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Considerations regarding the evolution of the De Martonne Aridity Index in the eastern part of the Pannonian Plain

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Abstract— The phenomenon of climate aridization is becoming increasingly prominent in both scientific and popular discourses. A plethora of studies have been conducted on this subject, including studies covering the Pannonian Plain; however, comparatively fewer have focused on its eastern region. The present article aims to address this knowledge gap by exploring the potential for aridization at the local scale. We are aware that only by analyzing the evolution of the De Martonne Aridity Index it may not be possible to draw final irrevocable conclusions about the aridization of the climate in the study area, but we believe that it may be a start in this direction. The present study was conducted using data from eight meteorological stations, four from Romania and two each from Hungary and Serbia, for the 1951–2020 time period, and data from three meteorological stations, two from Hungary and one from Romania, for the 1901–2020 time period. The evolution trends of the De Martonne Aridity Index and its component parameters (temperature and precipitation) were analyzed with the help of the non-parametric Mann-Kendall test.

Key-words: De Martonne Aridity Index (DMAI), temperatures, precipitation amounts, Mann-Kendall test, Pannonian Plain

1. Introduction

The subject of climate change has been the focus of worldwide discussion since the late 19th century, with an increasing level of engagement observed in recent decades from both scientific and political communities. The most evident of the climate changes, at least at the local level, is the rise in temperatures. The present study will concentrate on the phenomenon of aridization, which is caused not only by a decrease in precipitation, but also by an increase in water demand, which in turn is partly caused by rising temperatures.

In order to express the level of aridization in the area under study, the De Martonne Aridity Index (DMAI) will be employed. Widely used in climatology in order to identify dry/wet climatic conditions in different regions: *Baltas* (2007), for northern Greece, *Deniz et al.* (2011), for Turkey, *Croitoru et al.* (2013), for the extra-Carpathian regions of Romania, *Nistor* (2016), for the Emilia-Romagna region in Italy, *Moral et al.* (2017), for Extremadura, in southwestern Spain, *Vlăduţ* and *Licurici* (2020), for Oltenia, in southern Romania etc., the De Martonne Aridity Index (DMAI) is an indicator that includes both temperature and precipitation and can be calculated for different time scales.

The aim of the present study is to observe the evolution over time of temperatures, precipitation, and the De Martonne Aridity Index in the eastern part of the Pannonian Plain, in an attempt to complete the image provided by the numerous studies carried out on this subject at the level of the Pannonian Plain or certain parts of it (*Gocić and Trajković*, 2012; *Hrnjak et al.*, 2014; *Toşić et al.,* 2014; *Gavrilov et al.*, 2015, 2016, 2019, 2020; *Milentijević et al.*, 2022; *Kiss et al.*, 2023), studies that do not cover the part of the plain included within the border of Romania.

2. Materials and methodology

2.1. Study area

The area under discussion (*Fig.1*) is located east of the river Tisza, within the territories of three states: Hungary in the north-west, Serbia in the south-west and Romania in the east. The geographical location of the area, in conjunction with the general movement of the atmosphere, is a determining factor in the existence of a moderate temperate continental climate. Small variations in the main climatic elements are observed, both in terms of temperature, which increases from north to south, and precipitation, which decreases from east to west, with increasing distance from the mountainous area (*Table 1, Table 2*).

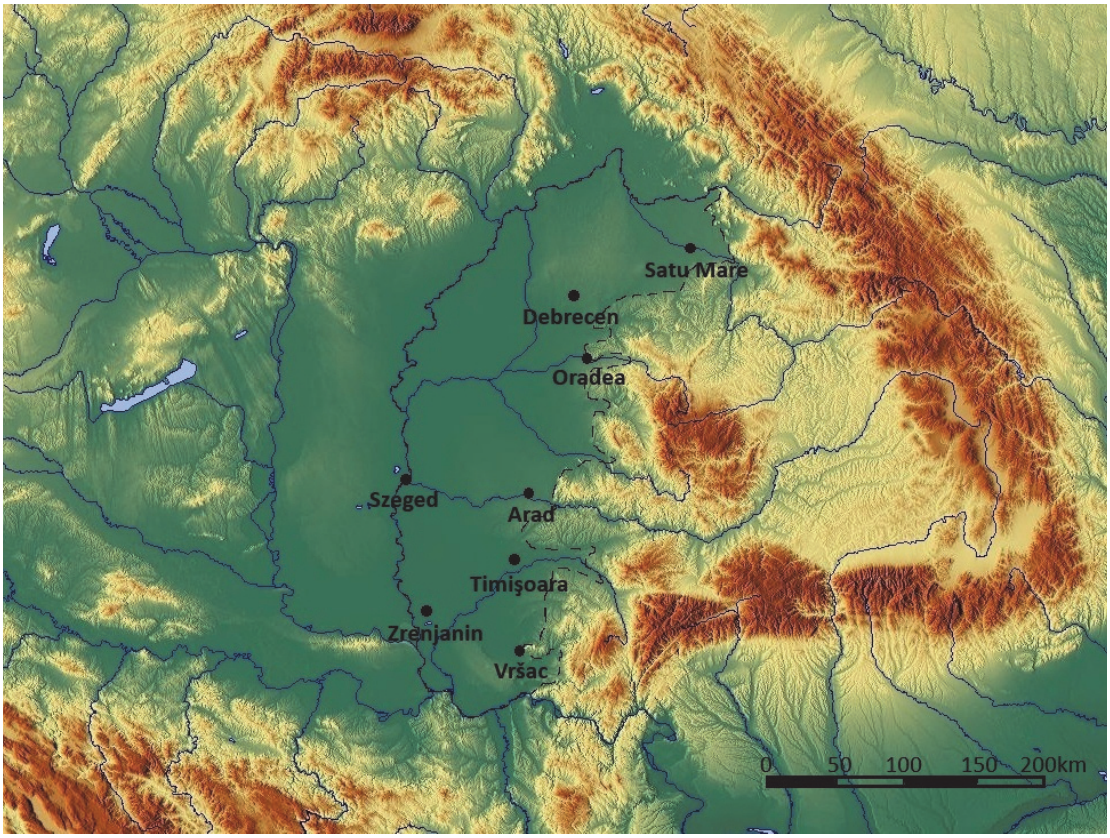

Fig.1. Location of the study area with the distribution of the main meteorological stations.

Table 1. Mean air temperatures (°C) and precipitation amounts (mm) for the 1951–2020 time period

Station name		Mean air temperature (°C) and precipitation amount (mm)				
		annual	**winter**	**spring**	**summer**	**autumn**
1.	Satu Mare	9.9 620	-0.7 131	10.3 145	20.0 208	10.0 136
2.	Oradea	10.6 613	0.1 123	10.8 145	20.5 210	10.9 136
3.	Arad	10.8 588	0.3 118	11.0 145	20.8 197	11.1 128
4.	Timişoara	11.1 602	0.6 126	11.4 147	21.1 195	11.3 136
5.	Debrecen	10.4 554	-0.4 108	10.8 132	20.4 194	10.6 120
6.	Szeged	10.9 516	0.3 97	11.2 124	20.9 177	11.2 117
7.	Zrenjanin	11.4 583	1.0 120	11.7 141	21.3 190	11.8 131
8.	Vršac	11.9 655	1.8 134	11.9 157	21.3 221	12.4 144
	average	10.9 591	0.4 120	11.1 142	20.8 199	11.2 131

Table 2. Mean air temperatures (°C) and precipitation amounts (mm) for the 1901–2020 time period

	Station name	Mean air temperature (°C) and precipitation amount (mm)				
		annual	**winter**	**spring**	**summer**	**autumn**
1.	Debrecen	10.0 566	-0.7 106	10.6 135	20.1 192	10.2 133
2.	Szeged	11.0 535	0.3 100	11.3 133	21.1 172	11.3 130
3.	Timişoara	11.1 611	0.4 126	11.4 151	21.0 191	11.4 143
	average	10.7 571	0.0 111	11.1 140	20.7 185	11.0 135

2.2. Data and methodology

Although the earliest known meteorological measurements in the area under study were recorded in the late 18th century (*Réthly*, 1918; *Dudaş* and *Urdea*, 2023; *Dudaş*, 2025), and during the 19th century measurements were taken in several localities (*Réthly*, 1970, 1998), the sporadic nature of these measurements, as well as their lack of accuracy according to current standards, led us not to mention them during this work. The lack of measurements or the incomplete data strings obtained from various meteorological stations for the 20th century, in addition to the difficulty in accessing meteorological data from Romanian stations, further constrained the selection of meteorological stations to be incorporated in this study. Under the given circumstances, we aimed to achieve a certain symmetry between the stations in Romania and those in Hungary and Serbia, as well as a relatively uniform distribution of these stations, finally opting for eight stations to calculate the De Martonne Index for the 1951–2020 time period and 3 meteorological stations for the 1901–2020 time period (*Fig.1*, *Table 1*, *Table 2*).

The completion of this project necessitated the execution of several distinct stages. Initially, a small database was constructed in Excel, containing temperature and precipitation values from the meteorological stations under consideration. These data were then analyzed to avoid discrepancies. Datasets for Szeged and Debrecen can be accessed online on the website of the HungaroMet Hungarian Meteorological Service (*https://www.met.hu/*). Data for Zrenjanin and Vršac can be found in the Meteorological Yearbooks (Meteorološki godišnjak) of the Federal Hydrometeorological Institute of Yugoslavia / Republican Hydrometeorological Service of Serbia, available online on the website of the Serbian Republican Hydrometeorological Service (*http://www.hidmet.gov.rs/*), or on the www.meteologos.rs meteorological website. The data for the four meteorological stations in Romania (Satu Mare, Oradea, Arad, and Timișoara) were partly purchased from the Regional Meteorological Center Banat–Crișana (Centrul Meteorologic Regional Banat–Crişana), partly collected from meteorological reports (*Berecz E.*, 1901–1910; *Berecz O.*, 1910–1917; *Ehmann*, 1918; *Institutul Meteorologic Central al României*, 1921–1959) or Romanian Statistical Yearbooks (*Direcţia Centrală de Statistică*, 1961–1989; *Comisia Naţională pentru Statistică*, 1990–1999; *Institutul Naţional de Statistică*, 2000 – 2021).

The annual and seasonal De Martonne Aridity Index was calculated for all the meteorological stations included in the study. Widely used in applied climatology, the De Martonne Aridity Index (DMAI) is given by the equations:

$$I_{\mathrm{a}} = \frac{P_{\mathrm{a}}}{T_{\mathrm{a}}+10}, \tag{1}$$

for the annual DMAI, where P_a is the annual amount of precipitation (mm) and T_a is the mean annual surface temperature (°C), and

$$I_{\mathrm{s}} = \frac{4P_{\mathrm{s}}}{T_{\mathrm{s}}+10}, \tag{2}$$

for the seasonal DMAI, where P_s is the seasonal amount of precipitation (mm) and T_a is the mean seasonal surface temperature (°C).

