Extreme precipitation amounts and dry periods in the Hungarian Great Plain (1980–2020): four urban stations

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Abstract

This study explores changes in the frequency and spatiotemporal distribution of precipitation-free periods in the Hungarian Great Plain (1980–2020), with a focus on agricultural challenges under climate change. During the study, we analysed the occurrence of dry periods lasting up to 16 days, their seasonal frequency, and their differences in four cities (Szolnok, Hódmezővásárhely, Nyíregyháza, Kalocsa). Based on the data, the frequency of dry periods increased slightly in certain locations; however, the statistical significance of the trend was inconclusive; F-tests mainly indicated increased variance. The two-sample Kolmogorov–Smirnov test revealed that the differences in distribution between cities were not significant, indicating that the hypothesis of regional divergence was not confirmed. The research also emphasizes the need for increased soil moisture retention capacity, especially in sandy and saline soils, which lose moisture more quickly due to a lack of precipitation, negatively affecting their agricultural productivity.

Keywords

Hungarian Great Plain, precipitation analysis, extreme weather events, climate change, water shortage.

Csapadékszélsőségek vizsgálata 1980–2019. között négy alföldi városban Magyarországon

Kivonat

A tanulmány célja, hogy feltárja a csapadékmentes periódusok gyakoriságának, időbeli és térbeli eloszlásának változásait a magyarországi Alföld térségében 1980–2020 között, különös tekintettel a klímaváltozás mezőgazdasági kihívásaira. A vizsgálat során elemeztük a 16 napot elérő száraz időszakok előfordulását, évszakos gyakoriságát, azok különbségeit négy alföldi város (Szolnok, Hódmezővásárhely, Nyíregyháza, Kalocsa) esetében. Az adatok alapján a száraz periódusok gyakorisága bizonyos helyeken enyhén növekedett, bár a tendencia statisztikai szignifikanciája nem volt egyértelmű, az F-próbák elsősorban szórásnövekedést jeleztek. A kétmintás Kolmogorov–Smirnov-próba azt mutatta, hogy a városok közötti eloszlásbeli eltérések nem szignifikánsak, így a térségi divergencia hipotézise nem igazolódott. A kutatás továbbá hangsúlyozza a megnövelt talajnedvesség-megtartó képesség szükségességét, különösen homokos és szikes talajok esetén, amelyek a csapadékhiány hatására gyorsabban veszítenek nedvességet, ami negatívan befolyásolja a mezőgazdasági termelékenységüket.

Kulcsszavak

Alföld, csapadékelemzés, extrém időjárási események, klímaváltozás, vízhiány.

INTRODUCTION

The Great Plain is one of the most important agricultural regions of Hungary, where the success of production directly depends on the physical properties of the soil, especially its water retention capacity. Its natural features – loose sedimentary rocks, horizontal or gently sloping surface, and the complexity of the surfaces and underground water network – dynamically interact to create a complex environment in which the interdependent processes of soil formation, water management, and land use take place (*Keveiné Bárány 1998, Pálmai 2005*). The climate of the Great Plain is temperate continental, shaped by the low altitude, the closed nature of the Carpathian Basin, and the dominance of continental influences. The average annual temperature in the region is typically 10-11 °C, and the number of hours of sunshine exceeds 2 000 per year, while the amount of precipitation is low in national terms: less than 550 mm (*HungaroMet 2022*).

According to the consensus of several studies (*Bartholy and Pongrácz 2007, Barcza et al. 2013, Mezősi et al. 2017, Fehér and Rakonczai 2019, Lakatos 2021*), the Great Plain is particularly exposed to the harmful effects of climate change: temperature increases, precipitation variability, and droughts (*Kis et al. 2025*). More recent regional analyses further confirm that the Great Plain belongs to the most climate-vulnerable areas of Hungary, especially with respect to drought frequency and water balance changes (*Kis et al. 2025*). Measurements in Hungary between 1901 and 2009 show that the annual and all-season mean temperatures have an increasing trend. The national annual mean temperature increased by 0.99 °C from the beginning of the last century to 2009 (*Barcza et al. 2013*). The change (+1.17 °C) is particularly noticeable in the summer (*Barcza et al. 2013*). The study by *Barcza et al.* (*2013*) examined the change in the seasonal mean temperature of five major Hungarian cities (Budapest, Debrecen, Szeged, Szombathely, Pécs) between 1980 and 2009. It was found that the two Great Plain cities (Debrecen: +2.08 °C, Szeged: +2.14 °C) had the highest average summer temperature increase. These tendencies are also reflected in more recent observational datasets and model-based assessments, indicating that warming during the summer half-year has continued in the Great Plain after 2009 (*Lakatos 2021*). Recent work by *Bihari and Szentes (2024),* based on 30-year climate normals and a forthcoming high-resolution climate atlas, confirms the continuation of these climate change trends, providing a detailed regional perspective for Hungary. Moreover, the HISTALP precipitation dataset for the Central European region, including Hungary, provides a homogenized, long-term record that allows for more accurate detection of regional precipitation trends, supporting observations of decreasing rainfall and increasing dry spells in the Great Plain (*Chimani et al. 2023*). Detailed analyses of recent drought events also provide important context for these trends, highlighting the increasing frequency and intensity of dry periods in Hungary (*Szentes 2023*). In addition, modern climate monitoring indices and real-time datasets provided by HungaroMet further support the assessment of regional temperature, precipitation, and drought trends (*Lakatos et al. 2024*).

