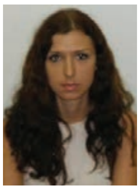
Primljen / Received: 22.6.2014.
Ispravljen / Corrected: 28.12.2014.
Prihvaćen / Accepted: 23.1.2015.
Dostupno online / Available online: 10.2.2015.

Comparison of different drought assessment methods in continental Croatia

Authors:

Assoc.Prof. Lidija Tadić, PhD. CE
University J. J. Strossmayera in Osijek
Faculty of Civil Engineering
ltadic@gfos.hr

Tamara Dadić, MCE
University J. J. Strossmayera in Osijek
Faculty of Civil Engineering
tamaradadic@gfos.hr



Mihaela Bosak, MCE
Valenčak d.o.o
Našice
mihaela5.na@gmail.com

Subject review

Lidija Tadić, Tamara Dadić, Mihaela Bosak

Comparison of different drought assessment methods in continental Croatia

Drought is an extreme hydrological event that causes great economic and environmental damage. Various methods are used for the identification and quantification of drought. The analysis of five drought identification methods was conducted for continental Croatia on 15 weather stations in the period from 1981 to 2011: standardised precipitation index, deciles index, percent of normal precipitation, rainfall anomaly index, and threshold level method. Results have revealed that each of these methods has its specific features but that all are applicable for the area under study. There is a significant correlation between the standard precipitation index and the deciles index, rainfall anomaly index, and percent of normal.

Key words:
drought, standardised precipitation index, deciles index, percent of normal, rainfall anomaly index, threshold level method

Pregledni rad

Lidija Tadić, Tamara Dadić, Mihaela Bosak

Usporedba različitih metoda za ocjenu suše na području kontinentalne Hrvatske

Suša je ekstremna hidrološka pojava koja izaziva velike gospodarske i ekološke štete. Identifikacija i kvantifikacija suše provodi se primjenom različitih metoda. Za područje kontinentalne Hrvatske, na 15 meteoroloških postaja od 1981. do 2011. godine, provedena je analiza 5 metoda za identifikaciju suše: indeks standardiziranih oborina, metoda decila, postotak od normale, indeks anomalije oborina i metoda koraka. Rezultati su pokazali da svaka od metoda ima svoje specifičnosti, ali su sve primjenjive za analizirano područje. Indeks standardiziranih oborina ima značajnu korelaciju s metodom decila, postotkom od normale i indeksom anomalije oborina.

Ključne riječi:
suša, indeks standardiziranih oborina, metoda decila, postotak od normale, indeks anomalije oborina, metoda koraka

Übersichtsarbeit

Lidija Tadić, Tamara Dadić, Mihaela Bosak

Vergleich der Methoden zur Beurteilung von Dürre im kontinentalen Kroatien

Dürre ist ein extremes hydrologisches Phänomen, das große wirtschaftliche und ökologische Schäden verursacht. Die Identifizierung und Quantifizierung von Dürre wird mittels verschiedener Methoden durchgeführt. Im kontinentalen Raum Kroatiens ist für 15 meteorologischen Stationen im Zeitraum von 1981 bis 2011 eine Analyse der folgenden fünf Methoden zur Identifizierung von Dürre durchgeführt: standardisierter Niederschlagsindex, Dezil-Methode, Normalprozentsatz, Index der Niederschlagsanomalie und Schrittverfahren. Die Ergebnisse haben gezeigt, dass die einzelnen Methoden ihre Besonderheiten haben, aber für das analysierte Gebiet anwendbar sind. Der standardisierte Niederschlagsindex hat eine bedeutende Korrelation zur Dezil- Methode, dem Normalprozentsatz und dem Index der Niederschlagsanomalie.

Schlüsselwörter:
Dürre, standardisierter Niederschlagsindex, Dezil-Methode, Normalprozentsatz, Index der Niederschlagsanomalie, Schrittverfahren

1. Introduction

The issue of frequency of droughts has been intensively studied by researches over the past two decades, particularly as an extreme hydrological phenomenon with strong negative impacts on the economy of any area or region. There is practically no climatic area in which droughts of various intensities have not occurred in past decades, mostly as a result of the greatest threat facing world in the 21st century: climate changes. In Europe, droughts are most frequent in the southern and south-eastern parts of the continent, but droughts recorded in 1989, 1991, and especially in 2003, have affected the whole of Europe. The analysis of drought in south Italy in the period from 1923 to 2000 has shown a greater frequency of droughts in the period after 1975, and a significant reduction in precipitation during winter months [1]. The emphasis is usually placed on the effects of drought in agriculture, but it enormous negative impact on natural eco-systems has not yet been sufficiently explored, which might be due to the slowness of the process, and the size of the area affected by it. The complexity of drought lies in the fact that it can not easily be predicted, it affects extensive areas, it develops slowly, and it is usually registered when it has already been present for weeks or months. There is no single definition of drought, and there is no reliable methodology for its quantification. It may be said in most general terms that drought is every reduction of precipitation with respect to the normal (average) quantity of precipitation in a given climatic zone. This by itself makes drought the most complex hydrological event that affects all climatic zones, with varying duration, intensity and frequency, while on the other hand the efficiency of drought protection is very low [3].

This is why a great number of drought indices are proposed in current hydrological research papers. They are mostly based on hydrological parameters (discharges and water levels) and meteorological parameters (precipitation and air temperatures). None of the methods currently in use can be considered universal, or absolutely correct. Their use is mostly based on regional aspects, but also on the availability of data. The selection of a method in a given area depends on available data and on the capability of a method to estimate in the best possible way the occurrence of drought in time and space, and its variability [4]. That is why criteria for selecting the best drought analysis method would be: independence with regard to geographic and climatic characteristics of an area, including extreme climatic conditions (desert or polar conditions), physical foundations of a method, and simplicity of calculation [3]. Time units on which various indices are based are a separate problem. These units are mostly months, which can lead to erroneous conclusions in specific and stochastic distributions of precipitation during one month [5]. None of the currently recommended methods is capable of meeting all of the above mentioned criteria.

The Palmer drought index [6] and the standardised precipitation index [7] are most often used in the USA, the deciles index [8] prevails in Australia, and Z-index in China [9]. Other methods include the threshold level method [10], rainfall anomaly index [11], and the simplest method based on precipitation anomaly or percent of normal precipitation. The common feature of these methods, and of all other existing methods, is that they describe and quantify in different ways the lack of water as related to the average soil humidity conditions, precipitation quantities, or flow rates.

Many papers presenting comparison of various drought quantification methods have so far been published all over the world. Based on the 73-year series of precipitation in the Lokoja area in Nigeria, four methods were compared, i.e. stochastic component time series (SCTS), rainfall anomaly index (RAI), drought severity index (DSI), and cumulative rainfall information (CRI). It was concluded that the most favourable method is the rainfall anomaly index (RAI) as it provides the greatest quantity of information about the frequency and intensity of drought in the area under study [12]. The comparison of three methods for meteorological evaluation of droughts, i.e. Palmer drought index (PDI), Bhalme-Mooley drought index (BMDI), and rainfall anomaly index (RAI) in the area of Nebraska (USA), shows that all three methods are favourable for drought identification, and that the precipitation is the dominant drought-occurrence factor. Consequently, simple methods based on rainfall analysis only, can be considered to be as good as very complex drought indices [13]. The studies conducted for the USA area show a very high correlation (r = 0.97) between the standardised precipitation index (SPI) and rainfall anomaly index (RAI), while the correlation between the Palmer drought severity index (PDSI) and rainfall anomaly index is much weaker [14]. Recently developed methods are attempting to take into account all of the most important water balance components (precipitation, evapotranspiration, soil moisture, surface runoff, and snow) while also trying to be relatively simple to use [15]. One of them is the effective drought index (EDI) which differs from others already by being based on daily information, while the time step of one month has so far been considered as the most favourable for drought quantification [16]. The effective drought index is based on the daily accumulation of rainfall with the weight factor for the passage of time. The comparison of this method with the standardised precipitation index points to a very low correlation in case of short time period. This correlation however increases when the time period extends to nine months or a year [16, 17].

