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CLIMATE CHANGE INFLUENCE ON THE OCCURRENCE OF EXTREME DRY-WET PERIODS IN BOSNIA AND HERZEGOVINA

SUMMARY

The air temperature in Bosnia and Herzegovina is increasing (0.3 - 0.6 °C per decade), while rainfall events are more extreme. Additionally, there is an increased variability in weather conditions across all seasons, marked by rapid shifts from extremely cold to warm weather, as well as transitions from periods of exceptionally high rainfall to exceedingly dry periods. Droughts and floods pose the most significant risks. However, Bosnia and Herzegovina faces a lack of adequate information and analyses of extreme climate events, especially regarding their timing, intensity, magnitude, duration, and spatial extent. Therefore, this study aims to address these questions using the precise drought index SPEI. The identified wet years were: 1969, 1970, 1976, 1978, 1999, 2001, 2010, 2013, and 2014, while the dry years were 1961, 1971, 1983, 1990, 2000, 2003, 2007, 2011, 2012, and 2020. In the northern and western regions of BiH, the longest wet period in terms of duration and spatial extent occurred from May 2014 to July 2015. In the central and southern parts of BiH, the longest wet period extended over 19 months from February 1969 to August 1970. The longest drought with the largest spatial extent was the drought from August 2011 to July 2013. The obtained data shows a significant shift towards drier weather, as dry months have increased by 15% compared to wet months. At the same time, there has been a decrease in near-normal conditions and an increase in extremely wet months.

Keywords: SPEI, Drought, Flood, Climate change, extreme weather conditions

INTRODUCTION

Many studies on climate change in Bosnia and Herzegovina (BiH) agree that air temperatures are rising (0.3 - 0.4°C per decade), with the most

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pronounced increases occurring during the summer (up to 0.6°C per decade)(Čadro et al., 2023; Popov, 2020; Popov et al., 2018a; Popov et al., 2018b; Trbic et al., 2017). On the other hand, precipitation trends are not consistent (Čadro et al., 2020; Čadro et al., 2023; Popov et al., 2019; Popov et al., 2017; PSP-BiH, 2023), and in most cases, there are no significant changes in annual precipitation totals (FNC, 2021; TNC, 2016). However, these studies consistently emphasize that due to the increased occurrence of heavy rainfall in the total precipitation, the risk of floods has heightened, particularly in the northeastern region of Bosnia and Herzegovina (FNC, 2021; NAP, 2021).

According to regional climate models (RCM), under the Representative Concentration Pathway RCP8.5 or "worst-case scenario", the projected change in mean daily temperature for the near future (up to 2035) in BiH, varies between 0.5 to 1.5°C, while for the last period temperature increase ranges from 2.5 to 5°C. Notably, there is a particular emphasis on the rise in maximum daily temperatures during the June-July-August (JJA) season (FNC, 2021). Additionally, JJA is the period with the most significant reduction in precipitation, which for the last period of the prediction may be as much as a 30% decrease, particularly in the southern part of the country (FNC, 2021). Such a situation primarily contributes to the increasing occurrence of extreme weather conditions, such as heatwaves, spring frosts, and intense rainfall leading to floods, and droughts.

During the last 20 years, nearly every year in BiH was characterized by extreme weather conditions. Specifically, 2001, 2003, 2004, 2009, 2010, 2014, and 2019 are classified as flood years, while 2000, 2003, 2007, 2011, 2012, 2013, 2015, 2016, and 2017 are categorized as years of droughts and heatwaves (FACP, 2014; NAP, 2021; PSP-BiH, 2023; TNC, 2016; UNDP, 2020). Floods and droughts are one of the main natural causes of agricultural, economic, and environmental damage (Vicente-Serrano et al., 2010).

Given this situation, significant effort has been invested globally in developing a unified approach to drought monitoring. Currently, the most widely used indices worldwide are the Palmer Drought Severity Index – PDSI (Palmer, 1965), the Standardized Precipitation Index – SPI (McKee et al., 1993), and more recently, the Standardized Precipitation Evapotranspiration Index – SPEI (Vicente-Serrano et al., 2010). SPEI is defined as a drought index. However, similar to the SPI, it has a multi-scalar character (Christidis & Stott, 2021) and it can also be utilized to represent wet periods. It requires more input data compared to the SPI but provides a more realistic depiction as it incorporates the evapotranspiration factor (Pei et al., 2020), i.e., the difference between precipitation and evapotranspiration: PRCP-ET_o (Čadro et al., 2017).

If basic climate data is available, such as air temperature (T_{min} and T_{max}), it may be sufficient for estimating evapotranspiration using methods like Thornthwaite (1948) or Hargreaves and Samani (1985). However, if there are data on relative humidity (RH_{min} and RH_{max}), wind speed (u), and sunshine duration (n), more accurate methods like standardized FAO56-PM (Allen et al., 1998) can be used to obtain more precise results.

Responsibility for climate data collection necessary for Early Warning (EW) and Decision Support Systems (DSS) is divided among the BiH entities, for the Federation of Bosnia and Herzegovina (FBiH) the Federal Hydrometeorological Institute BiH (FHMI) and for the Republika Srpska (RS) the Republic Hydrometeorological Service of Republika Srpska (RHMS). Monitoring involves daily collection of basic climate data, calculating reference evapotranspiration (Hargreaves & Samani, 1985), measuring water levels and flows of major rivers, monitoring soil temperature, and various phenological characteristics (FHMZ, 2022, 2023; RHMZ, 2023). Drought is determined using the Standardised Precipitation Index – SPI (McKee et al., 1993), with a spatial representation of moisture conditions by FBiH and RS entities, along with SPI_2 indicating the moisture condition of the last two months and the forecasted SPI_1 for the next 30 days. FHMI and RHMS are more focused on weather forecasts and drought alerts, while river basin agencies, such as the Agency for the Sava River Basin (AVP Sava) and Waters of Republika Srpska (JU VS), focus on hydrology and floods. These institutions use a hydrological-hydraulic forecasting platform and a Water Information System for stream monitoring (ISV) as part of the flood early warning system. Their responsibility is to inform relevant institutions in Bosnia and Herzegovina, as well as the public, about activities related to the protection and rescue of people and property (AVP, 2021).

Based on numerous national plans and strategic documents (NAP, 2021; TNC, 2016; Trbic et al., 2018; UNDP, 2013, 2020; WBG, 2021), BiH is committed to supporting a wide range of climate change adaptation measures including the implementation of improved water resources management systems, investments in new irrigation-drainage systems (WB, 2020), development of an early warning system for meteorological and climatic extremes with special focus on floods and droughts, support for the application of Smart Agriculture practices (drones, remote sensing, software, sensors as well as automatization and digitalization), and new farming systems more appropriate for hotter and more arid climates. Although these activities are fully aligned with European objectives and the Sofia Declaration (RCC, 2021) that Bosnia and Herzegovina signed on November 10, 2020, their implementation is delayed due to the insufficiently robust institutional, policy, and legislative framework for risk management and adaptation to climate change. Additionally, sustainable financial mechanisms for their implementation are needed (FNC, 2021; MAWFFiB, 2022).

