HRVATSKI GEOGRAFSKI GLASNIK 80/1, 7–25 (2018.)

UDK 551.577.38(497.2)
911.2:551](497.2)

DOI 10.21861/HGG.2018.80.01.01

Original scientific paper
Izvorni znanstveni članak

Received / Primljeno
2017-10-09 / 09-10-2017

Accepted / Prihvaćeno
2018-02-15 / 15-02-2018

Kalina Radeva
Nina Nikolova
Martin Gera

Assessment of hydro-meteorological drought in the Danube Plain, Bulgaria

Procjena hidrometeorološke suše u Dunavskoj ravnici u Bugarskoj

The purpose of this study is to evaluate occurrences of hydro-meteorological drought in the Danube Plain territory, located in northern Bulgaria. As a natural hazard, drought is best characterized by multiple climatological and hydrological parameters. In this study, meteorological drought is analyzed with the Standardized Precipitation Index (SPI), and hydrologic drought is defined by the Streamflow Drought Index (SDI). Both indices are calculated on a time scale of 6 to 12 months over the 1993–2009 period. Future drought occurrence probability is analyzed for two periods: 2021–2050 and 2051–2080 by downscaling the data from regional model KNMI. The results based on the SPI and SDI showed that almost all the investigated areas suffered from mild to moderate droughts during the study period. It is expected that there will be an increasing frequency of occurrences of moderate drought during the second half of 21st century.

Svrha ovoga rada procjena je pojava hidrometeorološke suše na području Dunavske ravnice u sjevernoj Bugarskoj. Sušu kao elementarnu nepogodu najbolje karakteriziraju višestruki klimatski i hidrološki parametri. U ovom se radu meteorološka suša analizira standardiziranim oborinskim indeksom (engl. *Standardized Precipitation Index* – SPI), a hidrološka suša definirana je indeksom protoka (engl. *Streamflow Drought Index* – SDI). Oba su indeksa izračunata za vremensko razdoblje od 6 i 12 mjeseci u razdoblju od 1993. do 2009. godine. Buduća vjerojatnost pojave suše analizirana je za dva razdoblja: 2021. – 2050. i 2051. – 2080. prilagodbom podataka iz regionalnoga modela KNMI. Rezultati temeljeni na standardiziranom oborinskom indeksu (SPI) i indeksu protoka (SDI) pokazali su da je tijekom razdoblja istraživanja sva promatrana područja pogodila blaga do umjerena suša. Tijekom druge polovine 21. stoljeća očekuje se povećanje učestalosti pojave umjerenih suša.

Key words: drought indices, river runoff, precipitation, Danube Plain, Bulgaria

Ključne riječi: indeksi suše, protok, oborine, Dunavska ravnica, Bugarska

Introduction

Drought has affected 37% of the European Union's territory over the past three decades, causing ecological, social, and economic damage, and impacting more than 100 million inhabitants (European Commission, 2007). Bulgaria is situated in a moderate climatic zone but, despite its location, there are droughts with negative consequences, causing serious ecological, social, and economic problems. Droughts in Bulgaria are observed when periods without rain, or periods with below-average rainfall, occur. This is a state of indeterminate frequency, duration, intensity, and unpredictability, which has the overall effect of reducing the water resources and adaptability of the ecosystem. In recent years, an escalation in drought conditions in Bulgaria, especially in agriculture, has indicated the need for more pronounced research and an implementation of guidelines to develop and enforce action programs in the region, especially the areas at risk of drought. Among all the risks associated with the weather, droughts are the phenomenon that is the most complex. Both the causes and the effects are not yet well investigated and understood. Impacts of droughts, in contrast to floods, are not immediate. This phenomenon is growing slowly, and its consequences are apparent in the long term. Drought is less visible and extends over larger areas then other extreme weather events. The impact on the environment, society, and economy in a region affected by drought depends not only on its duration, intensity, and spatial extent, but also on the vulnerability of the area to the negative effects of drought. The factors that increase drought vulnerability include inappropriate use of land, or irrational water management-including the lack of proper management and planning-and governance of consumption. Among the different types of droughts, the hydrological component is the most important, given the high dependence of many activities (industrial, urban water supply, and hydropower generation) on surface water resources (Vasiliades et al., 2011). Therefore, it is important to identify both hydrological and meteorological drought in the river basin. We used not only the Streamflow Drought Index (SDI), but also the Standardized Precipitation Index (SPI), for better identification of long-term dry/drought periods. Assessment of meteorological and hydrological drought is essential for monitoring

Uvod

Suša je u posljednja tri desetljeća pogodila 37 % teritorija Europske unije uzrokovavši ekološku, društvenu i gospodarsku štetu te utječući na više od 100 milijuna stanovnika (Europska komisija, 2007). Bugarska se nalazi u umjerenom klimatskom pojasu, no usprkos svojem položaju suočava se sa sušama, čije posljedice uzrokuju ozbiljne ekološke, društvene i gospodarske probleme. Suše u Bugarskoj opažaju se u razdobljima bez kiše ili u razdobljima s ispodprosječnom količinom oborina. Radi se o razdoblju neodređene učestalosti, trajanja, intenziteta i predvidivosti koje uzrokuje smanjenje vodnih resursa i slabiju prilagodljivost ekosustava. Posljednjih godina porast sušnih uvjeta u Bugarskoj, posebice u poljoprivredi, upozorio je na potrebu za izraženijim istraživanjem i primjenom smjernica za razvoj i provođenje akcijskih programa u regiji, osobito u područjima u kojima postoji rizik od suše. Među svim rizicima povezanim s vremenskim uvjetima suše su najsloženija pojava. Uzroci i utjecaji suše još nisu dovoljno dobro istraženi niti ih se dovoljno razumije. Za razliku od poplava, učinak suše nije trenutan. Radi se o polagano rastućoj pojavi čije se posljedice osjećaju u dugoročnom razdoblju. Učinci suše manje su vidljivi, a javljaju se na većem području u usporedbi s drugim ekstremnim vremenskim pojavama. Utjecaj na okoliš, društvo i gospodarstvo regije pogođene sušom ne ovisi samo o njezinu trajanju, intenzitetu i prostornom opsegu, nego i o ranjivosti područja na negativne utjecaje suše. Među čimbenicima koji povećavaju ranjivost na sušu jesu neprimjereno iskorištavanje zemlje ili neracionalno upravljanje vodom, uključujući pomanjkanje ispravnoga upravljanja i planiranja te nadziranja potrošnje. U različitim vrstama suša najvažnija je hidrološka sastavnica zbog toga što mnoge aktivnosti (industrija, opskrba urbanih područja vodom i proizvodnja hidroenergije) uvelike ovise o površinskim zalihama vode (Vasiliades i dr., 2011). Stoga je u porječju rijeke važno identificirati i hidrološku i meteorološku sušu. Radi bolje identifikacije dugoročnih suhih/sušnih razdoblja koristili smo se indeksom protoka (SDI), ali i standardiziranim oborinskim indeksom (SPI). Procjena meteorološke i hidrološke suše nužna je za praćenje i and forecasting future drought events, and in water management planning.

The water balance structure in Bulgaria is unfavorable, resulting from interactions between geographical location, specific atmospheric circulation, and landscape structures. In the newly adopted national strategy for management and development of the water sector in Bulgaria, mean annual resources of fresh water for the country, calculated for the period of 1974–2006, are 15,754 × 10^6 m^3, of which 10,786 × 10^6 m^3 is surface and 4,968 × 10^6 m^3 is underground (MOEW, 2012). The country also faces serious challenges, mainly related to its location in a dry area, in relation to global climate change, and unequal distribution of precipitation on its territory. The negative trends in many years' precipitation changes, established in various regions of Bulgaria, show that there is a high probability of occurrences of frequent and intensive drought in the country (Nikolova et al., 2012).

There have been various studies in Bulgaria in the field of drought risk assessment. The majority of publications assessing drought variability are concerned with its temporal and spatial distribution (Koleva and Alexandrov, 2008; Alexandrov, 2011; Knight et al., 2004). Classification of atmospheric drought periods has been conducted on the basis of different indices, e.g. the Palmer drought severity index (PDSI) and the standard precipitation index (SPI) (Gocheva et al., 2010; Alexandrov et al., 2011; Nikolova et al., 2012). In this study, to identify hydrological drought we used the Streamflow Drought Index (SDI). This index has not been previously used in studies in Bulgaria, but it has been applied to the analysis of regional droughts in Europe (Nalbantis and Tsakiris, 2009; Rimkus et al., 2013), Asia (Li et al., 2012; Tabari et al., 2013; Hong et al., 2015), and the U.S. (Madadgar and Moradkhani, 2013).

Despite many publications on precipitation variability in Bulgaria, deep statistical and geographical analyses are needed in order to answer the various questions related to features, dynamics, and consequences of the different types of drought. So this study was conducted to analyze drought characteristics in the Bulgarian Danube Plain, based on meteorological and hydrological variables.

predviđanje budućih pojava suša te za planiranje upravljanja vodom.

Struktura vodne bilance u Bugarskoj nepovoljna je, a uzrokuju je interakcije između geografskoga položaja, specifične atmosferske cirkulacije i strukture krajolika. U novousvojenoj nacionalnoj strategiji za upravljanje i razvoj vodnoga sektora u Bugarskoj srednje godišnje vodne zalihe slatke vode za zemlju izračunate za razdoblje od 1974. do 2006. godine iznosile su 15,754 × 10^6 m^3, od čega su 10,786 × 10^6 m^3 površinske, a 4,968 × 10^6 m^3 podzemne zalihe vode (MOEW, 2012). Bugarska je također pred ozbiljnim izazovima zbog svojeg položaja u suhom području prema projekcijama klimatskih promjena te nejednake raspodjele oborina na svojem teritoriju. Negativni trendovi u višegodišnjem oborinskom režimu koji su ustanovljeni u raznim regijama Bugarske pokazuju da u zemlji postoji velika vjerojatnost pojave čestih i intenzivnih suša (Nikolova i dr., 2012).

