Climate Change Impact on Flood Hazard in the Sava River Basin

Mitja Brilly, Mojca Šraj, Andrej Vidmar, Miha Primožič, and Maja Koprivšek

Abstract In the past few years, the topic of climate change impact on the water regime of the Sava River basin has been presented in several studies. Average seasonal precipitation and temperature data were calculated and presented, but results are not useful for climate change impacts on floods. The maximum daily precipitation data for each season and temperature data from the meteorological report are taken for the hydrological analysis. Maximum daily precipitations were provided with twenty-year and hundred-year return periods. The hydrological analysis was derived using a hydrological model calibrated for the flood event in 1974 before large flood protection scheme was developed along the Sava River. Flood peak discharges were calculated for autumn season by twenty- and hundred-year return period daily precipitation for the periods 2011–2040, 2041–2070 and 2071–2100. Changes in peak discharge probability functions were developed for the water station along the river for each period. The peak discharges will increase by the end of the twenty-first century for the 100-year return period from 9 % at the mouth up to 55 % at the head part of the river basin.

Keywords Climate Change • Probability of Floods • Sava River

1 Introduction

In the past few years, the topic of climate change impact on the water regime of the Sava River basin has been presented in several studies. The studies focus mainly on the trends of temperature and mean discharge values. Climate trends in the Sava River basin were analysed in the World Bank study [1]. The study focused on mean values based on observations and empirical analyses. In the study, peak flood flows and droughts were not analysed. Notably, mean yearly temperatures show stronger trends over shorter periods (trends of the last 10 years) and are weaker in the long term. In the study conducted by Jupp [2], the climate change impact was analysed by the results calculated using a series of model simulations. Average seasonal

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precipitation data were calculated and presented. In the forecast, the mean seasonal precipitation mainly decreases, except in winter time. The results are not useful for flood prediction.

Each country in the basin produces its own country report on climate change, which is submitted for the United Nations Framework Convention on Climate Change with scenarios A1B and C. In Slovenia's Fourth and Fifth National Communication under the United Nations Framework Convention on Climate Change [3, 4], it is mentioned that weather extremes will be more frequent. Floods are not specifically referred in the reports. In the Second, Third, Fourth and Fifth National Communications of the Republic of Croatia under the United Nations Framework Convention on Climate Change [5, 6], there is a short note on the Danube river flood in 2003. Furthermore, the reports predicted more frequent flood events. Also, the evident concern regarding the increase of erosion in the head water parts of watersheds is expressed in the report. However, specific measures to be adopted are not listed. The last report stresses the importance of decreasing precipitation and corresponding decrease of run-off. In the Initial National Communication of Bosnia and Herzegovina under the United Nations Framework Convention on Climate Change, Banja Luka, October 2009 [7], it is mentioned that the intensity and frequency of storms, floods and droughts will increase from 50 years to 5 to 10 years. The Ministry for Spatial Planning and Environment published the report the Initial National Communication on Climate Change of Montenegro to the United Nations Framework Convention on Climate Change, in 2010 [8]. Generally they take the statement that "lack of water and severe droughts are expected as main issue for water management and more frequent floods are also expected". A few chapters in the Initial National Communication of the Republic of Serbia under the United Nations Framework Convention on Climate Change [9] deal with hydrology and climate change. The trends and changes of mean values of precipitation, evapotranspiration and discharges are well documented. It is clearly exposed "that the above projections show that climate change might cause more intense flood and drought episodes, greater both in scope and duration".

The International Commission for the Protection of the Danube River (ICPDR) [10] study country reports for Middle Danube River Basin and stress impacts on the increase in frequency and magnitude of flood events in head parts of watersheds. In the same study only Serbia is addressing floods and for other countries in the Sava River basin no data are available.

The topic of climate change impacts is broad. Various scenarios are being examined, based mainly on increase of air temperature. The reports that we reviewed were mainly related to mean yearly or seasonal values and not to extremes.

The formation of flood run-off is a complex non-linear process that cannot be easily transformed from precipitation data. For the transformation of extreme precipitation data, we developed a hydrological model and then incorporated the precipitation data calculated for different projections for the A1B scenario.

2 Hydrological Model of the Sava River Watershed

The Sava River watershed, from its source to the discharge into the Danube, extends over an area of around 95,000 km^2. The south-east border of watershed is in the Dinaric Karst region and could not be precisely determined. To ensure the rigidity and robustness of the model, the subbasins were generated to be as large as possible while covering not more than one major tributary stream. As a result, the watershed was divided into 13 subbasins with areas ranging from 2,000 to 14,000 km^2 (Table 1, Fig. 1). The subbasins are linked together, and the outflow from the upstream ones is routed through the downstream ones.

All the subbasins were divided into elevation (three were chosen) and vegetation zones. The upper and south-east part of the Sava River watershed is mountainous; as a result, the subbasins in that area have three elevation zones (Fig. 2). The subbasins in the plain area (north-west part of the watershed), where altitudes generally do not exceed 200 m, have two elevation zones (Fig. 2). Each elevation zone was then further divided into two areas according to land coverage (Fig. 2), i.e. into the so-called vegetation zones: forest and field (non-forest). The division into elevation and vegetation zones is especially important for the snow calculating routine.

It is based on the simple degree–day relation. In this routine, a threshold temperature (TT), which is usually close to 0 °C, is used to define the temperature above which snowmelt occurs. The threshold temperature usually decides whether the precipitation falls as rain or as snow. Within the threshold temperature interval (TTI), the precipitation is assumed to be a mix of rain and snow (decreasing linearly from 100 % snow at the lower end to 0 % at the upper end). The snowpack is assumed to retain meltwater as long as the amount does not exceed a certain fraction of the snow. When the temperature decreases below TT, the water

Table 1 List of subbasins

#	Subbasin number	Subbasin name	Stream	Subbasin area (km^2)
1	I	Sava I	Sava	10,073
2	II	Sava II	Sava	3,481
3	III	Kolpa/Kupa	Kolpa/Kupa	9,501
4	IV	Sava III	Sava	6,701
5	V	Una	Una	9,907
6	VI	Sava IV	Sava	1,880
7	VII	Vrbas	Vrbas	5,295
8	VIII	Sava V	Sava	4,403
9	IX	Bosna	Bosna	10,261
10	X	Sava VI	Sava	5,021
11	XI	Drina I	Drina	13,781
12	XII	Drina II	Drina	5,979
13	XIII	Sava VII	Sava	8,424
			Watershed total	94,708

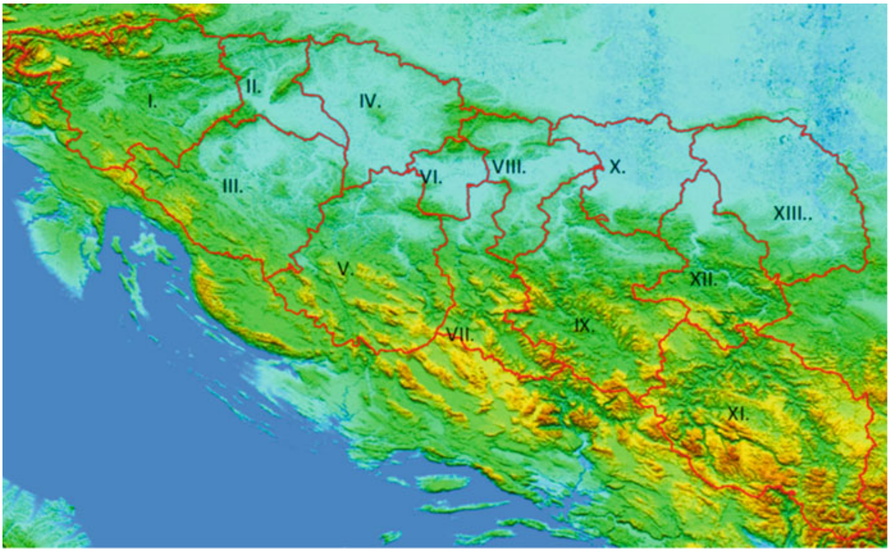

Fig. 1 Modelled Sava River watershed—from its source to its confluence with the Danube—with orographic subbasin and watershed borders

