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Droughts in Serbia through the analyses of De Martonne and Ped indices

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Abstract Due to global warming, droughts have become one of the focal points of researchers in the field of climate and water, all over the world. The analyses in this paper include spatial pattern and temporal trend for the territory of Serbia, over the 1949–2016 period. The De Martonne aridity index and the Ped drought index have been applied. Eighteen pairs of temperature and precipitation stations all over the country have been analyzed. The obtained results show a tendency toward a drier condition, which are not yet drastic. Drought areas for the territory of Serbia are increasing, but drought intensity and frequency should certainly be lower than those predicted for the Mediterranean coastal area, except in regions with very high human water use. Comparing the obtained results from stations at the original altitude and calculated data for the same stations at fixed virtual altitudes has shown that the natural direction of drought, which decreases from west to southeast, has shifted to a north to south direction.

Keywords Drought · De Martonne index · Ped index · Temperature · Precipitation · Climate change · Serbia

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Introduction

Drought affects our lives in many ways because water is crucial for many of our activities. People, animals, and plants need water to live. We need water to grow the food we eat and for many other purposes. Droughts are usually explained as periods of extremely dry weather that persist long enough to cause problems such as crop damage and water shortages. But drought is caused not only by a lack of precipitation and high temperatures, but also as a result of overuse and overpopulation, and it can occur in virtually all climates. Due to its complex behavior, there is no single acceptable definition of a drought (Yevjevich, 1967). One of the widely cited definitions is that drought is a natural disaster that causes enormous damage to human life and/or the environment (Hatmoko et al., 2013).

Droughts are commonly classified by type as meteorological drought, hydrological drought, agricultural drought, and socioeconomic drought (WMO, 2006). Meteorological drought is related only to weather conditions, so it is easier to define. However, agricultural, hydrological, and socioeconomic drought place greater emphasis on the human or social aspects of drought, highlighting the interaction between the natural characteristics of a meteorological drought and human activities that depend on precipitation to provide adequate water supplies to meet social and environmental demands.

In the context of water demand growth and global warming, water use efficiency becomes more important than ever in the past, especially in regions with a decreasing precipitation trend, like the Mediterranean (Baltas, 2007; Barajas, 2007; Tsitsifli et al., 2018). So, studying drought has become an important issue in such regions. Consequently, there is a need to compare droughts and categorize them. Drought indices are variables, less or more complex, which describe the frequency, duration, severity, and spatial extent of a drought. Two indices, quite often used in papers, are De Martonne aridity index — DMI and Ped drought index — PED (Rahimi et al., 2013; Lungu et al., 2011; Voropay & Ryazanova, 2018; Koleva & Alexandrov, 2008). Both use just monthly temperature data (T) and precipitation (P) for their calculation. This paper presents different analyses of these indices, on an annual and seasonal (only spring and summer) level: DMI for both spatial and temporal drought change analyses and PED only for temporal change analyses.

The objective of this study is to have an overall view of drought spatial pattern changes and temporal trends on the whole territory of Serbia using two analyzed indices. Secondly, the objective is to compare results with other research on drought, done for certain parts of the country (Gavrilov et al., 2019; Milentijević et al., 2018), as well as to compare with results of T and P changes and forecasts, available in national and international manuscripts (CC-WaterS, 2009–2012; Rajkovic et al., 2013; Djurdjevic, 2020). Thirdly, it is also important to consider differences in results of the same occurrence obtained from different indices, in this case temporal drought changes obtained using DMI and PED indices.

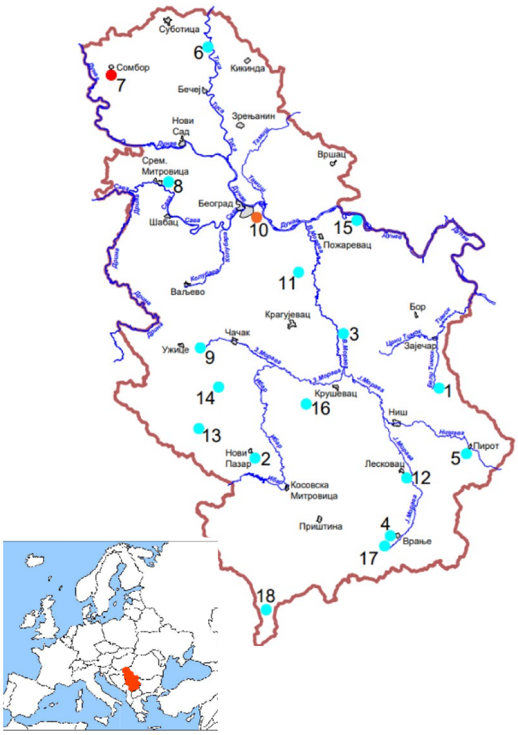
Study area and data sources

Serbia covers an area of about 90,000 km^2, and more than 95% belongs to the Danube catchment. The River Danube has a discharge of about 2500 m^3/s upon entering Serbia and a discharge of about 5500 m^3/s upon exiting. Only 9% of the Danube's discharge exiting Serbia is generated from domestic rivers, and the remaining 91% are waters which enter the country with international rivers (Danube, Sava, Tisza, and others). About 30% of the total country's territory is forested, where the central and southern part of the country has higher forest coverage than the north.

Most of the territory of Serbia belongs to the temperate climate zone. The southwestern part is located on the border of the Mediterranean climate and the continental climate. The mountains that surround the southwestern part are intersected by river valleys that cause climate variations, both Mediterranean (coming from the south and west) and Continental (coming from the north and east). In the north and in the central lowland parts of Serbia, there is a temperate continental climate, with warm summers and cold winters and an annual average temperature fluctuation of over 22 °C (January–July). The mountain climate is present in the middle and high mountains. The basic climatic characteristics (temperatures and precipitation) are used on the basis of the results of measurements of the Republic Hydrometeorological Service of Serbia, i.e., completed time series of monthly meteorological data for 1949–2016 period.

In the north of Serbia, the average annual air temperatures range from 10.8 to 11.5 °C and from 10 to 12.1 °C in the lowland parts of the central and southern Serbia. Lower temperatures occur in hilly and mountainous regions. The precipitation regime is very heterogeneous in space. The amount of annual precipitation ranges from about 500 mm in the north to over 1000 mm in mountainous regions, while the average precipitation in Serbia is about 730 mm/year. Almost all lower parts experience precipitation of below 700 mm, which increases with elevation.

In this paper, the expression "drought station" comprises one pair of T and P stations. Eighteen pairs of T and P stations have been analyzed. Their names, locations, and altitudes are shown in Fig. 1. Due to data (un)availability, number of stations is not higher, and two of these pairs are not in the same location: P Bezdan and T Sombor are at distance of about 10 km (red point), and P Jajinci and T Beograd are at distance of about 5 km (orange point). The chosen period for analysis was 1949–2016, which was convenient because of its length (68 years), and the available data that could be obtained from numerous monitoring stations in Serbia (Dimkić, 2019).



	T station – Altitude	P station - Altitude
1	Knjaževac – 280 m.a.s.l.	Knjaževac – 281 m.a.s.l.
2	Novi Pazar – 545 m.a.s.l.	Novi Pazar – 545 m.a.s.l.
3	Ćuprija – 123 m.a.s.l.	Ćuprija – 123 m.a.s.l.
4	Vranje – 432 m.a.s.l.	Vranje – 432 m.a.s.l.
5	Pirot – 370 m.a.s.l.	Pirot – 370 m.a.s.l.
6	Senta – 80 m.a.s.l.	Senta – 80 m.a.s.l.
7	Sombor – 87 m.a.s.l.	Bezdan – 90 m.a.s.l.
8	Sr. Mitrovica – 82 m.a.s.l.	Sr. Mitrovica – 82 m.a.s.l.
9	Požega – 310 m.a.s.l.	Požega – 310 m.a.s.l.
10	Beograd – 132 m.a.s.l.	Jajinci – 175 m.a.s.l.
11	Sm. Palanka – 121 m.a.s.l.	Sm. Palanka – 122 m.a.s.l.
12	Leskovac – 230 m.a.s.l.	Leskovac – 230 m.a.s.l.
13	Sjenica – 1038 m.a.s.l.	Sjenica – 1038 m.a.s.l.
14	Ivanjica – 465 m.a.s.l.	Ivanjica – 465 m.a.s.l.
15	Vel. Gradište – 82 m.a.s.l.	Vel. Gradište – 82 m.a.s.l.
16	Aleksandrovac – 360 m.a.s.l.	Aleksandrovac – 360 m.a.s.l.
17	Bujanovac – 400 m.a.s.l.	Bujanovac – 400 m.a.s.l.
18	Dragaš – 1062 m.a.s.l.	Dragaš – 1062 m.a.s.l.

