DOI: 10.31577/ahs-2025-0026.01.0004

ACTA HYDROLOGICA SLOVACA

Volume 26, No. 1, 2025, 40 – 51

Analysis of the fluctuations of main water balance components at six forest stands in the Great Hungarian Plain

Bence BOLLA*, Ján SZOLGAY, Zoltán GRIBOVSZKI, Péter KALICZ, Márton DOBÓ, András SZABÓ

The hydro-meteorological measurement network of the Forest Research Institute of the University of Sopron monitored the water balance of six aged lowland forest stands (Bócsa: Grey poplar Gyula: Pedunculate oak, Jászberény: Pedunculate oak, Kecskemét: Scots pine, Püspökladány: Pedunculate oak, Pusztaszer: Black locust). Meteorological, soil moisture, and groundwater level data were used to estimate the differences between reactions of the water use of forest stands and changes in water balance in a predominantly dry period of 2019 to 2024. The available groundwater resources for the forest decreased significantly during this period, and the annual recharge cycle dampened or even diminished after the 2022 extreme compound warming and drought event, while the moisture stored in different soil layers, crucial for the survival of lowland forests, continued its recharging. The results contribute to understanding the variability and decrease of the access of the lowland forests to groundwater and soil moisture under conditions of warming climate, prolonged droughts and compound extremes.

KEY WORDS: lowland forests, precipitation, temperature, groundwater, soil moisture, drought

Introduction

Droughts may significantly alter the forest ecosystem in central Europe in the future. Cook et al. (2022) discovered that megadroughts may significantly increase in duration and temperature in the future, exacerbating drought risk and severity over Europe. Aalbers et al. (2023) suggested that the probability of drought in western and central Europe may markedly rise, reducing the recovery time for forest stands between drought periods. Forzieri et al. (2022) demonstrated that temperate forests are among those exhibiting reduced resilience owing to climate change, attributed to increased water supply restrictions. Moravec et al. (2021) identified an extraordinary intensity of soil moisture drought, taking into account the legacy of the multi-year period from 2014 to 2018 in Central Europe. Rakovec et al. (2022) examined the severity of the year 2018. They determined that anticipated future occurrences throughout Europe may have similar intensities to the 2018–2020 event, although possess significantly longer durations than any recorded in the past 250 years (Danáčová, 2024; Gáspár and Škrinár, 2023). Consequently, the increasing frequency and intensity of drought occurrences in Central Europe (Pavelková et al., 2023; Soľáková et al., 2023), may pose an escalating threat to its forests. This study examines the impact of an arid period from 2019 to 2021, followed by a compound heatwave and drought in 2022 (Rattayová, 2024), on the water balance of the lowland forests on the Great Hungarian Plain. In 2022, Central Europe and Hungary experienced a large drought coupled with an Intense heatwave, constituting a compound event. Tripathy and Mishra (2023) determined the return period to be 354 years in Northern Italy. Subsequently, there was a recovery in 2023, followed by a drought in 2024.
The introduction aims to set the framework for evaluating the outputs from the Hungarian lowland forest monitoring program analyzed in this paper. We do not aim to provide a comprehensive literature review on drought impacts on forests here, we will focus on findings that point to those connected to the water balance of forests in general, and the soil moisture and groundwater regime in six lowland forests stands in the Great Hungarian Plane. The paper's discussion section will address site-specific problems from the literature.
In Hungary's lowland forests, groundwater utilization by trees (evapotranspiration) during the growing season is an essential aspect of the lowland hydrological cycle, as forests are substantial consumers of groundwater and soil moisture. Groundwater recharge during the dormant season pertains to the complex mechanisms through which precipitation, surface water, or alternative sources

infiltrate both vegetated and bare soil, thereby recharging aquifers (Gribovszki et al., 2017). Recharge is an essential element of the natural water cycle and is crucial for preserving the health of various wooded habitats. Alterations in regional and local climate can profoundly affect the groundwater regime for both quality and quantity (Atawneh et al., 2021). Consequently, examining the spatiotemporal dynamics of evapotranspiration and recharge rates amid evolving land use and climatic conditions is essential (Hou et al., 2023) and consistently garners scholarly attention worldwide (Andualem et al., 2021; Móricz et al., 2016; Obuobie et al., 2012; Szabó et al., 2022; Yadav et al., 2023).

Recent and expected afforestation efforts aimed at climate change adaptation in Hungary also include the Hungarian Great Plain. Most forests can only survive by exploiting underground water supply surplus from groundwater (Gribovszki et al., 2017). Climate change can modify precipitation patterns, temperature regimes, snowmelt timing, and vegetation zones, as well as the duration of the growing season (e.g., Kupec et al., 2021), all of which influence evapotranspiration and, consequently, the quantity and distribution of groundwater consume and recharge.

Consequently, understanding the impact of changing climate patterns on groundwater recharge rates is essential (Wojkowski et al., 2023). Examining alterations in forested ecosystems is also essential for ensuring continued sustainability of forest and water resource management, as well as the response of forests to environmental changes. A significant area of European forests is situated in the Carpathians, which also include some of Hungary's woodlands. Kholiavchuk et al. (2024) conducted a review of 251 literature pertaining to the Western and Eastern Carpathians. They determined that recent environmental alterations had adversely affected forest health in numerous areas. Vacek et al. (2023) analyzed 365 studies on the impact of climate change on European forests from 1993 to 2022, revealing the migration of tree species and an increase in severe large-scale forest disturbances. Seidl et al. (2017), through an extensive global literature assessment, stated that elevated temperatures and reduced precipitation may promote disturbances due to drought, however alterations in vegetation may diminish sensitivity to climatic disturbances.

Nonetheless, further damage to forests may manifest following droughts (drought-legacy effect). The capacity of forest ecosystems to withstand and recover from anthropogenic and natural disturbances, such as water scarcity, droughts, and heatwaves, determines their resilience (Forzieri et al., 2022). The prolonged drought from 2018 to 2020 had a significant enduring impact on European woodlands (Knutzen et al., 2025). Central European forests experienced significant damage from droughts preceding 2022, particularly from 2018 to 2022. The specific impacts of drought on these forests can differ based on factors such as the intensity and duration of drought events, local ecological conditions, and existing forest management practices, among other variables. Bolla et al. (2024) present a comprehensive analysis of the impacts of water scarcity and climate warming, encompassing heatwaves and compound events, on forest health over that era, highlighting diminished growth, defoliation, and heightened mortality in Central Europe and Hungary.

Forest vegetation can evaporate more water than herbaceous plants due to its greater leaf area and deeper root zone (Calder, 1998; Jackson et al., 1999; Kelliher et al., 1993; Nosetto et al., 2005; Schenk and Jackson, 2002). Interactions among groundwater, soil water, and ecosystems in the Hungarian Plain demonstrate the cumulative influence of local variables. This is especially applicable in wooded regions with shallow groundwater, where groundwater dynamics can be a reliable indicator of the area's hydro-ecological characteristics. Consequently, water uptake by forest vegetation can substantially surpass that of herbaceous vegetation (Csáfordi et al., 2017; Fan et al., 2014; Nachabe et al., 2005; Schilling, 2007), leading to diverse types of groundwater depressions beneath the forests or to its decline.

The established heightened sensitivity of Pedunculate oaks to water balances in eastern Hungary (Árvai et al., 2018) supports the hypothesis that forests in the Sandridge region and the Great Plain may face increased risk and vulnerability due to both drought and escalating challenges in accessing groundwater. Monitoring and research initiatives are therefore essential for understanding the particular effects of climate change on the groundwater regime of lowland forest ecosystems. Given the regional variations in the manifestation of compound effects from climate extremes in temperature and precipitation deficit, considerable knowledge needs to be acquired regarding the dynamics and spatial distribution of disturbances affecting soil moisture regimes, groundwater levels, and their recharging in lowland forests. The sample areas researched in this paper are old lowland forest stands representative of the Hungarian lowland tree stands, both in terms of species and soils (Aridic arenosol and Chernic gleysol): Bócsa: Grey poplar; Gyula: Pedunculate oak; Jászberény: Pedunculate oak; Kecskemét: Scots pine; Püspökladany: Pedunculate oak; Pusztaszer: Black locust.