Fig. 2 Sava River watershed with discharge stations (used for model calibration)

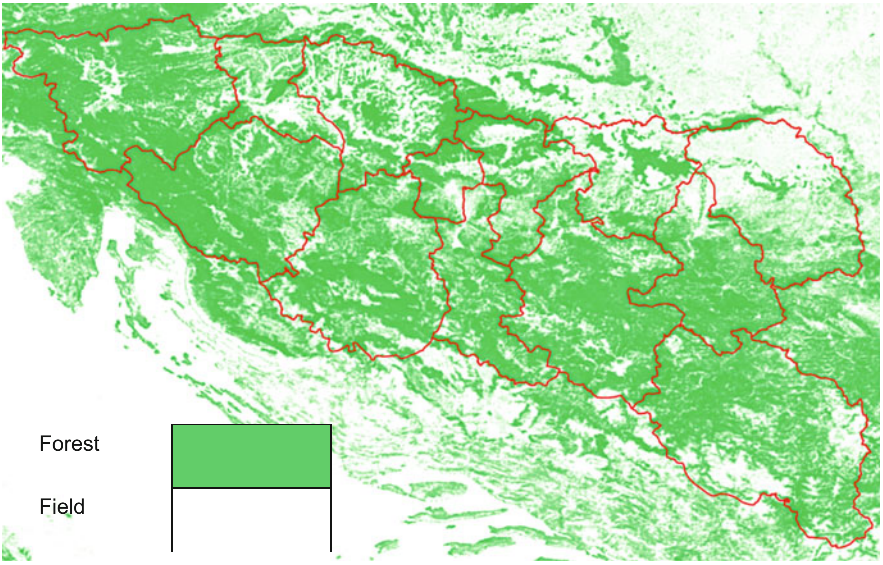

Fig. 3 Modelled Sava River watershed—from its source to its confluence with the Danube—with all the subbasins and the forest coverage [11]

refreezes. Different melting and refreezing factors are used for forest and non-forest zones (Fig. 3) [11].

The following input data are required to calibrate/run the model:

– Precipitation (32 measurement stations were chosen) (Fig. 4)
– Temperatures (8 measurement stations were chosen)
– Discharge data (12 measurement stations were chosen)
– Potential evapotranspiration (8 measurement stations were chosen)

The temperature and precipitation data were prepared as a set of data with a 1-day time step. The time step of evapotranspiration data is usually greater than that of the model. So a transformation to the model time step is required. This is done automatically by the model. In this case, average monthly values (mm/day) are transformed to the 1-day time step by linear interpolation.

To describe areas of influence of points (which represent different stations), Thiessen polygons were used. Precipitation data were obtained from Meteorological Yearbooks 1974 and 1978 [12, 13], discharge data from Hydrological Yearbooks 1974 and 1978 [14, 15], and temperature and potential evapotranspiration data from the database collected for the World Bank report [1].

Model calibration and validation were developed with data for flood events from years 1974 and 1978, for the period of time before a large flood protection system has been developed on the watershed and modified flood events. The number of parameters normally used in the model is in the order of 20–33. While in most cases

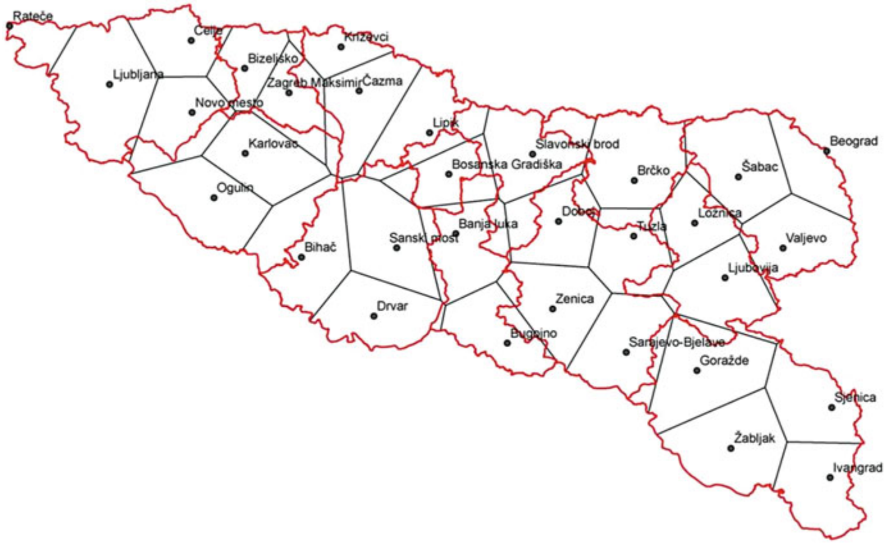

Fig. 4 Sava River watershed with precipitation stations and Thiessen polygons

five of them are set to standard values, it is very important to calibrate approximately 15 of the parameters.

Three main criteria of fit are used while calibrating: visual inspection of the computed and observed hydrographs, Nash/Sutcliffe criterion R^2 and inspection of the accumulated error. The R^2 efficiency criterion was introduced by Nash and Sutcliffe [16] and is commonly used in hydrological modelling. R^2 has a value of 1.0 if the simulation and the observations agree completely and 0 if the model does not perform any better than the mean value of the run-off record. In practice, values between 0.8 and 0.95 can be achieved if the quality of observed data is good. Negative values can be the result of poor model performance or poor data. In addition to the R^2 criterion, there is another very important performance indicator: the accumulated error.

The calibration is an interactive process. First, one must carefully observe the hydrographs where the differences appeared. Then it is necessary to determine if there is a problem of volume or a problem of shape. After this, one has to look at the conditions during the period of poor results (temperature, presence of snow, precipitation, maximum discharge before, droughts) and change the relevant parameters. Finally, the R^2 value is checked. Sometimes the result is better with the R^2 criterion a bit less strong because the peaks are better modelled.

For the calibration purposes, we collected the data (input data: precipitation, temperature, evapotranspiration, discharge) for the period from June 1 to December 31, 1974 (Table 2). An important characteristic of the 1974 flood event was major rainfall that moved with time from the east to the west part of the Sava River basin. In the east, head part of the watershed, maximum rainfall occurred on September 25 and in the west part on September 27, 1974 [12, 14].

Table 2 Model calibration peak discharges in m^3/s (1974)

Subbasins	WS	Area	Measured	Calibrated	%
Sava I	Čatež	10,173	2,294	2,308	0.6
Kolpa	Šišinec	7,321	1,250	1,419	13.5
Sava II	Crnac	23,102	2,147	2,295	6.9
Una	Kostajnica	9,171	1,370	1,445	5.4
Sava III	Jasenovac	29,565	2,580	2,515	−2.5
Vrbas	Delibašino selo	5,469	691	762	10.3
Sava IV	Slavonski Brod	54,134	3,460	3,422	−1.1
Bosna	Doboj	9,618	1,095	753	−31.3
Sava V	Županja	62,22	3,930	4,057	3.2
Drina I	Bajina Bašta	14,797	3,359	2,715	−19.2
Drina II	Kozluk	17,735	3,041	2,640	−13.2
Sava V	Sremska Mitrovica	87,996	6,275	6,540	4.2
Confluence in Danube				6,653	

Table 3 Model performance

Watershed no.	Watershed name	Calibration		Verification		Station name
		R^2	Acc. diff. (mm)	R^2	Acc diff. (mm)	
I	Sava I	0.8183	−23.7937	−0.4213	20.8903	Čatež
III	Kolpa/Kupa	0.9029	−19.8823	0.7461	−25.4299	Šišinec
IV	Sava III	0.7689	−27.8047	0.4193	4.7807	Crnac
V	Una	0.7921	18.8697	−3.2602	63.4986	Kostajnica
VI	Sava IV	0.6361	−180.7203	0.6881	−24.1327	Jasenovac
VII	Vrbas	0.3133	−10.3829	−1.5449	46.8637	Delibašino Selo
VIII	Sava V	0.8646	−46.2497	−0.4608	24.1783	Slavonski Brod
IX	Bosna	0.2735	−91.3311	−2.9617	102.6221	Doboj
X	Sava VI	0.8553	−14.7998	−2.0815	48.1689	Županja
XI	Drina I	0.7999	−45.7861	−3.3535	4.6146	Bajina Bašta
XII	Drina II	0.7830	−19.3865	−5.2540	22.571	Kozluk
	Sava VI + Drina	0.8561	10.1821	−3.1442	48.0747	Sremska Mitrovica
XIII	Sava VII					Confluence

The selected verification period was from September 1, 1978, to November 30, 1978 [13, 15]. The peak discharges are quit high and data form weather stations was available for modelling.

