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DROUGHT ANALYSIS USING THE STANDARDIZED PRECIPITATION INDEX (SPI)

ANALIZA SUŠNIH RAZMER S POMOČJO STANDARDIZIRANEGA PADAVINSKEGA INDEKSA (SPI)

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Effects of drought on agricultural land.
Posledice suše na kmetijskih površinah.

Drought Analysis Using the Standardized Precipitation Index (SPI)

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ABSTRACT: Drought indices are commonly used for detection, monitoring and evaluation of drought events. One of the most commonly used drought indices is the Standardized Precipitation Index (SPI). This paper presents the effect of theoretical distribution selection on SPI values, and the analysis of drought events for five selected meteorological stations in Slovenia. We found that the SPI on the annual time scale shows a similar pattern of occurrence of dry and wet periods at Ljubljana-Bežigrad, Novo mesto, and Trieste meteorological stations; something similar can be said for the Celje and Maribor-Tabor stations. The analysis of the correlations between the standardized data river discharge and precipitation data for the selected river basin of the River Pesnica shows the strongest correlation between the SPI-2 and standardized discharges.

KEY WORDS: geography, drought, precipitation, probability analysis, Standardized Precipitation Index (SPI), standardized river discharge data, the River Pesnica, Slovenia

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1 Introduction

Drought results from a combination of meteorological, physical, and human factors (Natek 1983; Sustainable Water Use 2001; Sušnik 2006). Drought events, in comparison with other natural disasters, differ in several aspects (Wilhite 2003; Wilhite and Buchanan-Smith 2005):

- There is no accurate, universal and objective definition of drought. Consequently, this leads to doubts about whether or not drought conditions are present in a given period, and if it is established that they are present, what is their intensity. This leads to indecision and lack of action from the competent authorities.
- It is difficult to determine when a drought event began and when it ended. Usually, its consequences accumulate slowly throughout a long period of time, and can remain present in an area for several years.
- Drought impacts do not have a one-off effect and are spread over a large geographical area. These characteristics of drought have hindered the development of accurate, reliable, and timely estimates of severity and impacts and, ultimately, the formation of drought preparedness plans.
- Problems in the quantification of drought impacts and providing disaster relief. Drought must be considered a relative, rather than an absolute condition, since it reflects a deviation from the long-term average over a long period of time.

Drought events differ in the following aspects: intensity, duration, and spatial coverage (Wilhite 2003; Wilhite and Buchanan-Smith 2005). The intensity of a drought event refers to the degree of precipitation deficit and/or the severity of impacts. The spatial extent and impact of a drought event depend mostly on the time of the onset of precipitation deficit, its intensity, and duration. The impacts and consequences of drought can be direct and indirect. For example, loss of crops due to drought is a direct impact. The consequences of this impact (i.e. loss of crops) include loss of income, damage claims from farmers; these are indirect impacts, i.e. secondary or tertiary impacts. The impacts of drought can be economic (energy industry, tourism industry, fishery production, water supplies), environmental (loss of biodiversity, degradation of environment, erosion of soils, water quality and quantity effects) and social (food shortages, increased groundwater depletion, loss of natural and cultural heritage, decreased quality of life; Wilhite 2003).

In order to implement adequate and timely measures, it is necessary to know the characteristics of drought and how it affects the different levels of society and its functioning. Today, drought indices are indispensable tools to detect, monitor and evaluate drought events (Niemeyer 2008). One of the most commonly used indices is the Standardized Precipitation Index (SPI) (Guttman 1999), distinguished by simplicity and temporal flexibility, due to which the index can be used over different time scales.

The purpose of this paper is to identify drought conditions, i.e. to analyse and compare drought periods using the SPI for the five selected sites, and try to describe hydrological drought events in the selected river basin using standardized monthly river discharge data and the SPI.

2 Methods

2.1 Data

The only input data for calculating the SPI are monthly precipitation data. We selected four meteorological stations in Slovenia (Ljubljana-Bežigrad, Maribor-Tabor, Celje, and Novo mesto) and one station in Italy (Trieste), which are evenly spaced and for which long-term data series are available (ARSO 2011a; UL FGG 2012) (Table 1).

Table 1: Features of the selected meteorological stations (ARSO 2009).

Meteorological station	Elevation (AMSL)	Latitude	Longitude	Considered period
Ljubljana-Bežigrad	299	46° 04'	14° 31'	1853–2010
Maribor-Tabor	275	46° 32'	14° 39'	1876–2010
Celje	240	46° 15'	15° 15'	1853–2010
Novo mesto	220	45° 48'	15° 11'	1951–2010
Trieste	32	45° 38'	13° 45'	1851–2004

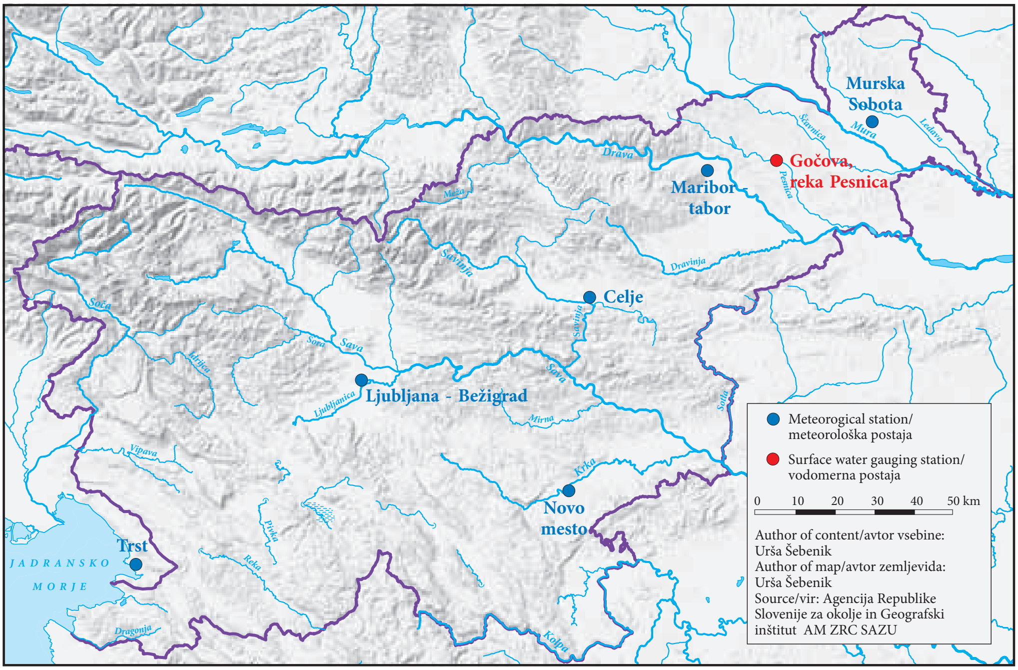


Figure 1: Locations of the selected meteorological stations and the Gočova gauging station located on the River Pesnica.

SPI values were calculated for six different time scales: one-month (SPI-1), two-month (SPI-2), three-month (SPI-3), six-month (SPI-6), nine-month (SPI-9), and twelve-month, i.e. annual, (SPI-12) time scales for the entire observation period of the selected meteorological stations as well as for the cross-sectional period (1951–2004).

We chose the River Pesnica with a rain-snow regime for the comparison between the SPI and river discharges. The Maribor-Tabor station was used for SPI calculation. The comparison was made using mean monthly river discharge data from the Gočova gauging station for the longest available period (1970–2009) (ARSO 2011b).

2.2 Standardized Precipitation Index (SPI)

SPI was developed by McKee et al. (1993) as a relatively simple index to be used for determining precipitation deficit or excess. Through SPI, we can also determine the frequency of extremely dry or wet events for a certain time scale for any location where precipitation data series are available (Gregorič and Ceglar 2007). The standardized nature of the index allows us to obtain comparable data on drought frequency for any location (Guttman 1999).

