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The Bosna River floods in May 2014

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Abstract. In May 2014, extreme floods occurred in the lower Sava River basin, causing major damage, with catastrophic consequences. Based on the data gathered, the weather situation in Bosnia and Herzegovina's (BiH) Bosna River basin was analysed and the hydrological conditions were provided, including the results of the probability analysis of the size of the recorded precipitation and flow rates. According to the observed data, extremely high precipitation intensities produced specific discharges of $1.0\,\mathrm{m^3\,s^{-1}\,km^{-2}}$. A hydrological model of the Bosna River basin was developed using HBV light for the purposes of reconstructing and forecasting such events more effectively. All analyses confirmed that the May 2014 event was an extreme extraordinary event whose return period greatly exceeds 100 years. The study is the basis for further flood safety measures and flood forecast development in the Bosna River basin.

1 Introduction

Devastating floods are a rare and unique phenomenon that prompts an in-depth hydrological analysis. This may involve the use of various statistical analysis tools, including hydrological modelling (Atta ur and Khan, 2013; Faisal et al., 2003; Grillakis et al., 2010; Silvestro et al., 2012).

This paper will address the May 2014 flooding of the Bosna River. The Bosna River basin (Fig. 1) comprises $10\,420\,\mathrm{km^2}$ according to the orographic boundary (ZV and FHMZ, 2012). The river, whose headwaters are in the Dinaric Mountains with peaks rising more than 2000 m above sea level, flows from the south to the north. Next to Sarajevo, the capital of BiH, which is situated in the Bosna River headwaters, there are important industrial towns located along its main channel: Zenica, Zavidovići, Maglaj, Doboj, Modriča, and Šamac – the latter at the confluence of the Bosna and Sava rivers.

In May 2014, flooding occurred because of precipitation that continuously fell for 4 days over the Sava River and its lower reach tributaries in the territories of Croatia, Bosnia and Herzegovina (BiH), and Serbia. The floods caused 23 fatalities, while more than 100 000 people were displaced from their homes, and many landslides and debris flows affected the area. All told, the flood event affected more than 50 % of BiH territory. The total estimated losses and damages, based on the recovery needs assessment, were almost EUR 2 billion (BiH, EU, UN, WB, 2014).

As is usually the case in such extreme hydrological events, water also damaged the hydrometric stations. It was those very stations which were to record the extremely high water levels that were particularly damaged or destroyed. Therefore, a hydrological model was produced and employed in the analysis.

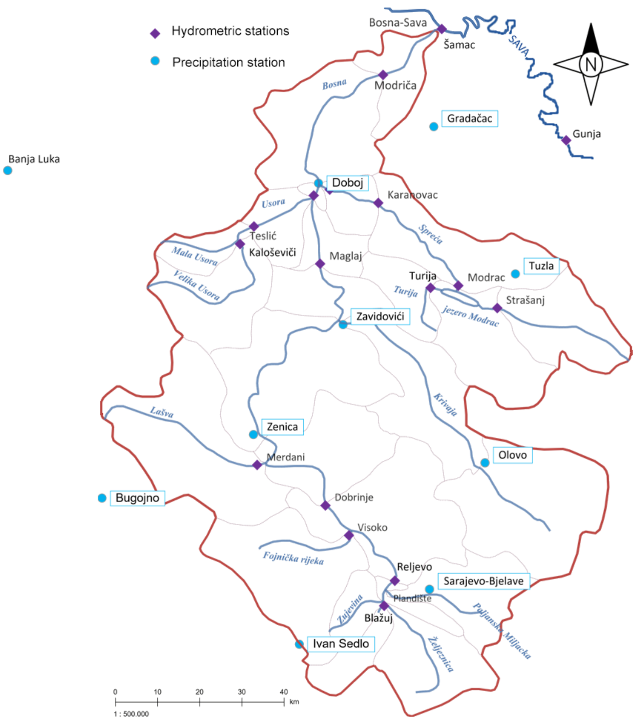

Figure 1. The Bosna River basin with major tributaries, locations of hydrometric stations, and precipitation stations (ZV and FHMZ, 2012).

2 Description of weather conditions

The May 2014 floods in the Balkans were the consequence of extraordinary precipitation due to the extensive low-pressure area, which moved from the South Adriatic Sea across Bosnia and Herzegovina and Serbia to Hungary. Even before the flood event, the soil in the flooded area was saturated due to the heavy rainfall in April, with the highest monthly rainfall amount recorded since 1961 at the weather stations Banja Luka with 214 mm, Tuzla 193 mm, and Zavidovići 170 mm, respectively (Table 1). At some weather stations, there was more than double the average historical rainfall for April. In April, Bosnia and Herzegovina was hit by as many as seven cyclones, while already on 2 May a new upper-level low formed over the Gulf of Genoa, which caused excessive rainfall on 3 and 4 May, particularly in the north (RHMZ RS, 2014).

On Monday 12 May 2014, a cold front passed through the affected zone, which brought in cooler air, particularly in the atmosphere's upper layers. By early Wednesday morning, a shallow low-pressure area had formed above the territory and began to intensify (DHMZ, 2014). From the west, upper-level jet streams brought in moist and unstable air. The inflow of cold air across the Alps on Wednesday 14 May caused a huge cyclone to form with its centre over Bosnia and Herzegovina. The cyclone reached its peak on 15 and 16 May when the centre moved towards the northeast, and it was only on Saturday 17 May, when it weakened. This resulted in prolonged rainfall in BiH, Croatia, and Serbia. The cyclone picked up moisture in the Mediterranean Sea and the Black Sea, while at high altitudes the cool air led to snowfall. The processes in the deep cyclone were very intensive since the cyclone's axis was vertical. Additionally, the cyclone was stationary, while on 15 May it moved further west. In addition to the extreme rainfall, the situation deteriorated due to the seasonally unusually low temperatures and severe winds (Renko, 2014). The cyclone took 3 days to pass through the central Balkans. At the same time, the high-pressure area persisted over western Europe and part of central Europe.

