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Comprehensive flood frequency analysis of major Sava River affluents in Bosnia and Herzegovina: risks, and implications for water resources management

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Abstract— This study addresses the pressing issue of flood frequency analysis in Bosnia and Herzegovina (BH), focusing on major rivers—Una, Sana, Vrbas, and Bosna. In light of the global impact of floods on lives, property, and infrastructure, the research aims to understand and predict these events, particularly considering climate change and socioeconomic development. Employing goodness-of-fit tests such as Kolmogorov-Smirnov and Cramér-Von Mises, the study identifies the most suitable probability distributions for modeling river discharge data. Pearson 3, generalized extreme value (GEV), and Gumbel distributions emerge as best fits, demonstrating variations across rivers. The research emphasizes the importance of tailoring models to specific hydrological characteristics, with the Bosna River best modeled by the Pearson 3 distribution and the Sana River by the GEV distribution. Calculated return periods for extreme flood events provide valuable insights into potential discharge magnitudes, highlighting the crucial role of accurate probability distributions in informed risk management and infrastructure planning. This study fills a critical gap in flood frequency analysis for selected rivers in BH, offering essential information for water resource management and flood risk assessment in the context of ongoing climate change.

Key-words: flood frequency analysis, flood, L-moments, Bosnia and Herzegovina, river discharge modeling

1. Introduction

Floods are the most widespread and destructive natural disasters, endangering many lives and causing damage to property, agriculture, and infrastructure worldwide *(Blöschl,* 2022; *Chen et al.,* 2021; *Heinrich et al.,* 2023). In addition, the damage caused by floods has increased in recent decades and is expected to increase further, mainly due to socioeconomic progress and climate change *(Nguyen et al.,* 2020; *Steinhausen et al.,* 2022). With an average of 163 events per year, floods have contributed to 44% of all natural disasters affecting 1.6 billion people around the world in the last two decades (*CRED* and *UNDRR,* 2020). The total economic loss from weather-related natural disasters in the European Economic Area amounted to 487 billion euros in the period 1980-2020 and can be attributed to weather-related extremes (*Snizhko et al.,* 2023). Fluctuations in river flow regimes are primarily caused by climate change and human-induced impacts (*Khoi et al.,* 2019).

Recording the frequency of flooding events is necessary but challenging due to the lack of hydrological stations and their limited geographical coverage (*Benito et al.,* 2023). Numerous studies conducted over the last decade have investigated changes in flood events, their seasonality, and trends in Europe (*Arnell* and *Gosling*, 2016; *Alfieri et al.,* 2015*; Bertola et al.,* 2020; *Blöschl et al.,* 2019*; Lehmkuhl et al.,* 2022; *Tramblay et al.,* 2023). Flood events in northwestern Europe have increased due to increased autumn and winter precipitation, while lower precipitation and less snow cover, together with a significant warming of the air, have led to a decrease in flood events in southern and eastern Europe (*Blöschl et al.,* 2019). *Fang et al.* (2022) reported a distinct regional pattern of average flood dates in summer (Jun-Aug) in the Alps and in winter (Dec-Feb) across western Europe and the Mediterranean region. Flood-related studies have also increased in the southeastern region of Europe in the last decade. Some authors used regional flood frequency analysis (*Kavcic et al.,* 2014*; Leščešen et al.,* 2022), while other studies for the same area focused on using a general flood frequency and seasonality analysis (*Ilinca* and *Anghel,* 2022; *Morlot et al.,* 2019; *Trobec,* 2017). Overall, it can be said that a significant amount of flood studies is still missing (especially in the Western Balkans region), which makes this problem even more important, especially as floods have become more frequent in the region.