The classification of the DMAI is presented in *Table 3*, with the studied area belonging to the semi-humid and humid climate types.

Table 3. The De Martonne Aridity Index (DMAI) classification (*Gavrilov et al.*, 2020)

Types of climate	**Values of DMAI**
arid	$I < 10$
semi-arid	$10 \leq I < 20$
mediterranean	$20 \leq I < 24$
semi-humid	$24 \leq I < 28$
humid	$28 \leq I < 35$
very-humid	$35 \leq I \leq 55$
extremely humid	$I > 55$

The next step in the research was to create graphs representing the evolution of this parameter over time and to obtain the trend equation using linear regression, both for annual and seasonal trends. The trend equation was calculated by Excel with the formula $y = ax+b$, where y represents the parameter in a given year, a the slope, x the time in years, and b the parameter at the beginning of the period. Easy to perform and interpret, there are three possible scenarios: if $a \geq 0$, the trend is positive, increasing, if *a* = 0, there is no trend, and if *a* ≤ 0 the trend is negative, decreasing (*Gavrilov et al.*, 2016; *Dudaş* and *Urdea*, 2023).

The Mann-Kendall non-parametric test was employed to ascertain the presence of trends in both annual and seasonal values. Under MK test, two hypotheses have been tested: the null hypothesis, H_o, indicating no trend in the time series, and the alternative hypothesis, H_a, indicating that there is a significant trend in the time series for a given level of significance. The probability, *p*, has been calculated in percents to determine the level of confidence in the hypothesis. When the *p* value calculated is less than the assumed significance level a (e.g. *a*=5%), the H_o hypothesis has to be rejected (no trend) and the Ha (there is a significant trend) should be accepted. If *p* is higher than significance level *a*, the H_o hypothesis (no trend) cannot be rejected (*Gavrilov et al.*, 2016; *Dudaş* and *Urdea*, 2023). XLSTAT software (*http://www.xlstat.com/en/*) has been used to calculate the probability and hypothesis testing.

3. Results

As previously mentioned, the following discussion will attempt to illustrate the evolution trends of the DMAI in the eastern part of the Pannonian Plain. However, prior to the discussion of the DMAI itself, we consider it necessary to briefly analyze the evolution over time of the two parameters that define the DMAI: temperature and precipitation.

3.1. Temperature

The analysis of temperature data over the **1951**–**2020** time period reveals a consistent increase at all analyzed meteorological stations, both in terms of annual and seasonal averages. The Mann-Kendall trend test confirmed the trend of the annual, spring and summer averages for all analyzed meteorological stations. However, the test did not confirm the trend of winter temperatures, with the exception of Zrenjanin meteorological station, and the trend of autumn temperatures, with the exception of Oradea and Zrenjanin meteorological stations (*Table 4*). Considering the average temperature of the eight meteorological stations, over the 1951–2020 time period temperatures have increased both annually and seasonally, with the MK test confirming this trend only for the annual, spring and summer averages (*Fig. 2, Table 5*).

Table 4. Annual and seasonal temperature trends for the 1951–2020 time period

	Station name	Temperature trends (1951–2020)									
		annual		winter		spring		summer		autumn	
		p-value	Sen's slope	p-value	Sen's slope	p-value	Sen's slope	p-value	Sen's slope	p-value	Sen's slope
1.	Satu Mare	**0.001**	0.020	0.140	0.019	**0.000**	0.024	**<0.0001**	0.031	0.490	0.005
2.	Oradea	**<0.0001**	0.027	0.089	0.022	**<0.0001**	0.030	**<0.0001**	0.037	**0.049**	0.015
3.	Arad	**0.000**	0.020	0.203	0.014	**0.000**	0.022	**<0.0001**	0.031	0.402	0.007
4.	Timişoara	**<0.0001**	0.027	0.057	0.020	**<0.0001**	0.031	**<0.0001**	0.037	0.078	0.013
5.	Debrecen	**<0.0001**	0.024	0.084	0.020	**<0.0001**	0.029	**<0.0001**	0.030	0.081	0.013
6.	Szeged	**<0.0001**	0.024	0.082	0.019	**<0.0001**	0.029	**0.000**	0.027	0.103	0.012
7.	Zrenjanin	**<0.0001**	0.030	**0.022**	0.025	**<0.0001**	0.033	**<0.0001**	0.031	**0.033**	0.018
8.	Vršac	**<0.0001**	0.026	0.201	0.017	**<0.0001**	0.032	**<0.0001**	0.035	0.171	0.012

Table 5. Annual and seasonal temperature trends for the 1951–2020 time period as an average for the entire area

Variable	Minimum	Maximum	Mean	Std. deviation	Kendall's tau	p-value	Sen's slope
annual	9.3	12.9	10.9	0.871	0.365	**<0.0001**	0.025
winter	-5.1	4.1	0.4	1.991	0.137	0.094	0.019
spring	8.3	13.5	11.1	1.113	0.364	**<0.0001**	0.028
summer	18.5	23.5	20.8	1.170	0.371	**<0.0001**	0.032
autumn	8.5	13.9	11.2	1.137	0.133	0.106	0.013

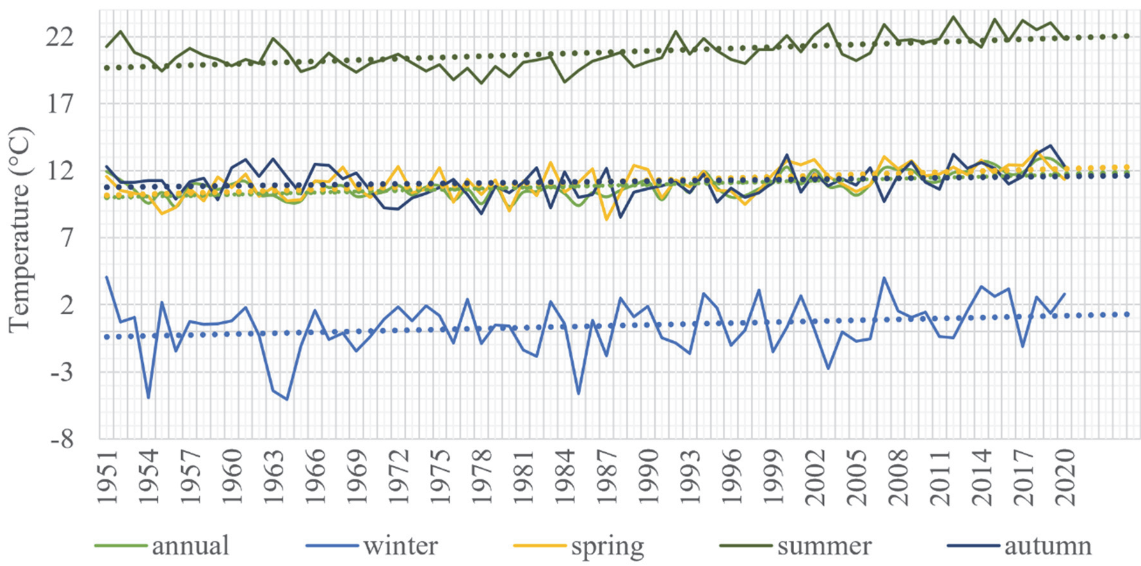

Fig. 2. Annual and seasonal temperature trends for the 1951–2020 time period as an average for the entire area. Dotted lines indicate linear trends.

For the **1901–2020** time period, temperatures have increased at all analyzed meteorological stations, either as annual or seasonal averages. The evolution trend is confirmed by the Mann-Kendall trend test for Debrecen, for both the annual and seasonal averages, and for Timişoara, only for the annual, spring and summer averages (*Table 6*). Considering the average temperature of the three meteorological stations, over the period 1901–2020 temperatures have increased both annually and seasonally, with the MK test confirming this trend only for the annual, spring and summer averages (*Fig. 3, Table 7*).

Table 6. Annual and seasonal temperature trends for the 1901–2020 time period

	Station name	Temperature trends (1901–2020)									
		annual		winter		spring		summer		autumn	
		p-value	Sen's slope	p-value	Sen's slope	p-value	Sen's slope	p-value	Sen's slope	p-value	Sen's slope
1.	Debrecen	**<0.0001**	0.015	**0.008**	0.015	**<0.0001**	0.017	**<0.0001**	0.016	**<0.0001**	0.013
2.	Szeged	0.204	0.003	0.390	0.005	0.141	0.005	0.720	0.000	0.902	0.000
3.	Timişoara	**0.020**	0.005	0.142	0.008	**0.045**	0.006	**0.011**	0.007	0.906	0.000

Table 7. Annual and seasonal temperature trends for the 1901–2020 time period as an average for the entire area

Variable	Minimum	Maximum	Mean	Std. deviation	Kendall's tau	p-value	Sen's slope
annual	8.4	12.8	10.7	0.810	0.208	**0.001**	0.007
winter	-5.3	3.7	0.0	2.012	0.101	0.104	0.010
spring	8.4	14.4	11.1	1.168	0.182	**0.003**	0.009
summer	18.5	23.3	20.7	1.055	0.172	**0.005**	0.008
autumn	7.7	13.6	11.0	1.217	0.080	0.199	0.005

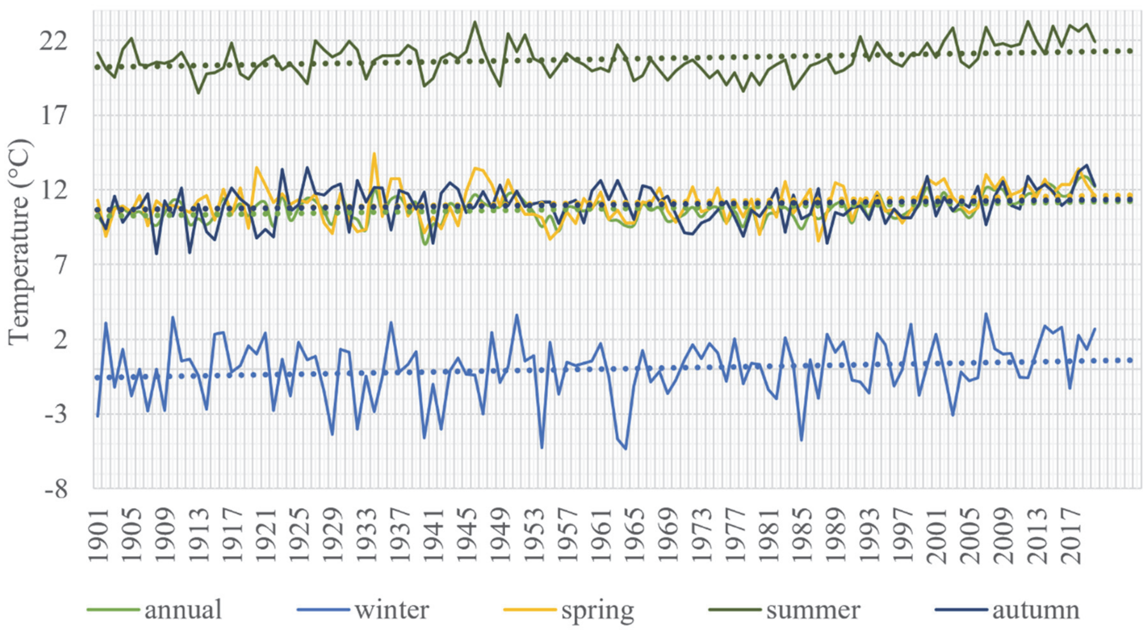

Fig. 3. Annual and seasonal temperature trends for the 1901–2020 time period as an average for the entire area. Dotted lines indicate linear trends.

