Environ Earth Sci (2017) 76:675
DOI 10.1007/s12665-017-7002-1

ORIGINAL ARTICLE

Factors controlling the daily change in groundwater level during the growing season on the Great Hungarian Plain: a statistical approach

Péter Csáfordi[1] · **András Szabó**[2] · **Kitti Balog**[1] · **Zoltán Gribovszki**[3] · **András Bidló**[4] · **Tibor Tóth**[1]

Received: 30 November 2016 / Accepted: 28 September 2017 / Published online: 12 October 2017

Abstract The phenomenon of diurnal fluctuation in the groundwater level (GWL) often reflects the water uptake by plants. The rate of evapotranspiration from the groundwater (ET_{gw}) can be calculated from the daily rate of change in GWL, but several factors may influence the vertical groundwater dynamics. The occurrence of diurnal fluctuation and the daily rate of change in GWL were determined in 20 monitoring wells on the Great Hungarian Plain with different vegetation cover (*Quercus robur* L., *Robinia pseudoacacia* L., *Populus* × *euramericana* and unforested control sites) and with differences in the water table depth (WTD) and in soil and salinity characteristics. ET_{gw} was calculated for eight selected sites. Forest vegetation significantly increased the occurrence of diurnal fluctuation (8 out of 11 cases), and the mean daily change in GWL multiplied by the specific yield (S_y) was 2.2 times higher for forest sites than for the unforested control sites. The median daily change in GWL showed a significant negative correlation with S_y, where the vegetation effect was manifested as ET_{gw}-induced diurnal fluctuation. A significant correlation was obtained at each monitoring well between the meteorological parameters controlling the evaporative demand and the daily rate of change in GWL. A reduction in groundwater uptake after rainfall events and increasing groundwater consumption during dry periods were also revealed. A significant positive correlation was found at some study sites between the daily change in GWL and WTD, and between ET_{gw} and the leaf area index (LAI). Mean ET_{gw} was 8.2 mm day^{-1} for oak stand and 0.4 mm day^{-1} for black locust stand, while it ranged from 1.7 to 6.0 mm day^{-1} for the four poplar stands, which may reflect the variability in water demand, LAI, groundwater and soil characteristics.

Keywords Diurnal fluctuation of water table · Evapotranspiration · Forest vegetation · Soil texture · Meteorological parameters

✉ Péter Csáfordi
csafordi.peter@agrar.mta.hu

[1] Institute for Soil Sciences and Agricultural Chemistry, Centre for Agricultural Research, HAS, Herman Ottó út 15, Budapest 1022, Hungary

[2] Forest Research Institute, National Agricultural Research and Innovation Centre, Frankel L. út 1, Budapest 1027, Hungary

[3] Institute of Geomatics and Civil Engineering, Faculty of Forestry, University of Sopron, Bajcsy-Zsilinszky u. 4-6, Sopron 9400, Hungary

[4] Institute of Environmental and Earth Sciences, Faculty of Forestry, University of Sopron, Bajcsy-Zsilinszky u. 4-6, Sopron 9400, Hungary

Introduction

Short-term changes in the groundwater level (GWL) are an important issue not only for the quantification of available water resources, but also for determining the permissible rate of water use and for the eco-hydrological and hydrogeological characterization of the given region or watershed (Gribovszki et al. 2010). Early studies reported daily variations in GWL due to air pressure fluctuations (Salama et al. 1994) and temperature-induced pressure changes (Turk 1975). The main reason for changes in aquifer storage, the most relevant process for the present study, is the dynamics of water discharge (extraction) and recharge (redistribution) at a given location in the soil. According to the review of Gribovszki et al. (2010), several natural or artificial processes might be responsible for changes in aquifer storage. Natural driving forces, for example, are the response to rainfall events (Ward 1963; Zhang and Schilling 2006) and tidal effects, while artificial reasons are the operation of hydroelectric plants and municipal well fields.

Vincke and Thiry (2008) pointed out that the daily net change in GWL reflected the net variation in several fluxes, such as recharge, baseflow (groundwater seepage into a stream channel), evapotranspiration from the groundwater (ET_{gw}) and from the capillary fringe, and net subsurface flow. However, the present study on the driving forces and control factors of the daily change in GWL focused on recharge and water extraction, mostly induced by evaporation and transpiration.

In most cases, air temperature and solar radiation are considered as the main inducing factors for the daily change in shallow GWL (Gribovszki et al. 2010). de Ochoa and Reinoso (1997) investigated the direct (higher air temperatures increase the rate of evaporation due to the warming of the soil) and indirect (higher temperatures increase the vegetation transpiration up to a given point, at which the plants close their stomata and transpiration ceases) effects of the air temperature on the water table. Both processes reduce the water table depth (WTD) during a given day. They observed that shallow GWL fluctuations can also be explained by changes in temperature.

The special dynamics of the short-term change in the water table during the growing season is known as diurnal fluctuation, which is detected on the basis of high-frequency time series. The phenomenon was first described by White (1932), who observed a decline in the daytime, beginning at about the same hour every morning, and a rise at night starting at about the same hour every night. He found evidence of the effect of evaporation and especially of plant transpiration on the vertical groundwater movement, because no diurnal fluctuation was detected in areas without vegetation cover and where WTD was large. The identification of the direct link between the rate of change in GWL and ET_{gw} led to the development of the basic principle of ET_{gw} estimation on the basis of diurnal fluctuation (White 1932), and later several authors used the original model or elaborated their own methods to calculate the rate of ET_{gw}, as reviewed by Gribovszki et al. (2010) and Fahle and Dietrich (2014).

Szodfridt (1990) drew attention to the fact that the forest–groundwater relationship could only be reliably assessed if the water demand of different tree species and age groups was taken into account. According to Hatton and Wu (1995), the water uptake by trees at hydrological equilibrium (e.g. when soil water is unlimitedly available) is linearly related to their leaf area. Forest ET_{gw} is generally higher than the ET_{gw} of adjacent grasslands due to the increased leaf area index (LAI) and root depth of woody vegetation (Calder 1998; Nosetto et al. 2005; Móricz et al. 2012), resulting in higher groundwater consumption. The relationship between the occurrence of diurnal fluctuation, WTD and its availability for plant roots was clearly proved by Fan et al. (2014).

Differences in soil texture play an important role in determining the water balance (e.g. percolation, groundwater recharge, capillary rise and ET_{gw}) across the region. Several authors revealed the importance of soil texture in the variability of GWL (Ward 1963; White 1932). The rate (velocity, height) of capillary rise of water in soils showed inverse proportionality with the pore diameter of the soils and is highly dependent on particle size distribution, porosity, clayiness (hygroscopicity), upper limit of plasticity according to Arany, organic matter content and adsorbed Na ion content (Di Gléria et al. 1962). The results of Wang and Pozdniakov (2014) confirmed the significant effect of the specific yield (S_y) and hydraulic conductivity of the aquifers on the amplitude of diurnal fluctuation.

The term soil salinity designates a condition, in which the soil water contains a soluble salt with a concentration likely to be harmful to plants due to the increased osmotic potential of the soil solution and the toxicity of specific ions. Salinity may directly influence the water uptake of plants and the hydrological processes of infiltration and redistribution, and may cause additional plant stress (Saxton and Rawls 2006). An increase in salinity alters the osmotic conditions, resulting in a decline in plant transpiration in the daytime (Akram and Liaghat 2010). Salinity might be an inhibitory factor for forest growth and water uptake, and diurnal fluctuation might also decline due to the reduced rate of ET_{gw} (Benyon et al. 1999; Silberstein et al. 1999; Thorburn 1997).

In the light of future climate change, finding the ideal tree species and sites for afforestation objectives on areas where the precipitation is less than the water demand of woody vegetation is a great challenge, since trees can only survive dry periods if they can access and take up groundwater (Ijjász 1939; Magyar 1961). Considering that water uptake by vegetation is a major factor inducing the diurnal cycle of GWL, analysing the ET_{gw}-driven changes in GWL could help to quantify the water demand of plant species. The present paper investigates daily changes in GWL on the Great Hungarian Plain, which has a subhumid climate interrupted by dry periods, in order to gain a better understanding of water uptake processes in the unconfined and unsaturated zone and to provide data for the ongoing afforestation campaign (National Afforestation Programme).

The main objectives of the study were to

1. compare monitoring sites and categories (vegetation cover and soil texture) based on the occurrence of the

phenomenon of diurnal fluctuation and the rate of daily changes in GWL;
2. reveal which site characteristics and meteorological parameters have a significant effect on the rate of daily changes in GWL;
3. calculate ET_{gw} under different vegetation covers. The idea of primarily investigating diurnal changes in GWL instead of ET_{gw} is similar to that followed by Soylu et al. (2012), who based their ET_{gw} calculation method on the relationship between the diurnal range of GWL fluctuation and ET_{gw}.

Figure 1 summarizes hypotheses relating to the groundwater dynamics induced by different factors. Note that in this study the rate of daily change in GWL (cm) means the difference between the daily minimum and maximum of GWL, involving either (1) a near-linear increase or decrease or (2) a stepwise decrease or (3) regular fluctuation (amplitude in cm) as first described by White (1932) or (4) irregular variability (subdaily fluctuation) in GWL.

