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Analysis of the long rainfall data series of Mosonmagyaróvár with special regard to the water demand of the vegetation period of winter wheat

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Abstract— The present study analyzes the long-term (1871–2020) precipitation time series of Mosonmagyaróvár (Hungary) and investigates the precipitation trends affecting winter wheat production. Understanding precipitation trends is important for agriculture due to the increasing frequency and intensity of droughts caused by climate change.

In this study, parametric and non-parametric trend tests (linear and Mann-Kendall trend test) were applied, which showed a significant decrease in April and October. A significant downward shift of the mean can be demonstrated in spring by Pettitt's test. This decrease has a negative impact on key growing periods for winter wheat, which poses a serious challenge to conventional wheat production in the region. The research highlights the importance of different agrotechnical solutions to reduce yield losses due to climate change. The results obtained are in line with trends observed in Keszthely (Hungary), which confirms the regional changes.

These climatic changes can have a significant impact on the cultivation of our most important domestic food crop, winter wheat, so it is worth preparing for adaptation from this point of view as well.

Key-words: climate change, rainfall, vegetation period, water, winter wheat

1. Introduction and literature review

The global climate is changing, with temperatures rising globally, and this rise in global temperature is expected to cause a modification in the annual mean precipitation (*IPCC,* 2021). Simulation results from global climate models (GCMs) have indicated that the intensity, duration, and frequency of future extreme rainfalls are projected to change in many regions around the world (*Lee et al.,* 2011; *Asadieh* and *Krakauer,* 2015; *Wen et al.,* 2016).

Reported analyses of observed extreme precipitation show that there is some evidence of a general increase in extreme precipitation. The review of likely future changes based on climate projections indicates a general increase in extreme precipitation under a future climate, which is consistent with the observed trends. Only a few countries have developed guidelines that incorporate a consideration of climate change impacts (*Madsen et al.,* 2014).

Significant increases in extreme precipitation and drought events have been detected in Europe in the past few decades. In a study by *Berényi et al.* (2023), 16 selected climate indices were used for the analysis of the temporal changes and spatial distribution of precipitation patterns in European plain regions during 1950–2022. Their results suggest a general intensification of precipitation events over the continent, as many regions show a significant increase in the indices related to the intensity of extreme precipitation, and also the frequency of these events increased in a lot of regions. Extreme indices related to dry periods changed significantly in only a few cases. An increase may only be observed in the southern part of the continent, while a significant decrease can be seen in three regions in northern Europe.

Spinoni et al. (2015) reported that in Central Europe and the Balkans, drought variables show a moderate increase. Concerning changes under a future climate, climate modeling studies have shown that an increase in heavy precipitation is likely in most parts of the world in the 21st century (*IPCC,* 2012).

The expected increase in the intensity and frequency of extreme precipitation under climate change has already been experienced in different parts of the world (*Janssen et al.,* 2014; *Wang et al.,* 2017; *Tabari* and *Willems,* 2018; *Zobel et al.,* 2018). While an increase in extreme precipitation events can be detected worldwide (*Donat et al.,* 2016), the pattern of increase is less spatially coherent and often non-significant (*Groisman et* al., 2005) compared to the increase in temperature.

Increasing trends in European extreme precipitations have been discussed in several studies. These studies concluded that a general intensification of extreme events may be observed (*Sun et al.,* 2021). However, the actual rate of the precipitation trends may vary across the continent, for instance, the trends of heavy precipitation events in northern Europe are similar to the trend of total precipitation, but this is not true in southern Europe where heavy precipitation tends to increase while total precipitation is decreasing (*van den Besselaar et al.,* 2012).

The climate became wetter in several regions in Europe through the increase in extreme and total precipitation (*Ntegeka* and *Willems,* 2008; *Madsen et al.,* 2014). Opposite trends may be observed in some of the southern countries where the decrease in total precipitation coincided with the increase of extreme events resulting in an intensification of precipitation events (*Bartholy* and *Pongrácz,* 2007) or an overall decrease in extreme precipitation events (*Norrant* and *Douguédroit,* 2005).

Between 1901 and 2009, the highest precipitation declines over the territory of Hungary occurred in the spring, nearly 20% of them (*Lakatos* and *Bihari,* 2011).

Bartholy and *Pongrácz* (2007) examined several precipitation extreme indices and suggested that regional intensity and frequency of extreme precipitation increased in the Carpathian Basin in the second half of the last century, while the total precipitation decreased. A 20–33% decrease in precipitation in Hungary is predicted for the summer half-year, and there is high uncertainty for the rainfall for the winter half-year (*Bartholy et al.,* 2007). *Bartholy et al.* (2015) projected that the frequency of extreme precipitation will increase in Central Europe, except in summer, when decreasing tendency is very likely.

Future climate change would further amplify the effects of precipitation variations (*Liu et al.,* 2023). Improved knowledge of the likely future risk profiles also plays an important role in decision-making when considering, for example, societal adaptation to future climate change (*Hall et al.,* 2012; *Bormann et al.,* 2012).