Accurate and consistent forecasting of river flows is essential for many purposes, such as water resources management, modernization strategies, maneuvers, and maintenance activities (*Samantaray* and *Sahoo,* 2020). Flood risk assessment is often carried out to reduce the damage caused by floods in a particular location (*Ahmed et al.,* 2023). In this regard, flood frequency analysis (FFA) is crucial for flood risk assessment and management, as it provides predictions of the frequency and intensity of flood events, which are essential for planning infrastructure and defining risk-related measures (*Pan et al.,* 2023). To ensure that flood dynamics and magnitude are accurately assessed, the most accurate FFA requires a significant number of accurately observed peak discharges (*Bartens* and *Haberlandt,* 2024). A statistical method such as FFA is commonly used to determine the extent of flooding within a given return period (*Šraj et al.,* 2016) and is often used in water management studies (*Ahn* and *Palmer,* 2016). The conventional FFA approach extrapolates the tails of the distribution to determine the probability and magnitude of extreme events by fitting mathematical functions to the given data (*Leščešen et al.,* 2022). FFA is essential to engineering practice to establish links between design variables that correlate to a chosen hydrological risk (*Šraj et al.,* 2016).

In Bosnia and Herzegovina (BH), FFA is almost non-existent given that numerous evaluations of flood frequency covering the 1961–1990 period were created, mostly for project studies, and they are not accessible to the general public. For this analysis, we selected four hydrological profiles on the largest right affluents of the Sava River (SR) in BH (Una, Sana, Vrbas, and Bosna rivers). Four out of five selected profiles have near-natural streamflow regimes, whereas the only station influenced by the dam is Delibašino Selo on the Vrbas River. In BH, the two main causes of flooding are sudden snowmelt that happens in the late winter/early spring or cyclone-originated precipitation. There has been a noticeable increase in the frequency of flooding events since the year 2000. Since the SR basin is made up primarily of impermeable rock layers with a dense hydrographic system (*Gnjato et al.,* 2023), most floods in BH have taken place in this part of the country *(Gnjato et al.,* 2024). Consequently, FFA is of great importance for engineering practice, since severe floods in the SR basin in BH are predicted to be generated more frequently as a result of climate warming. Hence, the principal task of this research was to perform a comprehensive flood frequency analysis for the main affluents of the SR in BH for the period 1961–2020.

2. Study area

Roughly 40% of the SR basin encloses the BH area, while the entire basin encompasses territories of several adjacent countries. Starting in Croatia at the mouth of the Una River and finishing at the mouth of the Drina River, the Sava River flows 345 km through BH. The SR basin in BH encompasses central mountainous (Dinaric) and northern mostly plain (Peripannonian) areas which make up around 75% of BH (*Fig. 1*). The northern lower areas of the basin experience a moderate continental climate. In contrast, the mid and southern areas of the basin are exposed to continental and mountain climates. The biggest Sava tributaries in BH are the Una, Vrbas, Bosna, and Drina rivers. All aforementioned tributaries of the SR experience pluvial-nival river regimes with maximum streamflow values in the spring season, while minimum streamflows occur in the summer (*Gnjato et al.,* 2021).

Fig. 1. Location of the Sava River basin along with analyzed hydrological stations.

3. Data and methods

In this paper, a 60-year (1961–2020) database of the maximum peak discharge for each month for four gauging stations that are located in the BH (*Fig. 1*) was used. Discharge data was obtained from the Republic Hydrometeorological Service – Republic of Srpska. Statistical characteristics of these data sets and the whole period are presented in *Table 1*.

Table 1. Descriptive statistics of monthly maximum discharge (m^3/s) at the selected rivers

Parameter	**River**			
	Una	**Sana**	**Vrbas**	**Bosna**
Mean annual discharge (m^3/s)	499.13	220.69	262.85	473.00
Standard error (m^3/s)	13.05	6.14	11.48	15.53
Median (m^3/s)	436.30	185.10	208.00	387.00
Standard deviation (m^3/s)	350.32	164.84	228.46	416.77
Kurtosis	0.874	0.838	0.79	0.82
Skewness	0.957	0.961	2.68	2.51
Minimum annual discharge (m^3/s)	42.80	8.80	29.00	22.00
Maximum annual discharge (m^3/s)	2059	1014	1752	4205

To define the flood frequency at a specific site, the selection of a suitable probability distribution is of crucial importance. We have considered the generalized extreme value (GEV), Pearson type-III (P3), Log Pearson type III (LP3) and Gumbel (GUM) distributions for the analysis of flood frequency at four gauging stations at the four rivers in the northern part of BH. The probability density function (pdf) and quantile function y(F) of these distributions are presented in *Table 2*. These distributions are most commonly used for FFA in the literature and are frequently applied in many countries (*Petrović et al.,* 2024; *Cassalho et al.,* 2019; *Drissia et al.,* 2019; *Ul Hassan et al.,* 2019).