Materials and methods

Site description

The study sites (Table 1) were part of the monitoring network established on the Great Hungarian Plain in the framework of the National Scientific Research Programme (OTKA NN 79835, Hungary). The network sites were selected using geographic and soil maps (Kuti 1981, 1982, 1984; Laborczi et al. 2016; Pásztor et al. 2016) based on parameters which influence the accumulation of salts, i.e. WTD, groundwater salinity and texture. Forestry databases (Forestry Web Map) describing tree species and stand age were also used.

The study sites were located in four geographical regions (Fig. 2). The topographic conditions were characterized as alluvial plains and fluvial terraces with low average relief (below 5 m km^{-2}) (North Alluvial Plain, Central Tisza region, Hajdúság) and alluvial plains with aeolian landforms with higher relief (above 10 m km^{-2}) (Nyírség). From west to east, the main watercourses were the Galga River, Zagyva River, Hajta Stream, Tarna River, Tápió River, Tócó Stream, Kondoros Stream, Derecskei-

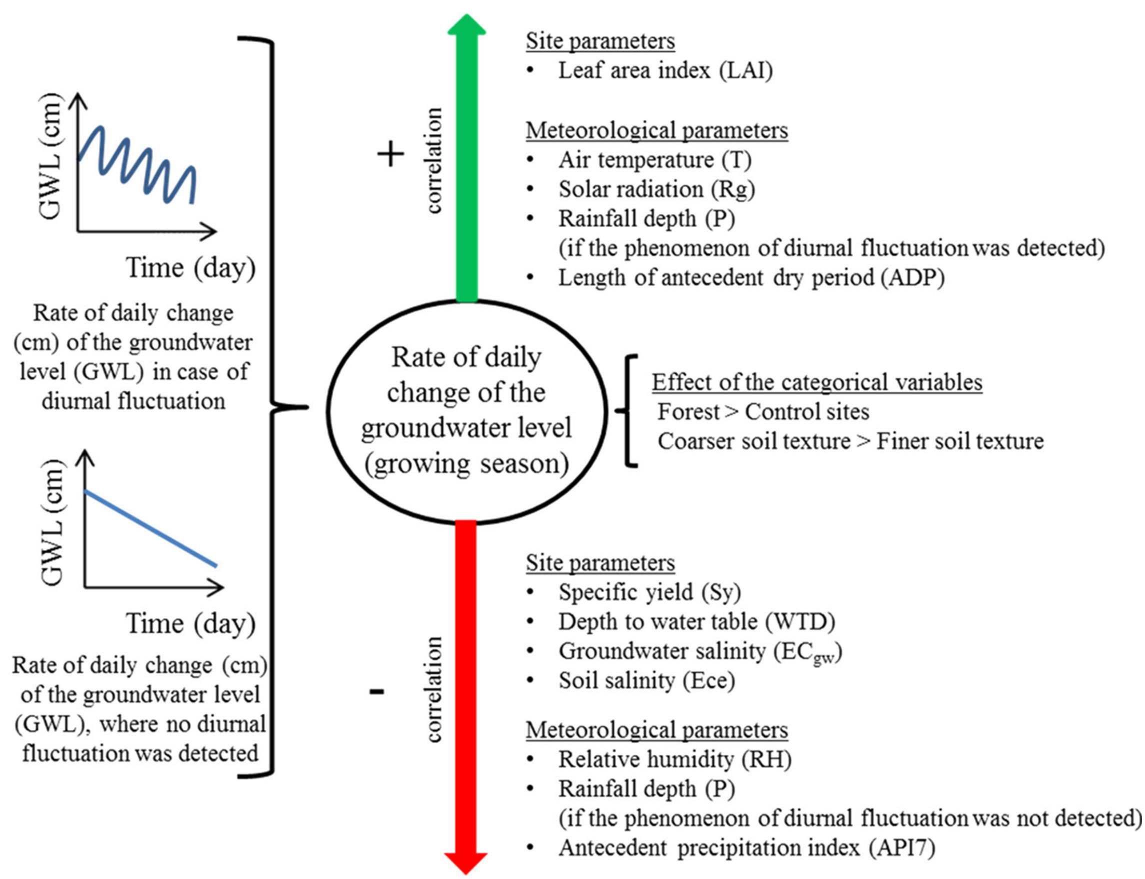

Fig. 1 Hypotheses concerning the sign of correlations between the rate of daily change in GWL, site and meteorological parameters and the effects of vegetation cover and soil texture on the rate of daily change in GWL

Table 1 Basic characteristics of the study sites

Monitoring wells (location, No.)	Coordinates [elevation; m a.s.l.]	Vegetation cover	Stand age (years)	Depth to water table (at time of well drilling) (m) [mean depth to water table during the study period; m]	Soil texture	Ground water salinity (at time of well drilling) (mg dm^{-3})
Nyírbogát 2	47°47′3.82″N 22° 1′41.79″E [155.0]	Poplar	21	3.25 [3.0]	Loamy sand (LS)	466.6
Nyírbogát 3	47°47′4.14″N 22° 1′49.70″E [155.6]	Control (ploughed field)	n.r.	2.5 [2.6]	Sand (S)	599.0
Mikepércs 4	47°27′29.14″N 21°39′31.25″E [109.1]	Oak	43	2.9 [2.6]	LS	807.0
Mikepércs 5	47°27′25.75″N 21°39′22.20″E [108.0]	Control (meadow)	n.r.	2.1 [1.7]	LS	435.8
Jászjákóhalma 6	47°31′44.36″N 20°0′58.78″E [95.4]	Black locust	16	4.0 [2.5]	Sandy loam (SL)	1792.0
Jászjákóhalma 7	47°31′41.34″N 20°0′56.10″E [95.9]	Control (ploughed field)	n.r.	5.5 [3.3]	SL	1071.4
Jászberény 9	47°27′44.44″N 19°52′11.75″E [108.0]	Control (ploughed field)	n.r.	8.1 [7.0]	LS	308.5
Jászberény 53	47°27′44.93″N 19°52′39.26″E [106.3]	Black locust	23	6.3 [6.1]	LS	681.0
Jászfelső-szentgyörgy 12	47°28′40.68″N 19°46′21.02″E [105.4]	Poplar	16	3.1 [2.5]	SL	753.9
Jászfelső-szentgyörgy 13	47°28′50.82″N 19°46′25.88″E [105.7]	Oak	62	3.1 [2.5]	SL	658.6
Jászfelső-szentgyörgy 14	47°28′45.53″N 19°46′28.10″E [105.4]	Control (meadow)	n.r.	3.8 [2.5]	LS	597.1
Hajdúsámson 21	47°37′6.77″N 21°47′55.91″E [139.6]	Control (ploughed field)	n.r.	2.4 [1.5]	LS	542.7
Hajdúsámson 22	47°37′1.95″N 21°47′57.10″E [139.8]	Poplar	26	3.75 [3.7]	LS	969.6
Kunhegyes 124	47°25′18.87″N 20°37′16.67″E [86.9]	Control (ploughed field)	n.r.	3.4 [3.2]	SL	1053.4
Kunhegyes 125	47°25′20.85″N 20°37′9.14″E [86.2]	Poplar	23	8.3 [6.7]	L	723.2

Table 1 continued

Monitoring wells (location, No.)	Coordinates [elevation; m a.s.l.]	Vegetation cover	Stand age (years)	Depth to water table (at time of well drilling) (m) [mean depth to water table during the study period; m]	Soil texture	Ground water salinity (at time of well drilling) (mg dm^{-3})
Kunhegyes 126	47°25′20.78″N 20°37′4.75″E [85.3]	Poplar	23	6.5 [4.3]	L	2777.6
Püspökladány 127	47°20′29.48″N 21°5′42.16″E [85.8]	Oak	89	8.9 [6.5]	L	1177.6
Püspökladány 128	47°20′26.29″N 21°5′37.46″E [85.8]	Control (meadow)	n.r.	6.5 [5.9]	L	4384.0
Püspökladány 131	47°21′41.83″N 21°5′42.94″E [87.0]	Oak	56	5.9 [5.5]	L	10,080.0
Püspökladány 132	47°21′41.92″N 21°5′47.00″E [87.0]	Control (meadow)	n.r.	6.5 [5.4]	SL	1337.6

Soil textures were determined according to the USDA system (USDA 1987)