The average annual precipitation in Hungary shows a decreasing trend. Wet years occurred more frequently in the first half of the last century; the decrease was 7% between 1901-2009 (*Barcza et al. 2013*). According to the unanimous conclusion of several studies, periods of low precipitation have become increasingly frequent, which in many cases also represents a significant change (*Bartholy et al. 2008*). This is especially true for spring. The largest decrease among the seasons between 1901-2009 occurred in spring, at almost 20% (*Barcza et al. 2013*). Recent analyses based on homogenized station data and grid-point datasets indicate that this long-term decrease is increasingly accompanied by pronounced interannual variability and longer dry spells, particularly in the central and eastern parts of the Great Plain (*Kis et al. 2025*).

More frequent low-rainfall periods adversely affect not only the overall water balance but also soil structure, porosity, and fertility. Evaporation increases, which further reduces soil moisture. The strengthening of evapotranspiration and the decrease in groundwater levels can already be observed, especially in the Danube–Tisza basin and in some parts of the Nyírség (*Keveiné Bárány 1998, Mezősi et al. 2020*). *Fehér and Rakonczai (2019)* also highlight that climate-induced groundwater decline has become a key driver of landscape sensitivity in several regions of the Great Plain, directly linking meteorological trends with soil degradation processes. The change in the water balance of the Great Plain affects not only the surface water system, but also directly affects the groundwater level. The decrease in water levels in the Danube–Tisza basin in recent decades has had serious consequences for both soil moisture and the state of vegetation. According to research by *Ladányi (2009),* in the Homokhátság, the groundwater has sunk by more than 5 meters in some places compared to the 1980s, which has already caused a significant transformation in the composition of the natural vegetation. Similar tendencies have been confirmed by recent drought-monitoring and impact assessment studies, which emphasize that groundwater-dependent ecosystems are among the most sensitive to ongoing climatic changes in the Great Plain (*Fiala et al. 2018*). The previously water-saturated saline and marsh habitats have dried up, and in their place have appeared steppe-like plant communities with lower water requirements. The physical and chemical characteristics of the soil have also changed: the salt and sodium content of the upper layer has decreased, while the humus concentration has increased, which indicates an improvement in the soil structure and a retreat of salinization. The deepening groundwater table has serious ecological and economic consequences: maintaining cultivation requires ever more irrigation water, withdrawn from the same dwindling supply. This self-perpetuating process is unsustainable in the long run (*Ladányi 2009*).

A problem is that precipitation often does not fall at an optimal time for plants. This highlights the great difficulty of the agricultural areas of the Great Plain that rely on natural precipitation (*Mezősi 2020*). A study examining the Danube–Tisza basin found that a decrease in the amount of precipitation resulted in a significant decrease in groundwater. On one hand, this causes significant damage to farming, and on the other hand, it causes the transformation of natural vegetation (*Makra et al. 1986, Nováky 1993, Ladányi 2009*). More recent regional climate impact studies confirm that this temporal mismatch between precipitation occurrence and crop water demand has intensified during the last decades, increasing production risks under rain-fed conditions (*Kis et al. 2025*).

It is worth noting, however, that the seemingly clear trends in national average precipitation amounts mask the actual regional variability. These are primarily influenced by distance from the sea, topography, land cover, land use, and micrometeorological conditions (*Makra et al. 1985, Konkolyné et al. 2008*). Regions closer to the Tisza, such as Szolnok, receive more precipitation on average than regions in the southern Great Plain, such as Hódmezővásárhely or Kalocsa. The difference can be as much as 50-100 mm per year (*Demeter 2016*). Behind the simplicity of the Great Plain's topography lie subtle structural and climatic differences, which directly influence the condition of the soils and their usability through different water management characteristics. Clayey, more cohesive sediments let water through more slowly, thus being able to store moisture for a longer period of time, while soils formed from loose sandy or loess bedrock dry out more quickly. This geological background partly explains why significant differences can occur in the effects of a lack of precipitation, even under identical meteorological conditions. Geological conditions are, therefore, not just passive background factors, but actively influence water management processes, thus indirectly, affecting the frequency, intensity and consequences of dry periods (*Molnár and Várallyai 1993*).