Table 2. Probability density and quantiles functions of the probability distributions

Distribution	**Probability density function f(y)**	**Quantile function y(F)**
GEV	$\frac{1}{\alpha} = \left[1 - k\left(\frac{y-\mu}{\alpha}\right)\right]^{\frac{1}{k}-1} \exp\left\{-\left[1 - k\left(\frac{y-\mu}{\alpha}\right)\right]^{\frac{1}{k}}\right\}$	$\mu + \frac{\alpha}{k}\left[1 - (-\log F)^{k}\right]$
P3	$\frac{1}{\beta^{\alpha}\Gamma\alpha}(y-\mu)^{\alpha-1}\exp\left\{-\frac{(y-\mu)}{\beta}\right\}$	Explicit analytical form is not available
LP3	$f(y) = \frac{1}{\sigma(y)\sqrt{2\pi}}\exp\left[-\frac{1}{2}\left(\frac{y-\mu(y)}{\sigma(y)}\right)^{2}\right]$	$y(f) = \mu(y) + \sigma(y)x\left[Z + \frac{1}{2}\left(\frac{Z^{2}-1}{3}\right)\right]$
GUM	$\frac{1}{\alpha}\exp\left[-\frac{y-\mu}{\alpha} - \exp\left(-\frac{y-\mu}{\alpha}\right)\right]$	$\mu - \alpha\log(-\log F)$

Hosking and *Wallis* (1997) introduced L-moments as linear functions of probability weighted moments (PWM's), offering an alternative to conventional moments. Computed from linear combinations of order statistics, L-moments can be defined for any random variable *Y* with an existing mean. PWM was applied for L–moments calculation as outlined by *Hosking* and *Wallis* (1997):

$$\beta_r = E\{X[F_x(x)]^r\}\,, \tag{1}$$

where, β_r is the *r*th order PWM and $F_X(x)$ characterizes the cumulative distribution function (CDF) of *X*. Sample estimators (β_i) of the first four PWMs are explaind in *Hosking* and *Wallis* (1997):

$$\beta_0 = m = \frac{1}{n}\sum_{j=1}^{n} X_j, \tag{2}$$

$$\beta_1 = \sum_{j=1}^{n-1}\left[\frac{n-j}{n(n-1)}\right] x_{(j)}, \tag{3}$$

$$\beta_2 = \sum_{j=1}^{n-2}\left[\frac{(n-1)(n-j-2)}{n(n-1)(n-2)}\right] X_{(j)}, \tag{4}$$

$$\beta_3 = \sum_{j=1}^{n-3}\left[\frac{(n-j)(n-j-1)(n-j-2)}{n(n-1)(n-2)(n-3)}\right] X_{(j)}\ , \tag{5}$$

where, $X_{(j)}$ is the rank of AMS with $X_{(1)}$ which represents the highest value and $X_{(n)}$ that represents the lowest value. Regarding PWMs, the initial four L-moments, signifying the mean, scale, skewness, and kurtosis of the distributions, are established through linear combinations of PWMs (*Hosking* and *Wallis*, 1997):

$$\lambda_1 = \beta_0\ , \tag{6}$$

$$\lambda_2 = 2\beta_1 - \beta_0\ , \tag{7}$$

$$\lambda_3 = 6\beta_2 - 6\beta_1 + \beta_0, \tag{8}$$

$$\lambda_4 = 20\beta_3 - 30\beta_2 + 12\beta_1 - \beta_0\ . \tag{9}$$

Finally, the L-moment ratios defined by *Hosking* and *Wallis* (1993) are specified below:

$$L - C_v = \tau_2 = \frac{\lambda_2}{\lambda_1}, \tag{10}$$

$$L - C_s = \tau_3 = \frac{\lambda_3}{\lambda_2}, \tag{11}$$

$$L - C_k = \tau_4 = \frac{\lambda_4}{\lambda_2}, \tag{12}$$

where τ_2 is the L coefficient of variation, τ_3 is the L coefficient of skewness, τ_4 is the L coefficient of kurtosis.

