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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. 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 event whose returning period greatly exceeds 100 years.

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 km^2 according to the orographic boundary (ZV and FHMZ, 2012). The river, whose headwaters are in the Dinaric Alps with peaks rising more than 2000 m a.s.l., 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, Zvidoivići, Maglaj, Doboj, Modriča, and Šamac – the latter at the confluence of the Bosna and Sava rivers.

In May 2014, flooding occurred as a consequence of precipitation that continuously fell for several 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 the area was also affected by many landslides and debris flows. All told, the flood event affected

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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 water stations. It was those very stations which were to record the extremely high water levels which were particularly damaged or destroyed. Therefore, a hydrological model was produced and employed in the analysis.

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 flooded area was saturated due to the heavy rainfall in April, with the highest monthly rainfall amount recorded since 1961 at the weather stations Prijedor with 214 mm, Doboj 177.4 mm, and Prijedor 163.8 mm, respectively. 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 (DMHZ, 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 more or less 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). It took the cyclone 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 was recorded in Tuzla, followed by Gradačac and Olovo. The precipitation recorded in Sarajevo, Tuzla, and Zavidovići was lower than in the 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 p.m. on 13 May until the early morning of 16 May. Then, over the course of 16 May 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.

3 Probability analysis of multi-day precipitation in May 2014

By comparing the probability analysis values of maximum multi-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 per the BiH precipitation stations considered. The analysis included the reports and precipitation data (FHMZ BiH, 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 %. 11 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.

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 the 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.

Various sources were used for quantifying daily precipitation amounts for April and May 2014; to complete the data sets we used the method of extracting data from graphical records, infilling of missing data on daily precipitation by reference to precipitation distribution at nearby stations based on known monthly quantities, and quantitative precipitation estimates and distribution from forecasts (WMO, 2008). 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. 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 2, 3, 4, 5, 10, 30, 40 and 50 day precipitation return periods in the selected precipitation stations are spatially interpolated using the inverse distance weighted method and shown in Fig. 2. 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. The return periods of longer precipitation events are shorter than those of shorter precipitation events. 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, two- and three-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 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 2014, 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.

By comparing the probability analysis values during 1960–2013 (Table 4) and 2000–2010 (Table 5), it is evident that in all seven stations the shorter data sets compared to the longer data sets give the same, or higher, precipitation values with the same return periods. We estimate that the return periods of multi-day precipitation in April and May 2014 at the precipitation stations with shorter data sets, i.e. Zavidovići, Olovo, and Sokolac, could be somewhat higher.

4 Hydrological description and the May 2014 event

The hydrological study report (ZV, FHMZ BiH, 2012) complies 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 flood plains of the Sava River, 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 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. 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, Table 6. The river basin is mostly covered in forest, i.e. more than 56 %, Fig. 4.

All water 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, 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's maximum flow, in the second flood wave, occurred prior to the occurrence of the second flood wave in the Bosna River, which was, in fact, caused by the precipitation of the first flood wave. The data for the Usora river are not available for the second flood wave; however, the Usora's first flood wave arrived at the Bosna River 30 h prior to the maximum. Due to the influence of the Modrac reservoir and the extensive floodplain area, the Spreča's flow is almost fully balanced, and it increased the Bosna river flows by 10 %.

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 the flood wave peak in the Bosna itself.

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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), Fig. 7. The diagram shows that the reservoir reduced the discharge from 1602 and 1441 $m^3 s^{-1}$ to a total 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. Landslides and debris flows completely altered the morphology of the Željezno polje valley in a part of the Bosna river basin between Zavidovići and Zenica, Fig. 8.

The water stations at the Krivaja and Bosna rivers downstream of Doboj were damaged or destroyed.

The Sava at Bosanski Šamac, i.e. the Bosna Rivers discharge, started to increase on 14 May and reached its maximum when a flow of 6000 $m^3 s^{-1}$ was recorded under the Sava bridge. The part of the flow across the floodplain areas on the right bank of

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the river was not recorded. At the same time, at Gunja downstream, a flow 1400 $m^3 s^{-1}$ smaller was recorded, meaning that the floodplain areas downstream Šamac continued to fill with water.

