

Evaluating flood frequency analysis of the rivers in the Skopje Basin, North Macedonia – Statistical distribution fitting and hydrological insights

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Abstract

This study examines the flood frequency analysis (FFA) of four rivers in North Macedonia: Vardar, Treska, Lepenac, and Serava. The aim is to contribute to water resource management, flood risk mitigation, and resilience to climate change through detailed seasonal analysis. The most appropriate probability distributions were determined for each river: Pearson Type III (PIII) for the summer and winter seasons in the Vardar, PIII for summer, and Gamma for winter in the Treska, PIII for both seasons in the Lepenac, and PIII for summer and Log-Normal for winter in the Serava. For each distribution, discharge estimates were calculated for different return periods. The results show significant seasonal variations in discharge, especially for the Treska and Lepenac rivers. For the Treska, winter discharges are significantly higher than summer discharges in all return periods, indicating that winter conditions mainly determine the annual flood risk. The Lepenac shows a similar pattern with significantly higher discharges in winter. In contrast, the Vardar shows relatively constant discharges between summer and winter, suggesting a balanced seasonal contribution to the annual flood risk. The Serava shows less seasonal variation, indicating a less variable hydrological system. These results emphasise the importance of considering both annual and seasonal variability in the FFA to improve the accuracy of flood risk assessments and support effective water resource management. This research highlights the need for customised flood frequency models that account for seasonal runoff patterns to improve prediction accuracy and provide information for strategic planning in the face of climate change.

Keywords: flood frequency analysis, hydrological extremes, river discharge variability, hydrological data analysis, Vardar, Treska, Lepenac, and Serava rivers, North Macedonia

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Introduction

Floods are among the most widespread and devastating natural disasters, posing a serious threat to human lives and causing substantial damage to property, agriculture, and infrastructure worldwide (BLÖSCHL, G. 2022; HEINRICH, P. *et al.* 2023). The last few decades have recorded the increasing impact of floods,

a trend that will continue primarily due to the joint effects of socioeconomic progress and climate change (NGUYEN, V.D. *et al.* 2020). Floods account for more than 44 percent of all recorded natural disasters and occur at an alarming rate, with over 160 events annually. These disasters arise from a combination of natural and human-induced factors and are widespread environmental hazards impact-

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ing communities globally (CRED & UNDRR, 2020). Across Europe, recent studies have revealed substantial changes in flood occurrence, seasonality, and spatial distribution, reflecting the growing influence of changing hydro-climatic conditions and human pressures on river systems (e.g. FANG, B. *et al.* 2025). These changes are also evident in Southeast Europe and the Western Balkan region, where complex topography, increasing rainfall extremes, land-use changes, and expanding urban areas have contributed to heightened flood hazard and hydrological variability (e.g. PETROVIĆ, A. 2015; SABLJIĆ, L. *et al.* 2025). Within this regional context, the Republic of North Macedonia is also vulnerable because of its hilly-mountainous terrain, and pronounced hydro-climatic variability, which frequently generate floods and high-flow events with considerable environmental and socioeconomic consequences (RADEVSKI, I. *et al.* 2016; RADEVSKI, I. and GORIN, S. 2017). Rapid development within river catchments has further intensified flood problems by increasing surface runoff, reducing natural water retention, and altering river channel capacity (PETROVIĆ, A. 2015; FANG, G. *et al.* 2022; ADDIS, A. 2023). These regional characteristics underscore the importance of robust flood frequency analyses to improve flood hazard assessment and support sustainable water resources management in North Macedonia.

Flood frequency analysis (FFA), extreme river flood trends, and their relationship with global climate change have been the subject of extensive research that has been conducted worldwide (PETROW, T. and MERZ, B. 2009; BLÖSCHL, G. *et al.* 2017, 2019; BORMANN, H. and PINTER, N. 2017; BERTOLA, M. *et al.* 2019; CASSALHO, F. *et al.* 2019; LEŠČEŠEN, I. and DOLINAJ, D. 2019; LEŠČEŠEN, I. *et al.* 2019, 2022; ENGELAND, K. *et al.* 2020; LUDWIG, P. *et al.* 2023; PETROVIĆ, A.M. *et al.* 2024). The main aim of these studies is to develop practical and reliable tools for flood management and civil engineering design, while also enhancing the understanding of flood characteristics