The precipitation period started in April 2014 and continued through May, reaching its maximum between 13 and 16 May 2014, as shown in Table 1.

The highest amount of precipitation from 12 to 17 May was recorded in Tuzla (252 mm), followed by Gradačac (195 mm) and Olovo (172 mm). The precipitation recorded in Sarajevo was lower than in the central and eastern part of the basin, but still significant, as precipitation fell across the entire river basin with a relatively moderate intensity. Hourly precipitation data for 15 May in Zenica ranged between 0.7 and 10.7 mm. Sarajevo had the highest intensity of hourly precipitation, where 11.4 mm of rain fell per hour on 14 May. It rained continuously from 12:00 on 13 May until the early morning of 16 May. Then, over the course of 16 and 17 May, the rain settled down to a very moderate intensity. In Tuzla, 229.9 mm of rain fell during the 62 h of continuous precipitation. Moreover, between 13 and 16 May, the snow that fell in the mountains in April, or before, probably also melted because the 0 °C isoline was at 800 m a.s.l. in the mountain region during night-time.

3 Probability analysis of multi-day precipitation in May 2014

By comparing the probability analysis values of maximum 2, 3, 4, 5, 10, 30, 40, and 50 day precipitation during the 1960–2013 and 2000–2010 periods and the maximum multi-day precipitation in April and May 2014, the May 2014 event return period was estimated for each of the BiH precipitation stations considered. The analysis included the reports (FHMZ BiH and RHMZ RS, 2014; RHMZ RS, 2014) and some precipitation data published on websites (OGIMET, 2014; Tutiempo, 2014; METEOBLUE, 2014). The data on wind speed recorded at weather stations show very low speed not exceeding 7.1 m s^{-1}, so the losses in precipitation recording at the stations did not exceed 10 %. Eleven precipitation stations were analysed, for which historical daily precipitation data and the data on precipitation in April and May 2014 were available (Fig. 1). Geographical coordinates (locations), altitudes of stations, and periods of data availability are shown in Table 2.

Table 1. The daily precipitation and daily precipitation totals for the selected period at individual stations in millimetres (data source: FHMZ BiH, RHMZ RS).

	Sarajevo-Bjelave (mm)	Olovo	Zenica	Zavidovići	Gradačac	Tuzla	Modrac
1–30 Apr 2014	97	136.5	19.6	170		192.6	
1–11 May 2014	32	27.1	16.5	25.8	91.8	55	
12 May 2014	14.1	15.3	4.4	0.8	3.3	4.9	
13 May 2014	34.6	5.5	30.2	12.3	21.1	20.6	52
14 May 2014	71.3	72.9	53.7	57.1	68.3	92.3	79.5
15 May 2014	18	65.8	38.7	33.1	85.1	103.8	76.6
16 May 2014	4.6	8	11.4	9	13.6	28.6	14.4
17 May 2014	2.4	4.4	3.3	2.4	3.3	2.5	
13–16 May 2014	116.5	150.4	127.1	107.8	178	229.2	
12–17 May 2014	145	171.9	141.7	114.7	194.7	252.7	222.5
1–17 May 2014	177	156.6	274.6	113.9	382.8	247.8	
1 Apr–17 May 2014	274	335.5	293.2	310.5	286.5	500.3	
Yearly average 1961–1990	932		782			894	

For most stations, the data are available for more than 40 years, while for precipitation stations Olovo, Zavidovići, and Sokolac the data are available for only 8 or 11 years. When using the data sets ranging between 40 and 54 years, the results indicate a return period of approx. 200 years. The acquired higher return periods of multi-daily precipitation at these stations, or at the stations with the data sets no longer than 11 years, must be taken with caution. Precipitation distribution at precipitation stations in the selected periods in May 2014 is shown in Table 3.

Return periods for individual precipitation durations are determined using the Gumbel distribution function; see Table 4. Plots of return period isolines for the individual durations of maximum multi-day precipitation also show the estimates of spatial dimension of precipitation event intensity. The 1, 2, 3, 5, 10, 30, 40 and 50 day precipitation return periods in the selected precipitation stations are spatially interpolated using the inverse distance weighted method (Anzeljc and Đurović, 2014). The 1 and 2 day isolines are shown in Fig. 2a and b. Most 1 day precipitation has a 5- to 10-year return period, and in some points a 100-year return period; 2 and 5 day precipitation has in some points a 5000- to 10 000-year return period, and 30 day precipitation has a 1000-year return period in some points. Given the precipitation that occurred in more than half of the Bosna River basin, the event probability was between 100 and 200 years, and locally even more than 5000 years.

We find that in Tuzla, most of the multi-day precipitation reached a return period in excess of 500 years. In Olovo, 2 and 3 day precipitation had more than a 500-year return period, while 1, 4 or 30 day precipitation had a 100-year return period. All other precipitation events had a return period of 20 years or more. In Doboj, most instances of multi-day precipitation had a return period between 20 and 50 years, and 3 day precipitation a return period of over 100 years. Similarly, in Sarajevo and Zenica multi-day precipitation had a return period of more than 20 years, while 3 to 7 day precipitation had a return period of more than 100 years.

In Tuzla, maximum 3 day precipitation fell on 14 May 2014, and 4 day and 5 day precipitation on 13 and 12 May, respectively; the 2 day precipitation in Olovo had a 500-year return period on 14 May; and the 4 day precipitation in Sarajevo had a 100-year return period on 12 May, and in Zenica on 13 May. Given the precipitation that occurred in more than half of the Bosna River basin, the event probability was between 100 and 200 years, and locally even more than 500 years.

