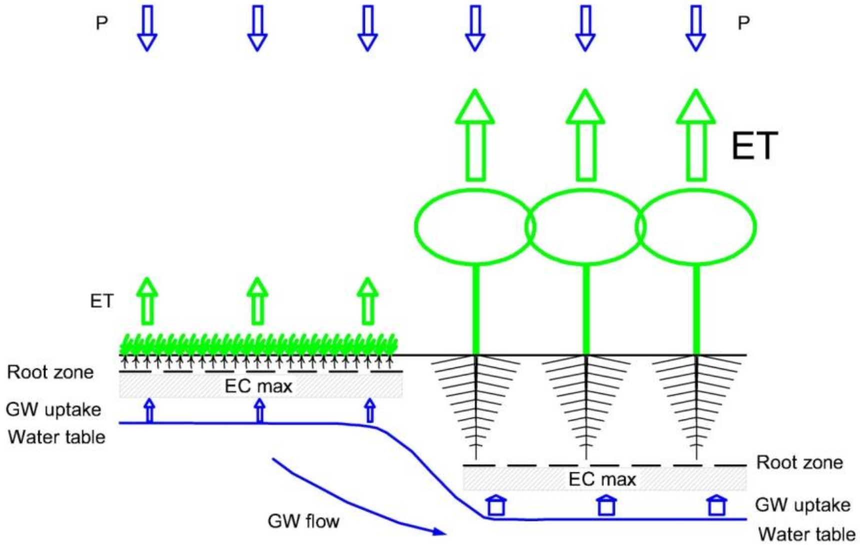

Figure 1. Impact of forest vegetation on water and salt balance of a shallow groundwater site (hypothetical model). ET evapotranspiration, P precipitation, EC (electrical conductivity), GW groundwater.

2 MATERIALS AND METHODS

2.1 Site description

Altogether 108 plots of forested and nearby non-forested land were sampled in the above mentioned project. At the stand scale, 18 representative forested and accompanied non-forested stands (from the 108) are monitored intensively. In this paper the dataset of two neighbouring plots (a common oak forest [60 years old, 22 m high closed forest] and a grass stand [without shrubs]) were compared next to Jászfelsőszentgyörgy (47 29' N, 19 46' E) in the very dry summer of 2012 (*Figure 2*). These vegetation types are very typical in the Hungarian Great Plain.

On historical land use maps, no forest cover could be found in the area between 1780 and 1914. Afforestation started after 1914 on the oak plot, but the pasture site was never forested. The area has a flat topography. The geological basis of the research area is fluvial sediments, mostly sand and silt.