3.2. Precipitation

For the **1951–2020** time period, an increasing trend in annual precipitation was observed for the average of the eight meteorological stations, as well as for Satu Mare, Oradea, Arad, Szeged, and Zrenjanin. Conversely, a decreasing trend was observed for Timişoara, Debrecen, and Vršac. Winter precipitation amounts are recording a decreasing trend for all meteorological stations and for their average, spring precipitation amounts are recording an increasing trend for the average and all meteorological stations, except Zrenjanin, summer precipitation amounts are recording an increasing trend for the average of the eight meteorological stations and for Oradea, Arad, Szeged, and Vršac, and a decreasing trend for Satu Mare, Timişoara, Debrecen, and Zrenjanin, and autumn precipitation amounts are recording an increasing trend for all meteorological stations and for their average (*Fig. 4, Table 8*, *Table 9*). The Mann-Kendal trend test confirms the trend only for the autumn precipitation amounts in Satu Mare (*Table 8*).

Table 8. Annual and seasonal precipitation trends for the 1951–2020 time period

Station name		**Precipitation trends (1951–2020)**									
		annual		**winter**		**spring**		**summer**		**autumn**	
		p-value	Sen's slope	p-value	Sen's slope	p-value	Sen's slope	p-value	Sen's slope	p-value	Sen's slope
1.	Satu Mare	0.282	0.782	0.271	-0.288	0.392	0.266	0.619	-0.212	**0.002**	1.083
2.	Oradea	0.453	0.571	0.250	-0.310	0.670	0.115	0.567	0.248	0.196	0.444
3.	Arad	0.378	0.613	0.230	-0.321	0.670	0.100	0.441	0.305	0.100	0.567
4.	Timişoara	0.988	-0.019	0.086	-0.443	0.847	0.038	0.984	-0.005	0.182	0.451
5.	Debrecen	0.776	-0.256	0.061	-0.417	0.715	0.086	0.375	-0.348	0.258	0.375
6.	Szeged	0.711	0.267	0.372	-0.194	0.746	0.100	0.530	0.292	0.118	0.495
7.	Zrenjanin	0.796	0.172	0.296	-0.306	0.560	-0.217	0.883	-0.042	0.086	0.594
8.	Vršac	0.895	-0.129	0.456	-0.247	0.435	0.187	0.956	0.053	0.567	0.267

Table 9. Annual and seasonal precipitation trends for the 1951–2020 time period as an average for the entire area

Variable	**Minimum**	**Maximum**	**Mean**	**Std. deviation**	**Kendall's tau**	**p-value**	**Sen's slope**
annual	336	858	591	99.077	0.045	0.584	0.368
winter	40	217	120	38.031	-0.124	0.130	-0.305
spring	58	244	142	37.157	0.046	0.577	0.126
summer	71	327	199	56.461	0.004	0.968	0.013
autumn	28	272	131	49.586	0.147	0.074	0.540

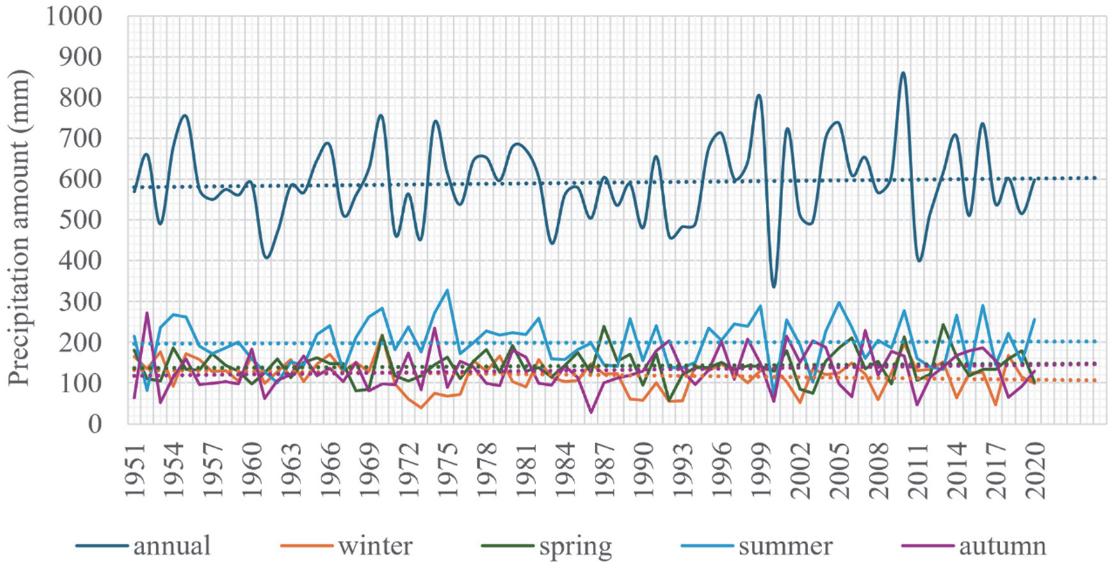

Fig. 4. Annual and seasonal precipitation trends for the 1951–2020 time period as an average for the entire area. Dotted lines indicate linear trends.

The general trend for the **1901–2020** time period is one of decrease, both for the three meteorological stations and for their averages, with the exception of the summer season. In this season, precipitation levels increased at the Timişoara and Szeged meteorological stations, as well as for the average of the three stations. The Mann-Kendal trend test does not confirm the trend for either annual or seasonal averages (*Fig. 5, Table 10, Table 11*).

Table 10. Annual and seasonal precipitation trends for the 1901–2020 time period

	Station name	Precipitation trends (1901–2020)									
		annual		winter		spring		summer		autumn	
		p-value	Sen's slope	p-value	Sen's slope	p-value	Sen's slope	p-value	Sen's slope	p-value	Sen's slope
1.	Debrecen	0.131	-0.498	0.705	-0.034	0.303	-0.108	0.980	-0.004	0.051	-0.270
2.	Szeged	0.074	-0.511	0.337	-0.104	0.051	-0.266	0.331	0.189	0.123	-0.249
3.	Timişoara	0.320	-0.291	0.380	-0.109	0.279	-0.119	0.599	0.075	0.686	-0.057

Table 11. Annual and seasonal precipitation trends for the 1901–2020 time period as an average for the entire area

Variable	Minimum	Maximum	Mean	Std. deviation	Kendall's tau	p-value	Sen's slope
annual	312	882	571	102.985	-0.096	0.121	-0.443
winter	40	214	111	36.536	-0.057	0.357	-0.094
spring	47	259	140	41.264	-0.089	0.151	-0.161
summer	70	324	185	55.494	0.040	0.515	0.098
autumn	21	257	135	49.663	-0.075	0.228	-0.178

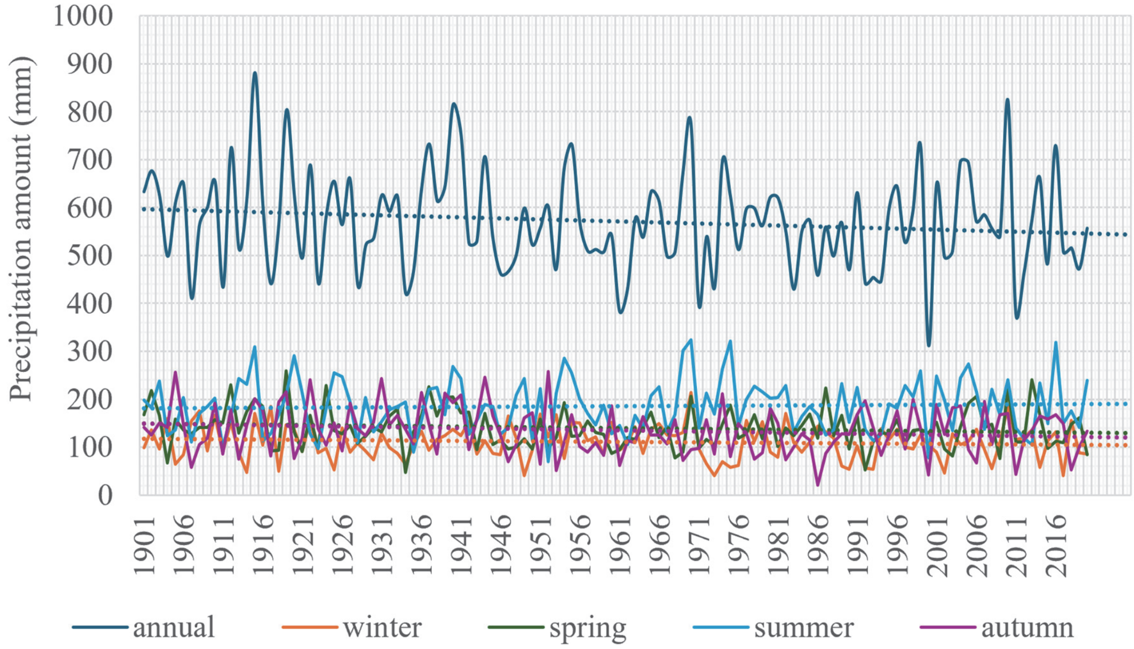

Fig. 5. Annual and seasonal precipitation trends for the 1901–2020 time period as an average for the entire area. Dotted lines indicate linear trends.

3.3. De Martonne Aridity Index (1951–2020)

The annual DMAI for the entire analyzed region has an average value of 28.4, with above-average values in Satu Mare, Vršac, and Oradea, close to average values in Timișoara and Arad, and below-average values in Szeged, Debrecen, and Zrenjanin (*Table 12*). The lowest average value was calculated for the year 2000 and the highest for 2010. The absolute minimum was calculated for Szeged in 2000 and the absolute maximum for Satu Mare in 2010.