This study establishes the following aims:

- To reveal the hydrological consequences of warming and droughts on soil moisture, groundwater levels and recharge in six selected lowland forest stands by combining contemporary results from in-situ field measurements conducted between 2019 and 2024.
- To examine the cumulative impact of the exceptional drought and heatwave of 2022 on the forest ecosystems over this era.
- To delineate the time and duration of the varying reactions of the forests’ water budget across species and locations.
- To support monitoring needs for effective forest management systems in this regions of Hungary.

Our investigation has the aim to enhance the understanding of the potentially damaging effects of climate change and compound weather extremes on local forest functions and their water balance. Such knowledge is crucial for recognizing the diverse responses of lowland forests and the vegetation-climate feedback to future prolonged droughts likely to increase in frequency, severity, and duration.

Material and methods

Monitoring

The Great Hungarian Plain, also known as Great Plain, is a vast plain that covers a significant portion of Hungary. It is the largest part of the wider Pannonian Plain which extends into parts of eastern Croatia, northern Serbia, and western Romania. This region is characterized by its flat, fertile lowlands and is known for its agricultural productivity. The 6 study sites are located in the central and eastern parts, and in the Sandridge region (Fig. 1). The sample plots were selected from the hydro-meteorological network of the Forest Research Institute (22 meteorological stations and 15 groundwater wells), considering the ecological and physiographic characteristics of the Great Plain and the Sandridge regions. We collected data from forests that differed regarding the trees' age, composition and planting technology. The sample sites are named according to the nearby settlements, as indicated in Table 1. The tree species at the stands are typical for the Hungarian lowlands, where the proportion of these species was 61% in the whole lowland woodland area in 2024 based on the National Land Centre database (Nagy et al., 2023). These are three aged Pedunculate oak (*Quercus robur*) forest stands in the north, central and south regions of the Great Hungarian Plain (Jászeberény, Püspökladány and Gyula). Furthermore, we also observed a Scots pine (*Pinus sylvestris*) forest stand near Kecskemét. The Black locust (*Robinia pseudoacacia*) stand is a 49-year-old coppice forest in the middle of the Sandridge region (Pusztaszer). The Grey poplar (*Populus pubescens*) monitoring site is near Bócsa, which is 40 km away from Kecskemét and Pusztaszer in the Sandridge region. The soil types at the tree stands investigated slightly differ among the six monitoring plots, i.e., from sand with a low or moderate amount of humus (aridic arenosol) to loam with a low amount of clay (chernic gleysol). The parameters of the trees and soils were confirmed by local measurements (soil type, age and height of the forest). The soil data was confirmed both by field and laboratory tests. The size of each forest site was 50x50 m. The meteorological data were collected in weather stations located near the tree stands between 01.01.2019 and 31.12.2024. Air temperature and precipitation data were measured using AgroMet-2 type GPRS weather

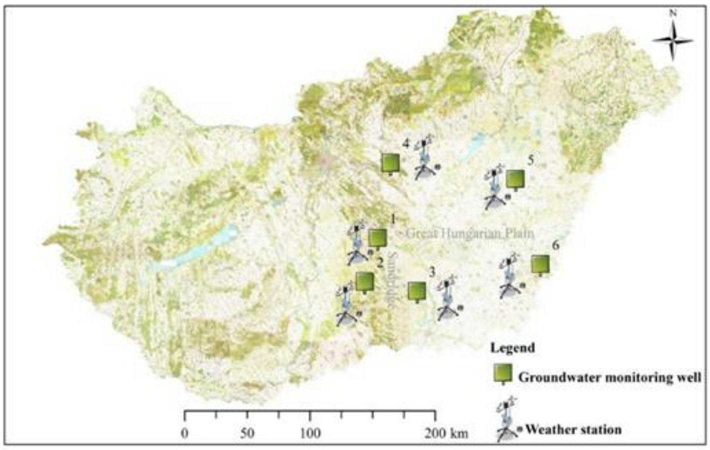

Fig. 1. Location of the monitoring plots and monitoring equipment.

Table 1. The main information about the monitoring sites

ID	Tree species	Age	Height [m]	Soil type (WRB)	GPS coordinates	Location
1	Scots pine (*Pinus sylvestris*)	37	8	Aridic arenosol	46.967224 19.553383	Kecskemét
2	Gery poplar (*Populus pubescens*)	45	16	Aridic arenosol	46.627763 19.494258	Bócsa
3	Black locust (*Robinia pseudoacacia*)	49	11	Aridic arenosol	46.555052 20.020371	Pusztaszer
4	Pedunculate oak (*Quercus robur*)	78	18	Aridic arenosol	47.480571 19.773845	Jászberény
5	Pedunculate oak (*Quercus robur*)	98	19	Chernic glaysol	47.340943 21.094648	Püspökladány
6	Pedunculate oak (*Quercus robur*)	74	26	Fragic gleysol	46.698669 21.323360	Gyula

stations manufactured by Boreas Measurement Technology Ltd. (boreas.hu), routinely operated in the Forest Research Institute hydro-meteorological system. Air temperature was measured at a height of 2 m. Open-field area precipitation was measured using a tipping bucket rain gauge with a surface area of 200 cm^2 at a height of 1 m with an unrestricted angle of incidence of 45° C. Data packets were transmitted hourly from the GPRS data loggers to the Forest Research Institute's server. All the methods applied complied with the ICP Forest manual, which contains documents for the harmonized methods for sampling and analysis as adopted by the participating countries of ICP Forests (ICP Forests Manual, 2020). The groundwater level was measured in Bócsa, Jászberény, Kecskemét, Püspökladány, Pusztaszer and Gyula using the Da-lub 222 pressure probe manufactured by Dataqua Electrical Kft. (dataqua.hu), which is part of the groundwater level monitoring system of the Forest Research Institute, also between 01.01.2019 and 31.12.2024. Groundwater level data were downloaded from the sensors' data loggers during local readouts every three months. Data were measured once a week at Pusztaszer using a manual method during the measurement period.

The soil moisture content of the six selected tree stands was measured at 10 and 70 cm depths using TSM-06 type GPRS measuring systems with a TDR system manufactured by Boreas Measurement Technology Ltd., which also transmitted data packets to the Institute's server every hour. The data collection period was between 01.01.2019 and 31.12.2024. in Kecskemét, Bócsa, Pusztaszer, Püspökladány and Gyula. In Jászberény, we received air temperature and precipitation data from the National Meteorological Service between 01.01.2019 and 31.12.2021. The period of data provision started from 01.01.2022.

The data series are presented here at annual and daily scales and characterize the vertical water balance processes in the forests.

Methodology

Comparative hydrology, which involves analyzing and comparing hydrological processes and characteristics across different regions or environments, was selected as the basic methodology here). These studies involve a combination of field measurements. Hydrological modelling was not involved in this study; collecting data on precipitation, groundwater levels, and soil moisture was essential for this comparative study. Conducting detailed case studies of the specific forest stands aimed at an in-depth comparison of hydrological processes and their influencing factors (Falkenmark and Chapman, 1989).

Inter-annual, seasonal and short-term fluctuations of groundwater levels and soil moisture result from many processes within and outside the aquifer and soil systems. Most subsurface processes are usually observed on a small scale and are generally influenced by natural processes (e.g. groundwater recharge) and anthropogenic influences (e.g. water abstraction, artificial recharge). Most natural processes are well known but have intrinsic spatial variability. In contrast to the limited availability of detailed spatial system characteristics, high-resolution data records of soil moisture and groundwater hydrographs were available for this study observed at a point scale. Upscaling to the regional scale, as required for generalizations by geostatistical methods or modelling, was unrealistic due to data scarcity and increasing complexity. Exploiting the information contained in these records by comparative hydrology and hydrogeology (Giese et al., 2020) was set as a priority for analysis because of the chronic lack of data describing spatial soil properties, groundwater system characteristics, and meteorological and ecological inputs. Following Falkenmark and Chapman (1989) and Giese et al. (2020), these methods have the potential to lead to arrive at an understanding of how and why the different stands respond to similar hydrological inputs.