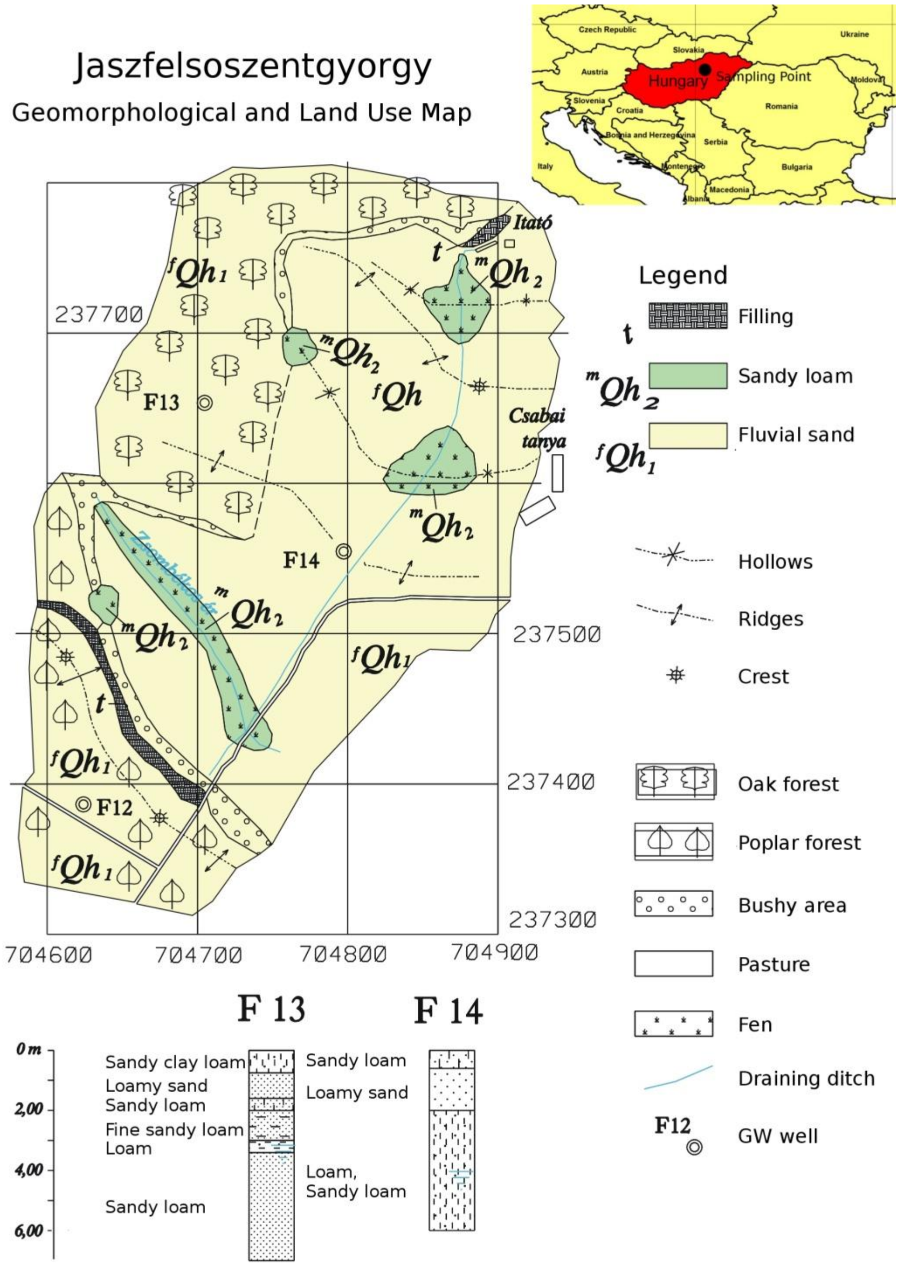

Figure 2. Geomorphological map with land use and location of monitoring plots with GW wells. Oak plot well is indicated by F13 and pasture plot well by F14.

2.2 Data collection

GW wells are installed in the common oak forest (F13) and in the grass covered pasture (F14) 7 and 6 m deep in the neighbourhood of Jászfelsőszentgyörgy (located in northern part of

Great Plain). The geological layers of the plots can be seen in *Figure 2*. GW wells were instrumented with vented pressure transducers (www. dataqua.hu) and a meteorological station was placed in the neighbourhood on a pasture in the first days of July, 2012. Pressure transducers take readings at 15 minute intervals (for calculation of ET from groundwater) and the meteorological station collects standard meteorological parameters (temperature, relative humidity, net radiation, wind speed and precipitation) every 5 minutes (for calculation of reference ET). Only the first month of dataset is adequate for further analysis because of an error in the data collectors.

Water table levels from the surface and precipitation can be seen in *Figure 4* as a representation of the collected dataset.

At both sites a mineral soil was sampled at depths of 10, 30, 50, 70, 90 cm (20 cm intervals) and at 50 cm intervals down to the depth of the GW wells. Electrical Conductivity was determined in a 1:2.5 soil-water extract (for calculation of salt content). Soil texture was specified according to particle size distribution determined by the pipette method. Groundwater was also sampled for electrical conductivity, measured by a conductivity meter.

2.3 Evapotranspiration calculation method

In shallow groundwater areas, vegetation can take up water both from unsaturated or saturated zones. If groundwater was used by vegetation, a diurnal signal can be detected in the water table hydrograph (White 1932, Gribovszki et al. 2010). The amplitude of the signal depends on the soil texture and magnitude of groundwater uptake (*Figure 5*). The riparian-zone groundwater ET estimation technique of Gribovszki et al. (2008), based on the diurnal fluctuations of the groundwater levels (by further developing of the original White (1932) method), were used.