Changes in precipitation have serious effects on human society and are the focus of investigation in many scientific fields, e.g. hydrology, agriculture, and environmental sciences (*Zhao et al.,* 2018).

Water scarcity has become an increasing threat to humans and ecosystem sustainability and is expected to be more serious under future climate change conditions (*Hoekstra,* 2012). Agriculture is the world's largest water user and is prominently impacted by climate change and population growth (*Ward* and *Pulido-Velazquez,* 2008; *Zhang et al.,* 2020).

Agriculture is one of the most vulnerable sectors to climate change and associated extreme weather events (*Pachauri et al.,* 2014). Shifts in precipitation, temperature, and other weather patterns may change the suitability of crop varieties to their present agro-ecosystems, change the need for pest and disease management, and increase the turnover of soil organic matter and the associated risk of nutrient loss (*Olesen et al.,* 2011). Extreme weather events (such as droughts) may also lead to reductions in areas suitable for agriculture, damage to infrastructure, and higher yield variability (*Olesen* and *Bindi,* 2002).

One of the main objectives of the research by *Bartholy* and *Pongrácz* (2010) was to analyze the possible tendency of future precipitation conditions for this century for the Carpathian Basin. Their results suggest that regional intensity and frequency of extreme precipitation increased in the Carpathian Basin during the second half of the 20th century, while the total precipitation decreased, and the mean climate became slightly drier during the whole 20th century. Furthermore, the climate simulations suggest that the climate of this region may become drier in summer and wetter in winter, which highlights the importance of hydrological and agricultural planning in Hungary.

Parametric methods (linear trend, t-test for slope) for analyzing time series are the simplest methods to get insight into the changes in a variable over time. These methods require normal distribution of the residuals that can be a limit for application. Non-parametric methods are distribution-free methods, and investigators can have a more sophisticated view of the variable tendencies in time series. Historical climate (precipitation) data covering the past almost one and a half centuries measured at the meteorological station in Keszthely, Hungary were analyzed by *Kocsis et al.* (2017) and *Kocsis* and *Anda* (2018) for detecting tendencies in the time series. The parametric method proved significant decreasing tendencies for spring, April, and October. Non-parametric tests show significant declining tendencies for spring, autumn, and October.

Kocsis et al. (2020) also tried to detect change points in the time series of monthly, seasonal, and annual precipitation records of Keszthely. Change points and monotonic trends were analyzed separately in annual, seasonal, and monthly time series. While no breakpoints could be detected in the annual precipitation series, a significant decreasing trend of 0.2–0.7 mm/year was highlighted statistically. Significant change points were found in those time series in which significant tendencies had been detected in previous studies. These points fell in spring and winter for the seasonal series, and October for the monthly series. The question, therefore, was raised that these trends were the result of a shift in the mean. The downward and upward shifts in the mean seasonal amounts in spring and winter led to a suspicion that changes in precipitation were also in progress in these seasons. The study concluded that homogeneity tests are of great importance in such analyses, because they may help to avoid false trend detections.

Wheat is one of the most valuable and widely grown cereal crops worldwide, with a cultivation area of around 245–250 million hectares. Its importance for food security is only rivalled by rice. The widespread distribution of wheat is made possible by the diverse climatic requirements of wheat species and varieties and their strong adaptability. It can be found from near the Equator to the 60°N and 40°S latitudes. As a result of its wide adaptation, wheat is grown at such diverse geographical latitudes that harvests occur year-round, but it is primarily a crop of continental climates.

In Hungary, wheat is also the most important cereal crop, cultivated on approximately 1 million hectares annually (Hungarian Statistical Office's website). In years with average weather conditions, with appropriate agrotechnics, and considering the varieties currently grown, the water demand of winter wheat in Hungary is estimated at 350–410 mm. This water amount is mostly not covered by natural precipitation. Of the 390–480 mm (50-year average) of precipitation falling from sowing to harvest, only 40–60% is effectively utilized, depending on the water management properties of the soil. Since wheat requires an average of 280–340 mm of water from late March to early July, and the precipitation during this period only partially covers this need, the available soil water at the end of winter is of fundamental importance for the water supply of winter wheat (*Harmati,* 1987).

Wheat needs water throughout its entire growth period, but there are certain stages during which water scarcity can cause significant yield reduction (*Araus et al.,* 2008). In the early stages of the growing season, drought can have severe consequences, as it reduces plant growth (*Jaleel* and *Llorente,* 2009). Early spring drought negatively affects the development of the secondary root system and tillering (*Harmati,* 1987; *Araus et al.,* 2008). Water deficiency also delays the appearance of side shoots and fertilization, leading to yield loss (*Mosaad et al.,* 1995).

In our study, we aimed to study the trends in the precipitation data from Mosonmagyaróvár between 1871 and 2020 and to draw conclusions about how these trends might impact winter wheat cultivation conditions in the Mosoni-plain.