Droughts are also analysed in the territory of Croatia. During the analysis of drought in Osijek area in the period from 1982 to 1990, conducted using the threshold level method, deciles index, and discrete Markov chain analysis, it was established that the results obtained are similar regardless of the method used [18]. The possibilities of predicting drought on the time scale from one to three months using the standardised precipitation index were analysed at five weather stations in Croatia, and it was concluded that predictions are quite accurate for one month period, while predictions over longer periods are less accurate [19]. The analyses of drought conducted at the Zagreb-Grič Weather Station in 2003 and 2004 using the standardised precipitation index revealed high accuracy for one month period, but the level of accuracy was lower for the periods of 3, 6, and 12 months [20]. Droughts on the Korčula Island were analysed for the period from 1948 to 2008 according to the standardised precipitation index, Palmer method, deciles index, and threshold level method [21].

These examples show that the drought issue is highly complex and present in various climatic zones, and also that researchers are trying to answer numerous questions about the frequency of its occurrence and quantification. At the same time, a relatively small number of papers have been published in Croatia about this extreme hydrological phenomenon. This fact is precisely the prime motivation for drought analysis in Croatia, particularly in its continental part where agriculture is a significant branch of economy, and where a considerable drought-related damage was registered in recent years. This will also present a good occasion for studying adequacy of methods that are most often used for drought analysis. The impact of drought on the environment should also be considered, as highly valuable ecosystems, such as Kopački rit and Lonjsko polje, are situated in this part of Croatia, and the survival of such ecosystems is highly dependant on the quantity of precipitation and flooding frequency.

Five drought analysis methods, namely the standardised precipitation index, threshold level method, rainfall anomaly index, deciles index, and percent of normal precipitation or precipitation anomaly, are presented in the following section. All these methods were applied for the same series of precipitation data (1981-2011), and the basic time unit was one month. The observed 31-year period is considered long enough for drought analysis purposes [8, 22].

2. Method description

2.1. Standardised precipitation index

Compared to other methods, the Standardised Precipitation Index (SPI) is the method that is most frequently used in all parts of the world, regardless of climatic or topographical features. According to some authors, it is not recommended to use this method on the global level. However, the World Meteorological Organisation considers that there are no limitations as to its use, because the method is independent of drainage basin characteristics. The SPI is based on normalised gamma distribution of precipitation and presents a number of standard deviations with regard to an average value. the basic advantage of this method lies in the fact that it necessitates only a set of precipitation for a longer period of time (30 or more years), and that it can be used for various time scales, the most frequent ones being 1, 3, 6, 12, and 24 months. Thus the same index can be used for the evaluation of precipitation deficit in various water resources (ground water, open watercourses, soil moisture) depending on the purpose for which the drought analysis is made. One to six months time scales are appropriate for the analysis of drought in agriculture, one to two months are needed for meteorological drought, and 6 to 24 months are needed for hydrological drought (a positive SPI points to a greater quantity of precipitation with respect to the mean multiyear value, while a negative SPI is an indication of lower precipitation compared to mean value). Its applicability is however questionable for dry areas with many months without any precipitation, and for periods shorter than twelve months, because the gamma distribution is not defined for values equal to zero. In this case, the expression for the cumulative probability function is extended by adding probability that the precipitation quantity will be equal to zero. The standardised precipitation index has the defined limit values dependent on the relative frequency of drought, which enables comparison of values for various locations or regions, as shown in Table 1 (according to [7]). The computer program "spi_si_6" (National Drought Mitigation Centre, USA) [23] was used for calculating monthly indices of standardised precipitation.

2.2. Deciles index

The Deciles Index (DI) is based on the distribution of a longer rainfall observation series into deciles or tenths of distribution [6, 26]. It was developed as an improvement to the percent of normal precipitation or precipitation anomaly. Deciles are calculated based on the number of occurrences arranged from 1 to 10. The lowest values show that the climate is drier compared to average conditions, while greater values point to more humid conditions. All monthly precipitation values in a given period are ranked from the lowest toward the highest, and then the first decile denotes 10 % of the lowest quantity of precipitation; the second decile denotes precipitation values between 10 and 20 %, etc. The median corresponds to the quantity of precipitation having 50 % probability of occurrence within the period under study. Each group is attributed a description of the level of dryness or humidity. The state of humidity marked as "normal" (30-70 %) in the original deciles index has a wider classification into "slightly lower than normal", "normal" and "slightly above normal", which has been simplified and converted into a single category to enable easier comparison with other methods, as shown in Table 1 [22].

2.3. Percent of normal precipitation

The percent of normal precipitation (PN) or precipitation anomaly is based on the relationship between the monthly precipitation and an average monthly precipitation in the period under study. It is a simple method that is used for rapid drought frequency analysis, and can be considered satisfactory if a longer series of precipitation data is available (no less than thirty years), and if it is applied within a single region with similar geographical characteristics. It would be difficult to compare locations that are far away from one another, as anomalies are defined in relation to a given location (weather station) separately.

2.4. Rainfall anomaly index

The Rainfall Anomaly Index (RAI) can be applied to weekly, monthly and annual precipitation data [8]. The basic expression is:

$$RAI = \pm 3 \frac{P - \overline{P}}{\overline{E} - \overline{P}} \tag{1}$$

where:

P - precipitation [mm]

$\overline{P}$ - average precipitation in a period [mm]

$\overline{E}$ - verage value of ten greatest recorded monthly precipitation values [mm].

Table 1. Limit values for standardised precipitation index (SPI), deciles index (DI), percent of normal (PN), and rainfall anomaly index (RAI)

Classification	SPI [7]	DI [%] [22]	PN [%] [4]	RAI [8]
Extremely wet	≥ 2,00	≥ 90	≥ 110	≥ 3,00
Very wet	1.50 to 1.99	80 to 90		2 to 2.99
Moderately wet	1.00 to 1.49	70 to 80		1 to 1.99
Normal	0.99 to -0.99	30 to 70	80 to 110	0.5 to -0.99
Moderately dry	-1.0 to -1,49	20 to 30	55 to 80	-1.00 to -1.99
Very dry	-1.5 to -1.99	10 to 20	40 to 55	-2.00 to -2.99
Extremely dry	≤ -2.00	≤ 10	≤ 40	≤ -3,00

The positive or negative sign is related to the positive or negative precipitation anomalies. The rainfall anomaly index, just like the deciles index, presents a classification into seven typical classes of humidity/dryness and, to enable comparison with the standardised precipitation index and the percent of normal, the state of normal humidity ranging from 0.49 to -0.49 was extended with slightly wet from 0.5 to 0.99, and slightly dry from -0.5 to -0.99, as shown in Table 1. These four methods have similar classifications of dryness or wetness, as expressed with a range of numerical values, and are therefore suitable for comparison.