U Bugarskoj su provedena brojna istraživanja na području procjene rizika od suše. Većina publikacija koje ocjenjuju varijabilnost suša bave se vremenskom i prostornom raspodjelom (Koleva i Alexandrov, 2008; Alexandrov, 2011; Knight i dr., 2014). Klasifikacija razdoblja atmosferske suše provedena je na osnovi različitih indeksa, primjerice Palmerova indeksa jakosti suše (PDSI) i standardiziranoga oborinskog indeksa (SPI) (Gocheva i dr., 2010; Alexandrov i dr., 2011; Nikolova i dr., 2012). U ovom smo se istraživanju za prepoznavanje hidrološke suše koristili indeksom protoka (SDI). Taj se indeks do sada nije primjenjivao u istraživanjima u Bugarskoj, no primijenjen je pri analizi regionalnih suša u Europi (Nalbantis i Tsakiris, 2009; Rimkus i dr., 2013), Aziji (Li i dr., 2012; Tabari i dr., 2013; Hong i dr., 2015) i Sjedinjenim Američkim Državama (Madadgar i Moradkhani, 2013).

Usprkos veliku broju publikacija koje se bave varijabilnošću oborina u Bugarskoj potrebno je provesti dubinske statističke i geografske analize kako bi se odgovorilo na razna pitanja povezana sa značajkama, dinamikom i posljedicama različitih vrsta suše. Ova je studija stoga provedena radi analiziranja karakteristika suše u Dunavskoj ravnici u Bugarskoj na osnovi meteoroloških i hidroloških varijabla.

Study area and data

The Danube Plain is situated in the northern part of Bulgaria - north of the Balkan Mountains and south of the Danube River. Its western border is the Timok River and its eastern border is the Black Sea (Fig. 1). The plain has an area of 31,523 km^2. The relief is dominated by lowlands, hills and plateaus in the east. The annual precipitation varies from 500 to 600 mm and the annual evaporation from 450 to 500 mm. The precipitation totals increase from north to south and decrease to the east. The highest monthly values are measured in June (in some places, May), with 55–75 mm of rainfall. February (in some places, March) is the driest month (Koleva, 1995).

According to the master plans for the management of the river basins, the territory of the investigated region is called the Danube River Basin District (DRBD). The catchment area covers a total surface area of 47,235 km^2 (42.5% of the total surface area of Bulgaria) and has a population of 3,361,344 (44% of the total population of Bulgaria). The total annual natural flow, without the ecological minimum of 10% in the Danube hydro-geographical region, is 5,413 × 10^6 m^3, for the period of 1930/31–2007/08. The investigated area is a rural region, with intense agricultural production, and a developed food industry. This is the poorest region in Bulgaria in terms of surface water resources. According to the updated River Basin Management Plan (2016–2021), severe or moderate droughts occur in the Danube plain nearly every year. The pressure on water resources increases during the summer, when water extraction is higher due to agriculture and an increased demand from the tourist sector. Drought frequency has unfortunately increased, primarily over the last two decades (Koleva and Alexandrov, 2008; Nikolova, 2013).

The monthly observed streamflow data were collected from seven hydrometric stations located in the Danube Plain over the period of 1993–2009. The period for this study was chosen based on the availability of recorded data for all stations in the basin. The hydrological stations are located on different independent, medium and large-sized rivers (Fig. 1). The monthly precipitation data was obtained from 12 meteorological stations situated in the Danube

Područje istraživanja i podatci

Dunavska ravnica nalazi se u sjevernom dijelu Bugarske – sjeverno od planine Balkan i južno od rijeke Dunav. Njezinu zapadnu granicu čini rijeka Timok, a istočnu Crno more (sl. 1). Površina ravnice iznosi 31 523 km^2. Reljefom dominiraju nizine, brežuljci i visoravni na istoku. Godišnja količina oborina varira između 500 i 600 mm, a godišnje isparavanje između 450 i 500 mm. Ukupna količina oborina povećava se od sjevera prema jugu i smanjuje prema istoku. Najviše mjesečne vrijednosti izmjerene su u lipnju (na nekim mjestima u svibnju) i iznose između 55 i 75 mm oborina. Najsuši je mjesec veljača (na nekim mjestima ožujak) (Koleva, 1995).

Prema glavnim planovima za upravljanje poriječjima teritorij istraživanoga područja naziva se slijevno područje rijeke Dunava (engl. *Danube River Basin District* – DRBD).Vodeni slijev pokriva ukupnu površinu od 47 235 km^2 (42,5 % ukupne površine Bugarske) koju nastanjuje 3 361 344 ljudi (44 % ukupnoga stanovništva Bugarske). Ukupan godišnji prirodni dotok bez ekološkoga minimuma od 10 % u dunavskom hidrogeografskom području iznosi 5,413 × 10^6 m^3 za razdoblje od 1930./31. do 2007./08. godine. Istraživano je područje ruralna regija s intenzivnom poljoprivrednom proizvodnjom i razvijenom prehrambenom industrijom. U pogledu površinskih zaliha vode radi se o najsiromašnijoj bugarskoj regiji. Prema ažuriranom Planu za upravljanje porječjem (2016. – 2021.) teške ili umjerene suše u Dunavskoj ravnici javljaju se gotovo svake godine. Opterećenje vodnih zaliha povećava se u ljetnim mjesecima, kada je crpljenje vode veće zbog poljoprivrede i povećanih potreba turističkoga sektora. Učestalost suša nažalost se povećala, posebice u zadnjim dvama desetljećima (Koleva i Alexandrov, 2008; Nikolova, 2013).

Mjesečni podatci o protoku prikupljani su od sedam hidroloških postaja u Dunavskoj ravnici u razdoblju od 1993. do 2009. godine. Razdoblje ove studije odabrano je na temelju dostupnosti zabilježenih podataka za sve postaje u slijevu rijeke. Hidrološke postaje nalaze se na različitim nezavisnim srednjim i velikim rijekama (sl. 1). Mjesečni podatci o oborinama dobiveni su s 12 meteoroloških postaja u Dunavskoj ravnici na bugarskom

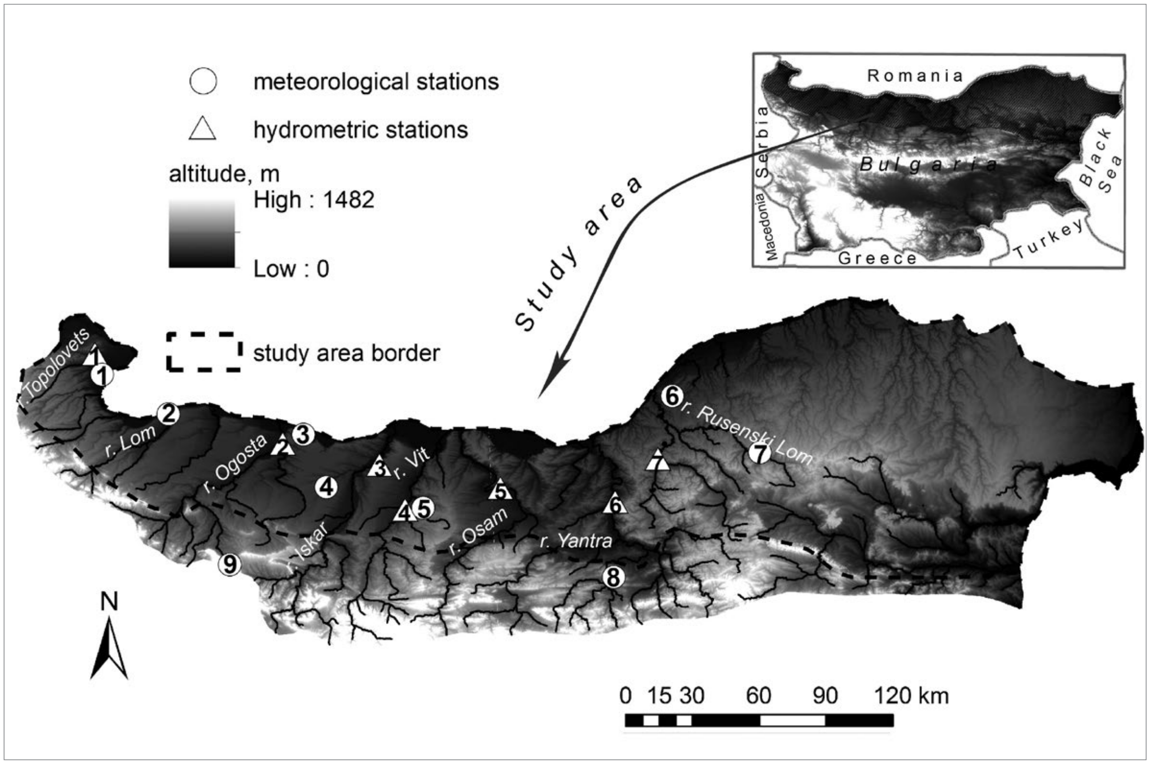

Fig. 1 Location of the study area and hydrometric stations and meteorological stations used for the research
Sl. 1. Položaj područja istraživanja te hidrološke i meteorološke postaje uključene u istraživanje

Meteorological stations: 1 – Vidin, 2 – Lom, 3. Oryahovo, 4 – Kneja, 5 – Pleven, 6 – Obraztsov chiflik, 7 – Razgrad, 8 – Veliko Tarnovo, 9 – Vratsa
Hydrometric stations: 1 – Topolovets – Akatsievo, 2 – Ogosta – Mizia, 3 – Iskar – Orehovitsa, 4 – Vit – Tyrnene; 5– Osam – Izgrav, 6 – Yantra – Karantsi, 7 – Cherni Lom – Shirokovo

Meteorološke postaje: 1 – Vidin, 2 – Lom, 3. Oryahovo, 4 – Kneja, 5 – Pleven, 6 – Obraztsov chiflik, 7 – Razgrad, 8 – Veliko Trnovo, 9 – Vratsa
Hidrometričke postaje: 1 – Topolovets – Akatsievo, 2 – Ogosta – Mizia, 3 – Iskar – Orehovitsa, 4 – Vit – Tyrnene; 5– Osam – Izgrav, 6 – Yantra – Karantsi, 7 – Cherni Lom – Shirokovo

Plain, on the territory of Bulgaria. In order to have more complete data about meteorological drought, we used two meteorological stations (Vratsa and Veliko Tarnovo), located in Fore Balkan Mountain, south of the Danube plain on the edge of the investigated river basins (Fig. 1).