2. Material and methods

2.1. Dataset

Monthly precipitation amount measured at Mosonmagyaróvár (northwestern edge of Hungary, of 47° 53' 23" N and 17° 16' 02" E, *Fig. 1*) was used for the analysis of tendencies for the period of 1871–2020. The dataset was collected in around a circle of a diameter of 5 kilometers in plain ground, and the original data were used. To gain coherent precipitation data over flat terrain in the mid-latitudes, even interpolation should yield acceptable results on scales smaller than 10 km (*Dingman,* 2015). The dataset was controlled but not homogenized by the MASH method (*Szentimrey*, 1999) that is usually used for homogenization of meteorological datasets in Hungary. In purpose of testing homogeneity of the time series, Pettitt's test (*Pettitt,* 1979) was applied. This test detects shifts in the average and calculates their significance (*Liu et al.,* 2012) in a hypothesis test. The 5% significance level was used as threshold.

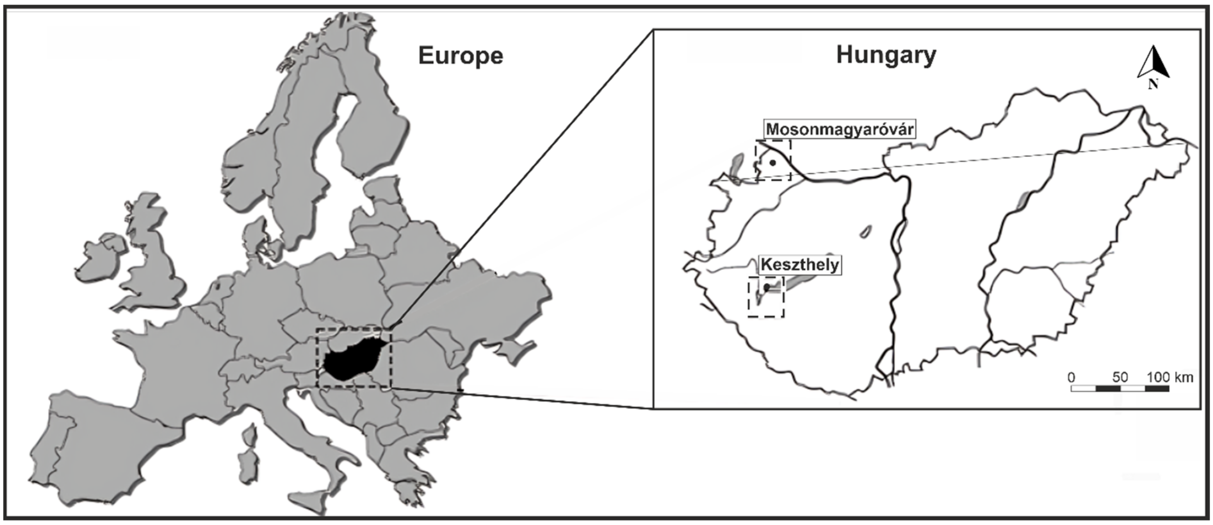

Fig. 1. Location of Mosonmagyaróvár (Hungary; 47°53'N, 17°16′E, elevation 121.5 m above Baltic Sea level) and Keszthely (Hungary; 46°44′N, 17°14′E, elevation 114.2 m above Baltic Sea level), redrawn from *Kocsis et al*. (2020, 2024)

The location of the meteorological station, which provides representative measurements of the region's climate, changed six times during the century and a half, but these relocations took place within a very narrow area. The time series of yearly, seasonal, and monthly amounts of precipitation were examined, and an analysis was conducted to detect linear or monotonic trends. Each time series used contained 150 data. The dataset was complete, without missing data.

2.2. Statistical methods

First, the tendency of the time series was estimated by a linear trend using the ordinary least squares method

$$\hat{y}_t = b_0 + b_1 * t \,, \tag{1}$$

where t is the serial number of the time step, $t = 1, 2, 3, \ldots, n$, where n is the number of the data, $\hat{y}_t$ is the estimated value of precipitation amount for a certain time step, b_0 is the intercept of the trendline, and b_1 is the slope coefficient on the trendline.

In the diagnostic stage of a linear trend, the normal distribution of the residuals was tested by the Kolmogorov-Smirnov test. In this case, the residuals' distribution could be accepted to be normal, the slope coefficient of the linear trend was tested in a parametric *t*-test for significance. Otherwise, when the distribution of the residuals could not be accepted to be normal according to the Kolmogorov-Smirnov test, the Mann-Kendall trend test was used. The Mann-Kendall trend test is based upon the work of *Mann* (1945) and *Kendall* (1975), and it is closely related to the Kendall's rank correlation coefficient. This test is suitable to detect monotonic trends in the time series. The Mann-Kendall trend test is widespread in climatological and hydrological analyses for time series, because it is simple and robust, it can cope with missing values and values under detection limit (*Gavrilov et al.,* 2016). This non-parametric test is commonly used to detect monotonic tendencies in a series of environmental data, too (*Pohlert,* 2016). This method has no requirement for the distribution, as the regression method requires normal distribution. No assumption of the normality is required (*Helsel* and *Hirsh,* 2002). The Mann-Kendall test statistic is given as (*Singh et al.,* 2024):

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^{n} sgn(x_j - x_i) \ , \tag{2}$$

where $j > i$ and $i = 1, 2, \ldots, n\text{-}1$; $j = 2, 3, \ldots, n$, and n is the number of the data.