The ET-estimation method employs the water balance equations (written for the saturated zone)

$$\frac{\partial S}{\partial t} = S_y(t,h)\frac{\partial WT}{\partial t} = Q_i - Q_o - ET_{gw} = Q_{net} - ET_{gw} \tag{1}$$

where dS / dt [L^3T^{-1}] is the time-rate of change in groundwater storage (S), h [L] the average groundwater level (above reference), S_y the specific yield, Q_i, the incoming discharge [L^3T^{-1}] to the unit land area, and Q_o, the outgoing discharge from the unit land area [L^3T^{-1}].

The net supply/replenishment rate is the difference of the incoming and outgoing discharges to and from, $Q_{net} = Q_i - Q_o$, [L^3T^{-1}]. ET_{gw}, is evapotranspiration (directly or indirectly) from the groundwater.

In order to obtain the net supply rate (Q_{net}), an empirical method (using characteristic points) was employed (*Figure 3*):

- The maximum of Q_{net} for each day was calculated by selecting the largest positive time-rate of change value in the groundwater level readings, such as $Q_{net} = S_y \Delta h/\Delta t$.
- The minimum of Q_{net} was obtained by calculating the mean of the smallest time-rate of change in h taken in the predawn/dawn hours. The averaging is necessary in order to minimize the relatively large measurement error when the changes are small.
- The resulting values of the Q_{net} extrema then were assigned to those temporal locations where the groundwater level extrema took place.
- It was followed by a spline interpolation of the Q_{net} values to derive intermediate values between the specified extrema (Gribovszki et al. 2008).

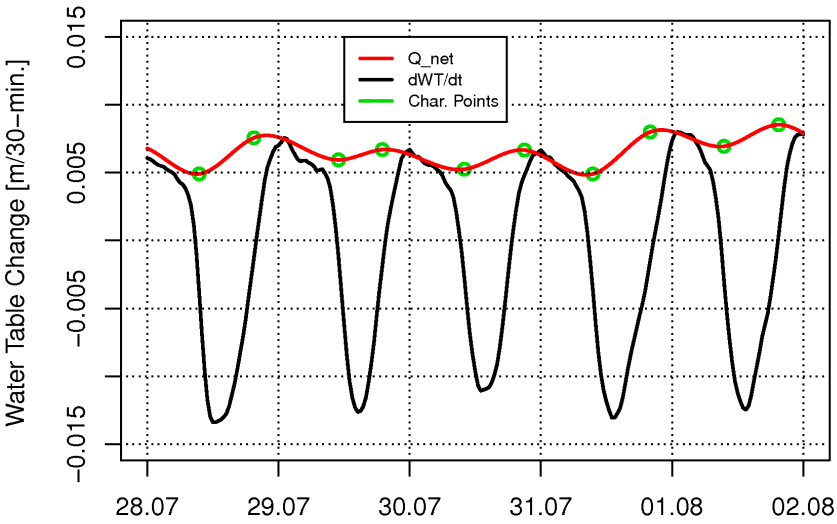

Figure 3. Graphic representation of the empirical method,
Q_{net} is replenishment rate, dWT/dt is the time rate of change of water table,
Char. Points is the characteristic points of replenishment rate

Finally, after calculating the Q_{net} values, the ET_{gw} rates can be obtained by rearranging the former water balance equation as

$$ET_{gw} = S_y\left(Q_{net} - \frac{dh}{dt}\right) \tag{2}$$

S_y values (as readily available specific yield) were estimated on the basis of the texture class of soil layers in the depth interval of diurnal fluctuations according to Loheide et al. (2005). The soil texture class (similar for both stands) was loam and sandy loam in the depth of the water table. Therefore S_y is between 0.045–0.055 roughly 0.05.

ET values Penman-Monteith ET (*PM_ET*) rates (for a grass reference surface) were calculated from the meteorological dataset as a comparative reference (Allen et al., 1998).

3 RESULTS AND DISCUSSION

3.1 Water table levels and fluctuation

Water table depression in the forest next to an adjacent pasture together with a significant difference in the amplitude of diurnal fluctuations suggested an increased groundwater use of the forest (*Figure 4*).