The optimal distribution function was determined by employing the Kolmogorov-Smirnov (K-S) and Cramer-von Mises (CvM) tests. These tests were selected for their robustness and reliability at different sample sizes, making them particularly suitable for flood frequency analysis where sample sizes may be limited. K-S and CvM tests are known for their ability to accurately assess goodness of fit even at minimum cell frequencies and provide a sound methodological basis for determining the optimal distribution function (*Petrović et al.,* 2024; *Leščešen et al.,* 2022*; Kousar et al.,* 2020). The K-S test is frequently employed method for assessing the consistency of probability distribution methods, delivering reliable results even with limited samples and minimal cell frequencies. The approach involves computing the value of D_{max} that represents the maximum unconditional deviation between the cumulative extent of two distributions, followed by comparison with the critical value of D to either accept or reject the proposed set hypothesis (*Bhat et al.,* 2019). In comparing two or more theoretical distributions, the distribution exhibiting lower values of the D_{max} statistics is considered the optimal fit with the empirical data. The K-S test goes as follows:

$$D_{max} = max|F_e(x) - F_t(x)| \ . \tag{13}$$

Similarly, the Cramer–von Mises test evaluates the concordance between empirical and theoretical distributions, with a diminished value of $N\omega$ indicating a closer conformity of the distribution with the empirical data:

$$N\omega^2 = \frac{1}{12N} + \sum_{i=1}^{N} \quad [F_e(x) - F_t(x)]^2 \ . \tag{14}$$

For further confirmation, the Monte Carlo approach was employed to assess the performance of different probability distributions in modeling river discharge data (*Zorzetto et al.,* 2016). The analysis involved conducting 1000 simulations to evaluate the Mean Absolute Error (MAE) and root mean squared error (RMSE) for each distribution, which are defined as follows:

$$MAE = \frac{1}{3}\sum_{i=1}^{n}|y_i - \hat{y}_i| \ , \tag{15}$$

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \ , \tag{16}$$

where n is the number of data points, y_i is the observed discharge value, and $\hat{y}_i$ is the estimated discharge value from the probability distribution. For each simulation, random data were generated using the parameters obtained from fitting the Pearson 3, log-Pearson 3, generalized extreme value (GEV), and Gumbel distributions to the observed discharge data. The MAE and RMSE were calculated for each distribution, providing insights into their ability to accurately represent the observed discharge values.

4. Results and discussion

When analyzing the flood frequency, the main objective is to accurately and rigorously determine the quantile values that define the range of low exceedance probabilities, as there are usually no observed values. The goodness-of-fit tests were performed to assess the suitability of different probability distributions for modelling the discharge data of the Bosna, Vrbas, Una, and Sana rivers, with further validation using the Monte Carlo approach (*Table 3*).

Table 3. Fit statistics and distribution selection for river discharge data

River	**Distribution**	**Goodness-of-Fit Test**				**Monte Carlo Approach**	
		Kolmogorov-Smirnov		**Cramer-von Mises**		**MAE**	**RMSE**
		Stat	**p-value**	**Stat**	**p-value**		
Una	GEV	0.058	0.019	0.641	0.017	391.33	525.40
	P3	0.061	0.008	0.751	0.009	400.56	533.40
	LP3	0.754	0.000	161.2	0.000	1331.00	3028.60
	GUM	0.058	0.013	0.635	0.018	377.23	487.70
Bosna	GEV	0.076	0.000	0.752	0.009	440.54	768.10
	P3	0.033	0.400	0.103	0.568	409.29	577.00
	LP3	0.632	0.000	0.104	0.567	1817.68	4584.40
	GUM	0.066	0.003	0.811	0.007	384.71	532.00
Sana	GEV	0.042	0.137	0.511	0.037	184.84	251.52
	P3	0.048	0.065	0.512	0.037	188.02	250.78
	LP3	0.590	0.000	96.315	0.000	2318.91	5907.70
	GUM	0.050	0.050	0.682	0.014	176.06	227.55
Vrbas	GEV	0.085	0.006	0.479	0.045	230.96	382.37
	P3	0.056	0.166	0.174	0.324	221.52	317.40
	LP3	0.778	0.000	96.24	0.000	356.84	1993.68
	GUM	0.091	0.003	0.547	0.030	205.74	289.00