4 Hydrological description of the Bosna River Basin

The hydrological study report ("Hidrološke studije površinskih voda Bosne i Hercegovine, Sliv rijeke Bosne", ZV, FHMZ BiH, 2012) compiles all the data available for the Bosna River basin. The central part of the Bosna River basin is hilly, while its lower reach flows on floodplains of the Sava River; see Fig. 3. Geologically the basin is extremely versatile, with distinct karst areas in its western part with rather undefined catchment borders. The Bosna River headwaters are defined by the Vrelo Bosne spring with its karst setting and with a small surface stream. Downstream, the Fojnica River and the Lašva River are its left-bank tributaries, while the Krivaja River joins it from the right at Zavidovići; see Fig. 1. At Doboj, the Usora River flows into the Bosna from the left side, and the Spreča River from the right. In the section between the Miljacka and Krivaja tributaries, there are many small streams flowing into the Bosna from the right with catchment areas of up to 200 km^2, and a total catchment area of approx. 1700 km^2; see Table 5. The river basin is mostly covered in forest, i.e. more than 56 %; see Fig. 4.

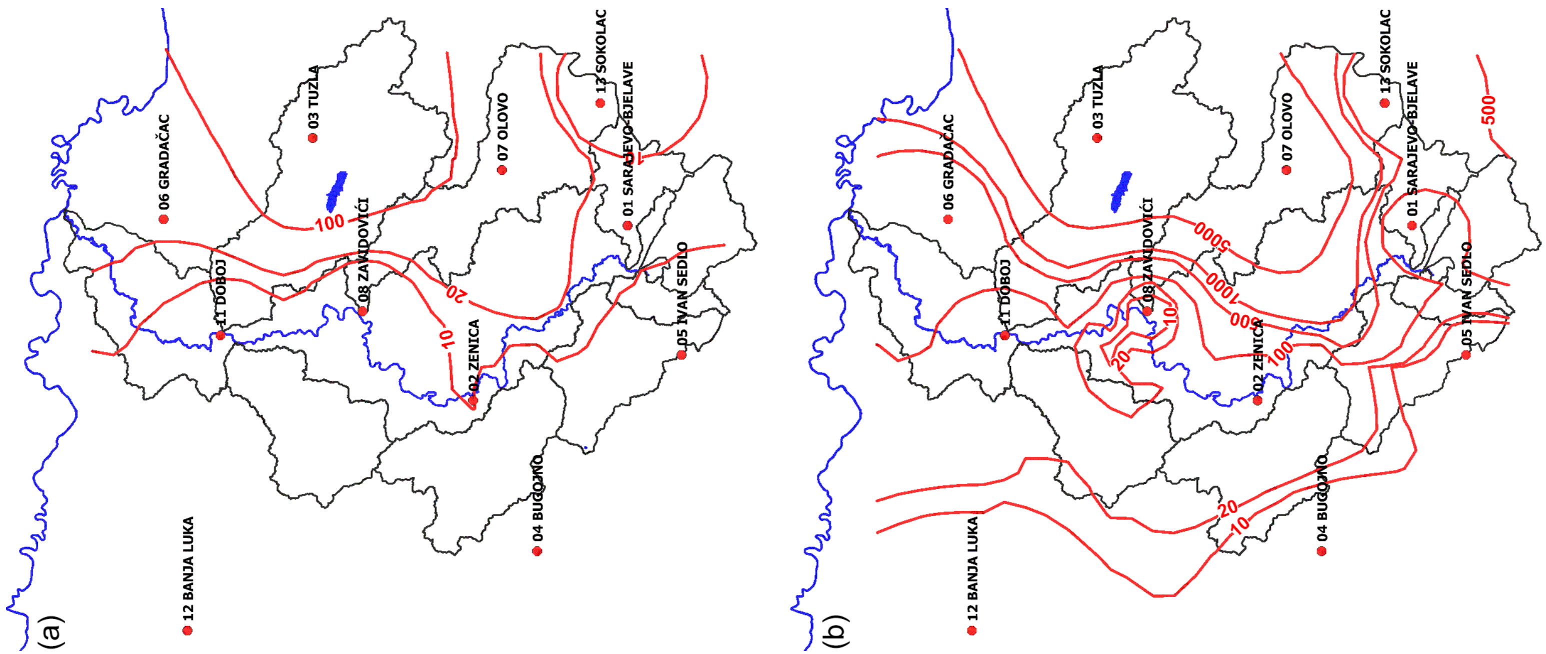

Figure 2. **(a)** The return period isolines of the 1 day maximum. **(b)** The return period isolines of the 2 day maximum, May 2014.

Table 2. Characteristics of precipitation stations (data source: FHMZ BiH, RHMZ RS, online information).

Precipitation station	Location of station			Period of precipitation data		No. of years of available data
	Lat	Long	Altitude	Daily	Hourly	
Sarajevo-Bjelave	43°52′04″	18°25′22″	630	1960–2013	April–May 2014	54
Zenica	44°11′57″	17°54′02″	344	1960–2013	April–May 2014	54
Tuzla	44°32′31″	18°41′06″	305	1960–2013	April–May 2014	54
Bugojno	44°03′43″	17°27′02″	562	1960–2013	April–May 2014[1]	53
Ivan Sedlo	43°45′03″	18°02′10″	967	1960–2013	April–May 2014[1]	49
Gradačac	44°51′32″	18°26′30″	230	1960–2013	April–May 2014[2]	52
Olovo	44°07′74″	18°35′22″	543	2006–2013[5]	2006–2014	8
Zavidovići	44°26′08″	18°10′02″	–	2003–2013[5]	2003–2014	11
Doboj	44°44′19″	18°05′42″	147	1961–1990, 2000–2010	May 2014[3,4]	41
Banja Luka	44°48′29″	17°12′46″	153	1960–1962[2], 1973–1996[2], 2000–2010	April–May 2014[3]	38
Sokolac	43°55′34″	18°47′21″	913	2000–2010	April–May 2014[3,4]	11

[1] The data retrieved from www.ogimet.com. [2] The data retrieved from www.tutiempo.net. [3] The data acquired from the report "Meteorological and hydrological aspects of floods in the Republika Srbska, May 2014" (RHMZ RS, 2014). [4] The data estimated based on the neighbouring precipitation stations. [5] Daily data evaluated from hourly data.