Flows of 6000 $m^3 s^{-1}$ were recorded on the Sava directly downstream of the confluence of the Bosna and the Sava, i.e. at the bridge at Šamac. The recordings were taken by the Croatian hydrometeorological service on 17 May – 2 days 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. In any case, the maximum Bosna River flow was larger than the discharge in the Sava River channel above the confluence.

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 is missing) using the Log Pearson III distribution (Fig. 9). 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 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 7 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.

[1]The database is available on request.

6 Hydrological model of the Bosna River

We developed a hydrological model for flow forecasting on the Bosna River and for analysis of the 2014 flood. To this end, we used the programmes 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 defined as forest and other land cover using the CORINE database (Fig. 4) (EEA, 2014). All subcatchments were divided into zones according to the altitude (3 zones). The height zones were: below 700 m, from 700 to 1400 m, and above 1400 m (Fig. 3).

The data necessary for model construction were provided by FHMZ BiH and RHMZ RS where a very good hydrological study of the entire basin was conducted by compiling all the recorded hydrological data and fundamental hydrological analyses to date (FHMZ BiH, RHMZ RS, 2014).

Input data needed for calibration or launch of the model:

- precipitation for 11 stations,
- temperature for 6 stations,
- flow for 31 stations,
- potential evapotranspiration for 6 stations.

The precipitation data were collected for six stations: Sarajevo-Bjelave, Zenica, Tuzla, Bugojno, Ivan Sedlo, and Doboj. For the same stations we also considered the data on temperature and evapotranspiration. The period 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. Due to the too-low flows, we had to increase the Vrelo Bosne river basin from 4 to 169 km^2. The river basins of Željeznica and Zujevina were correspondingly reduced.

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The coefficients of determination and efficiency are extremely good for the flows along the Bosna River, and somewhat poorer for individual tributaries where the precipitation runoff is retained due to the karst topography 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 is probably underestimated, while those of the Krivaja at Olovo and the Lašva are overestimated, Table 8.

The May 2014 flooding event was simulated using a daily time step for the April–May 2014 period (Fig. 11). According to the simulation results, the Bosna River flows in Maglaj exceeded the return period of 500 years, and 1000 years in other places. The runoff coefficients for the maximum flood wave in May for the Bosna ranged between 0.76 (Bosna Modriča) and 0.91 (Bosna downstream the Usora tributary). The runoff coefficient for the Bosna at the town of Doboj was 0.82.

7 Conclusions

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

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 drop from 1.500 to 500 $m^3 s^{-1}$. Also, the recorded specific discharge of 1.0 $m^3 s^{-1} km^{-2}$ is significantly high.

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. The analysis is the basis for further flood safety measures and flood forecast development in the Bosna River basin.

The hydrological model confirmed the analysis results and is already being used for forecasting flood flows in the Bosna River (ICPDR and ISRBC, 2015).

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

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

	Sarajevo-Bjelave	Olovo	Zenica	Zavidovići	Gradačac	Tuzla	Modrac
				[mm]			
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, 16:00–6:00	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	–
Average	932	–	782	–	–	894	–

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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	
01	Sarajevo-Bjelave	43°52′04″	18°25′22″	630	1960–2013	Apr–May 2014	54
02	Zenica	44°11′57″	17°54′02″	344	1960–2013	Apr–May 2014	54
03	Tuzla	44°32′31″	18°41′06″	305	1960–2013	Apr–May 2014	54
04	Bugojno	44°03′43″	17°27′02″	562	1960–2013	Apr–May 2014[a]	53
05	Ivan Sedlo	43°45′03″	18°02′10″	967	1960–2013	Apr–May 2014[a]	49
06	Gradačac	44°51′32″	18°26′30″	230	1960–2013	Apr–May 2014[b]	52
07	Olovo	44°07′74″	18°35′22″	543	2006–2013[e]	2006–2014	8
08	Zavidovići	44°26′08″	18°10′02″	–	2003–2013[e]	2003–2014	11
11	Doboj	44°44′19″	18°05′42″	147	1961–1990, 2000–2010	May 2014[c, d]	41
12	Banja Luka	44°48′29″	17°12′46″	153	1960–1962[b], 1973–1996[b], 2000–2010	Apr–May 2014[c]	38
13	Sokolac	43°55′34″	18°47′21″	913	2000–2010	Apr–May 2014[c, d]	11

[a] The data retrieved from www.ogimet.com.
[b] The data retrieved from www.tutiempo.net.
[c] The data acquired from the report "Meteorološki i hidrološki aspekti poplava u Republici Srpskoj, maj 2014".
[d] The data estimated based on the neighbouring precipitation stations.
[e] Daily data evaluated from hourly data.