"n.r." = not relevant for the control sites

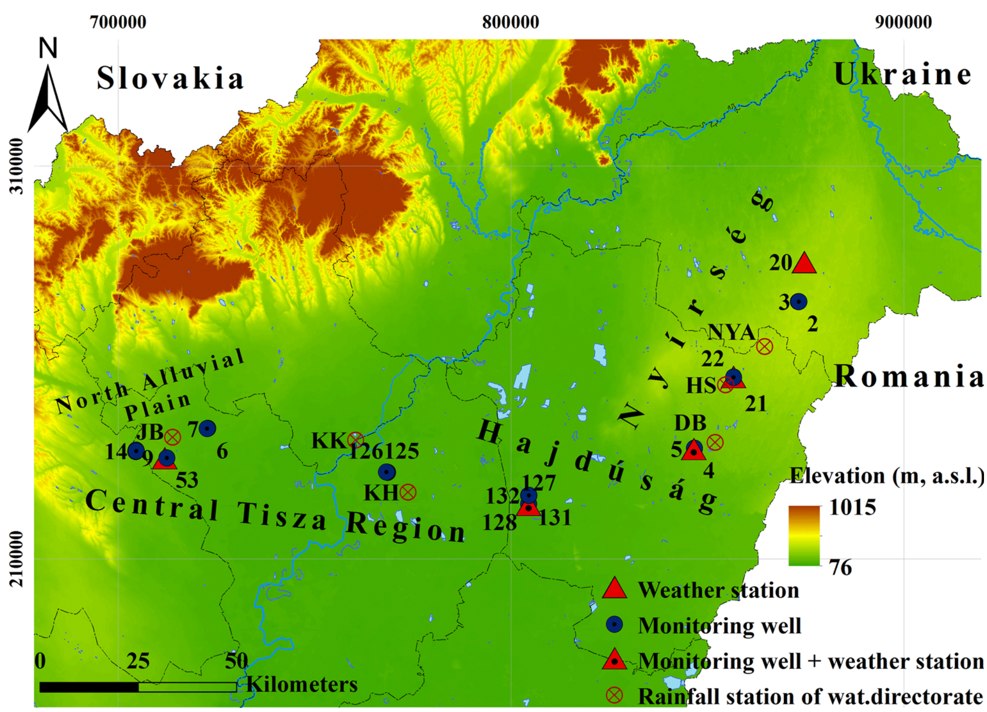

Fig. 2 Location of water table monitoring wells, weather stations and the precipitation stations of the water directorates

Kálló Stream and Árkus Stream; however, all the regions were considered to be dry, water-deficient areas with a sparse network of perennial watercourses.

The main meteorological parameters of the studied regions (reference period 1961–1990) are presented in Table 2. According to the reports of the Hungarian

Table 2 Meteorological conditions in the geographical regions in the study (reference period: 1961–1990) (Dövényi 2010)

Geographical region (subregion)	Well No.	Mean annual temperature (mm, °C)	Mean annual precipitation (growing season) (mm)	Aridity index (ratio of potential evaporation to precipitation)
Nyírség (Északkelet-Nyírség, Dél-Nyírség)	2, 3, 4, 5, 21, 22	9.5–10.0	550–590 (340–360)	1.16–1.28
Hajdúság (Dél-Hajdúság)	127, 128, 131, 132	9.9–10.1	520–560 (310–320)	1.26–1.34
Central Tisza Region (Jászság)	6, 7, 9, 53, 124, 125, 126	10.1–10.3	500–530 (300–310)	1.30–1.38
North Alluvial Plain (Hatvani-sík)	12, 13, 14	10.1–10.3	520–560 (300–320)	1.25–1.33

Meteorological Service (2015), the selected years (2012–2015) showed positive temperature anomalies (1.1–1.9 °C) compared with the mean annual temperatures from 1901 to the selected years, while the mean annual and monthly precipitation amounts also showed significant surpluses or deficits during the selected period compared to the 30-year mean values (reference period 1971–2000).

Hydrological and meteorological parameters

Water table monitoring wells on the selected 11 forest stands and 9 associated control sites (Fig. 2) were augered, and PVC tubes (5 cm diameter), extending 1 m below the water table, were closely fitted inside each borehole. To avoid border effects, the boreholes for groundwater monitoring and soil sampling were located at least 50 m away from the edges of the plantations in both forested and control plots. GWL (cm, below land surface) was measured with vented pressure transducers (models: "DA-LUB 222" and "DA-S-LRB 222", manufacturer: DATAQUA Kft.; accuracy: ± 0.2% of full scale, resolution: 0.1% of full scale) every 15 min. GWL was also reported relative to sea level. Time series of GWL were smoothed using the Simple Moving Average method, where the size of the moving windows (2, 4 or 6 h) was chosen based on a visual analysis of the time series.

The rate of daily change in GWL (amplitude in cm, difference between the daily maxima and minima) was calculated for each monitoring well during the period 1 April–31 October, which was selected as the growing season, since the GWL time series showed diurnal fluctuation even in October in some cases indicating vegetation activity. The extension of the vegetation period until the end of October was confirmed by a study made by Káposztás (2010), who estimated the length of the growing season in Bugacpuszta (Great Hungarian Plain) on the basis of photosynthetic activity. As data gaps in the time series may distort the calculated values, the rate of daily change was only calculated on days when at least 60% of the measurements resulted in the recording of reliable GWL data.

Weather stations (Model "Vantage Pro2" by the manufacturer Davis Instruments Co., with data logger Model "Hyga") were set up on four control stands (No. 5, 9, 20 and 21) and recorded standard meteorological parameters (air temperature, relative humidity, global solar radiation, wind speed and precipitation) every 15 min. To analyse periods when no precipitation data were available on the study sites, data from the regional water directorates (Trans Tisza Water Directorate, Water Directorate of Central Tisza Region, Fig. 2) were also included.

Calculations were made of the daily mean temperature (T, °C), daily mean of relative humidity (RH, %), daily sum of global solar radiation (Rg, W m^{-2}), daily rainfall depth (P, mm), length of antecedent dry period (ADP, number of days without precipitation before the current day) and antecedent precipitation index for 7 days (API7, mm) for the daily analyses. The same restriction as applied for the calculation of daily changes in GWL was applied to the calculation of RH, Rg and P. T was only calculated if none of the basic data were missing at 1:00 a.m., 7:00 a.m., 1:00 p.m. and 7:00 p.m.

Calculation of ET_{gw} using GWL time series

ET_{gw} (mm day^{-1}) was calculated for eight monitoring wells (Table 3) using the empirical version of the diurnal water table fluctuation method of Gribovszki et al. (2008), based on method of White (1932). As reported by Gribovszki et al. (2013), vented pressure transducers with proper maintenance and periodic calibration are suitable for diurnal ET_{gw} estimations.

The method employs the water balance equations (written for the saturated zone):

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

where dS/dt [L^3 T^{-1}] is the time rate of change in groundwater storage (S), h [L] the average GWL (above

Table 3 Monitoring wells and reference periods for (1) calculations of ET_{gw} and correlation analysis between ET_{gw} and LAI and (2) statistical analysis of the effect of meteorological parameters and depth to water table (WTD) on the rate of daily change in GWL

	Monitoring wells	Reference periods
(1) Calculations of ET_{gw}, correlation analysis between ET_{gw} and LAI (latter is in italics)	*No. 2*	21/07/2012–20/08/2014
	No. 6	08/07/2012–09/09/2014
	No. 12	07/07/2012–19/09/2015
	No. 13	07/07/2012–19/09/2015
	No. 14	07/07/2012–19/09/2015
	No. 22	23/07/2012–21/05/2015
	No. 124	29/05/2015–02/10/2015
	No. 126	28/05/2015–05/08/2015
(2) Effect of meteorological parameters and WTD on the rate of daily change in GWL and ET_{gw}	No. 2; No. 3	21/07/2012–16/08/2012, 05/10/2012–31/10/2012, 01/04/2013–07/04/2013, 12/05/2013–07/06/2013, 23/06/2013–18/10/2013, 09/05/2014–07/07/2014, 24/07/2014–27/09/2014
	No. 4; No. 5	05/10/2012–08/10/2012, 18/10/2012–31/10/2012, 01/04/2013–31/10/2013
	No. 6; No. 7	07/07/2012–02/08/2012, 13/10/2012–31/10/2012, 01/04/2013–09/09/2013, 01/04/2014–16/07/2014, 13/08/2014–30/10/2014
	No. 12; No. 13; No. 14	07/07/2012–06/09/2012, 15/05/2013–04/07/2013, 27/04/2014–05/06/2014, 24/06/2015–31/10/2015
	No. 21; No. 22	21/07/2012–26/08/2012, 05/10/2012–11/10/2012, 01/04/2013–05/05/2013, 05/07/2013–11/09/2013, 09/05/2014–31/05/2014, 01/04/2015–21/05/2015

In the case of (1), periods when diurnal fluctuation was disturbed by rainfall were omitted. In the case of (2), all periods when data were missing either at the monitoring wells of forested sites or the associated control sites were pairwise excluded from the correlation analysis. Furthermore, ET_{gw}, WTD, T, RH, Rg at each well and ADP and API7 at wells No. 3, 6, 7 and 21 were only calculated where ADP > 2

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

An empirical method (using characteristic points) was employed (Fig. 3) to obtain the net supply rate (Q_{net}):

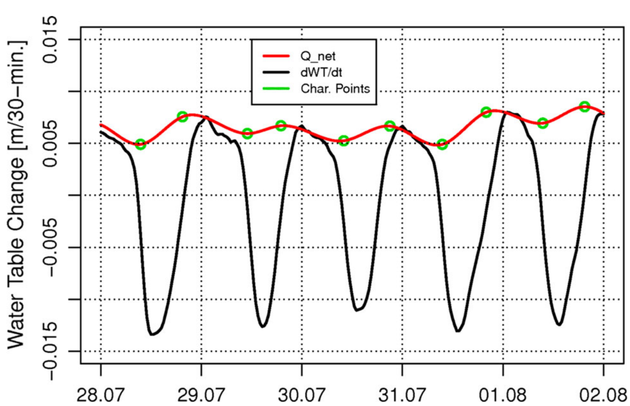

Fig. 3 Graphic representation of the empirical ET_{gw} estimation method according to Gribovszki et al. (2014). Q_{net} is replenishment rate, and dWT/dt is the time rate of change in GWL, Char. Points are the characteristic points of the replenishment rate

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

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

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

Intervals when diurnal fluctuation was disturbed by rainfall were excluded. Constant field-derived S_y values were applied, which were representative of the soil layers where the mean WTD values were recorded during the study period.

