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Front cover photography: The central part of the Durmitor mountains in Montenegro with the highest peak, Bobotov Kuk (2523 m), and distinctive high-mountain karst shaped by glacial processes (photograph: Jure Tičar).
Fotografija na naslovnici: Osrednji del gorovja Durmitor v Črni gori z najvišjim vrhom Bobotov kuk (2523 m) ter značilnim visokogorskim krasom, ki so ga preoblikovali ledeniški procesi (fotografija: Jure Tičar).

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WHAT IS HAPPENING WITH FREQUENCY AND OCCURRENCE OF THE MAXIMUM RIVER DISCHARGES IN BOSNIA AND HERZEGOVINA?

Slobodan Gnjato, Igor Leščešen, Biljana Basarin, Tatjana Popov

Štrbački buk (Una River).

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Slobodan Gnjato[1], Igor Leščešen[2], Biljana Basarin[2], Tatjana Popov[1]

What is happening with frequency and occurrence of the maximum river discharges in Bosnia and Herzegovina?

ABSTRACT: In this study, we explored the frequency and occurrence rate of maximum river discharges in the Una and Sana rivers, to understand hydrological variations amidst climate change. We categorized maximum discharges into severe (Una River M1 > 98.2 m^3/s; Sana River M1 > 118.2 m^3/s) and extreme (Una River, M2, > 123.4 m^3/s; Sana River M2 > 246.4 m^3/s) events, and identified trends in these events, crucial for assessing environmental impacts. Our findings reveal a nuanced pattern: both rivers experience an increase in severe events from 58 to 55 and 56 to 54 days return period respectively, indicating complex hydrological dynamics. The trends underscore the significant shifts in annual event occurrences, the evolving nature of river systems and underscore the necessity for adaptive management strategies.

KEYWORDS: Hydrology, maximum discharges, Una River, Sana River, Cox-Lewis test, trend, Bosnia and Herzegovina

Frekvenca in pojavnost največjih rečnih pretokov v Bosni in Hercegovini

POVZETEK: Članek proučuje frekvenco in stopnjo pojavnosti največjih pretokov bosanskih rek Une in Sane, kar omogoča boljše razumevanje hidroloških sprememb kot posledic podnebnih sprememb. Največji pretoki so razdeljeni v dve kategoriji, močno povečane pretoke (Una: M1 > 98,2 m^3/s; Sana: M1 > 118,2 m^3/s) in izjemne pretoke (Una: M2 > 123,4 m^3/s; Sana: M2 > 246,4 m^3/s), pri čemer so določeni trendi njihove pojavnosti, ki so ključni za proučevanje okoljskih vplivov. Izsledki raziskave kažejo, da se pri obeh rekah pojavnost močno povečanih pretokov povečuje, saj se povratna doba med njimi krajša (z 58 na 55 dni pri Uni in s 56 na 54 dni pri Sani), kar priča o zapleteni hidrološki dinamiki. Trendi razkrivajo pomembne spremembe v letni pojavnosti teh dogodkov ter opozarjajo na spreminjajočo se naravo rečnih sistemov in potrebo po prilagoditvenih strategijah upravljanja.

KLJUČNE BESEDE: hidrologija, največji pretoki, Una, Sana, Cox-Lewisov test, trend, Bosna in Hercegovina

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1 Introduction

Regarded among the most destructive natural hazards, flood events feature extremely high-water stages which cause flooding of areas in a variety of settings (Blöschl 2022). Moreover, they are the most frequent natural hazards impacting 1.6 billion people globally, with a mean of 163 occurrences per year (Centre for … 2020). As such, they have the potential to induce sudden and severe devastation in the environment and harmful effects on society in multiple ways (Kuntla, Saharia and Kirstetter 2022). The rising tendency in the damages induced by flood events is primarily caused by intense deforestation of river valleys, enhanced economic activities (i.e., increased wealth) in flood-risk areas, and climate change (Ionita and Nagavciuc 2021). More frequent and intense occurrences of extreme events (i.e., floods, droughts and storms) over the past few decades have proven to be related to the negative effects of global warming which has accelerated the water cycle (Chagas, Chaffe and Blöschl 2022; Wang and Liu 2023). Not only does climate change affect the principal components of the climate system but affects the processes that cause floods to form on the land surface as well (Tarasova et al. 2023). Hence, as a consequence of the growth in flood events on a global scale, there has been a proliferation of research tackling the problem of climate change impacts on these extreme hydrological events (Arnell and Gosling 2016; Hodgkins et al. 2017; Majone et al. 2022; Speight and Krupska 2021; Tabari 2020). Given the identified changes in the timing of floods throughout the year, it has been shown that snowmelt-generated floods are becoming less common in colder areas, whereas convective events are increasing in frequency at the expense of synoptic events (Blöschl et al. 2019; Chegwidden, Rupp and Nijssen 2020; Tarasova et al. 2023). Furthermore, besides meteorological and hydrological processes, watershed shape or size is a principal factor influencing flooding variations (Sharma, Wasko and Lettenmaier 2018). Smaller basins commonly experience changes similar to those in precipitation, although larger catchments may be more dominated by other warming-related changes (i.e., reduction of soil moisture and snowmelt; Hirabayashi et al. 2021). Overall, flood events in various areas of the Northern Hemisphere are primarily controlled by extreme precipitation events (Alifu et al. 2022). Thus, monitoring alterations in the frequency and severity of flooding is crucial for developing adequate adaptation and mitigation strategies given that future global floods are influenced by climate warming (Asadieh and Krakauer 2017).

Many European rivers have been impacted by extreme high streamflow events since the last decade of the 20th century, which resulted in damages worth billions of euros (Fischer and Schumann 2021), while extreme hydrological events are anticipated to increase even more in terms of frequency and severity (Paprotny et al. 2018). Over the last several years a substantial number of research on this issue has been carried out, where a majority of studies examined trends in flood events at the European level (Bertola et al. 2020; Blöschl et al. 2019; Brönnimann et al. 2022; Kemter et al. 2020; Tarasova et al. 2023). Overall findings suggest increased flood events in northwestern parts of Europe due to increased winter and autumn precipitation, whereas southeastern, central and eastern parts of Europe have experienced a reduction in flooding generally due to increased air temperatures and evaporation. Such results are also confirmed by various local and regional research in the southern (Vicente-Serrano et al. 2017), eastern (Venegas-Cordero et al. 2022), northern (Wilson and Hisdal 2013), central (Mudelsee et al. 2003; 2004; 2006) and western parts (Hannaford et al. 2021) of Europe. Studies on extremely high streamflows in southeastern Europe have also been carried out extensively during the past decade where authors usually employed either the regional flood frequency analysis method (Kavcic et al. 2014; Leščešen and Dolinaj 2019; Leščešen et al. 2022a) or different trend change methods (Pešić et al. 2023; Radevski et al. 2018; Tadić, Bonacci and Dadić 2016). Also, a substantial number of studies in the same region focused on the calculation of flood magnitude with a specific return period by applying a widely used flood frequency analysis (FFA) (Cerneagă and Maftei 2021; Leščešen et al. 2022a; Radevski and Gorin 2017; Tadić, Dadić and Barač 2013; Zabret and Brilly 2014). This method can provide vital knowledge about the hydrological behaviour of a river (Šraj and Bezak 2020), whilst the procedure fits various functions to data and extrapolates the tails of the distribution to assess the magnitude and probability of flood events (Leščešen et al. 2022a).

To this date, flood analysis in Bosnia and Herzegovina (BH) remains scarce and insufficiently covered. Many flood frequency analyses were produced for the period 1961–1990, mainly for project studies, and are not available publicly. However, recent studies in the form of research articles are extremely rare and treat either specific extreme events (Vidmar et al. 2016) or the extent of flooded areas using satellite and radar images (Ivanišević et al. 2022). Floods in BH are predominantly induced by humid air currents coming from the Atlantic or abrupt melting of snow that occurs late in the early winter/late spring period. In the 21st century and especially over the last decade the number of flooding events has substantially risen. The majority of flooding in BH has been occurring in the Sava River basin (76% of BH territory) on predominantly impermeable geological formations where the hydrographic network is well-developed (Gnjato et al. 2023). The most severe flood in recent history, which occurred in May of 2014, inflicted a significant portion of BH territory (> 50%) causing displacement of > 100,000 people with overall damage of 2 billion euros (Vidmar et al. 2016). Floods impacted mostly the northern and central parts of BH and were generally present in the lower areas of the major river basins (i.e., Una, Vrbas and Bosna). After 2014, major flood events occurred in 2018, 2019, 2021 and 2023 (see also reports at https://floodlist.com/tag/bosnia).

Frequency and occurrence rate of maximum river discharges are crucial for engineering practice since severe floods in BH are predicted to be generated more frequently as a result of climate change. Given the data availability, record length, and increased danger of flood risk, for this study, we chose to investigate two hydrological profiles in the Una River basin (Novi Grad and Prijedor). The major objective was to perform a comprehensive maximum discharge frequency and occurrence analysis for the Una and Sana Rivers covering the 60-year period, from 1961 to 2020. Furthermore, our targets were to identify trends in the extremely high discharges and to observe their seasonal features.