Despite regional variability, several regional studies in Hungary have shown a decreasing trend in precipitation. One study (*Marton and Szanyi 1997a, 1997b*) found that the increasing precipitation deficit makes Nyírség one of the most vulnerable regions of the Great Plain, which is not fed by surrounding precipitation flows. More recent investigations based on multimodel simulations suggest that these vulnerabilities are likely to persist or even intensify during the 21st century, particularly with respect to summer low-flow conditions and prolonged dry periods (*Kis et al. 2023*). Water shortages have been affecting the Debrecen region, as well as the stratigraphic and near-surface water bodies of the Hajdúság and Hortobágy regions, since the 1990s. A study examining the Upper Tisza region, based on multimodel simulations (*Kis et al. 2023*), projects that during the 21st century, the average daily water discharges are expected to decrease in the Tiszabecs section of the Upper Tisza compared to the annual averages. Furthermore, a significant decrease in the flow of the summer months is likely (especially in July and August), while a smaller increase can be expected for January and February. The number of cases exceeding the third flood protection readiness level is expected to be significantly lower by the middle and end of the 21st century, but these may occasionally be more severe in terms of flood volume than is currently usual. According to the study by *Kiss et al. (2019),* analysing more than 140 years of data, the average temperature in Mosonmagyaróvár (located in the Little Hungarian Plain, a region with slightly cooler and wetter conditions than the Great Plain) has increased significantly, and the precipitation distribution has become more extreme. While the trends observed in Mosonmagyaróvár illustrate long-term regional climate change, care should be taken when comparing them directly to the Great Plain, whose climate is generally warmer and drier, particularly in the central and southern areas. According to the study, precipitation does not show a significant decrease in the long term, but based on the results of GARCH modelling, the temporal distribution of precipitation is becoming increasingly unpredictable and the frequency of extreme precipitation events is increasing. A study conducted in the settlement of Nagybajom (*Szám et al. 2025a*) found that the frequency of periods without precipitation lasting at least 25 days increased significantly in the second half of the period studied (1965-2022). Another study conducted in the Szentes region (*Szám et al. 2025b*) examined the period between 1981 and 2020. It was found that the number of days with high rainfall increased by 19.3%, and the 201 number of days with extreme rainfall increased by 40.9%. Even larger increases were observed for the highest five-day rainfall totals (62.1%).

The decrease in average precipitation is in most cases accompanied by an increase in the frequency of extreme precipitation situations (*Bartholy and Pongrácz 2007*). A study analysing data series from 1901 to 2009 for the entire Great Plain (*Berényi et al. 2021*) draws attention to the increase in the daily precipitation intensity (SDII) index used to detect precipitation extremes. Recent local-scale studies further support this tendency, showing a simultaneous increase in both dry spell duration and short-term high-intensity precipitation events in several Great Plain settlements (*Szám et al. 2025a, Szám et al. 2025b*). The changes in the values of other indicators also indicate an increase in the frequency of precipitation extremes. An increase in the frequency of days with high precipitation (RR10) and extreme precipitation (RR20) can also be observed in several regions of the Great Plain. This poses a serious challenge for agriculture and environmental engineering interventions.

The results of the isotopic studies (conducted by *György Czuppon et al.* in collaboration with HungaroMet and CSFK) provide important new information on the origin of precipitation in Hungary (*Czuppon et al. 2021*). These findings add a new dimension to climate change assessments in the Great Plain, as changes in moisture source regions are expected to further enhance the variability and extremity of precipitation patterns in the future. Based on the analysis of the hydrogen and oxygen isotope composition (δD and $\delta^{18}O$) of the precipitation samples, it was determined that the majority of the precipitation falling on Hungary originates from the Mediterranean region. This source region has become dominant in recent years, overtaking the Atlantic, the North Sea region, and the local recycled moisture sources of the Carpathian Basin. This determination of the origin of precipitation was made using so-called backward atmospheric trajectories and isotopic signals (e.g., deuterium excess, d-excess). Based on the principal component analysis, it can be clearly shown that the warming of the Mediterranean Sea and the moisture from the Adriatic and Ionian regions play an increasingly decisive role in the formation of precipitation in Hungary. This trend is related to the warming of the Mediterranean region and the increased evaporation potential, which increases the moisture content of the airflows coming from there.

This change is significant from a meteorological and climatic perspective: on the one hand, it increases the probability of precipitation events of a shower and thunderstorm nature, and on the other hand, the unpredictability of the temporal and spatial distribution of precipitation. Based on the isotopic composition, therefore, not only the amount of precipitation but also its meteorological origin has changed, which contributes to the increase in the climate asymmetries of the region.