In this study, no single distribution was identified as the best fit for all gauging station locations. Similar results have been reported in several other studies (*Petrović et al.,* 2024*; Drissia et al.,* 2019; *Ul Hassan et al.,* 2019; *Castellarin et al.,* 2012) For the Una River, the LP3 distribution was found to be the best fit, as it had the lowest values in both the Kolmogorov-Smirnov and Cramér-Von Mises statistics. The P3 distribution was also identified as the best fitting model for the Bosna river, which was confirmed by its superior performance in both tests. Conversely, the Gumbel distribution showed the best fit for the Sana River and had the lowest statistics in both goodness-of-fit tests. Finally, for the Vrbas River, the P3 distribution also performed the best and had the lowest statistics in both tests. Graphical confirmation of the goodness-of-fit results was achieved through a box plot analysis, which further underpins the identified best-fit probability distributions for each river system (*Fig. 2*).

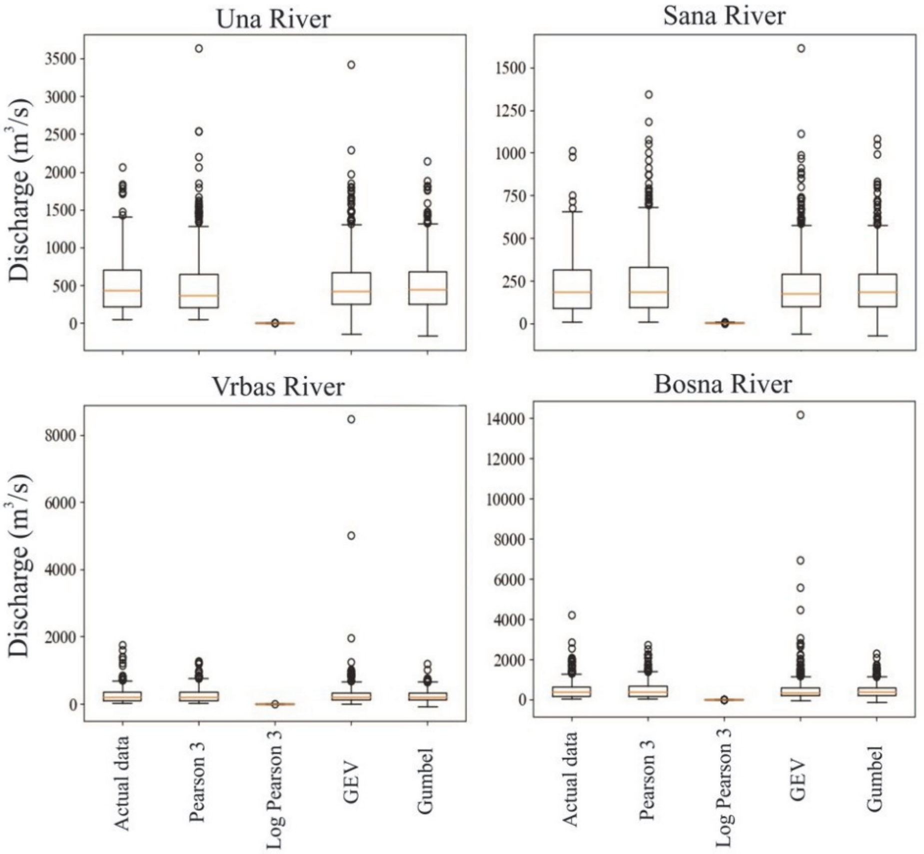

Fig 2. Box plot presentation of the fitting results for all considered distribution functions.