(WILCOX, C. *et al.* 2018). So far, no uniform changes have been recognized worldwide despite extensive research on the global and regional spatial-temporal patterns of hydrological extremes. When historical data is evaluated, both a decrease and an increase in extreme discharges are observed in different parts of the world (CONDON, L.E. *et al.* 2015). The standard FFA method is based on fitting mathematical functions to available datasets and extrapolating the distribution tails for the purpose of estimating the probability and magnitude of extreme events (ST. GEORGE, S. and MUDELSEE, M. 2019). When sufficient data is available at a single gauging station, an extreme value distribution is typically fitted to the observed data, resulting in an at-site FFA or local model (ARNAUD, P. *et al.* 2016). A suitable data length (>30) is essential for identifying the best-fit distribution function accurately, as the length of observed data plays a significant role in determining the best-fit probability distribution (AMIN, M.T. *et al.* 2016). Observational data from Europe over the past century have not shown a consistent trend in flood occurrence rates (PAPROTNY, D. *et al.* 2018). Despite this, almost every year new record-breaking hydrological extremes affect various regions of Europe, causing the debate between the effects of climate change and natural climate variability to intensify. The identification of the clear and statistically significant anthropogenic changes in atmospheric and climate variables, especially CO₂ concentration and air temperature are now clearly noticeable due to the increasing availability of high-quality hydrological and meteorological data (LEŠČEŠEN, I. *et al.* 2024). The Clausius-Clapeyron (CC) equation indicates that higher air temperatures are associated with increased atmospheric water vapour content, which influences the total precipitable water (ALFIERI, L. *et al.* 2015). Consequently, this CC relationship implies that the frequency of flooding could rise due to climate change (TABARI, H. 2020; PAPADOPOULOS-ZACHOS, A. and ANAGNOSTOPOULOU, C. 2023).

Despite extensive studies on flood frequency, a significant research gap remains, particularly in the Western Balkan region. This area has experienced an increase in flood frequency (LEŠČEŠEN, I. *et al.* 2023), yet comprehensive studies on peak discharge frequency analysis are sparse. The return period is a crucial hydrological tool as it estimates the interval between events of similar size or intensity (VOLPI, E. *et al.* 2019). This is why the FFA is most commonly used to estimate these return periods, which is essential for designing infrastructure like dams, bridges, culverts, storm drainage systems as well as for agricultural planning and flood prediction (TEMTEME, G.S. 2024).

This paper presents a flood frequency analysis carried out on a 30-year period (1991–2020) series of maximum monthly discharge data for the Vardar, Treska, Lepenac, and Serava rivers. The motivation for this study stems from the lack of comprehensive studies related to the frequency analysis of peak discharge in the Republic of North Macedonia. Therefore, the purpose of this

study is to compare the results obtained by applying various frequency analysis methods to identical sets of discharge data and to identify the best-fitting distribution through visual analysis and statistical testing. This research aims to fill the existing knowledge gap in flood frequency analysis for this part of Southeast Europe and to provide valuable insights for flood risk management and infrastructure planning in the region.

Study area

North Macedonia, located in the Balkan Peninsula of Southeast Europe, is a landlocked country bordered by Serbia to the north and northeast, Bulgaria to the east, Greece to the south, and Albania to the west (Figure 1). The country has a relatively small geographical area, covering approximately 25,713 km². The study area includes four major rivers in the north-western parts of the country: Vardar, Treska, Lepenac, and Serava, which cover 18.2 percent of the coun-

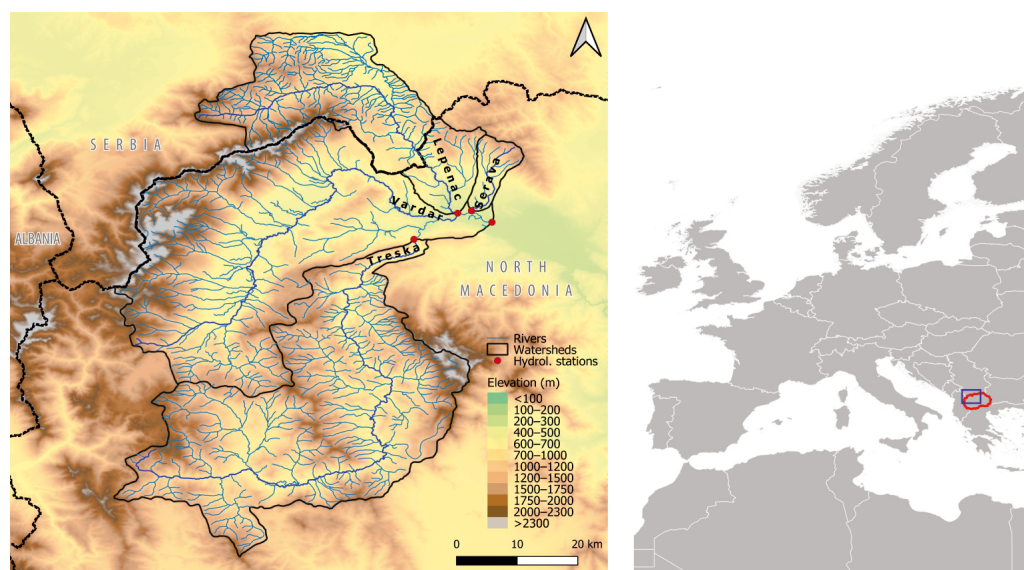


Fig. 1. Geographical location of the hydrological stations. Source: Authors' own elaboration.

try’s area. The Vardar is the longest and most significant river in North Macedonia, running through the central part of the country. It originates from the Gostivar area (Vrutok karst spring) in the western part of the country and flows southeast, eventually emptying into the Aegean Sea in Greece. The Treska is another important river in the study area, located in western North Macedonia. It is a tributary of the Vardar, joining it near the city of Skopje (PETROVSKA, I. and DIMOV, L. 2020). The Lepenac is situated in northern North Macedonia, flowing through the Polog Valley and joining the Vardar near Tetovo (SIMIĆ, S. *et al.* 2023). Lastly, the Serava is located in the northern part of the Skopje Basin before joining the Vardar.