MATERIAL AND METHOD

The aim of our study was to determine the precipitation conditions for the period 1980-2020, for which we used the historical data series of the Hungarian National Meteorological Service (HungaroMet). Following the introduction of HungaroMet's open data policy in 2021, meteorological observation data became freely and openly accessible via the odp.met.hu server. In this study, synoptic precipitation data series originating from HungaroMet measuring stations were used. These data series come from an automatic measuring station network. The network is regularly maintained, and the instruments are calibrated. HungaroMet took care of the quality assurance (validation, data supplementation) of the data series we analyzed.

We have daily precipitation data from four Great Plain meteorological stations (Szolnok, Hódmezővásárhely, Nyíregyháza, Kalocsa) between 1980 and 2020. In our first study, we were interested in the cross-correlations of our precipitation data for the four settlements. We determined the Pearson correlation coefficients (R values) of the six pairs of settlements. The methodology of this practically differs from a conventional correlation study in that here we do not compare the measured data to an independent variable (e.g., location or time), but we compare the precipitation data of two cities with each other and look for a correlation between the two measured values.

In our second study, we examined the frequency changes of longer dry periods. We considered dry periods to be consecutive days when the daily precipitation did not exceed 1 mm. We included periods of at least 16 days but no more than 40 days in the evaluation. The only exceptionally long period, 44 days, was registered in Hódmezővásárhely in the autumn of 1983, but this falls outside the compared range. We used statistical tests to compare the daily precipitation amounts of the first and second halves of the period (1980-1999, 2000-2019). We used the F-test to examine the variation in the standard deviation of long dry periods. In order to compare the distribution of dry periods lasting at least 16 days, we used the two-sample Kolmogorov–Smirnov test. This nonparametric test is sensitive to changes in the distribution shape, such as shifts in the incidence rate of extremely long or short periods, and is therefore well suited to examining skewed distributions in natural systems (*Figure 1*). The two-sample Kolmogorov test works even if the theoretical distribution of the samples to be compared is unknown (*Gibbons and Chakraborti 2003*).

Our third study focused on the seasonal distribution of dry periods. The data source was the previously used daily precipitation dataset between 1980 and 2020. We considered a dry day to be any day on which the daily precipitation total did not reach 1 mm. The seasonal comparison of dry periods was performed by first calculating the mean and standard deviation of the length of dry periods for each city separately for each season (spring, summer, autumn, winter). Subsequently, we compared the seasonal means and standard deviations of the cities in pairs in order to explore whether there were systematic differences in the length of dry periods between settlements. This "pair-by-pair" approach allowed us to see not only the difference in absolute values but also the relative differences between cities. In this way, we could identify those locations where dry periods are consistently longer or shorter at a given time of year.

The aim of our fourth study was to detect significant differences in the distribution of the length of dry periods (≥16 days) between the four studied stations. To do this, we compared each pair of cities based on the period 2000-2019. We used a two-sample Kolmogorov–Smirnov test to determine whether the two samples (here: city pairs) come from the same distribution. Based on the p-value, we determined whether the difference was statistically significant ($p < 0.05$).

The aim of the fifth study was to analyse and evaluate soil moisture data. The data come from the monitoring network of the General Directorate of Water Management (OVF - Országos Vízügyi Főigazgatóság), which provides data measured at a depth of 10 cm in the studied regions. For spatial interpolation and temporal filling, we used the ERA5 (*Hersbach et al. 2023*) database from the global reanalysis data (ERA5 - ECMWF Reanalysis 5th Generation), which is developed by the European Centre for Medium-Range Weather Forecasts (ECMWF) within the framework of the European Union's Copernicus Climate Change Service (C3S). ERA5 provides meteorological and soil moisture variables on a regular latitude–longitude grid with a horizontal spatial resolution of 0.25° × 0.25° (approximately 31 km), which is suitable for regional-scale climatic and hydrological analyses. ERA5 is particularly valuable for research, as it integrates measurements from Hungarian meteorological stations (including those collected by HungaroMet) in addition to global model-based estimates, thus providing a reliable basis for drawing regional conclusions. In this study, ERA5 grid-point data corresponding to the vicinity of the monitoring stations were used primarily to support spatial consistency and temporal completeness of the in situ soil moisture records. While the applied spatial resolution may smooth small-scale variability associated with localized convective precipitation events, it provides a robust representation of large-scale and regional soil moisture dynamics relevant to multi-decadal analyses. As a complementary source, we also used remote sensing data from the European Union Copernicus satellites Sentinel-1 and Sentinel-2, which supported the spatial assessment of soil moisture, land cover, and vegetation status through their radar and optical channels. The Sentinel-1 mission is the first satellite mission of the European Union Copernicus programme, implemented jointly by the European Space Agency (ESA) and the European Commission. Sentinel-1 is a radar-based Earth observation system consisting of two sun-synchronous polar-orbiting satellites (Sentinel-1A and Sentinel-1B) with a 180° phase shift. This configuration allows for regular and rapid coverage of the Earth's surface, regardless of weather conditions or time of day. The system is based on the Sentinel family of satellites, equipped with different types of sensors, making them suitable for various purposes in the field of land, sea, and atmosphere observations. Their application areas include monitoring land surface deformations, flood observations, detection of sea ice and oil spills, and support for disaster response (*EU Copernicus Programme 2025*). The integration of datasets from multiple sources enables the comparison of short- and long-term variables and the identification of regional characteristics. The data analysis toolbox includes spatial interpolation and time series decomposition, which support the detailed interpretation of climatic and soil moisture patterns. The calculations were performed in a programming and GIS environment, which ensures the structured processing and visualization of large amounts of data.