For clarity, a cumulative distribution function (CDF) chart was created to further validate the results and strengthen their credibility (*Fig. 3*). This diagram visually compares the distribution of observed discharge values with those estimated using different probability distributions. The x-axis represents the discharge values, while the y-axis indicates the cumulative probability of occurrence. The CDF diagram shows that the log-Pearson 3 distribution along the x-axis deviates significantly from the observed discharge values, indicating a lack of fit. In contrast, other distributions show a considerable overlap with the observed discharge data, indicating a better fit. Consistent with the conclusions drawn from the CvM test and the KS test, the CDF plot confirms that the generalized extreme value (GEV) distribution, the Pearson 3 distribution, and the

Gumbel distribution are best suited for modeling river discharge data. These distributions not only have a good statistical fit but also closely match the observed discharge values, which clearly demonstrates their suitability for the analysis.

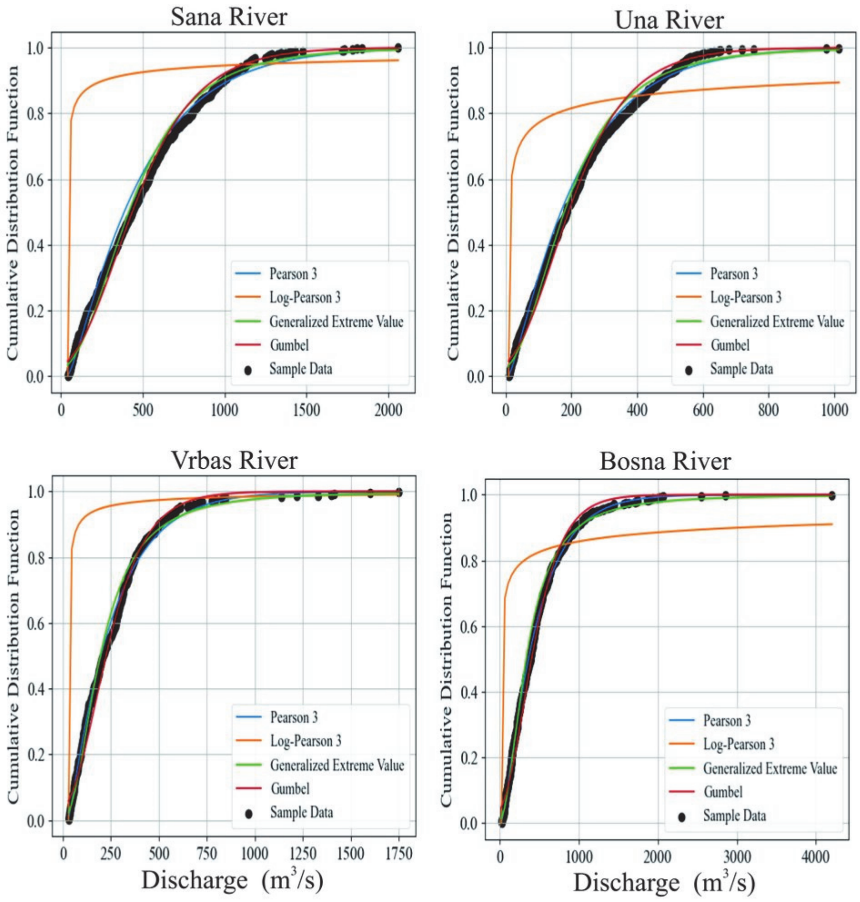

Fig. 3. Cumulative distribution function (CDF) analysis.