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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	1–17 May 2014	1 Apr 2014–17 May 2014	1–31 May 2014	1 Apr 2014–31 May 2014
		30 days	17 days	47 days	31 days	61 days
01	Sarajevo-Bjelave	97.0	177.0	274.0	184.4	281.4
02	Zenica	19.6	158.2	177.8	184.7	204.3
03	Tuzla	192.6	307.7	500.3	333.4	526.0
04	Bugojno	152.8	95.0	247.8	95.8	248.6
05	Ivan Sedlo	105.9	151.1	257.0	151.1	257.0
06	Gradačac	145.0	286.5	431.5	301.7	446.7
07	Olovo	136.5	199.0	335.5	210.5	347.0
08	Zavidovići	170.0	140.5	310.5	140.5	310.5
11	Doboj	–	232.5	232.5	232.5	232.5
12	Banja Luka	214.0	206.0	420.0	210.0	424.0
13	Sokolac	155.0	211.4	366.4	219.4	374.4
	Modrac	160.8	297.8	458.6	328.8	489.6

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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	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
01	Sarajevo-Bjelave	54/54	10	20[c]	50[c]	100[b]	100[b]	50[c]	20[c]	20[c]	20[c]	10	10	20[c]	20[c]	10	5	5
02	Zenica	54/54	10	50[c]	200[b]	200[b]	200[b]	100[b]	100[b]	50[c]	50[c]	50[c]	25[c]	20[c]	10	5	5	2
03	Tuzla	54/54	200[b]	10 000[a]	10 000[a]	10 000[a]	10 000[a]	10 000[a]	2000[a]	2000[a]	500[a]	500[a]	500[a]	1000[a]	2000[a]	500[a]	200[b]	200[b]
04	Bugojno	53/54	2	2	5	2	2	2	2	2	5	2	5	5	10	10	5	5
05	Ivan Sedlo	49/54	5	5	5	5	5	5	2	2	2	2	2	2	2	2	2	2
06	Gradačac	52/54	20[c]	200[b]	200[b]	200[b]	200[b]	100[b]	100[b]	50[c]	50[c]	50[c]	200[b]	200[b]	500[a]	200[b]	100[b]	50[c]
07	Olovo	8/54	100[b]	10 000[a]	500[a]	200[b]	50[c]	50[c]	50[c]	25[c]	25[c]	25[c]	50[c]	50[c]	100[b]	50[c]	50[c]	25[c]
08	Zavidovići	11/54	5	5	10	10	10	10	10	5	5	5	10	5	20[c]	20[c]	10	5
11	Doboj	41/54	5	25[c]	100[b]	50[c]	50[c]	25[c]	20[c]	20[c]	20[c]	20[c]	50[c]	20[c]	10	5	5	20[c]
12	Banja Luka	38/54	2	2	5	5	5	5	5	5	5	5	10	20[c]	50[c]	50[c]	50[c]	20[c]
13	Sokolac	11/54	5	100[b]	200[b]	200[b]	200[b]	200[b]	100[b]	50[c]	50[c]	50[c]	25[c]	50[c]	200[b]	100[b]	25[c]	25[c]

Note: the letters of the values above indicates the ranking of the precipitation return period: [a] 500–10 000; [b] 100–200; [c] 20–50; without letter 2–10.

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Table 5. The estimated return periods of multi-day precipitation in April and May 2014 (according to the period 2000–2010).