The results of calibration and verification of the model are not impressive, especially for sub-watersheds (Table 3). The sub-watersheds were modelled as homogenised areas except for the Drina River basin. The main task of the calibration was flood peaks, not water balance. In Figs. 5 and 6, the comparison of the

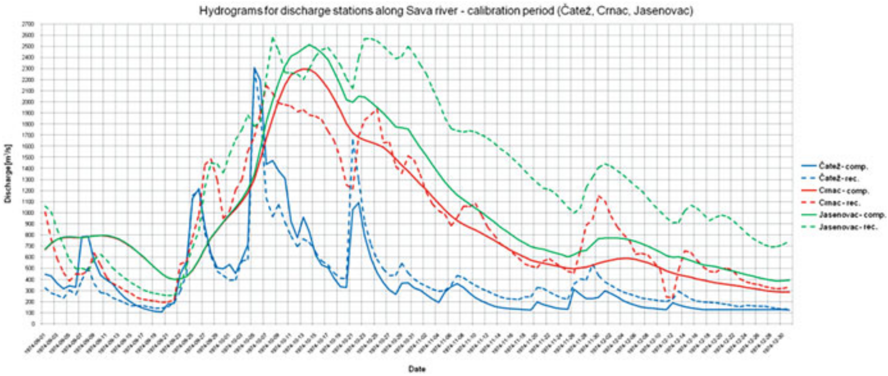

Fig. 5 Measured and modelled discharges at the selected stations in the upper part of the Sava River Basin (calibration period)

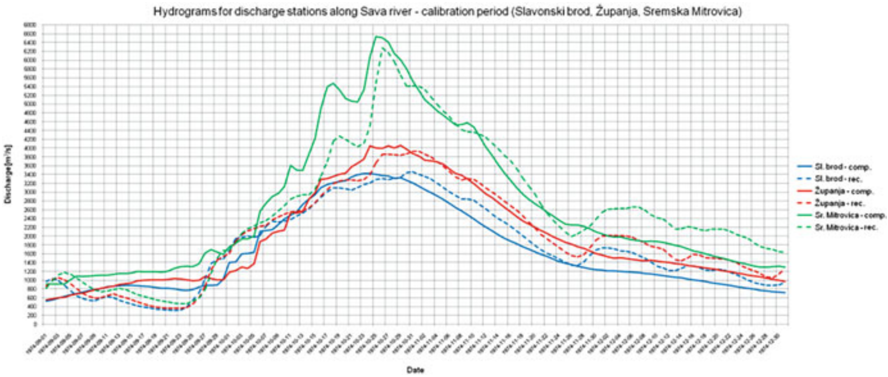

Fig. 6 Measured and modelled discharges at the selected stations in the lower part of the Sava River Basin (calibration period)

measured and modelled discharges for selected water stations is shown as a result of the hydrological model calibration procedure for the calibration period June 1–December 31, 1974.

3 Data Transformation for Hydrological Forecasts of Climate Change Impacts

The precipitation and temperature data from the meteorological report [17] are taken from figures based on the position of rain gauge stations and used for the hydrological model. Observed data from the grid database of the European observation system (E-OBS) are extracted E-OBS [18] and shown in Table 4. These data have been designed to provide the best estimate of grid box averages to enable a

Table 4 Daily maximum seasonal precipitation derived for weather station from E-OBS data for the period 1971–2010 with 20-year return period in mm

Longitude	Latitude	Station	Max. prec. [14]	Spring E-OBS	Summer E-OBS	Autumn E-OBS	Winter E-OBS
13° 43′ E	46° 30′ N	Rateče	42.6	98.2	99.0	131.9	99.6
14° 31′ E	46° 04′ N	Ljubljana	95.8	69.0	90.9	88.5	75.4
15° 15′ E	46° 15′ N	Celje	66.7	62.3	82.4	85.4	58.2
15° 42′ E	46° 01′ N	Bizeljsko	68	47.0	62.9	64.3	49.2
15° 11′ E	45° 48′ N	Novo Mesto	55	57.6	75.0	79.7	62.8
16° 33′ E	46° 02′ N	Križevci	26.5	34.2	47.0	47.1	38.6
15° 14′ E	45° 16′ N	Ogulin	63.2	58.0	85.6	86.6	70.9
15° 33′ E	45° 30′ N	Karlovac	42.5	46.3	61.0	62.0	52.1
16° 02′ E	45° 49′ N	Zagreb-Maksimir	34.5	34.6	47.2	43.6	36.4
16° 38′ E	45° 45′ N	Čazma	29.3	28.2	43.6	40.1	36.6
17° 10′ E	45° 25′ N	Lipik	49.3	27.2	39.9	32.3	35.1
18° 00′ E	45° 10′ N	Slavonski Brod	31.6	25.9	30.6	31.1	27.2
17° 16′ E	45° 09′ N	Bosanska Gradiška	38.4	27.7	33.5	31.7	31.4
15° 53′ E	44° 49′ N	Bihać	82.9	45.8	58.3	69.7	58.1
16° 24′ E	44° 23′ N	Drvar	58.6	39.9	47.9	54.9	42.3
16° 42′ E	44° 46′ N	Sanski Most	61.5	32.4	37.7	47.9	35.5
17° 13′ E	44° 47′ N	Banja Luka	56.2	25.2	29.9	34.0	29.0
17° 28′ E	44° 04′ N	Bugojno	40.4	25.9	32.6	38.0	30.1
17° 54′ E	44° 13′ N	Zenica	21.4	23.8	29.2	34.7	31.9
18° 06′ E	44° 44′ N	Doboj	24.2	25.5	30.2	30.7	28.9
18° 42′ E	44° 33′ N	Tuzla	21.5	25.9	33.5	31.7	29.7
18° 50′ E	44° 53′ N	Brčko	23.5	28.7	36.4	33.3	29.8
18° 26′ E	43° 52′ N	Sarajevo-Bjelave	36	26.2	34.6	37.6	38.2
18° 59′ E	43° 40′ N	Goražde	29.2	27.3	34.3	42.2	41.2
19° 14′ E	44° 33′ N	Loznica	26.5	33.5	50.5	34.6	32.9
19° 23′ E	44° 11′ N	Ljubovija	50.9	31.8	42.5	35.5	36.5
19° 41′ E	44° 46′ N	Šabac	46.8	34.4	52.2	36.0	31.5
19° 55′ E	44° 17′ N	Valjevo	49	39.5	49.7	39.3	38.5
20° 28′ E	44° 48′ N	Beograd	39.4	39.6	51.7	36.0	32.9
20° 01′ E	43° 16′ N	Sjenica	45.1	32.6	51.9	42.9	34.3
19° 08′ E	43° 09′ N	Žabljak	83.9	27.1	37.5	37.1	34.3
19° 52′ E	42° 50′ N	Ivangrad	39.2	31.5	48.6	44.0	33.5
		Average	46.2	37.9	49.6	49.5	42.0
		Max.	95.8	98.2	99.0	131.9	99.6
		Min.	21.4	23.8	29.2	30.7	27.2