Fig. 1 Names, locations, and origin altitudes of analyzed T and P stations

Methodology

Research has been performed using the De Martonne aridity index and Ped aridity index in Serbia on annual, seasonal, and monthly levels, while this paper shows results for annual and seasonal (spring and summer) levels.

As known, the De Martonne annual index is calculated using the following formula:

$$DMI_a = \frac{P}{T + 10} \tag{1}$$

where P is the annual sum of precipitation in mm; T the annual average temperature in °C; DMI_a the De Martonne annual index.

If we calculate De Martonne monthly or seasonal indices, the formulas are as follows:

Monthly index

$$DMI_m = \frac{12 \bullet P}{T + 10} \tag{2}$$

where P is the monthly sum of precipitation in mm, T the monthly average temperature in °C, DMI_m the De Martonne monthly index.

Seasonal index

$$DMI_s = \frac{4 \bullet P}{T + 10} \tag{3}$$

where P is the sum of precipitation for 3 seasonal months in mm, T the average temperature for 3 seasonal months in °C, DMI_s the De Martonne seasonal index.

Another drought index used for describing drought frequency and intensity is the Ped index. Ped drought index is calculated using the following formula:

$$PED = \frac{\Delta T}{\sigma T} - \frac{\Delta P}{\sigma P} \tag{4}$$

where ΔT is the anomaly of T in °C, relative to a given period; ΔP the anomaly of P in mm, relative to a given period; σT the standard deviation of temperature (in °C); σP the standard deviation of precipitation

Table 1 Climate classification according to the De Martonne's aridity index and Ped drought index

De Martonne index (DMI)	Climate classification	Ped index (PED)	Climate classification
$DMI < 10$	Arid	$3 \le PED$	Severe drought
$10 \le DMI < 20$	Semiarid	$2 \le PED < 3$	Moderate drought
$20 \le DMI < 24$	Mediterranean	$1 \le PED < 2$	Insignificant drought
$24 \le DMI < 28$	Moderate	$-1 \le PED < 1$	Moderate or neutral
$28 \le DMI < 35$	Humid	$-2 \le PED < -1$	Insignificantly wet
$35 \le DMI < 55$	Very humid	$-3 \le PED < -2$	Moderately wet
$55 \le DMI$	Extremely humid	$PED < -3$	Extremely wet

(in mm); and *PED* the Ped drought index (annual, monthly, or seasonal, depending on the used T and P data).

Several classifications can be found in literature for the De Martonne aridity index (Gavrilov et al., 2019; Lungu et al., 2011; Milentijević et al., 2018) and slightly fewer for the Ped drought index (Koleva & Alexandrov, 2008; Tri et al., 2019). In general, the differences between them are not great. We have used the classification shown in Table 1.

The first step in analyses was to calculate DMI and PED indices for all the stations on a monthly (and after that on a seasonal) and annual level for each year of the research period, based on the observed P and T monthly data.

Analyses of spatial changes

As stated in the introduction, spatial changes have been analyzed just for DMI aridity index. Assessment of the spatial distribution of any climate variable (like T or P), or parameter derived from climate variables (like DMI), requires a sufficient data density — to cover the entire area and to reduce the stochastic component, which is prominent when the number of analyzed stations is low. Reducing the stochastic component is also important for the trend analyses (Dimkić, 2019; Forootan, 2019). All the spatial charts shown were generated using Surfer software, based on relevant data of each station, minimizing the stochastic component by regional averaging (Dimkić, 2016).

DMI average values for the whole period were calculated for all drought stations and used to construct spatial distribution pictures on annual and seasonal (spring and summer) levels (pictures a, b, and c in Fig. 2; used color spectrum is yellow-blue). After that, the sum of years, which are classified as arid ($DMI < 10$) and arid + semiarid ($DMI < 20$) conditions have been numbered, and a percentage of years under such conditions was determined. The same was done with spring and summer DMI data. A yellow-green spectrum was used for presenting spatial DMI

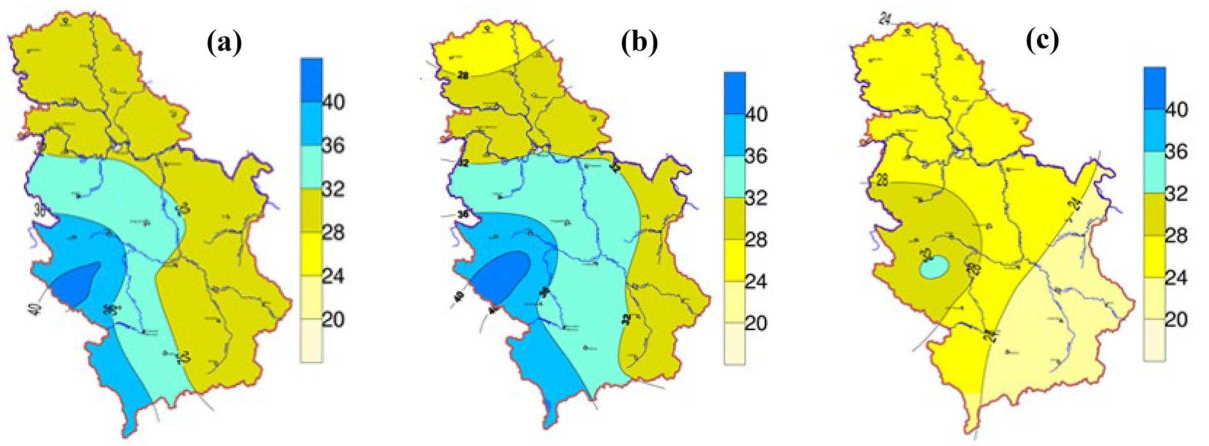


Fig. 2 DMI spatial distribution based on average DMI indices for **a** years, **b** springs, and **c** summers

distribution under semiarid conditions (pictures a, b, and c in Fig. 3), while a red spectrum was used for arid conditions (picture a in Fig. 3). Spatial distribution for years and spring periods under arid conditions are not presenting because their percentages are very low (averages for all drought stations are 0.1% and 0.5%). All corresponding results are shown in the "Analyses of spatial changes" section.

Analyses of temporal changes

In the frame of global warming, it is interesting to see has the frequency of drought changed in the analyzed period. The same question could be put regarding drought intensity. For this purpose, the analyzed period (1949–2016) has been divided into three parts:

- 1949–1970 (22 years)
- 1971–1993 (23 years)
- 1994–2016 (23 years)

Firstly, the same temporal change analyses were performed for each drought station, on annual and seasonal levels, and for both DMI and PED indices:

- Graphs were constructed to determine trends for the entire analyzed period (1949–2016).
- Charts with average values for three subperiods were constructed.
- Charts with the number of years under semiarid and arid conditions in 3 subperiods were developed.

These graphs and charts are not shown in this paper, due to limited number of pages and because the focus of the paper is a general overview of droughts in Serbia, and not for any particular station.

Secondly, the average values of 18 drought stations have been calculated for each month, season, and year, for both indices. The same type of graphs and charts, as described above for each single station, are developed with these average values, and corresponding results are shown in the "Analyses of temporal changes" section.