Precipitation station		No. of years	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
01	Sarajevo-Bjelave	11/11	5	10	20[c]	50[c]	50[c]	20[c]	20[c]	10	10	5	5	10	10	5	5	5
02	Zenica	11/11	5	50[c]	200[b]	200[b]	200[b]	100[b]	50[c]	50[c]	50[c]	25[c]	20[c]	10	5	5	2	2
03	Tuzla	11/11	50[c]	200[b]	200[b]	200[b]	100[b]	200[b]	200[b]	200[b]	100[b]	50[c]	50[c]	50[c]	50[c]	20[c]	20[c]	20[c]
04	Bugojno	11/11	2	2	5	2	5	2	2	2	5	2	5	5	10	20[c]	5	5
05	Ivan Sedlo	11/11	5	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
06	Gradačac	11/11	20[c]	20[c]	25[c]	25[c]	25[c]	20[c]	20[c]	20[c]	20[c]	20[c]	50[c]	50[c]	50[c]	25[c]	20[c]	20[c]
11	Doboj	11/11	5	10	10	10	10	10	5	5	5	5	10	5	5	5	2	5

Note: the letters of the values above indicates the ranking of the precipitation return period: [a] 500–10 000; [b] 100–200; [c] 20–50; without letter 2–10.

Table 6. 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

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Table 7. 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

Table 8. 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	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

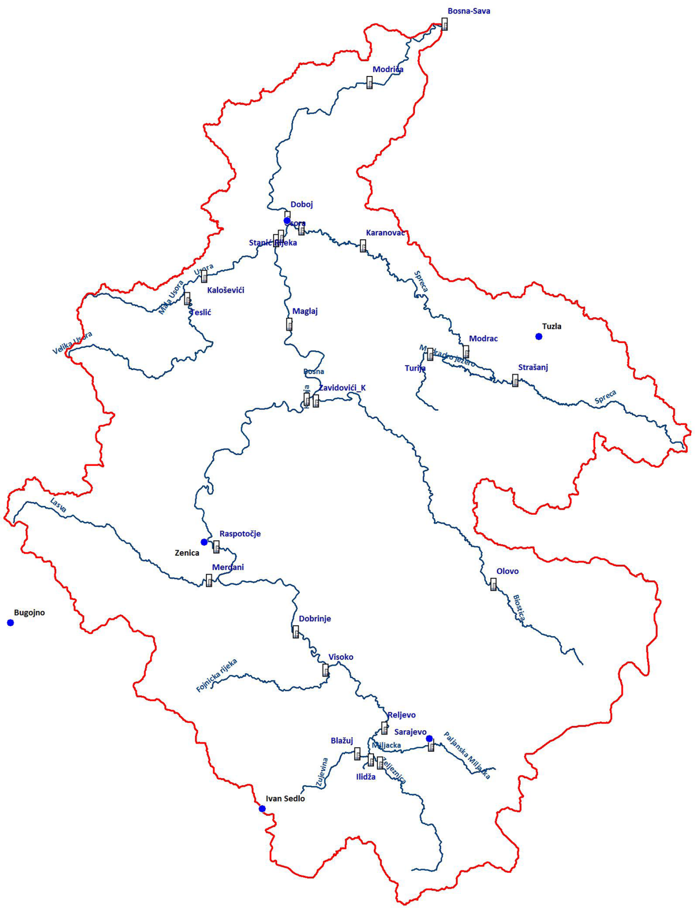

Figure 1. The Bosna River basin with locations of hydrometric stations and precipitation stations (ZV and FHMZ, 2012).

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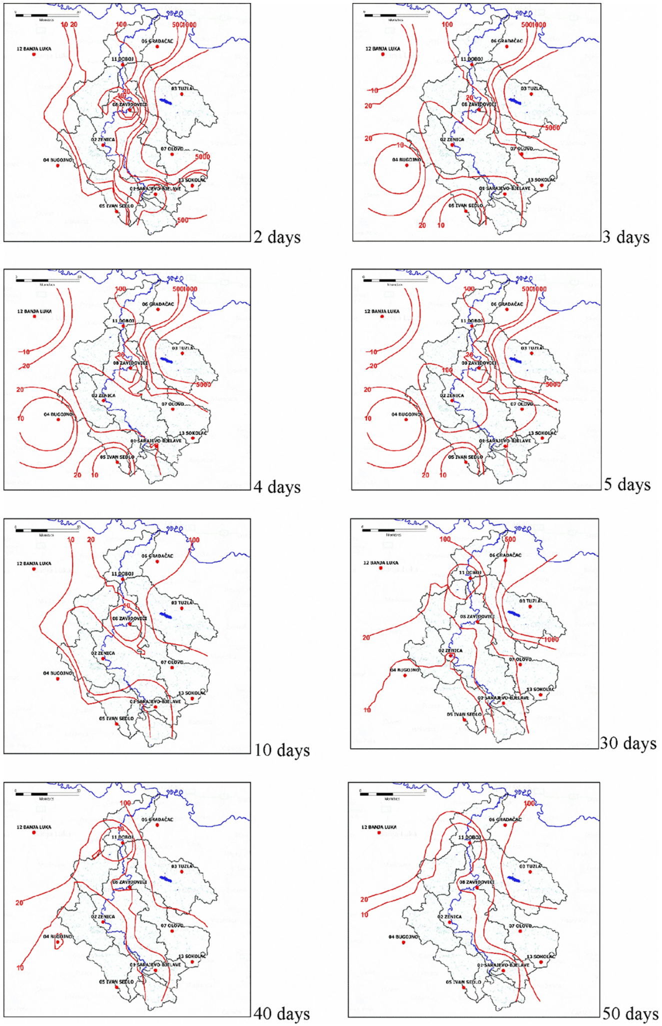

