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Long term analysis of groundwater uptake strategies based on groundwater level fluctuations in pedunculate oak and hybrid poplar forests in the Great Hungarian Plain

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This study examines the groundwater uptake characteristics of two tree species – hybrid poplar (*Populus × euramericana cv.* Agathe F) and pedunculate oak (*Quercus robur* L.) – in the Great Hungarian Plain using high-resolution groundwater level (GWL) measurements recorded over a 10-year period (2015–2024). Through analysis of diurnal GWL fluctuations, the relative groundwater consumption of each species and their responses to changing hydrological conditions were assessed. Results indicate that hybrid poplar exhibits higher water demand and larger seasonal GWL fluctuations compared to pedunculate oak. However, trends in daily GWL fluctuation suggest that groundwater uptake by hybrid poplar has decreased, while pedunculate oak has shown increasing reliance on groundwater in recent years. Precipitation events temporarily reduced groundwater dependency of the forest stands, with oak displaying a slower return to pre-rainfall groundwater uptake levels than poplar. Overall, the decline in groundwater levels hinders access to groundwater for both species, highlighting the need for sustainable forest management strategies to mitigate climate-induced water stress. These findings provide valuable insights for adaptive forestry planning in water-limited environments.

KEY WORDS: groundwater fluctuation, forest groundwater uptake, groundwater uptake strategies, hybrid poplar, pedunculate oak

Introduction

Forest vegetation is particularly vulnerable to rapid meteorological changes (Brodribb et al., 2020). This vulnerability manifests through reduced growth rates, increased susceptibility to pests and diseases, and potentially widespread mortality events or forest fires in cases of water stress and long dry periods (Allen et al., 2010; Hartmann et al., 2022; Pekar et al., 2008; Teshome et al., 2020). These changes could be drastic with a profound effect on the local hydrological cycle (Hlavčová et al., 2007; Valent et al., 2017).

The forest stands planted throughout the Great Hungarian Plain during the 20th century represent a critical case study of this vulnerability. Precipitation inputs alone increasingly fail to satisfy their water requirements. Many of these stands now face growing water deficits as changing precipitation patterns and increasing temperatures alter the local water balance (Kovács, 2018; Ladányi et al., 2009).

Different tree species exhibit varying water demands and exert various effects on hydrological processes within their ecosystems (Aranda et al., 2012; Armbruster et al., 2004; Mindas et al., 2018; Szabó et al., 2022). These species-specific dissimilarities in water use strategies and impacts on the hydrological cycle become critically important considerations under changing climate conditions. Understanding these variations is vital to developing effective forest management strategies and planning future forest compositions that can maintain resilience despite projected climate trends.

In the Hungarian Great Plain regions, groundwater serves as a supplementary water source for tree species with high water demands. Evaluating the impact of forests on the hydrological cycle entails quantifying their groundwater uptake. White developed a foundational method for estimating groundwater use by phreatophytic vegetation by calculating evapotranspiration based on daily groundwater recharge (White, 1932). Several researchers have since refined the method and it is still widely applied in contemporary studies. However, specific yield estimation (Sy) became an identified issue in the White method. To address this issue, the concept of readily available specific yield was applied as the basis for Sy estimation, which is determined based on sediment texture (Loheide II et al., 2005). Fahle and Dietrich (2014) utilised large-scale lysimeter data to test several groundwater evapotranspiration estimation methods that rely on daily groundwater level fluctuations. The methods assessed included those developed by White (1932), Dolan et al. (1984), Gribovszki (2008), Loheide II (2008), and Soylu et al. (2012). The results showed that while the methods exhibited significant correlations in estimating ET, they explained only up to 50% of the daily evapotranspiration rates and provided less accurate estimates of absolute ET values. Among the tested methods, the approach developed by Gribovszki showed the strongest correlation with measured values in estimating evapotranspiration rates.

This research uses on-site, high-frequency GWL measurements and the close relationship between diurnal groundwater level fluctuations and vegetation groundwater uptake. This methodology provides a valuable framework for comparing the relative groundwater consumption of vegetation and is based on the widely recognised White method and its subsequent modifications, which utilise the characteristic daily pattern of GWL rise and fall to estimate transpiration rates (Gribovszki et al., 2008; White, 1932).

Investigating the differential hydrological impacts and adaptability of key tree species in the Great Hungarian Plain could provide evidence-based guidance for sustainable forest management in water-limited environments.

This study investigates the effects the examined tree species have on daily groundwater level fluctuations – closely linked to groundwater uptake – and explores the differences in these effects under varying weather conditions and groundwater depths.