Analyses of combined spatial–temporal changes

Combined spatial–temporal changes comprise a presentation of observed spatial distribution of average

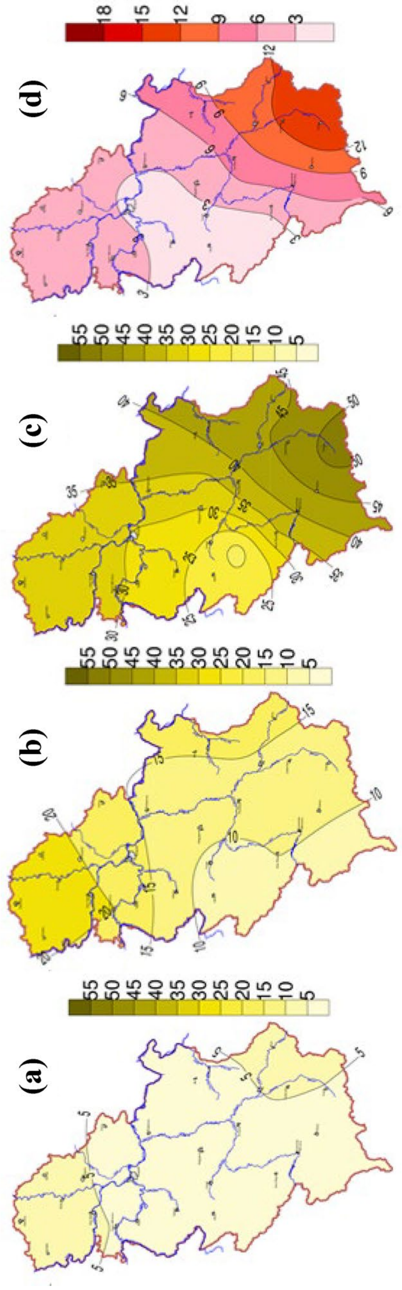


Fig. 3 DMI spatial distribution (percentages) under arid and semiarid conditions (DMI < 20) for **a** years, **b** springs, and **c** summers; and strictly arid conditions (DMI < 10) for **d** summers

drought indices values, for only three subperiods (1949–1970, 1971–1993, 1994–2016), instead for whole period which is presented in the "Analyses of spatial changes" section. Corresponding results for annual and summer levels are shown in the "Analyses of combined spatial–temporal changes" section. These pictures, as in the "Analyses of spatial changes" section (cases "a" and "c"), refer only to DMI index, and once again the yellow-blue spectrum was used.

Analyses of spatial changes for fixed station's virtual altitudes

Station altitudes differ considerably (Fig. 1). Two locations in close proximity (e.g., within a distance of several kilometers) could vary in altitude by over 1000 m. It is known that temperature decreases, and precipitation increases with increasing altitude. Hence the drought index significantly depends on the selected locations of the T and P stations. It is interesting to observe the drought spatial changes if all stations are on the same virtual altitude and to compare these results with results in the "Analyses of spatial changes" section (stations on original altitudes).

In Serbia, on average, one could expect a T decrease of about 0.5 °C and a P increase of about 25 mm per year for every 100-m increase in altitude. Therefore, the monthly data of all T and P stations were recalculated according to these average differences. DMI indices (only annual and summer) were analyzed for two fixed altitudes:

- T and P data of all stations have been recalculated for the virtual altitude of 200 m.a.s.l.
- T and P data of all stations have been recalculated for the virtual altitude of 600 m.a.s.l.

The same procedure was used, as described in the "Analyses of spatial changes" section. Results (for cases a, c, f, and g) are shown in the "Analyses of spatial changes for fixed station's virtual altitudes" section.

Analyses of temporal changes for fix station's altitudes

The same method was used as described in the "Analyses of temporal changes" section, but with DMI indices obtained for fix virtual altitudes (200 m.a.s.l. and 600 m.a.s.l.). All corresponding results are shown in the "Analyses of temporal changes for fixed station's virtual altitudes" section. Due to structure of the PED formula, changes of this index caused by altitude changes are negligible; therefore, the results of the PED indices are not included in the "Analyses of temporal changes for fixed station's virtual altitudes" section.

Results

Analyses of spatial changes

Seven spatial distribution pictures (each case analyzed the period from 1949 to 2016) for the territory of Serbia are developed for seven analyzed cases explained in the "Analyses of spatial changes" section. Pictures (cases) refer to:

(a) DMI yearly data averages
(b) DMI spring data averages
(c) DMI summer data averages
(d) Percent of years under arid and semiarid ($DMI < 20$) conditions
(e) Percent of springs under arid and semiarid ($DMI < 20$) conditions
(f) Percent of summers under arid and semiarid ($DMI < 20$) conditions
(g) Percent of summers under strictly arid ($DMI < 10$) conditions

Table 2 presents DMI data for 18 drought stations in Serbia used to construct the DMI yearly, spring, and summer spatial distribution (pictures a–b–c in Fig. 2) and the percentage of data which meet defined drought conditions (pictures a–b–c–d in Fig. 3). All pictures refer to period 1949–2016.

The DMI climate classification in Serbia on annual and spring level average for the 1949–2016 period mostly varies from humid to moderate, while mountainous part in the western part of the country face very humid conditions. During the summer, conditions vary from humid in the west to almost semiarid in the southeastern part of the country (Fig. 2). These are averages, while significant differences have been observed at drought stations from year to year. Semiarid conditions occur quite rare on an annual and spring level — less than 5% and

Table 2 DMI data used to construct pictures in Figs. 2 and 3

Drought station	Case →	Annual averages a	Spring averages b	Summer averages c	DMI < 20% of years d	DMI < 20% of springs e	DMI < 20% of summers f	DMI < 10% of summers g
1	Knjaževac	29.7	31.1	22.3	4.8	15.9	45.0	10.4
2	Novi Pazar	34.8	35.4	26.5	2.1	10.4	34.5	3.5
3	Ćuprija	32.3	33.8	25.6	2.1	13.2	34.2	4.8
4	Vranje	30.0	31.2	20.8	4.9	14.1	50.9	14.5
5	Pirot	29.0	30.9	21.8	6.7	15.5	42.8	11.7
6	Senta	28.4	27.5	24.2	7.3	22.9	34.2	4.0
7	Sombor (Bezdan)	28.6	27.5	24.2	6.3	20.4	34.0	3.9
8	Srem. Mitrovica	30.2	29.4	25.9	4.8	20.0	30.8	4.1
9	Požega	37.3	38.0	30.6	1.1	7.3	22.9	2.1
10	Beograd (Jajinci)	31.7	32.2	26.9	2.7	15.9	29.4	2.6
11	Smed. Palanka	32.2	32.7	26.6	2.7	13.5	32.0	2.7
12	Leskovac	30.1	31.9	21.4	5.3	13.7	46.8	12.5
13	Sjenica	40.5	40.5	31.2	0.9	5.0	23.6	1.9
14	Ivanjica	40.2	41.6	33.0	0.9	5.6	17.8	2.0
15	Vel. Gradište	31.1	31.9	25.9	3.7	14.4	36.2	3.6
16	Aleksandrovac	31.7	33.1	25.1	5.1	12.2	37.0	7.1
17	Bujanovac	30.2	31.4	20.8	4.4	14.0	52.1	14.7
18	Dragaš	38.4	40.2	24.4	1.6	5.8	42.2	5.8
Averages		**32.6**	**33.4**	**25.4**	**3.7**	**13.3**	**35.9**	**6.2**

20%, respectively, for most of the stations — while for summer they vary from 20% in the western to more than 50% in the southeastern part of the country (Fig. 3a–c). Arid conditions (DMI < 10) occur sporadically only during the summers, and percentages vary similarly (from west to southeast) from 2 to 15% (Fig. 3d). In the greatest agricultural area — in the north of the country — semiarid conditions during the summers occur once in 3 years, while arid conditions occur once in 20–25 years (Fig. 3c, d).