2.5. Threshold level method

The threshold level method is also known as the dry season method. It differs from the preceding methods by the approach to the drought problem, in which it differentiates between the duration of drought (T), severity of drought (S), and intensity of drought (I) [10]. In this paper, it was applied to the quantities of rainfall, although it can also be applied to flow rates and water levels. The duration of drought, or deficit, is the continuous duration or step of a series of months in which the analysed parameter (precipitation, discharge , or water level) is smaller than the mean monthly precipitation in the period under study, which is in this case the mean monthly precipitation in the area. The severity of deficit is the sum of deficits within a step (2), and the intensity is obtained by dividing severity with duration (3).

$$S = \sum_{i=1}^{\tau} x_i - \bar{x} \tag{2}$$

$$I = \frac{S}{T} \sum_{i=1}^{\tau} x_i - \bar{x} \tag{3}$$

where:
x - monthly precipitation, flow rate or water level (mm, m^3/s, cm),
$\bar{x}$ - mean value of analysed parameter for a given period (mm, m^3/s, cm).

In the threshold level method, the most prominent connection is that between severity and duration, the connection between severity and intensity is weaker, while the connection between duration and intensity is statistically completely irrelevant [18, 24, 25].

3. Drought in continental part of Republic of Croatia

The mentioned methods were applied for the monthly precipitation data from 1981 to 2011 in fifteen weather stations in continental Croatia that belong to the regular network of the Meteorological and Hydrological Service: Karlovac, Zagreb, Varaždin, Sisak, Križevci, Čazma, Bjelovar, Đurđevac, Daruvar, Slavonski Brod, Našice, Donji Miholjac, Osijek, Gradište and Vinkovci (from west toward the east). In addition to precipitation, the analysis also focused on annual air temperature at these stations in the same period. The data on monthly precipitation and air temperatures that were not available in war years on some stations (Sisak, Osijek, Vinkovci, Našice, Čazma) were interpolated using the method called IDW (Inverse Distance Weighting) by means of the QGIS computer program. In each of these five incomplete series of the precipitation and air temperature data, the number of interpolated data was £ 6 (<2 %). Those weather stations, also situated in this part of Croatia, where a considerable number of monthly precipitation and air temperature values was missing (Požega, N. Gradiška, Krapina, Vukovar and Ilok), were not taken into account.
Mean annual precipitations, presented in Table 2, show the territorial distribution of annual precipitation in this period, with values decreasing from west toward the east, although the decreasing trend was not registered at some stations based on the sum of annual precipitation values. In the west part of continental Croatia, a decrease in annual precipitation can be observed in the majority of ~~tows~~ towns, mostly in Varaždin, -19.7 mm/10 years, while the eastern part of the area exhibits an evident increase in the mean annual precipitation over the studied period, and this mostly at the easternmost analysed station, Vinkovci, 41.6 mm/10 years [27].
At the same time, an increase in the mean annual air temperature was registered at all stations in the period from 1981 to 2011. The increase in the mean air temperature also influences the increase in the potential and real evapotranspiration and their also positive trend, as was proven by the analysis of a much greater number of weather stations on the entire territory of Croatia [28]. The greatest increase in air temperature was registered in the zone of Zagreb

Table 2. Mean annual precipitation [mm] and mean annual air temperatures [°C] in the period from 1981 to 2011

Town/weather station (abbreviation)	Northern latitude	PRECIPITATION		AIR TEMPERATURE	
		Mean annual precipitation [mm]	Trend [°C/10 year]	Mean annual air temperature [°C]	Trend [°C/10 year]
Karlovac (KA)	15°34'	1056.8	28.1	11.1	0.094
Zagreb-Maksimir (ZG)	16°02'	834.5	-11.6	11.2	0.65
Varaždin (VŽ)	16°20'	820.7	-19.7	10.6	0.51
Sisak (SI)	16°22'	908.5	33.5	11.4	0.52
Križevci (KR)	16°33'	778.9	-17.4	10.4	0.62
Čazma (ČA)	16°38'	826.4	24.2	11.1	0.46
Bjelovar (BJ)	16°51'	781.8	-0.2	11.2	0.62
Đurđevac (ĐU)	17°04'	817.0	-2.3	10.6	0.47
Daruvar (DA)	17°14'	890.5	7.7	11.1	0.18
Slavonski Brod (SB)	17°23'	756.1	20.0	11.1	0.52
Našice (NA)	18°06'	807.9	20.1	11.1	0.31
Donji Miholjac (DM)	18°10'	713.2	28.4	11.4	0.36
Osijek (OS)	18°34'	664.8	24.0	11.3	0.38
Gradište (GR)	18°42'	676.2	30.9	11.6	0.52
Vinkovci (VK)	18°49'	661.9	41.6	11.5	0.35

(Maksimir) where it amounts to 0.65 °C/10 years. Table 2 shows geographical and meteorological characteristics for the analyzed stations, which belong to the regular network of the Meteorological and Hydrological Service.

The data about the sum of annual precipitations, and especially the data on mean air temperatures for the studied period, point to the presence of drought indicators, and show that the analysis of drought is justified.

Figure 1 shows the time distribution of the mean annual precipitation and air temperature data for the period under study. To get a better insight into the variability of precipitation over time and space, the analysed period was divided into three sub-periods (decades), from 1981 to 1990, from 1991 to 2000, and from 2001 to 2011.

This phenomenon will be analysed in more detail using various drought evaluation methods.

Figures 2.a, 2.b, 2.c, and 2.d show relative frequencies of dry months for each decade and for all above-mentioned places in continental Croatia according to the standardised precipitation index (SPI), deciles index (DI), percent of normal precipitation (PN), and rainfall anomaly index (RAI) for each of the sub-periods. First three methods feature classification into seven typical wetness conditions, while the percent of normal (PN) method features classification into five typical wetness conditions. To facilitate comparison, all values that are equal to or greater than 110 % of average precipitation are categorized as a wet period (Table 1). In figure 2a, based on standardised precipitation index, each sub-period has the greatest frequency of months with an average moisture, and with relative frequency of 0.72. (1981-1990), 0.68 (1991.-2000.) and 0.51 (2001-2011) Extremely wet months were registered relatively rarely, mostly in the third decade, just like the extremely dry months with greatest frequency of 0.032, also in the third decade. Thus, the period from 2000 to 2011 is characterized by the extremely dry and extremely wet months. Moderately dry months were most often registered in the second and third decades.

According to the deciles index (Figure 2.b), the frequency of average months is the greatest in each sub-period and amounts to 0.41 (1981-1990), 0.45 (1991-2000) and 0.36 (2001-2011). The frequency of wet months is almost negligible, but the frequency of drought is notable at all levels, especially with regard to moderately dry and very dry months. Extremely dry months with the frequency of 0.17 can be noted in the third sub-period from 2000 to 2011.

Unlike preceding methods, the percent of normal precipitation method (PN), shown in Figure 2c, exhibits the greatest frequency of wet months, especially in the period from 2001 to 2011, and amounts to as much as 0.43 and, hence, it greatly deviates from results obtained by other methods. Moderately wet months have a relative frequency varying from 0.20 to 0.23. Extremely dry months mostly occur in the sub-period from 2000 to 2011, just like in the standardised precipitation index.

According to the rainfall anomaly index (RAI), the relative frequency of average months is the greatest, and varies from 0.36 to 0.39 in all sub-periods. The frequency of wet months varies from 0.42 to 0.43, and the frequency of dry months is 0.39. None of the sub-periods stands out by its either dryness or wetness (figure 2d). According to this method, monthly precipitations of all analysed locations in continental Croatia have the almost normal distribution throughout the period under study.