Material and methods

Study area

The study area is located in the northern-central part of the Great Hungarian Plain near Jászfelsőszentgyörgy (Fig. 1). The region has a continental climate, characterised by annual precipitation levels ranging from 354 to 970 mm (average: 557.1 mm) and an average yearly air temperature fluctuating between 9.4 and 12.3°C (average: 11.0°C) during the 1991–2020 period (HungaroMet, 2023). Topographically, the area consists of lowlands covered with loess and alluvial sediments. The hydrogeological conditions of the Jászság Basin are characterised by its setting as a neotectonic depression filled with thick Neogene and Quaternary sedimentary sequences, primarily alluvial deposits from the Zagyva and Tarna rivers. These sediments form multilayered aquifer systems, including unconfined and confined aquifers. The basin's flat topography and sediment composition favour significant groundwater storage, with aquifers generally exhibiting moderate to high permeability, although local variations occur due to clay lenses and sediment heterogeneity (Püspöki et al., 2020). Historically, this region comprised marshes, temporary and permanent watercourses, and pastures, which have been transformed into extensive pastures and arable land through drainage system implementation.

The study site consists of two measurement points: one established within a pedunculate oak (*Quercus robur* L.) forest and another in a hybrid poplar (*Populus x euramericana cv*. Agathe F) plantation. Pedunculate oak (*Quercus robur*) is the most widespread native tree species in the Great Hungarian Plain. Its water demand often exceeds local precipitation, necessitating reliance on supplemental water sources such as groundwater (Arvai et al., 2018). Populus × euramericana hybrids, derived from spontaneous crossing over or artificial crossbreeding between *Populus nigra* and *Populus deltoides* variants and cultivars (Bartha, 2004), are widely planted in the region. Among the poplar hybrids cultivated in Hungary, Agathe F is relatively waterlogging-tolerant but achieves high yields under conditions of excess water availability (Bordács et al., 2019).

Data collection

Groundwater observation wells with 5 cm diameter PVC pipes were installed in each monitoring location in 2012. Groundwater levels were continuously recorded at 15-minute intervals using DA-LUB 222-type (dataqua.hu) vented pressure transducers with a measurement accuracy of ±0.2% (Table 1). Transducers of this type

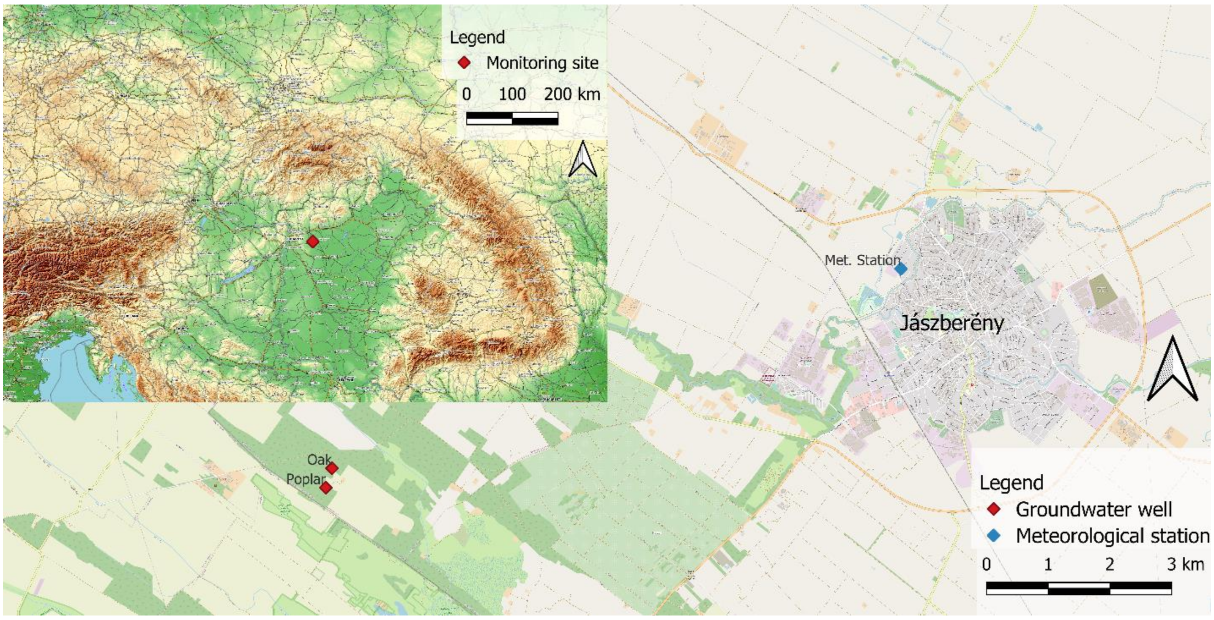

Fig. 1. Location of the study area and the data sampling points.

can deliver high-resolution data suitable for evapotranspiration estimation techniques based on diurnal groundwater level fluctuations (Gribovszki et al., 2013). During borehole drilling, soil samples were extracted at 20 cm intervals within the top 1 m and subsequently at 50 cm intervals below this depth. The soil texture classes in the soil layers were typically loam, sandy loam and loamy sand. Comprehensive precipitation data were obtained from a Hungarian Meteorological Service station in Jászberény (9 km from the monitoring site) (Fig. 1, Table 1).