However, BiH faces a lack of adequate information and analyses of extreme climate events, primarily floods and droughts. Often, it is not possible to get answers to a large number of questions such as: Which years in BiH were dry and which were wet? What was the strongest and longest such event? Which events had the greatest spatial extent? Are these events more frequent today than before? What is the best method for their determination? Is this process valid compared to recorded droughts and wet spells? Can this determination method be used for automatic monitoring of these occurrences and integrated into future early warning systems? Hence, the aim of this study is to address some of these questions. Specifically, using the precise drought index – Standardized Precipitation Evapotranspiration Index (SPEI), it aims to analyze the occurrence, intensity, magnitude, duration, and frequency of wet and dry periods in BiH, considering various locations (Bihać, Livno, Tuzla, Sanski Most, Sarajevo and Mostar) to analyze the spatial extent of these events. Additionally, through these analyses, the study aims to verify the credibility of the obtained data in comparison to recorded extreme floods and droughts across BiH.

MATERIAL AND METHODS

Study area and data availability

For this study, six weather stations (WS) were selected to represent all significant regions in BiH: Bihać, Tuzla, and Sanski Most in the north/west part of BiH and Sarajevo, Livno, and Mostar in the central/south part. From these WS, a dataset of continuous monthly values for the period from 1961 to 2020, covering 60 years or a total of 720 months. These data include maximum (T_{max}), average (T_{mean}), and minimum (T_{min}) air temperatures, monthly precipitation totals (PRCP), average relative air humidity (RH_{mean}), monthly insolation averages (n), and wind speed (u). The data was provided by the Federal Hydro-Meteorological Institute of BiH. The basic geographical characteristics of this location are given in Table 1.

Table 1. Basic geographical and climate characteristics of research locations

Weather station	°E	°N	Altitude (m)	PRCP (mm)	T_{mean} (ºC)	Köppen–Geiger
Bihać (BI)	15°51'	44°48'	246	1341	11.0	Cfb x"s
Tuzla (TU)	18°41'	44°32'	305	906	10.4	Cfb x"s
Sanski Most (SM)	16°40'	44°46'	158	1039	10.5	Cfb x"s
Sarajevo (SA)	18°25'	43°52'	630	940	9.9	Cfb x"s
Mostar (MO)	17°47'	43°20'	99	1493	15.0	Csa sx"
Livno (LI)	17°00'	43°49'	724	1151	9.4	Cfb x"s

Note: °E – longitude; °N – latitude; PRCP – precipitation; T_{mean} – mean air temperature; Csa sx" – Mediterranean climate; Cfb x"s – temperate warm and humid climates

In terms of altitude, the lowest WS is located in Mostar (99 m), while the highest is in Livno (724 m). All locations fall under the classification of a temperate warm and humid climate (Cfb), except for Mostar which exhibits a Mediterranean climate, and thus has distinctive climatic characteristics, including higher average air temperature (15.0°C) and a greater total precipitation (1493 mm). However, the locations differ in terms of annual precipitation totals and average air temperatures. Precipitation ranges from 906 mm in Tuzla to 1314 mm in Bihać, and average air temperatures range from 9.4°C in Livno to 11.00°C in Bihać.

Reference evapotranspiration (ET_0) and index (SPEI) calculation

Reference evapotranspiration (ET_0) was calculated using FAO56-PM (Allen et al., 1998):

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \frac{900}{T_{mean} + 273} u_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)}$$

where ET_0 is the reference evapotranspiration (mm/day), R_n the net radiation at the crop surface (MJ/m^2/day), G the soil heat flux density (MJ/m^2/day), T_{mean} the mean daily air temperature at 2 m height (^oC), u_2 the wind speed at 2 m height (m/s), es the saturation vapor pressure (kPa), e_a the actual vapor pressure (kPa), e_s - e_a the saturation vapor pressure deficit (kPa), Δ the slope of the vapor pressure curve (kPa/^oC) and γ is the psychrometric constant (kPa/^oC).

The calculation was performed based on all necessary parameters (air temperature, air humidity, solar radiation, and wind speed). The absence of solar radiation (R_s), required for R_n calculation, was compensated by using insolation data (n) and the Ångström equation (Ångström, 1924):

$$R_s = \left(a_s + b_s \frac{n}{N}\right) R_a$$

where R_a is the extraterrestrial radiation (MJ/m^2/day), N is the maximum possible duration of sunshine or daylight hours (h), a_s is the regression constant, expressing the fraction of extraterrestrial radiation reaching the earth on overcast days (n = 0) and a_s + b_s is the fraction of extraterrestrial radiation reaching the earth on clear days (n = N). Values of a_s = 0.25 and b_s = 0.5 were used as suggested by (Allen et al., 1998). Monthly values ET_0 following previously mentioned equations were calculated using the SRCLET tool available at: https://meet.motherlandia.org/srclet/.

To assess extreme wet and dry periods or spells standardized precipitation evapotranspiration index or SPEI (Vicente-Serrano et al., 2010) is calculated for a longer 12 months' time scale ($SPEI_{12}$). $SPEI_{12}$ is a long-term wet or dry period influencing groundwater storages and the hydrological regime in general, considered a hydrological drought.

SPEI can have both positive and negative values. Positive values indicate a wet period, while negative values indicate a dry one. Based on the intensity of the value, dry and wet events are categorized. Values between -1 and 1 are defined as "Near normal" conditions, indicating a period of typical weather conditions for the given area (McKee et al., 1993; Vicente-Serrano et al., 2010). In this study, "Near normal" is divided into two categories: values from 0.0 to 1.0, which we defined as "Near normal wet", and values from 0.0 to -1.0, which we defined as

"Near normal dry". This was done to allow for a more appropriate comparison of wet and dry periods. The following table provides the classification of SPEI based on these criteria (Table 2). Additionally, a color has been assigned to represent each value. Blue indicates a wet period, while red indicates a dry one.

Table 2. Dry and wet month categories based on SPEI values

SPEI category	SPEI value	Abbreviation
Extremely wet	> 2.00	EW
Very wet	1.50 - 2.00	VW
Moderately wet	1.00 - 1.50	MW
Near normal wet	0.00 - 1.00	NNW
Near normal dry	0.00 - -1.00	NND
Moderately dry	-1.00 - -1.50	MD
Severely dry	-1.50 - -2.00	SD
Extremely dry	< -2.00	ED

Each dry or wet event can be defined by its duration, which is calculated as the number of months from the moment when the index value was 1 or higher (wet period) or -1 or lower (dry period). When the value reaches the "near normal" level (from -0,99 to 0,99), this event comes to an end. The sum of accumulated SPEI values for such an event is defined as Drought magnitude – DM (McKee et al., 1993). Peak wet-dry event intensity or drought severity is defined as the value for each month following the SPEI classification.