These four rivers play a crucial role in the hydrological system of the Skopje Basin, providing water resources for irrigation, municipal use, and hydropower generation in the region. The Lepenac, flowing through the Kosovo Basin and Kachanik gauge, is influenced by the mountainous terrain of Shar Mountain and can experience rapid fluctuations in water levels during heavy rainfall events. The Serava, located in the northern part of the Skopje Basin, is influenced by both natural factors and human activities, such as agriculture and industrial development along its course. In

the present study, the focus is on analysing the flood frequency of these four rivers in North Macedonia. Skopje Basin with the mentioned four gauges belongs to the R2b stable pattern without a secondary winter maximum in the river regime. It has a spring maximum in April with around 15 percent of the total annual streamflow (RADEVSKI, I. *et al.* 2023).

Materials and methods

For the flood frequency analysis, crucial data were obtained from the National Hydrometeorological Service of the Republic of North Macedonia. This dataset includes the monthly maximum discharges recorded at four gauging stations located along four rivers in the northern part of North Macedonia. The analysis utilized data from the 1991–2020 period, which is detailed in Table 1, and visually represented in Figure 2.

Figure 2 presents the monthly maximum discharge time series (1993–2020) for the four investigated rivers. All these rivers show strong inter-annual and seasonal variability, with recurrent high-magnitude peaks superimposed on generally lower baseline flows. The Vardar and Treska rivers exhibit the largest discharges, reaching maxima of

Table 1. Geographical characteristics of the observed stations

River	Gauge	Latitude	Longitude	Height, m a.s.l.	Area, km ²
Vardar	Železnički Most	41.994630°	21.449720°	242	4,650
Treska	Sveta Bogorodica	41.960038°	21.296059°	286	1,880
Lepenac	Vliv	42.012906°	21.382173°	255	770
Serava	Momin Potok	42.018114°	21.409201°	257	67

Source: Compiled by the authors.