The connection between diurnal GWL fluctuation and evapotranspiration from groundwater

Several hydrological processes – freezing and thawing, regular rainfall events in the tropics, and water uptake by vegetation driven by the daily photosynthetic cycle – can cause diurnal fluctuation patterns in groundwater levels (Gribovszki et al., 2010). The setting and circumstances of the present research study (study periods in summer, temperate climate) exclude all of the above factors except the role of water uptake by vegetation. Therefore, it can be assumed that the measured daily GWL fluctuation can be utilised to compare the relative changes in daily groundwater evapotranspiration (Soylu et al., 2012). Fig. 2 illustrates the schematic representation of this methodology. Recharge and vegetation uptake are balanced at two points during the diurnal groundwater level fluctuation cycle – when the groundwater level reaches its daily peak and trough. Although groundwater uptake begins before the peak and continues beyond the trough, the vast majority occurs between these two points.

Data analysis

The research database consisted of groundwater time series measured every 15 minutes and daily precipitation data from the two forest stands between 2015 and 2024. To investigate the daily groundwater uptake patterns of the studied tree species, the present research focused on the summer period, encompassing June, July, and August, when forests experience the highest temperatures and, consequently, the most evaporative demand.

Table 1. Main parameters of the sample points

Sampling point	Coordinates	Elevation [surface, m a.s.l.]	Well bottom [m a.s.l.]	Average groundwater level [from surface, m]	Study period	Forest stand age [years]	Wood volume [m³ ha^{-1}]
Poplar	47°28'40.68"N 19°46'21.02"E	106.3	99.3	-2.99 (+/- 0.46)	2015.01.01-2024.12.31.	23	215
Oak	47°28'50.82"N 19°46'25.88"E	105.8	98.8	-3.02 (+/- 0.42)		69	301
Meteorological station	47°30'34.92"N 19°53'45.96"E	93	-	-		-	-

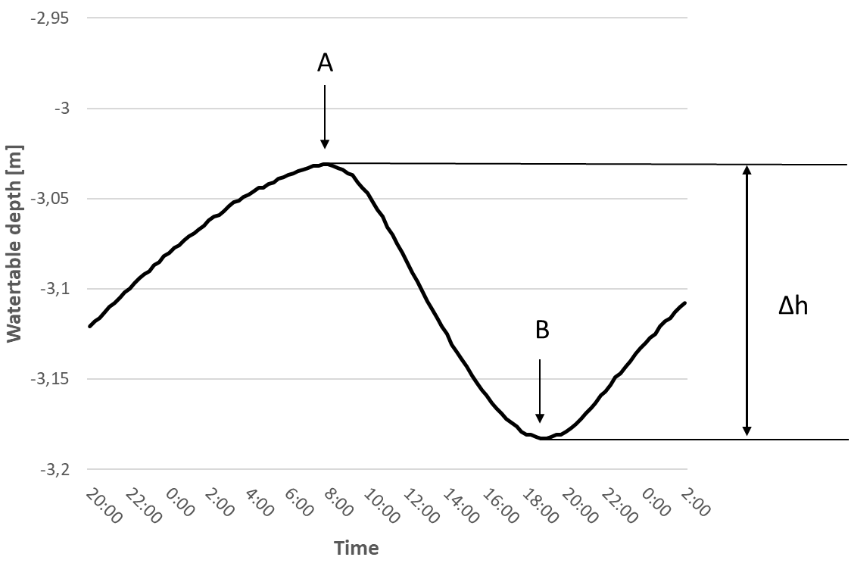

Fig. 2. Schematic representation of the connection between diurnal groundwater level fluctuation and groundwater uptake of the local vegetation (point A represents the peak, while point B is the trough of the daily groundwater table fluctuation driven by vegetation uptake, with Δh indicating the amplitude).

The data were analysed using R software, starting with data filtering to remove erroneous entries. The xts and tidyr packages in R were utilised to process the large time-series dataset. Analysing summer groundwater level trends at the two sites entailed visualising daily averages to filter out noise from daily fluctuations.

Due to data gaps, complete groundwater level datasets for both sites were only available during the summer periods of 2016, 2017, 2018, 2019, 2023, and 2024. In other years, data were either missing or incomplete for at least one of the forest stands. Years with more than 90 days of complete data for the summer season were selected for analysis. The most significant data gap affected 2021, which prevented the determination of annual maximum and minimum groundwater levels. Similarly, for the pedunculate oak site, the maximum groundwater level for 2015 and 2016 could not be determined.

Daily groundwater level fluctuations were identified by calculating the difference between the daily maximum and minimum groundwater levels for each day. Box plots were used to analyse these fluctuations at the two sample sites. For consistency, the box plots were generated with the same settings for all analyses: the boundaries of the box represent the first and third quartiles; whiskers are set to the 5th and 95th percentiles; data points beyond these are shown as outliers. The median values are shown in black, while the mean values are displayed in red. Additionally, to enhance clarity, the mean values were annotated with red numerical labels in the figures.