In this study, $SPEI_{12}$ is calculated to assess wet-dry events on an annual basis and determine wet and dry years. The number of wet-dry months is analyzed by categories, along with their percentage concerning the entire period (720 months). Furthermore, the duration, magnitude, and severity of wet-dry events are defined. To determine the influence of climate change on the occurrence of such events, the entire analysis period (1961 - 2020) is divided into two periods: the period from 1961 - 1990, defined as the “reference climatic period”, and the period from 1991 - 2020, defined as the "current state of the climate".

$SPEI_{12\ December}$, takes into account the state of the previous 12 months, considering December as the last month of that period. This allows it to be used to describe a specific year within the period of 1961 - 2020 with a single SPEI value. The values of this index are analyzed, and a linear trend is calculated to determine the impact of climate change on the occurrence of extremely wet and extremely dry periods. Additionally, the #ShowYourStripes principle is applied (Hawkins, 2023).

RESULTS AND DISCUSSION

Precipitation (PRCP) and reference evapotranspiration (ET_0)

Before we analyze wet-dry periods, it is important to examine the parameters used for their determination, namely precipitation (PRCP) and reference evapotranspiration (ET_0). Table 3 provides the average values of monthly, seasonal, and annual sums of PRCP and ET_0 for each of the six analyzed locations.

Table 3. Monthly, seasonal, and annual average sums of PRCP and ET_0 for the period 1961 - 2020.

	LO	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	DJF	MAM	JJA	SON	*Veg.*	*Ann.*
PRCP (mm)	BI	95	97	101	111	120	106	99	96	132	122	148	120	311	332	301	**402**	*664*	*1346*
	LI	96	88	92	95	82	83	52	66	98	115	154	132	316	268	201	**368**	*475*	*1153*
	TU	58	54	60	74	97	114	95	77	70	67	71	71	184	231	**286**	208	*527*	*909*
	SM	70	68	77	89	99	103	86	81	99	90	93	89	227	265	269	**282**	*556*	*1042*
	SA	69	67	69	76	85	89	78	67	80	84	90	87	223	229	234	**253**	*474*	*939*
	MO	154	140	134	125	97	74	49	66	117	151	194	180	**474**	357	189	462	*528*	*1482*
ET_0 (mm)	BI	16	23	46	72	100	118	**132**	114	74	46	26	17	57	218	**364**	146	*610*	*785*
	LI	16	26	46	69	98	116	**136**	122	81	49	27	17	59	214	**375**	157	*623*	*805*
	TU	14	22	43	67	95	110	**125**	114	75	46	24	15	50	206	**348**	145	*586*	*749*
	SM	14	23	46	70	99	115	**131**	116	76	47	25	15	52	215	**362**	148	*607*	*777*
	SA	15	23	47	70	98	114	**129**	117	79	49	26	16	54	215	**361**	154	*608*	*784*
	MO	32	42	67	87	120	144	**179**	163	110	69	39	33	107	273	**486**	218	*803*	*1084*

Note: LO – Location name; DJF – December, January, and February or winter; MAM – March, April and May or spring; JJA – June, July, and August – or summer; SON – September, October, and November or autumn; Veg. vegetation period; Ann - Annual; PRCP – Total precipitation in mm; ET_0 – Reference evapotranspiration in mm; BI – Bihać, LI – Livno; TU – Tuzla; SM – Sanski Most; SA – Sarajevo, MO - Mostar

Annually the highest sums of PRCP (1482 mm) and ET_0 (1084 mm) are recorded at the Mostar (MO) location. Following Mostar, the highest PRCP values are observed in Bihać (1346 mm) and Livno (1153 mm), while in Sanski Most (SM), Tuzla (TU), and Sarajevo, the values are similar, ranging around 1000 mm. The sum of ET_0, except for Mostar, ranges narrowly from 749 to 805 mm. When observing the seasons, only in the Tuzla location the highest amount of precipitation occurs during the summer period (June - August). In Mostar highest PCP is in winter (December – February) while in all other locations, the majority of the PRCP occurs in autumn (September - November).

Monthly, there are significant differences among the six research locations. In Mostar, which has the highest amount of PRCP, the smallest amount falls during the summer, whereas June in Tuzla (114 mm), Sanski Most (103 mm), and Sarajevo (89 mm) is one of the rainiest months of the year. In the locations of Bihać and Livno, autumn is by far the rainiest period, with September being the wettest month, averaging 148 mm in Bihać and 154 mm in Livno. The month with the highest ET_0 values at all locations is July, with its value ranging from 114 mm in Tuzla to 163 mm/month in Mostar.

Standardized precipitation evapotranspiration index (SPEI)

In this study, the Standardized Precipitation Evapotranspiration Index (SPEI) is computed using $SPEI_{12}$ and extracting $SPEI_{12\ December}$ to evaluate wet and dry events on an annual scale, enabling the identification of wet and dry years. This analysis also allows for the characterization of the duration (DU), magnitude (MA), and severity (PV) of these events.

$SPEI_{12}$

Given that any month with a SPEI value above 1 is considered a wet period, and a value below -1 is considered a dry period (table 1.), the following table provides the average values of all such months for $SPEI_{12}$, as well as the peak values for all six locations.

Table 4. The average and peak (max) values of $SPEI_{12}$ for all wet and dry months in the period from 1961 to 2020.

	Location	BI	TU	SA	SM	MO	LI	BiH
WET	Average	0.82	0.80	0.79	0.79	0.79	0.83	*0.80*
	Max	3.30 *10.2014*	2.74 *03.2015*	2.50 *06.1978*	2.94 *03.2015*	2.38 *12.2010*	2.33 *11.2010*	*3.30* *10.2014*
DRY	Average	-0.79	-0.79	-0.85	-0.81	-0.85	-0.81	*-0.82*
	Max	-2.62 *01.2004*	-2.39 *07.2012*	-2.33 *05.1983*	-2.54 *11.2011*	-2.15 *06.1989*	-2.31 *05.1989*	*-2.62* *01.2004*

Note: BI – Bihać, LI – Livno; TU – Tuzla; SM – Sanski Most; SA – Sarajevo, MO - Mostar

Based on the average values of $SPEI_{12}$ for all wet and dry months, the location with the highest values in the wet interval (1 >) is Livno (0.82), and the lowest values are in Sarajevo, Sanski Most, and Mostar (0.79). This indicates that Livno is the location where the changes in the number of wet months are most pronounced. On the other hand, the values in the dry interval (< -1) are most pronounced in Sarajevo and Mostar (-0.85), while the least pronounced are in Bihać and Tuzla (0.79). The average for BiH indicates greater changes in the direction of dry intervals (-0.82) than in wet (0.80). Moreover, if we examine the peak values, the SPEI of 3.30 is the highest value and occurred in Bihać in October 2014. Bihać also had the highest value for the dry period, which is -2.62, and occurred in January 2004. The lowest peak values were recorded in Livno and Mostar. According to the analysis of all $SPEI_{12}$ months, the highest values for wet conditions occur in the years 1978, 2010, 2014, and 2015. However, the lowest SPEI values, meaning the driest months, occurred in 1983, 1989, 2004, 2011, and 2012. Interestingly, in both the wet and dry periods, these are mostly years after 1991.