Table 12. Evolution of the annual DMAI for the 1951–2020 time period analyzed by Mann-Kendall trend tests

Station name	Trend equation	Min.	Max.	Mean	Std. deviation	Kendall 's tau	p-value	Sen's slope
Satu Mare	y= 0.011x + 30.75	19.0	**49.1**	**31.1**	5.600	0.017	0.839	0.006
Oradea	y= -0.0116x+30.267	16.5	45.2	29.9	6.105	-0.032	0.700	-0.010
Arad	y= 0.0011x+28.306	11.3	40.8	28.3	5.557	-0.005	0.951	0.000
Timişoara	y= -0.0448x+30.235	13.2	43.8	28.6	5.771	-0.087	0.292	-0.029
Debrecen	y= -0.0361x+28.587	15.6	48.3	27.3	6.021	-0.104	0.205	-0.031
Szeged	y= -0.0046x+24.933	**9.1**	39.7	**24.8**	5.659	-0.020	0.808	0.000
Zrenjanin	y= -0.0231x+28.085	12.0	41.7	27.3	5.899	-0.043	0.605	-0.012
Vršac	y= -0.0286x+31.067	14.0	46.6	30.1	6.665	-0.068	0.406	-0.020
average	y= -0.0171x+29.029	15.2	40.5	28.4	5.033	-0.043	0.605	-0.010

Observing the evolution of the annual DMAI (*Fig. 6, Fig. 11, Table 12*) reveals a relative constancy for the analyzed period, with slight decreases for average and for Oradea, Timişoara, Debrecen, Szeged, Zrenjanin, and Vršac, and a very slight increase for Satu Mare and Arad. No trend is confirmed by the Mann-Kendall trend test, neither for the average nor for the analyzed stations (*Table 12*).

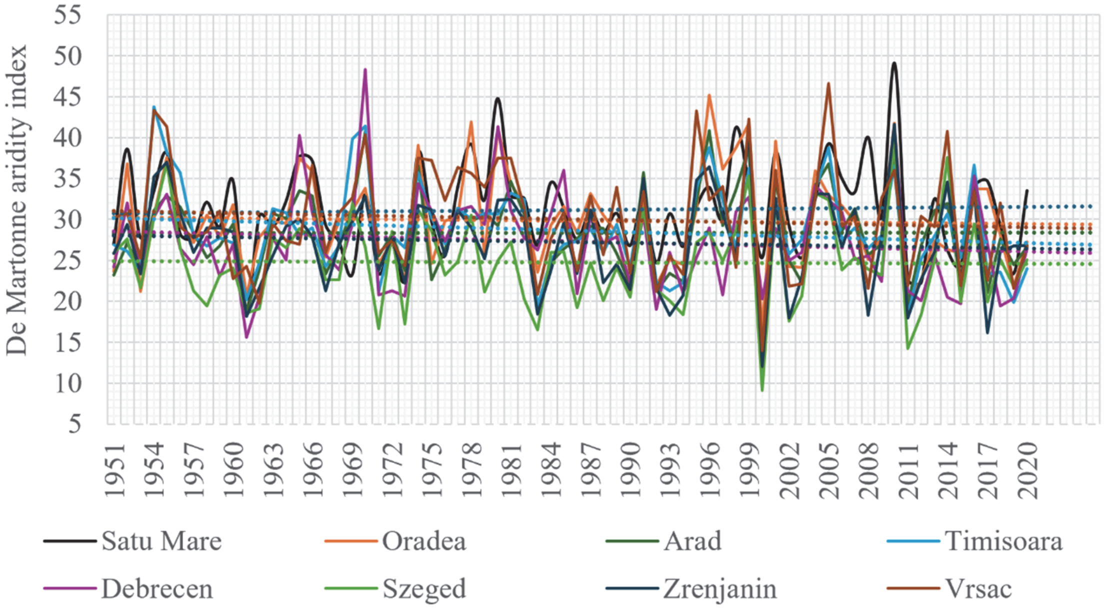

Fig. 6. Annual DMAI trends for the 1951–2020 time period. Dotted lines indicate linear trends.

The winter DMAI for the entire analyzed region has an average value of 48.6, with above-average values in Satu Mare, Oradea and Timişoara and below-average values for the other meteorological stations (*Table 13*). The lowest average value was calculated for the year 1973 and the highest for 1963. The absolute minimum was calculated for Zrenjanin in 1973 and the absolute maximum for Satu Mare in 1963.

Table 13. Evolution of the winter DMAI for the 1951–2020 time period analyzed by Mann-Kendall trend tests

Station name	Trend equation	Min.	Max.	Mean	Std. deviation	Kendall 's tau	p-value	Sen's slope
Satu Mare	y= -0.267x + 69.211	18.2	**146.7**	**59.7**	24.644	-0.125	0.128	-0.214
Oradea	y= -0.265x + 60.379	15.8	118.7	51.0	20.610	-0.193	**0.018**	-0.220
Arad	y= -0.2446x+56.454	13.5	102.6	47.8	19.644	-0.148	0.070	-0.174
Timişoara	y= -0.3562x+62.679	12.6	111.1	50.0	22.932	-0.205	**0.012**	-0.254
Debrecen	y= -0.2823x+56.997	17.0	112.5	47.0	19.080	-0.205	**0.012**	-0.221
Szeged	y= -0.1973x+46.646	10.8	95.3	**39.6**	19.092	-0.125	0.126	-0.145
Zrenjanin	y= -0.3379x+58.476	**9.5**	116.0	46.5	23.080	-0.148	0.071	-0.217
Vršac	y= -0.2449x+55.723	13.2	107.2	47.0	19.769	-0.133	0.105	-0.168
average	y= -0.2744x+58.321	14.8	113.8	48.6	19.291	-0.170	**0.038**	-0.215

Observing the evolution of the winter DMAI (*Fig. 7, Fig. 11, Table 13*) reveals a decrease for the analyzed period, either as an average for the entire region as well as for all meteorological stations. Mann-Kendal trend test confirms the evolution trend for the average and for Oradea, Timişoara, and Debrecen meteorological stations (*Table 13*).

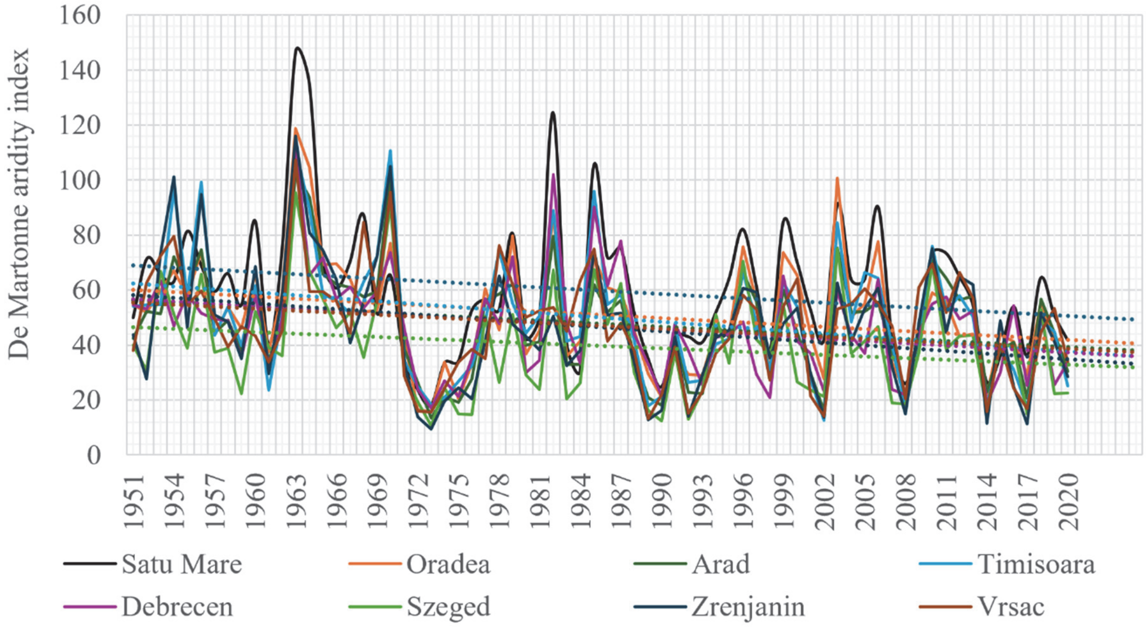

Fig. 7. Winter DMAI trends for the 1951–2020 time period. Dotted lines indicate linear trends.

The spring DMAI for the entire analyzed region has an average value of 27.1, with above-average values in Satu Mare, Oradea, Arad, Timişoara, and Vršac, and below-average values for the other meteorological stations (*Table 14*). The lowest average value was calculated for the year 1992 and the highest for 1987. The absolute minimum was calculated for Szeged in 1992 and the absolute maximum for Vršac in 1987.

Table 14. Evolution of the spring DMAI for the 1951–2020 time period analyzed by Mann-Kendall trend tests

Station name	Trend equation	Min.	Max.	Mean	Std. deviation	Kendall 's tau	p-value	Sen's slope
Satu Mare	y= 0.0271x + 27.608	11.6	57.3	28.6	10.061	0.025	0.766	0.000
Oradea	y= -0.0081x+28.306	9.8	50.2	28.0	9.055	-0.009	0.913	0.000
Arad	y= 0.0013x + 27.752	9.5	52.0	27.8	8.836	-0.024	0.773	0.000
Timişoara	y= -0.0369x+28.973	10.7	60.2	27.7	8.720	-0.057	0.487	-0.005
Debrecen	y= 0.0183x + 24.918	10.5	56.9	25.6	9.644	-0.022	0.789	0.000
Szeged	y= -0.0017x+23.678	**4.5**	42.7	**23.6**	8.555	-0.024	0.773	0.000
Zrenjanin	y= -0.0495x+28.096	8.4	57.7	26.3	9.693	-0.100	0.218	-0.056
Vršac	y= -0.0146x+29.378	8.6	**73.7**	**28.9**	9.990	-0.015	0.858	0.000
average	y= -0.008x + 27.339	10.9	52.1	27.1	7.582	-0.033	0.691	0.000

A relative constancy of the spring DMAI can be observed for the analyzed period (*Fig. 8, Fig. 11, Table 14*), with very slight decreases for average and for Oradea, Timişoara, Szeged, Zrenjanin, and Vršac meteorological stations and very slight increases for Satu Mare, Arad, and Debrecen. No trend is confirmed by the Mann-Kendal trend test (*Table 14*).