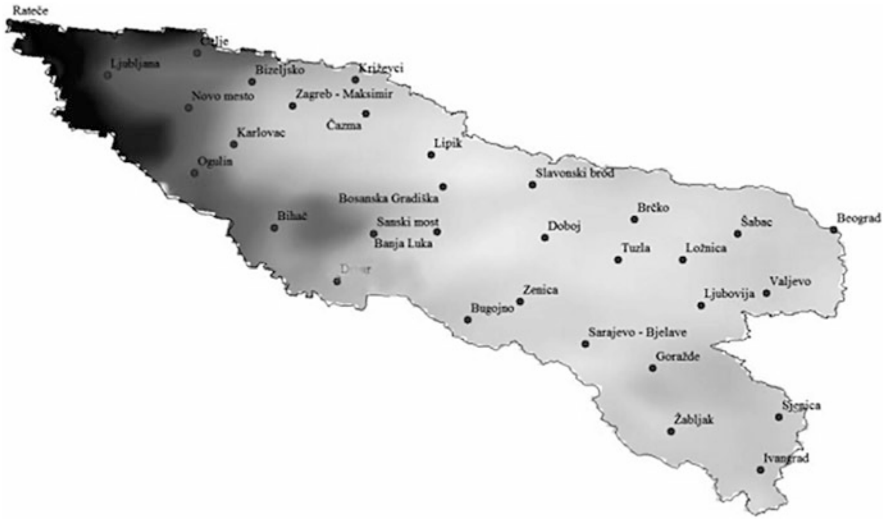

Fig. 7 E-OBS data. Precipitation distribution for the 100-year return period [17]

direct comparison with RCMs. The E-OBS data set was defined on the same 0.25° grid resolution, and data collected between 1961 and 2010 were used in this study. An example of the data set is on the map in Fig. 7.

The precipitation data in the meteorological report are in raster format, and we collected the data from the cell in which the precipitation station was positioned. Maximum daily precipitation values from E-OBS data are highest in summer and slightly lower (0.1 mm) in autumn.

The maximum daily values of the precipitation measured in 1974 are mainly slightly lower than the values of E-OBS. There is a high discrepancy between the E-OBS data and the measurements in the area of the Dinaric Mountains, especially in Montenegro (Fig. 7). The value at the Žabljak station is two times higher than that in E-OBS data with the 20-year return period and even the 100-year return period (Table 5). A concern is that for the E-OBS data set, precipitation from Montenegro was not used. The flood event in 1974 is one of the highest floods measured before large flood protection construction works started on the Posavina, and precipitation on all stations of basin has low probability.

Summer daily precipitation is slightly higher than in autumn. However, run-off in the autumn season is much higher, due to higher evaporation, and for further calculations and analysis, we chose the autumn values (Table 5).

Forecast data for the periods of 2011–2040, 2041–2070 and 2071–2100 are represented in Table 5 and show interesting dynamics. Data for some stations increase with time, while with other stations, first an increase and then a decrease

Table 5 Autumn rainfall values with 20- and 100-year return periods based on the E-OBS data with forecasts

	EOBS_20	EOBS_100	20_11-40	20_41-70	20_71-2100	100_11-40	100_41-70	100_71-100
Rateče	131.9	171.1	149.6	147.5	155.7	206.5	191.3	201.9
Ljubljana	88.5	110.0	99.1	110.0	113.3	131.1	148.0	153.2
Celje	85.4	105.3	92.7	105.9	111.1	122.4	140.1	149.8
Bizeljsko	64.3	77.1	71.1	83.2	86.8	94.5	119.5	126.9
Novo mesto	79.7	101.5	86.4	100.7	108.4	117.8	148.6	164.3
Križevci	47.1	55.9	50.3	56.5	59.7	61.9	73.1	80.4
Ogulin	86.6	103.8	89.8	102.6	110.8	108.8	138.6	148.7
Karlovac	62.0	71.9	67.0	74.1	82.0	81.9	94.5	111.7
Zagreb-Maksimir	43.6	50.3	46.0	52.0	56.3	56.2	67.4	80.4
Čazma	40.1	45.5	42.5	47.2	50.1	48.5	56.7	62.4
Lipik	32.3	34.3	36.4	37.9	37.3	40.5	42.4	38.9
Slavonski brod	31.1	38.6	36.2	36.3	36.8	48.1	47.8	45.0
Bosanska Gradiška	31.7	39.2	36.4	37.0	37.1	47.3	48.1	46.2
Bihać	69.7	83.4	76.3	81.0	88.4	95.8	101.8	114.2
Drvar	54.9	69.3	60.0	65.6	64.7	78.0	91.5	86.6
Sanski most	47.9	68.6	53.8	55.6	56.5	81.5	84.3	82.1
Banja Luka	34.0	44.0	38.2	38.9	39.1	51.9	53.4	50.7
Bugojno	38.0	50.4	43.1	44.8	43.9	61.6	66.6	62.2
Zenica	34.7	42.4	41.0	43.6	40.3	54.1	60.9	51.2
Doboj	30.7	34.9	36.9	38.2	35.8	46.4	51.3	41.6
Tuzla	31.7	35.2	39.0	40.7	39.3	50.1	51.6	48.6
Brčko	33.3	39.4	39.6	40.4	40.6	50.7	51.4	49.0
Sarajevo-Bjelave	37.6	42.6	45.1	49.6	44.5	58.8	66.5	52.8
Goražde	42.2	52.6	46.7	52.8	50.3	61.3	74.2	66.5
Ložnica	34.6	37.5	41.5	44.7	41.6	51.0	54.6	46.0

(continued)

Table 5 (continued)

	EOBS_20	EOBS_100	20_11-40	20_41-70	20_71-2100	100_11-40	100_41-70	100_71-100
Ljubovija	35.5	39.5	42.1	48.0	42.5	52.2	64.6	50.6
Šabac	36.0	43.4	43.9	47.2	43.3	59.5	62.1	53.0
Valjevo	39.3	47.2	43.5	51.1	47.2	55.1	70.3	59.4
Beograd	36.0	46.1	41.9	46.4	44.8	58.3	66.7	61.0
Sjenica	42.9	51.3	44.9	55.9	52.6	54.6	77.6	66.1
Žabljak	37.1	45.7	40.4	49.3	44.1	54.1	75.0	61.6
Ivangrad	44.0	53.1	49.8	63.5	58.5	62.2	98.7	76.6
Average	49.5	60.3	55.4	60.9	61.4	72.0	82.5	80.9

Table 6 Probability of maximum daily precipitation (mm) based on the report (Meerbach et al. 2010) in 1974 [12] and data from Table 4

Station name	Return period			Max. prec. in 1974	V1	V2	V3	V4
	1,000	100	20		EOBS_20	EOBS_100	20_41-70	100_41-70
Ljubljana	190.7	106.3	72.2	95.8	88.5	110.0	110.0	148.0
Rateče	214.9	121.2	83.2	42.6	131.9	171.1	147.5	191.3
Zagreb	117.2	65.9	45.2	34.5	43.6	50.3	52.0	67.4
Slavonski brod	104.1	59.1	40.9	31.6	31.1	38.6	36.3	47.8
Bihać	155.3	89.5	62.8	82.9	69.7	83.4	81.0	101.8
Bugojno	119.9	66.2	44.5	40.4	38.0	50.4	44.8	66.6
Sarajevo	120.0	67.0	45.5	36.0	37.6	42.6	49.6	66.5
Banja luka	86.0	57.4	45.8	56.2	34.0	44.0	38.9	53.4
Beograd	126.8	66.3	41.9	39.4	36.0	46.1	46.4	66.7
Sjenica	89.9	53.3	38.5	45.1	42.9	51.3	55.9	77.6

can be observed. Average values for rainfall with a 20-year return period show a very small increase between the periods 2041–2070 and 2071–2100 and an even smaller decrease for the 100-year return period.

The probabilities in Table 6 are based on the Gumbel probability distribution and were calculated using the data on precipitation from the report by Meerbach et al. (2010). The period of observation varied from 1908 or 1951 to 2009. The differences of values of precipitation with the 20-year return period calculated using the Gumbel distribution function and E-OBS varied. At some stations, the values calculated using the Gumbel distribution function were higher than those calculated using the E-OBS data, and vice versa. For the 100-year return period, only the values from Slovenia are lower if calculated using the Gumbel distribution function than those calculated using the E-OBS data. All other stations have higher values. Finally, the 100-year return period values for the forecast between 2041 and 2070 are lower than the values with the 1,000-year return period for all rainfall stations.