Differences in water table levels from the surface were 0.44 m on average during July 2012 (*Figure 4*). In contrast when groundwater levels are expressed in absolute values (a.s.l) the difference became 0.9 m (because of the lower elevation of the oak stand). Both of the differences mean a depression in water table under the forest. The magnitude of the depression was similar to the water table drop determined by Nosetto et al. (2007) on a planted oak forest and adjacent grassland in the Hortobágy region (0.26–0.60 m) and those determined by Móricz et al. (2012) by comparing a common oak stand and a neighboring fallow plot in Nyírség (in a dry period of the growing season 0.5–0.6 m).

The sinking of the water table was similar during the sampled period (0.37 m/month for oak and 0.35 m/month for pasture). It should be noted that the period analyzed was after a dry spring. Therefore the water table was almost in its lowest position. (Therefore we are close to the very end of the general groundwater recession curve, where further decay is very slow).

Rainfall interrupted the fluctuations at both places (e.g. July 11) but this is probably not the effect of a surplus recharge to the groundwater (because the water table was relatively deep) nor a cessation of groundwater use of vegetation (*Figure 4*).

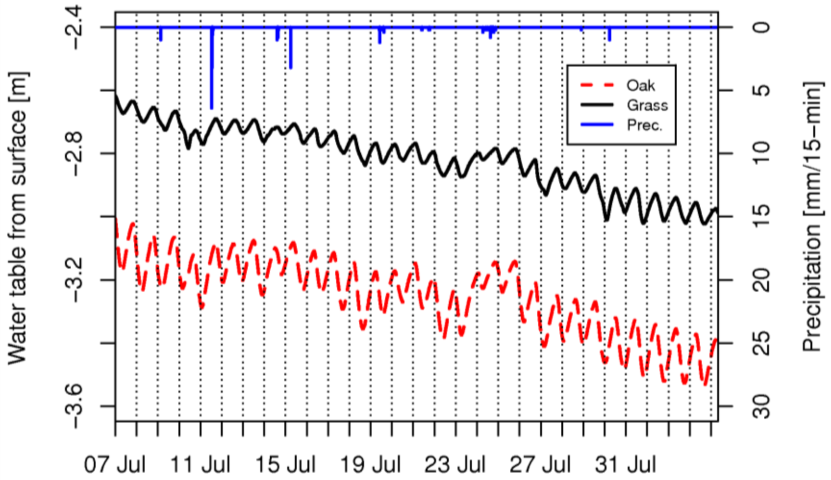

Figure 4. Water table from the surface under the oak (forest) and grass (pasture) sites (07. 07. 2012. – 05/ 08/ 2012.)

The amplitude of groundwater fluctuation for a forest is more than twice as large (16/2 cm) than for a pasture (7.2/2 cm) (*Figure 5)*. The appearance of a diurnal signal under a pasture shows us the groundwater uptake of grass vegetation. The magnitude of the fluctuation has a strong connection to groundwater use (Soylu et al. 2012) so it shows us the more significant groundwater use of a forest (because the soil textures of the two plots are similar: sandy-loam, loam). The magnitude of the fluctuation was higher than calculated by Nosetto et al. (2007) (5.5 cm on average for oak forest), but similar to that determined by Móricz et al. (2012) (14 cm for an oak forest and 2 cm for the fallow plot in dry periods) for similar soil types.

The time of the maximum and minimum groundwater levels were the same for both land covers (9h for max. and 20h for min.) validating that the inducing effect is the same (*Figure 5*).