2 Material and methods

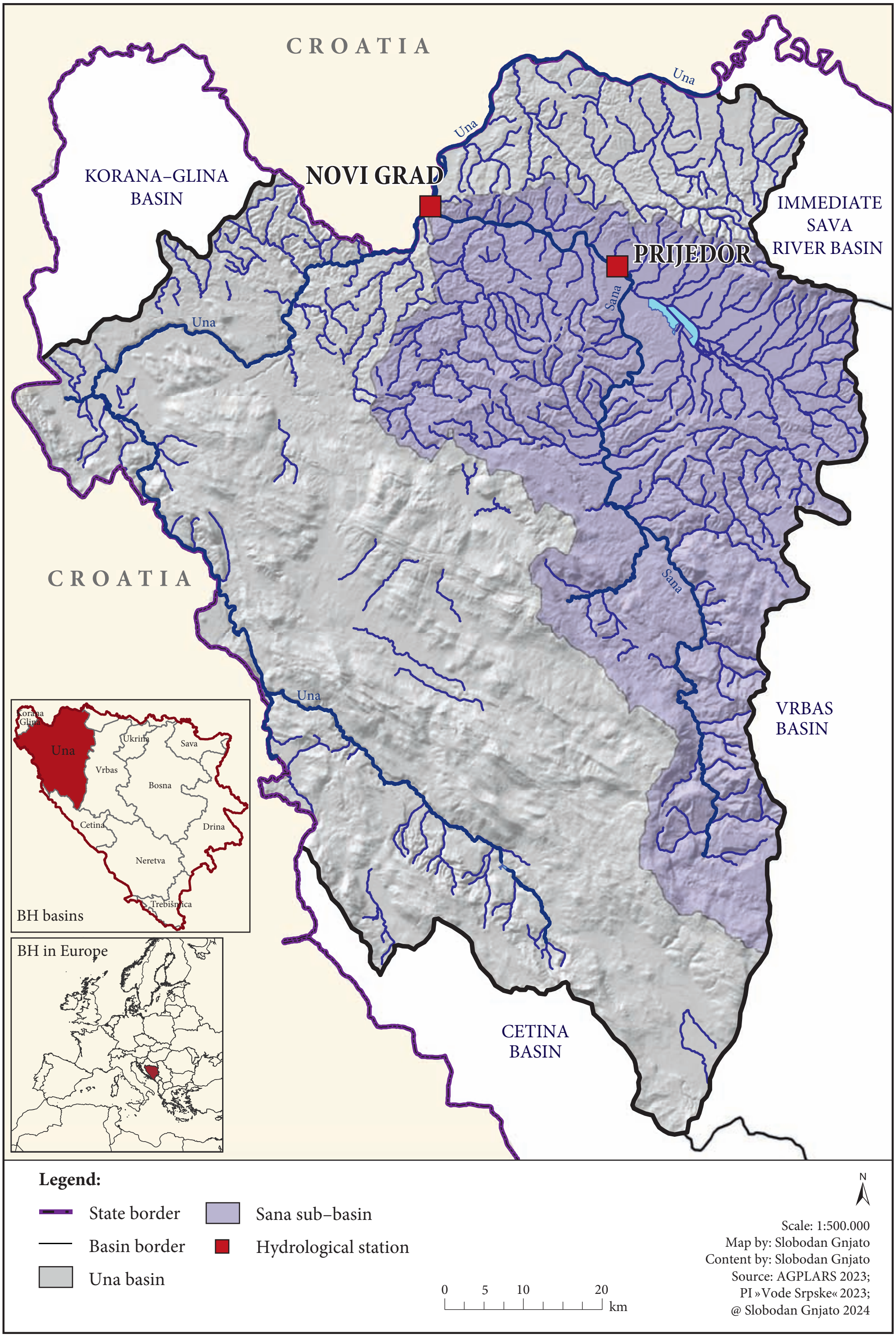
2.1 Study area

With an area of 9130 km^2 and a total river length of 210 km, the Una River basin is positioned in the northwestern part of BH (Figure 1). The source of the Una River consists of a large number of karst springs in the Dinaric Alps. Even though the main source is located in the Republic of Croatia, the river itself appears after a few kilometers in BH. The southern, western, and central parts of the Una basin are predominantly under the influence of karst as approximately 2/3 of the Una basin consists of karstified and significantly karstified areas with poorly developed surface river network (Gnjato 2022). Unlike the southern and central parts, the northeastern area of the watershed is a valley built from alluvial deposits. In this part, the river Una receives its largest right tributary, the Sana River (146 km of river length with an area of 3,782 km^2). The Una River has a characteristic hydrological regime, which is characterized by low summer and high spring flows. Also, extremely large winter flows are characteristic of this river. According to the classification of Ilešič (1948) the Una River, as well as most of the large tributaries of the Sava in BH, is characterized by the Posavina variant of the pluvio-nival water regime, determined by the highest discharges in April and March, and the minimum flows in August and September (Gnjato et al. 2021) The climate conditions in the basin change from the mountain in the southern parts of the basin to continental and moderate continental climate types in the central and northern parts, respectively.

2.2 Data

Input data for this research were obtained from the Hydrometeorological Service of the Republic of Srpska and they consist of the maximum discharges observed for each month for the Una River at Novi Grad station and Sana River at Prijedor station, spanning the interval from 1961 to 2020, as illustrated in Figure 2. The annual maximum discharge of a river is an important indicator of water availability and flood risk management (Higashino and Stefan 2019). It is known that not every high discharge value causes a flood but every flood is preceded by a high discharge value (Shiklomanov et al. 2007). Therefore, we chose to analyse monthly maximum discharges as a good indicator of potential floods. The data set had some missing values, mainly at Sana River the data was missing for the 1991–1994 period, while on Una River the data was missing for 1991, 1992, 2000, and 2001 (see Tables 1 and 2). Hydrological datasets frequently contain gaps, outliers, or incorrect data. If the issue of missing data is ignored it can lead to a reduction in the statistical power of the techniques used and even to incorrect conclusions about the study phenomenon (Łopucki et al. 2022). In order to assess the sensitivity of our study results to the presence or absence of data, we conducted a comprehensive sensitivity analysis by considering three hypothetical cases: (b1) where

Figure 1: Map of the Una River basin. ➤ p. 133


CROATIA
KORANA–GLINA BASIN
NOVI GRAD
Una
PRIJEDOR
Sana
IMMEDIATE SAVA RIVER BASIN
CROATIA
VRBAS BASIN
CETINA BASIN
Korana Glina
Una
Ukrina
Sava
Vrbas
Bosna
Cetina
Drina
Neretva
Trebišnjica
BH basins
BH in Europe
Legend:
State border
Basin border
Una basin
Sana sub–basin
Hydrological station
N
Scale: 1:500.000
Map by: Slobodan Gnjato
Content by: Slobodan Gnjato
Source: AGPLARS 2023;
PI »Vode Srpske« 2023;
@ Slobodan Gnjato 2024
0 5 10 20 km

all missing months were assumed to have Magnitude 1 (M1) events, (b2) where all missing months were assumed to have Magnitude 2 (M2) events, and (b3) where all missing months were assumed to have no events (see chapter 2.3 for definition of M1 and M2 events). We applied this method to fill the missing data, utilizing the median value of discharges that are below the average maximum discharges for the whole period in case of b1, and in case of b2, we used the median of the discharge values above the maximum averages for the whole period (Tables 3 and 4). When analysing the results, it can be noticed that b2 has a slightly higher mean, lower standard error, and a slightly lower skewness compared to b1 and b3. Additionally, b2 has the highest median value. These factors indicate that b2 has the most stable and consistent results compared to b1 and b3. Therefore, based on these analyses, we can conclude that the b2 scenario is the best for both rivers. That is why, we decided to adopt b2 and fill all of our missing data with median of the values above the average maximum discharge for the whole period, 261.4 m^3/s for Sana River and 584.5 m^3/s for Una River. This approach provided a valuable insight into the potential impact of missing data on our findings. This sensitivity analysis enhances the reliability of our conclusions and underscores the importance of acknowledging the uncertainties associated with missing data in hydrological studies. Prevalence of significant inter-annual and interdecadal variability in the records of maximum streamflows in Europe has been reported (Kundzewicz et al. 2005).

The dataset was partitioned into two distinct categories: hydrological summer (April to September) primarily triggered by heavy precipitation, and hydrological winter (October to March) driven by a combination of precipitation and snowmelt. We emphasize the necessity of distinguishing between winter and summer maximum discharges due to their distinct meteorological and hydrological origins (Mudelsee et al. 2003; 2004; 2006). This delineation in our analysis serves the purpose of providing valuable explanations and insights into the patterns and determinants of extreme events. It is crucial to recognize that maximum discharges typically do not confine themselves to a specific season, making this differentiation imperative for a comprehensive understanding of flood dynamics.

2.3 Methods

To examine the rates of maximum river discharge occurrences over time and assess any notable alterations, we employed kernel estimation along with confidence bands. This approach utilized a Gaussian kernel function denoted as K, which assigned weights to observed extreme event dates, $T(i)$, where i ranged from 1 to N (representing the number of maximum discharges). It was used to estimate the occurrence rate, λ, at a given time t using the following formula (Equation 1):

$$\lambda_{(t)} = \sum_i K\left(\left(t - T_{(i)}\right)/h\right). \quad (1)$$

In order to determine the bandwidth ($h = 20$ years), we employed cross-validation, which seeks an optimal balance between bias and variance. To establish 90% confidence bands around $\lambda(t)$, we adopted a bootstrap resampling technique, repeating the procedure 5,000 times and calculating a 90th percentile-t confidence band. This methodical framework, integrating the nonstationary Poisson process and bootstrap confidence bands, was initially introduced by Mudelsee et al. (2003; 2004; 2006) for risk analysis in climatology and hydrology. Later works by Mudelsee (2014; 2020) provided detailed explanations of the nonstationary methodical framework in two comprehensive books. Furthermore, our study included a trend analysis. This analysis was conducted within a nonstationary framework, and we estimated time-dependent occurrence rates using advanced kernel techniques supported by the construction of bootstrap confidence bands (Mudelsee 2020).

To assess the significance of the occurrence rate estimation curves we applied Cox-Lewis test, a statistical test that was outlined by Mudelsee et al. (2004). This test focuses on extreme events, examining whether there is an upward or downward trend. Detected trends in occurrence rate were validated for the measured interval (1961–2020) using the statistical Cox-Lewis test. This test compares the null hypothesis H0: constant occurrence rate against H1: increasing occurrence rate.

$$u = \left[\sum \frac{T(i)}{n} - \frac{(t_2 + t_1)}{2}\right] / \left[(t_2 - t_1)(12n)^{-\frac{1}{2}}\right]$$

Figure 2: The monthly maximum discharges of the Sana (a) and Una (b) rivers for 1961–2020. ➤ p. 135