According to its approach to the problem, the threshold level method differs from previously described methods, and it does not have a descriptive classification for the levels of dry or wet periods. Figure 3 shows frequency of droughts according to their durations for all sub-periods. The greatest frequency was registered for short droughts,

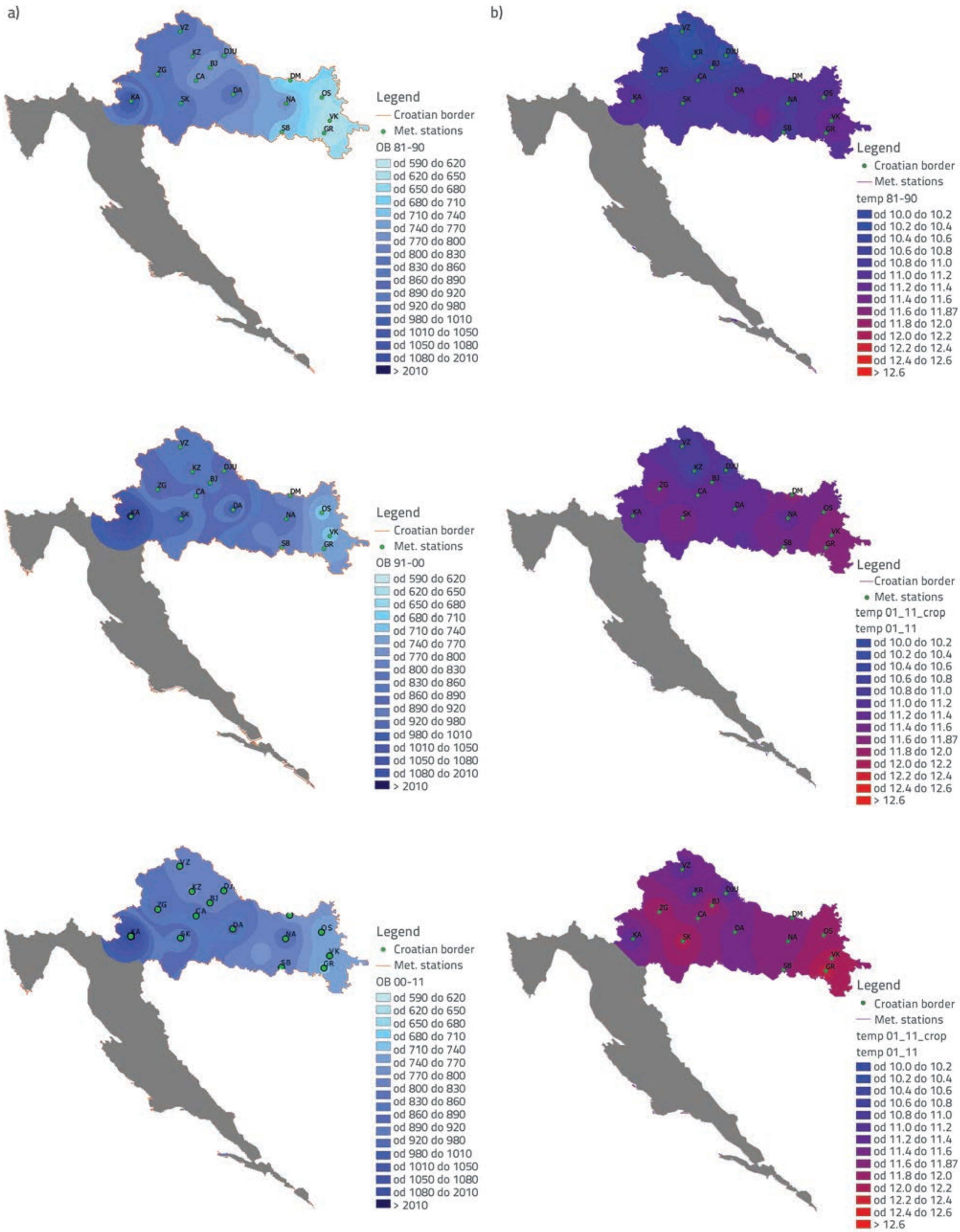


Figure 1. Territorial distribution of the sum of annual precipitation and mean annual air temperature values for three sub-periods, from 1981 to 1990, from 1991 to 2000, and from 2001 to 2011

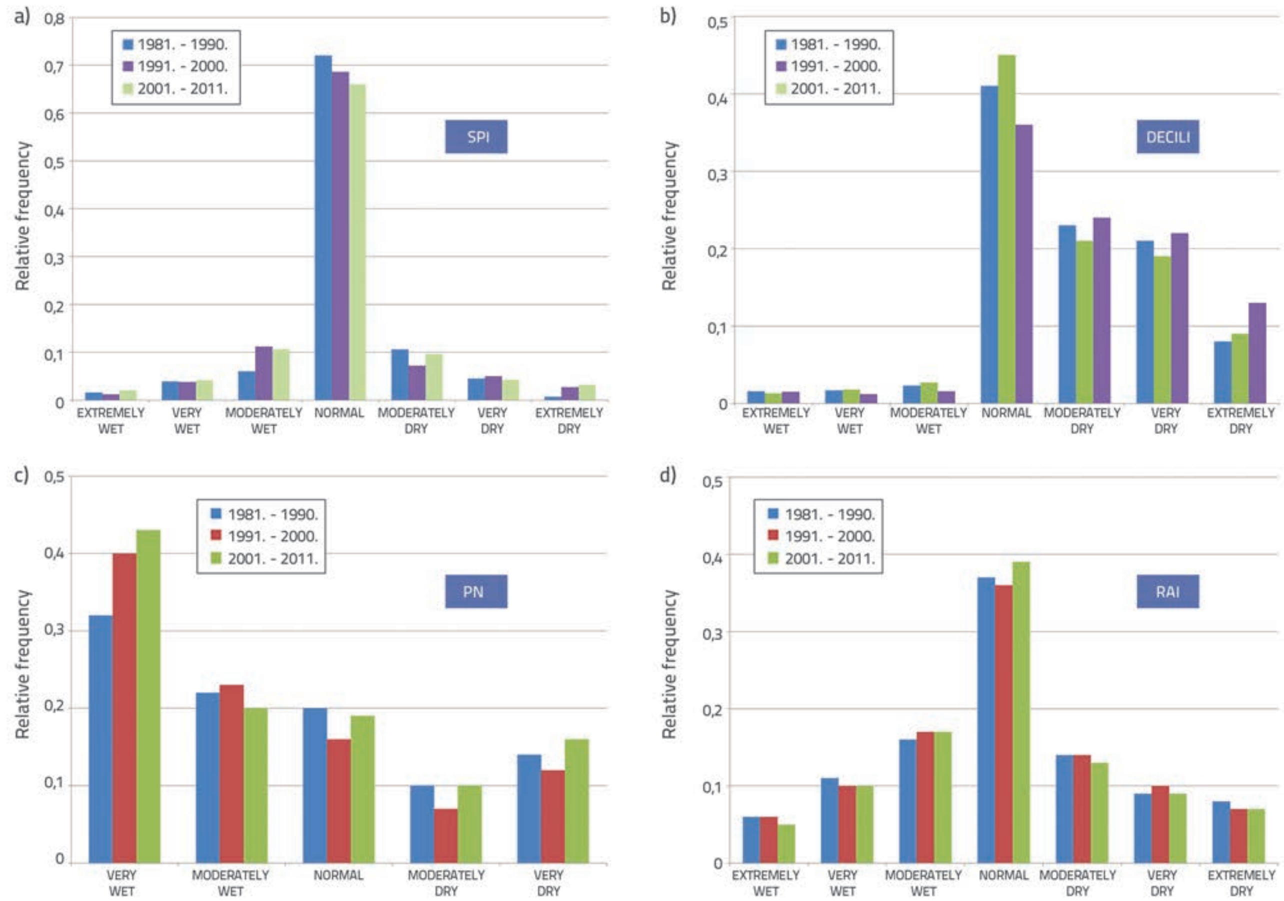


Figure 2. Relative frequency of wet and dry years according to a) SPI, b) Deciles c) PN and d) RAI for each sub-period (1981-1990,1991-2000 i 2001-2011)