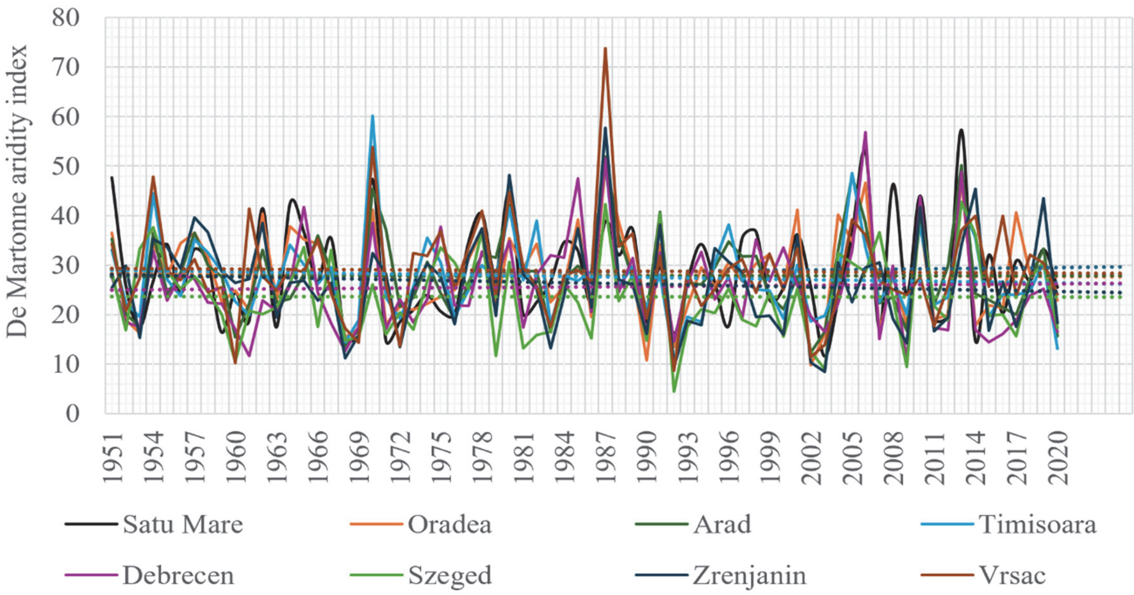

Fig. 8. Spring DMAI trends for the 1951–2020 time period. Dotted lines indicate linear trends.

The summer DMAI for the entire analyzed region has an average value of 26, with above-average values in Vršac, Satu Mare, and Oradea, close to average values in Arad and Debrecen, and below-average values for Timişoara, Zrenjanin, and Szeged (*Table 15*). The lowest average value was calculated for the year 2000 and the highest for 1975. The absolute minimum was calculated for Vršac in 2000 and the absolute maximum for Debrecen in 1970.

Table 15. Evolution of the summer DMAI for the 1951–2020 time period analyzed by Mann-Kendall trend tests

Station name	Trend equation	Min.	Max.	Mean	Std. deviation	Kendall 's tau	p-value	Sen's slope
Satu Mare	y= -0.0527x+29.725	6.9	48.1	27.9	9.826	-0.074	0.361	-0.031
Oradea	y= -0.0012x +27.718	8.9	52.8	27.7	9.365	0.001	0.992	0.000
Arad	y= 0.0204x + 25.039	4.9	44.6	25.8	8.444	0.021	0.796	0.000
Timişoara	y= -0.033x + 26.329	6.5	49.7	25.2	8.662	-0.050	0.545	-0.012
Debrecen	y= -0.0672x+28.045	7.5	**68.8**	25.7	10.463	-0.094	0.251	-0.040
Szeged	y= 0.0079x+22.873	5.4	42.4	**23.2**	9.358	0.023	0.781	0.009
Zrenjanin	y= 0.0022x+24.353	7.7	52.6	24.4	9.477	-0.037	0.655	0.000
Vršac	y= -0.0015x+28.436	**4.5**	62.0	**28.4**	12.025	-0.027	0.743	0.000
average	y= -0.0156x+26.565	8.9	43.7	26.0	7.632	-0.038	0.641	-0.004

Observing the evolution of the summer DMAI (*Fig. 9, Fig. 11, Table 15*) reveals a relative constancy for the analyzed period, with very slight decreases for the average and for Satu Mare, Oradea, Timişoara, Debrecen, and Vršac, and a very slight increase for Arad, Szeged, and Zrenjanin. No trend is confirmed by the Mann-Kendal trend test (*Table 15*).

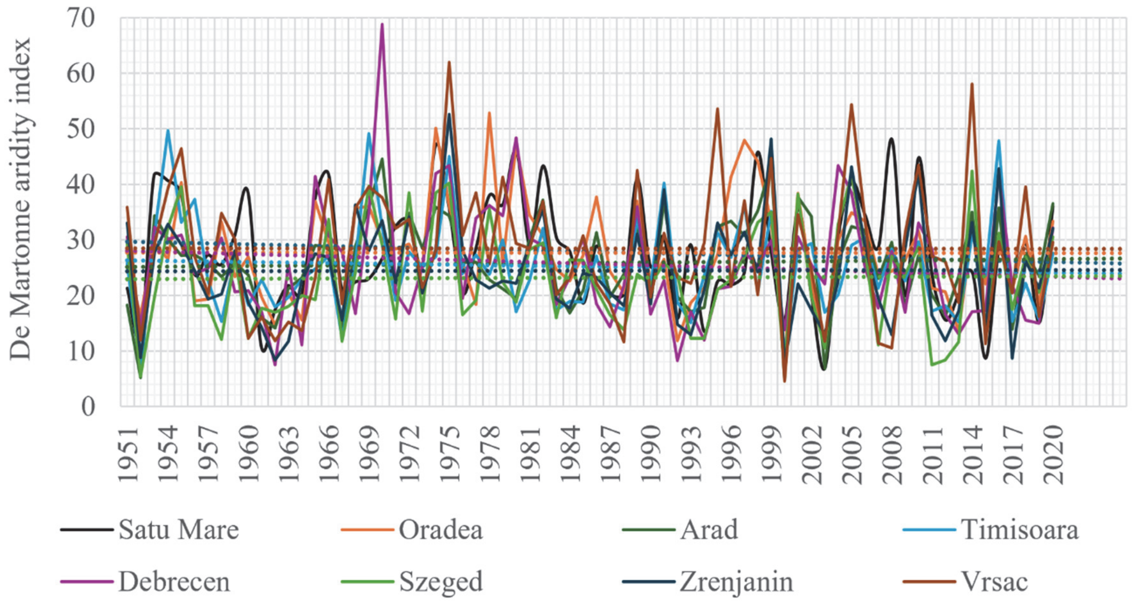

Fig. 9. Summer DMAI trends for the 1951–2020 time period. Dotted lines indicate linear trends.

The autumn DMAI for the entire analyzed region has an average value of 24.9, with above-average values in Satu Mare, Oradea, Vršac, and Timişoara and below-average values for Arad, Debrecen, Zrenjanin, and Szeged (*Table 16*). The lowest average value was calculated for the year 1986 and the highest for 1952. The absolute minimum was calculated for Szeged in 1986 and the absolute maximum for Oradea in 1952.

Table 16. Evolution of the autumn DMAI for the 1951–2020 time period analyzed by Mann-Kendall trend tests

Station name	Trend equation	Min.	Max.	Mean	Std. deviation	Kendall 's tau	p-value	Sen's slope
Satu Mare	y= 0.1696x + 21.249	8.0	64.1	**27.3**	11.793	0.232	**0.004**	0.184
Oradea	y= 0.0484x + 24.481	4.7	**66.3**	26.2	12.034	0.087	0.286	0.029
Arad	y= 0.0645x + 22.109	3.6	52.7	24.4	10.483	0.113	0.166	0.052
Timişoara	y= 0.0404x + 24.196	5.4	55.1	25.6	9.892	0.099	0.224	0.039
Debrecen	y= 0.0392x + 22.149	4.1	47.9	23.5	10.039	0.063	0.439	0.012
Szeged	y= 0.0396x + 20.887	**3.0**	60.3	**22.3**	9.877	0.114	0.163	0.057
Zrenjanin	y= 0.0731x + 21.629	7.0	52.1	24.2	10.412	0.120	0.140	0.051
Vršac	y= 0.0183x + 25.23	6.4	56.2	25.9	10.828	0.020	0.808	0.000
average	y= 0.0616x + 22.741	5.6	51.7	24.9	9.590	0.131	0.108	0.060

Observing the evolution of the autumn DMAI (*Fig. 10, Fig. 11, Table 16*) reveals a slight increase for the analyzed period, either as an average for the entire region as well as for all meteorological stations. Mann-Kendal trend test confirms only the trend for the Satu Mare meteorological station (*Table 16*).

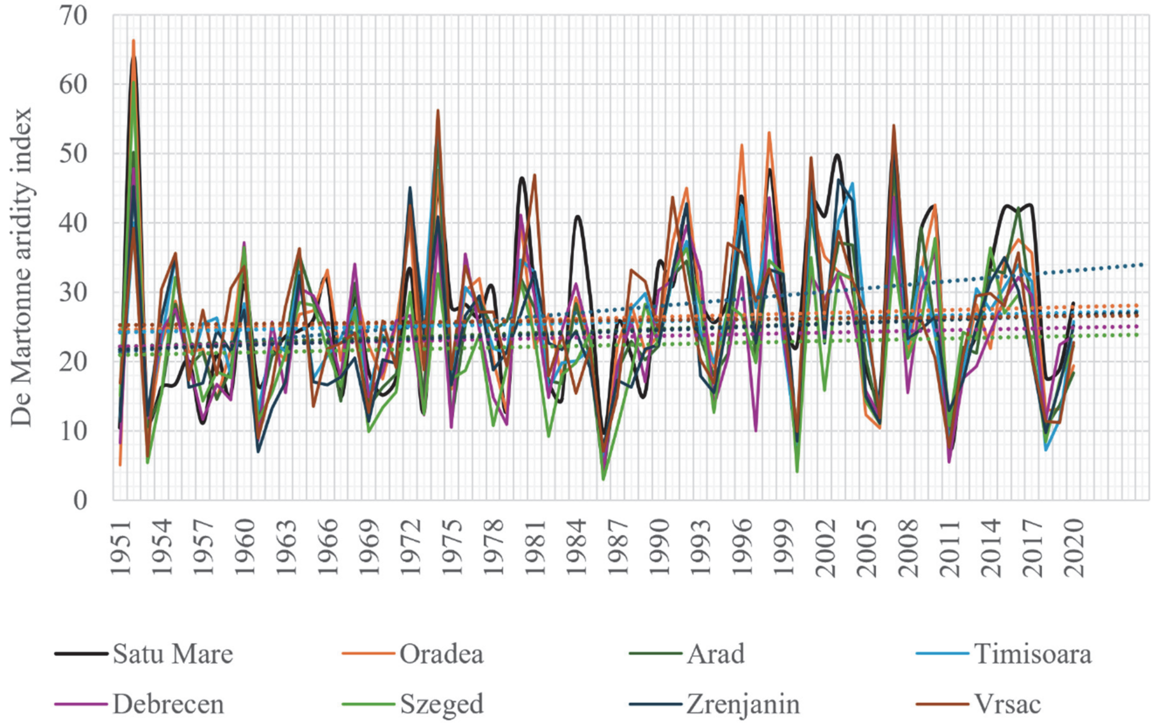

Fig. 10. Autumn DMAI trends for the 1951–2020 time period. Dotted lines indicate linear trends.