The probability the occurrence and severity of meteorological drought during the 21st century have been investigated (in this research) for two future periods: 2021–2050 and 2051–2080, on the basis of monthly precipitation data from the regional climate model KNMI. The selection of a suitable model for data downscaling was done by comparing global and regional model outputs to the climate observed in the control period of 1961–1990, in ac-

teritoriju. Kako bismo skupili što više potpunih podataka o meteorološkoj suši, koristili smo se dvjema meteorološkim postajama (Vratsa i Veliko Trnovo) koje se nalaze na Predbalkanu, južno od Dunavske ravnice, na granici promatranih porječja (sl. 1).

Vjerojatnost, pojavnost i jakost meteorološke suše tijekom 21. stoljeća ispitivane su (u ovom istraživanju) za dva buduća razdoblja: 2021. – 2050. i 2051. – 2080. na temelju mjesečnih podataka o oborinama iz regionalnoga klimatskog modela KNMI. Odabir odgovarajućega modela za prilagodbu podataka proveden je usporedbom izlaznih rezultata globalnoga i regionalnoga klimatskoga modela te zabilježenih obilježja klime u kontrol-

Tab. 1 Correlation coefficients between measurements and models data for air temperature, 1961–1990
Tab. 1. Koeficijenti korelacije između mjerenja i podataka modela za temperaturu zraka 1961. – 1990.

Model **/ Model**	**Correlation coefficients** **/ Koeficijenti korelacije**
KNMI-RACM02 MIROC3.2-hires	0.9372
VMGO-RRCM_HadCM3Q0	0.9364
KNMI-RACM02 ECHAM5-r1	0.9344
KNMI-RACM02 ECHAM5-r3	0.9316
KNMI-RACM02 ECHAM5-r2	0.9296
MPI-M-REMO_ECHAM5	0.9265
SMHIRCA_ECHAM5-r3	0.9276
C4IRCA3_HadCM3Q16	0.9266
SMHIRCA_BCM	0.9226
ICTP-REGCM3_ECHAM5_r3	0.9222
CNRM-RM4.5 ARPEGE	0.9162
METNOHIRHAM_BCM	0.9155
SMHIRCA_HadCM3Q3	0.9137
CNRM-RM5.1_ARPEGE	0.9124
DMI-HIRHAM5_ARPEGE	0.9110
DMI-HIRHAM5_ECHAM5	0.9074
ETH Z-CLM_HadCM3QO_CRU	0.9022
OURANOSMRCC4.2.1_CGCM3	0.9016
UCLM-PROMES,_HadCM3QO_25km	0.7301

cordance with Lapin et al. (2012). Nineteen models, or their variants, were investigated for accuracy of predictability of air temperature climatic characteristics. The results from correlation analysis between measurements and model data are presented in Table 1. Models with the best scores were then chosen, and precipitation amount, distribution, and annual course were analyzed. After this elaboration, the regional model KNMI (regional KNMI-RACMO2_A1B_ECHAM5-r3_DM_25km) was selected for further analysis and climate change scenarios were designed for Bulgaria. This model used HIRLAM dynamical core and ECMWF physics. The spatial resolution is 25x25 km, while the boundary conditions were taken from the global model ECHAM5. The comparison of the models was undertaken in the same manner as in Lapin et al. (2012).

nom razdoblju od 1961. do 1990. u skladu s Lapin i dr. (2012). Devetnaest modela, odnosno njihove varijante, istraživano je u svrhu točnosti predvidljivosti klimatskih značajka temperature zraka. Rezultati korelacijske analize između mjerenja i podataka modela prikazani su u tablici 1. Potom su odabrani modeli s najboljim rezultatima te je analizirana količina oborina, distribucija i godišnji hod. Nakon te elaboracije za daljnju je analizu odabran model KNMI (regionalni KNMI-RACMO2_A1B_ECHAM5-r3_DM_25 km) te su izrađeni scenariji klimatskih promjena za Bugarsku. Taj se model koristio dinamičkom jezgrom HIRLAM i fizikalnim procesima ECMWF. Prostorna rezolucija iznosi 25 x 25 km, a granični uvjeti preuzeti su iz globalnoga modela ECHAM5. Usporedba modela izvršena je na isti način kao i u Lapin i dr. (2012).

The emission scenario was selected in accordance with Lapin et al. (2012) and with the recommendations of the Intergovernmental Panel on Climate Change (IPCC, 2000). The scenario SRES A1B was applied in our computation. The A1B scenario is a medium pessimistic scenario with global warming of 2.9°C by 2100, compared to 1961–1990. This scenario corresponds relatively well to the present processes in the atmosphere, where the global air temperatures have increased by about 0.2°C per decade since 1980.

For monthly precipitation totals, we used only the values from the nearest grid point with similar topography. The period of 1961–1990 was applied as the reference for calculations of downscaling coefficients. The statistical adaptation of climate data from the regional model was performed taking into consideration the measured data at the meteorological stations. We have made corrections, for the bias and standard deviation, only to model data.

Precipitation is a variable that does not have a Gaussian probability density distribution. In this case, we only used a modification of model data with respect to the mean. Due to how much the data was skewed, we did not apply a modification to the variability, because it could have affected the mean correction. To modify the mean, the quotient method was implemented, because of the non-negative data values.

For the quotient given as the ratio of the means, we have:

$$\overline{q_j} = \frac{\frac{1}{n_r}\sum_{i=1}^{n_r} x_{i,j}^{s}}{\frac{1}{n_r}\sum_{i=1}^{n_r} x_{i,j}^{m}},$$

where x^m is the modeled monthly data and x^s the measured monthly data, n_r are the number of years in the reference period for the chosen month of the year, and n_d is the number of months in one year.

The overall correction of the model data based on quotient method is the following:

$$x_{i,j}^{mn} = x_{i,j}^{m}.\overline{q_j},$$

where $i \in (1,\ldots,n_r)$ $j \in (1,\ldots,n_d)$

Scenarij emisija odabran je u skladu s Lapin i dr. (2012) i uzimajući u obzir preporuke Međuvladina panela o klimatskim promjenama (IPCC, 2000). U našem smo izračunu primijenili scenarij SRES A1B. Scenarij A1B umjereno je pesimističan, s globalnim porastom temperature od 2,9 °C do 2100. godine u usporedbi s razdobljem od 1961. do 1990. godine. Taj scenarij razmjerno dobro odgovara trenutnim atmosferskim procesima, odnosno povećanju globalne temperature zraka za 0,2 °C po desetljeću od 1980. godine.

Za ukupnu mjesečnu količinu oborina služili smo se samo vrijednostima najbliže točke mreže sa sličnom topografijom. Razdoblje od 1961. do 1990. godine uzeto je kao referentno razdoblje za izračune prilagođavanja koeficijenata. Pri statističkoj prilagodbi klimatskih podataka iz regionalnoga modela u obzir su uzeti podatci izmjereni na meteorološkim postajama. Korekcije smo napravili samo na podatcima modela za pristranost i standardnu devijaciju.

Oborine su varijabla koja nema Gaussovu raspodjelu gustoće vjerojatnosti. U tom slučaju, koristili smo se samo modifikacijom podataka modela s obzirom na srednju vrijednost. S obzirom na to koliko su podatci odstupali, nismo primijenili modifikaciju na varijabilnost jer bi to moglo utjecati na korekciju srednje vrijednosti. Za modifikaciju srednje vrijednosti primijenjena je metoda kvocijenta zbog vrijednosti podataka koji nisu negativni.

Za kvocijent dan kao omjer srednjih vrijednosti imamo:

$$\overline{q_j} = \frac{\frac{1}{n_r}\sum_{i=1}^{n_r} x_{i,j}^{s}}{\frac{1}{n_r}\sum_{i=1}^{n_r} x_{i,j}^{m}},$$

pri čemu x^m označava modelirane mjesečne podatke, a x^s izmjerene mjesečne podatke, n_r je broj godina u referentnom razdoblju za odabrani mjesec u godini, a n_d je broj mjeseci u godini.

Ukupna korekcija podataka modela na temelju metode kvocijenta je kako slijedi:

$$x_{i,j}^{mn} = x_{i,j}^{m}.\overline{q_j},$$

pri čemu je $i \in (1,\ldots,n_r)$ $j \in (1,\ldots,n_d)$

The final result is that the modified model outputs have similar climatic characteristics to those measured in the reference period of 1961–1990. Despite some discrepancy, the annual cycle of precipitation after bias correction of model data is close to that of the observed data (Fig. 2). Similar corrections, as calculated for the period of 1961–1990, have been applied for each monthly value from the model outputs for the period of 1991–2100.