Table 3. Distribution of precipitation at precipitation stations in the selected periods in April and May 2014.

Precipitation station	Total precipitation in the period (mm)				
	1–30 Apr 2014 30 days	1–17 May 2014 17 days	1 Apr–17 May 2014 47 days	1–31 May 2014 31 days	1 Apr–31 May 2014 61 days
Sarajevo-Bjelave	97.0	177.0	274.0	184.4	281.4
Zenica	19.6	158.2	177.8	184.7	204.3
Tuzla	192.6	307.7	500.3	333.4	526.0
Bugojno	152.8	95.0	247.8	95.8	248.6
Ivan Sedlo	105.9	151.1	257.0	151.1	257.0
Gradačac	145.0	286.5	431.5	301.7	446.7
Olovo	136.5	199.0	335.5	210.5	347.0
Zavidovići	170.0	140.5	310.5	140.5	310.5
Doboj	–	232.5	232.5	232.5	232.5
Banja Luka	214.0	206.0	420.0	210.0	424.0
Sokolac	155.0	211.4	366.4	219.4	374.4
Modrac	160.8	297.8	458.6	328.8	489.6

Table 4. The estimated return periods of multi-day precipitation in April and May 2014 (according to the period 1960–2013).

Precipitation station	*No. of years*	**10 Multi-day precipitation (No. of days), return period (years)**															
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**15**	**20**	**30**	**40**	**50**	**60**
Sarajevo-Bjelave	*54/54*	10	20	50	100	100	50	20	20	20	10	10	20	20	10	5	5
Zenica	*54/54*	10	50	200	200	200	100	100	50	50	50	25	20	10	5	5	2
Tuzla	*54/54*	200	10000	10000	10000	10000	10000	2000	2000	500	500	500	1000	2000	500	200	200
Bugojno	*53/54*	2	2	5	2	2	2	2	2	5	2	5	5	10	10	5	5
Ivan Sedlo	*49/54*	5	5	5	5	5	5	2	2	2	2	2	2	2	2	2	2
Gradačac	*52/54*	20	200	200	200	200	100	100	50	50	50	200	200	500	200	100	50
Olovo	*8/54*	100	10000	500	200	50	50	50	25	25	25	50	50	100	50	50	25
Zavidovići	*11/54*	5	5	10	10	10	10	10	5	5	5	10	5	20	20	10	5
Doboj	*41/54*	5	25	100	50	50	25	20	20	20	20	50	20	10	5	5	20
Banja Luka	*38/54*	2	2	5	5	5	5	5	5	5	5	10	20	50	50	50	20
Sokolac	*11/54*	5	100	200	200	200	200	100	50	50	50	25	50	200	100	25	25

Note: the shading of the values above indicates the ranking of the precipitation return period

500-10000	100-200	20-50	2-10

All hydrometric stations in the river basin are also shown in Fig. 1. The flow measurement data are given in the report (Kastelic et al., 2014), which is a good basis for further hydrological analysis and insight in the Bosna River hydrological system. Furthermore, the data on the January 2010 flood are of interest. At the time, the hourly flow data were available; see Fig. 5. The data and Fig. 5 show that the 2010 flood wave was formed due to the coincidence of the flood wave peaks of the Bosna and the Krivaja at the confluence at Zavidovići. The Lašva River maximum flow occurred more than 40 h after the first flood peak in the Bosna River at Zavidovići. The data for the Usora River has no significant reaction on the flood event but there were also no data 24 h after the peak flow in the Bosna River at Zavidovići hydrometric station. Due to the influence of the Modrac reservoir and the extensive floodplain area, the Spreča River flow is almost fully balanced without significant changes. The flood discharges in the main stream of the Bosna River collect runoff from the head part of the catchment, upstream from the hydrometric station Dobrinje, from small tributaries close to the main stream and from the Krivaja River. Discharges rise simultaneously along the river with a concentration time from 6 to 12 h. The tributaries from the karst region, the Lašva River, the Usora River, and the Spreča River with a large reservoir and inundated areas, have concentration times from 1 to 2 days.

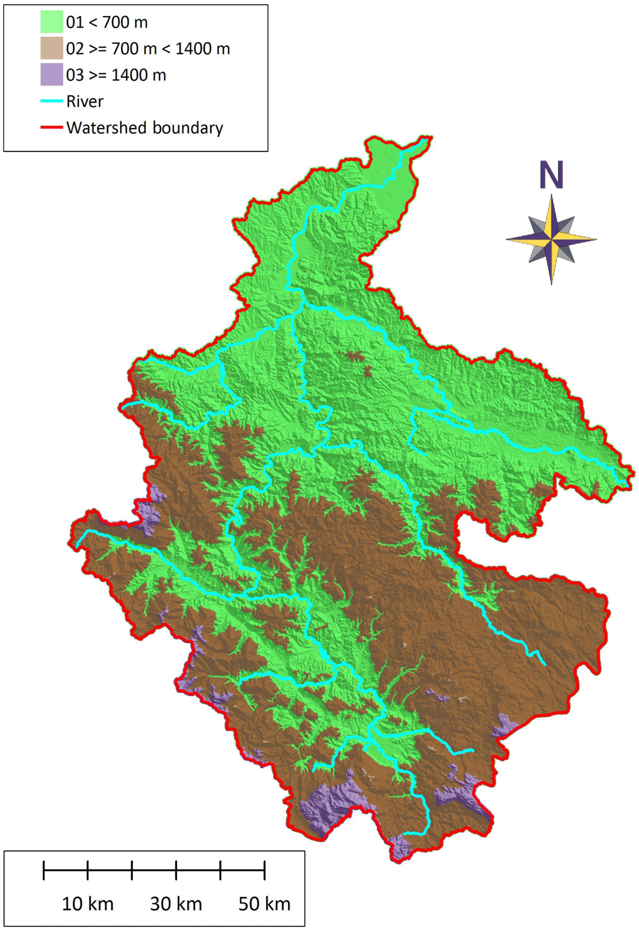

Figure 3. Elevation zones of the Bosna River basin.