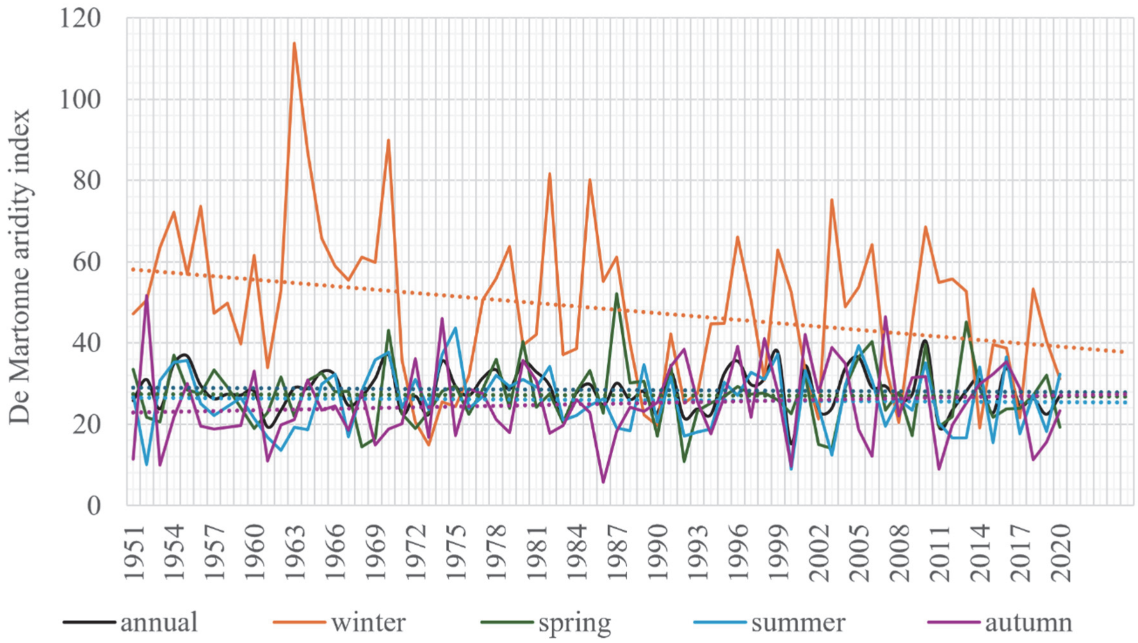

Fig. 11. Annual and seasonal DMAI trends for the 1951–2020 time period as an average for the entire area. Dotted lines indicate linear trends.

3.4. *De Martonne Aridity Index (1901–2020)*

The annual DMAI for the three analyzed meteorological stations has an average value of 27.7, with above-average values in Timişoara and Debrecen, and below-average values in Szeged (*Table 17*). The lowest average value was calculated for the year 2000 and the highest for 1940. The absolute minimum was calculated for Szeged in 2000 and the absolute maximum for Debrecen in 1970.

Table 17. Evolution of the annual DMAI for the 1901–2020 time period analyzed by Mann-Kendall trend tests

Station name	Trend equation	Min.	Max.	Mean	Std. deviation	Kendall 's tau	p-value	Sen's slope
Debrecen	y= -0.0427x+30.987	15.6	**48.3**	28.4	6.495	-0.167	**0.007**	-0.045
Szeged	y= -0.0259x+27.136	**9.1**	45.8	**25.6**	5.890	-0.109	0.079	-0.027
Timişoara	y= -0.0264x+30.714	13.2	47.2	**29.1**	5.990	-0.094	0.129	-0.024
average	y= -0.0317x+29.612	14.2	44.3	27.7	5.439	-0.130	**0.035**	-0.032

Observing the evolution of the annual DMAI (*Fig. 12, Fig. 17, Table 17*) reveals a decrease for the analyzed period for all three meteorological stations and for their average. The Mann-Kendal trend test confirms the evolution trend only for the average and for Debrecen meteorological station (*Table 17*).

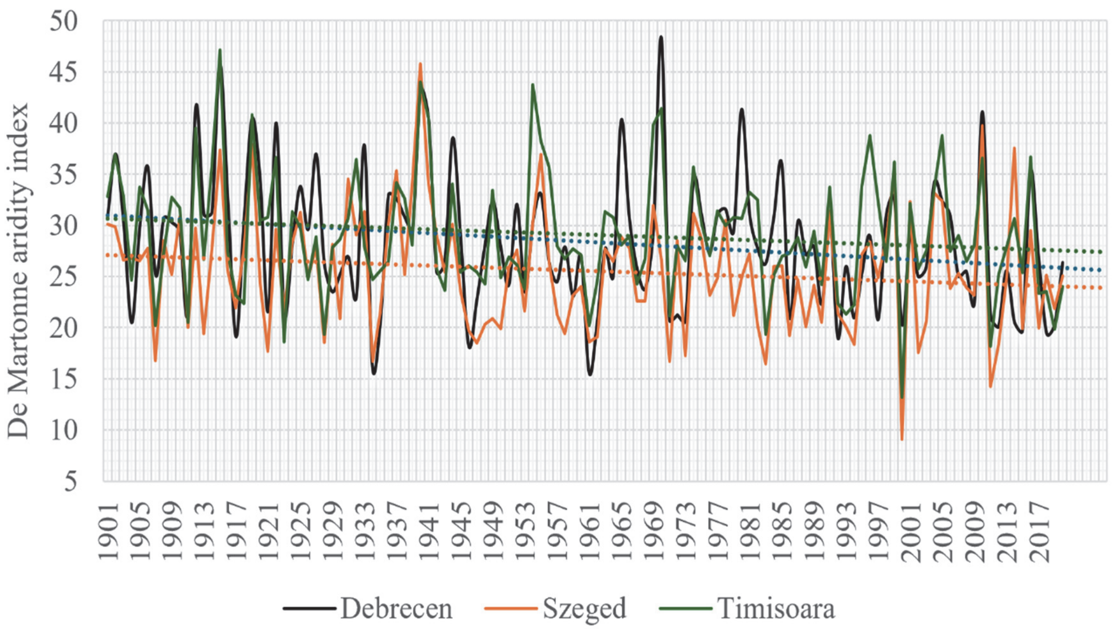

Fig. 12. Annual DMAI trends for the 1901–2020 time period. Dotted lines indicate linear trends.

The winter DMAI has an average value of 46.6, with above-average values in Timişoara and Debrecen, and below-average values in Szeged (*Table 18*). The lowest average value was calculated for the year 1973 and the highest for 1963. The absolute minimum was calculated for Szeged in 1973 and the absolute maximum for Debrecen in 1907.

Table 18. Evolution of the winter DMAI for the 1901–2020 time period analyzed by Mann-Kendall trend tests

Station name	Trend equation	Min.	Max.	Mean	Std. deviation	Kendall's tau	p-value	Sen's slope
Debrecen	y= -0.0976x+53.761	12.2	**131.2**	47.9	21.470	-0.085	0.167	-0.067
Szeged	y= -0.0619x+44.707	**10.8**	119.7	**41.0**	19.693	-0.079	0.202	-0.059
Timişoara	y= -0.0958x+56.689	12.6	111.1	**50.9**	22.652	-0.100	0.106	-0.084
average	y= -0.0851x+51.719	15.4	106.3	46.6	19.549	-0.094	0.128	-0.073

Observing the evolution of the winter DMAI (*Fig. 13, Fig. 17, Table 18*) reveals a decrease for the analyzed period for all three meteorological stations and for their average. No trend is confirmed by the Mann-Kendal trend test (*Table 18*).

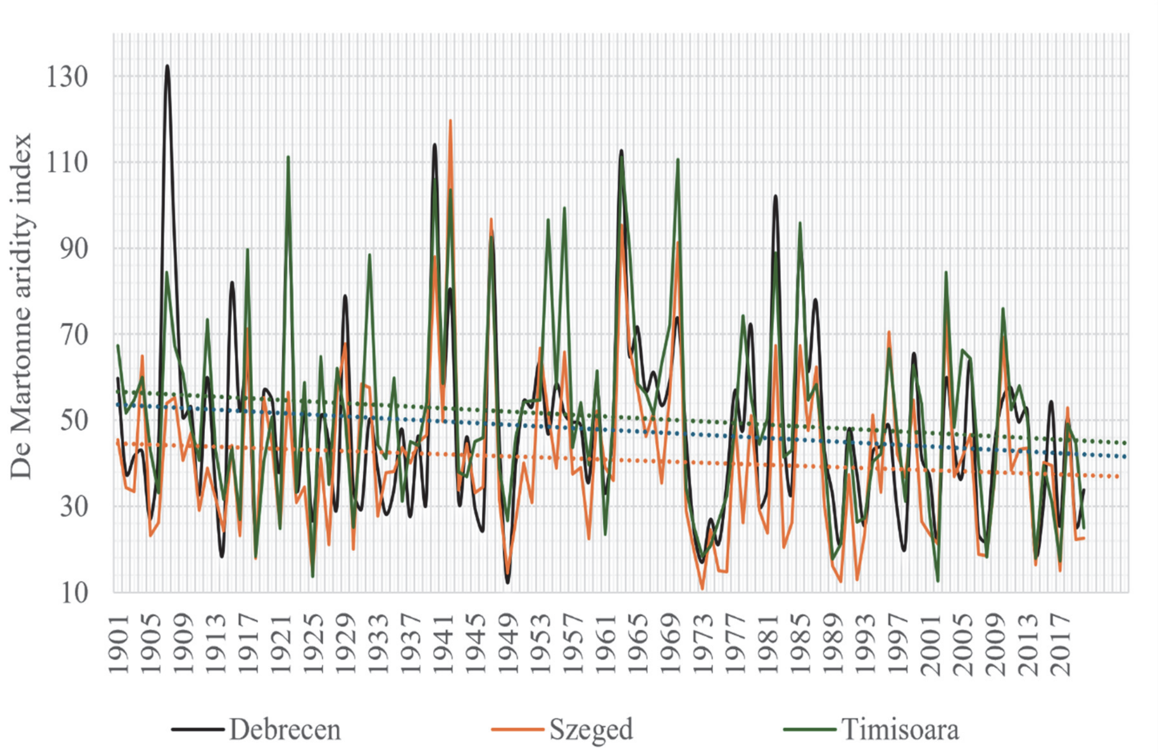

Fig. 13. Winter DMAI trends for the 1901–2020 time period. Dotted lines indicate linear trends.