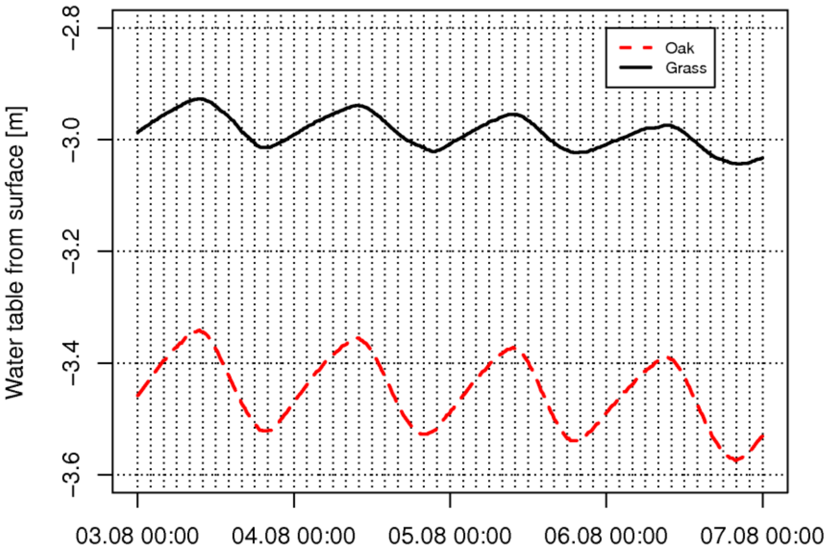

Figure 5. Diurnal fluctuations in water table levels comparing an oak (forest) and a grass (pasture) site

3.2 ET_{gw} values for an oak and a pasture site

Using the empirical ET estimation technique of Gribovszki et al. (2008), the groundwater uptake of different vegetation types, were calculated in a very dry period of summer 2012.

Figure 6 shows *ET* rates with 30-min frequency and in *Figure 7 ET* rates with daily frequency are shown.

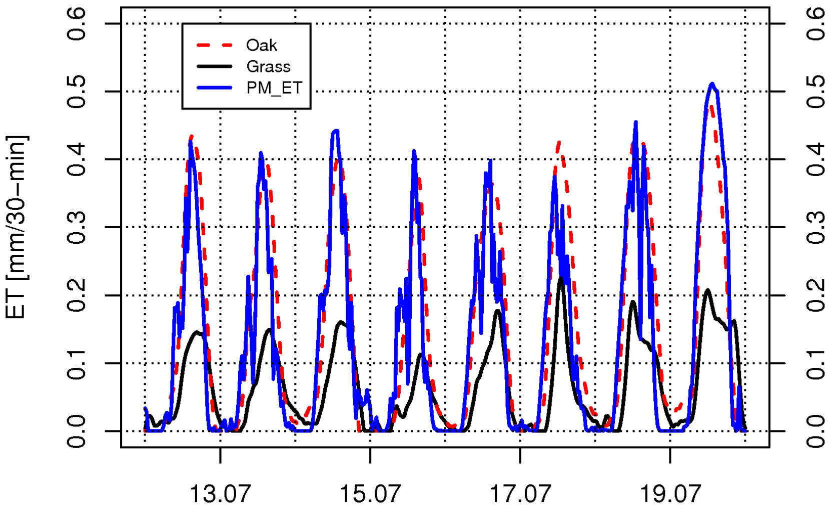

Figure 6. Calculated ET rates with 30-min frequency

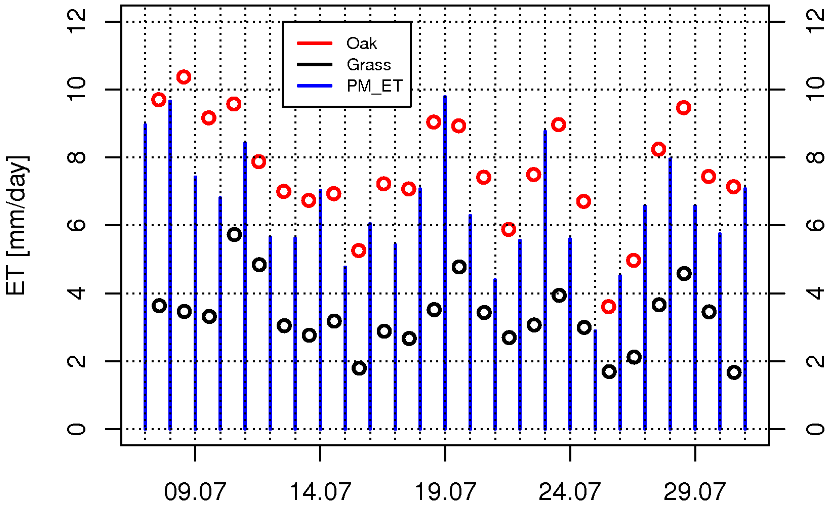

Figure 7. ET rates aggregated to a daily scale

ET rates have the following characteristics:

Groundwater uptake of an oak stand (mean: 7.5 mm/day) is a bit higher than *PM_ET*, (mean: 6.6 mm/day). Pasture (grass) ET_{gw} (mean: 3.5 mm/day) is less than half of the oak.