Even though results from FFA analysis in Slovenia (*Zabret* and *Brilly,* 2014), overall Sava River basin *(Leščešen et al.,* 2022) suggest that GEV distribution is the most appropriate for this region, from the presented results a single distribution does not appear as the best fitting distribution for all rivers. The size of the sample does not play a decisive role in favoring any specific distribution or estimation method. The Bosna River has the highest average of monthly maximum discharge, and it is best modeled by Pearson 3 distribution, while the Sana River has the lowest average of the monthly maximum and is best modeled by GEV distribution (see *Table 1*). The results for Sana River are in good accordance with the results presented by *Morlot et al.* (2019). The Pearson 3 distribution is more suitable for rivers that have lower values of the coefficient of kurtosis and low values of the coefficient of skewness (see *Table 1*). These sentences should be rephrased as follows: A crucial difference between our study and that of *Morlot et al.* (2019) lies in the suitability of the log-Pearson 3 distribution for the observed flows. Our results show that this distribution is not suitable for the fluxes investigated, whereas *Morlot et al.* (2019) indicate that it is most suitable for the rivers Una, Vrbas, and Bosna. This discrepancy could be due to differences in the data sets used for the analyses. In our study, monthly maximum values were used, while *Morlot et al.* used daily discharge values. This discrepancy raises interesting questions that should be investigated in future research projects.

To improve the robustness of our study, we conducted a Monte Carlo simulation to evaluate the performance of different probability distributions in modeling runoff data. This approach provided valuable information on the accuracy of the distribution fit and the reliability of the runoff estimates (*Table 4*). This comprehensive analysis ensures a more thorough understanding of the predictive capabilities of the selected distributions and thus increases the reliability of flood estimation, even for different return periods.

Table 4. MAE and RMSE comparison with Monte Carlo approach

River	**Monte Carlo approach**	
	MAE	**RMSE**
Una	370.81	734.81
Bosna	320.74	127.12
Sana	434.82	480.35
Vrbas	113.23	342.62

The results of the Monte Carlo simulation, presented in *Table 4*, show the performance of the model in simulating runoff data for the Sana, Vrbas, Una, and Bosna rivers. The MAE values range from 113.23 to 434.82 cubic meters per second (m^3/s), while the RMSE values range from 127.12 to 734.82 m^3/s. Lower MAE and RMSE values indicate better agreement between observed and simulated runoff values. The results indicate that the model works relatively well, especially for the rivers Vrbas and Bosna, where the MAE and RMSE values are comparatively lower. For the Una River, however, the model shows slightly higher errors, indicating that the discharge dynamics for this river can only be captured with limited accuracy. Although the model shows varying degrees of accuracy on the different rivers, its ability to approximate the discharge data with reasonable precision underlines its usefulness for the FFA.

A key objective of the flood frequency analysis is to determine the quantile in the extreme upper tail of the best-fit distribution for the Una, Sana, Vrbas, and Bosna rivers. Using the quantile function and the parameter values specific to the best-fit distribution at each gauging station, we calculate the quantile estimates corresponding to return periods of 5, 10, 25, 50, 100, 200, 500, and 1000 years, with 95% confidence intervals (*Fig. 4*). The confidence intervals for each distribution were determined as depicted in *Anghel* and *Ilinca* (2023).