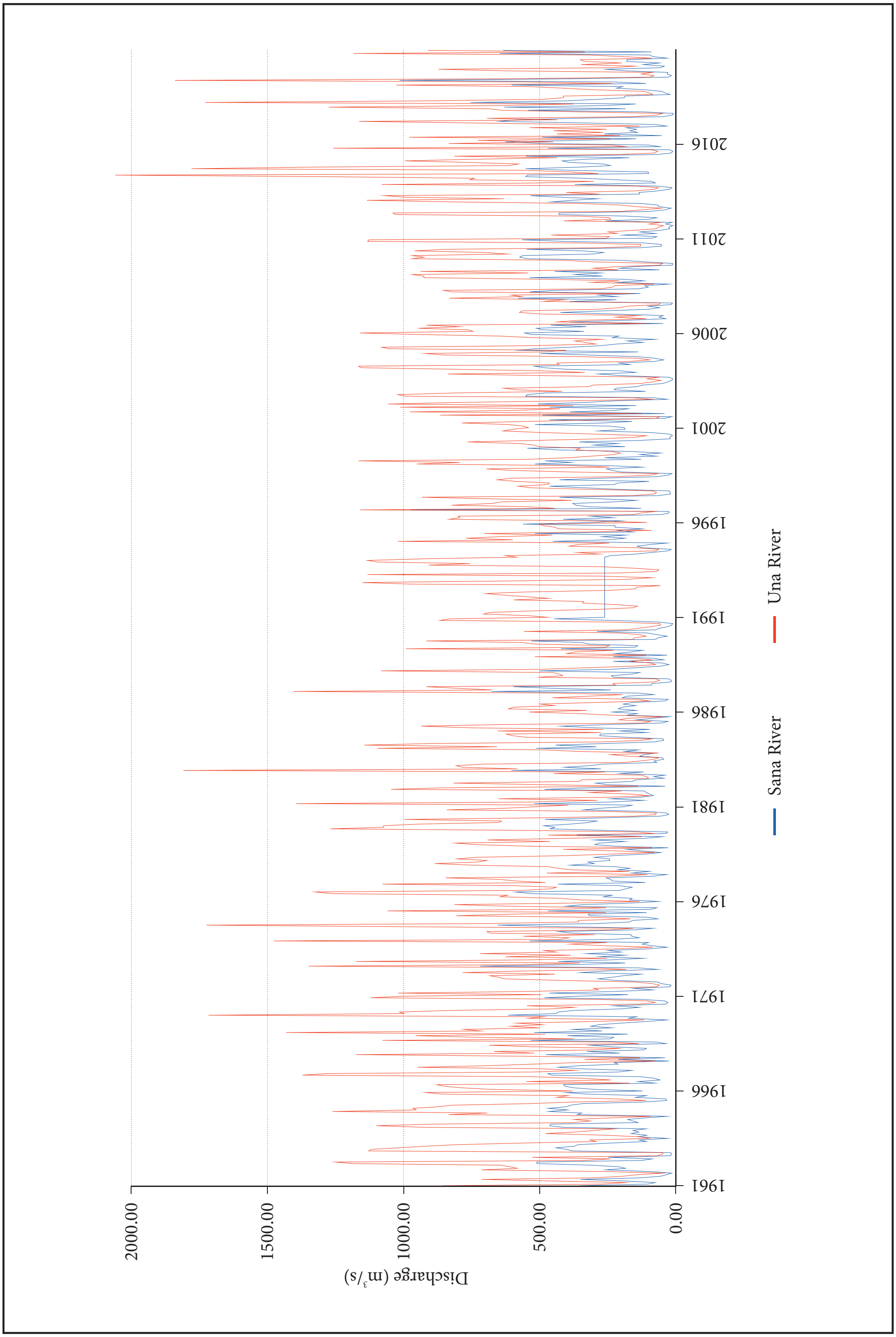

Una River
Sana River
Discharge (m³/s)
0.00
500.00
1000.00
1500.00
2000.00
1961
1966
1971
1976
1981
1986
1991
1996
2001
2006
2011
2016

Table 1: Monthly maximum discharge at the Sana River for 1961–2020.

Sana River (Prijedor station) Monthly maximum discharges (m3/s)												
	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
1961	352	102	76	185	350	131	56	34	14	93	257	185
1962	210	310	509	511	125	86	248	19	16	18	381	402
1963	439	372	360	241	107	135	29	137	106	164	136	157
1964	109	414	463	459	139	157	176	113	32	362	345	467
1965	397	469	402	386	343	122	33	37	148	108	330	404
1966	122	298	374	407	412	77	139	58	78	131	456	470
1967	213	161	338	432	355	211	226	25	211	39	313	478
1968	206	326	118	108	237	315	35	70	534	240	228	398
1969	176	521	270	379	235	313	283	202	104	32	174	143
1970	616	441	432	374	204	133	229	35	29	40	124	483
1971	360	175	465	227	83	157	22	17	54	66	221	285
1972	234	193	127	350	259	65	137	718	367	185	432	242
1973	118	281	185	327	200	250	101	31	91	123	100	537
1974	234	134	161	165	380	431	146	82	421	655	291	172
1975	158	66	100	315	322	107	470	91	70	402	341	166
1976	63	170	160	265	233	529	589	205	183	160	205	433
1977	111	233	239	256	85	32	160	95	212	168	222	388
1978	300	322	242	244	300	229	108	55	126	181	27	221
1979	298	280	185	298	116	48	364	36	29	258	461	444
1980	484	389	322	290	481	252	57	26	33	101	338	280
1981	190	161	521	243	117	239	126	82	96	108	116	482
1982	311	38	251	294	159	147	43	81	39	205	118	604
1983	275	408	319	270	69	80	44	50	133	115	74	188
1984	137	512	291	441	260	83	44	47	186	279	278	106
1985	205	95	298	421	244	51	28	145	83	22	179	141
1986	233	144	211	197	147	193	159	38	28	197	181	80
1987	138	678	238	462	597	90	87	18	15	27	227	237
1988	163	132	500	231	147	56	24	49	229	43	80	229
1989	31	223	163	121	422	149	139	318	345	530	74	65
1990	31	69	105	290	74	61	29	15	11	68	229	447
1991	MISSING DATA											
1992	MISSING DATA											
1993	MISSING DATA											
1994	MISSING DATA			240	146	88	29	17	122	142	98	32
1995	452	252	186	271	183	517	156	212	122	223	223	561
1996	301	199	414	229	313	54	24	24	975	127	322	366
1997	378	226	144	282	427	65	19	21	23	212	333	464
1998	226	212	98	427	284	69	29	14	202	233	255	123
1999	252	517	383	480	127	261	70	131	55	166	434	545
2000	186	301	211	355	126	20	22	11	24	93	284	186
2001	189	245	517	265	161	464	40	14	490	41	390	219
2002	174	464	145	506	333	229	32	83	551	545	477	111
2003	226	219	142	122	48	30	14	11	24	195	285	147
2004	200	400	485	520	168	209	77	44	76	137	317	498
2005	138	578	520	383	273	219	120	178	76	233	209	531
2006	555	337	490	512	328	459	47	390	189	36	62	46
2007	229	424	266	102	60	101	16	12	390	218	579	215
2008	284	130	537	445	135	101	114	24	213	116	189	537
2009	269	371	274	445	60	207	155	12	11	113	199	545
2010	573	561	302	265	341	548	130	53	53	117	414	564
2011	87	70	194	74	131	57	23	26	11	37	13	258
2012	98	70	181	429	429	94	41	17	63	64	128	457
2013	383	285	427	534	133	135	67	22	13	67	371	75
2014	88	215	341	551	545	99	102	395	551	352	240	263
2015	392	417	335	171	551	72	17	10	22	469	58	99
2016	485	626	352	145	490	51	263	140	168	144	182	33
2017	73	333	650	582	355	47	11	9	119	542	185	630
2018	265	147	754	407	284	189	186	21	39	51	113	218
2019	195	603	109	226	1014	348	27	16	32	29	185	255
2020	56	42	120	60	179	179	31	84	96	646	89	634

Table 2: Monthly maximum discharge at the Una River for 1961–2020.

Una River (Novi Grad station)
Monthly maximum discharges (m^3/s)

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
1961	856	270	181	449	713	307	195	142	47	254	713	582
1962	610	643	1187	1250	342	240	527	69	47	47	1128	1118
1963	1015	922	805	568	292	316	97	132	256	480	367	299
1964	225	930	1100	892	376	314	374	236	89	835	692	1261
1965	953	965	874	821	538	379	109	217	437	395	860	919
1966	379	677	785	849	878	169	549	238	344	530	1372	1280
1967	522	367	489	948	697	528	362	76	335	131	573	1174
1968	520	668	309	202	530	685	135	233	1077	376	737	956
1969	478	1432	715	779	499	606	489	584	292	115	541	484
1970	1717	998	1015	834	458	371	546	129	75	104	296	1120
1971	1006	494	1019	557	283	302	72	59	88	154	426	629
1972	651	682	443	782	557	181	304	1348	541	353	1174	546
1973	253	626	385	718	438	484	218	84	271	388	253	1476
1974	426	392	560	298	682	694	243	157	1015	1724	694	357
1975	357	165	300	806	606	257	1059	436	255	620	813	374
1976	132	348	426	645	617	1263	1325	565	458	438	595	1077
1977	478	587	648	845	229	104	473	170	378	433	466	747
1978	885	728	694	803	734	399	231	77	216	414	87	541
1979	731	809	461	691	407	125	468	82	140	546	1269	1073
1980	1073	948	651	640	998	481	151	74	71	247	841	634
1981	515	395	1395	530	287	651	239	100	169	317	198	1046
1982	856	138	496	816	355	344	100	106	128	448	259	1808
1983	581	782	806	712	189	126	80	61	174	239	63	357
1984	476	1096	657	1144	897	279	124	88	552	601	623	275
1985	653	266	753	936	643	120	92	208	180	43	240	353
1986	539	326	615	595	445	497	291	97	139	453	322	196
1987	439	1404	675	807	917	221	231	78	60	72	507	415
1988	426	450	1082	494	326	157	74	93	167	91	157	518
1989	108	401	367	229	991	258	244	515	567	917	157	151
1990	109	132	212	559	184	138	91	55	58	244	865	831
1991							MISSING DATA					
1992					MISSING DATA				56	976	1151	612
1993	184	87	275	1132	207	70	62	148	275	908	755	1094
1994	1132	916	584	625	280	361	72	62	143	392	361	244
1995	1021	598	770	646	454	703	326	89	431		MISSING DATA	
1996	106	326	832	793	800	156	127	75	1160	442	545	824
1997	675	639	382	696	933	159	81	70	85	312		
1998	469	464	584	655	605	223	95	65	387	605	696	244
1999	387	951	793	1165	545	392	312	227	203	240	366	351
2000							MISSING DATA					
2001		MISSING DATA		785	540	285	73	59	865	122	976	584
2002	425	1012	377	1057	800	398	89	156	994	1021	808	417
2003	584	632	322	303	130	86	54		63	474	837	334
2004	495	804	1156	1165	428	436	170	95	138	339	849	921
2005	483	401	1053	1080	517	294	331	371	271	520	646	942
2006	1160	744	762	946	793	916	108	434	364	107	221	138
2007	495	574	564	289	209	177	61	56	486	411	832	564
2008	605	163	820	853	273	234	223	80	312	207	480	925
2009	925	968	542	938	211	303	221	58	48	303	406	968
2010	925	968	618	703	959	853	273	129	129	356	1132	1127
2011	255	244	457	215	248	159	72	64	45	98	58	411
2012	238	244	351	1030	1039	199	122	54	149	203	351	821
2013	1135	631	995	1071	280	403	149	79	64	146	1080	495
2014	301	757	739	1286	2059	284	387	557	1779	1341	610	578
2015	757	995	745	436	814	219	79	65	92	1259	184	236
2016	834	450	727	240	979	203	436	266	448	253	536	133
2017	341	745	1163	436	693	154	67	49	356	637	687	1275
2018	646	377	1729	916	487	413	412	84	97	119	298	411
2019	535	1027	232	554	1839	562	94	80	125	87	627	872
2020	239	149	348	198	336	351	89	196	318	1184	335	911

Table 3: Sensitivity analysis results for Sana River.