The first step in calculating the SPI index is to determine the probability density function for selected precipitation series. The distribution most commonly used in calculating the SPI is the gamma distribution (McKee et al. 1993; Hayes et al. 1999; Guttman 1999; Hayes 2000; Lloyd-Hughes and Saunders 2002; Ceglar and Kajfež-Bogataj 2008). Guttman 1999, Vicente-Serrano and Lopez-Moreno (2005) as well as Blain (2011) used Pearson III distribution in their analysis. Guttman (1999) compared the SPI values calculated with different distributions and found that the gamma and Pearson III distributions fitted data the best. The distribution function of each monthly amount of precipitation for the given time scale is then computed. Distribution function is then normalized into a standard normal random variable Z, which represents the value of SPI index (Lloyd-Hughes and Saunders 2002); this quantifies the drought intensity (Table 2).

Table 2: Drought classification by SPI value and corresponding event probabilities (Lloyd-Hughes 2002, 67).

SPI value	Category	Probability (%)
2.00 or more	Extremely wet	2.3
1.50 to 1.99	Severely wet	4.4
1.00 to 1.49	Moderately wet	9.2
0.00 to 0.99	Mildly wet	34.1
0.00 to –0.99	Mildly drought	34.1
–1.00 to –1.49	Moderate drought	9.2
–1.50 to –1.99	Severe drought	4.4
–2 or less	Extreme drought	2.3

McKee et al. (1993) established the criteria for determining the beginning and the end of a drought event. A drought event begins when the SPI is continuously negative and reaches the value of –1 or less. The event ends when the SPI value becomes positive.

2.3 Standardized river discharge data

Water resources, such as watercourses, groundwater, snow cover, etc., are highly dependent on the amount of precipitation. The response of individual components of the hydrological cycle to the time period for which the SPI is calculated varies. In order to determine the relationship between precipitation and river discharges, we have to use a normal distribution to standardize mean monthly discharge data for each gauging station (Vicente-Serrano and Lopez-Moreno 2005; Gregorič and Ceglar 2007).

3 Results and analysis

3.1 Effects of probability distribution selection on SPI values

We calculated the index values for the Ljubljana-Bežigrad meteorological station using Gumbel distribution (G) and Pearson III distribution (P3) in addition to the two-parameter gamma distribution (G2). Results are compared using Pearson's correlation coefficient (Table 3).

Table3: Correlation coefficients between selected distributions, for SPI-1 to SPI-12 (Šebenik 2012).

	SPI–1 G	SPI–1 P3	SPI–2 G	SPI–2 P3	SPI–3 G	SPI–3 P3	SPI-6 G	SPI-6 P3	SPI-9 G	SPI-9 P3	SPI-12 G	SPI-12 P3
SPI-1 G2	0.992	0.987										
SPI-2 G2			0.997	0.997								
SPI-3 G2					0.994	0.988						
SPI-6 G2							0.986	0.9961				
SPI-9 G2									0.988	0.876		
SPI-12 G2											0.993	0.539

Unlike Pearson III distribution, Gumbel distribution closely correlates with the gamma distribution on all time scales. All correlation coefficients reached at least 0.98. Pearson III distribution has higher variability. It correlates better on longer time scales than on shorter ones (Table 3). All SPI calculations below referred to the gamma probability distribution.

3.2 SPI values for individual meteorological stations for the entire measurement period

Annual SPI values for the Ljubljana-Bežigrad meteorological station show (Figure 2) three severe drought events before 1900, i.e. in 1858, 1865, and 1877. Between 1900 and 1950, the SPI-12 shows four extreme drought events. The first extreme drought event was detected between 1920 and 1922, as confirmed also by archival drought records in Slovenia (Trontelj 1997). Drought events were followed by wet periods, but then again dry periods were detected in 1943, 1947, and 1949. Only shorter time scales show a slightly higher frequency of extreme drought in Ljubljana in the second half of the 20th century, which occur more frequently after 1990. The year 2003 definitely stands out after 2000 and is detected on all time scales. 2006 and 2007 are also identified as years with negative deviations, as was noted also by Sušnik and Gregorič (2008), and by Zorn and Komac (2011).

Data analysis for the Maribor-Tabor meteorological station (Table 1) shows that extreme SPI values appear only on shorter time scales (Šebenik 2012). Before 1900, the SPI-12 scale shows two severe drought events with the lowest value (–1.52) in 1877. In the first half of the 20th century, annual index values indicate three moderate drought events with the minimum value of the SPI-12 (–1.64) in December 1921. The total annual precipitation for the same year was only 725 mm, which is lower than the long-term average (i.e. 1032 mm) (Trontelj 1997). After 1950, drought events occurred more frequently and reached the highest frequency of occurrence in the last decade of observation (2000–2010). Annual index values for these years do not significantly exceed the limits specified for moderate drought, with the exception of December 1971 (–1.75) and December 2003 (–1.68). Index values for the year 2003 differ significantly less on shorter time scales. Since only short-period precipitation totals are taken into account in the calculation of SPI values at shorter time scales, such index values do not reflect past long-term drought conditions, which began already in 2000 and continued in 2001 and 2002, as confirmed also by Kobold (2003).

The annual time scale for the Celje meteorological station (Table 1) shows a long period of negative deviation between 1854 and 1859. A longer period of negative deviation repeated between 1861 and 1864 and also from 1865 to 1866, and from 1883 to 1885. Longer drought periods with constant negative index values occurred again during 1920–1922, in 1924, and 1925. Shorter negative deviations were followed by wet periods, which reached extreme index values in 1937 and 1938. Wet periods were again followed by two long drought periods lasting from 1941 to 1944, and from 1945 to 1948. The year 1946 stands out, when virtually all months of the year had negative index values. The exception after 2000 was the year 2003, when the SPI reached values indicative of severe drought.

The lowest values for the Novo mesto meteorological station (Table 1) on the annual time scale were within the limits of moderate or severe drought (Table 2). However, short periods of negative deviation occurred quite frequently (Šebenik 2012). Longer periods of precipitation deficit were more common in the last three decades. In 2007, negative deviation persisted throughout the year.