The following table presents the percentage distribution of months classified under $SPEI_{12}$ from extremely wet (SPEI >2) to extremely dry (SPEI <-2) for all research locations, as well as the average for BiH. The data is divided into two climatic periods, 1961 - 1990 and 1991 – 2020, and the difference in percentage values between these two periods is also provided (Table 5).

Based on the analysis of the percentage distribution of months in different $SPEI_{12}$ categories, which was conducted separately for two climatic periods (Table 5), and the calculated differences between them, it can be noted that there has been an increase in extremely wet months at all locations except Sarajevo, and a decrease in near normal conditions at all locations, with a particularly significant decrease in Tuzla, where the number is lower by 24%.

Table 5. The percentage distribution of months in different $SPEI_{12}$ categories

	1961 - 1990							1991 - 2020							Difference						
	B	T	S	SA	M	L	BiH	B	T	S	SA	M	L	BiH	B	T	S	SA	M	L	BiH
EW	1	1	3	0	1	0	1	4	4	0	4	1	2	2	**4**	3	-3	**4**	0	2	2
VW	2	3	6	6	7	9	5	3	7	4	2	5	4	4	1	4	-2	-4	-1	-4	-1
MW	9	6	10	11	14	11	10	13	9	11	8	6	9	9	3	3	1	-3	-8	-3	-1
NNW	36	47	37	36	38	32	38	31	23	33	36	32	32	31	-5	**-24**	-4	0	-6	0	-6
NND	38	31	30	34	27	36	33	33	39	29	33	34	33	33	-5	8	-1	-1	7	-4	1
MD	10	4	7	9	7	7	8	8	11	15	8	13	12	11	-3	**7**	**8**	-1	6	5	4
SD	3	5	5	3	6	2	4	6	5	7	7	8	8	7	2	0	2	4	2	6	3
ED	1	3	2	2	1	2	2	3	2	1	3	0	1	2	2	0	0	1	0	-1	0
WET	47	57	56	52	60	52	54	51	43	48	49	44	47	47	4	**-15**	**-8**	**-4**	**-15**	**-5**	**-7**
DRY	53	43	44	48	40	48	46	49	57	53	51	56	53	53	-4	15	8	4	15	5	7

Note: BI – Bihać, LI – Livno; TU – Tuzla; SM – Sanski Most; SA – Sarajevo, MO – Mostar; EW - Extremely wet; VW - Very wet; MW - Moderately wet; NNW - Near normal wet; NND - Near normal dry; MD - Moderately dry; SD - Severely dry; ED - Extremely dry

Essentially, the changes in dry months are less pronounced than the changes in wet months. There's a general increase in the number of dry months, particularly in the category of severely dry, and this increase is most noticeable in Tuzla and Sarajevo, where it's 7% and 8% respectively. The data indicates a marked shift towards drier weather conditions, with a general increase in dry months in contrast to wet months, except Bihać. The change is most pronounced in Tuzla and Mostar, where dry months have increased by 15% compared to wet months. Additionally, there has been a decline in near-normal weather conditions and a rise in extremely wet months. This could have a range of potential impacts in the future, such as changes in agriculture and water management, increased risk of flooding, and socio-economic implications for affected communities.

The following table presents the analysis of the magnitude (MA), duration in months (DU), and peak value (PV) of wet-dry periods based on $SPEI_{12}$ for each research location. The following table displays only the first 5 wet-dry periods ranked highest in magnitude (MA) value.

The data presented in Table 6, namely the wet and dry periods, are ranked according to their magnitude (MA), which is calculated as the sum of SPEI values from the beginning to the end of a given wet-dry.

In the overall analyzed period, the wettest period with the highest magnitude of 31.11 occurred in Bihać, lasting for 13 months from 07.2014 to 07.2015. The next wettest periods were in Sarajevo, with a magnitude of 30.48 (02.1969 - 08.1970), and in Sanski Most with a magnitude of 30.05 in the same period as Bihać. The longest recorded wet period (DU) was observed in Sarajevo and Sanski Most (02.1969 - 08.1970) when the monthly value of $SPEI_{12}$ remained above 1 for a remarkable 19 months.

Table 6. Magnitude (MA), duration in months (DU), and peak value (PV) of wet-dry periods based on $SPEI_{12}$