Temperature data are given in Table 7. Temperature data vary significantly inside the Sava River watershed. However, the forecast variation is rather small. For further calculations, we chose an increase of 0.8 °C in autumn in the period 2011–2040, 1.8 °C for autumn in the period 2041–2070 and 2.9 °C in the period 2071–2100, for watershed as whole.

Table 7 Temperature data and climate change forecast in °C

Station	EOBS temperature data for 1971–2010				Increase of temperature		
	Spring	Summer	Autumn	Winter	2011–2040	2041–2070	2071–2100
Rateče	4.8	14.0	6.4	−3.2	0.9	1.9	3.0
Ljubljana	8.9	17.9	9.5	−0.3	0.9	1.9	2.9
Celje	8.4	17.2	9.1	−0.8	0.8	1.8	2.9
Bizeljsko	10.2	18.8	10.4	0.5	0.9	1.8	2.9
Novo mesto	9.2	17.9	9.8	0.0	0.9	1.8	2.9
Križevci	11.0	19.7	11.1	1.0	0.8	1.8	2.8
Ogulin	8.4	17.4	9.6	0.2	0.8	1.7	2.7
Karlovac	10.8	19.7	11.4	1.7	0.8	1.7	2.7
Zagreb-Maksimir	11.2	19.9	11.4	1.5	0.8	1.8	2.8
Čazma	11.5	20.3	11.7	1.7	0.8	1.7	2.8
Lipik	10.9	19.8	11.3	1.2	0.9	1.7	2.8
Slavonski brod	11.3	20.2	11.5	1.2	0.9	1.8	2.8
Bosanska Gradiška	11.1	20.0	11.6	1.5	0.8	1.7	2.7
Bihać	8.5	17.5	9.5	0.0	0.8	1.6	2.7
Drvar	7.1	16.3	8.7	−0.6	0.9	1.8	3.0
Sanski most	10.1	19.2	11.0	1.4	0.7	1.6	2.5
Banja Luka	10.7	19.8	11.5	1.7	0.7	1.6	2.5
Bugojno	7.2	16.3	8.9	−0.5	0.8	1.8	3.0
Zenica	8.8	17.6	9.8	0.1	0.8	1.8	2.9
Doboj	11.0	19.8	11.4	1.3	0.8	1.6	2.6
Tuzla	10.1	18.8	10.4	0.4	0.8	1.7	2.8
Brčko	11.4	20.1	11.3	1.2	0.8	1.7	2.8
Sarajevo-Bjelave	8.1	16.9	9.2	−0.5	0.9	1.9	3.2
Goražde	8.2	17.0	9.4	−0.6	0.9	1.9	3.2
Ložnica	10.6	19.4	10.8	0.7	0.8	1.7	2.8
Ljubovija	9.1	17.9	9.8	−0.3	0.9	1.8	3.0
Šabac	11.5	20.3	11.4	1.1	0.9	1.8	2.9
Valjevo	10.2	19.1	10.6	0.4	0.8	1.8	2.9
Beograd	11.8	20.8	12.1	1.5	0.9	1.9	3.1
Sjenica	5.5	14.2	6.7	−3.5	0.9	2.0	3.3
Žabljak	4.8	13.8	6.7	−3.0	0.9	2.1	3.4
Ivangrad	5.7	14.7	7.3	−2.7	0.9	2.0	3.2
Average	9.3	18.2	10.0	0.1	0.8	1.8	2.9
Stand. dev.	2.1	2.0	1.6	1.5	0.1	0.1	0.2

4 Results of Climate Change Modelling

The hydrological model was used for modelling of the impact of climate change forecasts on the Sava River discharges at selected stations. For modelling of the impact of climate change, the same input data as those for the calibrated model for the flood in 1974 were used. We only changed the rainfall data for the day with maximum precipitation and increase temperature (Table 4). Instead of using the measured maximum daily precipitation, we used the predicted maximum daily precipitation from Table 4. First, we calculated peak discharges for E-OBS (1971–2010) data with 20- and 100-year return periods. The calibrated and measured discharges with the E-OBS data modelling are represented in Table 8.

Peak calibrated discharges and central parts of the watershed, down to Sava III, are lower than those calculated by E-OBS data for the 20-year return period. Values of discharge in the lower part of the watershed are between the values calculated for E-OBS data for 20- and 100-year return periods. The Drina River flood peak discharges are much higher than those calculated by the E-OBS 100-year return period data.

We calculated the impact of climate change in the same way as in the model calibration, by taking into account the change of the maximum daily values of precipitation with the data from Table 4 and the increase in temperature using the data from Table 7. The results of modelling for E-OBS data for the 20-year return period and for forecasts in the periods 2011–2040, 2041–2070 and 2071–2100 are represented in Table 9 and Fig. 8, and for E-OBS data with the 100-year return period, the results are shown in Table 10 and Fig. 9.

Forecasted flood peaks with the 20-year return period, in the period 2071–2100, will increase in average 14 % and up to 36 % in the upper part of the basin and on some tributaries (Table 9). The calculated base flow drops a little on Fig. 8 due to higher temperatures. The flood peaks along the main stream will increase in the next 60 years from 8 % on the inflow in Danube to 33 % on the head water part of the catchment. Forecasted discharges, due climate change, increase in time. Only discharges on the Drina River WS and downstream WS Sremska Mitrovica on the Sava River have lower predicted discharge for the period 2071–2100 than for the period 2041–2070. Discrepancies in peak discharges on the Drina River basin could be the result of fewer predictions used for the 2071–2100 periods of precipitation forecasts. Some results of climate change modelling [17], which were used for the periods 2011–2040 and 2041–2070, were not available for the period 2071–2100 forecasts.

Forecasted flood peaks with 100-year return periods are in Table 10. Data are presented with peak discharge values and in percentage of increase relative to calculation using the E-OBS data. Percentages of increase of flood discharges with the 100-year return period of floods (Table 10) show higher increase than values with 20-year return period, as presented in Table 9. The average increase, for the period up to 2100, is 14 % for the 20-year return period of flood and 31 % for

Table 8 Result of modelling recent climate flood peaks (in m^3/s)

Subbasins	WS	Calibrated	E-OBS_ret20	E-OBS_ret100
Sava I	Čatež	2,308	2,308	2,780
Kolpa	Šišinec	1,419	1,473	1,522
Sava II	Crnac	2,295	2,350	2,510
Una	Kostajnica	1,445	1,382	1,407
Sava III	Jasenovac	2,515	2,561	2,718
Vrbas	Delibašino Selo	762	620	707
Sava IV	Slavonski Brod	3,422	3,411	3,573
Bosna	Doboj	753	742	767
Sava V	Županja	4,057	4,068	4,227
Drina I	Bajina Bašta	2,715	2,336	2,474
Drina II	Kozluk	2,640	2,276	2,407
Sava VI	Sremska Mitrovica	6,540	6,328	6,603
Confluence with Danube		6,653	6,432	6,715

Table 9 Result of modelling climate change flood peaks with E-OBS data for 20-year return period (in m^3/s)

Subbasins	WS	E-OBS (m^3/s)	11–40 (m^3/s)	41–70 (m^3/s)	71–2100 (m^3/s)	11–40/ E-OBSE	41–70/ E-OBSE	71–2100/ E-OBSE
Sava I	Čatež	2,308	2,552	2,859	3,073	1.11	1.24	1.33
Kolpa/ kupa	Šišinec	1,473	1,523	1,568	1,591	1.03	1.06	1.08
Sava II	Crnac	2,350	2,428	2,520	2,571	1.03	1.07	1.09
Una	Kostajnica	1,382	1,637	1,726	1,718	1.19	1.25	1.24
Sava III	Jasenovac	2,561	2,630	2,717	2,742	1.03	1.06	1.07
Vrbas	Delibašino selo	620	676	687	691	1.09	1.11	1.11
Sava IV	Slavonski Brod	3,411	3,623	3,742	3,788	1.06	1.10	1.11
Bosna	Doboj	742	912	931	1,010	1.23	1.25	1.36
Sava V	Županja	4,068	4,346	4,554	4,826	1.07	1.12	1.19
Drina I	Bajina Bašta	2,336	2,471	2,617	2,456	1.06	1.12	1.05
Drina II	Kozluk	2,276	2,427	2,586	2,425	1.07	1.14	1.07
Sava VI	Sremska Mitrovica	6,328	6,659	6,862	6,854	1.05	1.08	1.08
Confluence		6,432	6,757	6,960	6,944	1.05	1.08	1.08
					Average	1.08	1.13	1.14
					Max.	1.23	1.25	1.36
					Min.	1.03	1.06	1.05