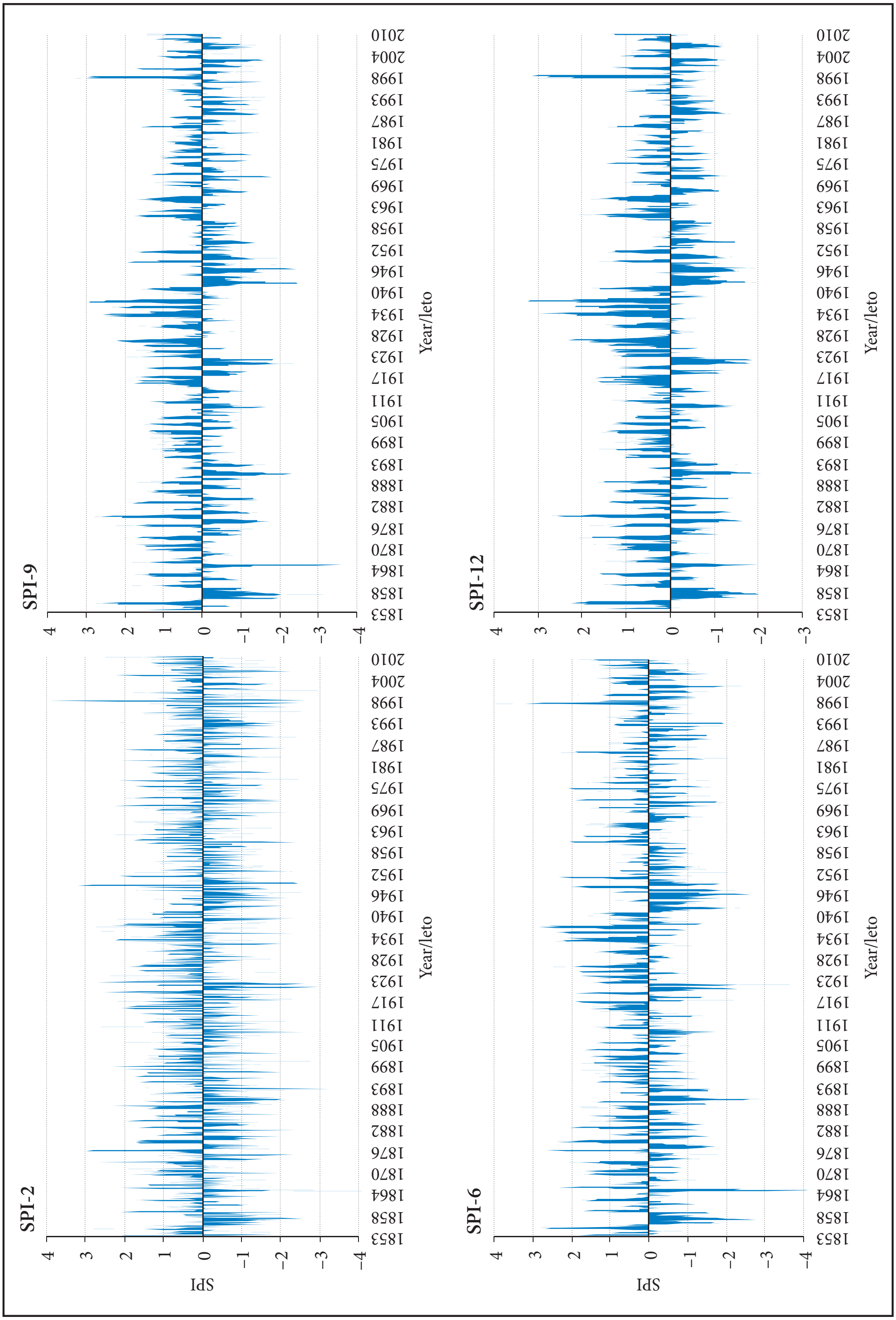
The calculations of the SPI-12 for the Trieste meteorological stations (Table 1) show that drought events were not particularly severe, since the lowest SPI value in the whole observation period is –1.01. Several long periods of negative deficits appear on the 12-month time scale before 1900, alternating with distinctively wet periods with extreme index values. It continued in a similar way in the 20th century, reaching the lowest index values in 1946. A similar pattern can also be observed in the second half of the 20th century. 2003 stands out from the last analyzed years, as it has extreme index values on all shorter time scales.

We can see that the year 2003 definitely stood out among all observed meteorological stations in the last observed decade. The 2003 extreme drought event in Europe caused EUR 8.7 billion in losses (Commission of the European Communities 2007). The substantial damage caused by drought relative to the total damage caused by natural disasters in 2003 in Slovenia, was as high as 83.3% (Zorn and Komac 2011).

3.3 SPI comparison between selected meteorological stations for the common period of measurement 1951–2004

SPI values for all selected meteorological stations and all time scales were also compared for the common measurement period. On longer time scales values for all stations have a similar distribution of major dry and wet periods (Figure 3). A major difference between stations occurred in 2002 when Trieste stood out with a distinctively wet year, while data for the other four stations already indicated extreme drought conditions, which later affected all the selected sites in 2003. If we examine the data for this period more

Figure 2: SPI-2, SPI-6, SPI-9 and SPI-12 for the Ljubljana-Bežigrad meteorological station for the 1853–2010 period (Šebenik 2012). ►


SPI-2
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SPI-12
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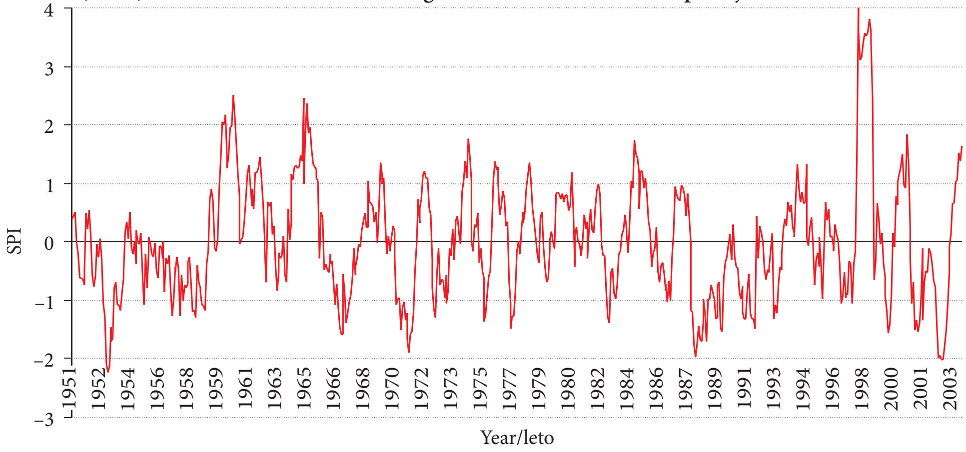
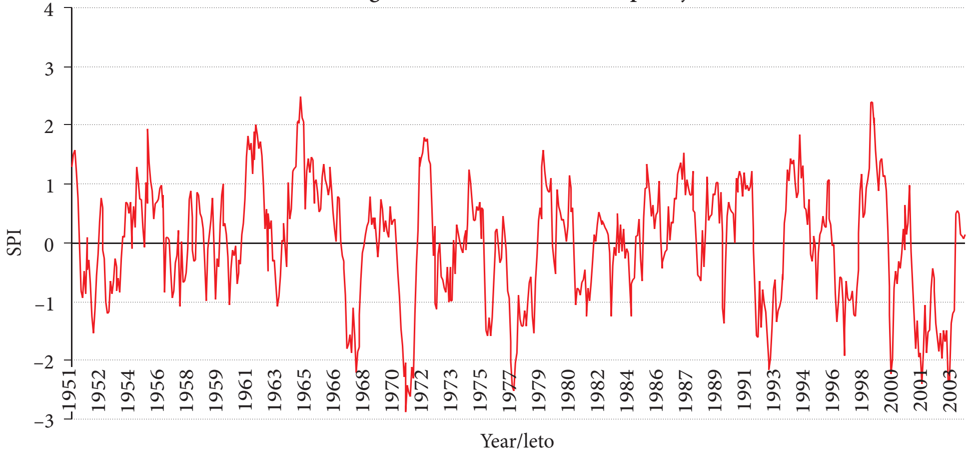
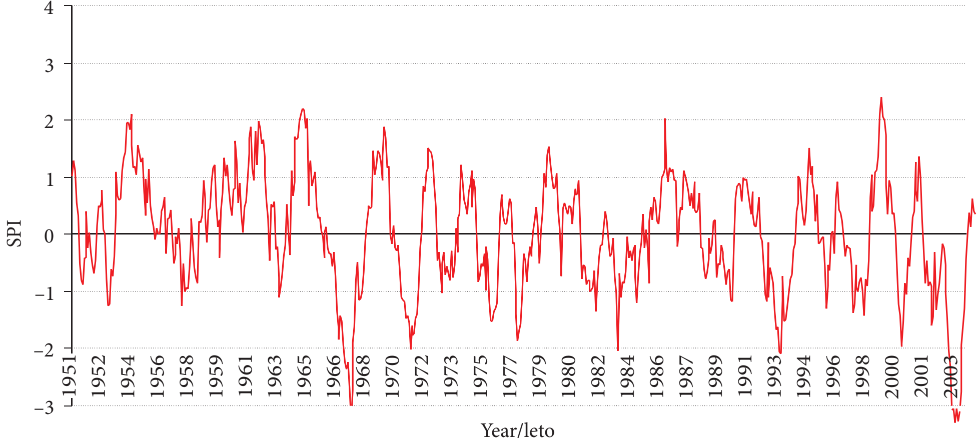