	WET					**DRY**				
	RA	Period	DU	MA	PV	RA	Period	DU	MA	PV
BI	1	***07.2014 - 07.2015***	13	31.11	3.30	1	***09.2011 - 10.2012***	14	-27.12	-2.41
	2	***01.1994 - 07.1994***	9	12.26	1.65	2	***08.2003 - 08.2004***	13	-24.55	-2.62
	3	***05.2010 - 12.2010***	8	15.43	2.78	3	*05.1990 - 02.1991*	10	-16.94	-2.27
	4	*01.1977 - 07.1977*	7	12.22	2.02	4	***04.2007 - 10.2007***	7	-11.94	-1.97
	5	***12.1999 - 05.2000***	6	8.71	1.70	5	*07.1971 - 03.1972*	9	-11.89	-1.59
TU	1	*02.1970 - 03.1971*	14	23.82	2.30	1	***08.2011 - 07.2013***	24	-42.93	-2.39
	2	***07.2001 - 08.2002***	14	23.42	2.25	2	*07.1971 - 06.1972*	12	-23.07	-2.23
	3	***05.2010 - 03.2011***	11	19.54	2.24	3	*06.1990 - 04.1991*	11	-19.64	-2.36
	4	***01.2015 - 06.2015***	6	12.91	2.74	4	***06.2007 - 04.2008***	11	-15.37	-2.12
	5	***06.2005 - 12.2005***	7	11.15	1.97	5	*11.1988 - 06.1989*	8	-12.54	-1.96
SM	1	***07.2014 - 07.2015***	13	30.05	2.94	1	***08.2011 - 01.2013***	18	-33.59	-2.54
	2	***05.2010 - 02.2011***	10	17.55	2.48	2	*05.1988 - 06.1989*	13	-18.46	-2.10
	3	*10.1974 - 09.1975*	12	16.72	1.89	3	***07.2000 - 05.2001***	11	-17.93	-2.01
	4	*07.1976 - 05.1977*	11	16.47	1.78	4	*07.1971 - 06.1972*	12	-17.77	-1.83
	5	*10.1972 - 07.1973*	10	15.78	1.86	5	*05.1990 - 02.1991*	10	-16.88	-2.34
SA	1	*02.1969 - 08.1970*	19	30.48	2.30	1	***12.2019 - 12.2020***	13	-21.55	-2.28
	2	*02.1978 - 04.1979*	15	28.52	2.50	2	***11.1992 - 01.1994***	15	-21.43	-2.10
	3	***01.2010 - 12.2010***	12	16.42	1.76	3	*07.1990 - 06.1991*	12	-21.21	-2.18
	4	***08.2005 - 01.2006***	6	8.78	1.67	4	*08.1982 - 08.1983*	13	-20.94	-2.33
	5	***02.2005 - 06.2005***	5	6.23	1.44	5	*09.1973 - 05.1974*	9	-12.00	-1.69
MO	1	***02.2010 - 02.2011***	13	23.65	2.38	1	*01.1989 - 01.1991*	25	-41.02	-2.15
	2	*03.1978 - 04.1979*	14	22.85	2.12	2	***11.2011 - 10.2012***	12	-18.89	-1.94
	3	***03.2013 - 01.2014***	12	21.65	2.16	3	***02.1993 - 12.1993***	11	-17.04	-2.01
	4	*12.1976 - 11.1977*	12	20.96	2.22	4	***10.1994 - 07.1995***	10	-16.19	-1.94
	5	*12.1969 - 08.1970*	9	14.22	1.91	5	***12.2006 - 11.2007***	12	-15.85	-1.73
LI	1	*02.1969 - 08.1970*	19	28.04	1.90	1	*05.1990 - 04.1991*	12	-21.39	-2.30
	2	***07.2014 - 06.2015***	12	21.68	2.13	2	***11.2011 - 09.2012***	12	-18.38	-2.03
	3	***03.2010 - 03.2011***	13	20.81	2.33	3	***09.1997 - 08.1998***	12	-16.26	-1.63
	4	*05.1978 - 04.1979*	12	17.7	1.77	4	***01.1993 - 10.1993***	10	-14.74	-1.95
	5	*11.1964 - 09.1965*	11	17.56	1.85	5	***07.2003 - 02.2004***	8	-13.94	-2.05
Bihać (BI)			43	79.74	2.29			53	-92.44	-2.17
Tuzla (TU)			52	90.84	2.30			66	-113.55	-2.21
Sanski Most (SM)			56	96.57	2.19			64	-104.63	-2.16
Sarejevo (SA)			57	90.43	1.93			62	-97.13	-2.12
Mostar (MO)			60	103.33	2.16			70	-108.99	-1.95
Livno (LI)			67	105.79	2.00			54	-84.71	-1.99

Note: BI – Bihać, LI – Livno; TU – Tuzla; SM – Sanski Most; SA – Sarajevo, MO – Mostar; RA – Rank; DU – Duration in months; MA – Magnitude; PV – Peak value

Summing up the values of the first five wet periods for each location points to the longest wet periods in Livno (105.79) and Mostar (103.33). However, the months with the highest SPEI values are in Tuzla (2.30) and Bihać

(2.29). It is also interesting to note that of 30 highest magnitude wet periods, 17 occurred after 1991. The wet period in 2010 and 2011 varied in duration but is present at all research locations. The wet period in 2014 and 2015 is present at all locations except in Sarajevo and Mostar. Other notable wet periods include 1976 - 1977, 1978 - 1979, and 2001 - 2002.

Based on the obtained magnitude values (MA), we can see that droughts are more pronounced than wet periods in BiH. Tuzla is the location where the highest drought magnitude of -42.93 was recorded, referring to a dry period that lasted for an extensive 24 months from 08.2011 to 07.2023. Following this drought in Tuzla, a high-magnitude drought period is observed in Mostar, with a value of -41.02. This dry period lasted even longer, spanning 25 months from 01.1989 to 01.1991. The drought in Bihać during 2003 and 2004 had the highest peak value (PV) of -2,62.

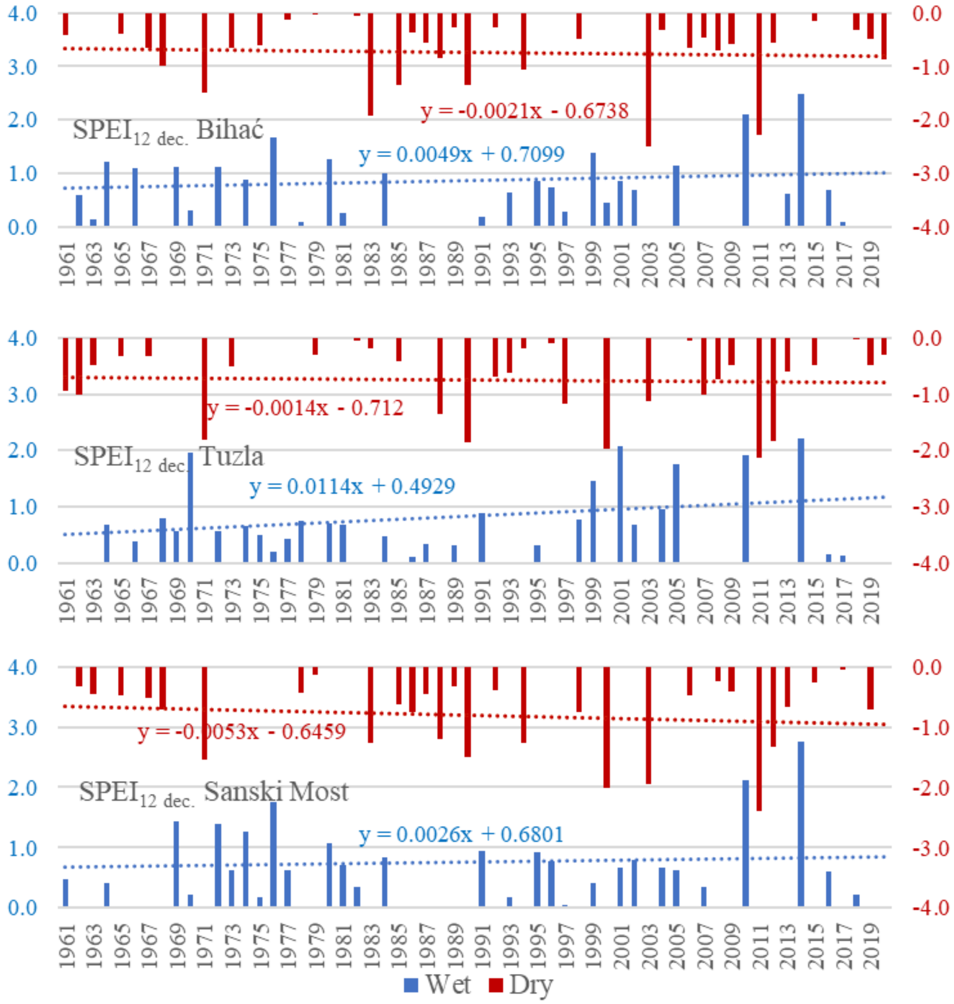
By summing up the values of the five most pronounced droughts for each location individually, the droughts with the highest magnitude are present in Tuzla (-113.55), where we also have the highest peak values (-2.21), followed by Mostar (-108.99) and Sanski Most (-104.63). Out of these 30 analyzed drought periods, similar to wet periods, 17 of them occurred after 1991. This clearly indicates a trend towards more extreme values of this indicator as a result of climate change.