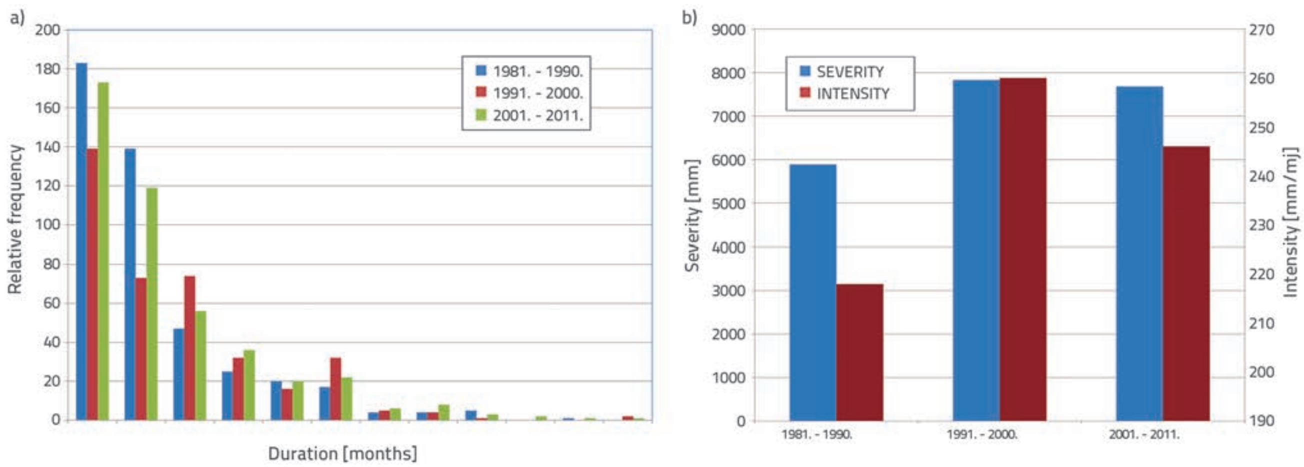


Figure 3. Drought evaluation according to threshold level method for each sub-period (1981-1990., 1991-2000. and 2001-2011.) a) duration, b) severity and intensity

lasting one and two months, and this in the first and third decades. The droughts lasting 3, 6, and 7 months were more frequent in the second and third decades. According to the severity of droughts, the second and third decades were dryer, while no decade stands out by the intensity of droughts (Figure 3.b). Although the frequency of droughts lasting longer than six months is very low, it is not negligible because of great damage such long-lasting droughts are likely to cause. For instance, in the area of Donji Miholjac and Gradište, the drought lasted throughout the year 2000, and in Bjelovar area throughout the year of 2011. No drought stands out by its intensity in any of the decades under study. The drought is quantified in Figures 2 and 3 using various methods, based on monthly precipitation data, in the studied period divided into three decades, and also generally for all precipitation data regardless in which of the fifteen analysed stations they were registered. The frequency of dry months by decades was quantified quite differently by each of these methods, which is why the territorial distribution of drought parameters was analysed via these methods in order to facilitate evaluation of the frequency of drought in terms of space. The decade approach was selected as the influence of drought on water balance, climate changes, and environment, can not be registered in shorter periods of time (one year for instance).

4. Comparison of methods

The analysed methods were compared for all months in the period under study, and for fifteen weather stations.
To illustrate the methods used in drought evaluation, Figures 4.a and 4.b show results for two weather stations, the westernmost one (Karlovac) and the easternmost one (Vinkovci), for the entire period under study, i.e. from January 1981 to December 2011. Correlation coefficients for individual method pairs are shown in Table 3. A considerable correlation is exhibited between the standardised precipitation index method and other analysed methods (from 0.68 to 0.82), which is followed by the rainfall anomaly index and percent of normal precipitation (r = 0.72). There is no correlation between the deciles index and percent of normal precipitation, while the correlation between the rainfall anomaly index and deciles (r = 0.35) is regarded as weak.
A graphical presentation of the correlation between the standardised precipitation index and deciles index, rainfall anomaly index and percent of normal precipitation, is given in Figure 5. It can be seen that the correlation is more pronounced in case of normal humidity conditions and droughts of lower intensity, when compared to drought of extreme proportions.

Table 3. Correlation coefficients (r) for analysed methods

	SPI	DI	RAI	PN
SPI	1	0.77	0.68	0.82
DI		1	0.35	0.06
RAI			1	0.72
PN				1

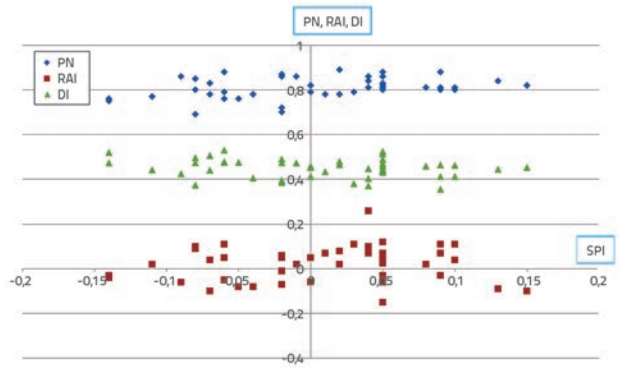


Figure 5. Relationship between SPI and other methods under study (PN, RAI and DI)

The results show that the standardised precipitation index is adequate, but that other methods are also adequate for use in