Analyses of temporal changes

DMI and PED yearly indices, calculated as the averages of 18 drought stations, are shown in Table 3. Averages are given for three analyzed subperiods (1949–1970, 1971–1993, and 1994–2016). The same values occur in Fig. 5 in columns Annual, for both indices.

Figure 4 presents graphs and trends on annual, spring, and summer levels for both, De Martonne and Ped indices, for the entire period (1949–2016). Each of the indices has been obtained as averages of 18 drought stations across Serbia. Figure 5 presents data and charts with average values in 3 subperiods of both indices on annual, spring, and summer levels.

Figure 6 presents the number of years with De Martonne and Ped indices under semiarid (moderate drought) or arid (severe drought) conditions (DMI < 20; PED > 2) on annual, spring, and summer levels in 3 subperiods, while Fig. 7 presents the same, but strictly under arid (severe drought) conditions (DMI < 10; PED > 3).

Regarding temporal changes, PED indices registered a very clear increasing drought signal for all three classes (annual, spring, summer), and as well for the subperiods, while De Martonne indices registered a weak increasing drought signal only for summers (Figs. 4 and 5). In line with that, semiarid conditions tend to occur a little bit more frequently, while arid conditions for both indices, on a national level, are still very rare even in summer (Figs. 6 and 7).

Table 3 Calculated DMI and PED yearly indices

		1949	1950	1951	1952	1953	1954	1955	1956	1957	1958	1959	1960	1961	1962	1963	1964	1965	1966	1967	1968	1969	1970	Aver
DMI		31	24	30	30	26	42	46	33	35	29	34	33	26	33	33	36	32	33	31	31	34	40	32.8
PED		−0.3	2.5	1.4	1.3	0.5	−2.7	−2.3	−1.6	−0.4	1.0	−0.7	0.2	1.3	−0.5	−0.4	−1.2	−0.5	0.4	0.0	0.3	−1.1	−1.5	−0.20
	1971	1972	1973	1974	1975	1976	1977	1978	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992	1993	Aver
DMI	29	35	33	37	37	39	34	37	35	39	38	26	29	29	34	29	34	28	35	23	32	28	24	32.3
PED	0.2	−0.4	−0.8	−1.0	−0.9	−2.2	−0.3	−1.8	−0.5	−2.3	−1.3	0.8	0.3	−0.2	−1.2	−0.1	−0.7	0.5	−0.6	1.9	−0.8	1.0	1.1	−0.41
	1994	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	Aver
DMI	25	35	36	32	35	39	20	36	34	29	39	40	34	34	28	35	39	22	29	31	44	30	39	33.2
PED	2.3	−0.6	−1.1	−0.4	−0.1	−0.5	3.5	0.0	0.8	0.9	−0.9	−1.5	0.0	1.1	2.0	0.6	−0.3	2.1	1.7	1.5	−0.5	1.8	0.0	0.54

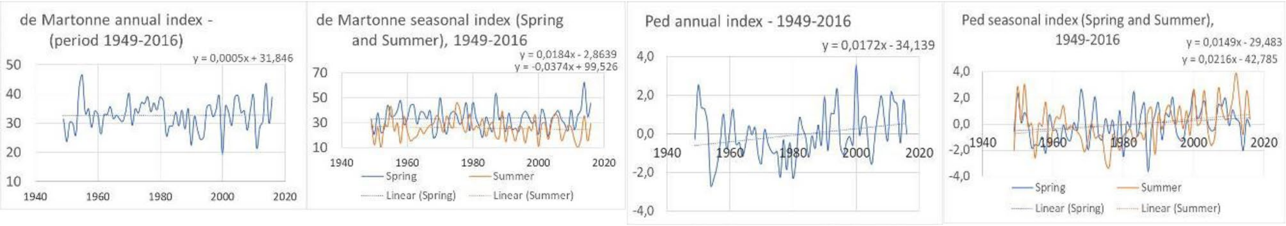
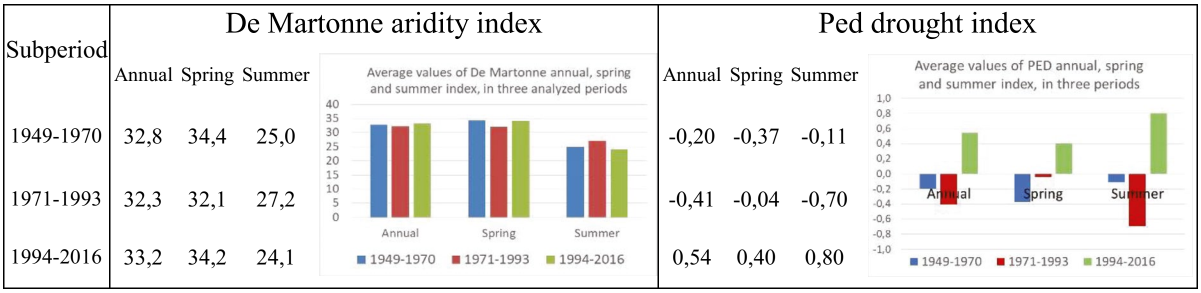
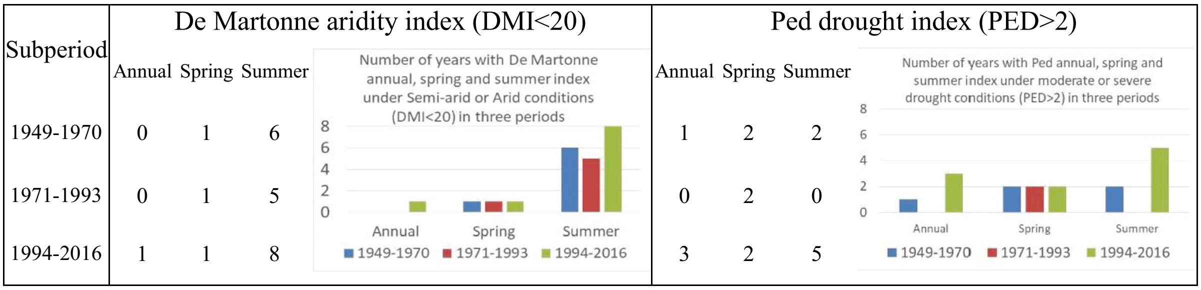


Fig. 4 Graphs with trends on annual, spring, and summer levels (period 1949–2016), for De Martonne and Ped indices



Subperiod	De Martonne aridity index			Ped drought index		
	Annual	Spring	Summer	Annual	Spring	Summer
1949-1970	32,8	34,4	25,0	-0,20	-0,37	-0,11
1971-1993	32,3	32,1	27,2	-0,41	-0,04	-0,70
1994-2016	33,2	34,2	24,1	0,54	0,40	0,80

Fig. 5 Average values in 3 subperiods of De Martonne and Ped annual, spring, and summer indices



Subperiod	De Martonne aridity index (DMI<20)			Ped drought index (PED>2)		
	Annual	Spring	Summer	Annual	Spring	Summer
1949-1970	0	1	6	1	2	2
1971-1993	0	1	5	0	2	0
1994-2016	1	1	8	3	2	5

Fig. 6 Number of years in 3 subperiods with De Martonne and Ped annual, spring, and summer indices under semiarid (moderate drought) or arid (severe drought) conditions (DMI < 20; PED > 2)

Analyses of combined spatial–temporal changes

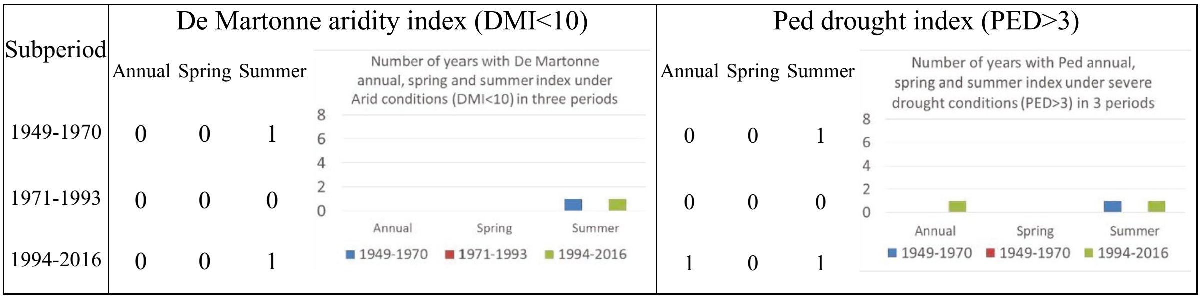
Figure 8 presents DMI annual spatial distribution in three subperiods, (1) 1949–1970, (2) 1971–1993, and (3) 1994–2016, while Fig. 9 presents DMI summer spatial distribution in the same three subperiods.