S serves for the hypothesis test, where the null hypothesis is that there is not a significant trend, and the alternative hypothesis is that a significant monotonic trend over time is present. $Sgn(x_j\text{-}x_i)$ is calculated as (*Hipel* and *McLeod,* 1994; *Hu et al.,* 2020):

$$sgn(x_j - x_i) = \begin{cases} +1 \ if \ \ x_j - x_i > 0 \\ \ \ 0 \ if \ \ x_j - x_i = 0 \\ -1 \ if \ \ x_j - x_i < 0 \end{cases} \ . \tag{3}$$

Decisions were made based on the *p*-value in the hypothesis tests, at 5% significance level as a threshold. After determining the presence of the trend, the Sen's slope estimator (*Sen,* 1968) was applied. It is a non-parametric method that can calculate the change per time unit (direction and volume) and is commonly used in hydro-meteorological time series to calculate the magnitude of a trend (*Lone et al.,* 2022).

Calculations were carried out using IBM SPSS and R softwares.

3. Results

3.1. Descriptive statistics of the annual, seasonal, and monthly precipitation sums

The average annual precipitation amount at Mosonmagyaróvár was 593.32 mm between 1871 and 2020 with a standard deviation of 104.13 mm. The median of the dataset is 586.25 mm. Based on the relation of the average and the median (average > median), the ratio of those values that are less than the mean is supposed to be more than 50%, but the boxplot of the annual data does not represent this skewness, probably for the reason that two data have been considered as outliers (*Fig. 2*).

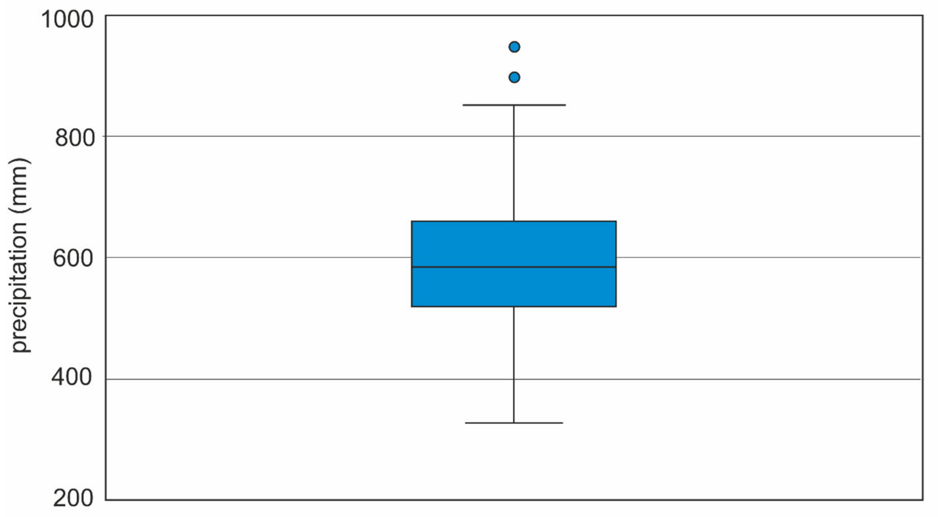

Fig. 2. Boxplot of the annual precipitation amount (mm).
The box indicates the interquartile range, the black line in it is the median.

Table 1 summarizes the descriptive statistics of the seasonal precipitation sums. It can be observed that the order of the mean, median, and mode is the same for all seasons, as the mean is greater than the median, and the median is greater than the mode. When the mode is the lowest one, a positively skewed distribution should be supposed, where the values of lower than the average are overrepresented. This can also be observed in *Fig. 3.* The same type of skewness can be seen in the case of the monthly precipitation sums, as well. A skewness can be observed towards the values lower than the average of the dataset (*Table 2, Fig. 4*). The highest monthly amounts can be expected in June and July, so the maximum of the yearly course is in summer. Usually, a peak can be observed in May and a secondary maximum in September. This yearly course seems to be rearranged at Mosonmagyaróvár.