The period from May 1990 to no later than June 1991, emerges as a significant drought period at all locations, with magnitudes ranging from -16.94 to -41.02. Additionally, the drought in 2011 and 2012 is present at all locations except in Sarajevo. Other notable droughts occurred in the following periods: 1971 - 1972, 1988 - 1989, 1993 - 1994, 2000 - 2001, 2003 - 2004, 2007 - 2008, and 2019 - 2020.

$SPEI_{12\ December}$

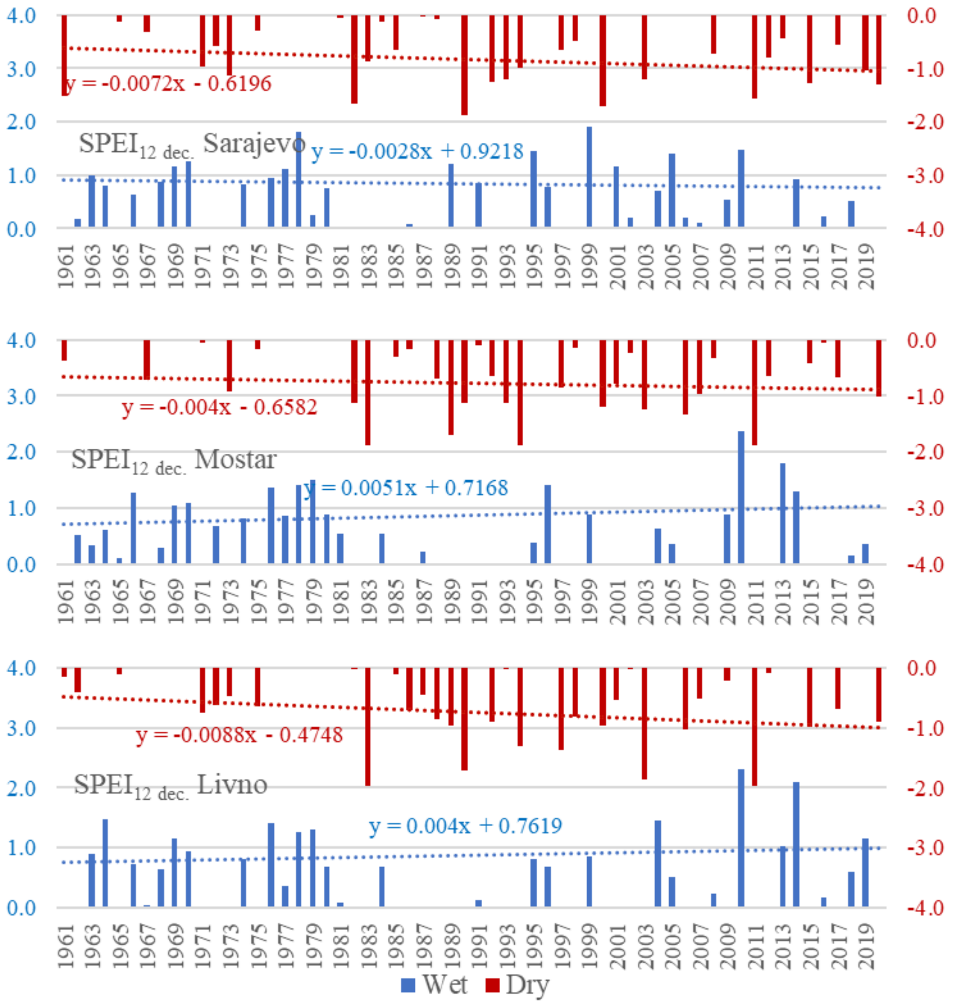
The results for $SPEI_{12\ December}$, are presented in the following graphs 1 and 2. This index considers the conditions of the preceding 12 months, with December as the concluding month of this period. Consequently, it can be used, to sum up a specific year within the timeframe of 1961 - 2020 using a singular SPEI value. Additionally, trend analysis can be applied to these data to assess the influence of climate change on the future occurrence of wet and dry years. Graph 1 illustrates the $SPEI_{12\ December}$ status for the first three research locations, namely: Bihać, Tuzla, and Sanski Most.

It can be observed that after the year 1991, there are years with higher SPEI values, indicating an increased occurrence of severe and extreme years, both wet and dry. The trend analysis of wet years indicates a positive trend, most pronounced in the Tuzla area. Similarly, the trend of dry conditions shows an increase in all locations, with the most pronounced in Sanski Most. Across these three locations, there are certain differences. Firstly, the trend in wet conditions shows an increase in Mostar and Livno, but a decrease or rather a fairly stable state with no significant changes in Sarajevo. It is interesting to note that the unstable period with many wet years during the 1970s was replaced by a stable condition up until the year 2000, after which we have fewer wet years but with high index values. Regarding drought, similar to the previous three locations, here we also observe a positive trend. More intense drought years are becoming increasingly common. The trend is particularly pronounced in the Livno area. It can be noted that we can see a fairly stable condition until the year 1983, after which there were regular drought years of strong intensity.



Graph 1. The values of $SPEI_{12\ December}$ and the trend of wet and dry conditions in Bihać, Tuzla, and Sanski Most.

Graph 2 illustrates the $SPEI_{12\ December}$ status for the second three research locations, namely: Sarajevo, Livno, and Mostar.