DMI annual and summer indices do not show significant changes in spatial distribution for the three analyzed subperiods (Figs. 8 and 9).

Analyses of spatial changes for fixed station's virtual altitudes

Figure 10 presents DMI spatial distribution for years and summers (as in cases "a" and "c" in Fig. 2), for period 1949–2016, in the virtual conditions that all stations are on the altitudes of 200 m.a.s.l. or 600 m.a.s.l.

Figure 11, similarly as Fig. 3c, d, presents DMI summer spatial percentage data distribution which



Subperiod	De Martonne aridity index (DMI<10)			Ped drought index (PED>3)		
	Annual	Spring	Summer	Annual	Spring	Summer
1949-1970	0	0	1	0	0	1
1971-1993	0	0	0	0	0	0
1994-2016	0	0	1	1	0	1

Fig. 7 No. of years in 3 subperiods with DMI and Ped indices under arid (severe drought) conditions (DMI < 10; PED > 3)

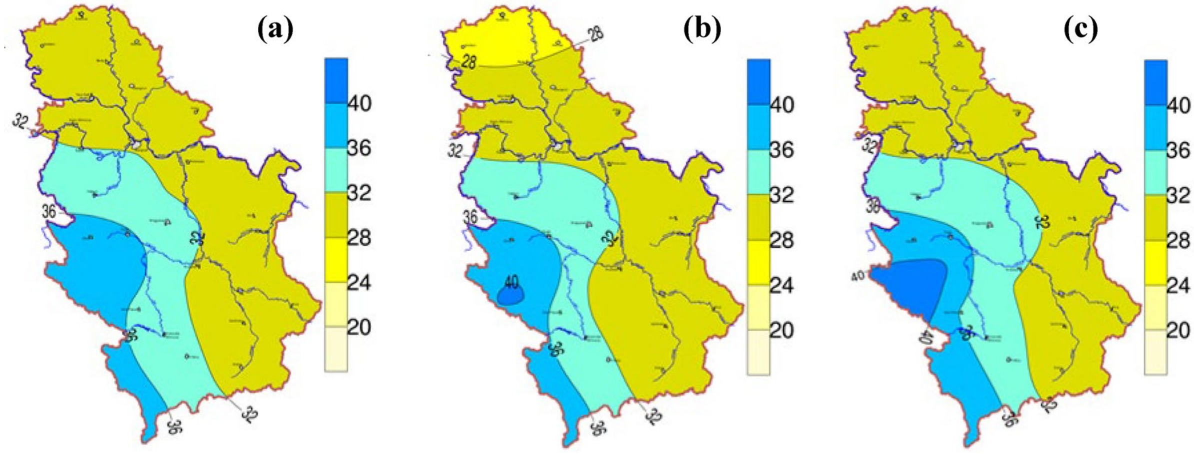


Fig. 8 DMI annual spatial distribution for subperiods **a** 1949–1970, **b** 1971–1993, and **c** 1994–2016

meets defined drought conditions, if all stations are on the virtual altitudes of 200 m.a.s.l. or 600 m.a.s.l.

The direction of changes that could be observed (both, DMI spatial distribution on annual and summer levels and occurrences of arid and semiarid conditions) is from north to south (Figs. 10 and 11). A small exception is observed in an area about 50–100 km north and south from the capital city of Belgrade, with slightly wetter condition than those in the surrounding areas (Fig. 10). Reasons could be related to both climate impacts: Mediterranean — coming from the south and west, and Continental — coming from the north and east.

As expected, DMI indices increase with an increase in altitude (Fig. 10), and occurrences of semiarid and arid conditions decrease with an increase in altitude (Fig. 11).

Analyses of temporal changes for fixed station's virtual altitudes

Figure 12, similarly to Fig. 4, presents trends in the annual (only) De Martonne aridity index (1949–2016), for all stations at virtual altitudes of 200 m.a.s.l. and 600 m.a.s.l. Figure 13, similarly to Fig. 5, presents average values in 3 subperiods of

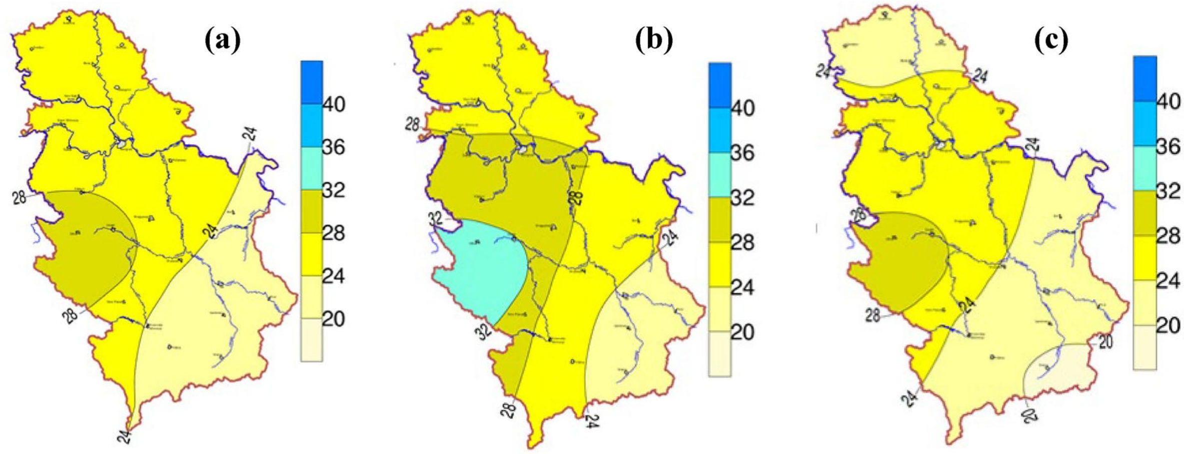
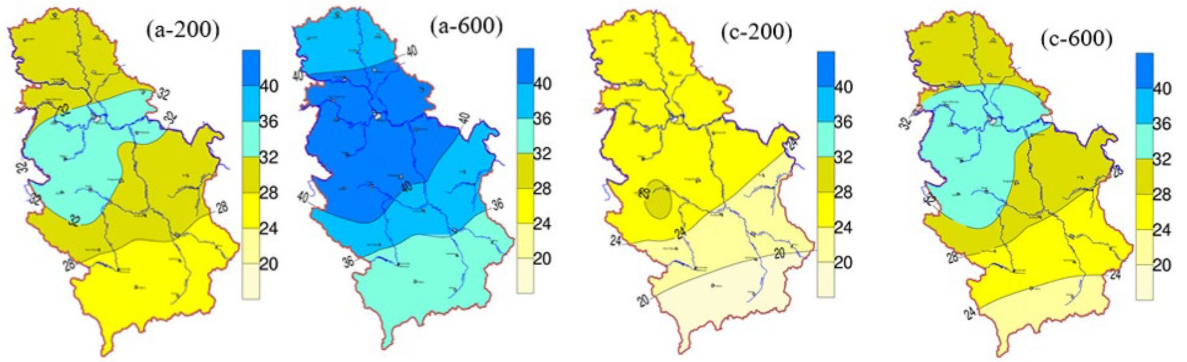
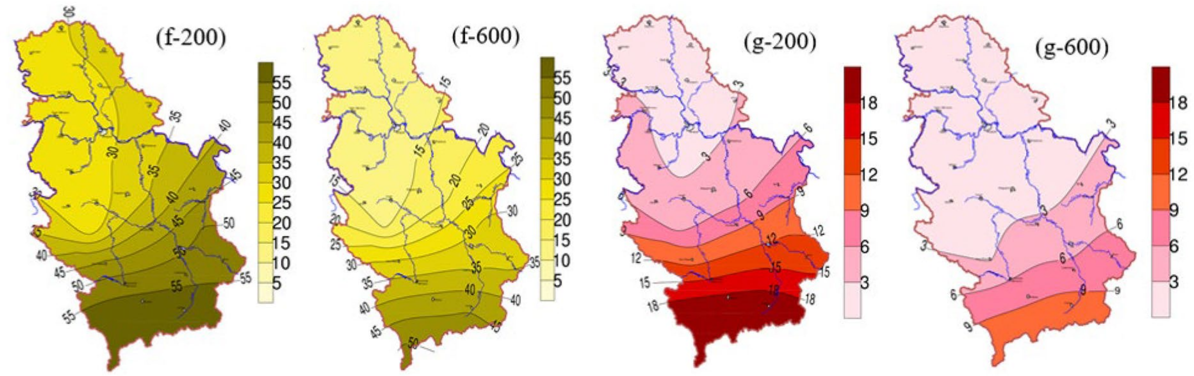