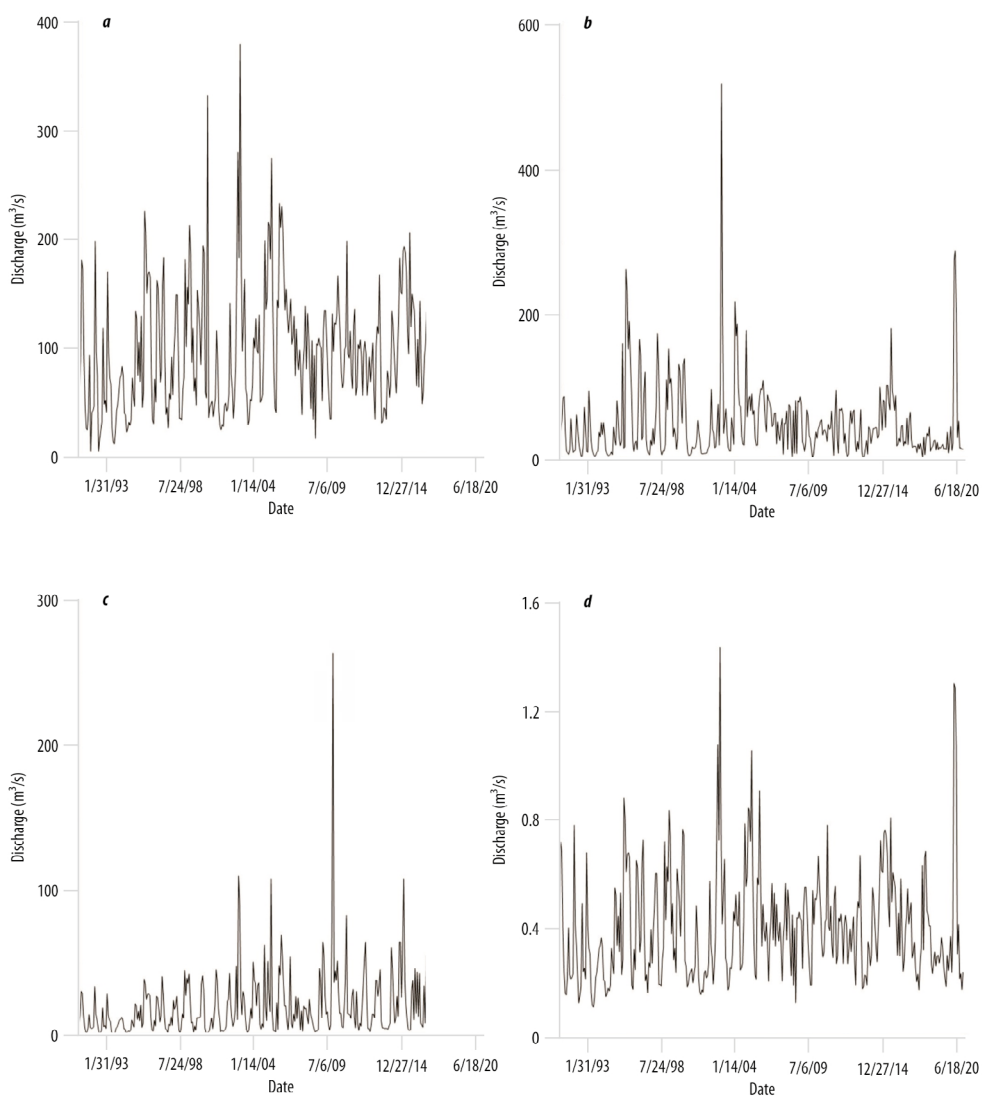


Fig. 2. The monthly maximum discharges of the investigated rivers: Vardar (a), Treska (b), Lepenac (c), and Serava (d). Source: Authors' own elaboration.

approximately $345 \text{ m}^3/\text{s}$ and $510 \text{ m}^3/\text{s}$, respectively, while the Lepenac and Serava rivers show comparatively lower magnitudes, peaking at around $260 \text{ m}^3/\text{s}$ and $1.4 \text{ m}^3/\text{s}$. Notable extreme events are visible around 2004 and 2020 across most rivers.

The time series data were plotted on probability paper, with points determined according to the Weibull formula. Subsequently, eight widely used probability distributions: Log-Normal (LN), Gamma (G), Pearson Type III (PIII), Log-Pearson Type III (LPIII), Gumbel

(GUM), Weibull (W), Generalized Extreme Value (GEV), and Pareto (Pr) (Table 2) were computed and employed for frequency analysis (VASILESKI, D. and RADEVSKI, I. 2014). The corresponding distribution lines were also plotted on probability paper for comparative analysis.

Furthermore, two statistical tests were applied to evaluate whether the empirical data followed the proposed theoretical distributions. The chi-squared (χ^2) test was utilized to determine if a sample originates from a specific distribution. However, it is important to recognize that the chi-squared test is not considered a high-power statistical test and has limited utility (TURHAN, N.S. 2020). This test depends on binned data, with the number of bins (k) determined by the following formula:

$$\chi^2 = \sum_{i=1}^n \frac{O_i - E_i}{E_i}, \tag{1}$$

where χ^2 represents Pearson’s parameter, O_i is the observed frequency of type i , n is the total number of observations, and E_i is the expected theoretical frequency of type i . To obtain the critical value for the χ^2 test, the degrees of freedom ($d = k - 1$), must be calculated, where k is the number of bins. The critical value is then referenced from the Pearson table. If the χ^2 statistic exceeds the critical value, the null hypothesis is rejected, indicating that the theoretical distribution does not adequately fit the empirical data (RADEVSKI, I. et al. 2016).

The Kolmogorov-Smirnov (K-S) test was employed to determine the best-fitting distribution, using the key parameter, maximum difference (D_{max}), between Weibull data points and each probability distribution (LEŠČEŠEN, I. et al. 2019, 2022; PETROVIĆ, A.M. et al. 2024). The K-S statistic for a given cumulative distribution function $F(x)$ is defined as

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

Distribution	Probability density function $f_{(y)}$	Quantile function $y(F)$
Log-Normal	$f_{(y)} = \frac{1}{y\sigma\sqrt{2\pi}} \exp\left(-\frac{(\ln y - \mu)^2}{2\sigma^2}\right)$	$y(F) = \exp(\mu + \sigma\Phi^{-1}(F))$
Gamma	$\frac{1}{\beta^\alpha \Gamma \alpha} (y - \mu)^{\alpha-1} \exp\left\{-\frac{(y - \mu)}{\beta}\right\}$	$y(f) = \Gamma^{-1}(k, F)$
Pearson III	$\frac{1}{\beta^\alpha \Gamma \alpha} (y - \mu)^{\alpha-1} \exp\left\{-\frac{(y - \mu)}{\beta}\right\}$	Explicit analytical form is not available
Log-Pearson III	$f(y) = \frac{1}{\sigma(y)\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left(\frac{y - \mu(y)}{\sigma(y)}\right)^2\right]$	$y(f) = \mu(y) + \sigma(y)x\left[Z + \frac{1}{2}\left(\frac{Z^2 - 1}{3}\right)\right]$
Gumbel	$\frac{1}{\alpha} \exp\left[-\frac{y - \mu}{\alpha} - \exp\left(-\frac{y - \mu}{\alpha}\right)\right]$	$\mu - \alpha \log(-\log F)$
Weibull	$f(y) = \frac{k}{\lambda} \left(\frac{y}{\lambda}\right)^{k-1} \exp\left(-\left(\frac{y}{\lambda}\right)^k\right)$	$y(F) = \lambda(-\ln(1 - F))^{1/k}$
Generalized Extreme Value (GEV)	$\frac{1}{\alpha} = \left[1 - k\left(\frac{y - \mu}{\alpha}\right)\right]^{\frac{1}{k}-1} \exp\left\{-\left[1 - k\left(\frac{y - \mu}{\alpha}\right)\right]^{\frac{1}{k}}\right\}$	$\mu + \frac{\alpha}{k} [1 - (-\log F)^k]$
Pareto	$f(y) = \frac{\alpha y_m^\alpha}{y^{\alpha+1}}$	$y(F) = y_m \left(\frac{1}{1 - F}\right)^{1/\alpha}$