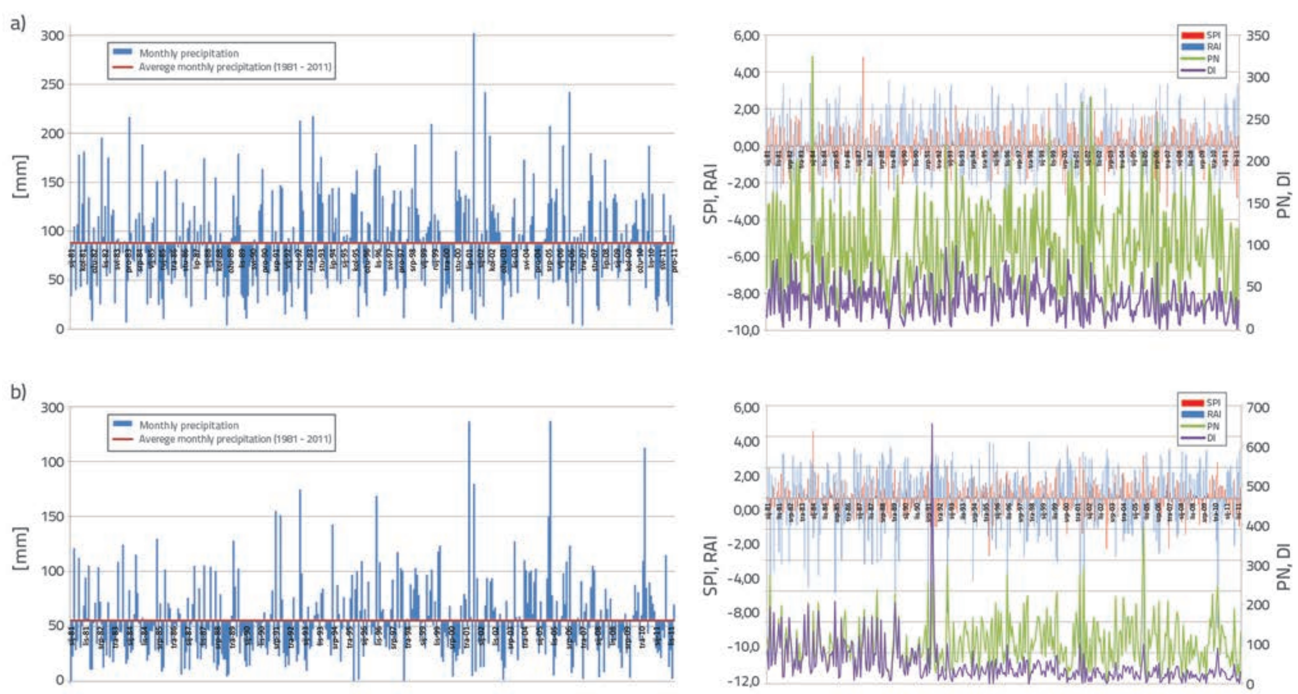


Figure 4. Drought evaluation according to all analysed methods in the period from January 1981 to December 2011: a) Karlovac, b) Vinkovci

continental Croatia. The standardised precipitation index has a very poor correlation with the duration of drought (r=0.14), drought intensity (r=0.05), and drought severity (r=0.024), according to the threshold level method (Figure 6).

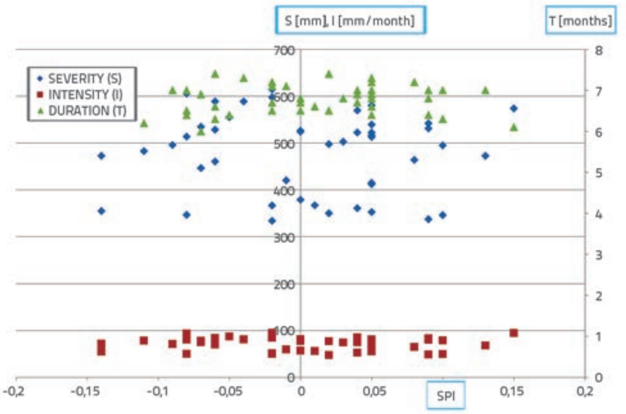


Figure 6. Relationship between SPI and duration, severity, and intensity of drought, according to threshold level method

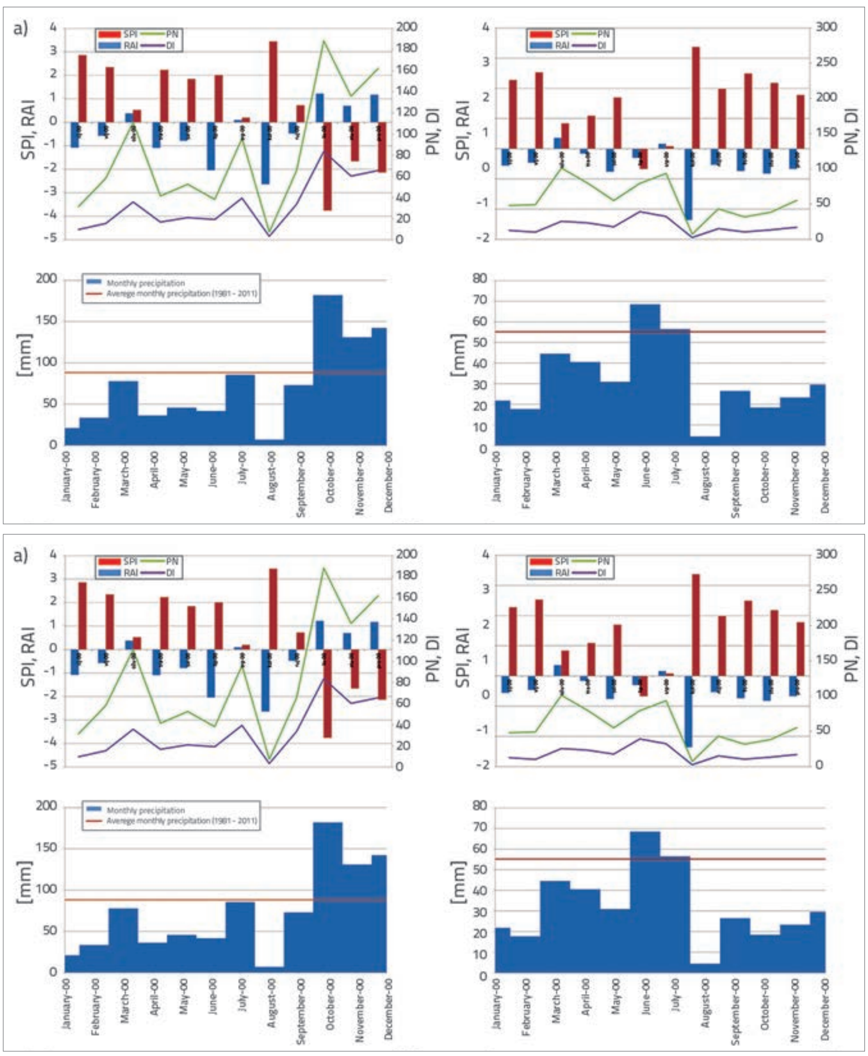


Figure 7. Drought analysis according to all analysed methods for driest years: a) Karlovac and Vinkovci (January – December, 2000), b) Karlovac and Vinkovci (January – December, 2011)

Table 4. Correlation coefficient (r) for severity (S), duration (T), and intensity (I) of drought according to threshold level method

	S	T	I
S	1	0.07	**0.96**
T		1	0.47
I			1

As earlier indicated, the threshold level method is formed of the duration, intensity, and severity of drought. The correlations within this categorisation of drought are shown in Table 4. The most pronounced relationship is the one between severity and intensity, while a weaker, but still significant, is the relationship between duration and intensity. The relationship between severity and duration is practically inexistent. These results are not in harmony with the published results where a strong link between severity and duration is usually emphasized. The explanation would be in the presence of less severe droughts of longer duration.

The methods under study are also not consistent in the quantification of driest years in the analysed period from 1981 to 2011. However, the years of 2000 and 2011 stand out: they can be considered as years with pronounced drought, according to most methods. The cases of weather stations Karlovac and Vinkovci are once again taken as an illustration, while drought evaluations according to all analysed methods are presented by months for 2000 and 2011 (Figures 7.a and 7.b). In 2000, the drought in Karlovac lasted nine months, while in Vinkovci it lasted 10 months, and its severity was higher. In 2011, the drought lasted eight months in Karlovac, while it lasted ten months in Vinkovci, but with lower severity. The methods SPI, deciles, and percent of normal precipitation, also show a more pronounced dry periods in Vinkovci in 2000, and in Karlovac in 2011. According to RAI, the drought was not so pronounced at these two weather stations in 2000 and 2011, except in some months.