A rate higher than the potential rate values for oak can be found because the potential ET value was calculated for a grass reference surface. If calculation of potential ET had been conducted for rougher surface conditions and for higher LAI of the forest, the ET values would have been higher because of the greater atmospheric and canopy conductance of the forest canopy.

The daily groundwater uptake seems to be great, but the data seem to be acceptable taking into account that the period of analyses was very hot and till July of 2012 soil profile had already lost almost all of the moisture stored in preceding periods and all around there is a dry and warm environment. (Therefore the oasis effect can enhance *ET*).

As a comparison, ET values of Nosetto et al. (2007) in Hortobágy determined a 1.9 mm/day (up to 3.2 mm/day) groundwater ET for an oak forest on the basis of diurnal fluctuation of the water table. In that study the groundwater levels were significantly lower (on average 5 m) and the measurement period was in autumn. Therefore the higher values are possible in our case. In contrast using a diurnal method Butler et al. (2007) obtained groundwater ET rates of 2.9–9.3 mm/day for mixed vegetation types based on continuous groundwater level readings at groundwater depths between 0.3 and 3.4 m from the surface. Therefore calculated groundwater ET rates were close to total ET as in our case.

It must be noted that determination of readily available S_y is a weak point in all diurnal signal based ET estimation methods. Therefore the above determined ET values are not absolutely accurate, but the ratio of ET for different land covers is more accurate.

The correlation values between *PM_ET* and estimated groundwater ET rates are the following (*Table 1*).

Table 1. Correlation coefficients (r) between reference PM_ET and estimated ET_{gw} values

Stand	30-min scale	Daily scale
Oak-PM	0.938***	0.853***
Pasture-PM	0.816***	0.743***

Oak-PM means correlation between ETgw of Oak site and reference ET (PM_ET)
Pasture-PM means correlation between ETgw of Pasture site and reference ET (PM_ET)
*** Signif. code, p-value is less than 0.001

The stronger correlations (also for 30-min and daily scales) between *Oak_ET* and *PM_ET* showed that during the analyzed period these parameters are very similar. It means that *Oak_ET* reached the magnitude of potential ET and the water used for *ET* was mostly consumed from groundwater according to the meteorological constraint because there is no usable soil moisture in the soil column in this very dry period. The better correlation of pasture at a 30-min scale means that the diurnal shape of the two curves is similar, but the lower correlation for the daily scale shows a lower correspondence of *Pasture_ET* to meteorological factors. (Probably the root system of grass is not as adequate for as much groundwater uptake as that of the forest).

3.3 Salt Dynamics

Specific electric conductivity, which is strongly correlated with salt content, was measured to evaluate salt accumulation (*Figure 8*). The greatest difference in soil salt content between two land use types was detected in the upper part of the soil and at a depth of 350 cm. The specific conductivity values were 127 and 70 µS/cm higher in the soil of an oak forest at that depth. As a comparison, conductivity values measured by Nosetto (2007) in a similar oak and grassland comparison in Hortobágy) were generally 2–5 times higher than in this study. The vertical profile distribution was different in Hortobágy (Nosetto 2007) showing significantly higher conductivity values for grass in upper soil layers, which cannot be detected in Jászfelsőszentgyörgy. The higher conductivities of lower soil layers (above the groundwater) for oak forests showed a similar tendency at Jászfelsőszentgyörgy and Hortobágy.

The salt content of the groundwater was also slightly greater under the oak plot. (The conductivities of groundwater are: oak-1023, pasture-960 µS/cm). The differences do not mean any problem for forest vegetation productivity and vitality, but salt accumulation induced by climate change can be a long term effect of afforestration in these kinds of soils and hydrological combinations. Nosetto et al. (2007) also detected a higher conductivity of groundwater under an oak forest than under grassland in Hortobágy, but the absolute magnitudes were significantly higher at 4900 µS/cm and 2000 µS/cm under an oak forest and grassland.