Fig. 9 DMI summer spatial distribution for subperiods **a** 1949–1970, **b** 1971–1993, and **c** 1994–2016



Altitude 200 m.a.s.l.- years Altitude 600 m.a.s.l.- years Altitude 200 m.a.s.l.- summers Altitude 600 m.a.s.l.- summers

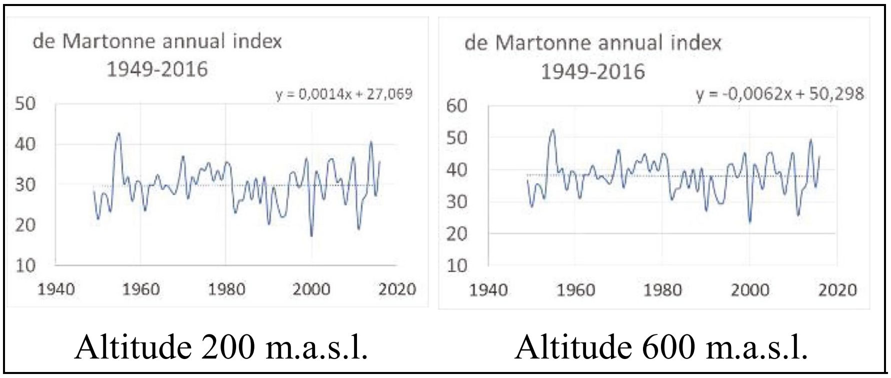
Fig. 10 DMI spatial distribution on annual and summer levels, for period 1949–2016, in the virtual conditions that all stations are on the altitudes of 200 m.a.s.l. or 600 m.a.s.l. **a-200** Altitude 200 m.a.s.l., years; **a-600** altitude 600 m.a.s.l., years; **c-200** altitude 200 m.a.s.l., summers; **c-600** altitude 600 m.a.s.l., summers



Semiarid-altitude 200 m.a.s.l.Semiarid- altitude 600 m.a.s.l. Arid - altitude 200 m.a.s.l. Arid - altitude 600 m.a.s.l.

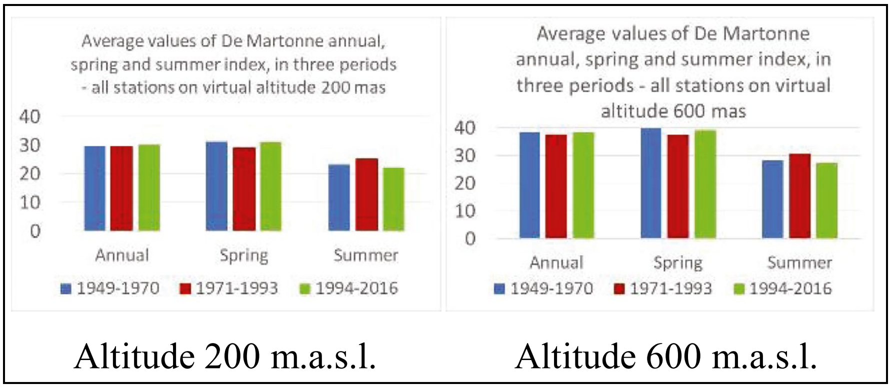
Fig. 11 DMI spatial summer's distribution (percentages) under arid and semiarid conditions (DMI < 20); and strictly arid conditions (DMI < 10), if all stations are on the virtual altitudes of 200 m.a.s.l. or 600 m.a.s.l. **f-200** Semiarid, altitude 200 m.a.s.l.; **f-600** semiarid, altitude 600 m.a.s.l.; **g-200** arid, altitude 200 m.a.s.l.; **g-600** arid, altitude 200 m.a.s.l

Fig. 12 De Martonne index trends for annual levels in the virtual conditions if all stations are altitudes of 200 m.a.s.l. and 600 m.a.s.l



De Martonne annual, spring, and summer indices, for all stations at virtual altitudes of 200 m.a.s.l. and 600 m.a.s.l., but without numbers — just as charts.

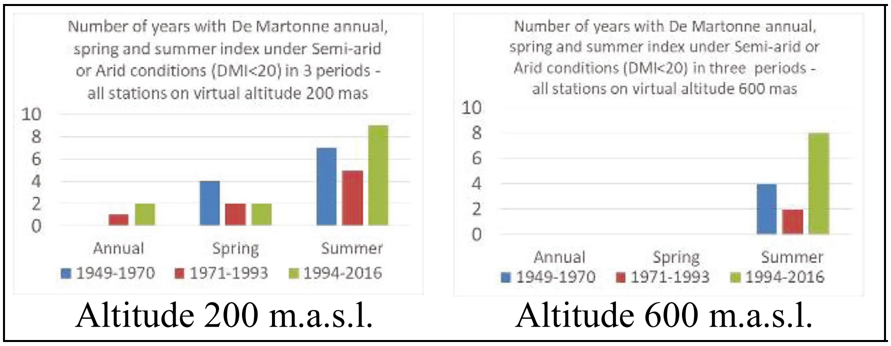
Figure 14, similarly to Fig. 6, presents the number of years in 3 subperiods with De Martonne annual, spring, and summer indices under semiarid or arid conditions (DMI < 20), for all stations at virtual altitudes of 200 m.a.s.l. and 600 m.a.s.l., but without numbers — just as charts. Figure 15, similarly to Fig. 7, presents the number of years in 3 subperiods with De Martonne annual, spring, and summer indices under arid conditions (DMI < 10), for all stations at virtual altitudes of 200 m.a.s.l. and 600 m.a.s.l., but without numbers — just as charts.



Altitude 200 m.a.s.l. Altitude 600 m.a.s.l.

Fig. 13 De Martonne average annual, spring, and summer indices in 3 subperiods, if all stations are virtual altitudes of 200 m.a.s.l. and 600 m.a.s.l

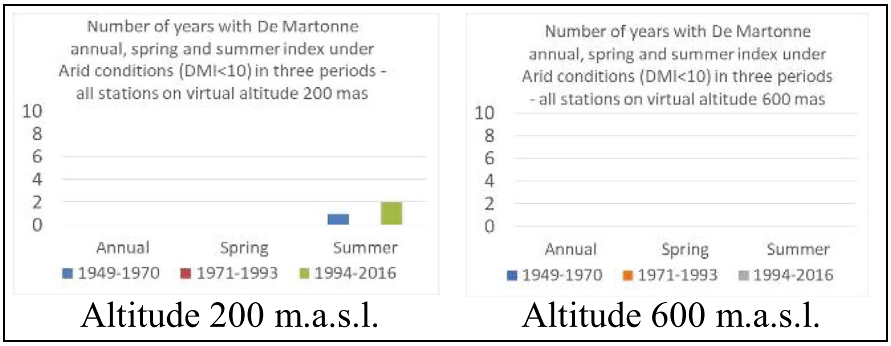
Semi-arid or Arid conditions (DMI<20)



Altitude 200 m.a.s.l. Altitude 600 m.a.s.l.