Sana River (Prijedor station)												
B1	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
n	56.0	56.0	56.0	57.0	57.0	57.0	57.0	57.0	57.0	57.0	57.0	57.0
mean (m^3/s)	239.9	284.8	295.5	312.7	256.2	173.1	112.3	91.1	154.6	183.6	235.3	308.2
Standard error	18.1	21.5	20.6	17.7	22.3	17.5	14.9	16.0	23.7	20.6	16.6	23.4
Median (m^3/s)	207.8	248.5	268.2	289.9	218.5	134.8	73.8	45.8	96.0	143.0	221.7	256.7
Standard dev	135.5	161.0	154.1	133.4	168.4	132.4	112.4	121.0	179.1	155.3	125.6	176.7
Kurtosis	0.9	0.9	0.9	0.9	0.9	0.8	0.7	0.5	0.6	0.8	0.9	0.8
Skewness	0.9	0.6	0.7	0.1	1.8	1.4	2.1	3.1	2.3	1.6	0.5	0.2
Minimum	31.3	38.4	75.8	59.6	48.2	19.8	11.4	8.8	10.6	18.3	13.1	31.5
Max	616.1	677.8	754.0	582.0	1014.0	548.0	588.6	717.7	975.0	654.6	579.0	634.0
Quartile 1	153.3	167.8	181.9	226.4	134.5	75.4	29.1	20.4	31.5	67.7	134.0	170.0
Quartile 3	299.9	402.0	404.9	427.5	341.6	221.5	156.6	117.2	186.5	219.3	324.0	467.7
Range	584.8	639.4	678.2	522.4	965.8	528.2	577.2	708.9	964.4	636.4	565.9	602.5
B2	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
n	56.0	56.0	56.0	57.0	57.0	57.0	57.0	57.0	57.0	57.0	57.0	57.0
mean (m^3/s)	245.2	290.1	300.8	316.7	260.2	177.1	116.3	95.1	158.6	187.6	239.2	312.1
Standard error	18.0	21.2	20.2	17.3	22.2	17.7	15.4	16.6	23.9	20.7	16.6	23.1
Median (m^3/s)	227.5	261.4	268.2	289.9	240.6	134.8	73.8	45.8	96.0	143.0	227.2	261.4
Standard dev	134.6	158.8	151.4	130.6	167.6	133.8	116.2	125.2	180.6	156.2	125.1	174.7
Kurtosis	0.9	0.9	0.9	0.9	0.9	0.8	0.6	0.5	0.6	0.8	0.9	0.8
Skewness	0.8	0.5	0.7	0.1	1.8	1.3	1.9	2.8	2.2	1.5	0.4	0.2
Minimum	31.3	38.4	75.8	59.6	48.2	19.8	11.4	8.8	10.6	18.3	13.1	31.5
Max	616.1	677.8	754.0	582.0	1014.0	548.0	588.6	717.7	975.0	654.6	579.0	634.0
Quartile 1	153.3	167.8	183.9	237.8	134.5	75.4	29.1	20.4	31.5	67.7	134.0	170.0
Quartile 3	299.9	402.0	404.9	427.5	341.6	242.0	156.6	117.2	211.5	234.6	324.0	467.7
Range	584.8	639.4	678.2	522.4	965.8	528.2	577.2	708.9	964.4	636.4	565.9	602.5
B3	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
n	56.0	56.0	56.0	57.0	57.0	57.0	57.0	57.0	57.0	57.0	57.0	57.0
mean (m^3/s)	227.7	272.7	283.3	303.6	247.1	164.0	103.2	82.0	145.5	174.5	226.2	299.1
Standard error	19.8	23.4	22.6	19.6	23.4	18.2	15.1	16.0	24.1	21.3	18.0	24.8
Median (m^3/s)	207.8	248.5	268.2	289.9	218.5	126.2	56.4	36.6	80.8	128.9	221.7	256.7
Standard dev	147.9	174.8	169.3	147.7	177.0	137.7	113.8	120.7	182.1	160.5	135.5	187.5
Kurtosis	0.9	0.9	0.9	1.0	0.9	0.8	0.5	0.4	0.6	0.7	1.0	0.9
Skewness	0.6	0.4	0.4	–0.2	1.6	1.3	2.2	3.3	2.4	1.5	0.3	0.1
Minimum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Max	616.1	677.8	754.0	582.0	1014.0	548.0	588.6	717.7	975.0	654.6	579.0	634.0
Quartile 1	120.9	141.6	156.3	226.4	126.8	65.3	28.6	17.0	28.4	61.1	117.3	146.1
Quartile 3	299.9	402.0	404.9	427.5	341.6	221.5	140.9	85.6	186.5	219.3	324.0	467.7
Range	616.1	677.8	754.0	582.0	1014.0	548.0	588.6	717.7	975.0	654.6	579.0	634.0

Table 4: Sensitivity analysis results for Una River.

Una River (Novi Grad station)												
B1	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
n	56.0	56.0	56.0	57.0	57.0	57.0	57.0	59.0	58.0	57.0	56.0	55.0
mean (m3/s)	555.4	581.8	633.8	690.2	559.4	333.2	234.6	173.4	323.8	420.8	542.9	640.3
Standard error	46.6	46.6	46.7	42.2	50.1	31.2	31.0	27.4	44.9	48.4	45.6	56.3
Median (m3/s)	505.0	612.0	633.0	715.0	508.0	289.5	150.0	89.0	209.5	354.5	543.0	571.0
Standard dev	348.4	348.5	349.6	318.3	378.1	235.5	234.2	210.5	341.8	365.3	341.1	417.4
Kurtosis	0.9	1.1	1.0	1.0	0.9	0.9	0.6	0.5	0.6	0.8	1.0	0.9
Skewness	0.7	0.2	0.5	–0.4	1.6	1.5	2.6	3.5	2.1	1.5	0.3	0.4
Minimum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Max	1717.0	1432.0	1729.0	1286.0	2059.0	1263.0	1325.0	1348.0	1779.0	1724.0	1372.0	1808.0
Quartile 1	331.0	326.0	380.8	521.0	286.0	166.5	87.0	67.0	91.3	142.3	286.8	346.8
Quartile 3	776.3	835.8	805.3	898.0	748.8	405.5	315.5	202.0	398.0	522.5	768.3	945.5
Range	1717.0	1432.0	1729.0	1286.0	2059.0	1263.0	1325.0	1348.0	1779.0	1724.0	1372.0	1808.0
B2	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
n	56.0	56.0	56.0	57.0	57.0	57.0	57.0	59.0	58.0	57.0	56.0	55.0
mean (m3/s)	594.3	620.7	672.7	719.4	588.6	362.4	263.8	193.2	343.3	450.0	581.9	689.0
Standard error	42.0	41.6	40.9	36.7	47.1	30.2	31.7	28.7	44.6	46.8	41.2	50.0
Median (m3/s)	537.0	612.0	633.0	715.0	539.0	305.0	206.5	95.0	255.5	390.0	584.3	584.0
Standard dev	314.6	311.4	306.0	277.1	355.3	228.3	239.6	220.7	339.3	353.5	308.1	370.6
Kurtosis	0.9	1.0	0.9	1.0	0.9	0.8	0.8	0.5	0.7	0.9	1.0	0.8
Skewness	0.9	0.4	0.9	–0.1	1.9	1.5	2.2	3.0	2.0	1.5	0.4	0.6
Minimum	106.0	87.0	181.0	198.0	130.0	70.0	54.0	49.0	45.0	43.0	58.0	133.0
Max	1717.0	1432.0	1729.0	1286.0	2059.0	1263.0	1325.0	1348.0	1779.0	1724.0	1372.0	1808.0
Quartile 1	415.5	388.3	453.5	558.5	333.5	194.5	91.8	72.0	118.0	206.0	347.0	401.8
Quartile 3	776.3	835.8	805.3	898.0	748.8	481.8	365.0	222.0	439.8	584.0	768.3	945.5
Range	1611.0	1345.0	1548.0	1088.0	1929.0	1193.0	1271.0	1299.0	1734.0	1681.0	1314.0	1675.0
B3	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
n	56.0	56.0	56.0	57.0	57.0	57.0	57.0	59.0	58.0	57.0	56.0	55.0
mean (m3/s)	555.4	581.8	633.8	690.2	559.4	333.2	234.6	173.4	323.8	420.8	542.9	640.3
Standard error	46.6	46.6	46.7	42.2	50.1	31.2	31.0	27.4	44.9	48.4	45.6	56.3
Median (m3/s)	505.0	612.0	633.0	715.0	508.0	289.5	150.0	89.0	209.5	354.5	543.0	571.0
Standard dev	348.4	348.5	349.6	318.3	378.1	235.5	234.2	210.5	341.8	365.3	341.1	417.4
Kurtosis	0.9	1.1	1.0	1.0	0.9	0.9	0.6	0.5	0.6	0.8	1.0	0.9
Skewness	0.7	0.2	0.5	–0.4	1.6	1.5	2.6	3.5	2.1	1.5	0.3	0.4
Minimum	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Max	1717.0	1432.0	1729.0	1286.0	2059.0	1263.0	1325.0	1348.0	1779.0	1724.0	1372.0	1808.0
Quartile 1	331.0	326.0	380.8	521.0	286.0	166.5	87.0	67.0	91.3	142.3	286.8	346.8
Quartile 3	776.3	835.8	805.3	898.0	748.8	405.5	315.5	202.0	398.0	522.5	768.3	945.5
Range	1717.0	1432.0	1729.0	1286.0	2059.0	1263.0	1325.0	1348.0	1779.0	1724.0	1372.0	1808.0

As the sample size (n) increases, the test statistic, u, rapidly conforms to a standard normal distribution. Here, $T(i)$, where $i = 1,…, n$, represents the extreme event dates, n denotes the data size, and [t1, t2] indicates the observation interval (Mudelsee 2020).

In our study, we analysed two categories of events based on different threshold levels. Initially, we set the threshold at the 30-year average maximum discharge (1961–1990) as that is the reference period most commonly applied by WMO, for both summer (April-September) and winter (October-March) seasons. Further, we classified maximum discharges into two magnitudes as follows: Magnitude 1 (M1), severe events – maximum discharge up to the threshold; and Magnitude 2, extreme events (M2) with all discharge values above the threshold (Table 1).

In terms of annual assessments, severe events (M1) along the Una River are characterized by flow rates up to 504.4 m^3/s, while extreme events (M2) are delineated by values surpassing this threshold. This distinction is similarly observed during the summer season, where M1 events are defined as those with flow rates up to 405.2 m^3/s, and M2 events are those exceeding this level. During the winter season, the delineation remains consistent, with M1 events being those with discharge values up to the threshold of 605.6 m^3/s, and M2 events being those exceeding this threshold.

Turning to the Sana River, annual M1 events are denoted by flow rates up to 224.9 m^3/s, with M2 events representing values surpassing this threshold (Table 5). In the summer, the threshold is set at 181.2 m^3/s, with M1 events defined below this threshold and M2 events above it (Table 5). Similarly, for the winter season, the threshold is established at 249.1 m^3/s, with M1 events identified as those falling below this threshold, and M2 events as those exceeding it (Table 5).

Table 5: Thresholds applied to define severe (M1) and extreme (M2) events.

River	Annual	Summer season	Winter season
Una	504.4 m^3/s	405.2 m^3/s	605.6 m^3/s
Sana	224.9 m^3/s	181.2 m^3/s	249.1 m^3/s

3 Results and discussion

3.1 Flood seasonality

Severe (M1) and extreme (M2) events on the Una and Sana rivers mainly occurred during the winter half of the year (October to March) while no annual maximum occurred during June (Figure 3). Seasonal variations significantly impact the occurrence of annual maximum discharges in the Una and Sana Rives. Winter maximums are predominantly observed in April, these events are primarily the result of snowmelt in the upper regions of the basin and rainfall in the lower areas.