Results

Longterm air temperature and precipitation regime

Data from the Kecskemét monitoring plot describes the region's long-term air temperature regime well. That site is also an ICP Forests Level II sample area and has been collecting meteorological data since 1999 within the framework of intensive monitoring (The Forest Protection Measuring and Monitoring System, klima.erti.hu). Our annual temperature data (Fig. 2) show a warming trend between 1999 and 2024. That's double the national average over the same period (Horváth el al. 2025). Warming over Hungary has gradually accelerated over the past 27 years according to our database of The Forest Protection Measuring and Monitoring System. Extremely high average annual temperatures were recorded in 2007, which at the time was treated as a localized extreme by scientists and forest managers alike. Between 2019 and 2024, temperatures gradually increased by 0.6°C.

Annual precipitation data show a 10% decline over the past six years and high average temperatures. The average annual precipitation between 2019 and 2024 was 550 mm in Kecskemét, which aligns with the World Meteorological Organization reference period regional average (1991–2020) based on data from the National Meteorological Service. Based on the national report of the Hungarian Meteorological Service, the national average temperature was 11.8°C in 2022 in Hungary, which was 1.1°C warmer than the 1991–2020 climate average. The verified, homogenized and interpolated data from the National Database show that 2022 was the third warmest year after 2019 and 2018 in the last 122 years. The average annual temperature has risen significantly nationwide (Hoyk and Kanalas 2025) (Fig. 2).

Air temperature and precipitation regime during 2019–2024

Regarding precipitation and temperature, drought and water scarcity periods are well described in the data for

2019–2024 in the study region. Average annual temperatures were highest in 2022 and 2024. Drainage of the areas started already in 2021 as no significant precipitation was recorded during the recharge period (autumn, winter). Historical drought was observed in 2022 for all sample areas, with high temperatures and an average annual precipitation of 350 mm, well below the Great Plain regional average of 550 mm recorded by the National Meteorological Service. The annual precipitation totals increased in 2023, averaging 617 mm in the sample areas. The year 2023 was 18% wetter than the long term average, but in the Pusztaszer sample area, it still barely exceeded 500 mm per year (which would be the minimum amount of precipitation needed to maintain forests in the region). The year 2024 had the highest average annual temperatures in Bócsa and Püspökladány. For the sample area of Bócsa, the year 2024 was the driest. The total annual precipitation was only 295 mm. In only two of the last six years (2020 and 2023) did the annual precipitation reach 500 mm in the sample area of Pusztaszer (Fig. 3). Three of the six years studied were extremely dry, with annual rainfall totals of less than or equal to 400 mm and average annual temperatures twice exceeding 12°C in the sample areas.

In all six years observed, long periods without precipitation occurred not only during the growing season but also during the dormant season. In many cases, this phenomenon negatively affected the water balance of the sample plots. The most severe drought occurred in 2022. The number of heat days (T(max) ≥ 30°C) and the number of hot days (T(max) ≥ 35°C) increased (62 heat days in 2022, 14 hot days in 2022, 68 heat days in 2024, 21 hot days in 2024). The increasing rate of atmospheric drought, as the subtype of the meteorological drought [low air humidity (RH≤40%), high temperature (T(max) ≥ 25°C), plant physiological symptoms (e.g. early leaf loss) at the same time (Lakatos et al. 2005).] was extremely high in 2022, 361 h/year, and in 2024, 312 h/year, based on weather station data. The precipitation data for the first half of 2022 in Gyula were 71.2 mm in the primary growing months (May, June, July). In Püspökladány, the three-month precipitation totals were 24.2 mm in January, February and March. In 2023, on average, 20% more precipitation was received in the lowland sample areas compared to the average period between 1991–2020. In 2024, after the spring precipitation, the average seasonal precipitation sum from June to September was 68 mm for the six sample areas (Fig. 4).

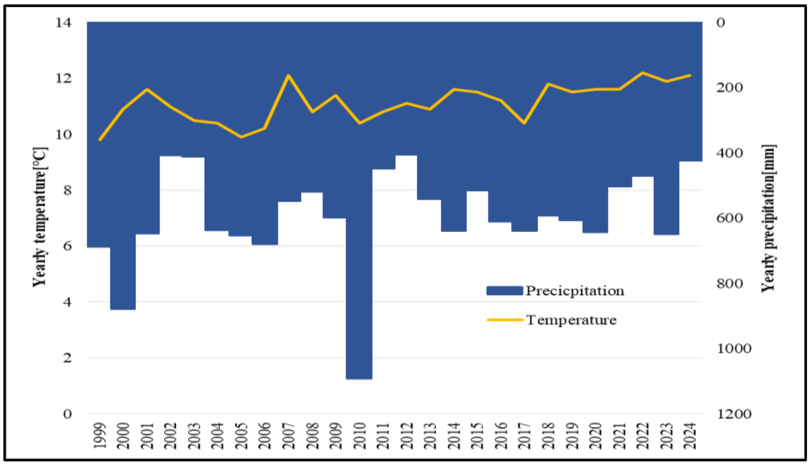

Fig. 2. Annual temperature and precipitation in Kecskemét (1999–2024).

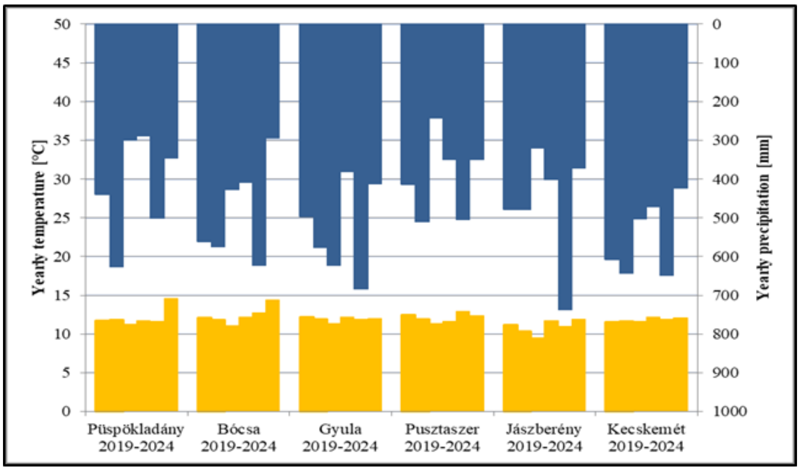

Fig. 3. Annual temperature and precipitation in six monitoring plots during 2019–2024.