Fig. 14 Number of years in 3 subperiods with De Martonne annual, spring, and summer indices under semiarid or arid conditions (DMI < 20), for all stations at virtual altitudes of 200 m.a.s.l. and 600 m.a.s.l

Arid conditions (DMI<10)



Altitude 200 m.a.s.l. Altitude 600 m.a.s.l.

Fig. 15 Number of years in 3 subperiods with De Martonne annual, spring, and summer indices under arid conditions (DMI < 10), for all stations at virtual altitudes of 200 m.a.s.l. and 600 m.a.s.l

Very similar graph shapes of graphs are obtained for the original and virtual altitudes (comparison of Figs. 12 and 4, and as well as Figs. 13 and 5), only the average values differ. Values for the original altitudes are always between two virtual values and on both pairs of figures, they are closer to values for virtual altitudes of 200 m.a.s.l. Similar could be said for the occurrence of drought (comparison of Figs. 14 and 6 and Figs. 15 and 7).

It is interesting to note that no year, spring, or summer have had strictly arid conditions for drought stations at virtual altitudes of 600 m.a.s.l. (Fig. 15).

Discussion

Drought occurrence and spatial and temporal changes across Serbia

Conditions for drought occurrence have clearly increased for most of the territory of Serbia, due to the significant global increases in temperature. In the 1949–2016 period, observed trend for most T stations varies from 1.2 to 2.0 °C/100 years, and a small decreasing precipitation trend — up to − 5%/100 years — has been recorded in the eastern and southern part of the country (Dimkić, 2019; Djurdjevic, 2020). Western Serbia could be an exception, due to an observed increasing P trend — up to + 10%/100 years. Water demand was increasing until 1995 and stagnated in the subsequent period. Favorable circumstances, from the drought occurrence point of view, could be a slightly increasing trend in forested land coverage (Gavrilović et al., 2013).

It could be said that majority of the obtained results for the DMI and PED indices, presented in this paper, are in line with the above observations. Semiarid conditions occur quite rarely on annual and spring levels, while summer occurrences vary from 20% in the western to more than 50% in the southeastern part of the country (Fig. 3a–c). Arid conditions occur sporadically only during the summer, with the same increasing direction — from west to southeast (Fig. 3d).

Small confusion is present related to temporal drought changes. PED indices recorded a clear increasing drought signal for annual, spring, and summer levels, while DMI indices recorded a weak increasing drought signal only for summers (Fig. 4). When data are divided into subperiods, PED indices again recorded a clear increasing drought signal for all three time levels, while DMI indices did not show any significant changes (Fig. 5).

Differences between averages and particular stations

Results presented in the "Analyses of temporal changes" section (all graphs in Figs. 4–7) are on a national level, but values of any of the parameters vary from station to station, of course. It could be said that these results (values of parameters) for any drought station do not differ essentially and do not differ too much from the values presented in this paper, for the great majority of stations (not presented in this paper due to the need of significantly greater number of pages).

Physical description regarding differences in spatial changes

Practically all figures of drought spatial changes show a decreasing trend from west or northwest to east or southeast. That is absolutely in line with the observed spatial changes for precipitation and run-off in Serbia (Dimkić, 2019), and as well with direction of the same trends in northern Greece (Baltas, 2007), and the Balkan Peninsula (at least the central part) in general. In addition to P changes, important role in drought condition changes and water resources availability have T changes, but also changes in land use (changes in % of forest, changes in urban and agricultural land use) and changes in human water use. It would be challenging to investigate the degree of impact of these four drivers on water resources in one region, as well as on different parts of one river catchment.

Direction of drought condition changes and differences in natural condition if stations are at virtual altitudes

If we compare drought conditions obtained from 18 stations on origin altitudes (Figs. 2, 3, 8, and 9), with the same stations at fixed virtual altitudes (Figs. 10 and 11), it can be seen that the natural direction of changes — from west to southeast (reasons are likely geographic and climate conditions) — has shifted to the direction from north to south, which could be declared as expected.

Degree of drought vulnerability across Serbia

Based on DMI indices, it is obvious that the southeast is the most vulnerable part of Serbia. A paper written by Milentijević et al. (2018) analyzes drought conditions and changes in the Leskovac basin (large valley in the South Morava basin in the southern part of Serbia, surrounding of drought station 12 in this paper), with DMI and some other drought indices. They obtained significantly higher DMI increasing trend for the 1981–2010 period ($a = 0.2078$) than found in this paper ($a = 0.0474$), but for 1949–2016 period. Both are correctly calculated, and the reason for this difference underlines the importance of the length and relevance of the analyzed period (Dimkić, 2019). The second most vulnerable area is the north of the country, which could be critical in summer, due to high levels of agricultural activity. Figure 9 shows that summer DMI indices decreases in this region over time. A paper written by Gavrilov et al. (2019) analyzes drought conditions and changes in Southeastern Banat (a region slightly north of drought station 15 in this paper — left side of the Danube River), for 1949–2017 period, with the DMI aridity index. They have found an insignificant trend ($a = 0.016$), as did we ($a = -0.0176$) for a similar period (1949–2016). Gavrilov indicates the importance of including evapotranspiration in analyses. The least vulnerable is the western part of Serbia. In addition to significant natural water availability, climate change brings an increase in precipitation in this area. The degree of drought vulnerability also increases with decreasing altitude. Additionally, agricultural, hydrological, and particularly socioeconomic types of drought usually increase with high water demand accompanied with low natural groundwater aquifer capacity, which occurs in the vicinity of big cities and central parts of the country. There, water shortages occur more frequently than in the most vulnerable areas in Fig. 3. Similar scenario occurs in most of the neighboring countries in Southeast Europe (CCWaters, 2009–2012; Curk et al., 2015).

The contribution, novelty, and limitations of this study

In our opinion, this study has contributed to a better understanding of drought occurrence – primarily from a spatial distribution perspective. Temporal changes need to be further analyzed, which could be acknowledged as a limitation of the presented results. Additionally, the novelty of this study is the analyses regarding the spatial distribution of drought when all the stations are at fixed virtual altitudes, including their comparison with results obtained for stations at original altitudes.

Conclusion

Global warming and climate change (including a precipitation decrease for some parts) is present in Serbia. Therefore, increased drought conditions (meteorological drought) can be expected in Serbia with great certainty, but the question is how fast these changes are likely to happen. The second question is what other types of drought risk drivers exist in Serbia and how much is whose impact.

If the forecasts of climate models of the reduction of precipitation on the territory of Serbia in the future are realized (especially critical forecasts are for distant future), with an almost certain increase in temperature, a more significant occurrence and severity of droughts could be expected (Djurdjevic, 2020; Krzic et al., 2011; CC-WaterS, 2009–2012; Rajkovic et al., 2013). And if we look at the observed T and P changes in Serbia on annual, seasonal, and monthly levels (Dimkić, 2019), drier conditions could be expected in the future, but to a lower extent. The results presented in this paper show a tendency toward a drier area, but not overly sever. The reason for the small differences between results in regional climate models and results from analyses of observed data may be due to a slight increase in annual precipitation over the last 10 years, and a P increasing trend in the low-flow months (Aug–Oct).

However, conditions for drought occurrence have certainly increased for the territory of Serbia, but drought intensity and frequency should certainly be lower than those predicted for the Mediterranean coastal area (Baltas, 2007; Barajas, 2007; Ballesteros et al., 2020). Exceptions are areas with very intensive human water consumption. That fact points out the importance of analyses related to hydrological, agriculture, and socioeconomic types of droughts. For these, the primary drought driver in Serbia is probably water demand, like in many parts of the world (Bou-Zeid & El Fadel, 2002; Durdu, 2009; Fujihara et al., 2008), and climate change provides additional pressure to the scarcity issue.