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Figure 2. The return period isolines of maximum 2, 3, 4, 5, 10, 30, 40 and 50 day precipitation in April and May 2014.

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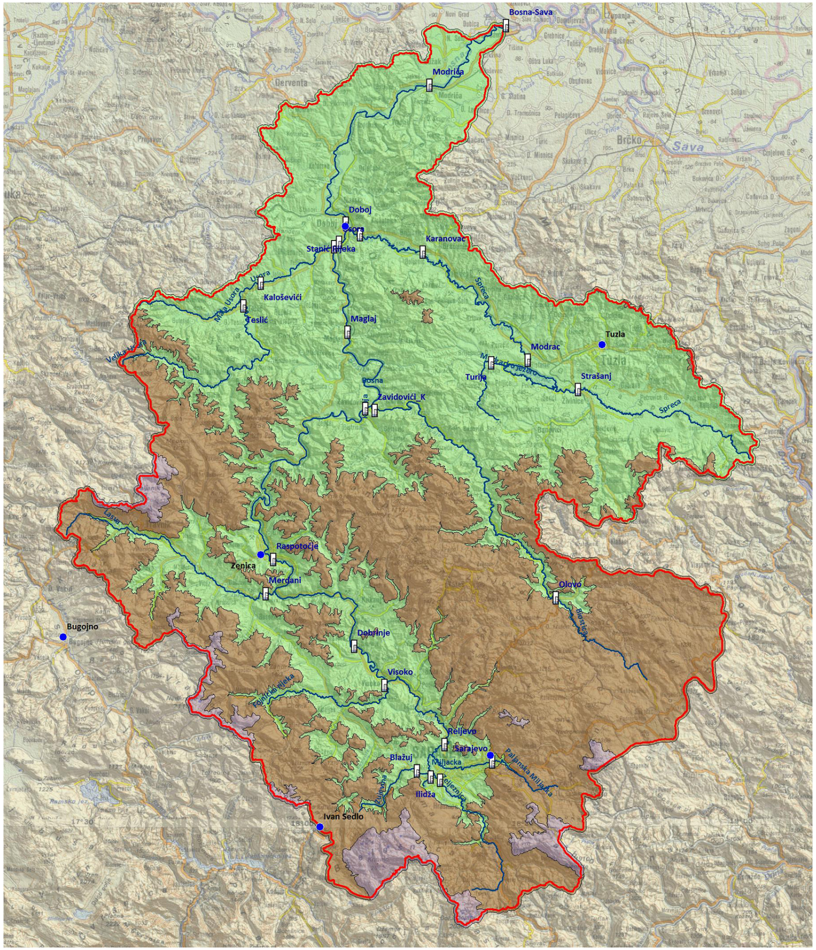

Figure 3. Elevation zones of the Bosna River basin.