RESULTS

The strongest correlation was found between the precipitation data of Szolnok and Hódmezővásárhely (R=0.90), followed by Kalocsa and Hódmezővásárhely (R=0.86), indicating that these stations are frequently affected by similar large-scale atmospheric situations. In contrast, Nyíregyháza shows considerably weaker correlations with the other Great Plain cities, especially with Kalocsa (R=0.55) and Hódmezővásárhely (R=0.61) (*Table 1*). This suggests that the northeastern part of the Great Plain is more often influenced by precipitation-generating mechanisms that differ from those dominating the central and southern regions.

Previous studies have shown that summer precipitation over the Great Plain is increasingly dominated by convective processes, which are highly localized and sensitive to mesoscale conditions such as surface heating, soil moisture feedbacks, and atmospheric instability (*Bartholy and Pongrácz 2007, Lakatos et al. 2021*). The lower inter-station correlation involving Nyíregyháza is therefore consistent with findings that the eastern and northeastern Great Plain are more frequently affected by isolated convective events, while the Danube–Tisza Interfluve and southern regions are more often influenced by spatially coherent precipitation associated with Mediterranean cyclones or frontal systems (*Mezősi et al. 2017*). Consequently, the observed correlation differences likely reflect regional contrasts in dominant precipitation regimes, particularly during the summer half-year.

Table 1. Pairwise comparison of precipitation patterns of the four examined Great Plain cities
1. táblázat. A négy vizsgált alföldi város csapadékmintázatainak páros összehasonlítása

Municipality 1	Municipality 2	Correlation coefficient (R)
Szolnok	Hódmezővásárhely	0.90
Szolnok	Nyíregyháza	0.66
Szolnok	Kalocsa	0.82
Hódmezővásárhely	Nyíregyháza	0.61
Hódmezővásárhely	Kalocsa	0.86
Nyíregyháza	Kalocsa	0.55

In the case of Szolnok, Hódmezővásárhely, and Nyíregyháza, the frequency of dry periods lasting 16-20, and 21-25 days increased significantly between 1980 and 2020. A decrease occurred only in the case of Kalocsa. The frequency of dry periods lasting 26 days or longer has developed differently in the four settlements (*Figure 1*).