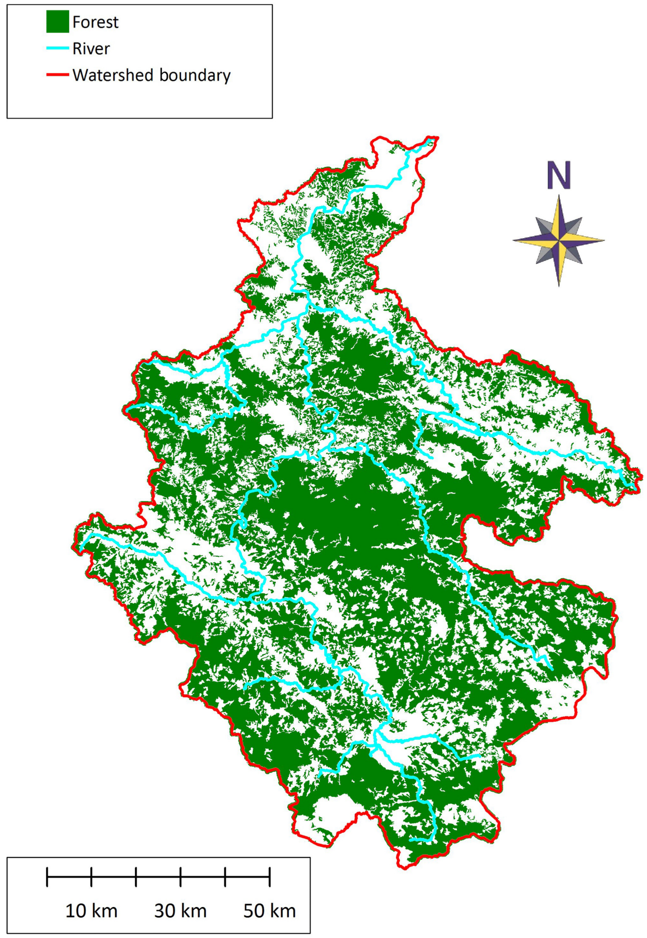

Figure 4. Forest zone in green in the area of the Bosna River basin.

This analysis also highlights the complexity of the Bosna River hydrological system. The maximum flows are subject to the coincidence of flood waves and precipitation duration, or are under strong influence of the river basin's karstic region. This phenomenon can be well observed from the Lašva River flows, which during the first flood wave (7 January 2010) did not significantly increase, while its relatively small flood wave coincided with that of the Bosna River. During the second event, the flows significantly increased, culminating in a flood wave that reached the Bosna River channel 10 h prior to the flood wave peak in the Bosna itself.

5 Flood in May 2014

The April and May precipitation caused several flood waves in the Bosna River basin. The maximum flows occurred on 15 May. Figure 6 shows the flood wave discharges during the May 2014 floods at hydrometric stations on the Bosna River and its major tributaries. The data show how the flood wave formed along the Bosna River flow, together with an almost simultaneous increase in discharges. The left tributaries of the Bosna, i.e. the Lašva and Usora rivers, whose recharge area is karst, increased very slowly and reached their maxima when most of the flood wave had already run off. The Krivaja River increased simultaneously and significantly contributed to maximum flows. The Spreča River flows were small due to the retention of water in the Modrac reservoir and the impact of the extensive flooded area which slowed down the rising of flows; in fact, the flows decreased by more than 50 %. The Modrac reservoir has a capacity of 68 million m^3 and collects water from an area of 1189 km^2; flows into the reservoir are very well monitored (Spreča d.d. Tuzla, 2014); see Fig. 7. The diagram shows that the reservoir reduced the discharge from 1602 and 1441 $m^3\,s^{-1}$ to a maximum of 1137 $m^3\,s^{-1}$ and delayed the maximum flow by 10 h. The specific discharges at the reservoir section were around 1 $m^3\,s^{-1}\,km^{-2}$. The flooded area of the Spreča River further decreased the river discharge at the confluence with the Bosna River to only 496 $m^3\,s^{-1}$ and delayed the discharge peak by 11 h. Hence, maximum flows were formed by the tributaries in the upper reach, from the areas whose smaller streams directly joined the Bosna River and its tributary, the Krivaja River. Land-

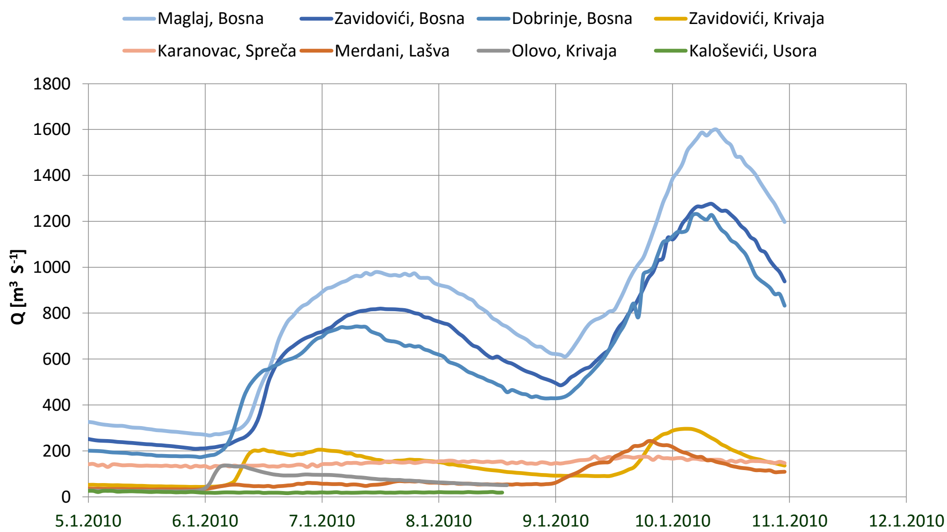

Figure 5. The discharges at hydrometric stations during the January 2010 flooding (data source: FHMZ BiH, 2014).