Changes in daily groundwater level fluctuations at the two sample sites were analysed separately for years with complete data sets using box plots. The dependence of daily groundwater level fluctuations on the daily mean groundwater level was also examined. The fluctuation data were grouped into half-meter depth clusters based on the daily mean groundwater level for each day, and these clusters were then visualised using box plots. Since the clusters contained different amounts of data, the number of data points for each cluster was displayed above the corresponding box plot.

Data processing found that daily groundwater level fluctuations in the pedunculate oak study site occasionally exceeded those observed in the hybrid poplar stand in late summer despite the species' lower water demand. To investigate this phenomenon, daily groundwater level fluctuations in the two sample plots were compared between the first (1 June–15 July) and second (15 July–31 August) halves of summer to elucidate potential differences in water use strategies between the two tree species. After splitting the groundwater dataset by date, the fluctuations were analysed using box plots, following the previously described methodology.

Results and discussion

The present study observed annual and daily groundwater level fluctuations throughout the examined 10-year period. The amplitude of annual fluctuations exceeded two meters in the hybrid poplar stand in most years (average and standard deviation over the years: 2.17 m ± 0.44 m), whereas the average annual groundwater level fluctuation remained around 1.5 meters in the pedunculate oak stand (average and standard deviation over the years: 1.54 m ± 0.31 m) (Fig. 3). These observations indicate that the groundwater level was shallower in the hybrid poplar stand at the end of the winter recharge phase, and the lowest groundwater levels were also observed here by the end of the growing season. Although groundwater data for 2021 are unavailable, a marked decline in both the maximum and minimum groundwater levels is evident between 2020 and 2021, likely due to the exceptionally low precipitation recorded during 2021 and 2022 (Table 2). Site conditions, including soil characteristics and recharge-discharge processes, were identical due to the proximity of the sample areas. Consequently, the observed differences in groundwater level dynamics were from the varying groundwater uptake habits of the various tree species. Previous research (Járó, 1981) published data on the water

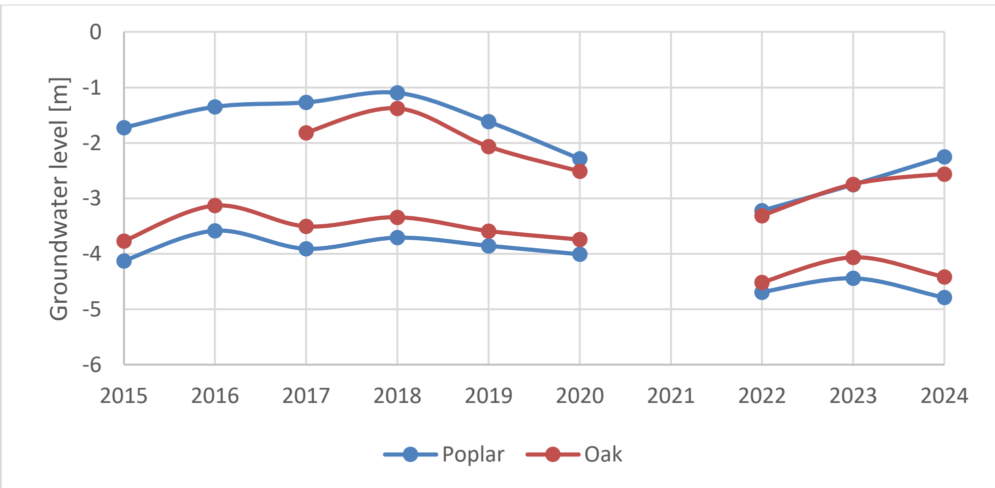

Fig. 3. Maximum and minimum values of annual groundwater depth in pedunculate oak and hybrid poplar forest stands.

consumption of the tree species, which were calculated by averaging the maximum annual water consumption of the species in different habitats. The estimated water demand is 680 mm for hybrid poplar and 441 mm for pedunculate oak, highlighting hybrid poplar's higher water demand.

Groundwater uptake for forest stands is crucial because precipitation alone does not meet the water demands of the trees (Table 2). When interception losses are considered 24.9% for pedunculate oak (Herbst et al., 2008) – annual precipitation during most years was insufficient even for pedunculate oak. Therefore, groundwater uptake plays a crucial role in satisfying water requirements.

A decline in groundwater levels occurred at both sample sites throughout the examined 10-year period. After 2019, groundwater levels did not rise closer to the surface than 2 meters, while minimum levels dropped below 4 meters (Fig. 3). The average decrease in the groundwater table from the beginning (2015–2017) to the end (2022–2024) of the study period exceeded 0.6 meters in both forest stands.

The groundwater level (Fig. 4) showed a declining trend during the summer period of each year, occasionally interrupted by short recharge periods. The most significant recharge event occurred in 2016, resulting in the lowest groundwater levels at the end of August. In some years (e.g., 2019), noticeable differences between the two stands were primarily reflected in the steepness of the curves.