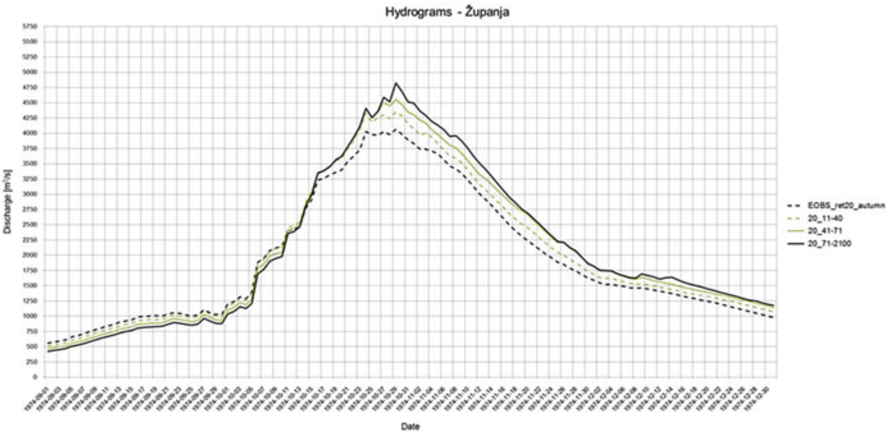

Fig. 8 Discharges calculated with E-OBS data for 20-year return periods for WS Županja, Sava V

Table 10 Results of modelling climate change flood peaks with E-OBS data of the 100-year return period (in m^3/s and %)

Subbasins	WS	E-OBS (m^3/s)	2011–40 (m^3/s)	2041–70 (m^3/s)	2071–2100 (m^3/s)	2011–40/ E-OBSE	2041–70/ E-OBSE	2071–2100/ E-OBSE
Sava I	Čatež	2,780	3,297	3,770	4,134	1.43	1.63	1.79
Kolpa/ kupa	Šišinec	1,522	1,595	1,664	1,722	1.08	1.13	1.17
Sava II	Crnac	2,510	2,670	2,817	2,929	1.14	1.20	1.25
Una	Kostajnica	1,407	2,060	2,245	2,188	1.49	1.63	1.58
Sava III	Jasenovac	2,718	2,863	2,993	3,086	1.12	1.17	1.21
Vrbas	Delibašino selo	707	813	845	825	1.31	1.36	1.33
Sava IV	Slavonski Brod	3,573	3,895	4,062	4,142	1.14	1.19	1.21
Bosna	Doboj	767	985	1,025	1,103	1.33	1.38	1.49
Sava V	Županja	4,227	4,699	4,957	5,270	1.16	1.22	1.30
Drina I	Bajina Bašta	2,474	2,683	3,087	2,719	1.15	1.32	1.16
Drina II	Kozluk	2,407	2,639	3,059	2,686	1.16	1.34	1.18
Sava VI	Sremska Mitrovica	6,603	7,143	7,580	7,409	1.13	1.20	1.17
confluence		6,715	7,253	7,695	7,509	1.13	1.20	1.17
					Average	1.21	1.31	1.31
					Max.	1.49	1.63	1.79

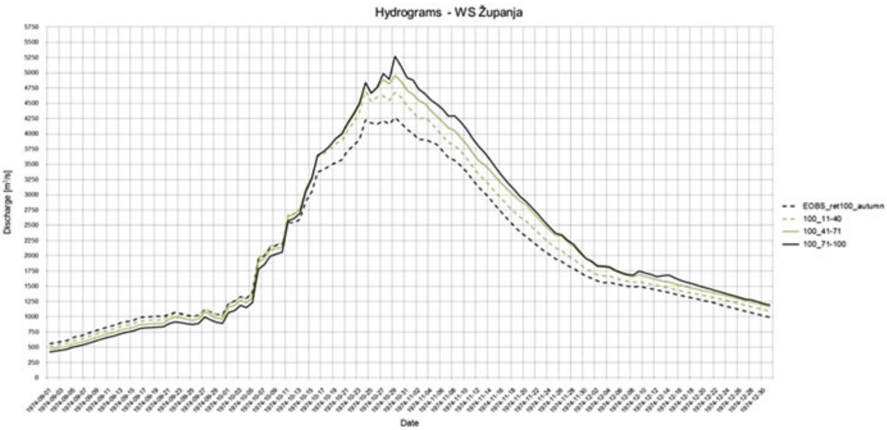

Fig. 9 Discharges calculated with E-OBS data for the 100-year return period for WS Županja, Sava V

Table 11 Probability of peak discharges for WS Čatež (m^3/s)

	E-OBS_20	E-OBS_100		
	26 %	3.05 %	1 %	0.1 %
1926–1965	2,308	2,780	3,027	3,400
2011–2040	2,551	3,296	3,694	4,056
2041–2070	2,859	3,770	4,248	4,627
2071–2100	3,072	4,133	4,687	5,060

100-year return period. The highest increase is observed at WS Rateče on the main stream with 79 %, followed by the Bosna River tributary (49 %) and the Una River tributary (58 %). Changes on the Drina River catchment and WS Sremska Mitrovica have similar anomalies as the discharges with the 20-year return period.

Calculated values in Table 11 are valid for the river mouth and not up to the most downstream water station, but percentage of increase could be used for watershed as a whole. The upper part of the watershed at WS Čatež has the greatest increase, up to 79 %. The Kolpa River tributary has much lower increase up to 17 %. The Una River tributary has a 63 % increase of discharge up to 2070 and then a smaller increase, because of smaller precipitation (Table 10). Similar is the dynamics of flood discharge with 100-year return period forecast for the Vrbas River tributary, which increases by 36 % and then decreases to 33 %. Flood discharge of the Bosna River tributary will increase by 49 % up to the end of the century. The Drina River has similar dynamics like the Una River and Vrbas River, but the drop, in the last period of forecast, is more significant. The flood discharge will increase up to 34 % and then drop to 18 %, which is similar to the increase in the first period of forecast. The forecasted discharges increase along the Sava River, indicating a drop from WS Čatež (79 %) to 25 % on WS Crnac and to 21 % on WS Jasenovac, which is the same value as that on WS Slavonski Brod. The percentage of discharges increases downstream down to WS Županja to 30 %. Downstream of the Drina River mouth, the percentage increases for the period 2041–2070 up to 20 % on the WS Sremska Mitrovica and then drops to 18 % for the period 2071–2100.

5 Climate Change Impact on Probability of Flood Peaks

The probability analysis was derived from the probability analysis represented in the report by Prohaska [19]. Probability analysis in the report was derived from the data collected in the period 1926–1965. There is no impact of flood protection measures in Central Posavina developed later on. Data about 10, 1 and 0.1 percentage of probability were used as basic relations for WS. Discharge values calculated for E-OBS data with 20-year return period and 100-year return periods were transformed based on the new probability according to the basic relations. In this way, we estimated the new probability for E-OBS_20 and EOS_100 according to the probability function from the report prepared by Prohaska [19].