Table 1. Main descriptive statistics of the seasonal precipitation sums

	Descriptive statistics (mm)			
Season	Mean	Median	Mode	Standard deviation
Spring	142.28	138.50	77.0	51.12
Summer	190.53	185.05	121.0	65.34
Fall	149.29	148.50	126.0	52.72
Winter	111.33	102.50	87.0	41.91

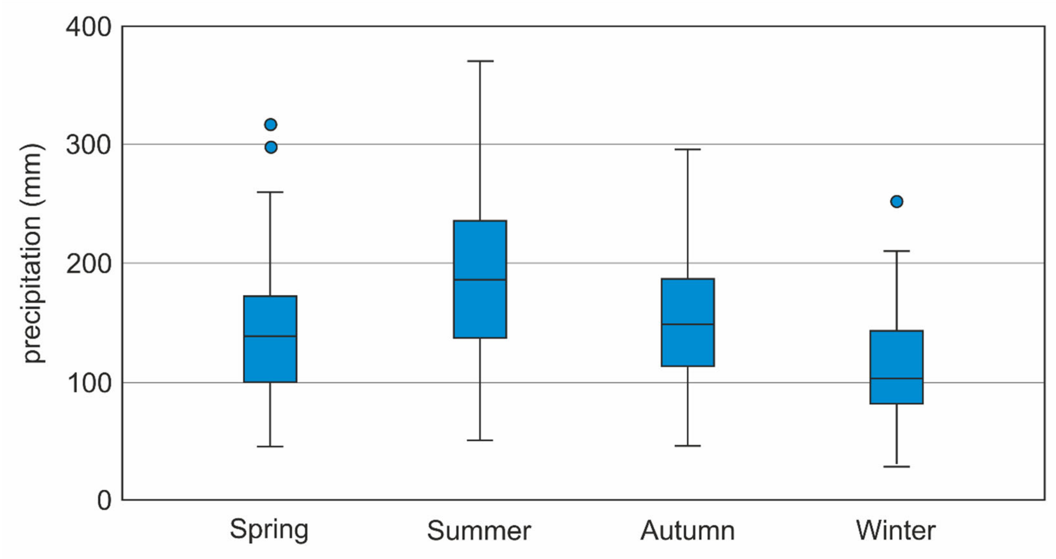

Fig. 3. Boxplots of the seasonal precipitation amount (mm).
The boxes indicate the interquartile range, the black line in it is the median.

Table 2. Main descriptive statistics of the monthly precipitation sums

	Descriptive statistics (mm)			
Month	Mean	Median	Mode	Standard deviation
Jan	34.53	32.00	28.0	19.31
Feb	32.32	27.00	16.0	22.25
Mar	37.77	34.50	39.0	23.78
Apr	42.46	37.50	19.0	26.72
May	62.05	54.50	39.0	37.40
Jun	65.36	59.25	53.0	34.68
Jul	65.56	58.30	49.0	39.25
Aug	59.62	51.50	57.0	36.08
Sept	50.03	43.35	31.0	33.39
Oct	49.64	46.00	60.0	33.00
Nov	49.61	40.90	31.0	31.94
Dec	44.38	42.40	37.0	24.29

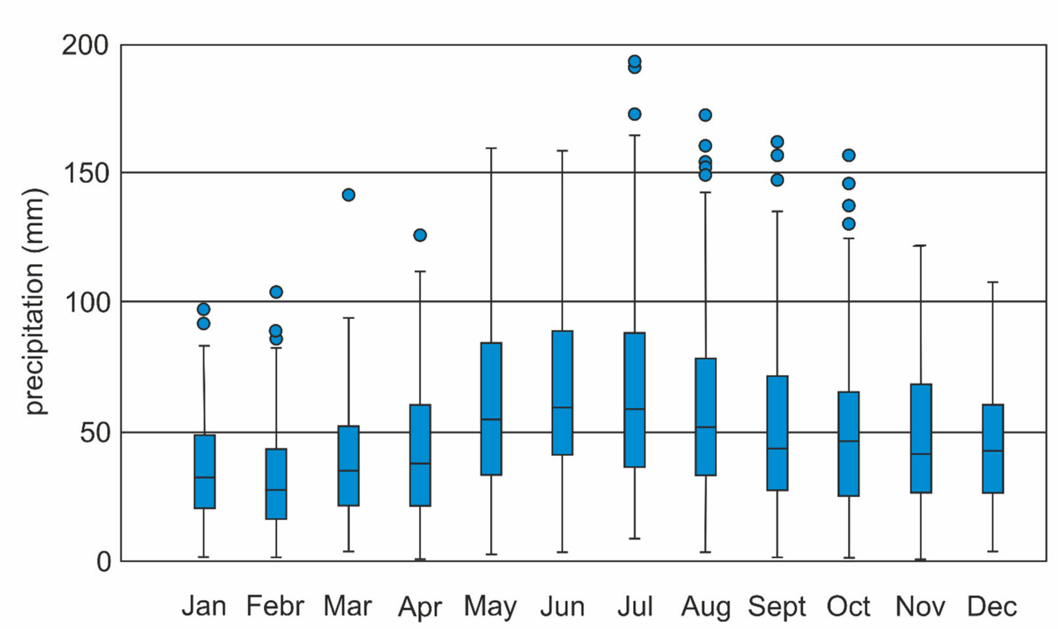

Fig. 4. Boxplots of the monthly precipitation amount (mm).
The boxes indicate the interquartile range, while the black line in the middle is the median.