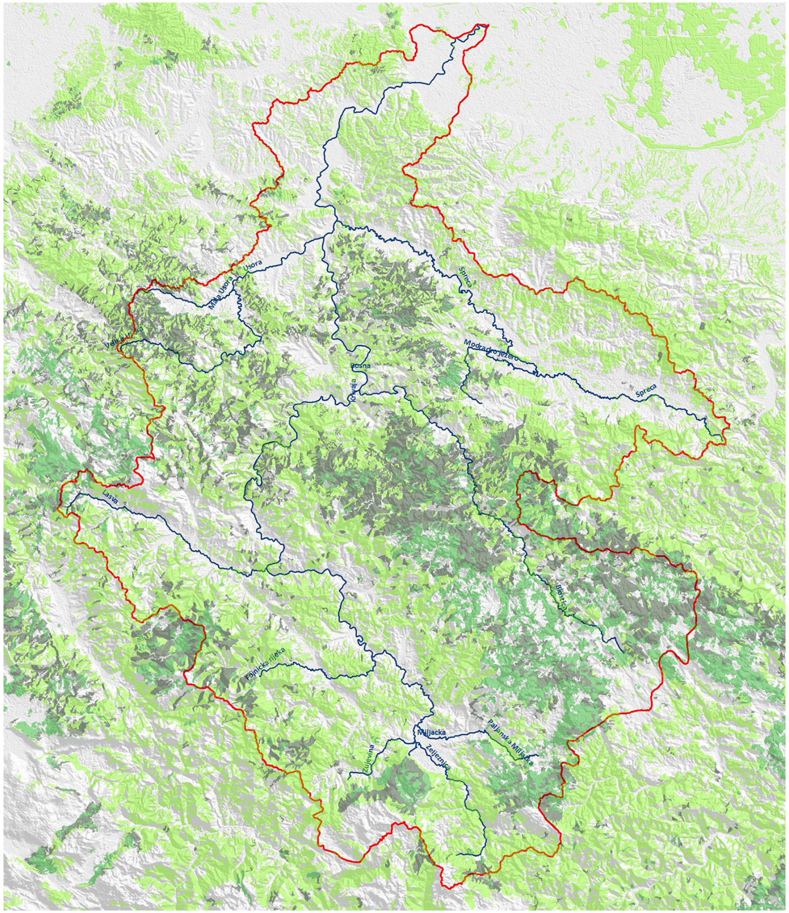

Figure 4. Vegetation zones in the area of the Bosna River basin.

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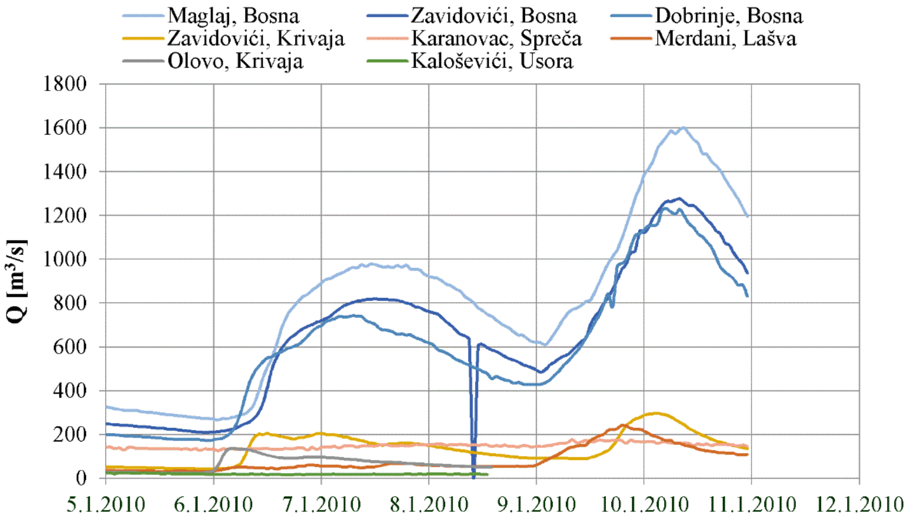

Figure 5. The discharges at hydrometric stations during the January 2010 flooding (data source: FHMZ BiH, 2014).