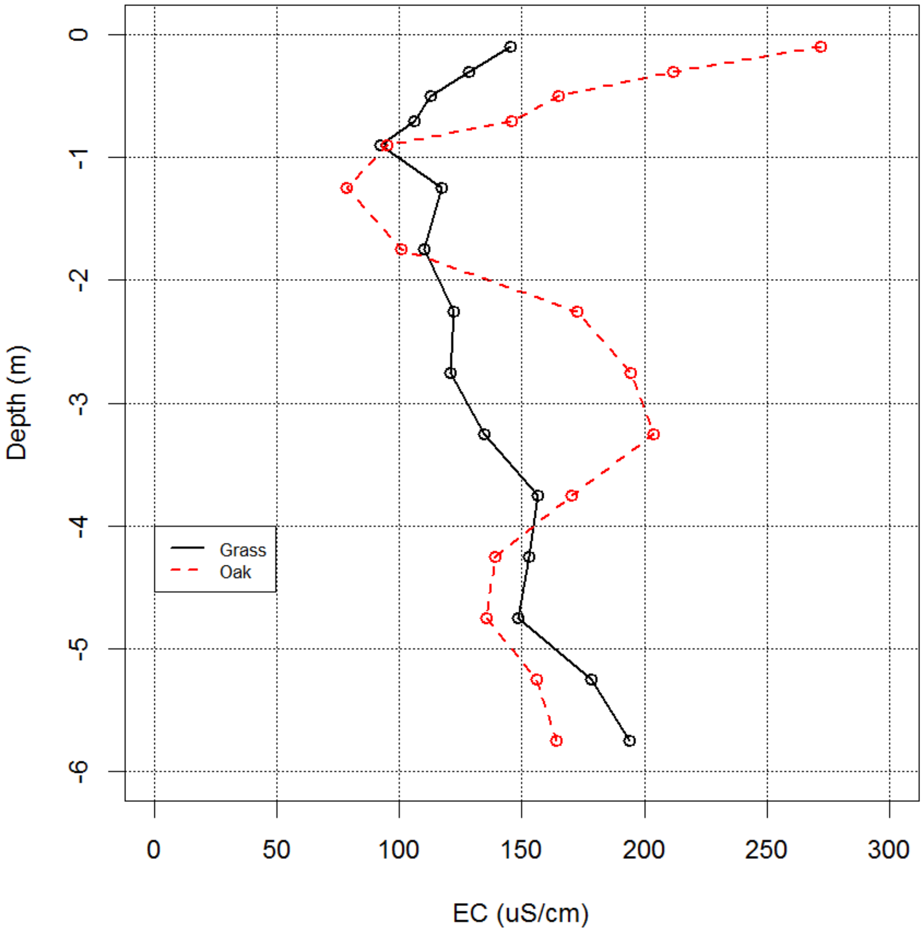

Figure 8. Electrical conductivity (EC) profile under the pasture and oak forest

4 CONCLUSIONS

Hydrological characteristics of earlier land uses during the last century (grassland and arable land) in the Great Plain are significantly different from those of the forest. A larger biomass needs a higher amount of transpiration which can be taken up from the groundwater by the deeper root system of the forest if precipitation is insufficient. Increased groundwater uptake results in a depression of the water table under forest covered sites in areas with a shallow groundwater table.

The larger amount of forest groundwater use is not parallel with salt uptake. Therefore salts can accumulate in both the soil and groundwater. The measured differences in salt content are small compared to similar research results for clayey soils (Nosetto et al. 2007). However in the long run, and taking into account longer dry periods induced in the future by climate change, this process can result in the decline of biological production of a forest.

Table 1 summarizes the results of these processes comparing an oak forest and neighboring pasture on the basis of the dataset of this study.

Table 1. Summary of impacts of an oak forest on water and salt dynamics (EC=electric conductivity; GW=groundwater)

Parameter	Oak	Pasture	Process
EC GW (µS/cm)	1023	960	Salt cc. of GW increases
EC soil 0–20 cm (µS/cm)	272	145	Salt accumulation in upper soil layer
EC soil 300–350 cm (µS/cm)	204	134.9	Salt accumulation in lower soil layer
GW level (asl [mBf])	101.5	102.4	Water table depression (0.9 m)
Water table depth (m from suface)	3.26	2.82	Water table difference from surface (0.44 m)
Diurnal signal amplitude (cm)	16	7.2	Stronger diurnal signal of oak (ratio 2.2)
ET from GW (mm/day)	7.6	3.3	Greater GW uptake of oak (ratio 2.3)

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