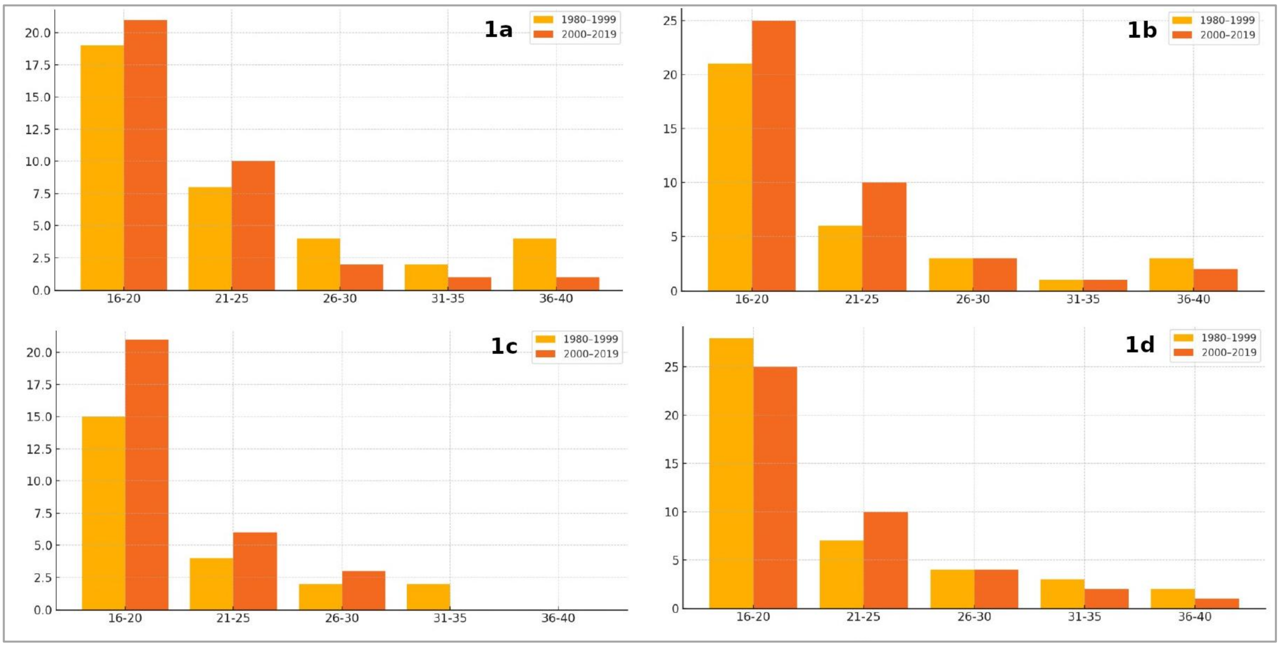

Figure 1. Distribution of the frequency of dry periods at the measuring stations of Szolnok (1a), Hódmezővásárhely (1b), Nyíregyháza (1c), Kalocsa (1d) in the periods 1980-1999 and 2000-2019 (Data source: HungaroMet)
1. ábra. A száraz időszakok gyakoriságának eloszlása a szolnoki (1a), hódmezővásárhelyi (1b), nyíregyházi (1c), kalocsai (1d) mérőállomásokon 1980–1999 és 2000–2019 időszakban. (Adatforrás: HungaroMet)

Based on the results, most long dry periods started in summer, but in Kalocsa and Nyíregyháza a significant number of events also occurred in autumn. The seasonal statistics of ≥16-day dry spells (*Table 2*) show that summer remains the dominant season for the onset of long dry periods in all four cities. A secondary maximum appears in autumn, especially in Kalocsa and Szolnok. Spring dry spells became more frequent in Hódmezővásárhely and Nyíregyháza after 2000, in line with the seasonal shift already noted in the main text. Winter dry periods are also common, but their mean length is similar to that of autumn, indicating year-round drought sensitivity in the Great Plain.

Comparing (*Table 3*) the two periods (1980-1999, 2000-2019), there is no clear shift at all stations, but in the case of Hódmezővásárhely and Nyíregyháza the frequency of spring dry periods increased after 2000.

Based on the results of the two-sample Kolmogorov-Smirnov test, the differences between cities between 2000 and 2019 were not statistically significant; i.e., the distribution of long dry periods did not differ significantly from one station to another (*Table 4*). This supports the observation that these regions of the Great Plain show a similar climatic pattern in terms of drought susceptibility.

Table 2. Seasonal mean length and standard deviation of ≥16-day dry periods in the four examined Great Plain cities (1980–2020) (The column "n" indicates the number of dry spells detected in the given season)
2. táblázat. A ≥16 napos száraz időszakok szezonális átlagos hossza és szórása a négy vizsgált alföldi városban (1980–2020) (Az „n" oszlop az adott évszakban észlelt száraz időszakok számát jelzi)

Location	Spring (mean / std / n)	Summer (mean / std / n)	Autumn (mean / std / n)	Winter (Mean / std / n)
Szolnok	20.36 / 3.72 / 11	19.67 / 2.65 / 9	22.44 / 6.78 / 32	22.76 / 7.46 / 25
Hódmezővásárhely	19.42 / 3.99 / 12	21.55 / 4.46 / 11	22.12 / 6.85 / 33	20.83 / 6.32 / 24
Nyíregyháza	19.36 / 3.41 / 11	19.00 / 4.24 / 4	20.04 / 4.48 / 23	20.00 / 5.05 / 17
Kalocsa	18.23 / 2.49 / 13	20.44 / 3.16 / 16	22.20 / 6.14 / 35	22.21 / 6.04 / 28

Table 3. F-test of the dry periods of the four examined Great Plain cities for the time intervals between 1980-1999 and 2000-2019
3. táblázat. A vizsgált négy alföldi város száraz időszakainak F-próbája az 1980-1999 és a 2000-2019 közötti időintervallumokban

Municipality/ Station	16-40 days periods (1980-1999)	16-40 days periods (2000-2019)	F-test value	F-test assessment	Longer than 35-days periods	Significant difference (F probe)
Szolnok	37	35	0.0713	Borderline case	5	Not significant
Hódmezővásárhely	34	41	0.4215	Not significant	6	Not significant
Nyíregyháza	23	30	0.0598	Borderline case	0	Not significant
Kalocsa	44	42	0.2345	Not significant	3	Not significant