3.2. Trends of the examined time series

Following the steps of time series analysis written about in Section 2.2, a significant linear trend can be detected in spring ($\alpha = 0.05$, *Table 3, Fig. 5.*). Regarding the homogeneity of the time series, it should be noted that in case of only one time series, a change point could be detected by the Pettitt's test. This one is spring (p-value = 0.032). The change point took place in 1945, and no other change point could be found. Therefore, to be sure to detect a real trend, the time series was divided into two parts, but no significant trends could be seen in the separated parts. The Pettitt's test suggests a significant downward shift of the mean (*Fig. 5*), that can be the same proof of the changes, as the precipitation decrease can be realized not only as a gradual change, but also as an abrupt shift of the mean.

When analyzing the trends of the monthly precipitation sums, significant monotonic trends can be determined for April and October (*Table 4*). In April, 9.1 mm per 100 years declining trend could be found, and in October the average decrease was 11.08 mm per 100 years. These results are in good coincidence with the findings of *Kocsis* and *Anda* (2018) and *Kocsis et al.* (2020) at Keszthely (western Hungary). It should be highlighted that Keszthely and Mosonmagyaróvár are about 150 km far from each other, and there is the Bakony Hills region as a barrier for the vapour flows that can modify the direction of the air movements. Keszthely's microclimate is affected by the Balaton Lake. As a similarity, the proximity of the Mosoni-Danube River can be mentioned in the case of Mosonmagyaróvár.

Table 3. Results of the time series analysis

	Linear slope coefficient	***p*-value of *t*-test**	**Kolmogorov-Smirnov *p*-value**	**Kendall tau**	***p*-value of MK test**
Annual	-0.353	0.072	0.2		
Spring	**-0.213**	0.026*	0.2		
Summer	0.014	0.908	0.2		
Fall	-0.115	0.249	0.2		
Winter	-0.043	0.591	0.002*	-0.035	0.522

* *significant at the 5% significance level*

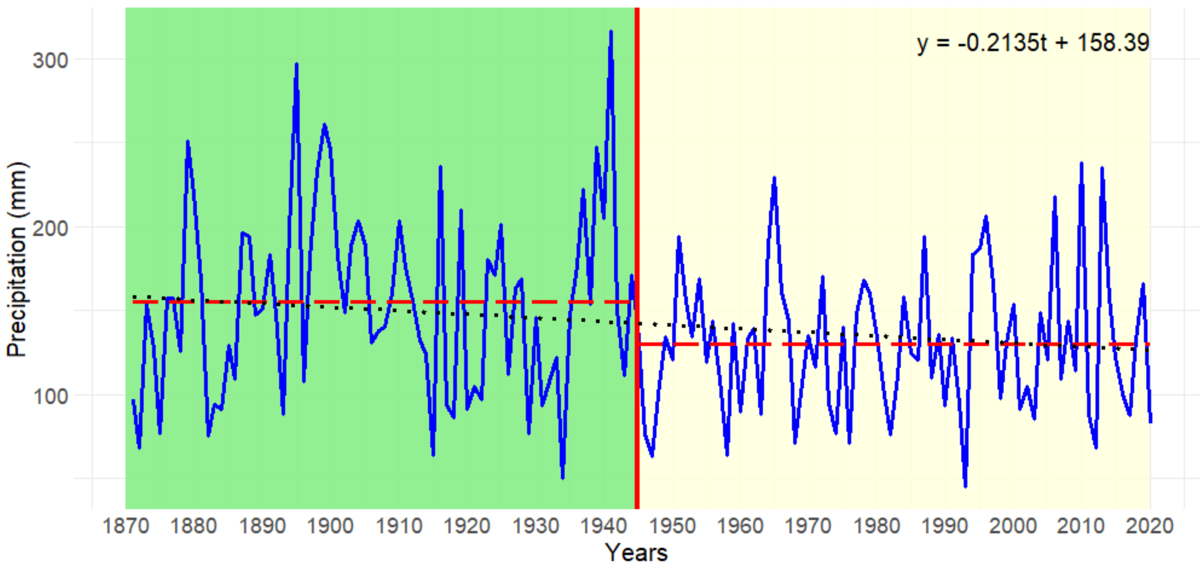

Fig. 5. Time series of the precipitation amount measured at Mosonmagyaróvár in spring (1871–2020). The blue line represents the observed data, while the black dotted line shows the significant decreasing linear trend. The red vertical line indicates the breakpoint obtained by the Pettitt's test and the red dashed lines show the means of the precipitation data in the separated time intervals.