LJUBLJANA-BEŽIGRAD meteorological station/meteorološka postaja



MARIBOR-TABOR meteorological station/meteorološka postaja



CELJE meteorological station/meteorološka postaja

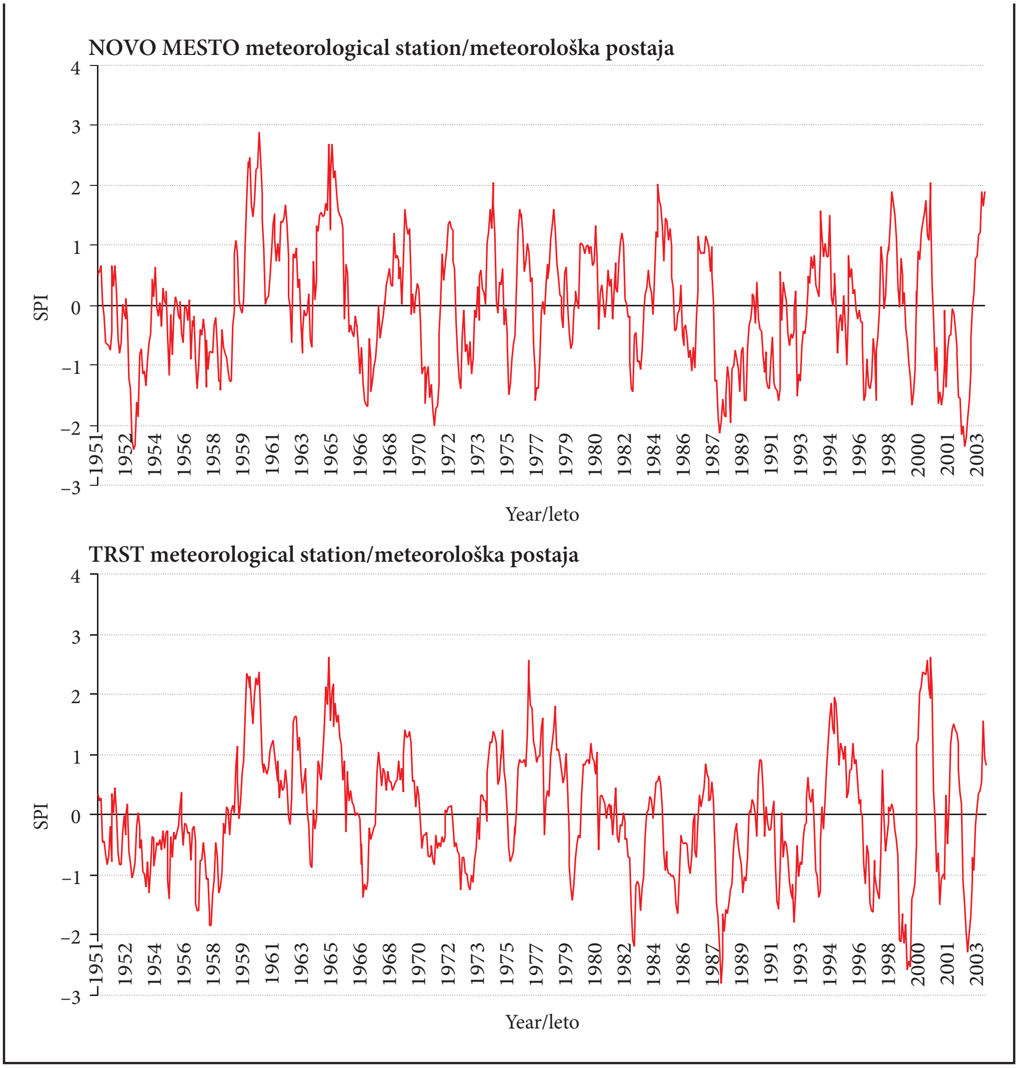


Figure 3: SPI-12 for the selected meteorological stations and the common measurement period 1951–2004.

closely, we can see that, in most cases, the Ljubljana-Bežigrad, Novo mesto and Trieste meteorological stations share a similar pattern of occurrence of dry and wet periods, and something similar can be said for the Celje and the Maribor-Tabor stations (Šebenik 2012). Differences within each group lie in drought severity (SPI values occasionally differ by more than one classification scale) and in the duration and the onset of a drought event, which differ by one or two months between the stations, in each group. Drought never affects the whole Slovenian territory evenly, which confirms the claim that drought is a regional phenomenon (Kobold 2003). During the last period the frequency and intensity of extreme events increased.

The results of the SPI-12 calculations for the entire period of observation for each station and selected common period show that the values of the correlation coefficient for all stations and all periods calculated are higher than 0.95, which means that, as regards the selected meteorological stations, the length of data series does not have a significant effect on SPI values (Šebenik 2012).

3.4 The relationship between the SPI and the standardized mean monthly discharge of the Pesnica river basin

The analysis of the results for the 1970–2009 period showed that the correlation between the standardized series of river discharge data and the SPI for the River Pesnica is positive for all time scales, but the value of Pearson correlation coefficient varies between different time scales. It is also evident that higher correlation coefficients were obtained on shorter time scales in late spring, summer (July and August), and autumn (September, November) (Figure 4).

The September SPI-2 and the September standardized discharge had the strongest correlation (= 0.754) (Figure 5). The results show that mean monthly discharges of the River Pesnica depend highly on precipitation amounts of the current and the past month, which means that the river's watercourse or basin responds quickly to rainfall. The primary water surplus of the River Pesnica occurs in April (Kolbezen 1998). It means that the River Pesnica responds quickly to increased amounts of water resulting from snowmelt or abundant precipitation. The secondary water surplus occurs in November (Kolbezen 1998), which also has high correlation with the index values at shorter time scales. Summer months have higher correlation