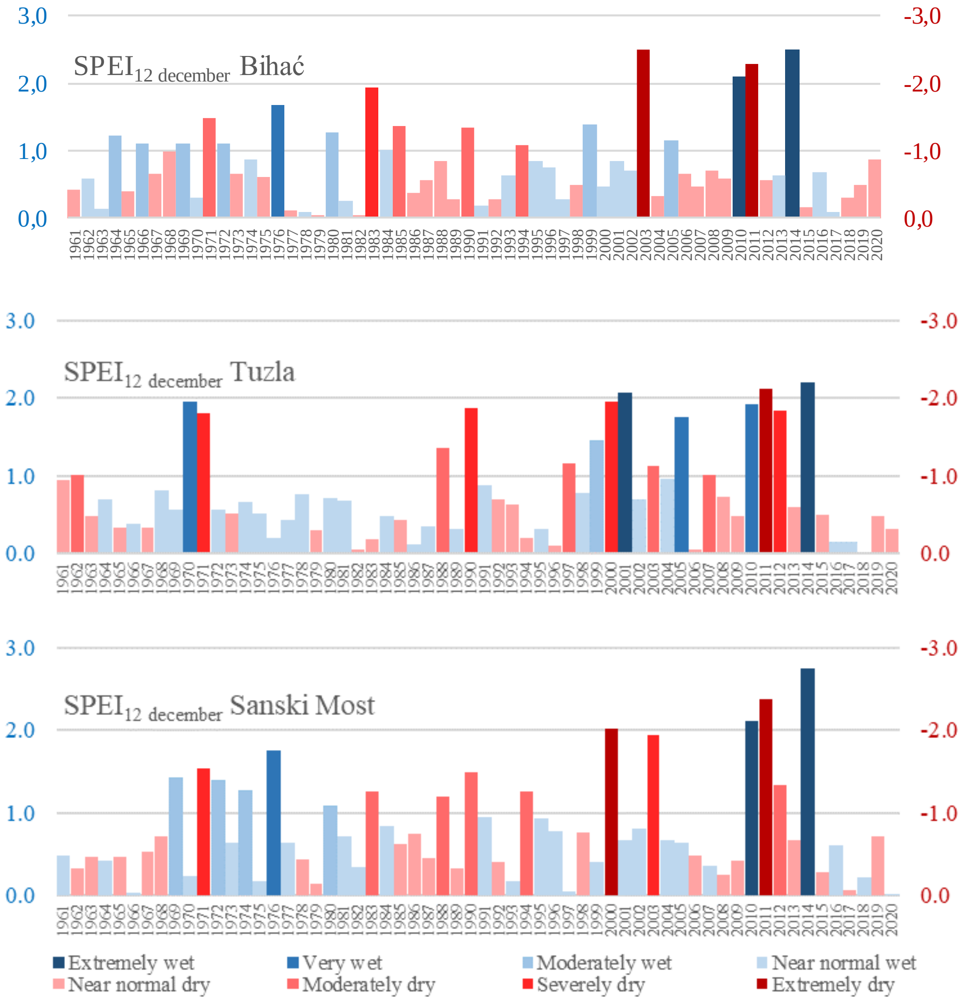


Graph 2. The values of $SPEI_{12\ December}$ and the trend of wet and dry conditions in Sarajevo, Livno and Mostar.

To illustrate all wet and dry years based on their intensity or categories, we applied the Ed Hawkins "ClimateSTripes" or "#ShowYourStripes" principle (Hawkins, 2023), specifically using Drought Stripes. Graph 3 displays drought stripes for the locations of Bihać, Tuzla, and Sanski Most. From Graph 3, wet and dry years as well as their intensity are clearly visible, represented by the intensity of the blue and red colors.

All extreme wet or dry years in all three locations have occurred in the last 20 years of the analyzed period (from 2000 – 2020). At each location, we have two extremely wet years. In Bihać and Sanski Most, these are 2010 (2.10 - 2.11) and 2014 (2.20 - 2.75), while in Tuzla, they are 2001 (2.07) and 2014 (2.02). In Bihać and Sanski Most, we have one severely wet year, which is 1976 (1.67 -

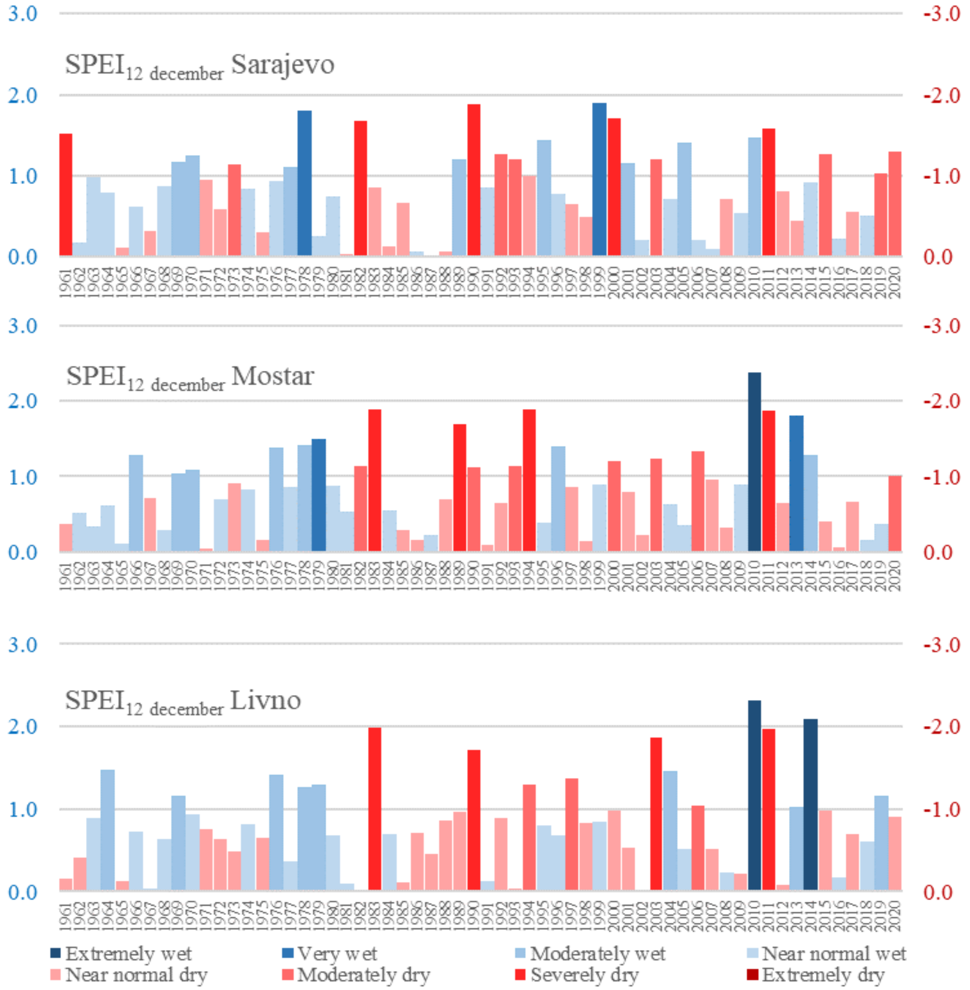
1.76), while in Tuzla, we have as many as three: 1970 (1.95), 2005 (1.75), and 2010 (1.91).



Graph 3. #DroughtStripes for Bihać, Tuzla, and Sanski Most locations

When it comes to dry years, extremely dry periods were observed in Bihać in 2003 (-2.50) and 2011 (-2.29), in Tuzla only in 2011 (-2.12), while in Sanski Most in 2000 (-2.01) and 2011 (-2.38). Additionally, in Bihać, we had one severely dry year in 1983 (-1.92). In Tuzla, there were as many as four: 1971 (-1.81), 1990 (-1.86), 2000 (-1.96), and 2012 (-1.83). In Sanski Most, two years stood out: 1971 (-1.53) and 2003 (-1.93). It is interesting to note a higher intensity of extreme conditions in the period after the 1990s. This is particularly noticeable at the location of Tuzla, where from 1972 to 1987, we have very consistent conditions with index values not exceeding an absolute value of 1.