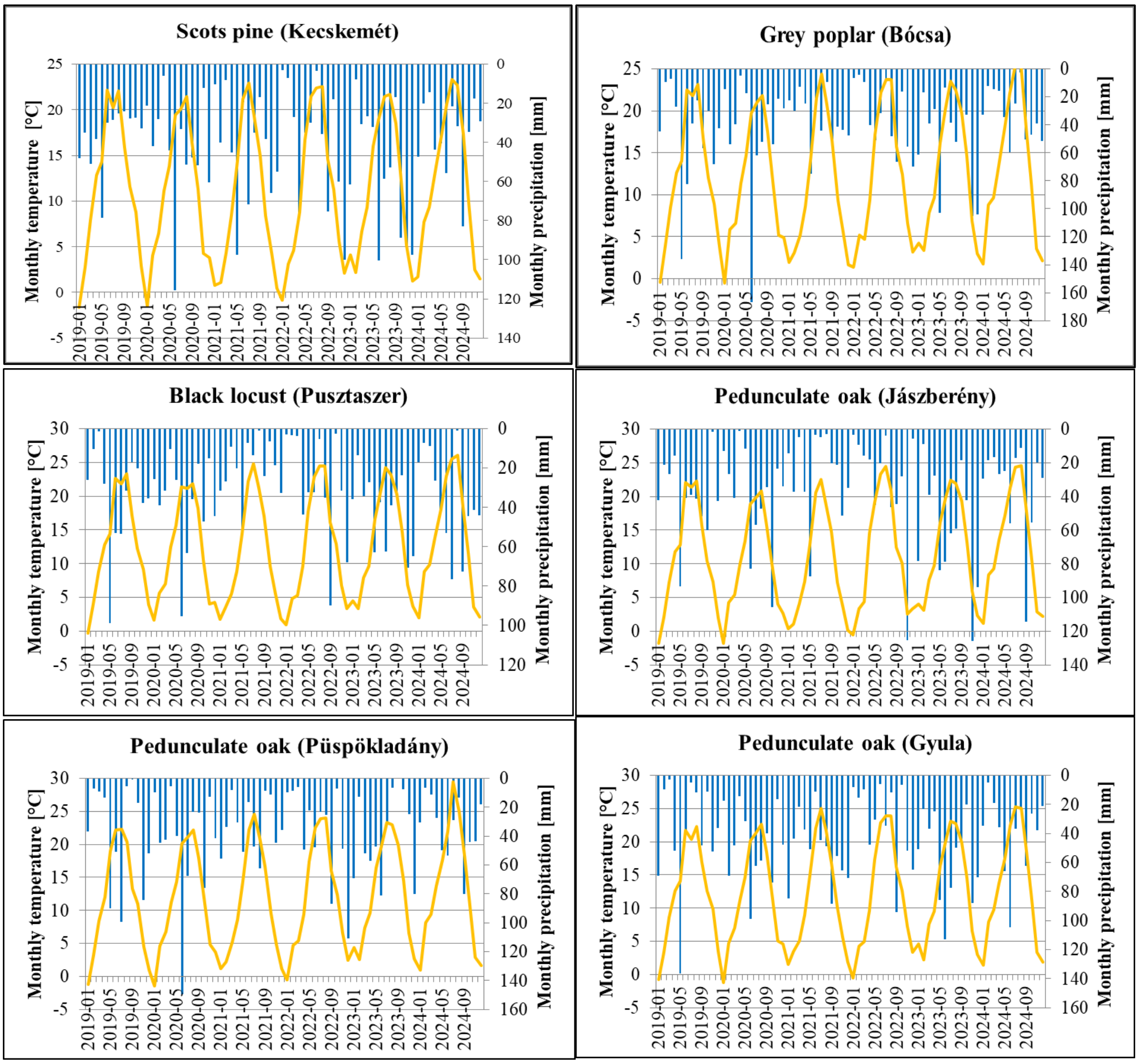

Fig. 4. Monthly precipitation and temperature courses between 2019 and 2024.

Groundwater regime (depletion and recharge)

The groundwater level in the Scots pine monitoring plot of Kecskemét has been continuously decreasing since the beginning of the observations (August 2018), which has not fundamentally changed by the annual cycle of precipitation infiltration and photosynthetic activity. In this case, there is no direct link between forest cover and groundwater, a phenomenon confirmed by the relatively deep groundwater (10.7 m). The groundwater depth also breaks the link between precipitation and groundwater (Fig. 5).

In Bócsa, the groundwater level of the monitoring well in the Grey polar stand also shows a continuous negative trend. The following dominant processes drive the seasonal signal of the groundwater in the vegetation period the significant water uptake of the trees causes water table decline while in the dormant season recharge becomes dominant resulting groundwater level raising. In the vegetation period, the abstraction by the tree stand, and in the dormant period, the recharge. Due to the extreme weather event in 2022, recharge was lost after the vegetation drawdown. The data indicate that the forest stand's root system cannot reach the groundwater table. The direct link between surface rainfall infiltration and the groundwater table has been broken, which may be partly because the forest stand is trying to uptake water to survive from the soil moisture. The groundwater level in 2024 is 4.4 m below the previous lowest level of 4 m in 2019.

The water level of the groundwater well in the Black locust in Pusztaszer has been dropping so much that the monitoring well has gradually lowered the groundwater level. In 2022, it dropped drastically, and recharge was only a minimum of 10 cm in the following dormant period. In 2019, the groundwater level in the aquifer was measured at 3.7 m, but this was undoubtedly below 6 m by the end of 2024. Like the Grey poplar stand, the Black locust stand also depends on soil moisture during the growing season. In the last two years, there was only a 12 cm difference between the recharge and the post-abstraction water levels, so there was still minimal potential for recharge observed.

The Pedunculate oak sample area in Jászság shows relatively stable groundwater levels with fluctuations (between 1 and 4 m). Groundwater dynamics show the usual fluctuations, driven by photosynthetic activity, both at annual and diurnal scales. That suggests that vegetation can directly absorb water from the groundwater, which is confirmed by its relatively shallow location. After this, in the dry year of 2022, a high level of abstraction (60 cm) was observed during the growing season. Fortunately, due to the rainy weather in 2023, the groundwater level could recover by recharge to a large extent to near the water level of the dormant period two years earlier. In 2024, the water table dropped again below 4.2 m after recharge due to the summer drought (Fig. 5).

In terms of groundwater resources, the impact of recent years of low precipitation is reflected in the previously observed trend in Püspökladány Pedunculate oak sample area, where, in contrast to August 2020, the photosynthesis-related fluctuation of soil water levels in the growing season was significantly reduced by August 2021, i.e. already before the drought of 2020, indicating a disconnection between groundwater and root system. That is clearly due to the continued subsidence of groundwater, which has been exacerbated by the two drought years since then (2021, 2022). As in the Black locust sample area, the recharge rate has gradually decreased (by 50 cm between 2021 and 2024), with water available for tree growth since 2022.

In the case of the Pedunculate oak forest stand in Gyula, the groundwater level has been gradually declining until 2021. The amplitude of recharge decreased moderately from 20 cm to 10 cm between 2019 and 2021. In 2022, the groundwater level decreased by 1.3 m compared to the previous year by the end of the growing season. The steep water level drop was associated with the extreme drought in 2022. As in the Pedunculate oak stand in the Jászberény sample area, the water level recovered to the previous dormant period in 2023 due to the wet weather. In contrast, in 2024, groundwater levels again dropped significantly due to poor precipitation and water uptake by old trees.