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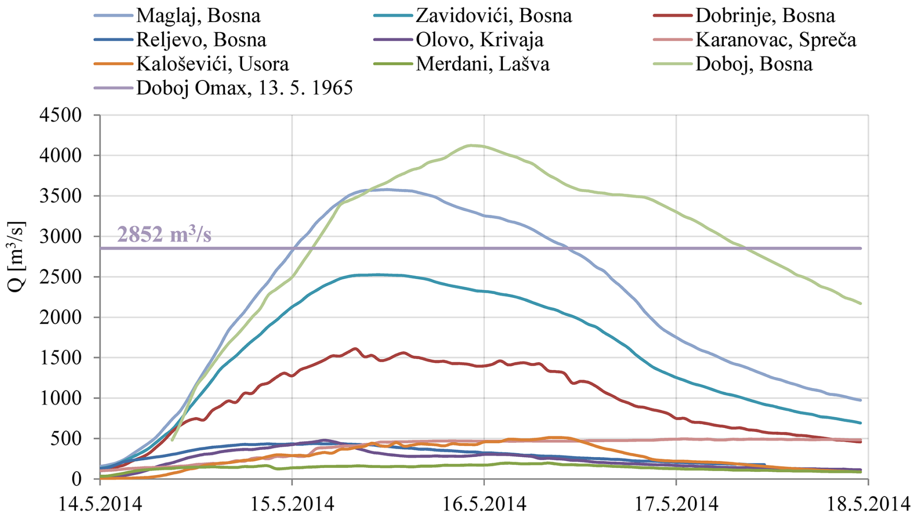

Figure 6. The discharges at hydrometric stations during the May 2014 flooding (data source: RHMZ RS and FHMZ BIH).

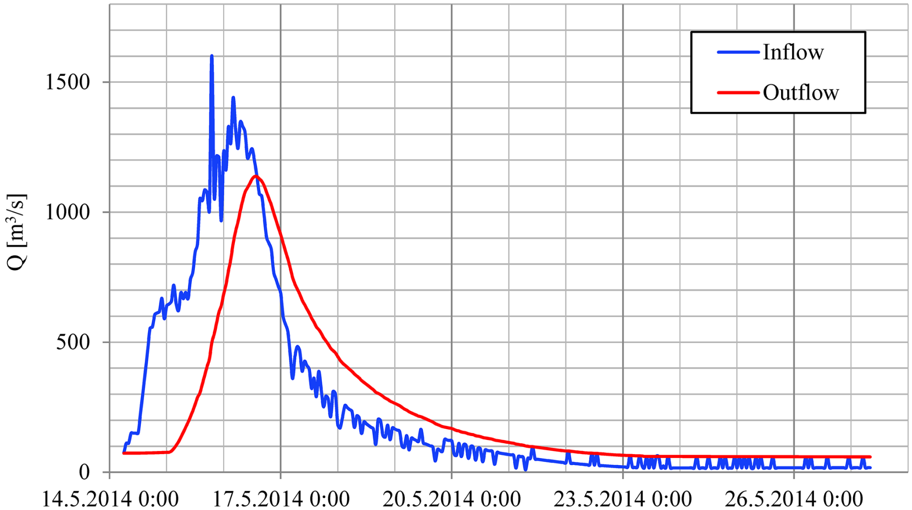

Figure 7. Inflow and outflow diagrams for the the Modrac reservoir (data source: Spreča d.d. Tuzla, 2014).

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

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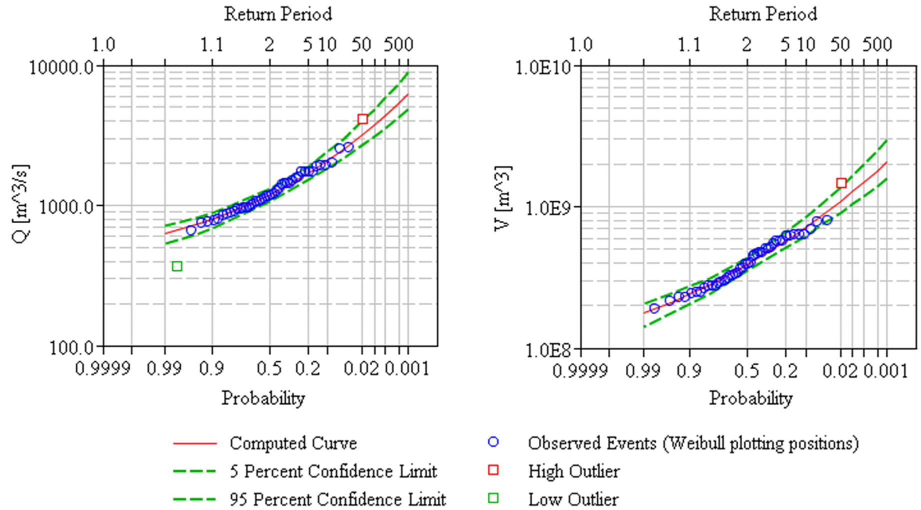

Figure 9. The probability analysis of annual maximum flows and maximum flood wave volumes of the Bosna at Doboj for the 1961–2014 period.