Table 4. Results of the time series analysis of the monthly precipitation amounts

Month	Linear slope coefficient	*p*-value of *t*-test	Kolmogorov-Smirnov *p*-value	Kendall tau	*p*-value of MK test	Sen's slope
Jan	0.009	0.798	0.013*	0.015	0.791	0.005
Feb	0.014	0.744	0.002*	0.037	0.501	0.024
Mar	-0.049	0.274	0.001*	-0.071	0.199	-0.048
Apr	-0.104	0.038*	0.001*	-0.107	0.048*	**-0.092**
May	-0.060	0.397	0.001*	-0.035	0.521	-0.042
Jun	-0.007	0.918	0.021*	0.001	0.979	0.000
Jul	0.034	0.652	0.001*	0.017	0.753	0.019
Aug	-0.013	0.854	0.001*	0.021	0.71	0.023
Sept	0.018	0.771	0.001*	-0.013	0.81	-0.013
Oct	-0.132	0.033*	0.032*	-0.11	0.046*	**-0.112**
Nov	-0.002	0.980	0.001*	0.028	0.619	0.026
Dec	-0.062	0.178	0.02*	-0.057	0.305	-0.045

* *significant at the 5% significance level*

3.3. Trends of the vegetation period of winter wheat

The precipitation conditions of the vegetation period of winter wheat were also studied, and the precipitation sums between September and the consecutive June were analyzed. The requirement for normality of the residuals of the linear trend was fulfilled (*p*-value of the Kolmogorov-Smirnov test was 0.087), therefore its slope can be interpreted as it was significant at the 5% significance level (*p*-value = 0.022). There was no significant change point in the time series (*p*-value = 0.108). A declining tendency could be detected by 0.411 mm per year on average. This means 40.89 mm less precipitation in a 100-year period.

4. Discussion

During the last years, Europe has been exposed to a continuous period of dry conditions, leading to increasingly frequent agricultural, meteorological, and hydrological droughts across the continent. The years 2021 and 2022 caused one of the most severe water shortages in Europe and Hungary in the past decades. Because of the historic drought of 2022, the yields of autumn and summer crops fell below the average of previous years.

Wheat, by origin, is a plant that generally prefers drier conditions, as its gene center is located in the Fertile Crescent of the Middle East. During centuries of breeding in Central Europe, the goal was to make the plant thrive under the local continental-type climate as much as possible, but even this essentially means drier conditions.

Wheat is a moderately water-demanding crop, requiring approximately 350–410 mm of precipitation in growing seasons with average weather conditions, when proper agrotechnics are applied. Its transpiration coefficient is 300–350 l/kg of dry matter (*Harmati,* 1987).

Our studies found that there has been a tendency to the reorganization of precipitation amounts in Mosonmagyaróvár between 1871 and 2020. Analysis of the data shows that both the spring and autumn periods have experienced a decrease, which was significant in the case of some months, in precipitation. This is particularly harmful for winter wheat, as these periods correspond to the phenological phases that greatly determine the quantity and quality of the yield.

The sowing time of winter wheat must be chosen so that the wheat can establish itself before the onset of winter. The crop's response to sowing time is specific and genetically determined, it generally occurs between September 20 and October 30, but it can be extended until early November.

From the perspective of water supply, the autumn period is critical in Hungary, as it is often dry, which can result in poor germination and uneven wheat stands. Our study results also indicate a significant decreasing trend in precipitation in October. The accompanying extreme weather conditions are generally unfavorable for wheat development and yield. Extremely dry autumn weather makes the proper germination, early development, establishment of a strong plant stand, and successful overwintering impossible. Germination can begin, only if the sown seeds receive sufficient water and the temperature is appropriate (*Varga-Haszonits et al.,* 2006).

The tillering phase lasts from December to the end of March, during which the formation of the secondary root system occurs. If there is a significant drought during this period, tillering may be delayed or fail. The more developed the secondary root system is the more resilient the wheat becomes.

The heading phase in our region lasts from mid-April to the end of May, which is the period of intense growth. The amount of precipitation during this period has a decisive impact on the maximum height of the varieties. During heading, wheat requires an uninterrupted water supply, as this phase - which lasts about 30 days - produces the most dry matter, nearly 50% of the total amount. Unfavourable water conditions disrupt plant development. If drought occurs during this developmental stage, the yield can be reduced to half. The vegetative organs become smaller, and assimilation activity decreases, leading to underdeveloped flowering organs in the spikes.

For this reason, it is crucial to ensure optimal soil moisture during this period, from mid-April to the end of May. The water demand closely approaches the evapotranspiration rate during this time, i.e., around 150–160 mm over this approximately 6-week period. The deeper and better water-managed the soil is, and the more abundant the natural precipitation is, the less irrigation is needed. However, higher production targets require better water availability (*Harmati,* 1987). The significant decrease in April and spring precipitation amounts can therefore be a cause for serious concern.