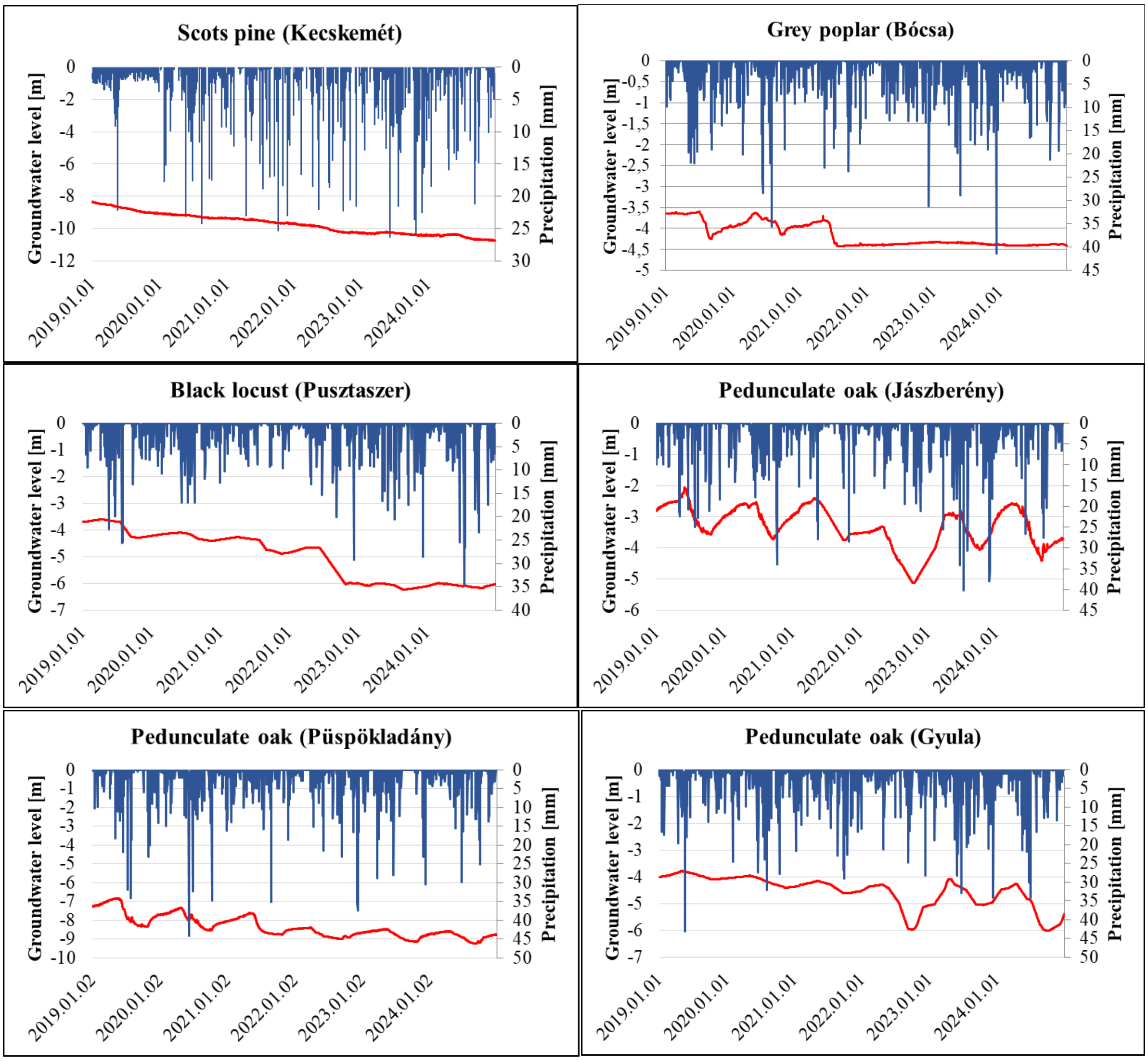

Fig. 5. Daily course of groundwater level and precipitation between 2019 and 2024.

Soil moisture monitored at 10 cm and 70 cm depth

Examining the soil moisture data at the surface (0–10 cm), as expected, the effect of precipitation events and the diurnal fluctuation caused by evaporation during the rainless period is evident, which is the smallest in sandy soils (Kecskemét, Bócsa, Pusztaszer, Jászberény). The most significant increase in moisture content was recorded on gleysol in Püspökladány and Gyula due to higher precipitation. The upper soil layer (0–20 cm) has super water-holding capacity and moisture conditions in that type of soils. The soil moisture measured here also returns to the original level relatively quickly after high-intensity rainfall events. The variation in measured soil moisture values is clearly related to increased evapotranspiration and plant water consumption during the growing season. The lowest values during the growing season were observed from mid-July to early November each year. Soil moisture content starts to trend upwards in October and November during the autumn-winter months. A full recharge can be observed at the end of the dormant season. In the year 2022, the top 10 cm soil layer in sandy soils dries out significantly within 5–7 days.

Due to gleysoils excellent water-holding capacity, the drying process was three times slower than in sandy soils. The highest moisture content was also measured in Püspökladány and Gyula on these soils. Based on the 70 cm deep measurements, 2022 showed a spectacular drying out of the sample plots on sandy soils. Even the clayey soil in Püspökladány could not be recharged due to the severe lack of precipitation. In that year, the lowest values in the 6 years were measured in the middle of the growing season for all sample plots. In the sandy soils, the deeper soil layer was recharged in all years except the Kecskemét site so that the initial water supply (70–84 mm) was available for vegetation year after year. Gleysoils were recharged more slowly, and water loss was accordingly slower. Thanks to the 2023 rainfall, the soils were rapidly recharged. In contrast, in 2024, the bound soils in Püspökladány and Gyula show a lag in recharge due to low moisture content in autumn and lack of precipitation. In the sample area of Gyula, the moisture stored in the soil was continuously available for vegetation; even in the year 2022, only an average decrease of 6–7% in soil moisture was observed in the resting period (Fig. 6).

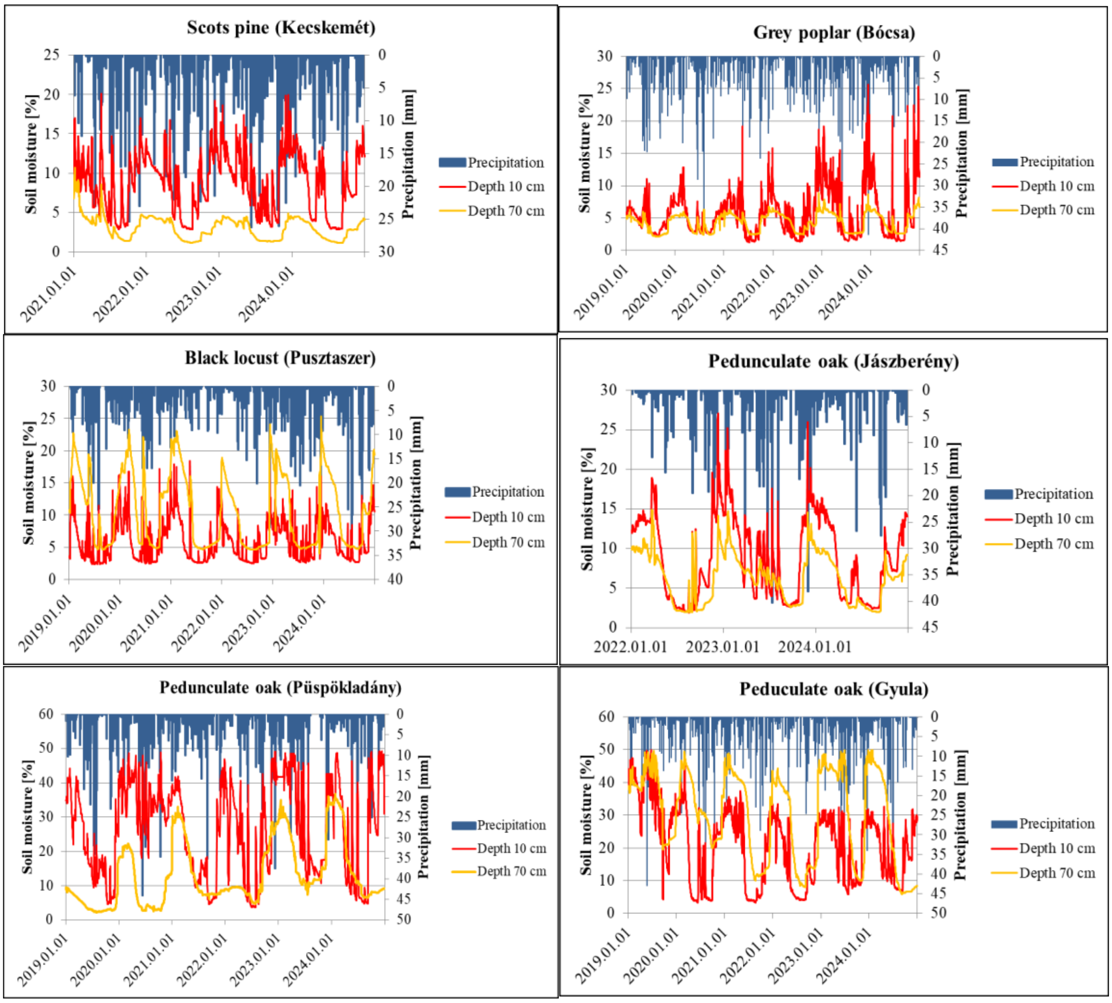

Fig. 6. Daily course of soil moisture (at depth 10 cm and 70 cm) and precipitation between 2019 and 2024.

Discussion

Based on our measurements, soil moisture responded to infiltration during the whole monitoring period. Water uptake by the forest was indirectly indicated by the observed ground water decline, since no other ground water uses are present in the region. For two sample plots (Bócsa, Pusztaszer), vegetation period infiltration to groundwater ceased as tree stands took moisture from the soil through their roots which This finding was confirmed by the root depths (0–150 cm) in the excavated soil profile pits.