Konačni rezultat označava da modificirani izlazni podatci modela imaju slične klimatske karakteristike kao oni izmjereni u referentnom razdoblju od 1961. do 1990. godine. Unatoč određenim odstupanjima godišnji ciklus oborina nakon korekcije pristranosti podataka modela sličan je ciklusu promatranih podataka (sl. 2). Slične korekcije, kako je izračunato za razdoblje od 1961. do 1990., primijenjene su za svaku mjesečnu vrijednost iz izlaznih podataka modela za razdoblje od 1991. do 2100. godine.

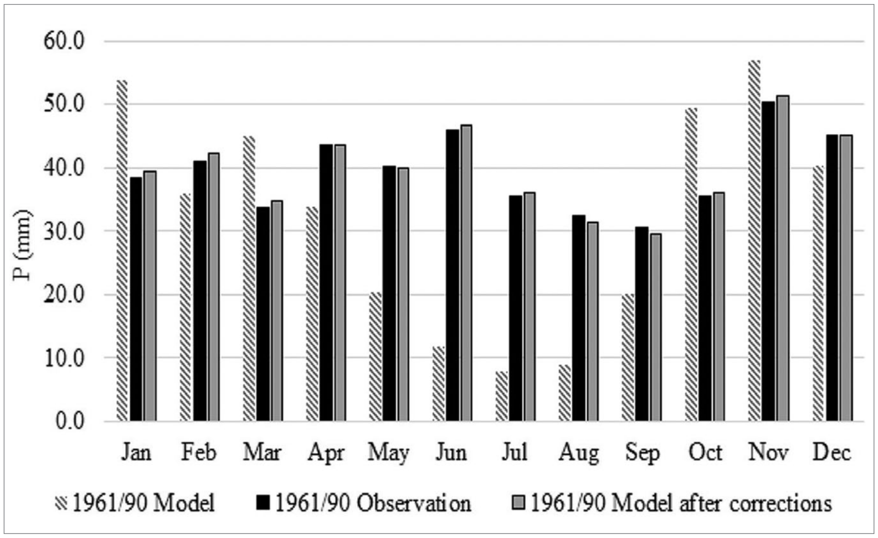

Fig. 2 Annual cycle of precipitation at station Varna for model data, observation data and model data after bias correction

Sl. 2. Godišnji ciklus padalina u stanici Varna za podatke modela, podatke promatranja i podatke modela nakon korekcije pristranosti

Methods

Different drought monitoring indices have been used to assess drought in various regions. In all of them, precipitation is the most important water resources supply component and a critical component of drought risk. For this purpose we used the Standardized Precipitation Index (SPI) as the most appropriate drought index. SPI was developed by McKee et al. (1993) to serve as a "versatile tool in drought monitoring and analysis." It is based only on the precipitation field. It is standardized and can be computed at different time scales, allowing it to monitor different kinds of drought (Keyantash and Dracup, 2002). The SPI calculation for any location is based on the long-term precipitation record for a desired period. This long-term record is fitted to a probability distribution, which is then transformed

Metode

Različiti indeksi praćenja suše primijenjeni su za procjenu suše u različitim regijama. U svim regijama oborine su glavna komponenta u opskrbi vodnih zaliha i ključna komponenta rizika od suše. U tu smo se svrhu koristili standardiziranim oborinskim indeksom (SPI) kao najprikladnijim indeksom za sušu. SPI su razvili McKee i dr. (1993) kako bi poslužio kao „višestruko upotrebljiv alat u praćenju i analizi suše". Temelji se samo na oborinama. Standardiziran je i može se izračunati u različitim vremenskim ljestvicama, što omogućuje praćenje različitih vrsta suše (Keyantash i Dracup, 2002). Izračun indeksa SPI za bilo koju lokaciju temelji se na dugoročnom bilježenju oborina u željenom razdoblju. To se dugoročno bilježenje prilagođava raspodjeli vjerojatnosti, koja se potom pretvara u normalnu into a normal distribution, so that the mean SPI for the location and desired period is zero (Edwards and McKee, 1997). The software provided by the National Drought Mitigation Center of the University of Nebraska, was used for the calculation of SPI[1].

Streamflow Drought Index (SDI) is a very simple and effective index for hydrological droughts. According to Nalbantis (2008), if a time series of monthly streamflow volumes $Q_{i,j}$ are available, in which "*i*" denotes the hydrological year and "*j*" the month within that hydrological year (j = 1 for November and j = 12 for October), $V_{i,k}$ can be obtained based on the equation:

(1)
$$V_{i,k} = \sum_{j=1}^{3k} Q_{i,j} \quad i = 1,2 \ldots \; j = 1,2 \ldots,12; \quad k = 1,2,3,4$$

in which $V_{i,k}$ is the cumulative streamflow volume for the *i*-th hydrological year and the *k*-th reference period, k = 1 for November–January, k = 2 for November–April, k = 3 for November–July, and k = 4 for November–October. Based on the cumulative streamflow volumes "$V_{i,k}$", the Streamflow Drought Index (SDI) is defined for each reference period *k* of the *i*-th hydrological year as follows:

(2)
$$SDI_{i,k} = \frac{V_{i,k} - V_k}{S_k} \quad i = 1,2 \ldots, k = 1,$$

where "V_k" and "S_k" are respectively the mean and the standard deviation of cumulative streamflow volumes of the reference period "*k*" as these are estimated over a long period of time. In this definition, the truncation level is set to "V_k" although other values based on rational criteria could also be used. Nalbantis and Tsakiris (2009) quantified 4 states (classes) of hydrological drought for SDI, which are determined in an identical way to those used in the meteorological drought indices SPI and RDI. States of drought are defined by an integer number using criteria, as show in Table 2.

In the proposed methodology, the reference periods starts from November of each year, which is considered the beginning of the hydrological year in Bulgaria. The drought assessment was made us-

---

[1] http://drought.unl.edu/MonitoringTools/ClimateDivisionSPI.aspx, accessed by 20 October, 2017

---

raspodjelu, tako da srednji SPI za lokaciju i željeno razdoblje iznosi nula (Edwards i McKee, 1997). Indeks SPI izračunali smo s pomoću softvera koji nam je omogućio Nacionalni centar za suzbijanje suša Sveučilišta u Nebraski.[1]

Indeks protoka (SDI) vrlo je jednostavan i učinkovit indeks za hidrološke suše. Prema Nalbantisu (2008), ako je dostupan vremenski niz mjesečnih količina protoka $Q_{i,j}$, pri čemu *i* označava hidrološku godinu, a *j* mjesec u toj hidrološkoj godini (j = 1 za studeni i j = 12 za listopad), $V_{i,k}$ se može izračunati prema jednadžbi:

(1)
$$V_{i,k} = \sum_{j=1}^{3k} Q_{i,j} \quad i = 1,2 \ldots \; j = 1,2 \ldots,12; \quad k = 1,2,3,4$$

pri čemu je $V_{i,k}$ kumulativni volumen protoka za hidrološku godinu $_i$ i referentno razdoblje $_k$, k = 1 za razdoblje od studenoga do siječnja, k = 2 za razdoblje od studenoga do travnja, k = 3 za razdoblje od studenoga do srpnja i k = 4 za razdoblje od studenoga do listopada. Na temelju kumulativnih volumena protoka „$V_{i,k}$" indeks protoka definira se za svako referentno razdoblje *k* hidrološke godine *i* kako slijedi:

(2)
$$SDI_{i,k} = \frac{V_{i,k} - V_k}{S_k} \quad i = 1,2 \ldots, k = 1,$$

pri čemu su „V_k" i „S_k" srednja, odnosno standardna devijacija kumulativnoga volumena protoka referentnoga razdoblja *k* jer se procjenjuju u dugoročnom razdoblju. U toj definiciji razina skraćivanja postavljena je na „V_k" iako se mogu upotrebljavati i druge vrijednosti na temelju racionalnih kriterija. Nalbantis i Tsakiris (2009) kvantificirali su 4 stanja (klase) hidrološke suše za SDI, koja se određuju na isti način kao ona korištena u indeksima suše SPI i RDI. Stanja suše definirana su cijelim brojem uz primjenu kriterija, kako je prikazano u tablici 2.

U predloženoj metodologiji referentno razdoblje počinje u studenom svake godine, što se smatra početkom hidrološke godine u Bugarskoj. Procjena suše provedena je primjenom triju

---

[1] http://drought.unl.edu/MonitoringTools/ClimateDivisionSPI.aspx (20. listopada 2017.)

Tab. 2 Classification of drought conditions according to the SDI and SPI
Tab. 2. Klasifikacija uvjeta suše prema indeksu SDI i SPI

State / Stanje	**Description** / Opis	**Criterion** / Kriterij
1	Extremely Wet / Ekstremno vlažno	SDI;SPI ≥ 2.0
2	Very Wet / Vrlo vlažno	1.5 ≤ SDI;SPI ≤ 1.99
3	Moderately Wet / Umjereno vlažno	1.0 ≤ SDI;SPI ≤ 1.49
0	Non-drought / Normalno	SDI;SPI ≥ 0
-1	Mild drought / Blago sušno	-1.0 ≤ SDI;SPI ≤ 0.0
-2	Moderate drought / Umjereno sušno	-1.5 ≤ SDI;SPI ≤ - 1.0
-3	Severe drought / Vrlo sušno	-2.0 ≤ SDI;SPI ≤ - 1.5
-4	Extreme drought / Ekstremno sušno	SDI;SPI ≤ - 2.0

ing three overlapping periods: at the annual level—hydrological year (November–October)—and at the seasonal level, i.e. the cold half of the year (November–April) and the warm half (May–October). In order to evaluate the drought during these three periods SDI and SPI were calculated with a 12 and 6-month step, respectively. The relation between SDI and SPI was investigated by Pearson correlation analysis and the statistical significance of correlation coefficients was determined using t-test.