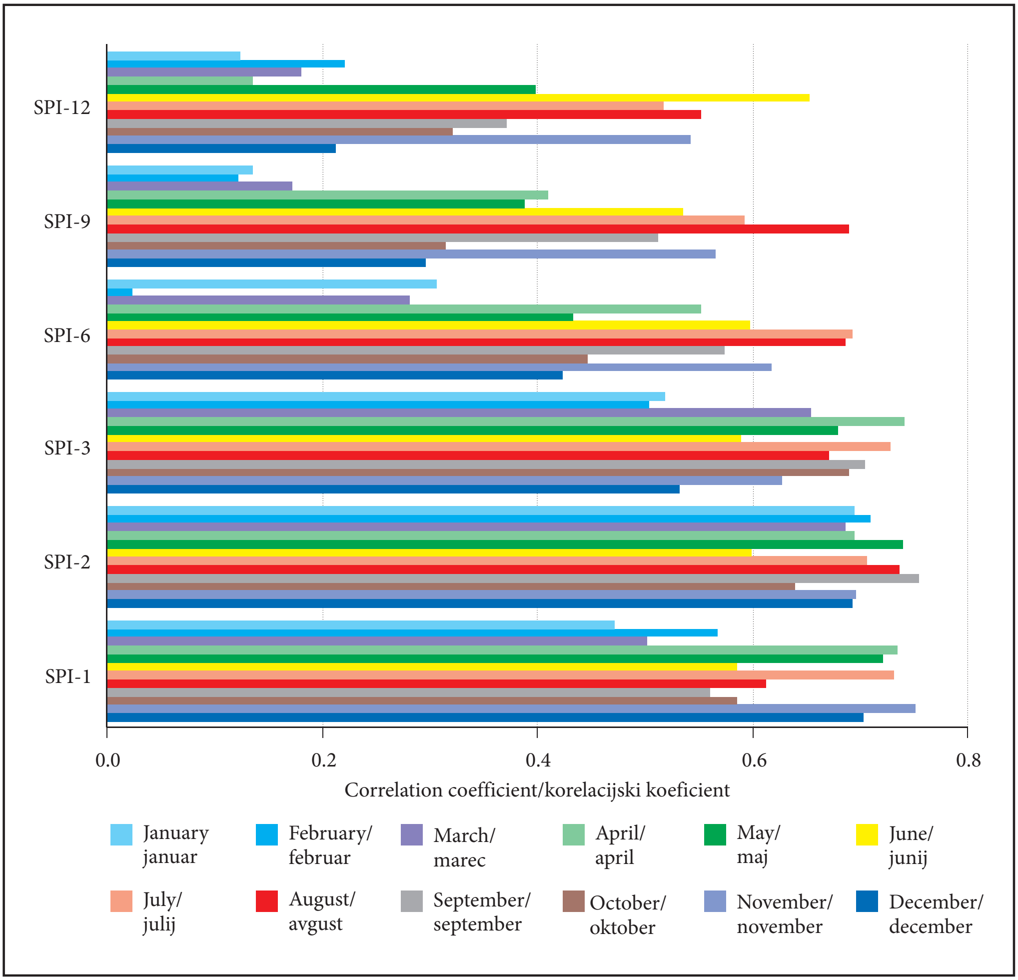


Figure 4: Representation of monthly correlations between standardized discharge data and the SPI.

coefficient values on longer time scales, where precipitation totals include early spring and winter months, which have higher precipitation levels. Extreme standardized discharge values coincide with extreme SPI-2 values, but the former are slightly higher than the latter.

4 Discussion

Analysis showed that the SPI at shorter time scales has high variability and shows more short-term drought events. Drought events occur less frequently, but last longer on longer time scales. Longer SPI time scales do not necessarily detect all the negative deviations that are evident on shorter time scales. It is also evident that SPI values at shorter time scales show slight increases in precipitation during dry periods, which do not necessarily reflect an improvement in drought situation on a longer time scale. When analyzing past periods, we have to keep in mind that several consecutive months of negative index values do not necessarily indicate drought. Negative index values actually identify the months with less precipitation compared against the long-term comparative period.

Precipitation deficit is one of the main causes of drought onset, but not the only one (Vicente-Serrano et al. 2010), since evapotranspiration, temperature, wind speed, water retention capacity of soil and human impacts also significantly influence the development of drought. Precipitation deficit in winter months is problematic with regard to groundwater recharge and recharge of other water resources, which are among the important factors affecting the status of drinking water supply in Slovenia. The SPI is based mainly on precipitation data, therefore, in order to analyze individual types of drought in more detail, we have to use other instruments: drought indices which include other variables in addition to precipitation, water balance models, low-flow analysis, etc. In particular, the SPI provides the first important information regarding drought conditions (Hayes et al. 1999).

In order to identify drought events, we also have to analyze long-time scales of SPI, which are also indicators of hydrological drought conditions of surface and groundwater sources (McKee et al. 1993; Hayes et al. 1999). The index value calculated at a specific time scale must be representative of the drought status in a hydrological system to be operative for water resources management purposes. The strongest

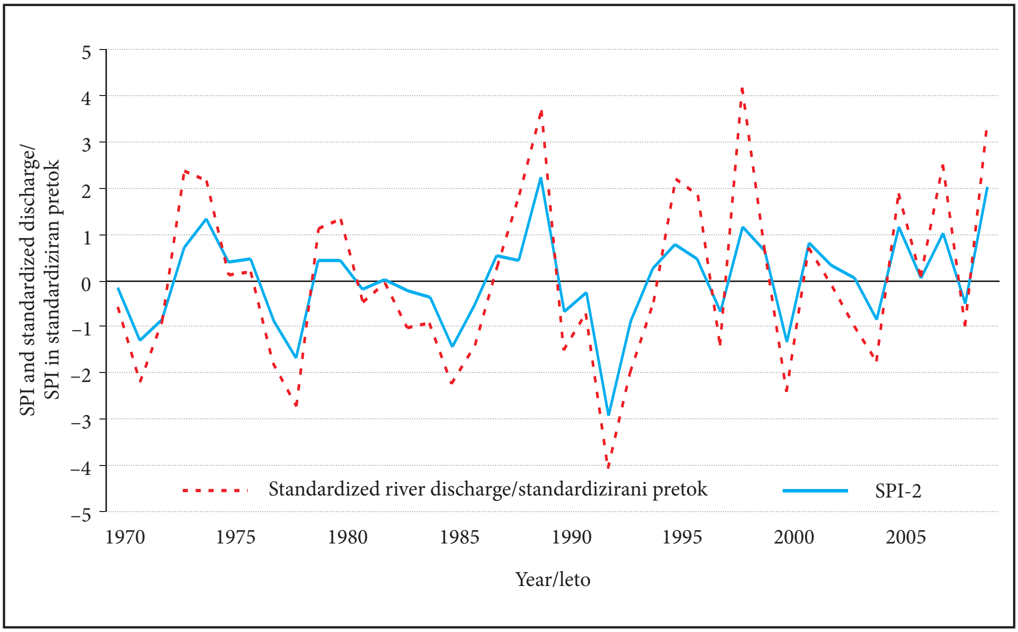


Figure 5: Standardized discharge and the SPI at two-month time scale in September.

correlations between standardized discharge data and the SPI were detected on the two-month time scale for the River Pesnica. This case shows that it is necessary to identify the most suitable scale for calculation, since hydrological, meteorological and terrain characteristics differ significantly between river basins. For the same reason, the results could not be generalized to the whole territory of Slovenia. To date, there have not been many studies conducted in this area and not many definite relationships were found between different drought monitoring periods and water resources.

We standardized discharge data using a normal distribution to achieve greater comparability and more accurate evaluation of correlations between the SPI and standardized discharge data, and thus facilitate the comparison between meteorological and hydrological variables. It would be possible to obtain even more accurate results if discharge data had been standardized using any other distribution function.

5 Conclusion

Droughts and associated water shortages are a global challenge, and Slovenia is no exception. Nevertheless, Slovenia is relatively abundant in water resources. However, despite the high total amount of rainfall, the timing of precipitation is often unfavourable for various activities (high-quality crop production, drinking water supply, hydroelectric power generation) (Gregorič and Sušnik 2008). In recent years, drought losses have reached extremely high levels in Slovenia also (Zorn and Komac 2011). The results show that the largest share (48.6%) of total losses in the period 2000–2005 was caused by drought (2007 Audit Report: Performance Audit of Drought Preventing and Drought Recovery in Agriculture by the Republic of Slovenia). The data therefore suggest that Slovenia, too, should seriously tackle drought-related problems.

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IZVLEČEK: Za zaznavanje, spremljanje in oceno sušnih razmer se danes pogosto uporabljajo sušni indeksi. Eden izmed najpogosteje uporabljenih je standardizirani padavinski indeks (SPI). V prispevku je predstavljen vpliv izbire teoretične porazdelitve na vrednosti SPI ter analiza sušnih obdobij za pet izbranih meteoroloških postaj v Sloveniji. Ugotovili smo, da SPI na letni ravni kaže podoben vzorec pojavljanja sušnih in mokrih obdobij za meteorološke postaje Ljubljana-Bežigrad, Novo mesto in Trst. Podobno lahko rečemo tudi za meteorološki postaji Celje in Maribor-Tabor. Analiza povezanosti standardiziranih pretokov in padavin za izbrano porečje reke Pesnice kaže najvišjo korelacijo med standardiziranim pretokom in SPI-2.