An analysis of M1 and M2 events occurrences throughout each month over the span of 1961–2020 unveils pronounced seasonal fluctuations. Notably, the frequency of winter events displayed an upward trajectory from October (three events) through March (nine events), gradually waning as the year advanced. In contrast, the prevalence of summer floods peaked in May (six events), gradually waning as the summer season approached its conclusion in September (three events).

3.2 Seasonal flood frequency and occurrence rate

To assess the trends in the occurrence of the M1 and M2 events, this study applied the Cox and Lewis test to inspect these trends. The statistical analysis affirmed these outcomes at a 95% confidence level, as illustrated in Figures 4 and 5. When analysis of the frequency of M1 events was conducted the same conclusion can be made for both stations during the summer season, and that is that there is an increasing trend at Una River ($u = 0.704$; $p = 0.241$) and Sana River ($u = 0.772$; $p = 0.220$), but these trends are not statistically significant. The frequency of M1 events at Una River increased from the beginning of the period from $\lambda_{(t)} \approx 3.3611\ a^{-1}$ to $\lambda_{(t)} \approx 3.635\ a^{-1}$ at the end of the period, or at the beginning of the period, one event was occurring every 54 days, while at the end of the period on the event was occurring every 50 days. Similarly, at Sana River frequency increased from 3.362 a^{-1} to 3.660 a^{-1}, this coincides with the increased frequency of these events from 55 days to 50 days. The occurrence rate of the M1 events during the winter season on Una and Sana rivers is characterized by a slight increase by the year 1990 followed by a flattening of the trend line indicating that no significant changes occurred during the winter season. At Una River, the frequency of M1 events during the winter season changed for just five days from 56 ($\lambda_{(t)} \approx 3.289$ a^{-1}) to 51

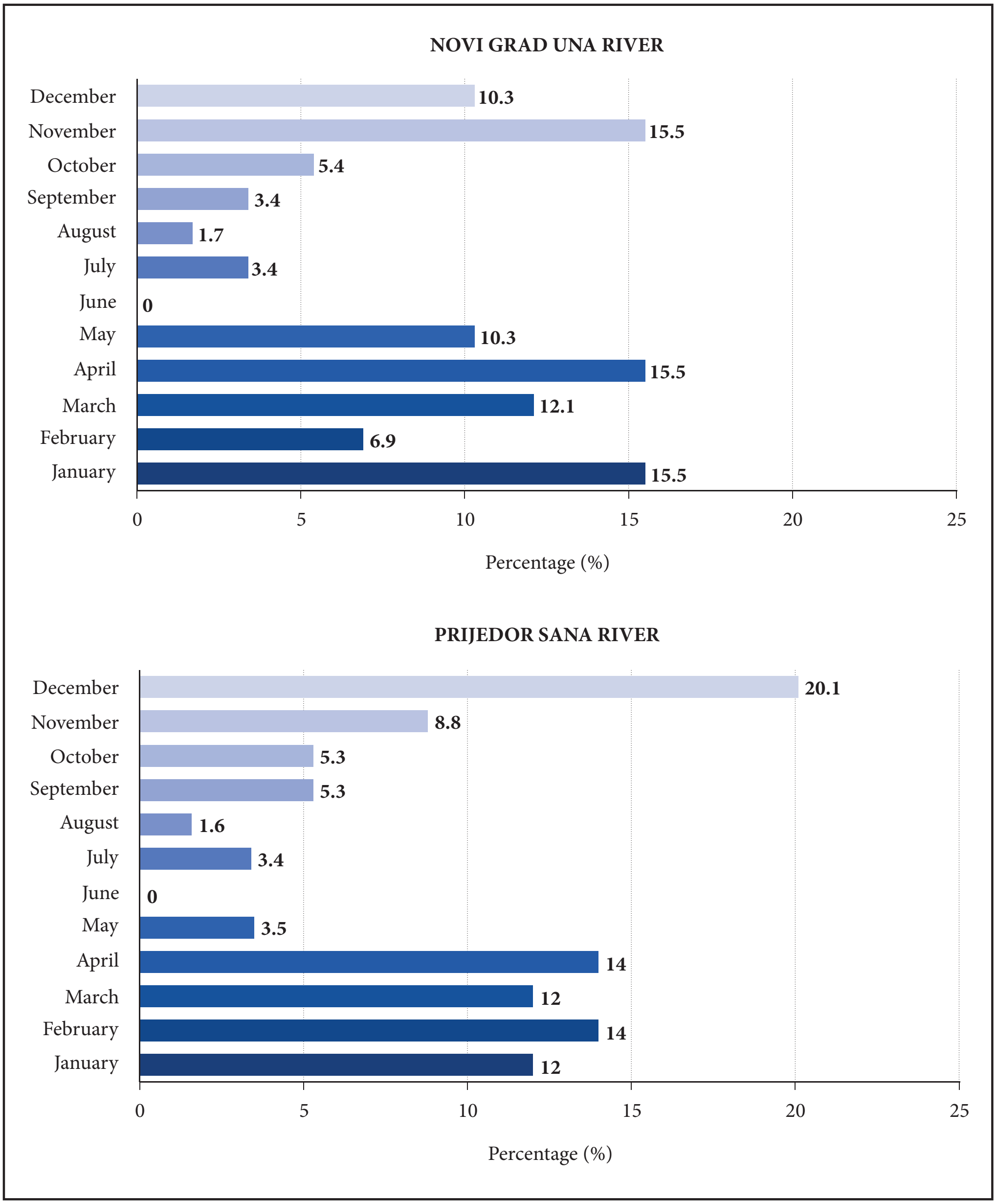


Figure 3: Percentage of annual maximum discharges per month for Una and Sana rivers.

day ($\lambda_{(t)} \approx 3.548\ a^{-1}$). Interestingly, on Sana River the decrease in the frequency of M1 events was observed during the winter season, at the beginning of the period it was 58 days ($\lambda_{(t)} \approx 3.165\ a^{-1}$), and at the end of the observed period 59 days ($\lambda_{(t)} \approx 3.112\ a^{-1}$).

During the observed period, the occurrence rate of the M2 events at Una River (Figure 4) shows a declining trend both during summer ($u = -0.819$; $p = 0.206$) and winter ($u = -0.799$; $p = 0.212$) but they were not statistically significant ($p < 0.05$). The frequency of summer M2 events on the Una River has exhibited a decrease over time. In the 1960s, the average frequency was approximately 68 days per event ($\lambda_{(t)} \approx 2.681\ a^{-1}$), while in 2020, it had extended to about 77 days per event ($\lambda_{(t)} \approx 2.406\ a^{-1}$). Similarly, during the winter season, a reduction in the frequency of M2 events was observed. At the start of the period, an event was expected approximately every 36 days ($\lambda_{(t)} \approx 2.692\ a^{-1}$), but by the end of the period, this frequency had decreased to one event every 76 days ($\lambda_{(t)} \approx 2.435\ a^{-1}$).

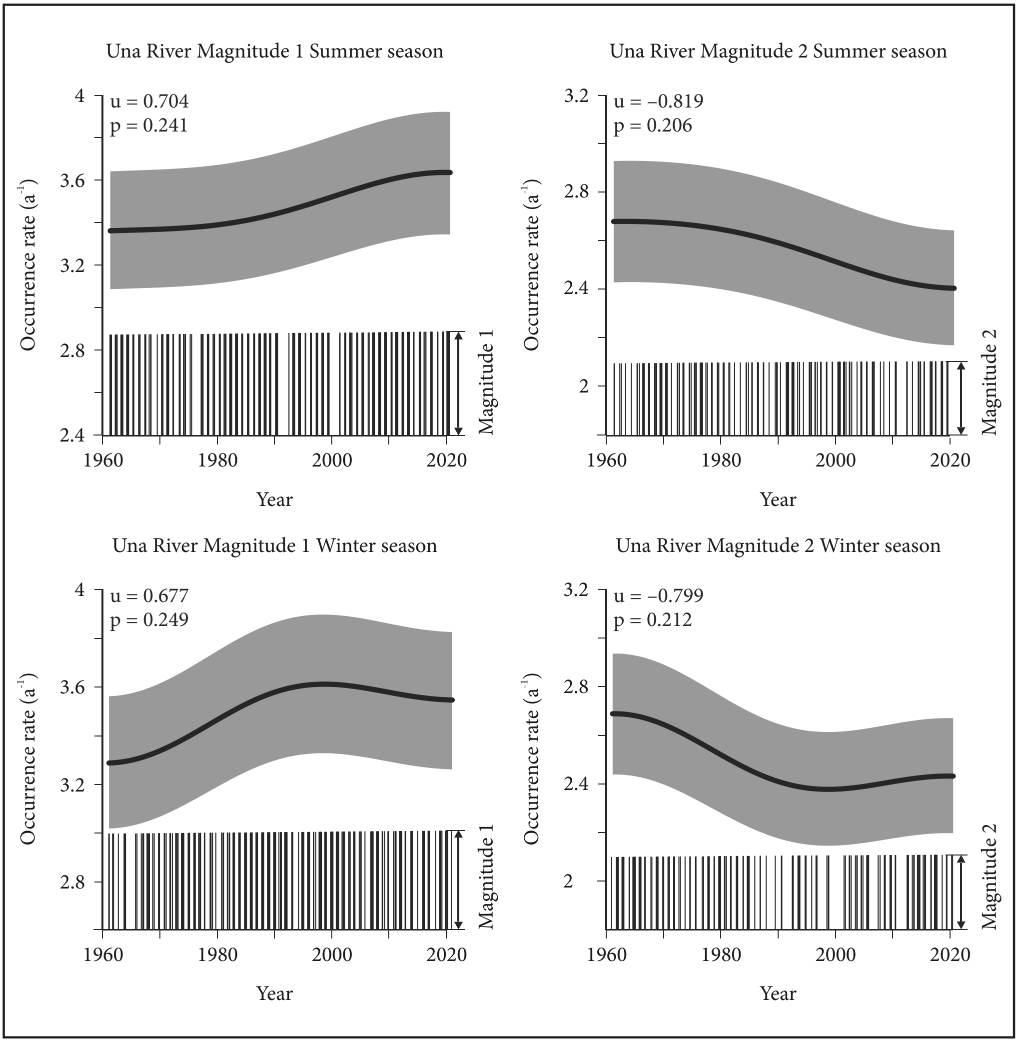


Figure 4: Occurrence rates (solid lines) of Una River monthly maximum discharge at Novi grad station for two magnitude classes with bootstrap 90% confidence band (shaded). Kernel estimation using a bandwidth of 20 years is applied to the flood dates with the Cox and Lewis test results for trend estimation (upper left-right corner of each graph).