On the basis of precipitation data from the KNMI model, SPIs were calculated and future occurrence and severity of droughts were analyzed.

Results and discussions

The cold period, from November to April (6 months), includes the winter season, when the precipitation and flow are at their minimums in the annual distribution of the hydrological year (November–October). SDI values indicate that during the periods of 1993–1995 and 2001–2002 all of the stations experienced from mild to moderate hydrological drought. The exception was the river Cherni Lom (in the eastern part of studied region). These drought periods were verified by SPI. Generally, there was good synchronicity between the results from the calculation of SDI and SPI, but some peculiarities appeared (Fig. 3).

preklapajućih razdoblja: na godišnjoj razini – hidrološka godina (studeni – listopad) te na razini godišnjih doba, to jest hladnoga razdoblja (studeni – travanj) i toploga razdoblja godine (svibanj – listopad). Kako bi se ocijenila suša tijekom tih triju razdoblja, SDI i SPI izračunati su u koracima od 12 odnosno 6 mjeseci. Odnos između indeksa SDI i SPI ispitivan je primjenom Pearsonove korelacijske analize, a statistički značaj koeficijenata korelacije određen je provođenjem t-testa.

Indeksi SPI izračunati su na temelju podataka o oborinama iz modela KNMI, a analizirane su buduća pojavnost i jakost suše.

Rezultati i rasprava

Hladno razdoblje od studenoga do travnja (6 mjeseci) uključuje zimu, kada su oborine i protoci na najnižim razinama u godišnjoj raspodjeli hidrološke godine (studeni – listopad). Vrijednosti indeksa SDI pokazuju da su u razdobljima od 1993. do 1995. i od 2001. do 2002. sve postaje zabilježile blagu do umjerenu hidrološku sušu. Iznimka je bila rijeka Cherni Lom (u istočnom dijelu proučavanoga područja). Ta su razdoblja suše provjerena primjenom indeksa SPI. Općenito je postojala dobra usklađenost između rezultata izračuna indeksa SDI i SPI, no pojavile su se neke osobitosti (sl. 3).

K Radeva
N. Nikolova
M. Gera

Assessment of hydro-meteorological drought in the Danube Plain, Bulgaria

Procjena hidrometeorološke suše u Dunavskoj ravnici u Bugarskoj

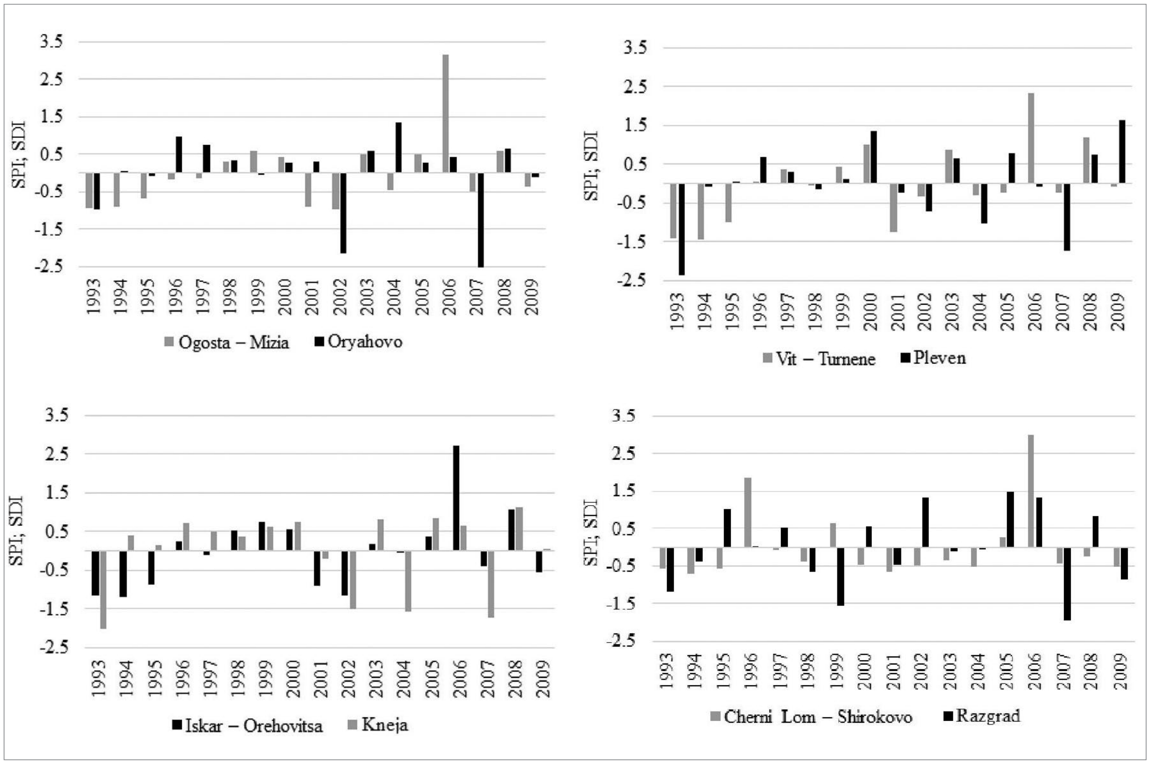

Fig. 3 SDI and SPI for selected hydrometric and corresponding meteorological stations for the period of November–April
Sl. 3. SDI i SPI za odabrane hidrološke i odgovarajuće meteorološke postaje za razdoblje od studenoga do travnja
grey column – SDI; black column - SPI / sivi stupac – SDI; crni stupac – SPI

For both of the aforementioned periods, meteorological drought occurred mainly in 1993 and 2002, but at some of the stations the intensity of the event was higher and the indices showed extreme drought. SPI indicated a period with severe and extreme drought in 2007 when the values of SDI showed only mild drought. This proves that low precipitation is not the sole factor causing hydrological drought in the investigated area.

According to SDI-6 (for November–April), hydrological drought was observed in 50–60% of the years in the investigated period (Tab. 2 and Tab. 3). The exception was the river Cherni Lom, flowing through the eastern part of study area—the poorest region in the country in terms of water resources. The surface waters there are concentrated in inconstant flows and with insignificant discharge. In this instance, the waters accumulated in subsurface karst formations are more important. Conversely, the precipitation data and SPI-6 showed that meteorological drought for the winter period manifested in 40–

U oba prije spomenuta razdoblja meteorološka suša nastupila je većinom 1993. i 2002. godine, no u nekim je postajama intenzitet suše bio jači, a indeksi su pokazivali ekstremnu sušu. SPI je pokazao 2007. godinu kao vrlo i ekstremno sušnu, no SDI je u tom razdoblju pokazao samo blagu sušu. To je dokaz da niska količina oborina nije jedini faktor koji uzrokuje hidrološku sušu u proučavanom području.

Prema SDI-6 (za razdoblje od studenoga do travnja), hidrološka suša opažena je u 50 do 60 % godina u ispitivanom razdoblju (tab. 2 i tab. 3). Iznimka je bila rijeka Cherni Lom, koja protječe kroz istočni dio ispitivanoga područja, što je u smislu vodnih resursa najsiromašnija regija države. Površinske vode u tom su području koncentrirane u nestalnim tokovima i bez značajnoga protoka. U ovom je slučaju važnija bila voda nakupljena u podzemnim krškim formacijama. S druge strane, podatci o oborinama i SPI-6 pokazali su da se meteorološka suša u zimskom razdoblju manifestirala

Tab. 3 Percentage of dry and non-dry winter periods (November–April) for 1992-2009
Tab. 3. Postotak suhih i nesuhih zimskih razdoblja (studeni – travanj) od 1992. do 2009.

Hydrological drought / Hidrološka suša			**Meteorological drought** / Meteorološka suša		
hydrometric stations / hidrološke postaje	**dry periods** / suha razdoblja	**non-dry periods** / normalna razdoblja	**meteorological stations** / meteorološke postaje	**dry periods** / suha razdoblja	**non-dry periods** / normalna razdoblja
			Vidin	41	59
			Lom	53	47
			Vratsa	41	59
Ogosta	59	41	Oryahovo	35	65
Iskar	53	47	Kneja	31	69
Vit	59	41	Pleven	47	53
Osam	53	47	V. Tarnovo	41	59
Yantra	47	53	Obr. Chifl	47	53
Cherni Lom	76	24	Razgrad	53	47

50% of the investigated years, but the severity was often higher than that of the hydrological drought.

For the summer period (May–October) SDI-6 showed drought in most of the investigated years and there were practically no territorial differences in drought occurrence. In most cases, the values of SDI for summer were negative but very close to 0, so we could consider this period as close to normal. The exception was the year 2005, when SDI indicated high water at the investigated hydrometric stations (Fig 4). During the summer of 2005, heavy rainfall occurred, and many regions in Bulgaria were flooded. In contrary to SDI, SPI showed well-determined droughts at all of the investigated stations for the summer months (May–October) only in 1993 and 2000. From the meteorological point of view, the year 2000 was one of the driest years in Bulgaria for the period of instrumental observation (Nikolova et al., 2012). A minimal increase of the amount of meteorological drought was observed in May–October in comparison to November–April, but the type of drought was mainly mild.