Source: Compiled by the authors.

$$D_{max} = \max |F_s(xi) - F_t(xi)|, \quad (2)$$

where D_{max} represents the maximum difference between the empirical distribution function $F_s(xi)$ and the theoretical cumulative distribution function $F_t(xi)$. The K-S test evaluates the goodness of fit by comparing the maximum difference. If the observed D_{max} is greater than the critical value from the K-S distribution, the null hypothesis that the data follows the proposed distribution is rejected. This test is advantageous because it is non-parametric and does not depend on

binning the data, providing a more direct comparison of the empirical and theoretical distributions.

For the frequency analysis, we used Hydromon, a free software for analysing and processing hydrological data, mainly in the form of time series (KOZANIS, S. *et al.* 2005; RADEVSKI, I. *et al.* 2016). This software includes the Pythia module, which enables frequency analysis and generates probability papers with cumulative frequency distributions (Figure 3a, b) and testing with K-S and χ^2 tests, with calculating of possibil-

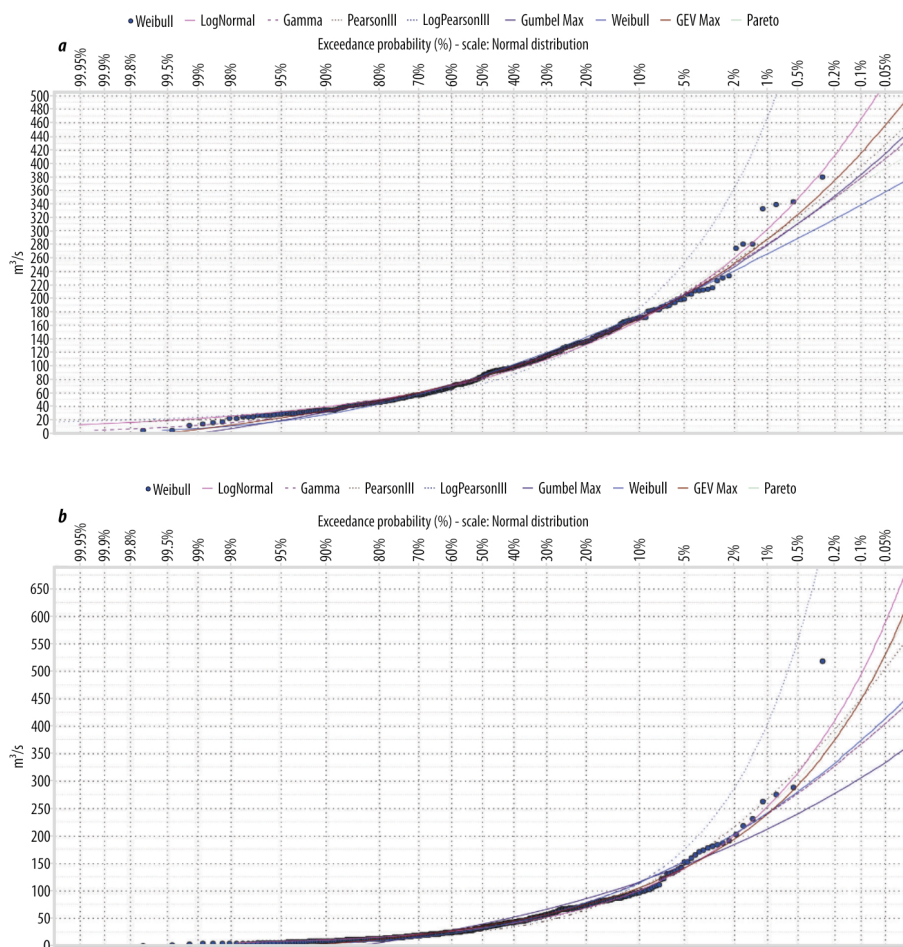


Fig. 3a. Probability paper with eight cumulative frequency distributions of monthly maximum discharge (m³/s) compared with Weibull plotted points at Vardar (a), and Treska (b) rivers. Source: Authors' own elaboration.