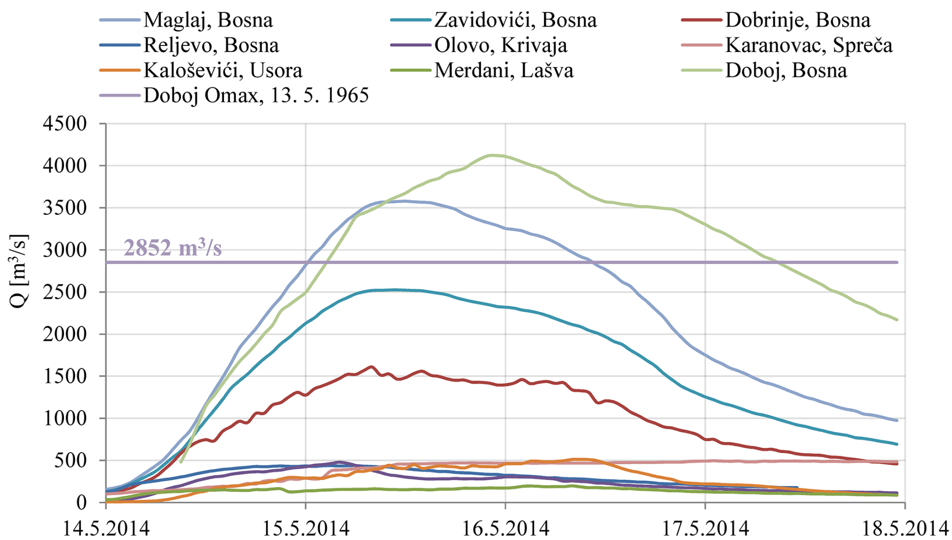

Figure 6. The discharges at hydrometric stations during the May 2014 flooding (data source: RHMZ RS and FHMZ BiH).

slides and debris flows completely altered the morphology of the Željezno polje valley in a part of the Bosna River basin between Zavidovići and Zenica; see Fig. 8.

The hydrometric stations at the Krivaja and Bosna rivers downstream of Doboj were damaged or destroyed. The hydrograph of the Bosna River at hydrometric station Doboj was reconstructed and estimated from observations during the flood event.

The Sava at Bosanski Šamac, i.e. the Bosna River's discharge, started to increase on 14 May and reached its maximum when a flow of 6009 $m^3\,s^{-1}$ was recorded under the Sava bridge. At the same time, at the Gunja hydrometric station downstream from the confluence with the Bosna River, a flow of 4621 $m^3\,s^{-1}$ was recorded, meaning that the floodplain areas upstream from Šamac continued to fill with water. The recordings were taken by the Croatian hydrometeorological service on 17 May – 1 day after the Bosna River reached its maximum at Doboj (Abdulaj et al., 2014). At the confluence, catastrophic floods occurred due to the water overtopping the embankments on both sides of the Sava, both in BiH and Croatia.

We analysed the probabilities of annual maximum flows and annual maximum flood wave volumes[1] of the Bosna River at the hydrometric station Doboj for the 1961–2014 period (the data from 1990 to 1999 are missing) using the Log-Pearson III distribution (Fig. 9, USWRC, 1982). The maximum flow of the Bosna at Doboj in May 2014 was 4121 $m^3\,s^{-1}$ and had a return period of 152 years according

[1] The database is available on request.

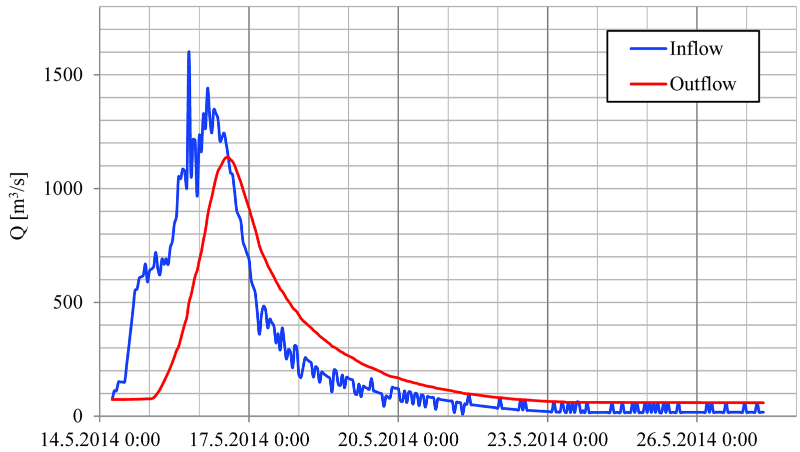

Figure 7. Inflow and outflow diagrams for the Modrac reservoir (data source: Spreča d.d. Tuzla, 2014).

Figure 8. Željezno polje – the consequences of the debris flow.

to the estimated flow probability for the 1961–2014 period. The maximum flood wave volume of the Bosna at Doboj in May 2014 was 1464 million m^3 and had a return period of 189 years according to the estimated volume probability for the 1961–2014 period. The maximum recorded flow of the Bosna at Doboj prior to the May 2014 event was 2852 $m^3\,s^{-1}$, and the maximum recorded flood wave volume was 789 million m^3.