The Sana River trends of the M2 events show that during summer season these events are decreasing ($u = -0.899$; $p = 0.184$) while during winter season a moderate increase can be observed ($u = -0.016$; $p = 0.493$) but this trend is not statistically significant ($p < 0.05$). The frequency of M2 events during summer season changed from 68 days ($\lambda_{(t)} \approx 2.681\ a^{-1}$) in 1961 to 77 in 2020 ($\lambda_{(t)} \approx 2.382\ a^{-1}$). Winter M2 events also changed, from 65 days ($\lambda_{(t)} \approx 2.817\ a^{-1}$) to 64 days ($\lambda_{(t)} \approx 2.870\ a^{-1}$).

In the latest Intergovernmental Panel on Climate Change (2023) report it is suggested that the assumption of stationary hydrology should be abandoned because of climate change and its effects that are likely to have a significant influence on the hydrological cycle. Consequently, several European Union (EU) countries have adopted modifications to their design standards, incorporating a precautionary approach that accounts for non-stationarity. That is why we applied the Cox-Lewis test which is expressly tailored to assess non-stationarity within the extremal component of the system responsible for generating a time series.

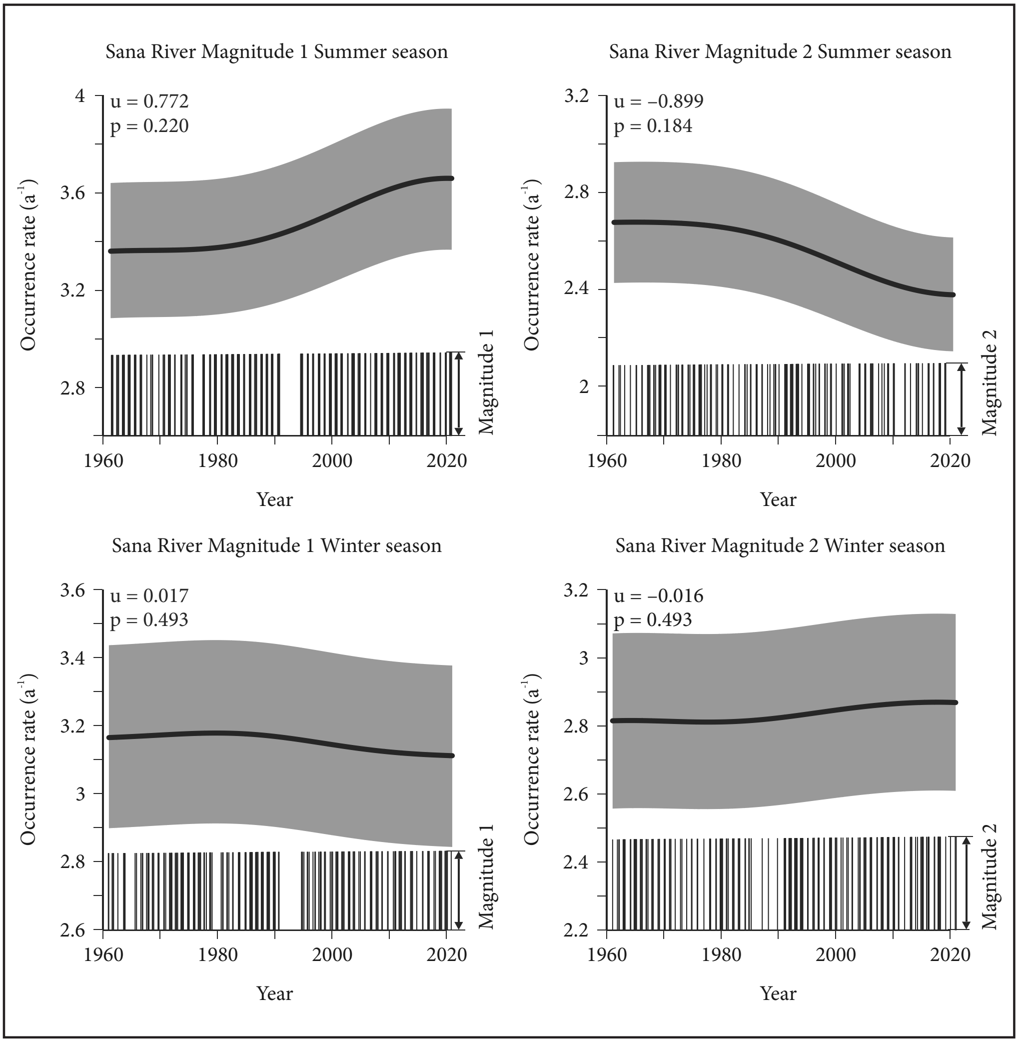


Figure 5: Occurrence rates (solid lines) of Sana River monthly maximum discharge at Prijedor station for two magnitude classes with bootstrap 90% confidence band (shaded). Kernel estimation using a bandwidth of 20 years is applied to the flood dates with the Cox and Lewis test results for trend estimation (upper left-right corner of each graph).

This aspect is particularly pertinent in hydroclimatic data analysis, as highlighted by Kundzewicz, Pińskwar and Brakenridge (2018). Results presented in Figures 4 and 5 imply that future changes in summer maximum discharge in the Una River basin mostly point to a rise in M1 events and to a decrease in the M2 events but these changes are not statistically significant. During the winter season, a similar increasing trend followed by a decrease in severe events is observed, while extreme events are showing an increase from the mid-1990s, but these changes are not statistically significant.

The analysis of seasonal data demonstrated that summer extreme events underwent more significant changes than winter events. When taking into account seasonal variations, winter and spring will become wetter due to a rise in precipitation by 20% caused mainly by higher temperatures (Myhre et al. 2019). These findings indicate that climate is the driving force behind the observed alterations in flood events as both winter and summer precipitations have also shown a statistically significant upward trend of precipitation over BH (Popov et al. 2017). According to the Clausius-Clapeyron relationship, there is an indication that the intensity of daily extreme precipitation escalates at a rate of approximately 7% for each 1 °C rise in air temperature (Mudelsee et al. 2004; Blöschl et al. 2019). This finding is further supported by empirical observations (Westra, Alexander and Zwiers 2013) and modeling experiments (O'Gorman 2015), both of which have rigorously examined the scaling hypothesis after the Clausius-Clapeyron equation across various spatial and temporal scales. Moreover, it's worth noting that cyclonic activity in Europe has seen an increase since the onset of the 21st century, leading to a heightened frequency of heavy rainfall events (Mikhailova, Mikhailov and Morozov 2012). For example, the highest one-day precipitation amount (Rx1day) trend has shown a statistically significant increase over most of the BH area during the winter period (October-March) (Leščešen et al. 2023). So, as the extreme precipitation in the region is increasing, it is expected that flooding in smaller basins could increase (Blöschl et al. 2019).

Consequently, alterations in these circulation patterns are anticipated to exert an influence on precipitation levels, thereby yielding substantial consequences for river discharge and water levels. There is a pressing need for further investigation to elucidate the intricate connections between circulation patterns, the frequency and scale of extreme hydrological events, and the geographical characteristics of the region. The findings of this study underscore the critical significance of meticulous scrutiny of shifts in flood behaviour when undertaking assessments for flood design and risk management (Petrow and Merz 2009). This analysis should be conducted again in the near future, to check if the seasonal change observed is a statistically significant change as the observation period is extended.

3.3 Annual flood frequency and occurrence rate

Further, we have analysed the occurrence and frequency of the M1 and M2 events at the annual time scale (Figure 6). Trend analysis of annual maximum discharges at Una River shows no statistically significant trends both for M1 ($u = 0.745$; $p = 0.228$) and M2 ($u = -0.802$; $p = 0.211$) events. Similarly, at the Sana River, no statistically significant trends were observed in both magnitudes, M1 events ($u = 0.612$; $p = 0.270$) and M2 events ($u = -0.675$; $p = 0.249$). This decrease in severe events is reported all over southeast Europe. A negative trend has been observed for major rivers in Serbia (Kovačević-Majkić and Urošev 2014; Leščešen et al. 2022a). Similarly, negative trends have been identified across the entirety of North Macedonia (Radevski et al. 2018). In Montenegro, the Morača River also exhibited a downward trend during the period from 1951 to 2010 (Burić, Ducić and Doderović 2016). In Slovenia, a reduction has been observed at the majority of hydrological gauges (Oblak, Kobold and Šraj 2021; Bezak, Brilly and Šraj 2016). Conversely, a negative trend has been reported in Croatia during the summer (Čanjevac and Orešić 2015). The trends in river flow observed in BH closely resemble the patterns identified in the southeastern part of Europe. Specifically, notable downward trend has been reported for rivers such as Bosna, Vrbas, Vrbanja and Sana (Gnjato et al. 2023).

The observed variations in these values provide valuable insights into the frequency of these events and the potential implications of long-term environmental changes. For the Una River, we observed an increase in the M1 events from 58 days ($\lambda_{(t)} \approx 6.320$ a^{-1}) at the beginning of the investigated period to 55 days ($\lambda_{(t)} \approx 6.653$ a^{-1}) at the end. This shift suggests a rise in the annual occurrence of M1 events over time, which may be indicative of changing hydrological conditions in the Una River basin. In contrast, the M2 events in the Una River exhibited a decreasing trend, decreasing from 64 days ($\lambda_{(t)} \approx 5.663$ a^{-1}) at the outset to 69 days ($\lambda_{(t)} \approx 5.332$ a^{-1}) by 2020. This reduction in the annual rate of occurrence for M2 events could signify a decrease in the frequency of more extreme events, raising questions about potential mitigating factors or environmental changes within the river's catchment area.

In the case of the Sana River, the findings revealed a rise in the M1 events, increasing from 56 days ($\lambda_{(t)} \approx 6.505$ a^{-1}) in 1960 to 54 days ($\lambda_{(t)} \approx 6.779$ a^{-1}) by 2020. This shift suggests a notable increase in the annual occurrence of M1 events, which could be related to a range of factors, including land use modifications, climate trends, or other environmental alterations. Interestingly, the M2 events in the Sana River decreased from 67 days ($\lambda_{(t)} \approx 5.478$ a^{-1}) at the beginning of the period to 70 days ($\lambda_{(t)} \approx 5.185$ a^{-1}) by 2020, indicating a significant decline in the frequency of more extreme events. This decline raises concerns about the potential impact of these extreme events on the river ecosystem, infrastructure, and local communities.