Forest stand data, soil and groundwater salinity parameters

The dominant tree species of the selected forest stands were common oak (*Quercus robur* L.), black locust (*Robinia pseudoacacia* L.) and poplar (*Populus* × *euramericana* Moench). LAI data (MODIS/Terra + Aqua Leaf Area Index; layer: LAI_500m (MCD15A3H.006); spatial resolution: 500 m; time resolution: 4-day) were retrieved from the online Application for Extracting and Exploring Analysis Ready Samples (AppEEARS), courtesy of the NASA EOSDIS Land Processes Distributed Active Archive Center (LP DAAC), USGS/Earth Resources Observation and Science (EROS) Center, Sioux Falls, South Dakota (https://lpdaacsvc.cr.usgs.gov/appeears/). To exclude noise and outliers from the time series of LAI, the Simple Moving Average method was applied (36-day moving windows) and the data were validated with field-derived LAI values based on the litter collection method. The 4-day time series of validated satellite-based LAI were extended to daily time series using spline interpolation.

Soil sampling was performed once, during well drilling, and was scheduled for late summer or early fall (September–October) when the water table was the lowest. Soil sampling was carried out to the depth of the groundwater table + 1 m. "Soil" as used in this study includes the vadose zone. Samples were taken every 20 cm from the topsoil (0–1 m) and every 50 cm below 1 m. Table 4 includes the soil parameters used in this study and the methods used to measure them, based on the study of Tóth et al. (2014).

Water samples were taken with a hand vacuum pump, and groundwater salinity (EC_{gw}, μS cm^{-1}) was measured on all groundwater samples using an electrical conductivity meter.

Statistical analysis

Statistical analysis was performed with the software STATISTICA v.13. Since the normality, homogeneity and equal sample size criteria for parametric statistical tests were not fulfilled for each variable, nonparametric tests were applied.

Based on the 20 sites in Table 1, the occurrence of diurnal fluctuation at the monitoring wells was determined by the visual analysis of GWL time series. The Chi-square test of independence was carried out to statistically prove whether the number of wells where diurnal fluctuation occurred was significantly influenced by the categorical variables (vegetation cover, soil texture). Furthermore, the median test was used to determine whether the selected categories were significantly different from each other. The reference period for the former analyses included all periods of the growing seasons from July 2012 to October 2015 when reliable data on the daily change rate were obtained from the GWL time series.

The Spearman's rank-order correlation was applied to reveal the parameters influencing the rate of daily change in GWL. As only constant values were available for soil and salinity parameters (hy1, S_y, EC_e, EC_{gw}), correlation analysis could only be performed on the descriptive statistical variables (mean, median, maximum, range, interquartile range) of daily change in GWL at the monitoring wells in this case. This analysis focused only on wells where diurnal fluctuation was detected due to discharge in daytime and recharge at night (wells No. 2, 12–14, 22, 53, 124, 126, 126). The effect of meteorological parameters and WTD on the rate of daily change in GWL was analysed using daily values derived from pairs of monitoring wells and reference periods, as summarized in Table 3. To ensure the pairwise comparison of forested and control sites, only periods when no data gaps interrupted the time series of daily change in GWL at the corresponding monitoring wells were included in the analyses. To exclude the effect of soil texture, values of daily change in GWL were multiplied by S_y; in addition, the potential influence of precipitation (that is, days where ADP ≤ 2) was omitted in the analyses involving T, RH and Rg, based on the suggestions of Gribovszki et al. (2008). The correlation between ET_{gw} and LAI was also analysed using daily

Table 4 List of soil parameters and measurement methods used in this paper

Parameters	Measurement method
Hygroscopicity (hy1, %) (mean values for different soil layers: 0–1 m, 1 m–water table, whole soil profile)	Method of Di Gléria et al. (1962), Verstraeten and Livens (1971) and Wuddivira et al. (2012)
k coefficient of soil permeability (m day^{-1}) (mean value for the borehole)	Slug test method (van Beers 1958)
Specific yield (mean value for the borehole)	Calculation from the *k* coefficient (Juhász 2000)
Soil salinity (ECe, μS cm^{-1}) (mean values for different soil layers: 0–1 m, 1 m–water table, 0 m–water table)	With EC electrode in 1:2.5 soil:water suspension (weight ratio)

Hygroscopicity refers to water content retained in the soil at 1.6×10^6 cm tension. This value is proportional with soil clayiness data; however, only six wells with an extended reference period were included in the analysis (Table 3).

Results

Number of wells where diurnal fluctuation occurred and the rate of daily change in GWL

GWL showed diurnal fluctuation at several monitoring wells (Fig. 4). The start and cessation of diurnal fluctuation varied over time and space, but the phenomenon was clearly linked to the growing season, as it was mostly detected from the second half of May to the second half of October (extreme values: first half of March and first half of November).

The box plot in Fig. 4 exemplifies the variability in the descriptive statistical parameters of the rate of daily change in GWL at each monitoring well. The categorization of the wells based on the presence of diurnal fluctuation was justifiable as the median test showed a significant difference ($p < 0.0001$) between the daily change in the groundwater data of both categories and substantial differences were also observed between other descriptive statistical variables for both categories. Nevertheless, the main reason for the categorization was that different processes were assumed to be primarily responsible for the daily change in GWL in the two categories, direct groundwater uptake by plants being the major process at wells with diurnal fluctuation, while this process was negligible at wells without diurnal fluctuation. However, some outliers were observed, such as well No. 125, where the relatively higher values of daily change were caused by unidentified noise in the time series, and well No. 6, where stepwise diurnal fluctuation (without recharge at night) was detected, resulting in relatively lower values of daily change. As regards vegetation cover, only 22% of the control sites exhibited the phenomenon of diurnal fluctuation, compared with 73% of the forest stands (Table 5). Oak (median 1.7 mm; SD ± 4.0 mm) and poplar stands (median 2.2 mm; SD ± 2.5 mm) produced a greater daily change in GWL (values are multiplied by S_y) than unforested control sites (median 0.8 mm; SD ± 1.8 mm). The lowest (median 0.8 mm; SD ± 0.6 mm) daily change was observed in black locust stands.

The phenomenon of diurnal fluctuation could not be detected in wells with sandy soil texture, and the daily change in GWL was the lowest in this category. Nevertheless, the daily change in GWL in different soil texture classes did not show the expected sequence, namely that the coarser the soil texture, the lower the rate of change in GWL (sand: median 6.0 mm, SD ± 4.0 mm; loamy sand: median 14.1 mm, SD 3.0 mm; sandy loam: median 10.4 mm, SD 58.1 mm; loam: median 17.2 mm, SD 19.3 mm; values are not multiplied by S_y). If only wells with diurnal fluctuation were considered with the exception of well No. 6 (stepwise fluctuation), the same sequence was

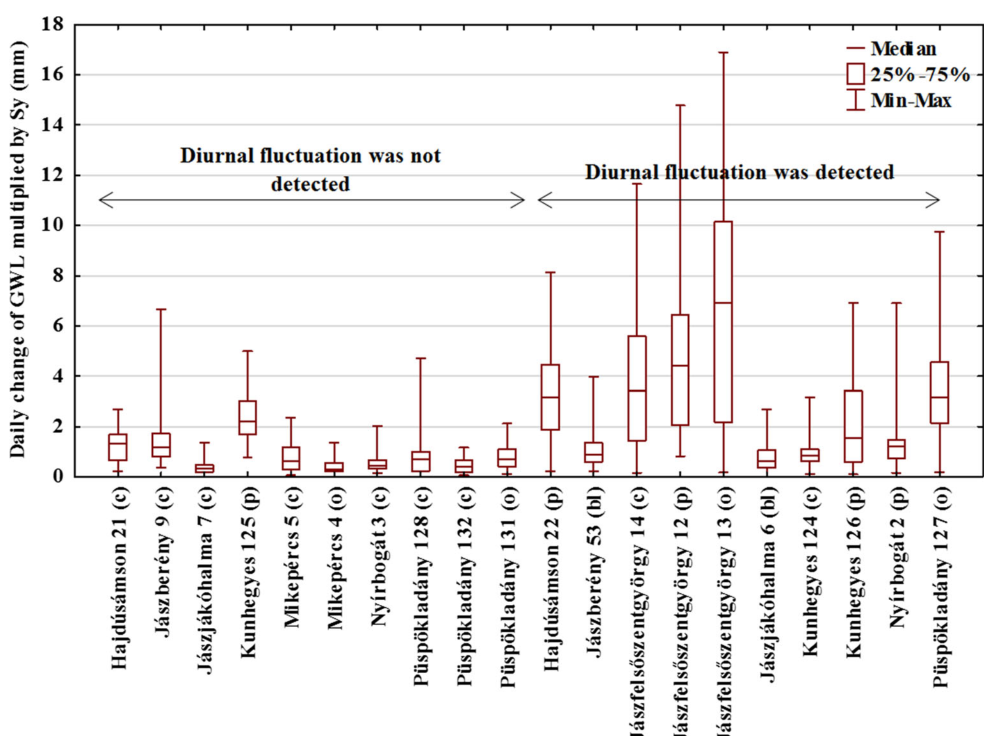

Fig. 4 Box plot of the rate of daily change in GWL multiplied by the specific yield (S_y) at monitoring wells during the growing season, with sites grouped on the basis of the number of wells where diurnal fluctuation occurred (letters in brackets indicate the vegetation cover: c = control, o = oak, bl = black locust and p = poplar. Data where the length of antecedent dry period (ADP) was ≤ 2 days were excluded.)