In order to study drought at the annual scale, the SDI-12 and SPI-12 were calculated for the hydrological year of November–October, as shown in Fig. 5. In general, the hydrological periods of 1993–

u 40 do 50 % proučavanih godina, no intenzitet je često bio jači od intenziteta hidrološke suše.

U ljetnom razdoblju (svibanj – listopad) SPI-6 pokazao je sušu u većini ispitivanih godina te gotovo da i nije bilo prostorne razlike u pojavnosti suše. U većini slučajeva vrijednosti indeksa SDI za ljeto bile su negativne, no vrlo blizu nuli, stoga to razdoblje možemo smatrati gotovo normalnim. Iznimka je bila 2005. godina kada je SDI pokazao visoku razinu vode na hidrološkim postajama uključenim u ispitivanje (sl. 4). U ljeto 2005. godine padale su obilne kiše te su mnoge regije u Bugarskoj poplavljene. U usporedbi s indeksom SDI indeks SPI jasno je pokazao sušu u svim proučavanim postajama za ljetne mjesece (svibanj – listopad) samo 1993. i 2000. godine. U meteorološkom pogledu 2000. godina bila je jedna od najsuših godina u Bugarskoj u razdoblju instrumentalnoga mjerenja (Nikolova i dr., 2012). Minimalno povećanje količine meteoroloških suša primijećeno je u razdoblju od svibnja do listopada u usporedbi s razdobljem od studenoga do travnja, no ta je suša bila uglavnom blaga.

Kako bi se suša proučavala na godišnjoj razini, izračunati su SDI-12 i SPI-12 za hidrološku godinu od studenoga do listopada, kako je prikazano na slici 5. Općenito su hidrološka razdoblja od 1993.

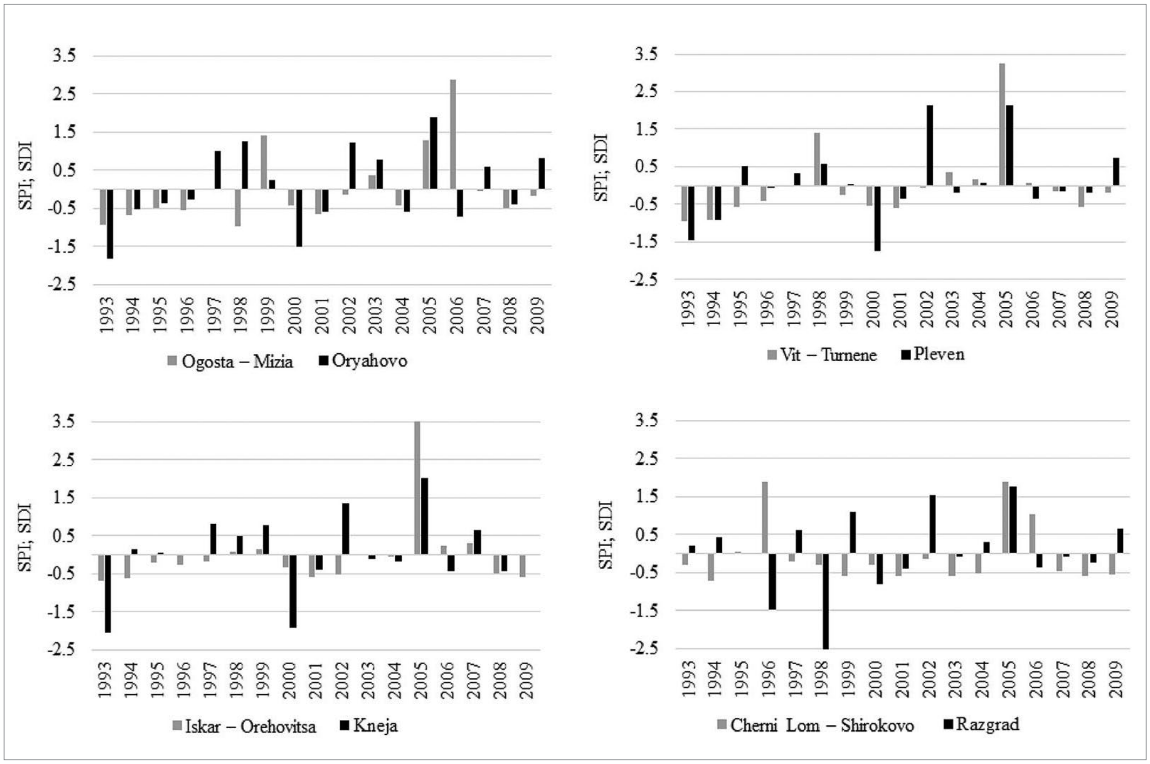

Fig. 4 SDI and SPI for selected hydrometric and corresponding meteorological stations for the period of May–October

Sl. 4. SDI i SPI za odabrane hidrološke i odgovarajuće meteorološke postaje za razdoblje od svibnja do listopada

grey column – SDI; black column - SPI / sivi stupac – SDI; crni stupac – SPI

1994 and 2001–2002 were the driest. The most sever streamflow drought occurred during the period of 1993–1994 for the rivers Vit, Osam, and Yantra. This event was verified by the SPI values which indicated extreme drought condition (Fig. 5).

All the drought periods coincided and showed similar results, however SPI showed more severities (Fig. 5). Furthermore, according to SDI, dry conditions of different magnitudes characterized the entire period of 1993–2005; and for the entire investigated period, there were only two years where no drought was present. The correlation coefficient, between SDI-12 of each of the 5 sub-basins and SPI-12 calculated for corresponding meteorological stations, varied between 0.44 (Ogosta river) and 0.70 (Yantra river). According to the t-test, these correlations are statistically significant, at a level of 0.05. The percentage of surface runoff in total river runoff is higher in the basins of rivers Yantra, Vit, and Osam. Thereby, the river runoff is more sensitive to rainfall than in the eastern part of the

do 1994. i od 2001. do 2002. bila najsuša. Najveće smanjenje protoka dogodilo se u razdoblju od 1993. do 1994. za rijeke Vit, Osam i Yantra. To je potvrđeno vrijednostima indeksa SPI koje su ukazivale na uvjete ekstremne suše (sl. 5).

Sva su se sušna razdoblja podudarala i pokazala slične rezultate iako je indeks SPI pokazivao veći intenzitet (sl. 5). Nadalje, prema indeksu SDI suhi uvjeti različitih jačina obilježili su čitavo razdoblje od 1993. do 2005., a u čitavom proučavanom razdoblju samo u dvije godine nije bilo suše. Koeficijent korelacije između SDI-12 svakoga od 5 podslijevova i SPI-12 izračunatog za odgovarajuće meteorološke postaje varirao je između 0,44 (rijeka Ogosta) i 0,70 (rijeka Yantra). Prema t-testu te su korelacije statistički značajne na razini od 0,05. Postotak površinskih oborinskih voda u ukupnom riječnom dotoku veći je u porječjima rijeka Yantra, Vit i Osam. Stoga je riječni dotok osjetljiviji na oborine nego u istočnom dijelu Dunavske ravnice (primjerice rijeka Cherni Lom),

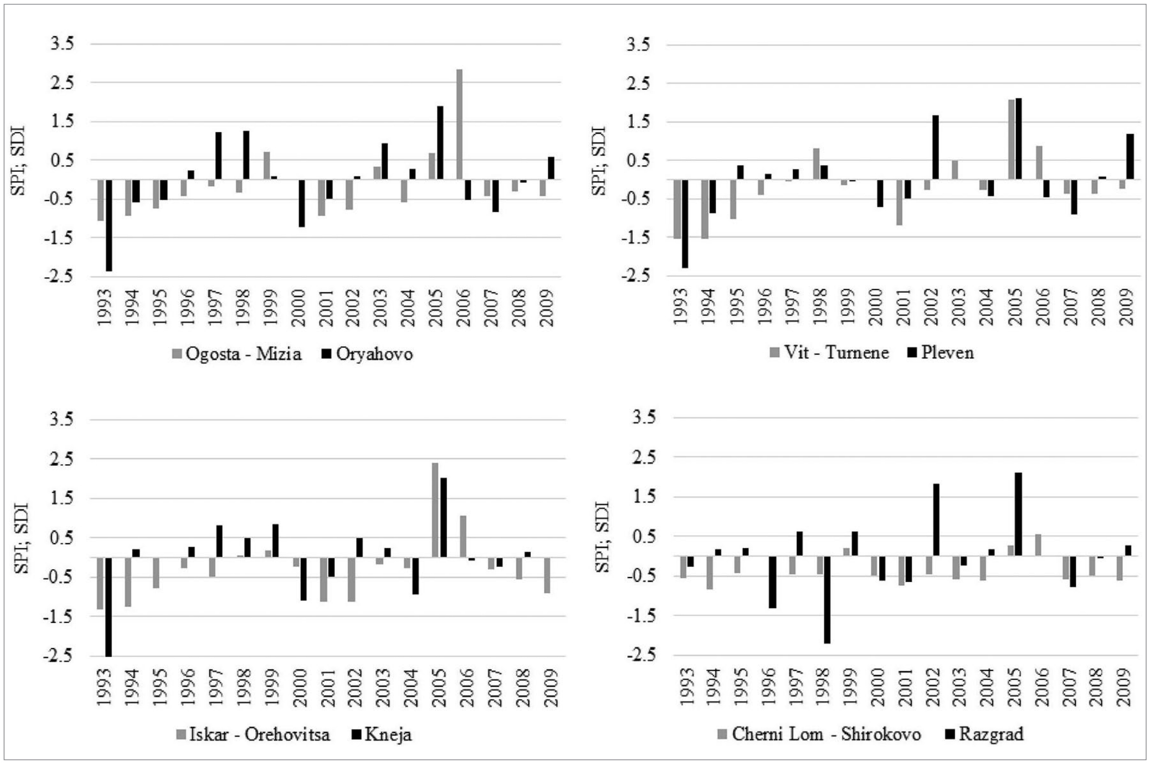

Fig. 5 SDI and SPI for selected hydrometric and corresponding meteorological stations for the period of November–October
Sl. 5. SDI i SPI za odabrane hidrološke i odgovarajuće meteorološke postaje za razdoblje od studenoga do listopada

grey column – SDI; black column - SPI / sivi stupac – SDI; crni stupac – SPI

Danube Plain (e.g. Cherni Lom river), where the groundwater contribution to runoff is higher.