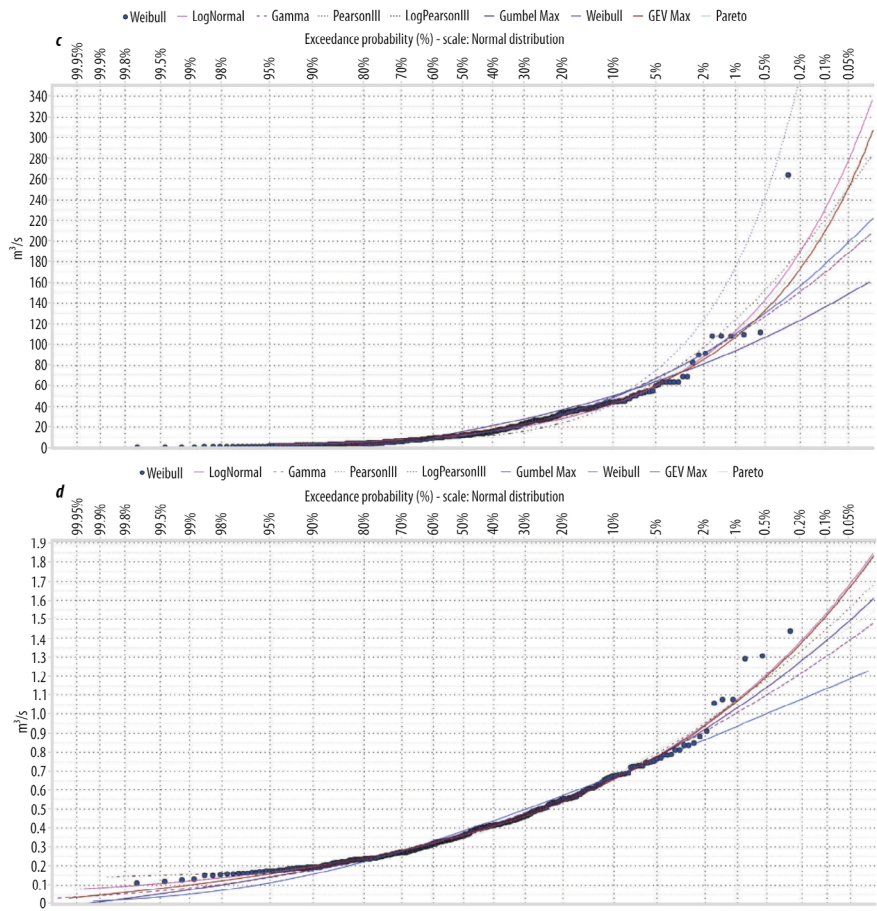


Fig. 3b. Probability paper with eight cumulative frequency distributions of monthly maximum discharge (m³/s) compared with Weibull plotted points at Lepenac (c), and Serava (d) rivers. Source: Authors’ own elaboration.

ity discharges according to four probability distributions, for return periods of 10, 20, 50, 100, 200 and 500 years. Estimating discharge values for high return periods is significantly challenging due to uncertainties from both the length of the data series and the chosen distribution shape parameter (Leščešen, I. et al. 2019). Consequently, caution is crucial, especially when estimating discharges for extended return periods like 1000 years (Leščešen, I. et al. 2022). Therefore, our analysis is limited to return periods of up to 500 years.

Results and discussion

This study evaluated several frequency distribution functions to estimate the return periods of major flood events in northern North Macedonia using annual maximum monthly discharge data from four hydrological stations for the period 1991–2020. The monthly runoff maxima showed considerable variation between the stations. The discharges of the selected stations follow a similar trend. The highest discharges at Vardar (380.00 m³/s), Treska (518.87 m³/s)

and Serava ($1.44 \text{ m}^3/\text{s}$) were measured in January 2003, while at Lepenac the highest discharge was measured in February 2018 ($111.60 \text{ m}^3/\text{s}$).

The monthly maximum discharges of the Vardar show a high variability with several significant peaks of over $300 \text{ m}^3/\text{s}$. These events occur at irregular intervals, suggesting episodes of heavy rainfall or snowmelt and a complex response to climatic and hydrological factors (see *Figure 2*). Similarly, the hydrograph of the Treska shows variable discharge patterns with remarkable peaks of almost $500 \text{ m}^3/\text{s}$, indicating that the river responds to extreme hydrological conditions. The frequent high discharges indicate significant flood events as recorded in 2010 (HEERINGEN, K.J. and BEKIC, D. 2022). In contrast, according to the visual observation, the hydrograph of the Lepenac shows more moderate discharge values, with peaks around $200 \text{ m}^3/\text{s}$. Finally, the hydrograph of the Serava shows the lowest discharge values with a peak value of about $1.2 \text{ m}^3/\text{s}$. The variability of the discharge is present, but less pronounced than in the larger rivers, which is due to the smaller catchment area. The lower discharge values and less frequent flood events indicate a relatively stable hydrological regime with occasional peaks, probably due to localized precipitation events. Together, these hydrographs provide a comprehensive overview of the hydrological behaviour of these four rivers and reflect the diverse climatic and hydrological influences in the region.