Table 5 Number of wells where diurnal fluctuation occurred in the vegetation cover and soil texture categories

	Vegetation cover				Soil texture			
	Control	Poplar	Black locust	Oak	S	LS	SL	L
Total number of wells	9	5	2	4	1	8	6	5
Number of wells with diurnal fluctuation	2	4	2	2	0	3	4	2

obtained and sites with loamy texture again had the highest median value of change in GWL.

No diurnal fluctuation was found where the groundwater salinity exceeded 4300 mg dm^{-3}, but the mean WTD was also greater than 5.4 m at these sites (No. 128, 131). The monitoring wells only showed diurnal fluctuation in two cases (No. 53, 127), when the mean WTD exceeded 5.0 m.

According to the test of independence, the occurrence of diurnal fluctuation only showed significant dependence on the vegetation cover categories. Combined categories (poplar + black locust + oak = "forest" vs. "control") were applied to obtain a meaningful result. Forests significantly increased the number of wells where diurnal fluctuation occurred at $p < 0.05$. The median tests revealed a significant ($p < 0.0001$) difference in the daily change in GWL between the different vegetation categories and soil textures.

Results of correlation analysis: effect of vegetation, soil, groundwater and meteorological parameters on daily change in GWL and ET_{gw}

Correlation analysis between the daily change in GWL and constant soil and salinity parameters only revealed a significant correlation between S_y and the mean and median daily change in GWL (correlation coefficient (r) = − 0.65, significant at $p < 0.05$). The negative sign of r indicated that sites with higher S_y were associated with lower daily change in GWL, because of the faster recharge of the decreased storage and the larger drainable pore space in the aquifer (Fig. 5).

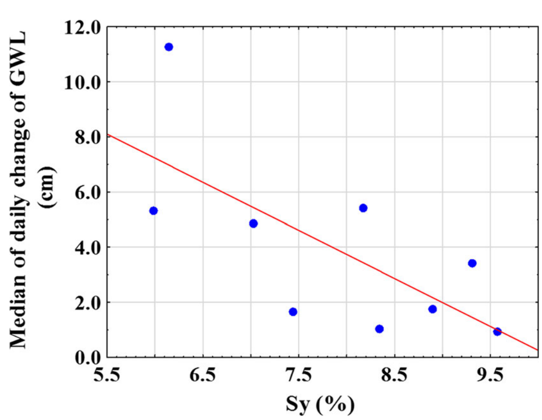

Fig. 5 Scatter plot of median daily change in GWL against S_y

Table 6 summarizes the correlation coefficients between the rate of daily change in GWL, meteorological parameters and WTD. Although the correlation coefficients were highly site and time dependent, the meteorological parameters exhibiting the strongest correlations with the daily change in GWL were generally T, RH and Rg. Increasing values of T and Rg intensified the rate of water extraction from the soil (through transpiration and evaporation) and thus the rate of daily change in GWL. Rg also affected the rate of transpiration and evaporation, being responsible for the start of this light-dependent process and contributing to the warming of the air and soil. RH showed the opposite effect, giving a significant negative correlation. A decrease in the vapour pressure in the air intensifies the movement of water from the leaf or the soil to the atmosphere, resulting in an increase in the rate of daily change in GWL (Fig. 6a).

The complex effect of rainfall on the groundwater movement (increasing or reducing the daily change in GWL) could only partially be confirmed statistically and with weaker r values (Fig. 6b). If the daily change in GWL was induced by plant water uptake (i.e. diurnal fluctuation was controlled by discharge in daytime and recharge at night, such as at wells No. 2, 12, 13, 14, 22), the rainfall had a significant negative effect on the rate of daily change in GWL. Groundwater consumption and thus a reduction in GWL remained moderate until the infiltrating rainfall was able to satisfy the water demand of the vegetation (Fig. 7). The direct effect of rainfall in increasing and intensifying the daily change in GWL could not be statistically corroborated at the study sites.

A significant positive correlation was obtained between the daily change in GWL and ADP, suggesting that long dry periods increased the vapour pressure deficit and reduced the residual moisture in the upper soil layer (Fig. 6b), resulting in evaporation increase and forcing plants to replace their water demand from the groundwater, with a consequent increase in the daily change in GWL. This is confirmed by the significant negative correlation between the daily change in GWL and API7, indicating the effect of drying soil on the groundwater movement.

Significant correlation coefficients of varying strength were observed between the daily change in GWL and WTD except for wells No. 12, 13 and 14, where the range and interquartile range of daily change in GWL were

Table 6 Spearman rank-order correlation coefficients between the rate of daily GWL change (multiplied by S_y), depth to the water table (WTD) and meteorological parameters

Well	T	RH	Rg	P	ADP	API7	WTD
No. 2 (poplar)	0.60**	− 0.51**	0.31**	*− 0.35***	*0.41***	*− 0.41***	0.49**
	(66)	(69)	(69)	*(324)*	*(329)*	*(329)*	(120)
No. 3 (control)	0.65**	− 0.38**	0.76**	*− 0.02*	*0.31***	*− 0.36***	0.78**
	(66)	(69)	(69)	*(324)*	*(120)*	*(120)*	(120)
No. 4 (oak)	0.58**	− 0.39**	0.72**	*− 0.01*	*− 0.03*	*0.08*	0.70**
	(90)	(93)	(93)	*(232)*	*(232)*	*(232)*	(93)
No. 5 (control)	0.54**	− 0.47**	0.77**	*0.08*	*− 0.06*	*0.14**	0.94**
	(90)	(93)	(93)	*(232)*	*(232)*	*(232)*	(93)
No. 6 (black locust)	0.40**	− 0.48**	0.46**	*− 0.07*	*0.31***	*− 0.20***	0.80**
	(104)	(109)	(158)	*(389)*	*(167)*	*(167)*	(167)
No. 7 (control)	0.27**	− 0.34**	0.27**	*0.03*	*0.21***	*− 0.13*	0.66**
	(104)	(109)	(158)	*(389)*	*(167)*	*(167)*	(167)
No. 12 (poplar)	0.50**	− 0.63**	0.63**	− 0.38**	0.45**	*− 0.40***	0.14
	(90)	(94)	(94)	(229)	(188)	*(239)*	(100)
No. 13 (oak)	0.52**	− 0.72**	0.45**	− 0.34**	0.40**	*− 0.46***	0.05
	(90)	(94)	(94)	(229)	(188)	*(239)*	(100)
No. 14 (control)	0.34**	− 0.84**	0.23*	− 0.31**	0.36**	*− 0.48***	− 0.01
	(90)	(94)	(94)	(229)	(188)	*(239)*	(100)
No. 21 (control)	0.67**	n.d.	0.30**	*− 0.06*	*0.48***	*− 0.49***	0.21*
	(103)		(106)	*(217)*	*(109)*	*(109)*	(109)
No. 22 (poplar)	0.57**	n.d.	0.38**	*− 0.23***	*0.38***	*− 0.31***	0.41**
	(103)		(106)	*(217)*	*(217)*	*(217)*	(109)

Missing data were pairwise deleted. A number of days on which samples were taken are given in brackets. *Italics* calculations are based on precipitation data derived from the regional water directorates. WTD, T, RH and Rg, and ADP, and API7 at wells No. 3, 6, 7, 21, were only calculated where ADP > 2

"n.d." = no reliable data were available

* Correlations significant at $p < 0.05$

** Correlations significant at $p < 0.01$

considerably higher than in the other sites (see Fig. 4). For wells with diurnal fluctuation, this might indicate that the lower the GWL, the less the groundwater was available to plant roots, resulting in a lower rate of daily change in GWL. Another reason for the significant correlation between daily change in GWL and WTD is that WTD generally decreases until the end of the growing season (due to plant water uptake), but at the same time the physiological activity also decreases, resulting in a lower daily change in GWL. At wells where the time series of GWL showed an almost linear decrease (e.g. No. 3, 5, 21), WTD increased over time, but the rate of change in GWL did not decrease (note that WTD values were < 0, so the sign of the correlation was the opposite to that expected in Fig. 1).