Daily groundwater level fluctuations serve as groundwater uptake indicators. The hybrid poplar stand exhibited a higher annual average of daily groundwater level fluctuations than the pedunculate oak stand over the study period (Fig. 5). Throughout the study period, the two sample areas showed similar patterns in the average of daily groundwater level fluctuations during the summer, likely driven by interannual variability in meteorological conditions and groundwater table dynamics.

The trend in daily groundwater level fluctuations is assumed to be related to declining groundwater levels. To assess this hypothesis, daily groundwater fluctuation data were plotted against daily mean groundwater levels using half-meter depth clusters (Fig. 6).

The results indicated that the amplitude of fluctuation initially increased with declining water table depth, followed by a decrease in both stands. Hybrid poplar exhibited bigger fluctuations in all clusters, consistent with its higher water demand. The highest groundwater uptake occurred in the (-3; -2.5) cluster for hybrid poplar and the (-3.5; -3) cluster for pedunculate oak, likely due to differences in root system structure. It is important to note that there are relatively few data for the deepest groundwater level clusters ((-5; -4.5), (-4.5; -4)). These data are almost exclusively from 2024, as groundwater levels only fell below 4 meters during the summer of that year.

Table 2. Precipitation data during the study period

	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	Mean
Annual precipitation[mm]	526	682	610	546	539	639	405	431	725	485	559
Summer precipitation [mm]	168	234	127	174	106	300	92	61	237	106	160

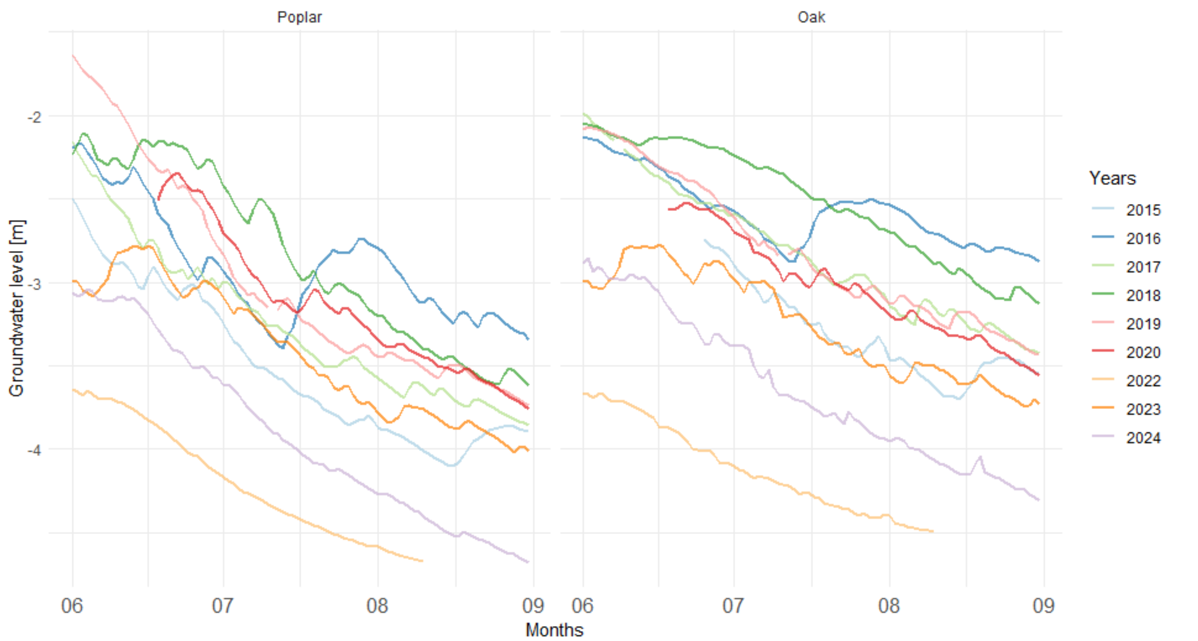

Fig. 4. Changes in groundwater levels in pedunculate oak and hybrid poplar stands during summer (years with incomplete data series are also represented).