Table 4. Results of the two-sample Kolmogorov-Smirnov test based on the number of dry periods for pairs of cities
4. táblázat. A kétmintás Kolmogorov-Szmirnov teszt eredményei a várospárok száraz időszakainak száma alapján

Municipalities	K-S stat	p value	Significance (p<0.05)
Szolnok - Hódmezővásárhely	0.0832	0.9284	Not
Szolnok - Nyíregyháza	0.1820	0.2225	Not
Szolnok - Kalocsa	0.1087	0.6777	Not
Hódmezővásárhely - Nyíregyháza	0.1103	0.7864	Not
Hódmezővásárhely - Kalocsa	0.0734	0.9632	Not
Nyíregyháza - Kalocsa	0.1837	0.1852	Not

We considered using a GARCH (Generalized Autoregressive Conditional Heteroskedasticity) model, which is suitable for time series with time-varying variance (*Korponai 2019*). However, the residuals of soil moisture data showed no such heteroskedastic behaviour, so a GARCH specification was not justified. Instead, a simple AR(1) model (first-order autoregressive) adequately described the temporal dynamics of soil moisture, reflecting the strong dependence of each day's values on those of the previous day.

The link between soil moisture and precipitation proved weaker than expected. Daily precipitation showed virtually no correlation with soil moisture. Aggregating rainfall over 7 days slightly improved the correlation, and over 30 days it was only marginally stronger. These results suggest that soil moisture is controlled not only by rainfall but also by evaporation, soil type, and groundwater conditions, which dilute the direct effect of precipitation.

The main findings can be summarized as follows:

- There is practically no correlation between daily precipitation and soil moisture in any city ($\rho \approx 0.01–0.02$).
- The 7-day precipitation total increases the correlation, but it still remains weak (Szolnok: $\rho \approx 0.029$).
- The relationship with the 30-day precipitation total is slightly stronger (Szolnok: $\rho \approx 0.036$), but it remains weak.
- The standard deviation of the residuals of the soil moisture AR(1) model is relatively stable in a 30-day time window, there is no strong heteroscedasticity in any city.
- Consequently, the application of the GARCH model is not justified for these data.

Figure 2 presents the 30-day rolling standard deviation of the AR(1) residuals of soil moisture. The variability remains within a moderate and physically plausible range throughout the examined period, and no systematic increase in residual variance is detected.

Following the analysis presented in *Figure 2*, it is evident that daily precipitation alone does not explain the variability of soil moisture in the four studied cities. The main findings indicate practically no correlation between daily precipitation and soil moisture ($\rho \approx 0.01–0.02$). Aggregating rainfall over 7 days slightly increases the correlation (e.g., Szolnok: $\rho \approx 0.029$), and over 30 days it becomes only marginally stronger (Szolnok: $\rho \approx 0.036$), but the relationship remains weak overall. The standard deviation of the AR(1) residuals remains relatively stable in a 30-day rolling window, showing no strong heteroskedasticity, confirming that a GARCH model is not justified for these data.

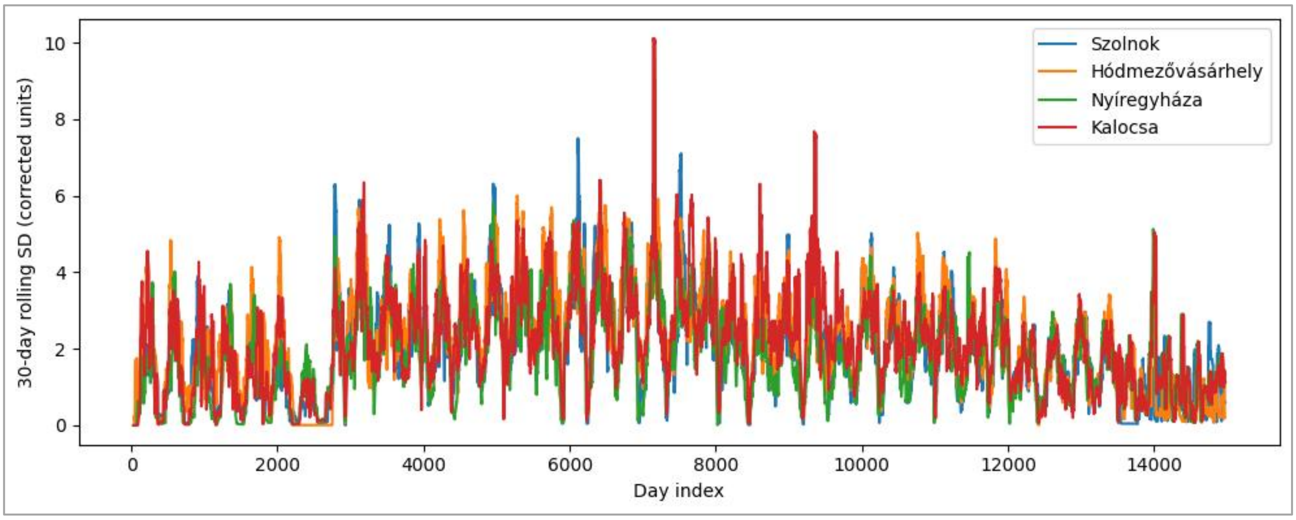

Figure 2. The 30-day rolling standard deviation of residuals of AR(1) models
2. ábra. Az AR(1) modellek reziduálisainak 30 napos gördülő szórása