KLJUČNE BESEDE: geografija, suša, padavine, verjetnostna analiza, standardizirani padavinski indeks (SPI), standardizirani pretok, Pesnica, Slovenija

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1 Uvod

Suša je rezultat združevanja vremenskih, naravnih in človeških dejavnikov (Natek 1983; Sustainable Water Use 2001; Sušnik 2006). Suša se od drugih naravnih nesreč razlikuje v več vidikih (Wilhite 2003; Wilhite in Buchanan-Smith 2005):

- Ne poznamo univerzalne in objektivne opredelitve suše. Posledično nastane dvom, ali suša v danem obdobju sploh obstaja in kakšna je njena intenzivnost, kar po navadi vodi v neodločnost in neukrepanje.
- Začetek in konec suše sta težko določljiva dogodka. Posledice se običajno kopičijo skozi daljše časovno obdobje in lahko obstajajo več let.
- Vplivi suše nimajo enkratnega učinka in so razširjeni prek večjega območja. To ovira razvoj zanesljive in pravočasne ocene intenzivnosti in vplivov suše ter tudi pripravo načrta pripravljenosti na sušo.
- Težave so pri količinski opredelitvi vplivov suše in zagotavljanju pomoči. Sušo upoštevamo v relativnem in ne absolutnem smislu, saj je izražena na podlagi odklona od dolgoletnega povprečja v daljšem časovnem obdobju.

Posamezne suše se med seboj razlikujejo po: intenzivnosti, trajanju in prostorski razsežnosti (Wilhite 2003; Wilhite in Buchanan-Smith 2005). Intenzivnost sušnega dogodka se nanaša na stopnjo primanjkljaja padavin in/ali resnost učinkov. Kakšen obseg in vpliv ima suša, je odvisno predvsem od časa nastopa primanjkljaja padavin, njegove intenzitete in trajanja. Vplivi in posledice suše so lahko neposredni in posredni. Izguba pridelka je primer neposrednega vpliva, katerega posledice so: izguba v dohodku, odškodninski zahtevki kmetov. To so posredni oziroma sekundarni ali terciarni vplivi. Govorimo tudi o vplivih suše na gospodarstvo (energetika, turizem, ribištvo, oskrba z vodo), okolje (zmanjšanje biotske pestrosti, degradacija okolja, erozija prsti, kakovost in količina vodnih virov) in družbo (pomanjkanje hrane, izčrpavanje podzemne vode, izguba naravne in kulturne dediščine, zmanjšana kvaliteta bivanja; Wilhite 2003).

Za ustrezno in pravočasno ukrepanje je nujno poznavanje značilnosti suše ter njenih vplivov na različne ravni delovanja družbe. Nepogrešljivo orodje za zaznavanje, spremljanje in oceno sušnih razmer so sušni indeksi (Niemeyer 2008). Eden izmed najpogosteje uporabljenih je standardizirani padavinski indeks (SPI) (Guttman 1999), ki ga odlikuje predvsem preprostost in časovna prilagodljivost. To omogoča njegovo uporabo na različnih časovnih lestvicah.

Namen članka je opredeliti sušne razmere oziroma narediti analizo in primerjavo sušnih obdobij s pomočjo SPI za pet izbranih lokacij in poskušati opredeliti tudi hidrološko sušo na izbranem porečju s pomočjo standardiziranega mesečnega pretoka in SPI.

2 Metode

2.1 Podatki

Edini vhodni podatek za izračun SPI so mesečne padavine. Za analizo smo izbrali štiri meteorološke postaje v Sloveniji (Ljubljana-Bežigrad, Maribor-Tabor, Celje in Novo mesto) in postajo iz sosednje Italije (Trst), ki so prostorsko enakomerno razporejene in za katere so na voljo daljši časovni nizi padavinskih podatkov (ARSO 2011a; UL FGG 2012) (preglednica 1).

Slika 1: Lega izbranih meteoroloških postaj ter vodomerne postaje Gočova na reki Pesnici.

Glej angleški del prispevka.

Preglednica 1: Značilnosti izbranih meteoroloških postaj (ARSO 2009).

meteorološka postaja	nadmorska višina [m]	zemljepisna širina	zemljepisna dolžina	obravnavano obdobje
Ljubljana-Bežigrad	299	46°04'	14°31'	1853–2010
Maribor-Tabor	275	46°32'	14°39'	1876–2010
Celje	240	46°15'	15°15'	1853–2010
Novo mesto	220	45°48'	15°11'	1951–2010
Trst	32	45°38'	13°45'	1851–2004

Izračun SPI smo izvedli na šestih časovnih lestvicah: enomesečni (SPI-1), dvomesečni (SPI-2), trimesečni (SPI-3), šestmesečni (SPI-6), devetmesečni (SPI-9) in dvanajstmesečni lestvici (SPI-12) za celotno opazovano obdobje posameznih meteoroloških postaj ter njihovo presečno obdobje (1951–2004).

Za primerjavo med SPI in pretoki smo izbrali reko Pesnico z dežno-snežnim rečnim režimom. Za izračun SPI smo uporabili podatke meteorološke postaje Maribor-Tabor. Primerjava je bila narejena s podatki srednjega mesečnega pretoka za vodomerno postajo Gočova za najdaljše dostopno obdobje meritev (1970–2009) (ARSO 2011b).

2.2 Standardizirani padavinski indeks (SPI)

SPI je razvil McKee s sodelavci (1993) kot razmeroma preprost indeks za ugotavljanje primanjkljaja oziroma presežka padavin. Omogoča določanje pogostosti ekstremno suhih oziroma ekstremno mokrih obdobij na določeni časovni lestvici za katerokoli lokacijo, za katero obstaja niz padavinskih podatkov (Gregorič in Ceglar 2007). Standardizirana narava indeksa omogoča primerljivost frekvenc sušnih dogodkov na katerikoli lokaciji (Guttman 1999).

V prvem koraku izračuna SPI določimo gostoto verjetnosti izbranega vzorca padavin. Najpogosteje uporabljamo gama porazdelitev (McKee in ostali 1993; Hayes in ostali 1999; Guttman 1999; Hayes 2000; Lloyd-Hughes in Saunders 2002; Ceglar in Kajfež-Bogataj 2008). Guttman (1999), Vicente-Serrano in Lopez-Moreno (2005) ter Blain (2011) pa so uporabili Pearsonovo III porazdelitev. Guttman (1999) je primerjal vrednosti SPI več porazdelitev, in ugotovil, da se podatkom najbolje prilagajata gama in Pearsonova III porazdelitev. V naslednjem koraku za mesečno vsoto padavin in izbrano časovno lestvico izračunamo porazdelitveno funkcijo. To nato normaliziramo v standardizirano normalno slučajno spremenljivko, kar predstavlja vrednost indeksa SPI (Lloyd-Hughes in Saunders 2002), s katerim ovrednotimo intenziteto suše (preglednica 2).

Preglednica 2: Klasifikacija suše ter pripadajoča verjetnost pojava sušnega dogodka pri določenem SPI (Lloyd-Hughes 2002, 67).

SPI	klasifikacija	verjetnost [%]
2,00 ali več	ekstremno mokro	2,3
1,50 do 1,99	zelo mokro	4,4
1,00 do 1,49	zmerno mokro	9,2
0,00 do 0,99	normalno	34,1
0,00 do –0,99	normalno	34,1
–1,00 do –1,49	zmerna suša	9,2
–1,50 do –1,99	huda suša	4,4
–2 ali manj	ekstremna suša	2,3

McKee in sodelavci (1993) so določili tudi kriterij za določitev začetka in konca sušnega dogodka. Ko je indeks SPI dalj časa negativen in doseže vrednost –1 ali manj, govorimo o začetku sušnega dogodka, ki se konča, ko vrednost indeksa postane pozitivna.