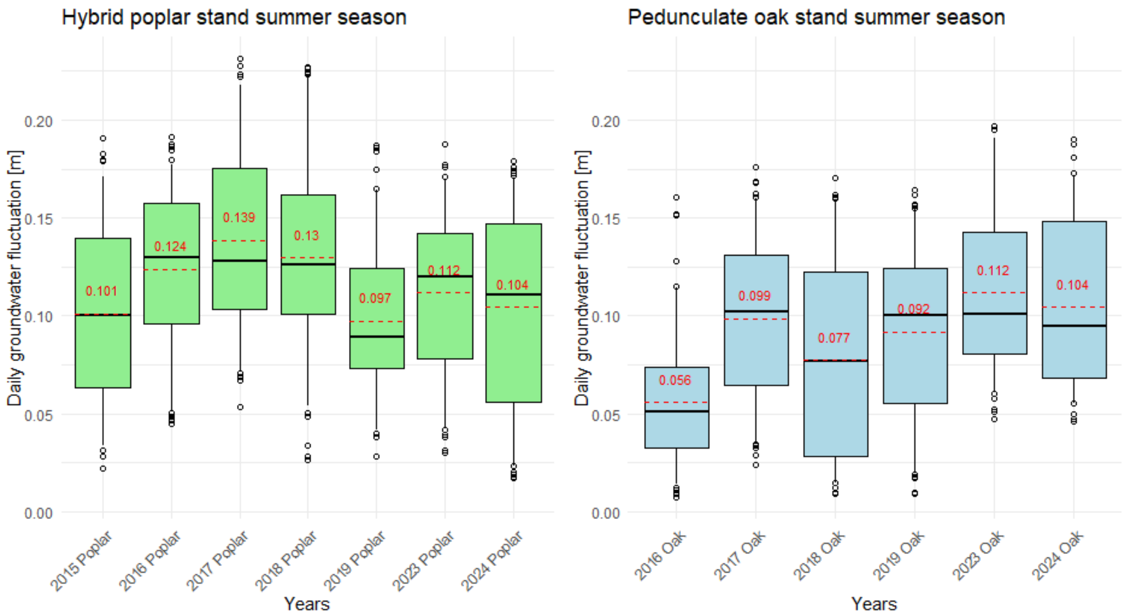

Fig. 5. *Change in daily groundwater level fluctuations during summer (June 1–August 31) in hybrid poplar (left) and pedunculate oak (right) stands. Red numbers and a dashed line indicate the average values.*

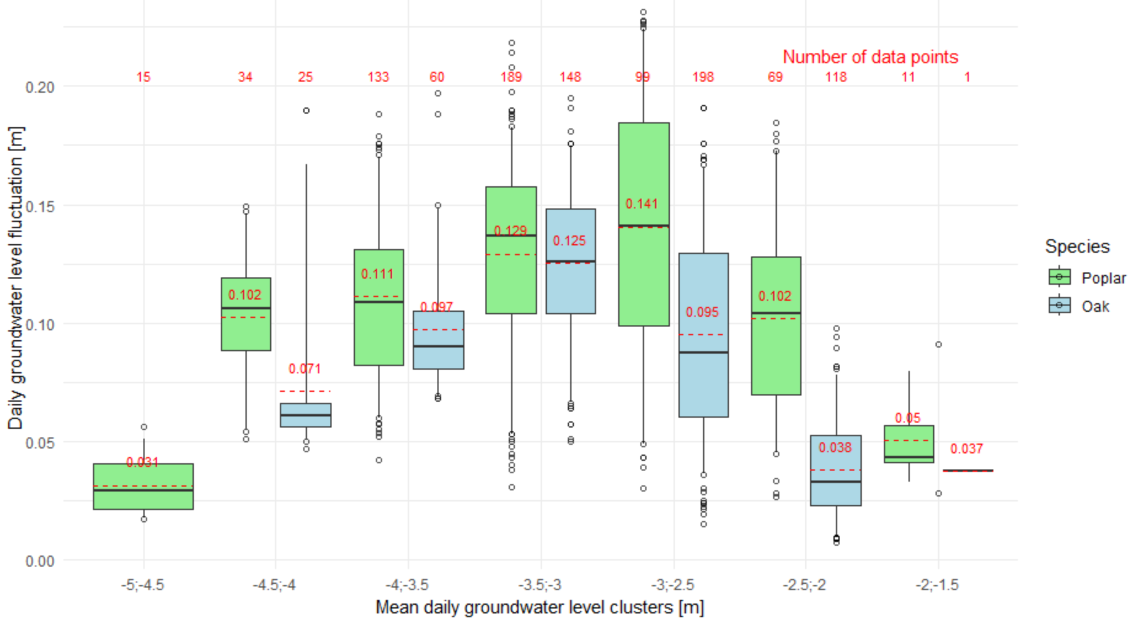

Fig. 6. *Daily amplitude of groundwater level fluctuation as a function of daily mean groundwater level, using half-meter depth clusters. The number of data points within each cluster is shown in red on the top axis. Red numbers and a dashed line represent the data set averages.*

Based on the groundwater level curves of the sample sites, we hypothesised that the two tree species might have different groundwater uptake profiles. Hybrid poplar exhibited more pronounced daily fluctuations in groundwater level in early summer (Fig. 7). The patterns observed in groundwater uptake intensity closely resembled those in Fig. 5, likely due to a decline in groundwater level. An exception occurred in 2023 when the daily groundwater fluctuation amplitude was higher in the pedunculate oak stand compared to the hybrid poplar stand. The wettest year of the study period was 2023, offering a possible explanation (Table 2), resulting in two recharge cycles in early summer (Fig. 4).