Table 7 summarizes the descriptive statistical variables of ET_{gw} and the values of S_y. An exceptionally low value was detected for black locust (mean 0.4 mm day^{-1} ± 0.3 SD), with higher values for poplar stands (mean 1.7–6.0 mm day^{-1} [0.3–2.8 SD]), and the highest rate of ET_{gw} for oak (mean 8.2 mm day^{-1} ± 3.6 SD). The ET_{gw} value on control plot No. 14 may have been distorted by the presence of trees located closer than 50 m to the well, but the other control plot, No. 124 (mean 0.9 mm day^{-1} ± 0.3 SD), clearly indicated the lower groundwater consumption of herbaceous vegetation.

Significant positive correlations ($p < 0.01$) were obtained between ET_{gw} and LAI at wells No. 6, 22 and 126, where LAI data for an area of 500 × 500 m were sufficiently representative of the given forest site. Nevertheless, inter- and intra-year variations were detected in the ET_{gw}–LAI correlations and the ET_{gw}–LAI relationship was found to be primarily interpretable over a single vegetation period. For instance, at well No. 22 the correlation between ET_{gw} and LAI was stronger in the separate years 2012 and 2013 ($r = 0.92$ in 2012 and $r = 0.72$ in 2013; $p < 0.01$) than over the entire reference period. However, the daily differences in ET_{gw} might be better explained by the daily T (Table 6).

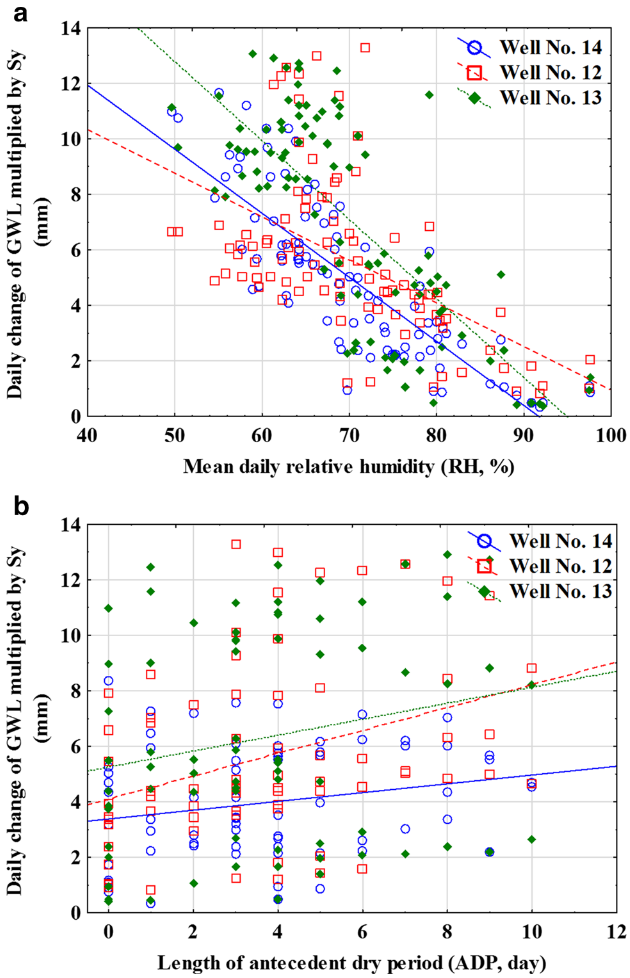

Fig. 6 **a** Scatter plot of daily change in GWL against mean daily relative humidity (RH) at wells No. 12–14. **b** Scatter plot of daily change in GWL against length of antecedent dry period (ADP) at wells No. 12–14

Discussion

Effect of vegetation parameters and groundwater availability on the groundwater movement and ET_{gw}

The results showed that the diurnal fluctuation in GWL was clearly associated with the vegetation period and was thus induced by water uptake by the vegetation, as also reported by White (1932) and Butler et al. (2007). When the vegetation cover categories were grouped into forested and control (unforested) sites, the forest vegetation showed a significantly higher number of wells where diurnal fluctuation occurred. This coincides with the findings of Nosetto et al. (2007) and Fan et al. (2014), who also investigated differences between the daily GWL dynamics of two woodlands and grassland, and detected no diurnal fluctuation for the grassland site, because the grasses had relatively shallow root depth compared to the trees and thus could not access the groundwater.

According to Gőbölös (2002), Magyar (1961) and Szodfridt (1993), the water uptake during the growing season for the studied tree species was the following: black locust 273 mm < common oak 441 mm < poplar 680 mm. In the present study, the median daily change in GWL under forested sites showed the same sequence. The low ET_{gw} rate for the black locust stand (range 0.1–1.2 mm day^{-1}) was similar to that found by Wang et al. (2010), who observed a mean stand transpiration of 0.41 mm day^{-1} (with a maximum of 0.89 mm day^{-1}) for a black locust plantation in the semiarid region of the Loess Plateau, China. However, the ET_{gw} recorded for the four poplar stands (range 0.8–12.8 mm day^{-1}) exceeded the ET_{gw} (range 2.9–9.3 mm day^{-1}) measured by Butler et al.

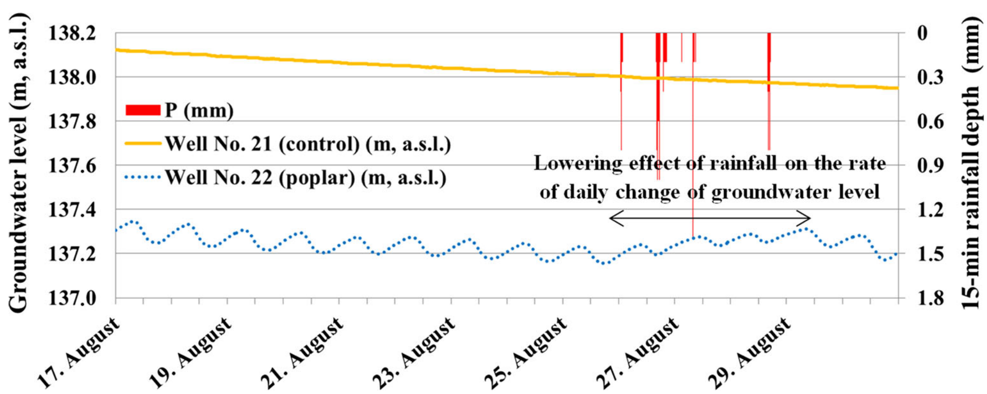

Fig. 7 Lowering effect of rainfall on the rate of daily change in groundwater level after a long dry period between August 17 and August 30, 2013, on the study sites Hajdúsámson 21 (control) and Hajdúsámson 22 (poplar). The first rainfall event occurred on 26 August. According to the time series, the effect of rainfall could be detected until 29 August. (Level of soil surface was 139.6 m a.s.l. at well No. 21 and 139.8 m a.s.l. at well No. 22.)

Table 7 Number of reference days, basic descriptive statistical parameters of daily ET_{gw}, field-derived values of S_y reduced by 50% (readily available specific yield, Meyboom 1964) and correlation coefficients between ET_{gw} and LAI

Monitoring well [No.]	Number of reference days	ET_{gw}				$S_y \times 0.5$	r between ET_{gw} and LAI
		Mean	Min	Max	SD		
2 (poplar)	139	1.7	1.0	2.6	0.3	0.037	− 0.09
6 (black locust)	68	0.4	0.1	1.2	0.3	0.044	0.73**
12 (poplar)	112	6.0	1.0	12.8	2.8	0.041	0.01
13 (oak)	112	8.2	0.7	13.5	3.6	0.031	− 0.13
14 (control)	95	6.2	1.6	14.1	3.4	0.035	n.d.
22 (poplar)	112	5.0	1.0	8.1	1.9	0.030	0.52**
124 (control)	79	0.9	0.4	1.6	0.3	0.042	n.d.
126 (poplar)	53	3.4	0.8	6.3	1.4	0.044	0.56**

ET_{gw} on control plot No. 14 might be distorted by the presence of trees located closer than 50 m to the well

"n.d." = no reliable data were available

** Correlations significant at $p < 0.01$

(2007) for a mixed poplar forest in the USA, and the ET_{gw} rate of the oak stand (range 0.7–13.5 mm day^{-1}) was considerably higher than obtained by Nachabe et al. (2005) for a mixed oak stand in the USA (range 1.7–6.3 mm day^{-1}) and that calculated by Nosetto et al. (2007) for three oak plantations in early autumn on naturally salt-affected soils in Hortobágy (Great Hungarian Plain) (range 0.55–3.19 mm day^{-1}). According to Fan et al. (2014) and Zhang and Schilling (2006), different WTD might also result in different rates of ET_{gw} for the same plant species.

The lower water uptake of herbaceous vegetation compared with that of forest stands could be due to the lower rate of LAI (Móricz et al. 2012) or to the fact that the groundwater is not available to the shallower roots of herbaceous plants (Fan et al. 2014; Móricz et al. 2016). The present results proved that WTD is a limiting factor for groundwater availability and uptake by plants, as a significant correlation was found between the daily change in GWL and WTD, and the depth limit for groundwater uptake by forests seemed to be about 5 m. The exceptions were wells No. 53 and 127. The fact that the old oak stand accessed the groundwater, resulting in diurnal fluctuation despite the 6.5 m mean WTD, agrees with the study of Nosetto et al. (2007), who also detected groundwater uptake by oak plantations from a depth of 5–6 m. Crow (2005) proved that the rooting depth of mature *Q. robur* may be > 4 m on intermediate loamy soils.