Graph 4 displays drought stripes for the locations of Sarajevo, Livno and Mostar.



Graph 4. #DroughtStripes for Sarajevo, Livno and Mostar locations

Extremely wet conditions were not recorded at the Sarajevo location. In Mostar, an extremely wet year was 2010 (2.37), while in Livno, there were two such years: 2010 (2.31) and 2014 (2.09). Nevertheless, in Sarajevo, two severely wet years were found: 1978 (1.79) and 1999 (1.89). Similarly, in Mostar, two such years were observed: 1979 (1.50) and 2013 (1.80). Severely wet years were not recorded in Livno.

Graph 4 shows that the period until 1981 is mostly characterized by wet conditions in most cases. Afterward, a period of drought followed, with the occurrence of extremely wet years after 2010.

Notably, Sarajevo experiences neither extremely wet nor extremely dry years. Among the locations analyzed, it appears to be the least sensitive to the influence of climate change in terms of extreme weather conditions. Similarly, Mostar and Livno do not have extremely dry years. However, all three locations do have a notable number of severely dry years. In Sarajevo, these years are: 1961 (-1.52), 1982 (-1.66), 1990 (-1.88), 2000 (-1.70), and 2011 (-1.57). In Mostar, four years exhibit this characteristic: 1983 (-1.88), 1989 (-1.70), 1994 (-1.88), and 2011 (-1.87). In Livno, there are also four such years: 1983 (-1.97), 1990 (-1.72), 2003 (-1.86), and 2011 (-1.97).

Based on the comprehensive analysis of extremely wet periods, it can be concluded that the north and west parts of BiH (Bihać, Tuzla, Sanski Most) experienced exceptionally wet years in 1970, 1976, 2001, 2010, and 2014. The central and southern parts of BiH (Sarajevo, Mostar, and Livno), due to their climatic characteristics, geographical location, and hydrological network, exhibit a higher degree of resilience to floods. In this region, exceptionally wet years were observed in 1969, 1978, 1999, 2010, 2013, and 2014. To confirm the wet years 1969, 1970, 1976, and 1978, we do not have adequate data sources. However, for 1999, 2001, 2010, 2013, and 2014, we can confirm they were years of significant floods in this area of BiH. The floods in June 2001, with rainfall ranging from 50 to 100 l/m^2, severely impacted Northern BiH (Posavina, Tuzla, Zenica-Doboj), resulting in extensive agricultural damage. In 2010, BiH experienced substantial floods that inflicted significant harm on agricultural production, with the most substantial destruction recorded in Tuzla, Zenica-Doboj (central), Posavina (north), Bosnia-Podrinje (east), and Herzegovina-Neretva Canton (south) (WBIF, 2019). Additionally, in late April and early May, as well as the beginning of August 2014, floods displaced hundreds of families, inundated numerous buildings, and damaged thousands of hectares of agricultural land. The worst situation was in the flooded areas of Zenica-Doboj, Tuzla, Brčko district, Semberija, and Posavina (CMBH, 2014; FACP, 2014).

Extremely dry periods in north and west BiH (Bihać, Tuzla, Sanski Most) were confirmed in the following years: 1971, 1983, 1990, 2000, 2003, 2007, 2011, and 2012. In the southern part of BiH, we have the exact same intensely dry years, and in the central part, in addition to the ones mentioned, 1961 and 2020 can also be considered very dry years. Given this situation, it can be stated that droughts have a larger spatial extent compared to floods. Just like with floods, these data align perfectly with the recorded droughts in BiH. Indeed, the drought in 2000 affected around 60% of agricultural production. In the summer of 2003, some regions in BiH faced a drought that resulted in over 2 billion euros in agricultural damage and impacted nearly 200,000 people. In the summer of 2007, drought destroyed more than 40% of the country's agricultural production and led to forest fires covering approximately 250 hectares of land (Čaušević et al., 2020; PSP-BiH, 2023; UNDP, 2020).

CONCLUSIONS

Considering the established aim of this study, which was to accurately determine which years in BiH can be characterized as extremely wet and which as extremely dry, when such an extreme event was most intense, lasted the longest, and covered the largest area, using the SPEI index, the wet years were identified as 1969, 1970, 1976, 1978, 1999, 2001, 2010, 2013, and 2014, while the dry years were 1961, 1971, 1983, 1990, 2000, 2003, 2007, 2011, 2012, and 2020.

In the period after 1991, fewer years are categorized as "Near Normal" or "Moderately" wet-dry, and there is an increasing number of severely dry years (2000, 2003, 2011, and 2012), often accompanied by the occurrence of extremely wet years (2010 and 2014). Given the established trend of SPEI, an intensification of this state can be expected at all locations. As a result of climate change, droughts will become more frequent and more intense, while wet years will lead to catastrophic floods, especially in the northwestern part of BiH. The obtained data shows a significant shift towards drier weather, as dry months have increased by 15% compared to wet months. At the same time, there has been a decrease in near-normal conditions and an increase in extremely wet months.

The period from 2010 to 2014 can be categorized as a period of extreme weather conditions, characterized by alternating extremely wet and extremely dry years. Historic climate trends, as well as climate projections, indicate the possibility of the recurrence of such periods, potentially even more intensified.

In the northern and western regions of BiH, the longest wet period in terms of duration and spatial extent occurred from May 2014 to July 2015. On the other hand, in the central and southern parts of BiH, the longest wet period extended over a total of 19 months from February 1969 to August 1970. The longest drought with the largest spatial extent was the drought from 2011 to 2012, which lasted up to 24 months in certain locations, such as Tuzla.

Taking into account the previous 12 months ($SPEI_{12}$), the month with the highest moisture intensity was October 2014 in Bihać, with an SPEI of 3.30. Conversely, the month with the lowest cumulative water content was also in Bihać, in January 2004, with an SPEI of -2.62.

The obtained SPEI index values align perfectly with recorded flood and drought years, indicating the potential for using this index in predictive models and early warning systems as crucial measures for climate change adaptation, enabling users to select a time interval and view the current state, as well as short-term and long-term forecasts for a specific location or on the interpolated map. Also, the next step would involve utilizing Regional Climate Models (RCM) for various Representative Concentration Pathway (RCP) scenarios to predict and analyze droughts and floods. Such analyses could be done using SPEI or similar indices.

Given the increasing occurrence of years with both droughts and floods, attributed to the intensified rainfall, such occurrences tend to be masked when analyzing $SPEI_{12}$ for the entire year. Therefore, future research should focus on analyzing shorter intervals of SPEI, especially for months where the most significant temperature changes are observed (June, July, and August) as well as precipitation levels (September and October).

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