The probability function for water station Čatež is in Fig. 10 and Table 11. The E-OBS_20 discharge has a probability of 26 % (instead of 5 %), and E-OBS_100 discharge has a probability of 3.05 % (instead of 1 %). The climate change values were then arranged in relation to the new estimated probability and in accordance with the basic relations from the report. New probability relations are estimated to be parallel to the basic ones published in the Prohaska report (2009). The hundred-

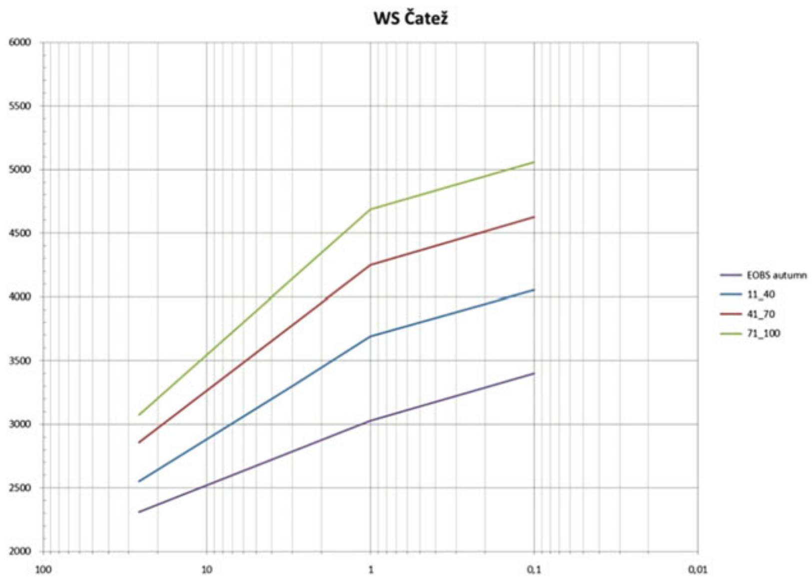

Fig. 10 Probability function (%) of peak discharges on WS Čatež for different periods of climate change forecast

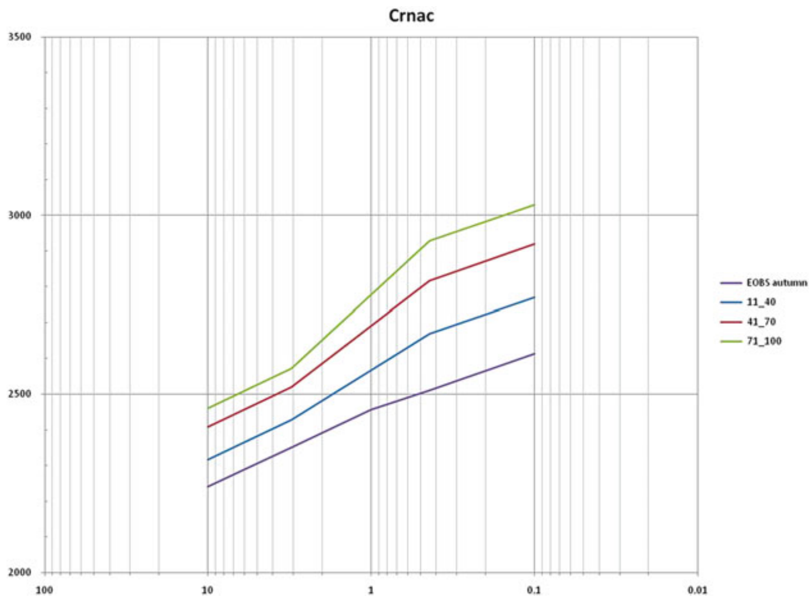

Fig. 11 Probability function (%) of peak discharges on WS Crnac for different periods of climate change forecast

Table 12 Probability of peak discharges for WS Crnac (m^3/s)

		E-OBS_20		E-OBS_100	
	10 %	3.10 %	1 %	0.44 %	0.10 %
1926–1965	2,240	2,350	2,456	2,510	2,613
2011–2040	2,317	2,670	2,570	2,428	2,770
2041–2070	2,409	2,817	2,690	2,520	2,920
2071–2100	2,460	2,929	2,780	2,571	3,030

year return period discharges (1 % in Table 11) will increase from 22 % in the first period 2011–2040 to 55 % in the last period 2071–2100, or the hundred-year return period of flood will increase, up to the year 2100, by 1.660 m^3/s, and the water level will increase by 225 cm.

The probability function for water station Crnac is in Fig. 11 and Table 12. The E-OBS_20 discharge has a probability of 3.1 % (instead of 5 %), and E-OBS_100 discharge has a probability of 0.44 % (instead of 1 %). The climate change values were then arranged in relation to the new estimated probability and in accordance with the basic relations from the report. New probability relations are estimated to be parallel to the basic ones published in the Prohaska report (2009). The hundred-year return period discharges (1 % in Table 12) will increase from 5 % in the first period 2011–2040 to 13 % in the last period 2071–2100. The huge inundation area of “Central Posavina” decreases not only flood discharges from the upstream part but also decreases significantly percentage of discharge increase due to the climate

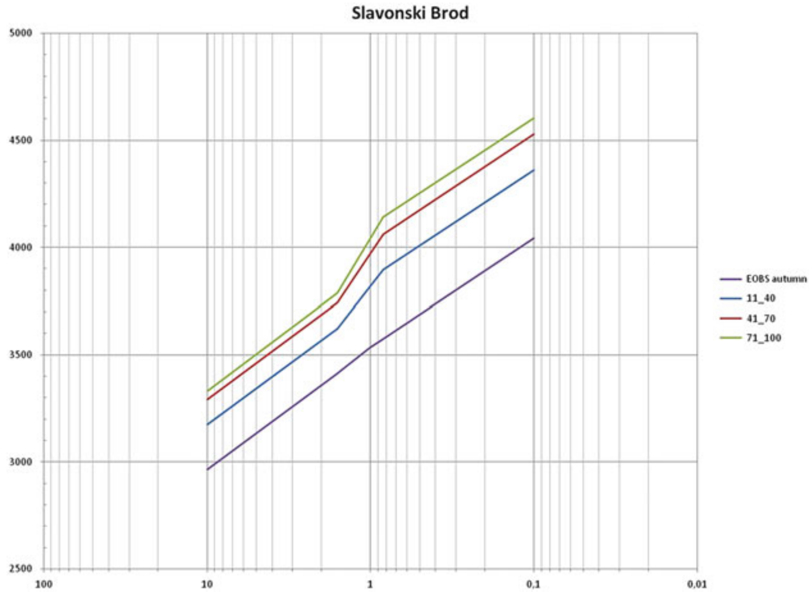

Fig. 12 Probability function (%) of peak discharges on WS Slavonski Brod for different periods of climate change forecast

Table 13 Probability of peak discharges on WS Slavonski Brod (m^3/s)

		E-OBS_20		E-OBS_100	
	10 %	1.62 %	1 %	0.84 %	0.10 %
1926–1965	2,966	3,411	3,535	3,573	4,041
2011–2040	3,175	3,623	3,825	3,895	4,360
2041–2070	3,291	3,743	3,975	4,062	4,530
2071–2100	3,332	3,788	4,050	4,142	4,605

change. The hundred-year return period of flood will increase, up to the year 2100, by 324 m^3/s, and the water level will increase by 82 cm.

The probability function for water station Slavonski Brod is in Fig. 12 and Table 13. The E-OBS_20 discharge has a probability of 1.62 % (instead of 5 %), and E-OBS_100 discharge has a probability of 0.84 % (instead of 1 %). The climate change values were then arranged in relation to the new estimated probability and in accordance with the basic relations from the report. New probability relations are estimated to be parallel to the basic ones published in the Prohaska report (2009).