It is important to highlight several advantages and disadvantages of the presented study. On the positive side, the study contributes valuable insights into the patterns and trends of severe (M1) and extreme

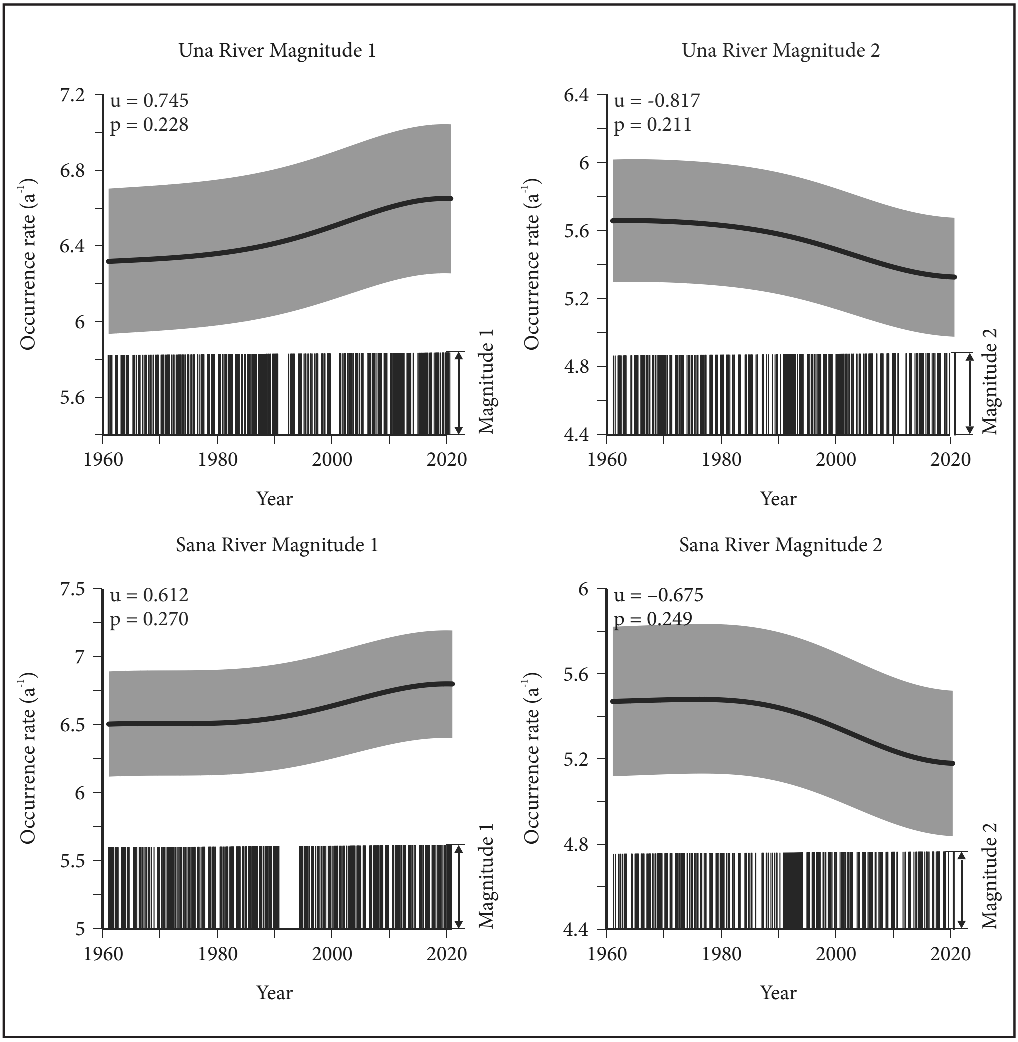


Figure 6: Occurrence rates of Annual Maximum Discharge (solid lines) of Una and Sana rivers for two magnitude classes with bootstrap 90% confidence band (shaded). Kernel estimation using a bandwidth of 20 years is applied to the maximum discharge data dates with the Cox-Lewis test results for trend estimation (upper left-right corner of each graph).

(M2) flood events, shedding light on their seasonal variations over a 60-year period. The use of sophisticated statistical methods, such as kernel estimation and trend analyses by means of the Cox-Lewis test, enhances the understanding of hydrological changes and allows for the identification of potential shifts in flood behaviour. Additionally, the inclusion of confidence bands in the results provides a measure of uncertainty, contributing to the robustness of the findings. However, some limitations exist. The absence of statistically significant trends in certain aspects of the data, particularly in M1 and M2 events during summer and winter, underscores the challenges in attributing observed changes solely to climate warming. Moreover, relying on a 30-year reference period for threshold determination may not fully capture the complexities of evolving climate patterns. Despite these limitations, the research serves as a foundation for future investigations and underscores the importance of continuous monitoring and analysis in the context of climate change impacts on flood events.

4 Conclusion

In this comprehensive analysis of severe (M1) and extreme (M2) events in the Una River basins, spanning from 1961 to 2020, we have unveiled critical insights into the dynamics of these extreme hydrological events in BH. Floods, regarded as one of the most destructive natural hazards worldwide, have exhibited intriguing seasonal variations and trends in this region. Our study highlighted the prevalence of winter maximum discharges, primarily occurring from October to March, while peak discharges are commonly observed in April due to snowmelt in the upper regions of the basin and rainfall in the lower areas. Conversely, summer maximum discharges peaked in May, diminishing as the summer season progressed. To assess trends in the occurrence of maximum discharges, we employed the Cox-Lewis test, revealing declining trends in the occurrence rate of Magnitude 2 events for both summer and winter seasons, though these were not statistically significant. Further, our findings suggest that future changes in summer and winter maximum discharges may indicate an increase in severe events, although these changes did not attain statistical significance.

Comparisons with neighbouring countries in Southeast Europe reveal a region-wide pattern of declining river discharges, similar to what we have observed in BH. However, extreme events exhibited a statistically significant increase in the Sana River, signalling a potential for more frequent extreme events in time to come.

Our study underlines the critical importance of ongoing monitoring and research into the intricate connections between climate change, circulation patterns, and flood behaviour. This comprehension is crucial for informed flood design and risk management strategies in a changing hydroclimatic landscape. By identifying non-stationarity in hydrology and emphasizing seasonal variations, our findings contribute to the broader understanding of the evolving nature of these hazards and the necessity for adaptive measures in BH and beyond. As flood events continue to pose significant threats to both human communities and the environment, proactive flood risk management strategies are essential on a global scale.

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5 References

Alifu, H., Hirabayashi, Y., Imada, Y., Shiogama, H. 2022: Enhancement of river flooding due to global warming. Scientific Reports 12. DOI: https://doi.org/10.1038/s41598-022-25182-6

Arnell, N. W., Gosling, S. N. 2016: The impacts of climate change on river flood risk at the global scale. Climatic Change 134-3. DOI: https://doi.org/10.1007/s10584-014-1084-5

Asadieh, B., Krakauer, N. Y. 2017: Global change in streamflow extremes under climate change over the 21st century. Hydrology and Earth System Sciences 21-11. DOI: https://doi.org/10.5194/hess-21-5863-2017

Bertola, M., Viglione, A., Lun D., Hall. J., Blöschl, G. 2020: Flood trends in Europe: are changes in small and big floods different? Hydrology and Earth System Sciences 24-4. DOI: https://doi.org/10.5194/hess-24-1805-2020
Bezak, N., Brilly, M., Šraj, M. 2016: Flood frequency analyses, statistical trends and seasonality analyses of discharge data: a case study of the Litija station on the Sava River. Journal of Flood Risk Management 9-2. DOI: https://doi.org/10.1111/jfr3.12118
Blöschl, G. 2022: Three hypotheses on changing river flood hazards. Hydrology and Earth System Sciences 26-19. DOI: https://doi.org/10.5194/hess-26-5015-2022
Blöschl, G., Hall, J., Viglione, A., Perdigão, R. A. P., Parajka, J., Merz, B., Lun, D. et al. 2019: Changing climate both increases and decreases European river floods. Nature 573. DOI: https://doi.org/10.1038/s41586-019-1495-6
Brönnimann, S., Stucki, P., Franke, J., Valler, V., Brugnara, Y., Hand, R., Slivinski, L. C. et al. 2022: Influence of warming and atmospheric circulation changes on multidecadal European flood variability. Climate of the Past 18-4. DOI: https://doi.org/10.5194/cp-18-919-2022
Burić, D., Ducić, V., Doderović, M. 2016: Poplave u Crnoj Gori krajem 2010. godine sa osvrtom na kolebanje proticaja Morače. Glasnik Odjeljenja prirodnih nauka 21.
Centre for Research on the Epidemiology of Disasters and United Nations Office for Disaster Risk Reduction 2020: The human cost of disasters: an overview of the last 20 years (2000-2019). Geneva, Brussels.
Cerneagă, C., Maftei, C. 2021: Flood frequency analysis of Casimcea river. IOP Conference Series: Materials Science and Engineering 1138. DOI: https://doi.org/10.1088/1757-899X/1138/1/012014
Chagas, V. B. P., Chaffe, P. L. B., Blöschl, G. 2022: Climate and land management accelerate the Brazilian water cycle. Nature Communications 13. DOI: https://doi.org/10.1038/s41467-022-32580-x
Chegwidden, O., Rupp, D. E., Nijssen, B. 2020: Climate change alters flood magnitudes and mechanisms in climatically-diverse headwaters across the northwestern United States. Environmental Research Letters 15. DOI: https://doi.org/10.1088/1748-9326/ab986f
Čanjevac, I., Orešić, D. 2015: Contemporary changes of mean annual and seasonal river discharges in Croatia. Hrvatski geografski glasnik 77-1. DOI: https://doi.org/10.21861/HGG.2015.77.01.01
Fischer, S., Schumann, A. H. 2021: Multivariate flood frequency analysis in large river basins considering tributary impacts and flood types. Water Resources Research 57-8. DOI: https://doi.org/10.1029/2020WR029029
Gnjato, S. 2022: Uticaj klimatskih promjena na proticaj rijeka u Bosni i Hercegovini. Ph.D. thesis, Univerzitet u Beogradu. Beograd.
Gnjato, S., Popov, T., Adžić, D., Ivanišević, M., Trbić, G., Bajić, D. 2021: Influence of climate change on river discharges over the Sava river watershed in Bosnia and Herzegovina. Időjárás 125-3. DOI: https://doi.org/10.28974/idojaras.2021.3.5
Gnjato, S., Popov, T., Ivanišević, M., Trbić, G. 2023: Long-term streamflow trends in Bosnia and Herzegovina (BH). Environmental Earth Sciences 82-14. DOI: https://doi.org/10.1007/s12665-023-11040-9
Hannaford, J., Mastrantonas, N., Vesuviano, G., Turner, S. 2021: An updated national-scale assessment of trends in UK peak river flow data: how robust are observed increases in flooding? Hydrology Research 52-3. DOI: https://doi.org/10.2166/nh.2021.156
Higashino, M. Stefan, H.G. 2019: Variability and change of precipitation and flood discharge in a Japanese river basin. Journal of Hydrology: Regional Studies 21. DOI: https://doi.org/10.1016/j.ejrh.2018.12.003
Hirabayashi, Y., Alifu, H., Yamazaki, D., Imada, Y., Shiogama, H., Kimura, Y. 2021: Anthropogenic climate change has changed frequency of past flood during 2010-2013. Progress in Earth and Planetary Science 8. DOI: https://doi.org/10.1186/s40645-021-00431-w
Hodgkins, G. A., Whitfield, P. H., Burn, D. H., Hannaford, J., Renard, B., Stahl, K., Fleig, A. K. et al. 2017: Climate-driven variability in the occurrence of major floods across North America and Europe. Journal of Hydrology 552. DOI: https://doi.org/10.1016/j.jhydrol.2017.07.027
Ilešič, S. 1948: Rečni režimi v Jugolsaviji. Geografski vestnik 19.
Ionita, M., Nagavciuc, V. 2021: Extreme floods in the eastern part of Europe: Large-scale drivers and associated impacts. Water 13-8. DOI: https://doi.org/10.3390/w13081122
Intergovernmental Panel on Climate Change (IPCC) 2023: Climate change 2021 – The physical science basis: Working Group I Contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge. DOI: https://doi.org/10.1017/9781009157896

Ivanišević, M., Savić, S., Pavić, D., Gnjato, S., Popov, T. 2022: Spatio-temporal patterns of flooded areas in the lower part of the Sana river basin (Bosnia and Herzegovina). Bulletin of the Serbian Geographical Society 102-2. DOI: https://doi.org/10.2298/GSGD2202067I

Kavcic, K., Brilly, M., Sraj, M. 2014: Regional flood frequency analysis in Slovenia. Geophysical Research Abstracts 16, EGU General Assembly. Vienna.