The spring DMAI has an average value of 26.7, with above-average values in Timişoara and below-average values in Szeged (*Table 19*). The lowest average value was calculated for the year 1934 and the highest for 1919. The absolute minimum was calculated for Szeged in 1992 and the absolute maximum for Timişoara in 1970.

Table 19. Evolution of the spring DMAI for the 1901–2020 time period analyzed by Mann-Kendall trend tests

Station name	Trend equation	Min.	Max.	Mean	Std. deviation	Kendall 's tau	p-value	Sen's slope
Debrecen	y= -0.0348x+28.63	7.3	56.9	26.5	10.247	-0.104	0.092	-0.045
Szeged	y= -0.0527x+28.356	**4.5**	52.4	**25.2**	9.589	-0.125	**0.044**	-0.054
Timişoara	y= -0.0374x+30.725	6.1	**60.2**	**28.5**	9.560	-0.082	0.183	-0.029
average	y= -0.0416x+29.237	7.7	53.3	26.7	8.506	-0.110	0.075	-0.042

Observing the evolution of the spring DMAI (*Fig. 14, Fig. 17, Table 19*) reveals a decrease for the analyzed period for all three meteorological stations and for their average. The Mann-Kendal trend test confirms the evolution trend only for Szeged (*Table 19*).

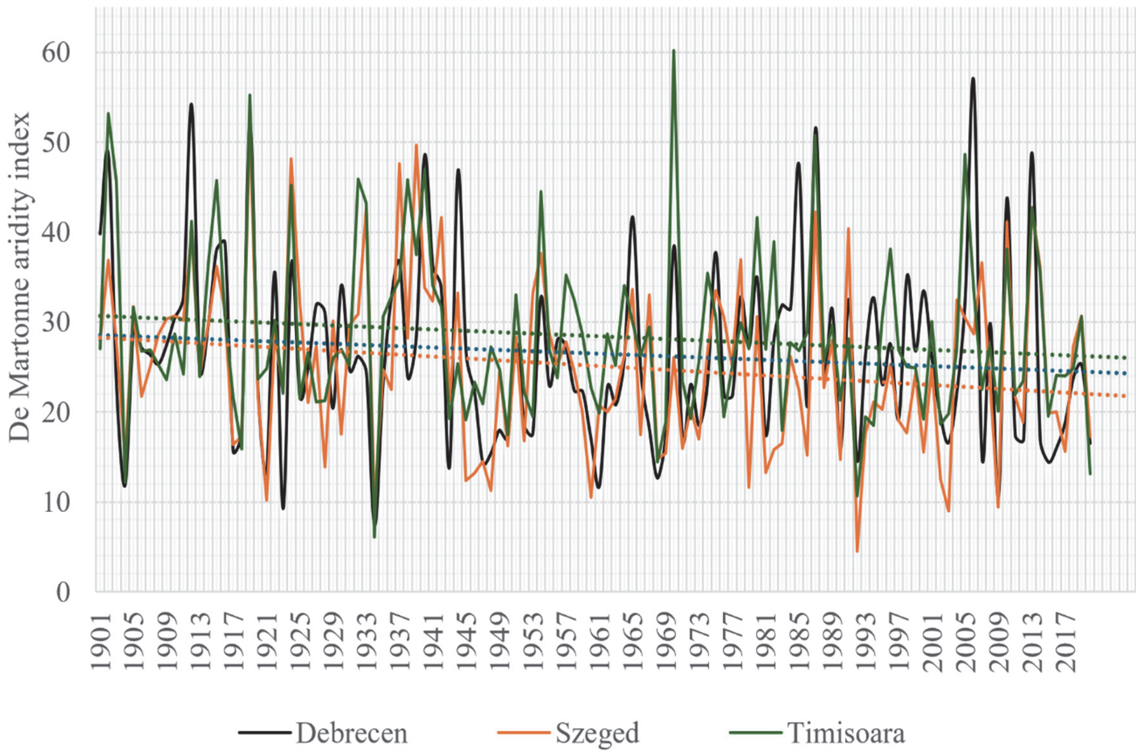

Fig. 14. Spring DMAI trends for the 1901–2020 time period. Dotted lines indicate linear trends.

The summer DMAI has an average value of 24.3, with above-average values for Debrecen and Timişoara and below-average values for Szeged (*Table 20*). The lowest average value was calculated for the year 1952 and the highest for 1970. The absolute minimum was calculated for Szeged in 1952 and the absolute maximum for Debrecen in 1970.

Table 20. Evolution of the summer DMAI for the 1901–2020 time period analyzed by Mann-Kendall trend tests

Station name	Trend equation	Min.	Max.	Mean	Std. deviation	Kendall 's tau	p-value	Sen's slope
Debrecen	y= -0.012x+26.494	7.5	**68.8**	**25.8**	10.512	-0.033	0.597	-0.011
Szeged	y= 0.0224x+20.969	**5.4**	42.4	**22.3**	8.580	0.056	0.363	0.022
Timişoara	y= -3E-05x+24.806	6.5	51.7	24.8	9.019	0.016	0.798	0.005
average	y= -0.0035x+24.09	8.7	43.4	24.3	7.650	0.017	0.787	0.005

Observing the evolution of the summer DMAI (*Fig. 15, Fig. 17, Table 20*) reveals a relative constancy for the analyzed period, with a very slight decrease for Debrecen and a very slight increase for Szeged. No trend is confirmed by the Mann-Kendal trend test (*Table 20*).

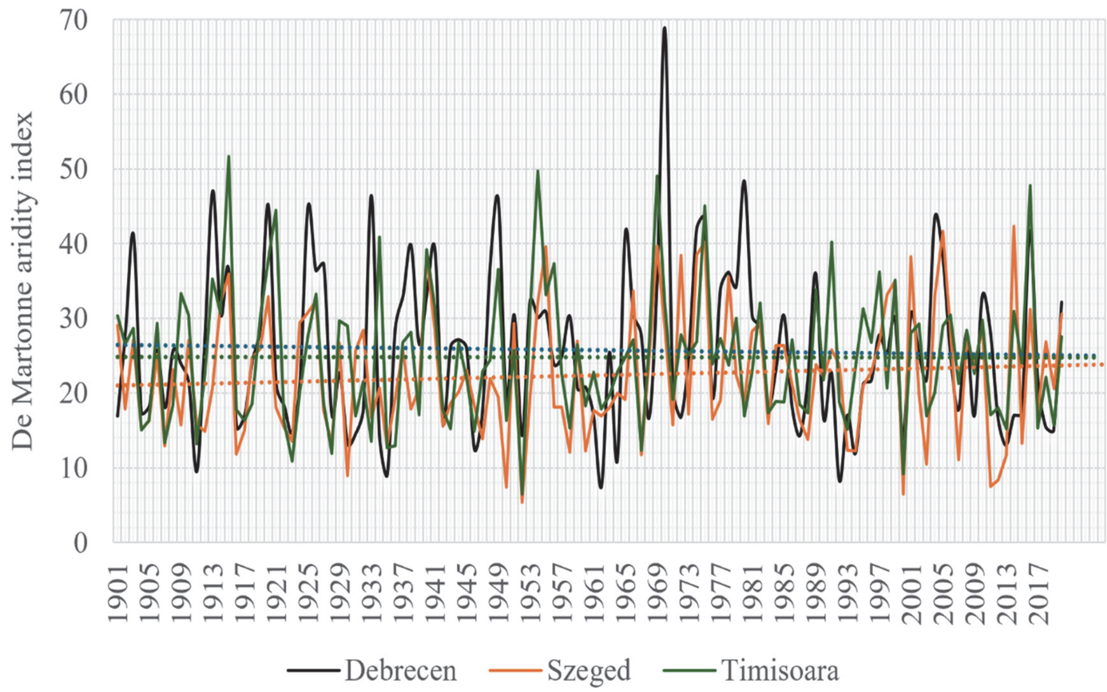

Fig. 15. Summer DMAI trends for the 1901–2020 time period. Dotted lines indicate linear trends.

The autumn DMAI has an average value of 26, with above-average values for Timişoara and Debrecen and below-average values for Szeged (*Table 21*). The lowest average value was calculated for the year 1986 and the highest for 1922. The absolute minimum was calculated for Szeged in 1986 and the absolute maximum for Timişoara in 1905.

Table 21. Evolution of the autumn DMAI for the 1901–2020 time period analyzed by Mann-Kendall trend tests

Station name	Trend equation	Min.	Max.	Mean	Std. deviation	Kendall's tau	p-value	Sen's slope
Debrecen	y= -0.0787x+31.24	4.1	60.2	26.5	4.1	-0.153	**0.014**	-0.072
Szeged	y= -0.0524x+27.636	**3.0**	60.3	**24.5**	3.0	-0.094	0.127	-0.043
Timişoara	y= -0.0278x+28.598	5.4	**62.2**	**26.9**	5.4	-0.026	0.678	-0.011
average	y= -0.053x+29.158	4.2	51.4	26.0	4.2	-0.092	0.137	-0.041

Observing the evolution of the autumn DMAI (*Fig. 16, Fig. 17, Table 21*) reveals a decrease for the analyzed period for all three meteorological stations. The Mann-Kendal trend test confirms the evolution trend only for Debrecen (*Table 21*).

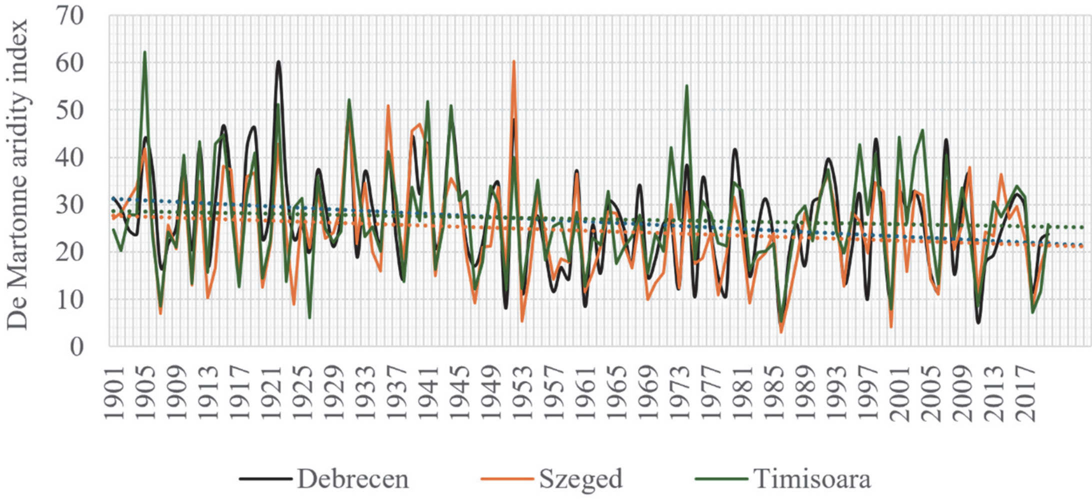

Fig. 16. Autumn DMAI trends for the 1901–2020 time period. Dotted lines indicate linear trends.