However, explaining the dampening of seasonal fluctuations in groundwater levels and the steady declining overall trend is a more complex problem. Methods to study such phenomena include micrometeorological techniques, lysimeter, and water balance modelling. A multitude of studies globally have focused on estimating groundwater evapotranspiration by various models, predominantly empirical statistical models, energy balance models, and supplementary correlation models (Hou et al., 2023; Kumar et al., 2022; West et al., 2022). Instead of modelling, this study described and compared observed regime changes on a regional scale.

The observed general decline in groundwater levels agrees with their generally observed and accepted regional behaviour (Ijjász, 1939; Pálfai, 1994; Szilágyi and Vörösmarty, 1993), which is present not only under the forests in the whole region. Decrease span from a few decimeters to meters.

We showed that besides the long-term decline (a study of that is out of the scope of the research in this study), groundwater levels beneath the forest pilots demonstrate the expected seasonal variations across distinct ranges, which attain zenith reach in spring and the lowest point by the end of the growing season (at least in the first part of the monitored period, see Bócsa, Pusztaszer) except for Kecskemét, where no connection to the deep roots to groundwater can be hypothesized. Our dataset showed the impact of three different forest stands (Jászberény, Püspökladány, Gyula) on groundwater level. Several authors investigated the magnitude of seasonal groundwater depression levels using monitoring data, and their results agree with our observations. Major (2002) established this measurement as a maximum of 0.8–1.1 meters in the studied area. Szodfridt and Faragó (1968) recorded depressions of 50–60 cm, Nosetto et al. (2007) evaluated depressions of 25–75 cm, whilst Markó (2014) noted even variations of 2–3 meters beneath noble poplar plantations.

In this study, we did not intend to explain the magnitude of seasonal changes and connect these to evapotranspiration. Much more detailed data would be needed for advanced modelling of evapotranspiration and the hydrodynamics of soil water movement. Vágás (1993) underscored in this respect the significance of hydraulic parameters associated with soil texture in the development of groundwater depression as a factor that could be an order of magnitude greater than that of the actual groundwater evapotranspiration. Szilágyi et al. (2012) discovered that in forested regions, evaporation exceeded precipitation by 70–80 mm (as an annual average for the period 2000–2008) at many sites. A negative water balance can only arise if forests utilize groundwater resources, including supplementary inflow from adjacent water bodies, potentially resulting in a decline in groundwater levels. Numerous researchers (Jackson et al., 2005; Jobbágy and Jackson, 2004; Lu et al., 2018) have documented the impact of forests on the formation of groundwater level depressions, primarily emphasizing the water absorption by trees.

Our investigations were limited to local point scale changes, and we have not attempted to connect the decline to external factors and investigate its spatial extent. On the other hand, we may connect the observed nonlinearity of the change around 2022 in Pusztaszer, Bócsa and Püspökladány to the observed spatial temperature anomaly (the extreme heatwave in 2022) in the region, the compound effects of the prolonged drought from 2018 to 2020 and the gradually ceasing connection of tree rooting system to the groundwater in course of the general decline. These factors need continuing attention for the future since they can be a significant risk factor for forest health in case of no recharge recovery. In this respect, the gradual increase in air temperature seems to be a decisive factor. The years 2022 and 2024 have been arid, with record-high annual average temperatures for all sample areas. The increasing rate of atmospheric drought was extremely high in 2022, 361 h/year, and in 2024, 312 h/year, based on weather station data. In 2022, there were long periods without precipitation. In 2023, there was an average of 20% more precipitation in the lowland sample areas than in the last 30 years. The observed nonlinearity can be attributed to drought legacy, which we described in detail in Bolla et al. (2024).

Conclusion

Groundwater level decline, which affects the Great Plain and the Sandridge region, is a problem which may have serious ecological and economic consequences. Research into the possible causes behind this phenomenon has been ongoing for decades, but the causes are still the subject of scientific debate. This paper aimed to contribute with concrete data and their explanation concerning the role of the water balance of the forests. Our results showed that the observed seasonally fluctuating groundwater regime additionally exhibited a steadily declining trend in all six monitoring points. That needs an explanation to assess the potential changes in future groundwater recovery levels. In this respect, it must be noted that the trend of groundwater decline at the regional scale has been observed in the region since the beginning of the 70s of the last century.

Groundwater levels confirmed the general negative trends for four of the six sample sites. Severe drought in 2022 was reflected in negative trends for all sample sites. In the sample plot at Bócsa, the groundwater level dropped so much from 2022 that it could not recharge in 2023. The negative trend continued in 2024, as confirmed by the water levels in the surrounding wells. Over the last 10 years, the groundwater level in Bócsa has dropped by 2.2 m (Bolla and Németh, 2017). The local results measured in the sample areas are clearly part of a regional trend. These constitute a serious risk of increasing water scarcity. The serious problem of drought legacy was also clearly demonstrated in our study at all sites. Complex monitoring of drought legacy needs to be extended in space and time.

Several authors stress that afforestation as a climate change adaptation measure may become a factor in reducing groundwater levels. This can take two forms: the uptake of water by vegetation and the reduction of recharge from precipitation (interception, soil moisture uptake). The functioning of these mechanisms was not investigated here. We focused on two system outputs: groundwater levels in six sample plots and soil moisture at 10 and 70 cm depth, which were measured with high temporal resolution.

The data showed the impact of three different forest stands (Jászberény, Püspökladány, Gyula) on groundwater level. The vertical distance between the root zone and the groundwater governed these. In the case of soil moisture, the seasonal drying effect of forest stands and the wetting effect by precipitation were evident in both layers. Soil moisture data for the deeper layer suggested that groundwater recharge from precipitation is potentially possible but did not always occur, probably caused by the water consumption of the shallower roots. Presumably, the effect of macropores was also not present. Results allow us to conclude that forest stands may have significantly different local effects on groundwater level fluctuations, and generalizations should be cautiously made. The background of the processes can only be elucidated based on detailed monitoring data of several elements of the hydrological system rather than general temporary and spatially sparse observations. These results also highlight that generalizations about the role of individual factors (e.g. the generally higher specific water use of forest stands) are not an appropriate starting point for understanding the processes in highly complex local hydrological systems. Instead, we need to rely on long-term detailed monitoring results, preferably covering as many elements of the local system as possible. That is particularly true for the scientific basis for land use change decisions. As for adaptation to climate change, in addition to continuing hydrological monitoring in forests, the solution could be to increase the resilience of existing forest stands and to use climate-resistant tree species (e.g. Greyish oak: *Quercus pedunculiflora*).

Acknowledgement

This work was supported by the Slovak Research and Development Agency under Contract No. APVV 20-0374, No. APVV 23-0332 and the VEGA Grant Agency No. VEGA 2/0115/25.

This article was made in frame of the project TKP2021-NKTA-43 which has been implemented with the support provided by the Ministry of Innovation and Technology of Hungary (successor: Ministry of Culture and Innovation of Hungary) from the National Research, Development and Innovation Fund, financed under the TKP2021-NKTA funding scheme.

References

Aalbers, E. E., van Meijgaard, E., Lenderink, G., Vries, H. de, Van den Hurk, B. J. J. M. (2023): The 2018 west-central European drought projected in a warmer climate: how much drier can it get? Natural Hazards and Earth System Sciences, v. 23, p. 1921–1946.

Andualem, T. G., Demeke, G., Ahmad, I., Sebhat, M., Dar, M. (2021): Groundwater recharge estimation using empirical methods from rainfall and streamflow records, Journal of Hydrology: Regional Studies, v. 37, p. 100917.

Árvai, M., Morgós, A., Kern, Z. (2018): Growth-climate relations and the enhancement of drought signals in pedunculate oak (Quercus robur L.) tree-ring chronology in Eastern Hungary, iForest - Biogeosciences and Forestry, v. 11, p. 267–274.