The hundred-year return period discharges (1 % in Table 13) will increase from 8 % in the first period of 2011–2040 to 15 % in the last period of 2071–2100. The increase is similar to the one on the upstream WS Crnac. The hundred-year return

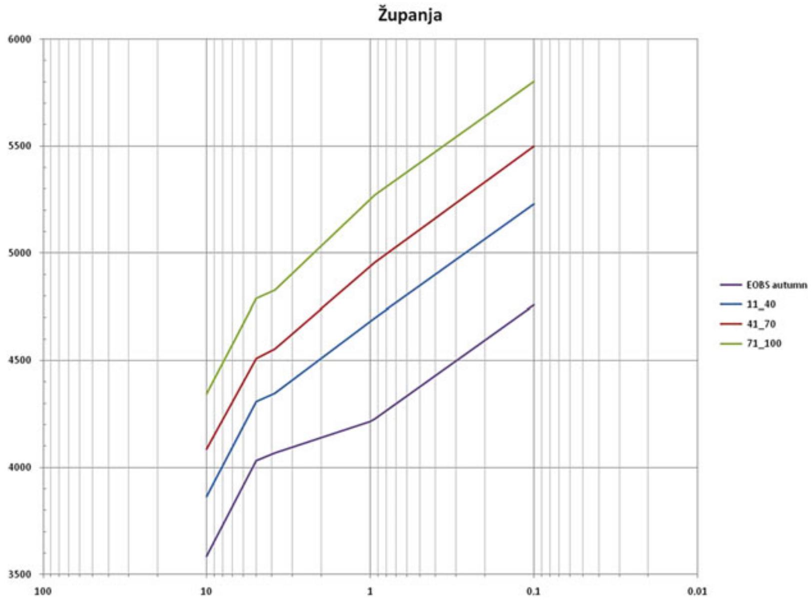

Fig. 13 Probability function (%) of peak discharges on WS Županja for different periods of climate change forecast

Table 14 Probability of peak discharges on WS Županja (m^3/s)

			E-OBS_20		E-OBS_100	
	10 %	5 %	3.85 %	1 %	0.94 %	0.10 %
1926–1965	3,585	4,031	4,068	4,215	4,227	4,759
2011–2040	3,863	4,309	4,346	4,687	4,699	5,231
2041–2070	4,086	4,510	4,554	4,945	4,957	5,500
2071–2100	4,343	4,789	4,826	5,268	5,270	5,802

period of flood will increase, up to the year 2100, by 515 m^3/s, and the water level will increase by 113 cm.

The probability function for water station Županja is in Fig. 13 and Table 14. The E-OBS_20 discharge has a probability of 3.85 % (instead of 5 %), and E-OBS_100 discharge has a probability of 0.94 % (instead of 1 %). The climate change values were then arranged in relation to the new estimated probability and in accordance with the basic relations from the report [19].

The hundred-year return period discharges (1 % in Table 14) in the WS Županja will increase from 11 % in the first period (2011–2040) to 25 % in the last period (2071–2100). The increase is higher than on the upstream WS Slavonski Brod. The hundred-year return period of flood will increase, up to year 2100, by 1,053 m^3/s, and the water level will increase by 181 cm.

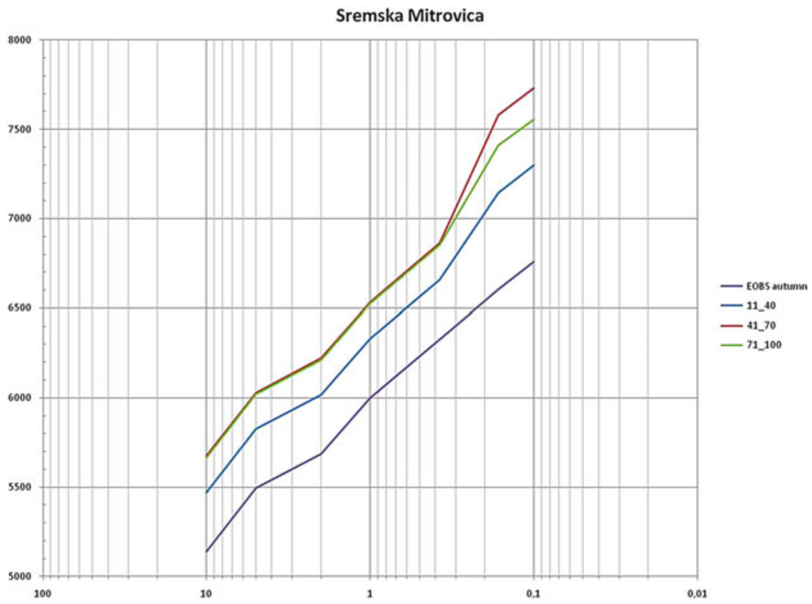

Fig. 14 Probability function (%) of peak discharges on WS Sremska Mitrovica for different periods of climate change forecast

Table 15 Probability of peak discharges on WS Sremska Mitrovica (m^3/s)

					E-OBS_20	E-OBS_100	
	10 %	5 %	2 %	1 %	0.38 %	0.16 %	0.10 %
1926–1965	5,140	5,495	5,687	6,000	6,328	6,603	6,760
2011–2040	5,471	5,826	6,018	6,331	6,659	7,143	7,300
2041–2070	5,674	6,029	6,221	6,534	6,862	7,580	7,731
2071–2100	5,666	6,021	6,213	6,526	6,854	7,410	7,556

The probability function for water station Županja is in Fig. 14 and Table 15. The E-OBS_20 discharge has a probability of 0.38 % (instead of 5 %), and E-OBS_100 discharge has a probability of 0.16 % (instead of 1 %). The climate change values were then arranged in relation to the new estimated probability and in accordance with the basic relations.

The breaks on the probability curves are caused by the logarithmic scale of probability on the abscissa. The hundred-year return period discharges (1 % in Table 15) will increase from 6 % in the first period (2011–2040) to 9 % in the last period (2071–2100). The increase is rather lower than on the upstream WS Županja. The hundred-year return period of flood will increase, up to the year 2100, by 526 m^3/s, and the water level will increase by 26 cm.

The discharges estimated as under the climate change impact are high but still much lower than the probability maximum flood of 7,081 m^3/s, calculated on the upper Sava for the Krško Nuclear Power Plant [20] and the discharge registered in 1896 on the lower part of the Sava River (in the extreme flood on the Drina River).

The process of reforestation decreases mean discharges on experimental river basin in Slovenia by 35 % [21]. The process of forestation will decrease flood discharges and mitigate the impact of climate change on floods in the Sava River basin. The process of reforestation should be researched in more detail for the Sava River basin as a whole.

On all water stations, the gradual increase of water levels of the 100-year return period floods over time is expected. The only exception is WS Sremska Mitrovica, where, at the first two periods up to year 2070, the water level rises and then it starts slightly to decrease. The largest increase in the level at the end of the century, i.e. more than 2 m, is expected in the upper part of the basin at WS Čatež. Downstream the Sava River, the water level rise is strongly reduced to 0.82 m at WS Crnac. Downstream of WS Crnac, the water level gradually increases up to 1.81 m at WS Županja. Then, downstream of WS Županja, the water level strongly drops to 0.27 m at WS Sremska Mitrovica. The modelling was derived from a model calibrated for the 1974 flood event when large construction on the system “Cenrealna Posavina” was not developed. The impact of the flood protection system “Central Posavina” and the impact of hydropower plant Mratinje on the Drina River could not be implemented in the model. The hydrological model presented seminatural conditions, without structures developed after 1974.

6 Conclusions

The reports on climate change impacts in the Sava River basin deal mainly with the average values of hydrological variables. All reports presented an expectation that in the future flood events will increase. There was no quantification of it [1–3, 5, 8, 9].

The E-OBS data set is useful for hydrological climate change forecasts of flood peak discharges in the Sava River basin. The assembly of data is not accurate enough on some parts of the basin, and additional improvements of the E-OBS data are required.

Climate change will increase peak discharges, mainly in the head part of the Sava River basin watershed. The peak discharges will increase by the end of the twenty-first century for the 100-year return period from 9 % at water station Sremska Mitrovica up to 55 % at water station Čatež.

There were some discrepancies in the Drina River basin that produced lower discharges in the forecast for the period 2071–2100 than those for the period 2041–2070. This also resulted in the lower discharge downstream of the confluence with the Sava River. Similar discrepancies, but not so strong, are presented on the following tributaries: Una River, Vrbas River and Bosna River.

The probability functions were derived for water stations, along the main stream of the Sava River, with an estimation of high flows up to the flows with the return period of 1,000 years. The climate change forecast was derived for the year periods 2011–2040, 2041–2070 and 2071–2100.

The impact of climate change on the water level forecasts with 100-year return period floods is quite high in the head part of the watershed, i.e. more than 2 m. Downstream, it first strongly decreases and then gradually increases up to 1.81 m and then drops tremendously to 0.27 m at water station Sremska Mitrovica.

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