2.3 Standardizirani pretok

Vodni viri, kot so voda v vodotokih, podzemna voda, snežna odeja, so ključno povezani s količino padavin. Odziv posameznih komponent hidrološkega kroga na časovna obdobja izračuna indeksa SPI je različen. Če želimo ugotoviti povezavo med padavinami in pretoki, moramo tudi podatke srednjega mesečnega pretoka za posamezno vodomerno postajo standardizirati z normalno porazdelitvijo (Vicente-Serrano in Lopez-Moreno 2005; Gregorič in Ceglar 2007).

3 Rezultati in analiza

3.1 Vpliv izbire verjetnostne porazdelitve na vrednost SPI

Za meteorološko postajo Ljubljana-Bežigrad smo poleg dvoparametrske gama porazdelitve (G2), uporabili še Gumbelovo (G) in Pearsonovo III (P3) porazdelitev ter rezultate primerjali s pomočjo Pearsonovega korelacijskega koeficienta (preglednica 3).

Preglednica 3: Korelacijski koeficienti izbranih porazdelitev za SPI-1 do SPI-12 (Šebenik 2012).

	SPI–1 G	SPI–1 P3	SPI–2 G	SPI–2 P3	SPI–3 G	SPI–3 P3	SPI-6 G	SPI-6 P3	SPI-9 G	SPI-9 P3	SPI-12 G	SPI-12 P3
SPI-1 G2	0,992	0,987										
SPI-2 G2			0,997	0,997								
SPI-3 G2					0,994	0,988						
SPI-6 G2							0,986	0,996				
SPI-9 G2									0,988	0,876		
SPI-12 G2											0,993	0,539

Gumbelova porazdelitev se v nasprotju s Pearsonovo III porazdelitvijo na vseh časovnih lestvicah dobro ujema z gama porazdelitvijo, saj korelacijski koeficienti dosežejo vrednost vsaj 0,98. Pearsonova III porazdelitev kaže večjo variabilnost. Bolje korelira na krajših kot na daljših časovnih lestvicah (preglednica 3). V nadaljevanju so vsi izračuni SPI narejeni z uporabo gama verjetnostne porazdelitve.

3.2 SPI za posamezne postaje za celotno obdobje meritev

Vrednosti SPI na letni ravni za meteorološko postajo Ljubljana-Bežigrad kažejo (slika 2) pred letom 1900 tri pomembnejša sušna obdobja in sicer v letih 1858, 1865 in 1877 (Šebenik 2012). Med letoma 1900 in 1950 SPI-12 kaže štiri ekstremna sušna obdobja. Prvega je zaznati med letoma 1920 in 1922, kar potrjujejo tudi arhivski zapisi o suši v Sloveniji (Trontelj 1997). Sledijo krajša mokra obdobja, tem pa zopet sušnejša v letih 1943, 1947 ter 1949. V drugi polovici dvajsetega stoletja so bila v Ljubljani ekstremna sušna obdobja le na krajših časovnih lestvicah, ki so pogostejša po letu 1990. Po letu 2000 po sušnih razmerah izstopa leto 2003, ki ga zaznajo vse časovne lestvice. Tudi v letih 2006 in 2007 SPI kaže negativno odstopanje, kar ugotavljajo tudi Sušnik in Gregorič (2008) ter Zorn in Komac (2011).

Slika 2: SPI-2, SPI-6, SPI-9 in SPI-12 za meteorološko postajo Ljubljana-Bežigrad za obdobje 1853–2010 (Šebenik 2012).
Glej angleški del prispevka.

Analiza podatkov za meteorološko postajo Maribor-Tabor (preglednica 1) je pokazala, da se ekstremne vrednosti SPI pojavljajo le na krajših časovnih lestvicah (Šebenik 2012). Pred letom 1900 nam SPI-12 kaže dve sušni obdobji z minimalno vrednostjo (–1,52) leta 1877. V prvi polovici dvajsetega stoletja letni indeks kaže tri zmerna sušna obdobja z minimalno vrednostjo SPI-12 (–1,64) decembra 1921. V tem letu je padlo le 725 mm padavin, kar je precej manj od dolgoletnega povprečja, ki je 1032 mm (Trontelj 1997). Po letu 1950 sledi večje število sušnih obdobij, z največjo pogostostjo v zadnjem desetletju (2000–2010). Vrednosti SPI-12 po klasifikaciji v teh letih bistveno ne presegajo meje zmerne suše, razen decembra 1971 (–1,75) in decembra 2003 (–1,68). Indeksi na krajših časovnih lestvicah imajo za leto 2003 bistveno manjše odklone. Ker upoštevajo le krajše obdobje vsot padavin, se v njih ne odražajo daljše pretekle sušne razmere, ki so se začele že leta 2000 in nadaljevale v leto 2001 in 2002, kar potrjuje tudi Kobold (2003).

Za meteorološko postajo Celje (preglednica 1) je na letni časovni lestvici opazen daljši negativen odklon med letoma 1854 in 1859. Daljše obdobje negativnega odklona se ponovno pojavi med letoma 1861 in 1864 ter se ponovi v obdobjih od leta 1865 do 1866 ter od leta 1883 do 1885. Sušna obdobja smo zaznali še v letih 1920 do 1922, 1924 in 1925. Krajšim negativnim odklonom sledijo namočena obdobja, ki dosežejo ekstremne vrednosti v letih 1937 in 1938. Sledita daljši sušni obdobji med letoma 1941 in 1944 ter med letoma 1945 in 1948. Izstopa leto 1946, ko so praktično vsi meseci imeli negativni indeks. Po letu 2000 izstopa leto 2003, ko vrednost indeksa po klasifikaciji doseže mejo hude suše.

Najnižji indeksi za meteorološko postajo Novo mesto (preglednica 1) se na letni časovni lestvici po klasifikaciji gibljejo v mejah zmerne do hude suše (preglednica 2). Krajša obdobja negativnega odklona so precej pogosta (Šebenik 2012). V zadnjih treh desetletjih so pogostejša tudi daljša obdobja primanjkljaja padavin. V letu 2007 se negativen odklon kaže skozi celo leto.

Izračuni SPI-12 za meteorološko postajo Trst (preglednica 1) kažejo, da obdobja s primanjkljajem ne dosegajo velike intenzivnosti, saj je minimalna vrednost indeksa v celotnem analiziranem obdobju enaka –1,01. Do leta 1900 se na letni časovni lestvici kaže predvsem izmenjava daljših ekstremno mokrih obdobij s krajšimi sušnejšimi obdobji. Podobno se nadaljuje tudi v dvajsetem stoletju z najnižjimi vrednostmi v letu 1946. Tudi v drugi polovici 20. stoletja se kaže podoben vzorec. V zadnjih analiziranih letih izstopa leto 2003, ki ga zaznajo vse lestvice krajšega trajanja.

Ugotovimo lahko, da v zadnjem analiziranem desetletju na vseh obravnavanih postajah izstopa leto 2003. V tem letu je ekstremna suša v Evropi dosegla enormne stroške v višini 8,7 milijarde evrov (Commission of the European Communities 2007). V Sloveniji je škoda zaradi suše glede na celotno škodo zaradi naravnih nesreč v letu 2003 znašala kar 83,3% (Zorn in Komac 2011).