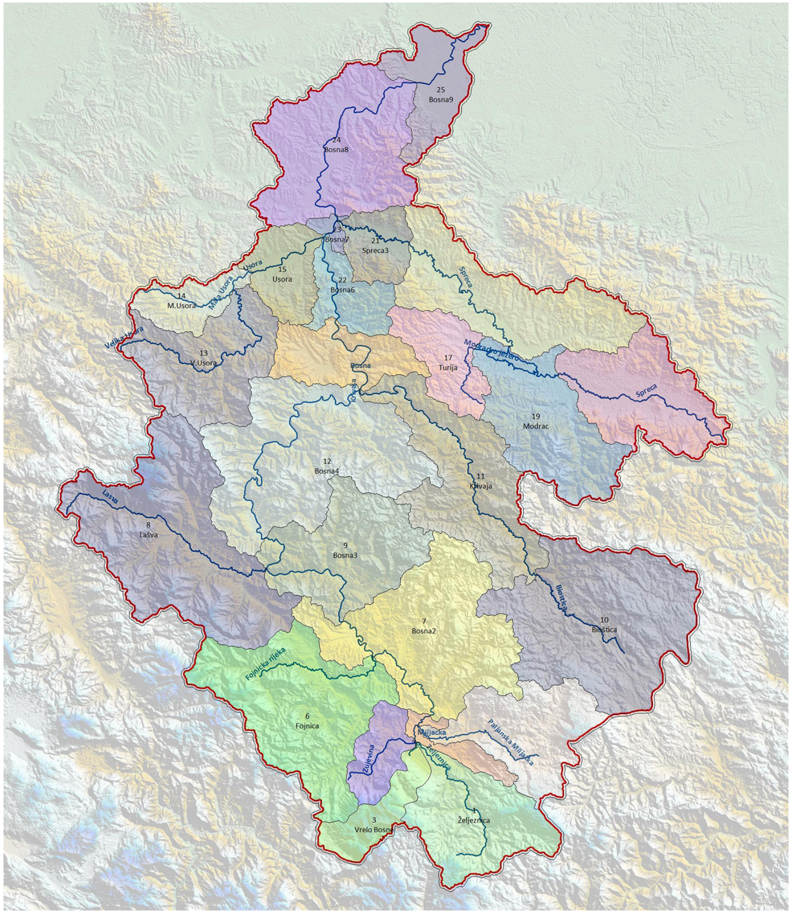

Figure 10. Hydrological model of the Bosna River basin divided into 25 subcatchments.

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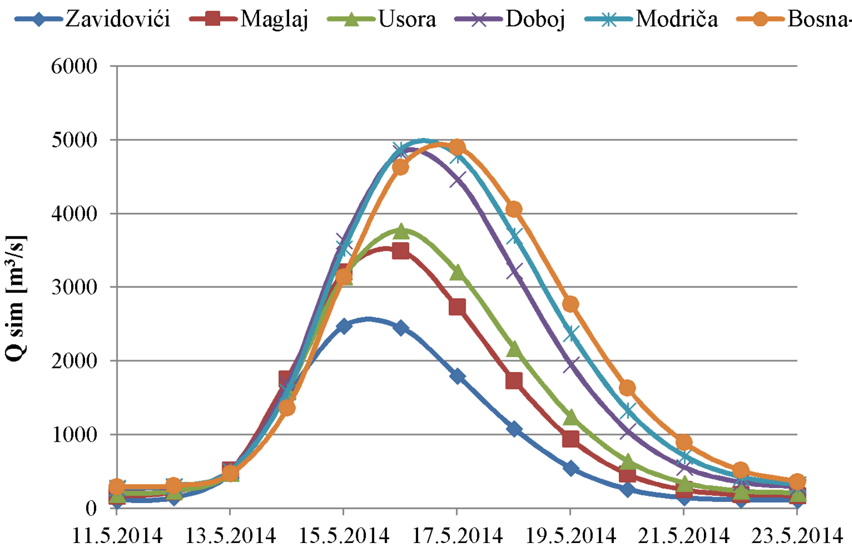

Figure 11. Simulated mean daily discharges on the Bosna River.

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