In late summer, we observed a shift in the daily groundwater uptake of the two species, with their average values converging. In some years, the average groundwater uptake of the pedunculate oak stand even exceeded that of the hybrid poplar stand. Compared to early summer, the groundwater consumption of both species showed a decline. This change was attributed to groundwater levels declining each year compared to early summer, and a long-term decline was also observed. As a result, the groundwater uptake potential of the stands decreased.

The effect of precipitation on groundwater level fluctuation was examined by comparing an average year (2019) and a wet year (2016) (Fig. 8). Similar groundwater level dynamics occurred in both years until mid-July. However, a 103 mm rainfall event in July 2016 caused groundwater levels to rise by almost half a meter,

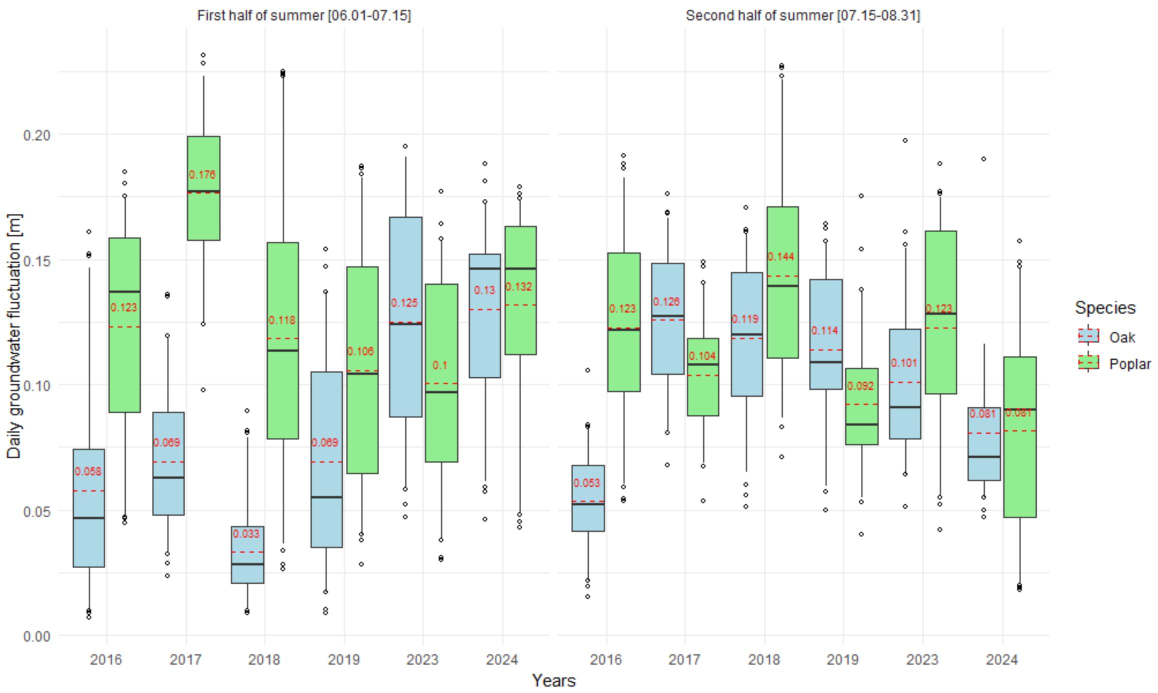

Fig. 7. Daily groundwater fluctuation amplitude in early (left) and late (right) summer in pedunculate oak and hybrid poplar stands. Red numbers and a dashed line represent the data set averages.