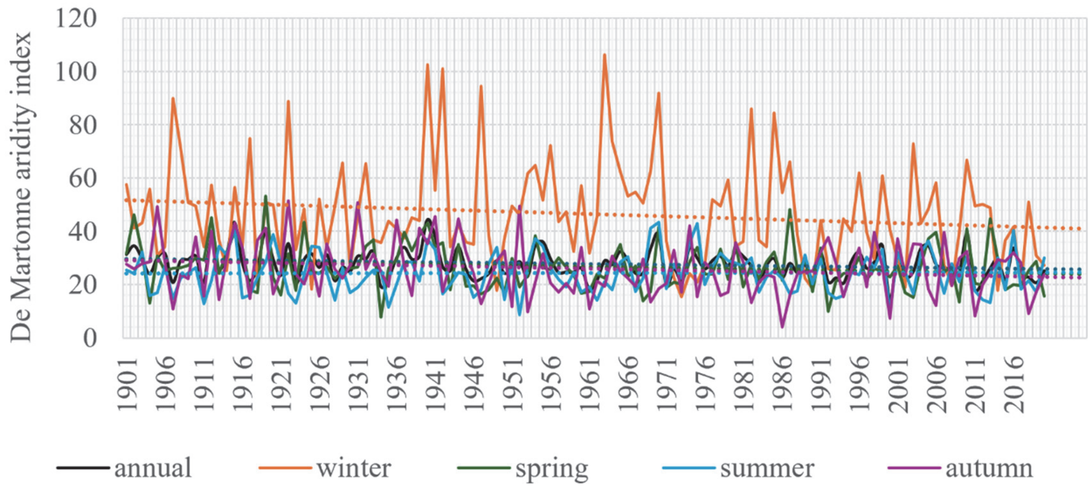

Fig. 17. Annual and seasonal DMAI trends for the 1901–2020 time period as an average for the entire area. Dotted lines indicate linear trends.

4. Conclusions

A synthesis of preceding pages leads to the conclusion that the annual values of the DMAI for the 1951–2020 time period place the studied region at the borderline of the humid and semi-humid zones. The spatial distribution of DMAI is directly related to the configuration of the Pannonian Basin, with DMAI values increasing towards the margins of the plain, as identified also by *Gavrilov et al.* (2020) in Hungary and Vojvodina, the increase of DMAI being caused by the increasing precipitation amounts. Accordingly, the meteorological stations closer to the mountainous area are classified as humid, while those at greater distances are classified as semi-humid. The temporal variability of this parameter reveals a certain constancy of the DMAI for the analyzed time period, with slight decreasing or increasing trends for certain meteorological stations not confirmed by the MK test. This consistency comes amid a clear increasing trend in temperatures and a slight increasing trend in precipitation amounts. The majority of years can be classified as humid and semi-humid, with only one arid year (2000 in Szeged) and no extremely humid years (*Table 22*). High values of the DMAI were calculated for the years 1955, 1970, 1974, 1999, 1999, 2005, and especially 2010, years with the highest amounts of precipitation and generally below-average temperatures, while low values were calculated for the years 1961, 1983, 2011, and especially 2000, dry years.

Table 22. Classification of years according to the DMAI for the 1951–2020 time period

	Station name	Number of years with:					
		$I < 10$ (arid)	$10 \leq I < 20$ (semi-arid)	$20 \leq I < 24$ (mediterranean)	$24 \leq I < 28$ (semi-humid)	$28 \leq I < 35$ (humid)	$35 \leq I < 55$ (very-humid)
1.	Satu Mare	-	1	6	15	35	13
2.	Oradea	-	2	9	18	27	14
3.	Arad	-	4	12	18	28	8
4.	Timişoara	-	4	8	25	22	11
5.	Debrecen	-	4	17	22	21	6
6.	Szeged	1	13	17	21	14	4
7.	Zrenjanin	-	8	14	16	27	5
8.	Vršac	-	2	13	14	25	16
	average	-	3	14	16	29	8

Considering a longer time period, 1901–2020, slightly higher values of the DMAI can be observed at the analyzed meteorological stations, as well as an increased proportion of semi-humid, humid and very-humid years to the detriment of semi-arid and mediterranean years and a decreasing trend of the DMAI, confirmed only for Debrecen by the MK test. The decreasing trend of the DMAI comes amid an increasing trend in temperatures and a decrease in precipitation amounts. In addition to the years mentioned in the previous paragraph, the years

1915 and 1919, with high amounts of precipitation, and especially 1940, with significantly below-average temperatures and high amounts of precipitation, are characterized by high values of the DMAI, while 1934, a dry year with above-average temperatures, is characterized by low values of the DMAI.

Table 23. Classification of years according to the DMAI for the 1901–2020 time period

	Station name	Number of years with:					
		I < 10 (arid)	10 ≤ I < 20 (semi-arid)	20 ≤ I < 24 (mediterranean)	24 ≤ I < 28 (semi-humid)	28 ≤ I < 35 (humid)	35 ≤ I < 55 (very-humid)
1.	Debrecen	-	7	25	30	41	17
2.	Szeged	1	21	25	34	31	8
3.	Timişoara	-	6	13	41	40	20
	average	-	4	24	26	52	14

Regarding the DMAI values for the winter months, during the 1951–2020 time period, they place the studied region in the very-humid zone, even extremely humid, if we talk about Satu Mare, with notable differences between the highest (Satu Mare) and the lowest (Szeged) values. On the background of decreasing precipitation amounts and increasing temperatures, the temporal dynamics of the DMAI reveals a decrease of this parameter for the analyzed time interval, for all the analyzed meteorological stations, the MK test only partially confirming these trends. High values of the DMAI can be observed in 1963, 1964 and 1985, years characterized by extremely cold winters, as well as in 1970, a year characterized by a particularly humid winter, and low values in 1990, 2014, and especially in 1973, the year with the driest winter of the analyzed interval.

A consideration of the 1901–2020 time period reveals that, although the graph displays a clear decrease in the DMAI values, this downward trend is not confirmed by the MK test. The analyzed stations belong to the very-humid zone, and in addition to the years listed in the previous paragraph, high values of the DMAI were calculated for the years 1940, 1942, 1947, years characterized by extremely cold winters, 1907 and 1922, and low values of the DMAI for the years 1925 and 1949, years characterized by dry winters.

The DMAI values for the spring months, for the 1951–2020 time interval, place the region in the semi-humid type, with four meteorological stations belonging to this category, three meteorological stations (Vršac, Satu Mare, Oradea) to the humid zone and one to the mediterranean zone (Szeged). The increase in temperatures for the spring season is balanced by a slight increase in precipitation amounts, so that the DMAI remains relatively constant for this period. The years 1987, a year characterized by a cold and rainy spring, 1970 and 2013, years characterized by high precipitation amounts in spring, stand out with high values of the DMAI, while the years 1992, 1968, and 2003, years with dry springs, stand out with low values.

For the 1901–2020 time period, the spring DMAI values are slightly higher, with a decreasing trend for the analyzed interval, which comes on the background of increasing temperatures and decreasing precipitation amounts; the MK test confirms this decrease only for Szeged. The analyzed meteorological stations belong to the semi-humid (Debrecen and Szeged) and humid (Timișoara) category, in addition to the years listed in the previous paragraph, standing out with high values of the DMAI the years 1902, 1919, 1940, years characterized by cold and rainy springs, 1912 and 1924, years with rainy springs, and with low values of the DMAI the years 1904, a year characterized by a dry spring, and, especially 1934, a year with a dry and particularly hot spring.

The DMAI values for the summer months, for the 1951–2020 time interval, place the region in the semi-humid type, except for the meteorological stations Vršac belonging to the humid type and Szeged to the mediterranean type. Similar to the spring months, the increase in temperatures for the summer season is compensated by a slight increase in precipitation amounts, so that the DMAI remains relatively constant for this period. High DMAI values were calculated for 1975, a year characterized by a rainy and cool summer, and low values for 2000, 1952, 1962 and 2003, years with dry summers.

Regarding the 1901-2020 time period, the picture is not significantly different, with slightly lower summer DMAI values for Timișoara and Szeged and a relatively constant trend. In addition to the years previously referenced, 1915, a year characterized by a rainy summer, stands out with a high value of the DMAI, while 1935, 1911, 1923, 1928, and 1950, years with dry summers, with low values of the DMAI.

The DMAI values for the autumn months, for the 1951–2020 time interval, place the region in the semi-humid type, except for the Szeged and Debrecen meteorological stations, which belong to the mediterranean type. On the background of the increase in both temperature and precipitation amounts, an increasing trend of the DMAI can be observed, a trend confirmed by the MK test only for Satu Mare. The years 1952, 1974, and 2007, years characterized by rainy and cold autumns, stand out with high values of the DMAI, while the years 1986, 2011, 2000, and 1953, years with dry autumns, stand out with low values.

The picture is different if we refer to the 1901-2020 time period, in the sense that all three meteorological stations belong to the semi-humid type, and the trend of the DMAI, confirmed by the MK test only for Debrecen, is decreasing, the amount of precipitation being also on a decreasing trend. In addition to the years previously referenced, the years 1922, 1931, 1905, 1941, 1944, 1936, 1915, etc., years characterized by high amounts of precipitation in autumn and generally low temperatures, stand out with high values of the DMAI, while with low values, the most notable year was 1907, a year with a dry autumn.

As a final conclusion, it can be stated that, in the area under study, although the temperatures increased during the 1951–2020 time period, this increase was compensated by a slight increase in precipitation amounts, so that we cannot talk about an aridization of the climate during the last 70 years, only, at most, an aridization of the winter months. Considering the 1901–2020 time period, we can conclude that the increase in temperature, combined with a decrease in precipitation amounts, has led to a slight aridization of the climate, a trend partly confirmed by the MK test. However, it should be noted that the small number of meteorological stations used in the study for this time period limits the consistency of these conclusions, which cannot be extended to the entire study area. In fact, the limitations of this study stem mainly from the lack of longer measurement series for meteorological stations covering the entire study area, as well as from the difficult access to meteorological measurements done in recent decades in the eastern part of the study area, a graphical representation of the spatial distribution of DMAI being difficult to achieve under these conditions. A correlation with other studies conducted in the Pannonian Plain indicates at most some minor differences, which are largely due to the slightly different time intervals covered by these studies.

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