The analysis of the ten highest monthly discharges for the rivers Vardar, Treska, Lepenac and Serava shows clear seasonal patterns and historical trends. For the Vardar, the highest discharges occurred mainly in the hydrological winter (October to March), with six of the ten highest discharges recorded during this period. Notable winter events include January 2003 ($380 \text{ m}^3/\text{s}$) and November 2022 ($280 \text{ m}^3/\text{s}$). However, 2020 showed significant summer discharges in April, May, and June, indicating an

unusual peak in summer floods. The data for the Treska also shows that winter discharges predominate, with seven of the top ten events occurring between October and March. The highest recorded discharge was in January 2003 ($518 \text{ m}^3/\text{s}$). Like the Vardar, the Treska also had notable summer peaks in 2020 (April, May, and June), highlighting the anomalous hydrological activity of the year. The highest discharges of the Lepenac are mainly concentrated in the winter months, with nine out of ten peak events occurring between October and March. The highest discharge was measured in December 2009 ($264 \text{ m}^3/\text{s}$). Only one significant summer discharge was observed in May 2005 ($108 \text{ m}^3/\text{s}$). The Serava showed a more balanced distribution with five winter and five summer peak discharges. The highest discharge occurred in January 2003 ($1.4 \text{ m}^3/\text{s}$), and the year 2020 also stands out with three significant summer discharges (April, May, and June). Historically, a higher percentage of these maximum discharges occurred in the 21st century, reflecting possible shifts in hydrological patterns likely influenced by climate change and increased precipitation variability. The data from the Vardar and Treska rivers in particular, point to 2020 as a period of increased flood activity, indicating the need for further investigation of the underlying climatic and hydrological patterns driving these changes.

Flood frequency analysis (FFA) is an important technique for understanding and predicting the frequency and magnitude of flood events, which is essential for effective water resource management and risk reduction strategies. The core requirements of FFA and the fitting of probability distributions include criteria such as randomness, independence, stationarity, and skewness of the data series. Therefore, the initial phase of the study involved calculating basic statistics for the monthly maximum data series, which included the mean value, median, standard error, standard deviation, skewness, and kurtosis for four gauging stations.

The results of these calculations are detailed in Table 3.

In subfigure (a) of Figure 4, which represents the Vardar, it can be seen that the Log-Normal, Gamma, Pearson III, and Log Pearson III distributions closely match the Weibull points, especially in the lower and middle range of discharge values. At higher discharge values, however, there is a clear deviation, especially for the Pareto and Gumbel distributions, which tend to overestimate

extreme discharges. This suggests that while multiple distributions can adequately model the central tendency of the data, accurately capturing the extreme values is a major challenge. Sub-figure (b), representing the Treska, shows a similar pattern, with the Log-Normal and Gamma distributions providing a reasonable fit for most discharge values. However, the Pareto distribution again overestimates the highest discharges, illustrating its tendency to predict more fre-

Table 3. Descriptive statistics of monthly maximum discharges of the four rivers in the North Macedonia

River	N	Mean, m ³ /s	Median, m ³ /s	Standard error	Standard deviation	Kurtosis	Skewness
Vardar	360	95.40	84.20	3.07	58.41	0.88	1.44
Treska	360	48.82	33.49	2.75	52.23	0.68	3.47
Lepenac	360	20.06	12.45	1.24	23.58	0.62	4.27
Serava	360	0.40	0.36	0.01	0.19	0.89	1.51

Source: Compiled by the authors.

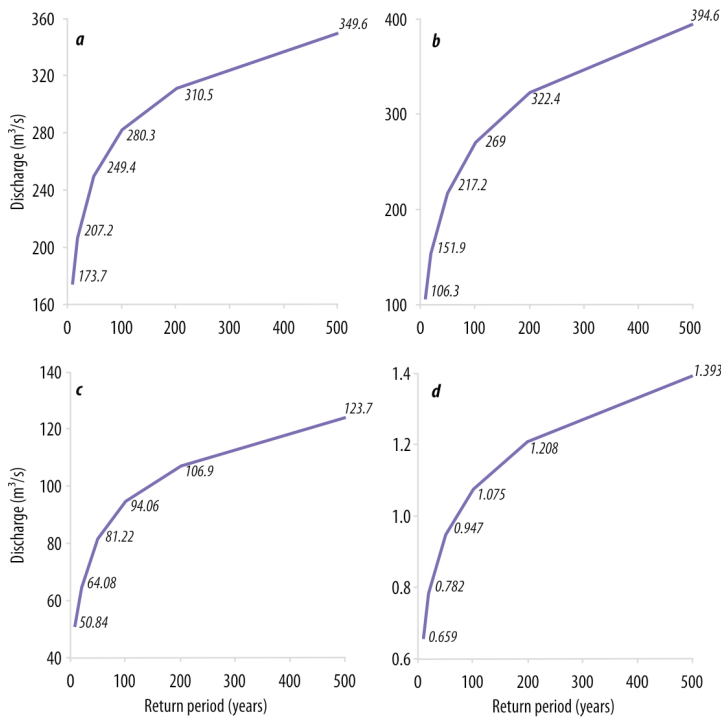


Fig. 4. Quantiles estimated for various return periods at the selected gauging stations. Source: Authors' own elaboration.

quent extreme events compared to empirical observations. The GEV and Log-Pearson III distributions provide a better fit for higher discharge values compared to the Pareto distribution. In subfigure (c) for the Lepenac, the discharge values are generally lower than for the Vardar and Treska rivers. The Log-Normal and gamma distributions show a good fit over the entire range of observed values. The discrepancies at higher discharge values are less pronounced, indicating a rela-

tively stable and less variable hydrological regime for the Lepenac. Finally, subfigure (d) for the Serava, which has the lowest discharge values, shows that the log-normal distribution has a good fit to the Weibull points over the entire range of discharges. This indicates that the log-normal distribution is particularly effective in modelling the hydrological behaviour of smaller rivers with less variability in discharge values (Table 4).