Table 4 shows the percentage of different types of drought as a percent of total dry events based on SPI and SDI. Overall, both indices indicate a domination of mild drought occurring in the area during the investigated period. SPI indicates more states of extreme and severe drought, where SDI shows a severe drought only for one station.

The occurrence of dry periods during the years of 2021–2050 and 2051–2080 was investigated by calculation of SPI-6 and SPI-12 on the basis of the KNMI model data. The results show that we could expect, on seasonal level, the occurrence of dry periods anywhere from 40–57% during the periods of 2021–2050 and 2051–2080. The frequency will be higher in the summer time and in the western part of the investigated territory. The increase in the occurrences of dry years will be observed for the two future periods. It is expected that the percentage of dry events will reach 62% of the years during the period of 2051–2080 (Tab. 5).

gdje je doprinos podzemnih voda riječnom dotoku veći.

Tablica 4 prikazuje postotak različitih vrsta suše kao postotak ukupnih pojava suše na temelju indeksa SPI i SDI. Općenito, oba indeksa upućuju na prevladavanje blage suše na tom području tijekom ispitivanoga razdoblja. SPI pokazuje više stanja ekstremne i jake suše, dok SDI prikazuje jaku sušu samo za jednu postaju.

Pojavnost suhih razdoblja od 2021. do 2050. i 2051. do 2080. godine ispitivana je izračunom indeksa SPI-6 i SPI-12 na temelju podataka modela KNMI. Rezultati pokazuju da na razini godišnjih doba možemo očekivati pojavnost suhih razdoblja od 40 do 75 % tijekom razdoblja od 2021. do 2050. i 2051. do 2080. godine. Učestalost će biti veća u ljetnom razdoblju i u zapadnom dijelu ispitivanoga područja. Očekuje se da će postotak pojava suša dostići 62 % u razdoblju od 2051. do 2080. godine (tab. 5).

Tab. 4 Types of drought as a % of total dry events
Tab. 4. Vrsta suše kao postotak ukupnih pojava suša

Hydrological drought / Hidrološka suša					**Meteorological drought** / Meteorološka suša				
hydrometric stations	**mild** / blaga	**moderate** / umjerena	**severe** / jaka	**extreme** / ekstremna	**meteorological stations**	**mild** / blaga	**moderate** / umjerena	**severe** / jaka	**extreme** / ekstremna
Topolovets	100	0	0	0	Vidin	67	0	17	17
					Lom	75	0	13	13
					Vratsa	78	11	11	0
Ogosta	92	8	0	0	Oryahovo	86	14	0	0
Iskar	69	31	0	0	Kneja	67	17	0	17
Vit	67	17	17		Pleven	88	0	0	13
Osam	77	23	0	0	V. Tarnovo	70	30	0	0
Yantra	83	17	0	0	Obr. Chifl	67	22	11	0
Cherni Lom	100	0	0	0	Razgrad	75	13	0	13

Tab. 5 Percentage of dry and non-dry periods for two 30-years periods in the 21st century
Tab. 5. Postotak suhih i normalnih razdoblja za dva tridesetogodišnja razdoblja u 21. stoljeću

	November–April / studeni – travanj		**May–October** / svibanj – listopad		**November–October** / studeni – listopad	
meteorological stations / meteorološke postaje	**dry periods** / suha razdoblja	**non-dry periods** / normalna razdoblja	**dry periods** / suha razdoblja	**non-dry periods** / normalna razdoblja	**dry periods** / suha razdoblja	**non-dry periods** / normalna razdoblja
2021 – 2050						
Vidin	52	48	53	47	59	41
Lom	52	48	57	43	59	41
Pleven	41	59	57	43	52	48
Russe	47	53	40	60	45	55
Shumen	43	57	43	57	48	52
Varna	43	57	50	50	55	45
2051 – 2080						
Vidin	48	52	55	45	62	38
Lom	48	52	52	48	62	38
Pleven	48	52	41	49	45	55
Russe	43	57	50	50	45	55
Shumen	57	43	50	50	62	38
Varna	43	57	47	53	52	48

Tab. 6 Types of droughts as a % of total dry events according to SPI 12
Tab. 6. Vrsta suše kao postotak ukupnih pojava suša prema SPI-12

	2021 – 2050				2051 – 2080			
	mild / blaga	**moderate** / umjerena	**severe** / jaka	**extreme** / ekstremna	**mild** / blaga	**moderate** / umjerena	**severe** / jaka	**extreme** / ekstremna
Vidin	76	12	6	6	68	32	0	0
Lom	82	6	12	0	72	28	0	0
Pleven	53	40	7	0	61	31	0	8
Russe	62	15	15	8	62	23	8	7
Shumen	57	36	0	7	72	22	6	0
Varna	68	19	13	0	60	33	7	0

Generally, there is a minimal projected difference in the occurrence of dry periods during the periods of 2021–2050 and 2051–2080. A decreasing percentage of dry periods during the winter and an increasing percentage of dry periods at the annual level is expected for the period of 2051–2080 in comparison to 2021–2050.

The droughts in 2021–2050 and 2051–2080 will be mainly mild and moderate (Tab. 6). During the period of 2051–2080, decreasing cases of mild and severe droughts, and increasing cases of moderate drought are expected in most of the region.

Despite of some difference in the periods, the results from the investigation of climate change in Bulgaria during the 21st century (MOEW, 2014) are similar to the results from this paper, indicating a decrease of precipitation and drought occurrences. According to RCP 2.6-scenario, IPCC AR 5 (IPCC, 2013; MOEW, 2014), the changes of annual precipitation in Bulgaria will be with a different sign for the periods of 2016–2035 and 2045–2065, and will vary ± 10% from the average for the period 1961–1990. The RCP 8.5 scenario shows that, during the period of 2016–2035, an increase of the average annual precipitation in almost the whole country by about 10% is expected. However by the end of the century, according the same scenario, a reduction of

Općenito postoji minimalna projicirana razlika u pojavnosti suhih razdoblja između razdoblja od 2021. do 2050. i 2051. do 2080. godine. Opadajući postotak suhih razdoblja tijekom zime i rastući postotak suhih razdoblja na godišnjoj razini očekuje se za razdoblje od 2051. do 2080. godine u usporedbi s razdobljem od 2021. do 2050. godine.

Suše u razdoblju od 2051. do 2080. godine i od 2021. do 2050. godine bit će većinom blage i umjerene (tab. 6). Tijekom razdoblja od 2051. do 2080. godine u većini istraživanoga područja očekuje se smanjenje broja slučajeva blagih i jakih suša te povećanje broja slučajeva umjerenih suša.

Unatoč nekim razlikama u razdobljima rezultati istraživanja klimatskih promjena u Bugarskoj tijekom 21. stoljeća (MOEW, 2014) slični su rezultatima ovoga rada, što upućuje na smanjenje količine oborina i pojavnosti suša. Prema scenariju RCP 2.6, IPCC AR 5 (IPCC, 2013; MOEW, 2014) promjene u godišnjim oborinama u Bugarskoj bit će različita predznaka za razdoblja od 2016. do 2035. i od 2045. godine do 2065. godine te će varirati ± 10 % od prosjeka za razdoblje od 1961. do 1990. godine. Scenarij RCP 8.5 pokazuje da se za razdoblje od 2016. do 2035. godine očekuje porast prosječne godišnje količine oborina u gotovo čitavoj zemlji od otprilike 10 %. Ipak, do kraja stoljeća prema istom scenariju očekuje se smanjenje prosječne godišnje the average annual precipitation total of 10–20% is also expected. The decrease in winter precipitation will also be roughly 10% by the end of century, but a considerable decrease is also expected for summer precipitation—of 20–30% (MOEW, 2014).

Taking into account the significant correlation coefficients between SDI-12 and SPI-12 (from 0.44 to 0.70), calculated on the basis of observation data and the results from SPI calculated on the basis of model data, we can expect a similar distribution of hydrological and meteorological drought and higher occurrences of mild and moderate droughts during the 21st century. The high degree of convergence between SPI and SDI and this relationship, along with the identified reference periods, can be used in the long-term forecasting of droughts and policy planning in the development of integrated water resource management in Bulgaria.

Conclusion

This paper has evaluated the past, present, and future occurrence of hydrological and meteorological drought in the Danube Plain territory, Northern Bulgaria by applying the SDI and SPI indexes. The conclusions of the study are as follows:

1. According to the results most of the investigated area is drought-prone and regional water management projects focusing on drought mitigation should be made a priority.
2. The SDI-SPI analysis results in this study showed significant drought characteristics at the annual (November–October) and the winter (November–April) periods.
3. Severe hydrological droughts occurred only once, in 1994/95(Vit River basin). Furthermore, in 1994/95, 2001/02, and 2007/08, most of the investigated areas were suffering from a mild to moderate drought. Analysis results for the occurrence probability of drought events showed that the occurrence probability of a drought event is higher in the Yantra and Topolnica River basins.
4. The results also showed good synchronicity between multi-year variability of the meteorological drought index (SPI) and the hydrologic

količine oborina od 10 do 20 %. Količina zimskih oborina također će se smanjiti za otprilike 10 % do kraja stoljeća, ali se značajno smanjenje očekuje i kod ljetnih oborina – od otprilike 20 do 30 % (MOEW, 2014).