A spatial distribution of the driest month in 2000, August, is given in Figure 8, according to various methods.

According to the standardised precipitation index (SPI), the drought that spread over the entire continental Croatia was very intensive to moderate (Figure 8a). According to the rainfall anomaly index (RAI), the month of August 2000

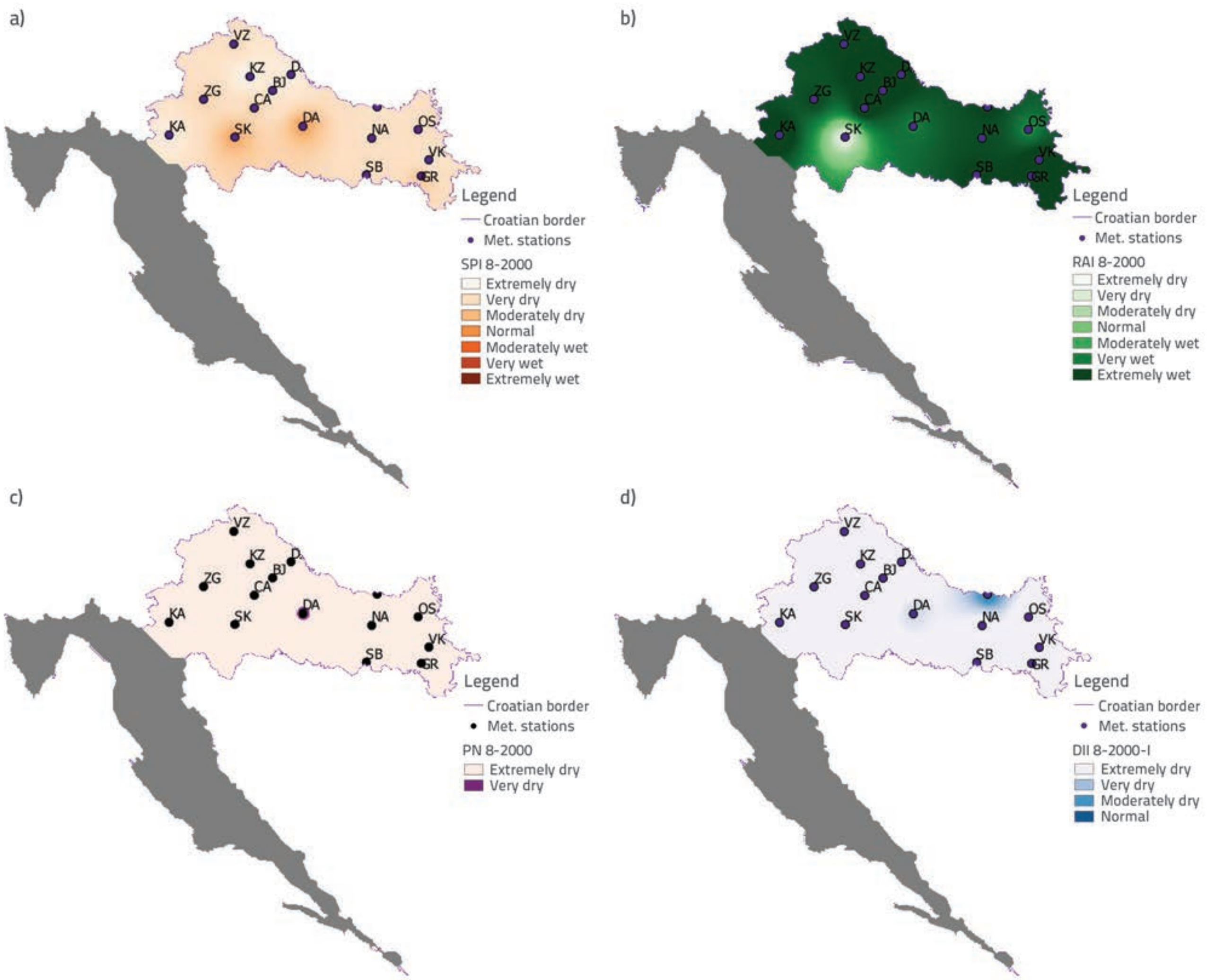


Figure 8. Spatial distribution of drought in continental Croatia, in August 2000: a) SPI; b) RAI; c) PN; d) DI

was normally to moderately wet, except around Sisak (Figure 8.b). According to the percent of normal precipitation (PN) and deciles method (DI), the drought was extreme (Figure 8.c, Figure 8.d). In 2011, the driest month was the month of November, with the intensity very similar to that registered in August 2000. According to the analysed drought-assessment methods, the driest years for all weather stations in continental Croatia are presented in Figure 9. According to all methods, the years of 2000 and 2011 were estimated as driest for most weather stations in the area under study, and these years are followed by 2003.

In 2000, the annual quantity of precipitation varied from 317 mm in Osijek to 748 mm in Sisak, and in 2011, the annual quantity of precipitation varied from 388 mm in Bjelovar to 742 mm in Karlovac.

In the period from 1981 to 2011, fourteen years can be categorised as dry years according to the analysed methods. This, however, does not mean that shorter drought periods did not occur in other years. In 2000 and 2011, the most intense droughts were registered at most weather stations. In

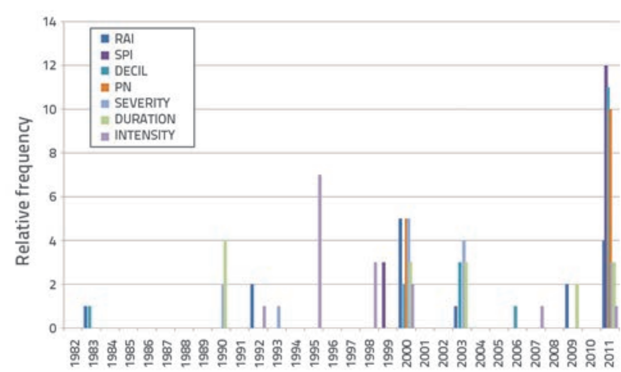


Figure 9. Frequency of driest years according to individual methods

2000, pronounced droughts were registered in eastern parts of continental Croatia (Našice, Osijek, Slavonski Brod, Donji Miholjac, Vinkovci, Gradište), while in 2011 droughts were more intense in western parts of the region (Bjelovar, Čazma, Daruvar, Karlovac, Križevci, Sisak, Đurđevac, Varaždin, Zagreb). Nonetheless, it can be said that during these two years the drought spread over the entire continental Croatia, with extreme to moderate intensity, and that the duration of these droughts ranged from 8 to 12 months, depending on location, but also on the method according to which the drought was evaluated (Figures 7.a and 7.b).