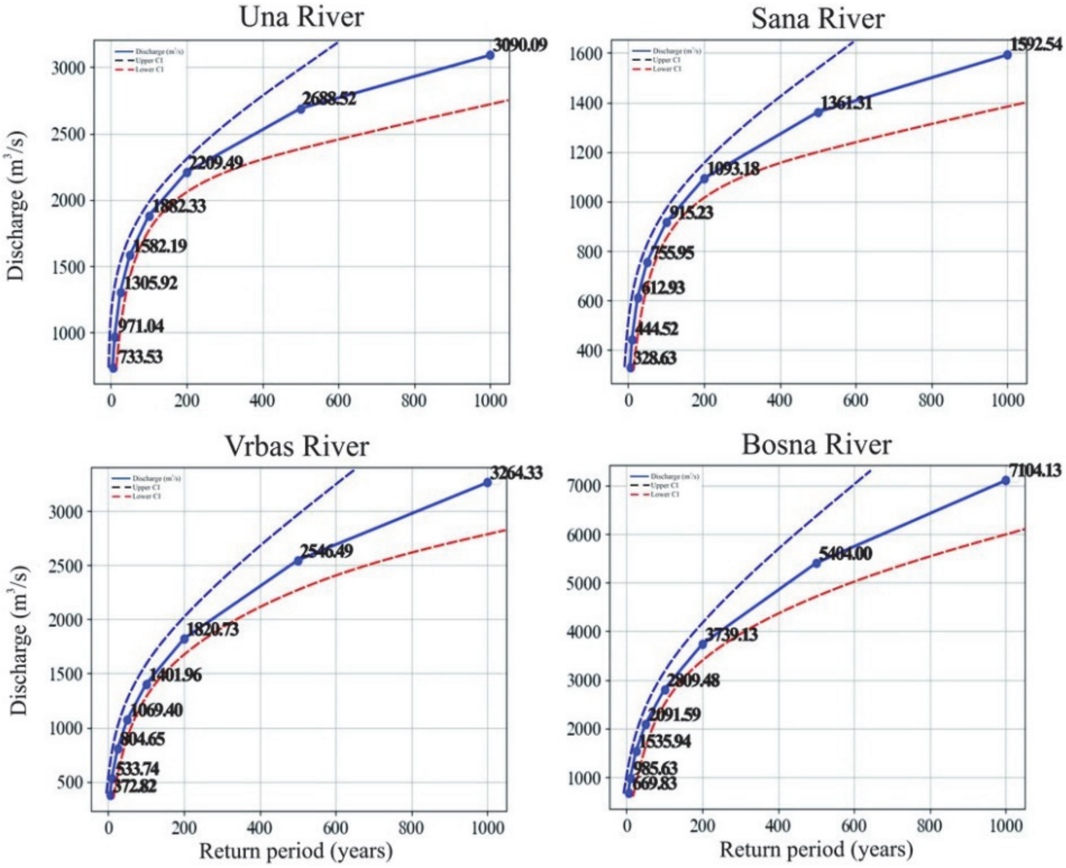

Fig. 4. Calculated return periods for selected rivers.

The analysis shows increasing discharge values for different return periods across several rivers, including the Una, Sana, Vrbas and Bosna. These results emphasize the importance of accurate probability distributions for estimating extreme flood magnitudes, which are crucial for effective risk management strategies in the northern parts of BH.

5. Conclusion

This study addressed the critical issue of flood frequency analysis in Bosnia and Herzegovina, focusing on the major rivers-Una, Sana, Vrbas, and Bosna. The global impact of floods on lives, property, and infrastructure underscores the urgency of understanding and predicting these events, especially in the context of climate change and socioeconomic development.

The comprehensive analysis included goodness-of-fit tests, including Kolmogorov-Smirnov and Cramér-Von Mises tests, to identify the most appropriate probability distributions for modeling river discharge data. The results showed differences between rivers, with the Pearson 3, generalized extreme value (GEV) and Gumbel distributions emerging as the best fits for different cases. Graphical analyzes using box plots and cumulative distribution function (CDF) diagrams visually confirmed the statistical results and substantiated the appropriateness of the identified distributions for each river system.

The study also highlighted that a single distribution is not universally appropriate for all rivers, emphasizing the importance of tailoring the models to specific hydrological characteristics. The Bosna River, characterized by the highest average monthly discharge, showed the best fit with the Pearson 3 distribution, while the Sana River, with the lowest average, was best modeled by the GEV distribution.

In addition, the calculated return periods for extreme flood events provided valuable insights into potential runoff magnitudes for different return intervals. The results emphasize the importance of accurate probability distributions in estimating extreme flood magnitudes, which are essential for sound risk management and infrastructure planning.

This research fills a critical gap in the analysis of flood frequency for the selected rivers in Bosnia and Herzegovina and provides valuable information for water resource management and flood risk assessment. As climate change continues to impact hydrological patterns, the results of this study contribute to our understanding of how different rivers respond to extreme events, helping to develop robust flood mitigation and adaptation strategies in the region.

Future research could focus on extending the scope of this analysis to other rivers and integrating more recent climate data to improve the robustness of flood prediction models. In addition, the inclusion of socioeconomic factors and land use changes could lead to a more comprehensive understanding of flood risks and enable more effective management strategies.

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