Atawneh, D. A., Cartwright, N., Bertone, E. (2021): Climate change and its impact on the projected values of groundwater recharge: A review, Journal of Hydrology, v. 601, p. 126602

Bolla, B., Németh, T. M. (2017): Monitoring of the Hydrological Balance in the Area of the Kiskunság National Park Directorate, Acta Silvatica et Lignaria Hungarica, v. 13, p. 097–111.

Bolla, B., Manninger, M., Molnár, T., Horváth, B., Szolgay, J., Gribovszki, Z., Kalicz, P., Szabó, A. (2024): Evaluation of the Compound Effects of the 2022 Drought and Heatwave on Selected Forest Monitoring Sites in Hungary in Relation to Its Multi-Year Drought Legacy, Forests, v. 15, p. 941.

Boreas.hu: http://www.boreas.hu/index.php?src=erzekelok &lang=eng, date of the access : 10.03.2025.

Calder, I. R. (1998): Water use by forests, limits and controls, Tree Physiology, v. 18, p. 625–631.

Cook, B. I., Smerdon, J. E., Cook, E. R., Williams, A. P., Anchukaitis, K. J., Mankin, J. S., Allen, K., Andreu-Hayles, L., Ault, T. R., Belmecheri, S., Coats, S., Coulthard, B., Fosu, B., Grierson, P., Griffin, D., Herrera, D. A., Ionita, M., Lehner, F., Leland, C., Marvel, K., Morales, M. S., Mishra, V., Ngoma, J., Nguyen, H. T. T., O'Donnell, A., Palmer, J., Rao, M. P., Rodriguez-Caton, M., Seager, R., Stahle, D. W., Stevenson, S., Thapa, U. K., Varuolo-Clarke, A. M., Wise, E. K. (2022): Megadroughts in the Common Era and the Anthropocene, Nature Reviews Earth & Environment, v. 3, p. 741–757.

Csáfordi, P., Szabó, A., Balog, K., Gribovszki, Z., Bidló, A., Tóth, T. (2017): Factors controlling the daily change in groundwater level during the growing season on the Great Hungarian Plain: a statistical approach, Environmental Earth Sciences, v. 76.

Danáčová, M., Danáčová, Z., Hlavčová, K., Škrinár, A., Kalicz, P., Výleta, R. (2024): Comparison of Eco-Hydrological Limits as Water Scarcity Indicators for the Water Balance Inventory of Slovakia. Slovak Journal of Civil Engineering, 32(4), 50–59.

Fan, J., Oestergaard, K. T., Guyot, A., Lockington, D. A. (2014): Estimating groundwater recharge and evapotranspiration from water table fluctuations under three vegetation covers in a coastal sandy aquifer of subtropical Australia, Journal of Hydrology, v. 519, p. 1120–1129.

Dataqua.hu: https://www.dataqua.hu/product.php?lang=en, date of the access: 13.03.2025.

Falkenmark, M., Chapman, T. (1989): Comparative

Hydrology: an ecological approach to land and water resources, UNESCO, Paris. p. 479.

Forzieri, G., Dakos, V., McDowell, N. G., Ramdane, A., Cescatti, A. (2022): Emerging signals of declining forest resilience under climate change, Nature, v. 608, p. 534–539.

Gáspár, V., Škrinár, A. (2023): The Impact of Climate Change and Regulation of the Water Regime on the Morphological Structure of the Floodplain Forests in Petržalka, Slovakia. Slovak Journal of Civil Engineering, 31(1), 52–57.

Giese, A, Boone, A., Wagnon, P., Hawley R. (2020): Incorporating moisture content in surface energy balance modeling of a debris-covered glacier, EGU Articles, v. 14. 1555–1577. (https://tc.copernicus.org/articles/14/1555/2020/)

Gribovszki, Z., Kalicz, P., Balog, K., Szabó, A., Tóth, T., Csáfordi, P., Metwaly, M., Szalai, S. (2017): Groundwater uptake of different surface cover and its consequences in great Hungarian Plain, Ecological Processes, v. 6.

ICP Forests Manual (2020): United Nations Economic Commission for Europe Convention on Long-range Transboundary Air Pollution International Co-operative Programme on Assessment and Monitoring of Air Pollution Effects on Forests (ICP Forests) https://icp-forests.net/page/icp-forests-manual date of the access : 10.03.2025.

Ijjász, E. (1939): A fatenyészet és az altalajvíz, különös tekintettel a nagyalföldi viszonyokra (Forest stands and groundwater, with special regard to the conditions in the Great Plain), Erdészeti Kísérletek, v. 42, p. 1–107. (in Hungarian)

Horváth, Á., Breuer, H., Simon, Cs. (2025): A forróság meteorológiája. (The meteorology of heat), Erdészeti lapok, v.160, p. 53–56. (in Hungarian)

Hou, D., Al-Tabbaa, A., O'Connor, D., Hu, Q., Zhu, Y.-G., Wang, L., Kirkwood, N., Ok, Y. S., Tsang, D. C. W., Bolan, N. S., Rinklebe, J. (2023): Sustainable remediation and redevelopment of brownfield sites. Nature Reviews Earth and Environment, v. 4, p. 271–286.

Hoyk, E., Kanalas, I. (2025): Kecskemét klímaváltozási kihívásai és alkalmazkodási lehetőségei. (Kecskemét's climate change challenges and adaptation opportunities), Kecskméti digitalis újság v.10. 148–166. (in Hungarian)

Jackson, R. B., Jobbágy, E. G., Avissar, R., Roy, S. B., Barrett, D. J., Cook, C. W., Farley, K. A., Le Maitre, D. C., McCarl, B. A., Murray, B. C. (2005): Trading water for carbon with biological carbon sequestration, Science (New York, N.Y.), v. 310, p. 1944–1947.

Jackson, R. B., Pockman, W. T., Hoffmann, W. A. (1999): The Importance of Root Distributions for Hydrology, Biogeo-chemistry, and Ecosystem Functioning: Integrating Hydrol. Ecosyst. Dyn. Biogeochem. 1999, 217–238.: Complex Landscapes, p. 217–238.

Jobbágy, E., G., Jackson, R., B. (2004): Groundwater use and salinization with grassland afforestation, v. 10, p. 1299 – 1312.

Klima.erti.hu: http://klima.erti.hu/home/intenziv-monitoring/ date of the access : 13.03.2025. (in Hungarian)

Kelliher, F. M., Leuning, R., Schulze, E. D. (1993): Evaporation and canopy characteristics of coniferous forests and grasslands, Oecologia, v. 95, p. 153–163.

Kholiavchuk, D., Gurgiser, W., Mayr, S. (2024): Carpathian Forests: Past and Recent Developments, Forests, v. 15, p. 65.

Knutzen, F., Averbeck, P., Barrasso, C., Bouwer, L. M., Gardiner, B., Grünzweig, J. M., Hänel, S., Haustein, K., Johannessen, M. R., Kollet, S., Müller, M. M., Pietikäinen, J.-P., Pietras-Couffignal, K., Pinto, J. G., Rechid, D., Rousi, E., Russo, A., Suarez-Gutierrez, L., Veit, S., Wendler, J., Xoplaki, E., Gliksman, D. (2025): Impacts on and damage to European forests from the 2018–2022 heat and drought events, Natural Hazards and Earth System Sciences, v. 25, p. 77–117.

Kumar, P. J., Schneider, M., Elango, L. (2022): The State-of-the-Art Estimation of Groundwater Recharge and Water Balance with a Special Emphasis on India, A Critical Review: Sustainability, v. 14, p. 340.

Kupec, P., Deutscher, J., Futter, M. (2021): Longer Growing Seasons Cause Hydrological Regime Shifts in Central European Forests, Forests, v. 12, p. 1656.