3.3 Primerjava SPI med izbranimi postajami za enotno obdobje meritev 1951–2004

Izračunane vrednosti SPI za vse izbrane postaje in vse časovne lestvice smo primerjali tudi za enotno obdobje meritev. Na daljših časovnih lestvicah vse postaje kažejo podobno razporeditev glavnih suhih in mokrih obdobij (slika 3). Do večje razlike pride v letu 2002, kjer izstopa Trst z izrazito mokrim letom, na ostalih meteoroloških postajah pa se v tem času že nakazujejo ekstremne sušne razmere, ki so v letu 2003 prizadele vse obravnavane lokacije. Podrobnejša analiza je pokazala, da meteorološke postaje Ljubljana-Bežigrad, Novo mesto in Trst kažejo podoben vzorec pojavljanja sušnih in mokrih obdobij, podobno pa bi lahko rekli tudi za meteorološki postaji Celje in Maribor-Tabor (Šebenik 2012). Razlike znotraj vsake skupine se kažejo v intenzivnosti suše, ki se lahko razlikuje za cel razred ter trajanju in začetku sušnega obdobja, ki se lahko razlikuje za mesec ali dva. Suša nikoli ne zajame enakomerno celotne Slovenije, kar potrjuje trditev, da je suša regionalen pojav (Kobold 2003). V zadnjem obdobju se število ekstremnih dogodkov povečuje in hkrati intenzivira.

Primerjava rezultatov SPI-12 za celotno obdobje meritev posamezne postaje in za izbrano enotno obdobje je pokazala, da so vrednosti korelacijskega koeficienta za vse postaje nad 0,95, kar pomeni, da časovno obdobje v primeru izbranih meteoroloških postaj ne vpliva v veliki meri na vrednosti SPI (Šebenik 2012).

Slika 3: SPI-12 za obravnavane meteorološke postaje za enotno obdobje meritev 1951–2004.
Glej angleški del prispevka.

3.4 Razmerje med SPI in standardiziranim srednjim mesečnim pretokom za porečje Pesnice

Analiza rezultatov za obdobje 1970–2009 je pokazala, da je medsebojna povezanost standardiziranih pretokov za reko Pesnico in SPI za vse časovne lestvice pozitivna, vendar se vrednosti Pearsonovega koeficienta korelacije spreminjajo glede na dolžino časovne lestvice. Ugotovimo lahko, da so korelacijski koeficienti višji na krajših časovnih lestvicah in da se pojavljajo pozno spomladi, poleti (julij in avgust) in jeseni (september, november) (slika 4).

Slika 4: Prikaz mesečnih korelacijskih koeficientov med standardiziranimi pretoki in SPI.
Glej angleški del prispevka.

Najvišja korelacija (= 0,754) je med septembrskim SPI-2 in septembrskim pretokom (slika 5). Rezultati kažejo, da na srednje mesečne pretoke reke Pesnice v večji meri vplivajo padavine tekočega in preteklega meseca, kar kaže na hiter odziv vodotoka oziroma porečja na padavine. Primarni višek vode reke Pesnice praviloma nastane v mesecu aprilu (Kolbezen 1998). Takrat se reka Pesnica hitro odzove na večjo količino vode zaradi taljenja snega ali obilnejših padavin. Sekundarni višek nastane v novembru (Kolbezen 1998), kar se ravno tako dobro ujema z indeksom SPI na krajših časovnih lestvicah. Poletni meseci kažejo boljše ujemanje na daljših časovnih lestvicah, ko so v vsotah padavin všteti tudi meseci zgodnje pomladi in zime, ko je količina padavin večja. Ekstremne vrednosti standardiziranega pretoka se časovno dobro ujemajo z ekstremnimi vrednostmi SPI-2, so pa nekoliko višje.

Slika 5: Standardizirani pretok in SPI na dvomesečni časovni lestvici v septembru.
Glej angleški del prispevka.

4 Razprava

SPI na krajših časovnih lestvicah kaže veliko variabilnost in večje število krajših sušnih dogodkov. Sušne razmere na daljših časovnih lestvicah so manj pogoste, vendar trajajo dlje. Daljše časovna lestvice ne prepoznajo nujno vseh negativnih odklonov, ki so vidni na krajših časovnih lestvicah. Prav tako krajši padavinski skoki na krajših časovnih lestvicah ne pomenijo nujno izboljšanja sušnih razmer na daljši lestvici. Pri analizi preteklih obdobij se je treba zavedati, da več zaporednih mesecev z negativnimi vrednostmi indeksa ne pomeni nujno sušnega obdobja. Negativna vrednost indeksa namreč predstavlja mesece, ko je padla manjša količina padavin v primerjavi z dolgoletnim primerjalnim obdobjem.

Pomanjkanje padavin je eden od glavnih vzrokov nastanka suše, vendar ne edini (Vicente-Serrano in ostali 2010), saj so pomembni vplivni dejavniki za razvoj suše tudi evapotranspiracija, temperatura, hitrost vetra, vodozadrževalna sposobnost tal ter vplivi človeka. Pomanjkanje padavin v zimskih mesecih je problematično z gledišča bogatenja podtalnice in drugih vodnih virov, ki so pomembni dejavniki pri oskrbi s pitno vodo v Sloveniji. SPI upošteva samo padavine, zato je treba za podrobnejšo analizo posamezne vrste suše uporabiti še druga orodja: sušne indekse, ki poleg padavin vključujejo tudi druge spremenljivke, vodnobilančne modele, analizo nizkih pretokov rek ipd. SPI zato predstavlja predvsem prvo informacijo o sušnih razmerah (Hayes in ostali 1999).

Za identifikacijo sušnih razmer smo analizirali tudi daljša obdobja, ki so hkrati kazalci hidroloških sušnih razmer na površinskih in podzemnih vodnih virih (McKee in ostali 1993; Hayes in ostali 1999). Indeks, primeren za operativno rabo pri upravljanju z vodnimi viri, mora biti reprezentativen za sušne razmere v hidrološkem sistemu na določeni časovni lestvici izračuna. Za reko Pesnico smo najvišjo korelacijo med standardiziranimi pretoki in SPI zaznali na dvomesečni časovni skali. Primer kaže, da je treba za vsako porečje posebej določiti najprimernejšo lestvico izračuna, saj se hidrološke, meteorološke in reliefne značilnosti bistveno razlikujejo. Iz istega razloga rezultata ne moremo posplošiti za celo Slovenijo. Na tem področju do sedaj še ni bilo veliko raziskav in ugotovljenih gotovih povezav med različnimi časovnimi obdobji spremljanja sušnih razmer in vodnimi viri.

V študiji smo pretoke standardizirali po normalni porazdelitvi zaradi večje primerljivosti ter boljše ocene medsebojne povezanosti SPI in standardiziranega pretoka, kar omogoča lažjo primerjavo meteoroloških in hidroloških spremenljivk.

5 Sklep

Suša in z njo povezano pomanjkanje vode se kažeta kot izziv za celoten svet, pri tem pa tudi Slovenija ni izjema. Slovenija se sicer uvršča med države, ki so z vidika vodnatosti relativno bogate. Vendar pa je kljub visokim skupnim količinam dežja za različne dejavnosti (kakovostna kmetijska pridelava, oskrba s pitno vodo, proizvodnja električne energije) časovna razporeditev padavin pogosto neugodna (Gregorič in Sušnik 2008). V preteklih letih je tudi v Sloveniji škoda zaradi suše dosegla visoke zneske (Zorn in Komac 2011). Rezultati kažejo, da je daleč največji delež (48,6 %) v celotnem obsegu ocenjene škode v letih od 2000 do 2005 povzročila prav suša (Revizijsko poročilo … 2007). Podatki nam torej kažejo, da moramo tudi v Sloveniji na sušo resno računati.

6 Literatura

Glej angleški del prispevka.