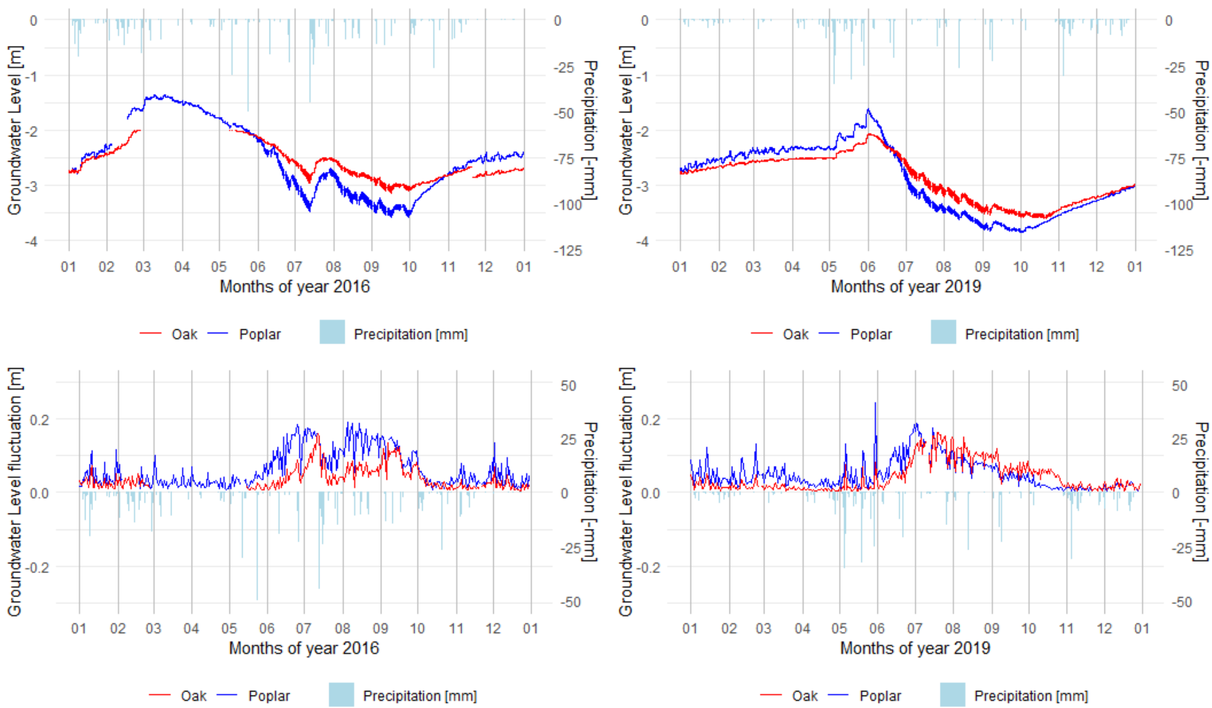

Fig. 8. Comparison of groundwater level dynamics and fluctuations in a wet year (2016) and an average year (2019) in hybrid poplar and pedunculate oak stands.

accompanied by a significant decrease in daily groundwater fluctuations. This reduction likely resulted from increased water availability in the upper unsaturated soil layers. Later, the daily groundwater level fluctuations increased again as the forest stands began to extract groundwater. By early August, hybrid poplar's groundwater uptake returned to pre-rainfall levels. Until the end of summer, the amplitude of groundwater level fluctuations at the hybrid poplar stand remained at a higher level than in 2019. In contrast, pedunculate oak required more time to resume its previous level of groundwater uptake due to different groundwater consumption strategies. Before the notable rainfall event in 2016, its groundwater uptake reached levels similar to those of the hybrid poplar, but after the rainfall event, it only matched those again by the end of the summer – when the groundwater level decreased under 3 meters again. This pattern can be attributed to the previously discussed relationship between daily groundwater level fluctuations and the average groundwater table depth (Fig. 6).

The observed decline in groundwater levels at the study sites over ten years may be a cause for concern. Our results indicate that a significant reduction in daily groundwater level fluctuations accompanies a sinking groundwater table. A marked decrease in daily fluctuations may suggest that forest stands are no longer able to access groundwater for uptake (Szabó et al., 2023).

Daily groundwater level fluctuations – which are related to vegetation groundwater uptake – are influenced not only by groundwater depth but also significantly by meteorological factors (Fan et al., 2014), as illustrated in Fig. 8. Furthermore, Yasuda et al. (2012) shows that during the growing season, daily groundwater fluctuations are synchronized with the variation in solar radiation.

Our results align with previous similar studies. According to Csáfordi et al. (2017), Sy value, groundwater table depth, meteorological parameters, and LAI significantly influence daily fluctuations. Their research also demonstrated that forest groundwater uptake increases during drought periods. Móricz et al. (2012) found that groundwater uptake can account for up to 90% of the total evapotranspiration of pedunculate oak during drought periods.

A previous study conducted in the same sample areas indicated that pedunculate oak stands extract more groundwater than hybrid poplar in mid-summer (Gribovszki et al., 2017), as we have shown in some years (Fig. 7), mainly because pedunculate oak increasingly relies on groundwater uptake during the second half of the growing season (Basu et al., 2024).

Conclusion

Analysis of groundwater level fluctuations revealed distinct groundwater uptake patterns for pedunculate oak and hybrid poplar. The primary factors influencing daily groundwater level fluctuation – which was used to characterise the groundwater uptake of tree stands – included daily mean groundwater levels and summer precipitation. Additionally, the two species show different groundwater uptake intensities in the first and second halves of the summer, which may be explained by the different physiological needs of the tree species. High-resolution groundwater level measurements enabled effective tracking of these processes.

To achieve a comprehensive water balance analysis in forest areas, we plan to install soil moisture meters in the sample plots. These sensors will provide crucial data on the water content of unsaturated soil layers, enhancing our understanding of how precipitation events influence groundwater uptake by forest stands.

As climate change progresses, groundwater availability will become increasingly crucial for meeting the water demands of these species. Continued groundwater level declines may reduce groundwater uptake, potentially leading to a deficit between water demand and water availability. In critical cases, disconnection from groundwater as a supplementary water source may occur. Climate change may induce a shift in forest tree species distribution. A 16–30% decline in suitable habitat for pedunculate oak is projected for 2071–2100 under both moderate (RCP 4.5) and high (RCP 8.5) emissions scenarios (Illés and Móricz, 2022). These findings underscore the necessity of considering groundwater conditions in sustainable forest management planning for this region.

Acknowledgements

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