The data in Table 6 show that at other stations the flows also greatly exceeded the 100-year return period flows. The flood duration was important, as the maximum flow recorded at hydrometric station Doboj in 1965, i.e. 2852 $m^3\,s^{-1}$, lasted for more than 55 h in the 2014 flood.

6 Hydrological model of the Bosna River

We developed a hydrological model of the Bosna River for analysis of the 2014 flood. We used HBV light (Seibert, 2005) and PEST model calibration software (Doherty, 2012, 2005; Lawrence et al., 2009; Zhulu, 2010). The Bosna River catchment area was divided into 25 subcatchments with surface areas ranging from 30 to 1000 km^2 (Fig. 10). Land use was set according to the CORINE database (Fig. 4) (EEA, 2014). All subcatchments were divided into zones according to altitude (three zones). The height zones were below 700, from 700 to 1400, and above 1400 m (Fig. 3).

The data necessary for model construction were provided by the national hydrological services, which conducted a very good hydrological study of the entire basin by compiling all the recorded hydrological data and fundamental hydrological analyses to date (FHMZ BiH, RHMZ RS, 2014). The available data were mainly collected on a daily step basis.

The precipitation data were collected for six weather stations: Sarajevo-Bjelave, Zenica, Tuzla, Bugojno, Ivan Sedlo, and Doboj. For the same stations, we also considered the data on temperature and evapotranspiration. Data from 31 hydrometric stations were available for modelling. The period of 1 January 1964–31 December 1968 was chosen as the calibration period, and the later period, i.e. 1 January 1984–31 December 1988, was chosen as the validation period. The calibration period was selected with the highest discharges observed in 1965. Due to the huge discrepancy between the measured and the simulated mass balance, we had to increase the huge karst spring of the Vrelo Bosne river basin (3) from 4 to 169 km^2 (Table 6). The river basins of Željeznica and Zujevina were correspondingly reduced. Even with such an extension in the river basin surface, the runoff coefficient of the Vrelo Bosne watershed is among the highest; see Table 6.

The coefficients of determination and efficiency are extremely good for the flows along the Bosna River, and some-

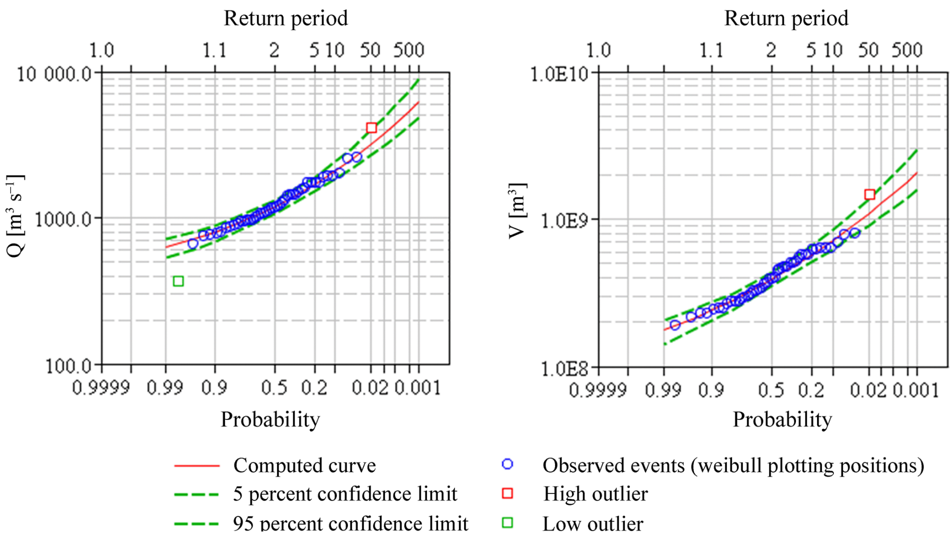

Figure 9. The probability analysis of annual maximum flows and maximum flood wave volumes of the Bosna at Doboj for the 1961–2014 period.

Table 5. Subcatchments with areas used in the hydrological model.

Subcatchment no.	Subcatchment name	Watercourse	Subcatchment area (km^2)
1	Željeznica	Željeznica	433.43
2	Zujevina	Zujevina	155.19
3	Vrelo Bosne	Bosna	169.14
4	Miljacka	Miljacka	412.91
5	Bosna1	Bosna	84.13
6	Fojnica	Fojnica	729.36
7	Bosna2	Bosna	773.76
8	Lašva	Lašva	958.18
9	Bosna3	Bosna	518.46
10	Bioštica i Stupčanica	Krivaja	890.73
11	Krivaja	Krivaja	603.42
12	Bosna4	Bosna	892.00
13	V_Usora	Usora	480.72
14	M_Usora	Usora	158.93
15	Usora	Usora	206.72
16	Bosna5	Bosna	266.34
17	Turija	Turija	233.03
18	Spreča1	Spreča	463.30
19	Modrac	Spreča	495.87
20	Spreča2	Spreča	596.49
21	Spreča3	Spreča	160.10
22	Bosna6	Bosna	182.29
23	Bosna7	Bosna	29.38
24	Bosna8	Bosna	690.79
25	Bosna9	Bosna	251.54
		Total area	10 836.20

Table 6. Maximum flow probability at selected hydrometric stations (data source: ZV, FHMZ BiH, 2012).

Return period	Q ($m^3\,s^{-1}$)						
	Modriča	Doboj	Maglaj	Zavidovići	Raspotočje	Dobrinje	Reljevo
10	2214	2091	1508	1164	904	600	345
20	2551	2420	1764	1320	1039	717	400
50	2990	2795	2120	1520	1220	880	464
100	3318	3087	2479	1673	1360	1058	510
2014 event		4121	3578	2525		1608	440

Figure 10. Hydrological model of the Bosna River basin divided into 25 subcatchments.