5. Conclusion

The precipitation data registered at fifteen weather stations in continental Croatia in the period from 1981 to 2011, and used in the drought evaluation analysis, confirmed the complexity of the drought phenomenon, and the difference between methods used in the quantification of this phenomenon. The standardised precipitation index, deciles index, percent of normal precipitation, rainfall anomaly index, and threshold level method, are single-parameter methods that are widely used worldwide at locations presenting various geographical and climatological characteristics. The comparison of these methods revealed that each one can actually be applied, which points to a significant correlation coefficient between the standardised precipitation index and deciles index, percent of normal precipitation, and rainfall anomaly index, while the correlation between the standardised precipitation index and severity, duration and intensity of drought according to the threshold level method is very weak. In addition, the link between the severity and duration of drought was not confirmed. The drought analysis by periods (1981-1990, 1991-2000, and 2001-2011) shows that the driest period is from 1981 to 1991 according to the standardised precipitation index and percent of normal precipitation. However according to severity and duration of drought it is the period from 2001 to 2011, while other methods do not present notable differences in the quantification of drought by individual sub-periods. Furthermore, according to most methods, the driest years are the years 2000 and 2011 and, according to territorial distribution of drought intensity, the eastern part of continental Croatia was more severely struck in 2000, and the western part in 2011, but it can not be said that in these years the varying intensity drought spread all over continental Croatia.

Droughts are an extreme and complex hydrological event which, due to its negative effects on the environment and economy, agriculture in particular, has been increasingly in the focus of attention of researchers. The water resource management is becoming more and more complex because of the growing demand for water in agricultural land irrigation, because of the need to ensure environmentally acceptable water discharge, and sufficient quantity of water for safe water supply, but also because of the growing deterioration of water quality during low- water level periods. At this time, it would be impossible to single out any of the methods as being absolutely reliable but, according to results obtained in the paper, a group of methods applicable for a specific region, in our case it is continental Croatia, could be recommended. These methods are the standardised precipitation index, deciles index, rainfall anomaly index, and percent of normal precipitation.

REFERENCES

[1] Piccarreta, M., Capolongo, D., Boenzi, F.: Trend Analysis of Precipitation and Drought in Basilicata from 1923-2000 within Southern Italy Context, *International Journal of Climatology* 24, pp. 907-922, 2004., doi: http://dx.doi.org/10.1002/joc.1038

[2] Mishra, A.K., Singh, V.P.: A review of drought concept, *Journal of Hydrology 391,* pp. 202-216, 2010., doi: http://dx.doi.org/10.1016/j.jhydrol.2010.07.012

[3] Wanders, N., van Lannen, H.A.J, van Loon, A.F.: Indicators for Drought Characterization on a Global Scale, *Technical Report No.24,* 2010.

[4] Morid, S., Smakhtin, V., Moghaddasi, M.: Comparison of Seven Meteorological Indices for Drought Monitoring in Iran, *International Journal of Climatology,* 26, pp. 971-985, 2006., doi: http://dx.doi.org/10.1002/joc.1264

[5] Byun, H.R, Wilhite, D.A.: Objective Quantification of Drought, *Journal of Climate*, 9, 12, pp. 2747-2756, 1999., doi: http://dx.doi.org/10.1175/1520-0442(1999)012<2747:OQODSA>2.0.CO;2

[6] Palmer, W.C.: Meteorological Drought, *Research Paper No.45*, US Department of Commerce Weather Bureau, Washington DC, 1965.

[7] McKee, T.B., Doeskin, N.J., Kleist J.: Drought Monitoring with Multiple Time Scales, *Conference of Applied Climatology*, American Meteorological Society, Boston, pp. 179-184, 1995.

[8] Gibbs, W.J., Maher, J.V.: Rainfall deciles as drought indicators, *Bureau of Meteorology Bulletin*, 48, Melbourne, 1967.

[9] Wu, H., Hayes, M.J., Weiss, A., Hu, Q.: An Evaluation of the Standard Precipitation Index, the China-Z index and the Statistical Z-score, *International Journal of Climatology*, 6, 21, pp. 745-758, 2001., doi: http://dx.doi.org/10.1002/joc.658

[10] Yevjevich, V.: An Objective Approach to Definitions and Investigations of Continental Hydrology Drought, Hydrology Paper No.23, Colorado State University., Fort Collins, 1967

[11] van Rooy, M.P.: A Rainfall Anomaly Index Independent of Time and Space, *Notos* 14, pp. 43-48, 1965.

[12] Alatise, M.O., Ikumawoyi, O.B.: Evaluation of Drought from Rainfall Data for Lakoja. A Confluence of two Major Rivers, *Electronic Journal of Polish Agricultural Universities*, 10 (1), 2007.

[13] Oladipo, E.O.: A Comparative Performance Analysis of Three Meteorological Drought Indices, *Journal of Climatology* 6, 5, pp. 655-664, 1985., doi: http://dx.doi.org/10.1002/joc.3370050607

[14] Keyantash, J.: The Quantification of Drought: An Evaluation of Drought Indices, *Bull.Amer.Meteor.Society* 83 (8), pp. 1167-1180, 2002., doi: http://dx.doi.org/10.1175/1520-0477(2002)083<1191:TQODAE>2.3.CO;2

[15] Heim, R.R.: A Review of Twentieth-Century Drought Indices Used in the United States, *Bullettin of American Meteorological Society,* 83 (8), pp. 1149-1165, 2002. doi: http://dx.doi.org/10.1175/1520-0477(2002)083<1149:AROTDI>2.3.CO;2

[16] Byun, H.R., Kim, D.W.: Comparing the Effective Drought Index and Standard Precipitation Index, *CIHEM,* pp. 85-89, 2010.

[17] Kim, D.W., Byun, H.R., Choi, K.S.: Evaluation, Modification and Application of Effective Drought Index to 200 Year Drought Climatology of Seoul, Korea, *Journal of Hydrology*, 378 (1-2), pp. 1-12, 2009., doi: http://dx.doi.org/10.1016/j.jhydrol.2009.08.021

[18] Bonacci, O.: Hydrological Identification of Drought, *Hydrological Processes*, 7 (3), pp. 249-262, 1993., doi: http://dx.doi.org/10.1002/hyp.3360070303

[19] Cindrić, K., Kalin, L: Analiza mogućnosti i prognoze suše na području Hrvatske, *Hrvatske vode* 79/80, 20, pp. 43-50, 2012.

[20] Mihajlović, D.: Monitoring the 2003-2004 Meteorological Drought over Pannonian part of Croatia, *International Journal of Climatology*, 26, pp. 2213-2225, 2006., doi: http://dx.doi.org/10.1002/joc.1366

[21] Ljubenkov, I., Bonacci, O.: Utvrđivanje i određivanje suše na otoku Korčuli, *Hrvatske vode* 77, 19, pp. 181-194, 2011.

[22] Smakhtin, V.U., Hughes, D.A.: Review, Automated Estimation and Analyses of Drought Indices in South Asia, Working Paper 83, *Drought Series Paper* 1, 2004.

[23] http://drought.unl.edu/MonitoringTools/DownloadableSPIProgram.aspx

[24] Ali M.G., Younes, K. Esmaeil, A, Fotemech, T.: Assessment of Geostatistical Methods for Spatial Analysis of SPI and EDI Drought Indices, World Applied Sciences Journal 15 (4), pp. 474-482, 2011

[25] Bonacci, O.: *Ekohidrologija vodnih resursa i otvorenih vodotoka*, GAF Split, 2003.

[26] Tallaksen, L.M., van Lanen, H.A.J.: Hydrological Drought Processses and Estimation Methods for Streamflow and Groundwater, Elsevier, 2004

[27] Bosak, M.: Analiza suše i potrebitost navodnjavanja kontinentalnog dijela Hrvatske, diplomski rad, Građevinski fakultet Osijek, 2013.

[28] Pandžić, K., Trninić, D., Likso, T., Bošnjak, T.: Long-term variations in water balance components for Croatia, *Theorethical and Applied Climatology*, (0177.798X)95, pp. 39-51, 2009.