Role of soil and salinity parameters in groundwater dynamics

The lowest median daily change in GWL was found for sites with sandy texture and the highest for plots with loamy texture. However, sandy texture was underrepresented (only one site) and the effect of other parameters must also be taken into account. On the sandy plot, the k coefficient of soil permeability (0.11 m day^{-1}) and S_y (7.18%) were not much lower than at the other sites, so the lack of diurnal fluctuation and the lowest median daily change in GWL could be due simply to the herbaceous vegetation. Nevertheless, the correlation coefficient between S_y and the median daily change in GWL indicated that S_y had a significant influence on the water extraction and recharge processes on the study area, as also reported by other authors. According to Lautz (2008), sand has higher S_y, so ET_{gw}-induced diurnal fluctuations are muted in sandy sediments. In coarser sediments, diurnal fluctuation with small amplitude releases a greater volume of water than in finer sediments, so the same ET_{gw} will generate a smaller daily change in GWL in coarser sediments. Based on the results of HYDRUS-1D simulations, Wang and Pozdniakov (2014) found a higher amplitude of diurnal fluctuation in aquifers with low hydraulic conductivity (silt and silty loam), while the amplitude of diurnal fluctuation was smaller in coarse aquifers (sand and sandy loam) due to the higher S_y and hydraulic conductivity.

It should be noted that no significant correlation was found between the mean k coefficient, mean S_y and hy1 values for different soil segments, suggesting the depth dependence of soil texture and soil permeability. One of the central questions in soil–groundwater studies is the spatial and temporal variability of hydraulic conductivity and S_y (Armstrong et al. 1991; Crosbie et al. 2005; Fan et al. 2014; Lautz 2008; Loheide et al. 2005; Salama et al. 1994), but some authors nevertheless apply constant values (Sueki et al. 2015), as in the present work. No diurnal fluctuation was detected at wells with high groundwater salinity. However, the effect of underrepresentation of sites with higher salinity and interactions with other variables (especially vegetation cover and WTD) also had to be considered, so salinity might not be the main reason for the lack of diurnal fluctuation in the present case. Despite the complexity of the problem, the lowering effect of salinity on groundwater uptake and thus on the change in GWL cannot be excluded, as demonstrated by the case of the mature oak stand (well No. 127), which had the highest EC_{gw}. This was confirmed by numerous authors. Benyon et al. (1999) proved that less salt-tolerant tree species produced lower LAI and thus lower water uptake, even on moderately saline soil. The investigations of Thorburn (1997) and Silberstein et al. (1999) also illustrated that forest growth and water uptake decrease at high salinity. Ultimately the water table begins to rise, and daily fluctuation may decline due to the reduced rate of ET_{gw}.

Interactions between vertical groundwater movement and meteorological parameters

Significant correlations were found between the rate of daily change in GWL and meteorological parameters (T, RH and Rg) at each well. Butler et al. (2007) pointed out the striking similarity between the patterns of global radiation and water movement in the trees in a poplar stand. As vapour pressure deficit, T and wind speed also play a crucial role, and they merged the multiple impacts using the parameter of reference evapotranspiration (ET_0, as described by Allen et al. 1998) to characterize the potential for transpiration by vegetation when water is not a limiting factor. Lautz (2008) also observed that the daily variability in ET_{gw} is largely controlled by T and Rg.

The spatial and temporal variability in GWL as a response to rainfall events was well depicted by Zhang and Schilling (2006), who provided a good explanation of the weak correlations or lack of significant correlations in the present case. Nevertheless, when soil moisture content is high after rainfall events, plants may be less dependent on phreatic water because soil water is so readily available (Lautz 2008). Therefore, the daily change in GWL and ET_{gw} may decline, resulting in a negative correlation between the daily change in GWL and P, as found in the present work.

Due to the significant correlations between the amplitude of diurnal fluctuation, ADP and API7, no real drought impact could be revealed on the ET_{gw}-driven daily change in GWL like that shown by Vincke and Thiry (2008) and Wang et al. (2010). As the soil moisture content declines during dry periods and conditions become water limited, plants may intensify their groundwater uptake, causing a relative increase in ET_{gw}, as also reported by Lautz (2008). In an oak and fallow site on the Great Hungarian Plain, Móricz et al. (2012) demonstrated that groundwater consumption was about 40% lower in a wet growing season than in a drier growing season, despite the fact that the water table was deeper during the dry period.

Conclusions

Great discrepancies were found between wells with diurnal fluctuation and those without diurnal fluctuation in terms of the descriptive statistical variables of daily change in GWL. The study confirmed that forest vegetation significantly increased the number of wells where diurnal fluctuation occurred. Due to the fact that monitoring wells with diurnal fluctuation generally had a higher daily change in GWL, that the diurnal fluctuation in GWL in the growing season was primarily related to the groundwater consumption of the vegetation and that forested sites showed the most occurrences of diurnal fluctuation, the presence of forests seems to have been the most dominant factor inducing a higher rate of daily change in GWL at the study sites.

Although the results indicated that the correlations were highly site and time dependent, S_y, WTD, the meteorological parameters and LAI were found to be significant factors controlling diurnal groundwater fluctuation through the regulation of water extraction, especially ET_{gw}, and recharge processes. Some of the results confirmed that long dry periods increased the amplitude of diurnal fluctuation, reflecting the greater demand for groundwater uptake. This is a very important finding in the light of climate change. In several wells, there was a daily change (near-linear decrease) in GWL without diurnal fluctuation, suggesting that these areas might behave as recharge zones contributing to the groundwater replenishment of discharge zones.

These findings could help forest managers to select ideal sites where tree species with different water demand could be sustainably grown. However, further investigations will be required in order to (1) generalize the results for use in other regions; (2) determine regions where the annual balance of groundwater inflow and outflow is negative, resulting in water table depression; and (3) reveal the dominant factors responsible for the negative water balance.

Acknowledgements The establishment of the monitoring network and data collection were funded by OTKA NN 79835 (National Scientific Research Programmes, Hungary), EU COST FA0901 and VKSZ_12-1-2013-0034–AGRÁRKLÍMA.2. Péter Csáfordi, Kitti Balog and Tibor Tóth acknowledge funding from the Postdoctoral Research Programme PD-029/2015 of the Hungarian Academy of Sciences and Zoltán Gribovszki from the European Union and the State of Hungary, co-financed by the European Social Fund in the framework of the TÁMOP 4.2.4. A/2-11-1-2012-0001 "National Excellence Program". The authors thank Dr. Norbert Móricz for his advice on the calculation of evapotranspiration and Dr. Klára Ádámné

Pokovai for her help with LAI calculations. Special thanks are due to the Trans Tisza Water Directorate and the Water Directorate of the Central Tisza Region for the daily precipitation data.

Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

References

Akram S, Liaghat H (2010) Performance of biodrainage systems in arid and semiarid areas with salt accumulation in soils. In: 9th international drainage symposium, Quebec City

Allen RG, Pereira LS, Raes D, Smith M (1998) Crop evapotranspiration—guidelines for computing crop water requirements. Irrig Drain Pap 56

Armstrong AC, Youngs EG, Arrowsmith R (1991) Modelling water–table movement in drained soils with depth-dependent hydraulic conductivity. Agric Water Manag 20:101–108

Benyon RG, Marcar NE, Crawford DF, Nicholson AT (1999) Growth and water use of *Eucalyptus camaldulensis* and *E. occidentalis* on a saline discharge site near Wellington, NSW, Australia. Agric Water Manag 39:229–244

Butler JJ, Kluitenberg GJ, Whittemore DO, Loheide SP, Jin W, Billinger MA, Zhan X (2007) A field investigation of phreatophyte-induced fluctuations in the water table. Water Resour Res 43:W02404

Calder IR (1998) Water use by forests, limits and controls. Tree Physiol 18:625–631

Crosbie RS, Binning P, Kalma JD (2005) A time series approach to inferring groundwater recharge using the water table fluctuation method. Water Resour Res 41:W01008

Crow P (2005) The influence of soils and species on tree rooting depth. Forestry Commission Information Note, November 2005

de Ochoa FC, Reinoso JCM (1997) Model of long-term water–table dynamics at Donana National Park. Water Res 31(10):2586–2596

Di Gléria J, Klimes-Szmik A, Dvoracsek M (1962) Bodenphysik und Bodenkolloidik. Akadémia Kiadó, Budapest

Dövényi Z (ed) (2010) Magyarország kistájainak katasztere [Register of Hungarian regions]. MTA Földrajztudományi Kutatóintézet, Budapest **(in Hungarian)**

Fahle M, Dietrich O (2014) Estimation of evapotranspiration using diurnal groundwater level fluctuations: comparison of different approaches with groundwater lysimeter data. Water Resour Res 50:273–286

Fan J, Oestergaard KT, Guyot A, Lockington DA (2014) Estimating groundwater recharge and evapotranspiration from water table fluctuations under three vegetation covers in a coastal sandy aquifer of subtropical Australia. J Hydrol 519:1120–1129