The heading-flowering phase, which lasts for a relatively short time, is also a critical period (*Varga-Haszonits et al.,* 2006). Due to high temperatures and poor water supply, partial death of the flowering organs occurs, resulting in incomplete fertilization and a significant decrease in yield. If the autumn and winter are wet and the spring is not too dry, the moisture stored in the soil can meet the water requirements of these two phases without irrigation, especially in deep, fertile soils. In a dry year, or shallow soils, irrigation before or during this critical period is essential and effective.

Winter wheat takes up the most water during the flowering and fertilization period (from the middle of May to early June), but the pre-ripening period is also significant in terms of water consumption. Lack of precipitation during the ripening period can result in deformed, shrivelled grains, and the kernels may shrink. In May and June, the average required amount of precipitation is about 115 mm (*Harmati,* 1987). Full maturity in Hungary typically occurs in the first part of July. If the weather is too rainy at this time, the grains may become overripe, and their baking quality can deteriorate.

In the Carpathian Basin and Hungary, extreme weather events have become more frequent, and it is also unfavourable that precipitation shows decreasing tendencies. Such a modification of the main water intake factor, together with unfavourable thermal changes affecting the water loss side of the water balance, may endanger the water supply of winter wheat. Most climate simulations suggest that this trend will continue in the future, and even decade-long extremes may occur in the second half of the century.

5. Conclusions

The main findings of this research are that between 1871 and 2020 decreasing trends were detected in April and October, and a significant downward shift of the mean can be found in spring. For the growing period of winter wheat (September- June), a significant precipitation decline can be demonstrated.

The entire area of Hungary is suitable for the cultivation of winter wheat, but due to climate change, the weather could be extreme sometimes. Unfortunately, dry years and even droughts are becoming more and more frequent. Such problems may also occur in the studied region. Therefore, we considered it important to quantify the trends in precipitation conditions based on the longest data series available. The good agreement with the results of previous, similar research on Keszthely suggests that the conclusions drawn from our investigations may be more general.

Winter wheat yields are expected to decrease by 8% by 2050 and by 21% by 2100 in Hungary (*Kemény et al.,* 2019), but the results may differ significantly by the model used for prognostications. More intensive nutrient management and irrigation cannot even compensate for the negative impact of climate change on average (*Kemény et al.,* 2019). The negative effects of climate change and more frequent dry periods can be mitigated in two ways: with passive and active methods. The passive methods are the right choice of varieties, as well as efficient agrotechnics in terms of water conservation and water use. Active intervention could be achieved through irrigation to reduce the water deficit.

With agrotechnics adapted to the environment and genotypes, we can keep the yield quantity and quality stable, and it is important to use genotypes that are not only capable of achieving high yield and good quality but are also able to keep it stable under different meteorological conditions and on different quality soils, with different agrotechnical levels. These varieties are characterized by good stress tolerance - such as drought tolerance, excellent winter resistance, and better resistance to diseases and pests, as well as good or excellent adaptability and a good reaction to agrotechnics. It is advisable to select successive plants in such a way that plants with lower and higher water consumption follow each other in the crop rotation.

A fundamental consideration for Hungary must be the use of a water-saving soil cultivation system that is minimized as much as possible. Preference should be given to tillage tools without rotation, sealing the soil at the optimal time, and increasing the water absorption and water retention capacity of the soil. In terms of nutrient supply, plant stands in better condition and can withstand drought better. The close interactive relationship between water and nutrient supply in our cultivated plants is well known. It is important to emphasize that the water supply plays a key role in the vegetative and generative development and crop formation of field plants; however, it also affects the effectiveness of various agrotechnical inputs (e.g., soil cultivation, plant protection, etc.).

In the case of sowing technology, the stand density of plants primarily affects the drought tolerance of plants. It is a common misconception that the sowing rate should be increased with the intention of "sowing more so that some will remain". This actually results in the opposite effect. By choosing the right sowing time, we can avoid the coincidence of the phenophase of the given plant species, which is sensitive to water shortage, and the typically dry period of the given area. Plant protection can also contribute to better drought tolerance of plant populations. Adequate weed control is particularly important, as weeds not only consume more water than cultivated plants, but they can take up water much more aggressively.

In these times, we can irrigate only 2% (approximately 100,000 ha) of the domestic arable land in Hungary, which is extremely small. Wheat is a plant that prefers drier conditions since its genetic center is located in the area called the Fertile Crescent of the Middle East. During centuries of breeding in Central Europe, the aim was to make the plant thrive under the local continental climate as well as possible in the continental-type climate, but even this basically means drier conditions. Under normal weather conditions, there is no need to irrigate winter wheat. In the case of extremely dry months, it is worth watering the plants.

Nowadays, one of the most important questions of arable crop production is how we can ensure optimal water supply for plants under changing and less favorable climatic conditions. In this, it must be taken into account that passive agrotechnical elements play a decisive role, as the irrigated area is extremely limited in Hungary today. This is the key issue for the further development of domestic crop production. We wanted to contribute to this with our work quantifying regional precipitation conditions and trends.

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