Kemter, M., Merz, B., Marwan, N., Vorogushyn, S., Blöschl, G. 2020: Joint trends in flood magnitudes and spatial extents across Europe. Geophysical Research Letters 47-7. DOI: https://doi.org/10.1029/2020GL087464

Kovačević-Majkić, J., Urošev, M. 2014: Trends of mean annual and seasonal discharges of rivers in Serbia. Journal of the Geographical Institute »Jovan Cvijic«, SASA 64-2. DOI: https://doi.org/10.2298/IJGI1402143K

Kundzewicz, Z. W., Graczyk, D., Maurer, T., Pińskwar, I., Radziejewski, M., Svensson, C., Szwed, M. 2005: Trend detection in river flow series: 1. Annual maximum flow. Hydrological Sciences Journal 50-5. DOI: https://doi.org/10.1623/hysj.2005.50.5.797

Kundzewicz, Z. W., Pińskwar, I., Brakenridge, G. R. 2018: Changes in river flood hazard in Europe: A review. Hydrology Research 49-2. DOI: https://doi.org/10.2166/nh.2017.016

Kuntla, S. K., Saharia, M., Kirstetter, P. 2022: Global-scale characterization of streamflow extremes. Journal of Hydrology 615. DOI: https://doi.org/10.1016/j.jhydrol.2022.128668

Leščešen, I., Basarin, B., Podraščanin, Z., Mesaroš, M. 2023: Changes in annual and seasonal extreme precipitation over southeastern Europe. Environmental Sciences Proceedings 26-1. DOI: https://doi.org/10.3390/environsciproc2023026048

Leščešen, I., Dolinaj, D. 2019: Regional flood frequency analysis of the Pannonian Basin. Water 11-2. DOI: https://doi.org/10.3390/w11020193

Leščešen, I., Šraj, M., Basarin, B., Pavić, D., Mesaroš, M., Mudelsee, M. 2022b: Regional flood frequency analysis of the Sava River in south-eastern Europe. Sustainability 14. DOI: https://doi.org/10.3390/su14159282

Leščešen, I., Šraj, M., Pantelić, M., Dolinaj, D. 2022a: Assessing the impact of climate on annual and seasonal discharges at the Sremska Mitrovica station on the Sava River, Serbia. Water Supply 22-1. DOI: https://doi.org/10.2166/ws.2021.277

Łopucki, R., Kiersztyn, A., Pitucha, G., Kitowski, I. 2022: Handling missing data in ecological studies: Ignoring gaps in the dataset can distort the inference. Ecological Modelling 468. DOI: https://doi.org/10.1016/j.ecolmodel.2022.109964

Majone, B., Avesani, D., Zulian, P., Fiori, A., Bellin, A. 2022: Analysis of high streamflow extremes in climate change studies: how do we calibrate hydrological models? Hydrology and Earth System Sciences 26-14. DOI: https://doi.org/10.5194/hess-26-3863-2022

Mikhailova, M. V., Mikhailov, V. N., Morozov, V. N. 2012: Extreme hydrological events in the Danube River basin over the last decades. Water Resources 39-2. DOI: https://doi.org/10.1134/S0097807812010095

Mudelsee, M. 2020: Statistical analysis of climate extremes. Cambridge. DOI: https://doi.org/10.1017/9781139519441

Mudelsee, M. 2014: Climate time series analysis: Classical statistical and bootstrap methods. Atmospheric and Oceanographic Sciences Library. Cham. DOI: https://doi.org/10.1007/978-3-319-04450-7

Mudelsee, M., Deutsch, M., Börngen, M., Tetzlaff, G., 2006: Trends in flood risk of the river Werra (Germany) over the past 500 years. Hydrological Sciences Journal 51. DOI: https://doi.org/10.1623/hysj.51.5.818

Mudelsee, M., Börngen, M., Tetzlaff, G., Grünewald, U. 2004: Extreme floods in central Europe over the past 500 years: Role of cyclone pat hway »Zugstrasse Vb«. Journal of Geophysical Research 109-D23. DOI: https://doi.org/10.1029/2004JD005034

Mudelsee, M., Börngen, M., Tetzlaff, G., Grünewald, U. 2003: No upward trends in the occurrence of extreme floods in central Europe. Nature 425. DOI: https://doi.org/10.1038/nature01928

Myhre, G., Alterskjær, K., Stjern, C. W., Hodnebrog, Ø., Marelle, L., Samset, B. H., Sillmann, J. et al. 2019. Frequency of extreme precipitation increases extensively with event rareness under global warming. Scientific Reports 9. DOI: https://doi.org/10.1038/s41598-019-52277-4

O'Gorman, P. A. 2015: Precipitation extremes under climate change. Current Climate Change Reports 1-2. DOI: https://doi.org/10.1007/s40641-015-0009-3

Oblak, J., Kobold, M., Šraj, M. 2021: The influence of climate change on discharge fluctuations in Slovenian rivers. Acta geographica Slovenica 61-2. DOI: https://doi.org/10.3986/AGS.9942

Paprotny, D., Sebastian, A., Morales-Nápoles, O., Jonkman, S. N. 2018: Trends in flood losses in Europe over the past 150 years. Nature Communications 9. DOI: https://doi.org/10.1038/s41467-018-04253-1

Pešić, A. M., Jakovljević, D., Rajčević, V., Gnjato, S. 2023: Extreme discharges trends in the rivers of the Balkan region – Examples from two adjacent countries (Bosnia & Herzegovina and Serbia). International Conference on Hydro-Climate Extremes and Society. Novi Sad

Petrow, T., Merz, B. 2009: Trends in flood magnitude, frequency and seasonality in Germany in the period 1951-2002. Journal of Hydrology 371-1-4. DOI: https://doi.org/10.1016/j.jhydrol.2009.03.024

Popov, T., Gnjato, S., Trbić, G., Ivanišević, M. 2017: Trends in extreme daily precipitation indices in Bosnia and Herzegovina. Collection of Papers - Faculty of Geography at the University of Belgrade 65-1. DOI: https://doi.org/10.5937/zrgfub1765005P

Radevski, I., Gorin, S. 2017: Floodplain analysis for different return periods of river Vardar in Tikvesh Valley (Republic of Macedonia). Carpathian Journal of Earth and Environmental Sciences 12-1.

Radevski, I., Gorin, S., Taleska, M., Dimitrovska, O. 2018: Natural regime of streamflow trends in Macedonia. Geografie 123-1. DOI: https://doi.org/10.37040/geografie2018123010001

Sharma, A., Wasko, C., Lettenmaier, D. P. 2018: If precipitation extremes are increasing, why aren't floods? Water Resources Research 54-11. DOI: https://doi.org/10.1029/2018WR023749

Shiklomanov, A. I., Lammers, R. B., Rawlins, M. A., Smith, L. C., Pavelsky, T. M. 2007: Temporal and spatial variations in maximum river discharge from a new Russian data set. Journal of Geophysical Research: Biogeosciences 112-G4. DOI: https://doi.org/10.1029/2006JG000352

Speight, L., Krupska, K. 2021: Understanding the impact of climate change on inland flood risk in the UK. Weather 76-10. DOI: https://doi.org/10.1002/wea.4079

Šraj, M., Bezak, N. 2020: Comparison of time trend- and precipitation-informed models for assessing design discharges in variable climate. Journal of Hydrology 589. DOI: https://doi.org/10.1016/j.jhydrol.2020.125374

Tabari, H. 2020: Climate change impact on flood and extreme precipitation increases with water availability. Scientific Reports 10. DOI: https://doi.org/10.1038/s41598-020-70816-2

Tadić, L., Bonacci, O., Dadić, T. 2016: Analysis of the Drava and Danube rivers floods in Osijek (Croatia) and possibility of their coincidence. Environmental Earth Sciences 75-18. DOI: https://doi.org/10.1007/s12665-016-6052-0

Tadić, L., Dadić, T., Barač, B. 2013: Flood frequency modelling of the Kopački rit Nature Park. Tehnički vjesnik 20-1.

Tarasova, L., Lun, D., Merz, R., Blöschl, G., Basso, S., Bertola, M., Miniussi, A. et al. 2023: Shifts in flood generation processes exacerbate regional flood anomalies in Europe. Communications Earth & Environment 4. DOI: https://doi.org/10.1038/s43247-023-00714-8

Venegas-Cordero, N., Kundzewicz, Z. W., Jamro, S., Piniewski, M. 2022: Detection of trends in observed river floods in Poland. Journal of Hydrology: Regional Studies 41. DOI: https://doi.org/10.1016/j.ejrh.2022.101098

Vicente-Serrano, S. M., Zabalza-Martínez, J., Borràs, G., López-Moreno, J. I., Pla, E., Pascual, D., Savé, R. et al. 2017: Extreme hydrological events and the influence of reservoirs in a highly regulated river basin of northeastern Spain. Journal of Hydrology: Regional Studies 12. DOI: https://doi.org/10.1016/j.ejrh.2017.01.004

Vidmar, A., Globevnik, L., Koprivšek, M., Sečnik, M., Zabret, K., Đurović, B., Anzeljc, D. et al. 2016: The Bosna River floods in May 2014. Natural Hazards and Earth System Sciences 16-10. DOI: https://doi.org/10.5194/nhess-16-2235-2016

Wang, X., Liu, L. 2023: The Impacts of climate change on the hydrological cycle and water resource management. Water 15. DOI: https://doi.org/10.3390/w15132342

Westra, S., Alexander, L. V., Zwiers, F. W. 2013: Global increasing trends in annual maximum daily precipitation. Journal of Climate 26-11. DOI: https://doi.org/10.1175/JCLI-D-12-00502.1

Wilson, D., Hisdal, H. 2013: Trends in floods in small Norwegian catchments – instantaneous vs. daily peaks. Geophysical Research Abstracts 15, EGU General Assembly. Vienna..

Zabret, K., Brilly, M. 2014: Hydrological regionalisation of flood frequency analyses in Slovenia. Acta hydrotechnica, 27-47.