The two analyzed indices (DMI and PED) explain a drought issue in Serbia significantly, but due to some differences in results regarding temporal changes, it is desirable and recommended to consider a several other drought indices. Of great interest, particularly for socioeconomic type of drought, would be to include the water demand issue in the analyses. Regarding future water availability, it would be promising to investigate which type of global changes (if we split them into T changes, P changes, land use changes, and changes in a human water use) has the greatest average impact on water resources in one region and on different parts of a river catchment.

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Author contribution All the authors have read and agreed to the published version of the manuscript. First author, DD wrote the paper, while first coauthor, AA, and second coauthor, MB helped in preparing spatial figures and calculations.

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Availability of data and materials The temperature, precipitation, and other datasets used for analyses during the current study are available from the corresponding author on reasonable request.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Conflict of interest The authors declare no competing interests.

References

Ballesteros, A. L., Aparicio, J. S., Martínez, C., & Sánchez, J. P. (2020). Assessment of future hydrologic alteration due to climate change in the Aracthos River basin (NW Greece). *Elsevier, 733*, 1. https://doi.org/10.1016/j.scitotenv.2020.139299

Baltas, E. (2007). Spatial distribution of climatic indices in northern Greece. *Meteorological Applications, 14*, 69–78. https://doi.org/10.1002/met.7

Barajas, S. M. (2007). Ecologistac en accion. The effects of climate change on water resources in Spain, 2007. Available at https://spip.ecologistasenaccion.org/IMG/pdf_CC_W_in_Spain.pdf

Bou-Zeid, E., & El Fadel, M. (2002). Climate change and water resources in Lebanon and the Middle East. *Journal of Water Resources Planning and Management, 128*, 343–355.

Climate Change and Impacts on Water Supply (CC-WaterS).(2009 – 2012). *International project for SE Europe*. Available at http://www.ccwaters.eu/index.php?option=com_content&view=article&id=48&Itemid=54&56b00064c3e6beb26da3b96d1578b92a=caac98a9a4248cd115a194c70c97a142

Curk, B. C., Vrhovnik, P., Verbovšek, T., Dimkić, D., Marjanović, P., Tahy, A., Simonffy, Z., Alessandro, C., Nistor, M. M., Cheval, S., Herrnegger, M., & Nachtnebel, H. P. (2015). Vulnerability of water resources to climate change in South-East Europe. Conference: AQUA 2015 42nd IAH Congress.

Dimkić, D. (2016). New method for estimation mean hydrological changes and question of reliability in forecasting future hydrological regimes. *Proceedings of EWAS2 Conference, Crete 2016, paper published by Elsevier in Procedia Engineering, 162*, 145–152. http://www.sciencedirect.com/science/article/pii/S1877705816333355

Dimkić, D. (2019). Characteristics of annual, seasonal and monthly observed climate and hydrologic changes in Serbia in the last seventy years. *Desalination and Water Treatment, 167, 359–369*. ISSN 1944–3994, Publisher: Desalination Publications. https://doi.org/10.5004/dwt.2019.24575

Djurdjevic, V. (2020). Drought initiative - republic of Serbia, recommendations for development of the national drought plan of the republic of Serbia. https://knowledge.unccd.int/sites/default/files/country_profile_documents/NDP_SERBIA_2020.pdf

Durdu, Ö. F. (2009). Effects of climate change on water resources of the Büyük Menderes river Basin, Western Turkey, 16.09.2009. Available at https://dergipark.org.tr/en/download/article-file/119648

Forootan, E. (2019). Analysis of trends of hydrologic and climatic variables. *Soil and Water Research, 14*(3), 163–171. https://doi.org/10.17221/154/2018-SWR

Fujihara, Y., Tanaka, K., Watanabe, T., Nagano, T., & Kojiri, T. (2008). Assessing the impacts of climate change on the water resources of the Seyhan river Basin in Turkey: Use of dynamically downscaled data for hydrologic simulations. *Journal of Hydrology*, *353*(1-2), 33–48. http://www.sciencedirect.com/science/article/pii/S0022169408000346 Accessed 20 May 2008.

Gavrilov, M. B., An, W., Xu, C., Radaković, M. G., Hao, Q., Yang, F., Guo, Z., Perić, Z., Gavrilov, G., & Marković, S. B. (2019). Independent aridity and drought pieces of evidence based on meteorological data and tree ring data in Southeast Banat, Vojvodina. *Serbia. Atmosphere, 10*, 586.

Gavrilović, Z., Dimkić, D., & Stefanović, M. (2013). The effects of forest on runoff regimes in Serbia. International conference 17–18 October. *Climate Change Impacts on Water Resources*. ISBN 978–86–82565–41–3, 203–210.

Hatmoko, W., Triweko, R. W., & Hadihardaja, I. K. (2013). Water resources drought: hydrological drought in developed river basins, 4th international seminar of HATHI, 6–8 September 2013, Yogyakarta. https://www.researchgate.net/publication/275341859_Water_Resources_Drought_Hydrological_Drought_in_Developed_River_Basins

Koleva, E., & Alexandrov, V. (2008). Drought in the Bulgarian low regions during the 20th century. *Theoretical and Applied Climatology, 92*, 113–120. https://doi.org/10.1007/s00704-007-0297-1

Krzic, A., Tosic, I., Djurdjevic, V., Veljovic, K., & Rajkovic, B. (2011). Changes in some indices over Serbia according to the SRES A1B and A2 scenarios. *Climate Research, 49*, 73–86. https://doi.org/10.3354/cr01008

Lungu, M., Panaitescu, L., & Niţă, S. (2011). Aridity, climatic risk phenomenon in Dobrudja. *Present Environment and Sustainable Development, 5*(1).

Milentijević, N., Dragojlović, J., Ristić, D., Cimbaljević, M., Demirović, D., & Valjarević, A. (2018). The assessment of aridity in Leskovac Basin, Serbia (1981–2010). *Journal of the Geographical Institute "Jovan Cvijić" SASA*, *68*(2), 249–264. https://doi.org/10.2298/IJGI1802249M

Rahimi, J., Ebrahimpour, M., & Khalili, A. (2013). Spatial changes of extended De Martonne climatic zones affected by climate change in Iran. *Theoretical and Applied Climatology, 112*, 409–418. https://doi.org/10.1007/s00704-012-0741-8

Rajkovic, B., Vujadinovic, M., & Vukovic, A. (2013). Report on revisited climate change scenarios including review on applied statistical method for removing of systematic model errors, with maps of temperature, precipitation and required climate indices changes; second national communication of the republic of Serbia under the United Nations framework convention on climate change. MERZ, Belgrade, Serbia. http://haos.ff.bg.ac.rs/climatedb-srb/model.html

Tri, D. Q., Dat, T. T., & Truong, D. D. (2019). Application of meteorological and hydrological drought indices to establish drought classification maps of the Ba River Basin in Vietnam. *Hydrology, 6*, 49. https://doi.org/10.3390/hydrology6020049

Tsitsifli, S., Papadopoulou, A., Kanakoudis, V., & Gonelas, K. (2018). Water use efficiency current status assessment in the context of watenergy cycle project. *Proceedings, 2*, 602. https://doi.org/10.3390/proceedings2110602

Voropay, N. N., & Ryazanova, A. A. (2018). A comparative assessment of the aridity indices for analysis of the hydrothermal conditions. *IOP Conference Series: Earth and Environmental Science*, *190*, 012041.

WMO. (2006). World meteorological organization CAgM report No.101 impacts of desertification and drought. Geneva.

Yevjevich, V. (1967). *An objective approach to definitions and investigations of continental hydrologic droughts*. Hydrology Papers Colorado State University Fort Collins.