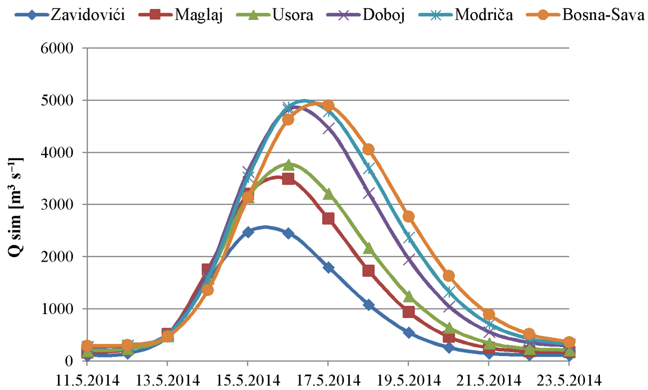

Figure 11. Simulated mean daily discharges on the Bosna River.

what poorer for individual tributaries where the precipitation runoff is retained due to the karst geology or the reservoirs. These are the Fojnica, Lašva, Upper Krivaja, Usora, Turija, and Spreča rivers. The model's results show that the catchment area of the Vrelo Bosne (3) is probably still underestimated, while those of the Krivaja River at Olovo and the Lašva River are overestimated; see Table 7. The May 2014 flooding event was simulated using a daily time step for the April–May 2014 period. In Fig. 11 just this flood event is presented. Modelled extremely high flows take 3 days like the measured one (Fig. 6). Discharges reached their maxima in Doboj on 16 May and at the confluence with the Sava River, the next day, on 17 May. High discharges simulated by the model were a little higher than the estimated one due to the improper simulation of the release of water in inundated areas. The runoff coefficients for the maximum flood wave in May for the Bosna ranged between 0.76 (Bosna River at Modriča water station) and 0.91 (Bosna River downstream confluence with the Usora tributary). The runoff coefficient for the Bosna at the town of Doboj was 0.82 (Kastelic et al., 2014).

7 Conclusions

The precipitation that caused the May 2014 floods of the Bosna River in some places and for 2 day duration exceeded the 5000-year return period. The maximum Bosna River flows at Doboj only reached a 152-year return period, while the flood wave volumes had a somewhat longer return period of 189 years.

The hydrological analyses performed show such a hydrological structure of the basin where the flood wave is formed, mainly in the central part of the river basin, and the Krivaja River tributary and rise simultaneously. The model simulated flood events with proper timing of discharges. The peaks seem a little overestimated. The model clearly presents that the catchment borders should be rearranged due to the karst geology of watershed. The recorded maximum flows

Table 7. The results of the model calibration with PEST software.

Hydrometric station	Subcatchment	The calibration of the model for the period 1 Jan 1961–31 Dec 1990				
		Coefficient of determination	Model effectiveness	Spearman coefficient	Runoff coefficient – measured	Runoff coefficient – simulated
Ilidža	Željeznica	0.63	0.63	0.9	0.76	0.70
Blažuj	Zujevina	0.62	0.62	0.8	0.54	0.55
Plandište	Vrelo Bosne	0.75	0.75	0.9	0.82	0.82
Sarajevo	Miljacka	0.58	0.58	0.8	0.55	0.52
Reljevo	Bosna1	0.73	0.72	0.9	0.79	0.77
Visoko	Fojnica	0.71	0.71	0.9	0.57	0.55
Dobrinje	Bosna2	0.77	0.77	0.9	0.66	0.68
Merdani	Lašva	0.65	0.64	0.9	0.70	0.67
Raspotočje	Bosna3	0.80	0.80	0.9	0.73	0.74
Olovo	Bioštica	0.52	0.52	0.8	0.42	0.40
Zavidovići_K	Krivaja	0.61	0.61	0.8	0.59	0.59
Zavidovići_B	Bosna4	0.77	0.76	0.9	0.77	0.77
Teslić	V.Usora	0.46	0.46	0.7	0.82	0.82
Kaloševići	M.Usora	0.47	0.47	0.7	0.75	0.77
Usora-Bosna	Usora	0.46	0.46	0.7	0.75	0.74
Maglaj	Bosna5	0.75	0.74	0.9	0.65	0.67
Turija	Turija	0.36	0.35	0.6	0.43	0.45
Strašanj	Spreca1	0.51	0.50	0.8	0.47	0.45
Modrac	Modrac	0.54	0.54	0.7	0.43	0.45
Karanovac	Spreca2	0.60	0.60	0.8	0.45	0.45
Stanić Rijeka	Spreca3	0.65	0.64	0.8	0.69	0.44

of the Bosna River in the flood event significantly exceeded the probability of a 100-year return period, while the hydrological model verified such discharges. The flood discharge on water station Doboj in May 2014 was 44 % higher than any previous recorded flow, and insufficiently designed levees collapsed, resulting in fatalities.

The analysis is the basis for further flood safety measures and flood forecast development in the Bosna River basin. The model should be developed on an hourly timescale and used for hydrological forecasting of floods on the Bosna River.

The flow recording data suggest the extreme impact of the reservoir and the Spreča River flooded area on the reduction of the flood wave peak that dropped from 1500 to 500 $m^3\,s^{-1}$. In addition, the recorded specific discharge of 1.0 $m^3\,s^{-1}\,km^{-2}$ is significantly high. Such extreme flood events are rare and we could learn a lot by analysing them.

Each occurrence of extreme floods is complex and the result of the coincidence of various factors. To be able to understand it, a proper data analysis and simulations with well-calibrated models are necessary.

8 Data availability

Data are available upon request from public official institutions: Federal Hydrometeorological Institute BiH and Republic Hydrometeorological Service of RS.

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