Lakatos, L., Karácsonyi, Z., Racskó, J., Zhong-Fu, S., Yingchun, W. (2005): A légköri szárazság hatásának vizsgálata a különböző kertészeti és szántóföldi növényfajok termésmennyiségének változására (Investigating the effect of atmospheric drought on the yield changes of various agricultural and arable plant species), Agrártudományi közlemények, v. 18, p. 40–45. (in Hungarian)

Lu, J., Xue, D., Gao, Y., Chen, G., Leung, L., R., Staten, P. (2018): Enhanced hydrological extremes in the western United States under global warming through the lens of water vapor wave activity, Climate and atmospheric science, v. 1, p.1–9.

Major, P. (2002): Síkvidéki Erdők Hatása a Vízháztartásra (Impact of lowland forests on water balance), v. 82, p. 319–323.

Markó, A. (2014): Ipari Nyár Ültetvények Környezeti Hatása Mezőgazdasági Területeken (Environmental impact of Noble poplar forest stands on agricultural lands), Hungarian Soil Science Society meeting on Keszthely.

Moravec, V., Markonis, Y., Rakovec, O., Svoboda, M., Trnka, M., Kumar, R., Hanel, M. (2021): Europe under multi-year droughts: how severe was the 2014–2018 drought period? Environmental Research Letters, v. 16, p. 34062.

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 - Biogeosciences and Forestry, v. 9, p. 696–701.

Nachabe, M., Shah, N., Ross, M., Vomacka, J. (2005): Evapotranspiration of Two Vegetation Covers in a Shallow Water Table Environment, Soil Science Society of America Journal, v. 69, p. 492–499.

Nagy, K.; Szalóki A. Hungary: in Michel A, Kirchner T, Prescher A-K, Schwärzel K (2023): (editors): Forest Condition in Europe: The 2023 Assessment. ICP Forests Technical Report under the UNECE Convention on Long-range Transboundary Air Pollution (Air Convention) Eberswalde: Thünen Institute. https://doi.org/10.3220/ICPTR1697801881000

Nosetto, M. D., Jobbágy, E. G., Paruelo, J. M. (2005): Land-use change and water losses: the case of grassland afforestation across a soil textural gradient in central Argentina, Global Change Biology, v. 11, p. 1101–1117.

Nosetto, M. D., Jobbágy, E. G., Tóth, T., Di Bella, C. M. (2007): The effects of tree establishment on water and salt dynamics in naturally salt-affected grasslands, Oecologia, v. 152, p. 695–705.

Obuobie, E., Diekkrüger, B., Agyekum, W., Agodzo, S. (2012): Groundwater level monitoring and recharge estimation in the White Volta River basin of Ghana, Journal of African Earth Sciences v. 71–72, p. 80–86.

Pálfai, I. (1994): Összefoglaló tanulmány a Duna—Tisza közi talajvízszint-süllyedés okairól és a vízhiányos helyzet javításának lehetőségeiről, A Duna-Tisza közi hátság vízgazdálkodási problémái v.3, 16 p. (in Hungarian)

Pavelková, D., Kandra, B., Tall, A., Hlavatá, H., Gomboš, M. (2023): Comparison of meteorological drought over two

normal periods. Acta Hydrologica Slovaca, v. 24, n. 2, 2023, p. 221 – 231.
Rakovec, O., Samaniego, L., Hari, V., Markonis, Y., Moravec, V., Thober, S., Hanel, M., Kumar, R., (2022): The 2018–2020 Multi-Year Drought Sets a New Benchmark in Europe, Earth's Future, v. 10.
Rattayová, V., Garaj, M., Hlavčová, K. (2024): How did the aridity of the climate in Slovakia change over last decades? In Acta hydrologica Slovaca. Vol. 25, No. 1, online, s. 64–72.
Schenk, H. J., Jackson, R. B., (2002): Rooting depths, lateral root spreads and below-ground/above-ground allometries of plants in water-limited ecosystems, Journal of Ecology, v. 90, p. 480–494.
Schilling, K. E. (2007): Water table fluctuations under three riparian land covers, Iowa (USA), Hydrological Processes, v. 21, p. 2415–2424.
Seidl, R., Thom, D., Kautz, M., Martin-Benito, D., Peltoniemi, M., Vacchiano, G., Wild, J., Ascoli, D., Petr, M., Honkaniemi, J., Lexer, M. J., Trotsiuk, V., Mairota, P., Svoboda, M., Fabrika, M., Nagel, T. A., Reyer, C. P. O. (2017): Forest disturbances under climate change, Nature climate change, v. 7, p. 395–402.
Szabó, A., Gribovszki, Z., Kalicz, P., Szolgay, J., Bolla, B. (2022): The soil moisture regime and groundwater recharge in aged forests in the Sand Ridge region of Hungary after a decline in the groundwater level: an experimental case study, Journal of Hydrology and Hydromechanics, v. 70, p. 308–320.
Szilágyi, J., Kovács, Á., Józsa, J. (2012): Remote-Sensing Based Groundwater Recharge Estimates in the Danube-Tisza Sand Plateau Region of Hungary, Journal of Hydrology and Hydromechanics, v. 60, p. 64–72.
Szilágyi, J., Vörösmarty, C. (1993): A Duna-Tisza közi talajvízszint-süllyedések okainak vizsgálata (Investigation of the causes of groundwater level decline between the Danube and Tisza rivers), Vízügyi Közlemények, v. 125, p. 280–291. (in Hungarian)
Szodfridt, I., Faragó S. (1968): Talajvíz és vegetáció kapcsolata a Duna–Tisza köze homokterületén (Relationship between groundwater and vegetation in the sandy area between the Danube and Tisza rivers), Botanikai Közlemények, v. 55, p. 69–75. (in Hungarian)
Solánková, T., Zelenáková, M., Abd-Elhamid, H., Gocic, M., Hlavatá, H., Peter Bujansky P., Garaj M. (2023): An assessment of historical short-time precipitation deficiency in eastern Slovakia and northern Serbia according to the SPI-3. Acta Hydrologica Slovaca, v. 24, n. 2, p. 294 – 302.
Tripathy, K. P., Mishra, A. K. (2023): How Unusual Is the 2022 European Compound Drought and Heatwave Event? Geophysical Research Letters, v. 50.
Vacek, Z., Vacek, S., Cukor, J. (2023): European forests under global climate change: Review of tree growth processes, crises and management strategies, Journal of environmental management, v. 332, p. 117353.
Vágás, I. (1993): Az erdők talajvizszint süllyesztésének kútelméleti értelmezése (monitoring well theory interpretation of groundwater depletion in forests), Hidrol. Közlöny, v. 73, p. 60–61. (in Hungarian)
West, C., Rosolem, R., MacDonald, A. M., Cuthbert, M. O., Wagener, T. (2022): Understanding process controls on groundwater recharge variability across Africa through recharge landscapes, Journal of Hydrology, v. 612, p. 127967.
Wojkowski, J., Wałęga, A., Młyński, D., Radecki-Pawlik, A., Lepeška, T., Piniewski, M., Kundzewicz, Z. W. (2023): Are we losing water storage capacity mostly due to climate change – Analysis of the landscape hydric potential in selected catchments in East-Central Europe, Ecological Indicators, v. 154, p. 110913.
Yadav, N., Upadhyay, R. K. (2023): Global Effect of Climate Change on Seasonal Cycles, Vector Population and Rising Challenges of Communicable Diseases: A Review, Journal of Atmospheric Science Research, v. 6., p. 21–59.

Bence Bolla*, Ph.D. senior research fellow (corresponding author: e-mail: bolla.bence@uni-sopron.hu)
Márton Dobó, Ph.D. student, research assistant
András Szabó, Ph.D. senior research fellow
Forest Research Institute, University of Sopron
Frankel L. str. 1
H-1027 Budapest
Hungary

Ján Szolgay, academic degree, Ph.D., professor emeritus
Department of Land and Water Resources Management
Faculty of Civil Engineering, Slovak University of Technology in Bratislava
Radlinského 11
810 05 Bratislava
Slovak Republic

Zoltán Gribovszki, academic degree, Ph.D., professor
Péter Kalicz, Ph. D., associate professor
Institute of Geomatics and Civil Engineering, Faculty of Forestry, University of Sopron
Bajcsy-Zsilinszky str. 4
H-9400 Sopron
Hungary