These results suggest that other factors—including soil type, evapotranspiration, and groundwater conditions—strongly influence soil water content, which dilutes the direct effect of precipitation. The temporal persistence observed in the AR(1) models reflects the buffering capacity of different soils against short-term rainfall variability. Although the four cities show broadly similar drought susceptibility patterns, local differences in soil texture and hydrological properties likely lead to variations in moisture retention and drainage. Therefore, considering soil type-specific characteristics, infiltration, and evapotranspiration is essential for more precise predictions of soil water content, particularly for agricultural and hydrological applications.

Our findings are consistent with previous studies emphasizing the dominant role of soil properties and local hydrology in controlling soil moisture (*Fehér and Rakonczai 2019, Mezősi et al. 2020*). The observed weak correlations align with results from *Lakatos et al. (2021),* who also reported that soil moisture in the Great Plain is buffered against short-term precipitation variability. Furthermore, local variability in soil moisture response supports earlier findings by *Ladányi (2009)* and *Kis et al. (2025),* highlighting that groundwater-dependent ecosystems and soil water availability are sensitive to both climatic and pedological factors. Our results also reflect conclusions by *Szentes (2023)* and *Bihari and Szentes (2024)*, stressing that accurate assessment of soil moisture requires integration of precipitation, soil type, infiltration, and evapotranspiration rather than relying on rainfall alone.

Overall, these observations underscore that even within regions with broadly similar drought susceptibility patterns, soil and hydrological characteristics modulate soil water availability, emphasizing the importance of including these factors in regional climate and agricultural impact assessments.

CONCLUSIONS

Our results clearly show that the frequency, timing, and spatial distribution of prolonged precipitation-free periods in the Great Plain have changed substantially in recent decades. One of the most important consequences of climate change – in addition to the increase in average temperatures – is the increasing occurrence of these dry periods, which pose a challenge for agriculture, especially in the spring and summer periods.

The frequency of long dry periods exceeding 16 days varied between the periods examined. In the case of some cities – especially Hódmezővásárhely and Nyíregyháza – the number of dry periods increased slightly; however, the change was not statistically significant in all cases. Based on the F-tests, the results indicating an increase in the standard deviation can be interpreted as a trend rather than a generally valid change. During the examination of the seasonal distribution, it was observed that the beginning of the dry periods shifted towards the vegetation period in some locations – for example, in the Hódmezővásárhely area – especially in spring. At the same time, the summer periods remained dominant, so the seasonal shift was not clearly evident in all the study locations. Based on the analysis of the regional differences, it can be stated that there was no significant difference in the distribution of long dry periods between the four cities examined. The results of the Kolmogorov–Smirnov test showed that the differences between the pairs of cities cannot be considered statistically significant, so the hypothesis that regional differences increased was not supported. It should be noted here that in the case of longer time intervals (and the necessary longer time series), significant differences can be detected between earlier and later intervals in the same geographical location. *Szám et al. (2025*) showed that in the eastern part of the Great Plain, the number of dry periods increased significantly, approximately twice, compared to intervals of the same length, and periods of previously inexperienced length also appeared.

The results of the research highlight the need to increase the water retention capacity of the soil. The moisture content of the topsoil is particularly sensitive to longer periods without precipitation, especially in sandy and saline soils with weaker water retention capacities. In these soil types, a lack of precipitation reduces moisture content more quickly to below critical levels. Below critical levels, soil structure deteriorates, which negatively affects agricultural production efficiency.

Predicting and monitoring dry periods associated with climate change is key to developing future agricultural strategies. The Sentinel satellite program (especially the Sentinel-1 and Sentinel-2 systems) now provides high temporal and spatial resolution data for monitoring soil moisture, vegetation status, and land cover. Over the past decade, monitoring has also become available through the use of agricultural drones, which have enabled higher-resolution assessments. Further potential is offered by innovative solutions such as precision water distribution, the results of drought tolerance analyses of different plant varieties, and plant protection monitoring using soil and leaf moisture sensors. These can help us preserve the agricultural potential of the Great Plain sustainably in the future.

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