Forestry Web Map—Magyarországi Erdészeti Webtérkép [Hungarian Forestry Web Map]. http://erdoterkep.mgszh.gov.hu. Accessed 29 Sept 2016

Gőbölös A (2002) A "vízhiányos" erdőgazdálkodás kérdései a Duna-Tisza-közi homokhátságon [Forest management in the case of water shortage in the sand ridge region between the Danube and Tisza Rivers]. Hidrológiai Közlöny 82:324–326 **(in Hungarian)**

Gribovszki Z, Kalicz P, Szilágyi J, Kucsara M (2008) Riparian zone evapotranspiration estimation from diurnal groundwater level fluctuations. J Hydrol 349:6–17

Gribovszki Z, Szilágyi J, Kalicz P (2010) Diurnal fluctuations in shallow groundwater levels and streamflow rates and their interpretation—a review. J Hydrol 385:371–383

Gribovszki Z, Kalicz P, Szilágyi J (2013) Does the accuracy of fine-scale water level measurements by vented pressure transducers permit for diurnal evapotranspiration estimation? J Hydrol 488:166–169

Gribovszki Z, Kalicz P, Balog K, Szabó A, Tóth T (2014) Comparison of an oak forest and of a pasture groundwater uptake and salt dynamics on the Hungarian Great Plain. Acta Silv Lign Hung 10:103–114

Hatton TJ, Wu H-I (1995) Scaling theory to extrapolate individual tree water use to stand water use. Hydrol Process 9:527–540

Hungarian Meteorological Service (2015) Weather in recent years. http://www.met.hu/eghajlat/magyarorszag_eghajlata/eghajlati_visszatekinto/elmult_evek_idojarasa/. Accessed 10 Nov 2016

Ijjász E (1939) A fatenyészet és az altalajvíz, különös tekintettel a nagyalföldi viszonyokra [Wood production and groundwater on the Great Hungarian Plain]. Erdészeti Kísérletek 42:1–107 **(in Hungarian)**

Juhász J (2000) Hidrogeológia [Hydrogeology]. Akadémiai Kiadó, Budapest **(in Hungarian)**

Káposztás N (2010) A vegetációs időszak hosszának vizsgálata különböző módszerekkel [Assessment of the length of vegetation period with different methods]. B.Sc. thesis, Eötvös Lóránd University **(in Hungarian)**

Kuti L (1981) Az Alföld földtani atlasza: Kecskemét [Geographical map of the Great Hungarian Plain: Kecskemét]. MÁFI, Budapest **(in Hungarian)**

Kuti L (1982) Az Alföld földtani atlasza: Debrecen-Nyírábrány [Geographical map of the Great Hungarian Plain: Debrecen-Nyírábrány]. MÁFI, Budapest **(in Hungarian)**

Kuti L (1984) Az Alföld földtani atlasza: Mátészalka [Geographical map of the Great Hungarian Plain: Mátészalka]. MÁFI, Budapest **(in Hungarian)**

Laborczi A, Szatmári G, Takács K, Pásztor L (2016) Mapping of topsoil texture in Hungary using classification trees. J Maps 12(5):999–1009

Lautz LK (2008) Estimating groundwater evapotranspiration rates using diurnal water–table fluctuations in semi-arid riparian zone. Hydrogeol J 16:483–497

Loheide SP, Butler JJ, Gorelick SM (2005) Estimation of groundwater consumption by phreatophytes using diurnal water table fluctuations: a saturated-unsaturated flow assessment. Water Resour Res 41:W07030

Magyar P (1961) Alföldfásítás II [Afforestation on the Great Hungarian Plain]. Akadémiai Kiadó, Budapest **(in Hungarian)**

Meyboom P (1964) Three observations on streamflow depletion by phreatophytes. J Hydrol 2:248–261

Móricz N, Mátyás C, Berki I, Rasztovits E, Vekerdy Z, Gribovszki Z (2012) Comparative water balance study of forest and fallow plots. iForest 5:188–196

Móricz N, Tóth T, Balog K, Szabó A, Rasztovits E, Gribovszki Z (2016) Groundwater uptake of forest and agricultural land covers in regions of recharge and discharge. iForest. doi:10.3832/ifor1864-009

Nachabe M, Shah N, Ross M, Vomacka J (2005) Evapotranspiration of two vegetation covers in a shallow water table environment. Soil Sci Soc Am J 69:492–499

Nosetto MD, Jobbágy EG, Paruelo JM (2005) Land-use change and water losses: the case of grassland afforestation across a soil textural gradient in central Argentina. Glob Chang Biol 11:1101–1117

Nosetto MD, Jobbágy EG, Tóth T, Di Bella CM (2007) The effects of tree establishment on water and salt dynamics in naturally salt-affected grasslands. Oecologia 152:695–705

Pásztor L, Laborczi A, Takács K, Szatmári G, Illés G, Fodor N, Négyesi G, Bakacsi Z, Szabó J (2016) Spatial distribution of

selected soil features in Hajdú-Bihar County represented by digital soil maps. Landsc Environ 10(3–4):203–213
Salama RB, Bartle GA, Farrington P (1994) Water use of plantation *Eucalyptus camaldulensis* estimated by groundwater hydrograph separation techniques and heat pulse method. J Hydrol 156:163–180
Saxton KE, Rawls WJ (2006) Soil water characteristic estimates by texture and organic matter for hydrologic solutions. Soil Sci Soc Am J 70:1569–1578
Silberstein RP, Vertessy RA, Morris J, Feikema PM (1999) Modelling the effects of soil moisture and solute conditions on long-term tree growth and water use: a case study from the Shepparton irrigation area, Australia. Agric Water Manag 39:283–315
Soylu ME, Lenters JD, Istanbulluoglu E, Loheide SP II (2012) On evapotranspiration and shallow groundwater fluctuations: a Fourier-based improvement to the White method. Water Resour Res 48:W06506
Sueki S, Acharya K, Huntington J, Liebert R, Healey J, Jasoni R, Young M (2015) Defoliation effects of *Diorhabda carinulata* on tamarisk evapotranspiration and groundwater levels. Ecohydrology. doi:10.1002/eco.1604
Szodfridt I (1990) Hozzászólás Major Pál és Neppel Ferenc: "A Duna-Tisza-közi talajvízszint süllyedése" című cikkéhez [Comment on "Depression of groundwater level between the River Danube and Tisza" by P Major and F Neppel]. Vízügyi Közlemények 72(3):287–291 **(in Hungarian)**
Szodfridt I (1993) Erdészeti termőhelyismerettan [Forestry production sites]. Mezőgazda Kiadó, Budapest **(in Hungarian)**
Thorburn PJ (1997) Land management impacts on evaporation from shallow, saline water tables. In: Taniguchi M (ed) Sub-surface hydrological responses to land cover and land use changes. Kluwer, Boston, pp 21–34
Tóth T, Balog K, Szabó A, Pásztor L, Jobbágy EG, Nosetto MD, Gribovszki Z (2014) Influence of lowland forests on subsurface salt accumulation in shallow groundwater areas. AoB PLANTS. doi:10.1093/aobpla/plu054
Turk LJ (1975) Diurnal fluctuations of water tables induced by atmospheric pressure changes. J Hydrol 26:1–16
USDA, United States Department of Agriculture, National Employee Staff, Soil Conservation Service (1987) Soil Mechanics Level I Module 3—USDA Textural Soil Classification—Study Guide, pp 1–53
van Beers WFJ (1958) A field measurement of the hydraulic conductivity of soil below the water table. ILRI Publication 1, International Institute for Land Reclamation and Improvement (ILRI), Wageningen
Verstraeten LMJ, Livens J (1971) Hygroscopicity as a valuable complement in soil analysis, 1. Characterization of the hygroscopic constant. Geoderma 6:255–262
Vincke C, Thiry Y (2008) Water table is a relevant source for water uptake by a Scots pine (*Pinus sylvestris* L.) stand: evidences from continuous evapotranspiration and water table monitoring. Agric For Meteorol 148:1419–1432
Wang P, Pozdniakov SP (2014) A statistical approach to estimating evapotranspiration from diurnal groundwater level fluctuations. Water Resour Res 50:2276–2292
Wang Y-L, Liu G-B, Kume T, Otsuki K, Yamanaka N, Du S (2010) Estimating water use of a black locust plantation by the thermal dissipation probe method in the semiarid region of Loess Plateau, China. J For Res 15:241–251
Ward RC (1963) The effect of site factors on water–table fluctuations. J Hydrol 1:151–165
White WN (1932) Method of estimating groundwater supplies based on discharge by plants and evaporation from soil—results of investigation in Escalante Valley, Utah. US Geological Survey, Water Supply Paper 659-A, 1–105
Wuddivira MN, Robinson DA, Lebron I, Brechet L, Atwell M, De Caires S, Oatham M, Jones SB, Abdu H, Verma AK, Tuller M (2012) Estimation of soil clay content from hygroscopic water content measurements. Soil Sci Soc Am J 76(5):1529–1535
Zhang Y-K, Schilling KE (2006) Effects of land cover on water table, soil moisture, evapotranspiration, and groundwater recharge: a field observation and analysis. J Hydrol 319:328–338