Uzevši u obzir značajne koeficijente korelacije između SDI-12 i SPI-12 (od 0,44 do 0,70) izračunate na temelju mjerenih podataka i rezultata SPI-a izračunatih na temelju podataka modela, može se očekivati slična raspodjela hidroloških i meteoroloških suša i veća pojavnost blagih i umjerenih suša tijekom 21. stoljeća. Visok stupanj konvergencije između indeksa SPI i SDI i taj odnos, zajedno s identificiranim referentnim razdobljima, može se primijeniti u dugoročnim predviđanjima suša i planiranju politika za razvoj integriranoga upravljanja vodnim resursima u Bugarskoj.

Zaključak

Ovaj je rad analizirao prošle, trenutne i buduće pojavnosti hidrološke i meteorološke suše na području Dunavske ravnice u sjevernoj Bugarskoj primjenom indeksa SDI i SPI. Zaključci studije su sljedeći:

1. Prema rezultatima veći dio ispitivanoga područja podložan je sušama te prioritet trebaju biti regionalni projekti upravljanja vodom s naglaskom na suzbijanje suša.
2. Rezultati analize SDI-SPI pokazali su značajne karakteristike suše u godišnjim (studeni – listopad) i zimskim (studeni – travanj) razdobljima.
3. Jaka hidrološka suša nastupila je samo jednom, 1994./95. godine (porječje rijeke Vit). Nadalje, 1994./95., 2001./02. i 2007./08. na većem dijelu ispitivanoga područja došlo je do slabe odnosno umjerene suše. Rezultati analize za vjerojatnost pojave suše pokazali su da je ona veća u porječjima rijeka Yantra i Topolnica.
4. Rezultati su također pokazali dobru usklađenost između višegodišnje varijabilnosti indeksa meteorološke suše (SPI) i indeksa hidrološke

drought index (SDI). The values of the correlation coefficients between SPI -12 and SDI -12 are higher than between SPI -6 and SDI -6. On the other hand, according to SPI, dry years represented about 40–50% of the years in the period 1993–2009, and SDI showed that more than 70% of the investigated years were dry. This indicated that rainfall was not the only factor that determined hydrological drought. Future investigation should be extended by including the new factors as evapotranspiration, air temperature, aquifer level, soil permeability, vegetation, etc.

5. A statistically significant correlation between SDI and SPI based on the observation data, and SPI calculated for future periods (2021–2050 and 2051–2080), led to the conclusion that we will observe an increasing frequency of occurrences of moderate hydrological drought during the second part of the 21st century.

suše (SDI). Vrijednosti koeficijenata korelacije između SPI-12 i SDI-12 veći su nego između SPI-6 i SDI-6. S druge strane, prema indeksu SPI suhe godine predstavljaju oko 40 do 50 % godina u razdoblju od 1993. do 2009. godine, a SDI je pokazao da je više od 70 % proučavanih godina bilo suho. To upućuje na činjenicu da oborine nisu bile jedini faktor koji je određivao hidrološku sušu. Buduća istraživanja trebala bi se proširiti tako da obuhvate nove čimbenike poput evapotranspiracije, temperature zraka, razine vodonosnika, propusnosti tla, vegetacije itd.

5. Statistički značajna korelacija između indeksa SDI i SPI na temelju podataka o promatranju i SPI izračunata za buduća razdoblja (2021. – 2050. i 2051. – 2080.) dovode do zaključka da će se bilježiti veća učestalost pojava umjerenih hidroloških suša tijekom druge polovine 21. stoljeća.

Note
Napomena

Professional Terms Editing:
Ivan Čanjevac, PhD, Assistant Professor

Translation: Martina Batinica

Stručna redaktura:
doc. dr. sc. Ivan Čanjevac

Prijevod: Martina Batinica

Acknowledgement
Zahvala

This article was partly supported by the Grant Agencies of the Slovak Republic under the project Vega No. 1/0940/17

Ovaj je članak djelomično potpomogla Agencija za dodjelu sredstava Republike Slovačke u sklopu projekta Vega br. 1/0940/17.

Literature
Literatura

Alexandrov, V. (ed), 2011: *Methods for monitoring and estimation of drought vulnerability in Bulgaria*, National Institute of Meteorology and Hydrology, Bulgarian Academy of Science, Sofia (In Bulgarian)

Alexandrov, V., Radeva S., Koleva E., 2011., Utilization of SPI, PDSI, and RDI as drought indicators in South Bulgaria, in: *11th International Multidisciplinary Geoconference Proceedings* II, 969-976.

Edwards, D. C., McKee, T. B., 1997: Characteristics of 20th century drought in the United States at multiple scales, *Atmospheric Science Paper* 634, 1–30.

European Commission, 2007: Drought management plan report. Including Agricultural, Drought Indicators and Climate Change Aspects. Water Scarcity and Droughts Expert Network of Common Implementation.

Gocheva, A., Malcheva, K. T. Marinova, 2010: Some Drought Indices for the Territory of Bulgaria, *3rd National Conference with International Participation "Opportunities for Limitation the Drought Damages on Agricultural Crops" and National Seminar DMCSEE*, Sofia.

Hong, X., Shenglian, G., Yanlai, Z., Xiong, L., 2015: Uncertainties in assessing hydrological drought using streamflow drought index for the upper Yangtze River basin, *Stochastic Environmental Research and Risk Assessment* 29 (4), 1235-1247.

IPCC, 2013: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change (eds. Stocker, T. F., Qin, D., Plattner, G. – K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, Y., Midgley, P. M.), Cambridge University Press, Cambridge and New York.

Keyantash, J., Dracup J.K. 2002: The quantification of drought: An evaluation of drought indices, *Bulletin of the American Meteorological Society* 83, 1167–1180.

Knight G, Raev I, Staneva M., 2004: *Drought in Bulgaria: A Contemporary Analog for Climate Change,* Ashgate, Aldershot.

Koleva, E., 1995: Drought in the lower Danube basin. *Drought network news* 1 (1), 6-7.

Koleva, E., Alexandrov V., 2008: Drought in the Bulgarian low regions during the 20th century. *Theoretical and Applied Climatology*.

Lapin, M., Bašták-Ďurán, I., Gera, M., Hrvoľ, J., Kremler, M., Melo, M., 2012: New climate change scenarios for Slovakia based on global and regional general circulation models. – *Acta Mathematica Universitatis Comenianae* 37, 25–74.

Madadgar, S., Moradkhani, H., 2013: Drought Analysis under Climate Change Using Copula, *Journal of Hydrologic Engineering* 18, 746–759

MOEW, 2012: National strategy for management and development of the water sector in Bulgaria, Sofia.

MOEW, 2014: Analysis and assessment of risk and vulnerability of sectors of the Bulgarian economy from climate change, http://www.moew.government.bg/static/media/ups/tiny/file/Climate/obshta_chast.pdf (14.01.2018.)

Nalbantis, I., 2008. Evaluation of a Hydrological Drought Index, *European Water* 23, 67–77.

Nalbantis, I., Tsakiris, G., 2009: Assessment of hydrological drought revisited, *Water Resources Manag*ement 23, 881–897.

Nikolova, N. 2013: The Impact of the Drought on the Main Crops Cultivated in the Northeast Bulgaria, *Forum geografic* 12 (1), 16-24, DOI: 10.5775/fg.2067-4635.2013.016.i

Nikolova N, Alieva G., Voislavova I., 2012: Drought Periods in Non-Mountainous Part of South Bulgaria on the Background of Climate Change, *Geographica Pannonica* 16 (1), 18-25.

Rimkus, E., Stonevičius, E., Korneev, V., Kažys, J., Valiuškevičius, G., Pakhomau, A., 2013: Dynamics of meteorological and hydrological droughts in the Neman river basin, Environmental Research Letters 8 (4), 1-10.

River Basin Management Plan for the Danube-River-Basin (2016-2021), http://www.bd-dunav.org/content/upravlenie-na-vodite/plan-za-upravlenie-na-rechniia-baseyn/aktualizaciia-na-purb/ (26 June 2018)

Tabari, H., Nikbakht, J., Talaee, P. H., 2013: Hydrological Drought Assessment in Northwestern Iran Based on Streamflow Drought Index (SDI), *Water Resources Manag*ement 27, 137–151.

Vasiliades L, Loukas A, Liberis N., 2011: A water balance derived drought index for Pinios River Basin, Greece, *Water Resources Management* 25, 1087–1101.

Authors
Autori

Kalina Radeva kradeva@gea.uni-sofia.bg
PhD, Assistant Professor, St. Kliment Ohridski University of Sofia, Faculty of Geology and Geography, Tsar Osvoboditel Blvd. 15, 1504 Sofia, Bulgaria

Nina Nikolova nina@gea.uni-sofia.bg
PhD, Associate Professor, St. Kliment Ohridski University of Sofia, Faculty of Geology and Geography, Tsar Osvoboditel Blvd. 15, 1504 Sofia, Bulgaria

Martin Gera mgera@fmph.uniba.sk
PhD, Assistant Professor, Comenius University, Faculty of Mathematics, Physics and Informatics, Mlynská dolina F1, 842 48 Bratislava, Slovakia