Table 4. χ^2 test and Kolmogorov-Smirnov test for eight theoretical functions

River	Distribution	χ^2 test		Kolmogorov-Smirnov (K-S) test	
		Attained α , %	Pearson parameter	Attained α , %	D_{max}
Vardar	Log-Normal	5.02	14.055	26.50	0.053
	Gamma	44.05	6.889	92.95	0.029
	Pearson III	60.93	4.500	60.09	0.040
	Log-Pearson III	0.00	32.667	0.20	0.098
	Gumbel	2.51	16.000	55.41	0.041
	Weibull	0.25	22.000	23.01	0.055
	GEV	24.22	7.944	63.34	0.039
	Pareto	3.88	13.278	25.00	0.419
Treska	Log-Normal	9.44	46.389	18.41	0.058
	Gamma	0.01	74.467	0.11	0.102
	Pearson III	100.00	1142.480	12.00	0.219
	Log-Pearson III	5.10	48.500	11.45	0.063
	Gumbel	1.08	191.633	11.60	0.172
	Weibull	0.19	64.122	0.31	0.095
	GEV	0.00	83.756	0.36	0.094
	Pareto	36.38	36.256	0.00	0.138
Lepenac	Log-Normal	0.01	75.522	2.72	0.077
	Gamma	0.00	85.233	0.02	0.113
	Pearson III	100.00	1824.160	6.86	0.278
	Log-Pearson III	0.29	61.167	25.81	0.053
	Gumbel	65.86	247.367	7.01	0.193
	Weibull	0.03	71.089	0.37	0.093
	GEV	10.00	103.178	0.06	0.106
	Pareto	26.25	38.789	5.97	0.069
Serava	Log-Normal	14.00	44.067	79.47	0.034
	Gamma	2.11	53.989	34.63	0.049
	Pearson III	48.12	33.722	51.07	0.043
	Log-Pearson III	10.36	44.700	73.75	0.036
	Gumbel	4.26	50.611	50.23	0.044
	Weibull	0.01	75.733	2.55	0.078
	GEV	11.57	44.067	62.23	0.039
	Pareto	0.00	89.878	0.00	0.349

Source: Compiled by the authors.

Selecting the most appropriate statistical distributions for hydrological data is crucial for accurate modelling and analysis. In this study, several distributions are evaluated using the χ^2 and Kolmogorov-Smirnov (K-S). In the following section, the best-fitting distributions for each river are discussed and supported by the statistical values of both tests. For the Vardar, the Gamma distribution is identified as the best fit. This conclusion is based on the achieved α -values and D_{max} values from the χ^2 and K-S tests. The Gamma distribution has an achieved α of 44.05 percent in the chi-square test, indicating a good fit. It also has the highest achieved α of 92.95 percent in the K-S test with a D_{max} value of 0.028, the lowest among all distributions tested. These results indicate that the Gamma distribution is closest to the empirical data and is the most reliable fit for the Vardar flow. These results are in contrast with previously published results which have shown that according to the both K-S and χ^2 tests, the best-fitting distribution for the Vardar is the Log-Normal distribution (RADEVSKI, I. and GORIN, S. 2017).

There are four possible reasons for this divergence; first, the length of the data series as the author of the earlier study is the 1971–2005 period compared to 1991–2020 used in the present one, second, the previous study used annual maximum discharge data while in this study monthly maximum discharge data was used, and thirdly, in the previous study, a total of five distribution functions were used (excluding the Gamma), while in this study eight distributions were used (including Gamma), and finally, the difference between two gauging stations on the Vardar used, with gauging station Demir Kapija (previous study) being located approximately 112 km to downriver from Skopje station that was used in this study.

In the case of the Treska flow, the Pearson III distribution stands out as the best fit. The χ^2 test shows an achieved α of 100.00 percent, indicating an excellent fit. Although the D_{max} value is not given in the K-S test, the perfect

result in the chi-square test strongly suggests the suitability of the Pearson III distribution for this data set. This distribution effectively reflects the statistical characteristics of the data and is, therefore, the optimal choice for modelling the first data set of the Treska flow.

For the Lepenac, the Gumbel distribution is considered the best fit. This distribution has an achieved α of 65.86 percent in the χ^2 test, which is a good fit. Although no specific α values are given for the K-S test, the balance between the chi-squared test results and the D_{max} value (0.193) suggests that the Gumbel distribution fits the data well. Its robust performance in the chi-squared test makes it a reliable model for the second data set of the Lepenac.

The log-normal distribution is the best-fitting distribution for the Serava. The results of the chi-square test show an achieved α of 14.00 percent, which is moderate but acceptable. However, the results of the K-S test provide strong support for this distribution, with an achieved α of 79.47 percent and the lowest D_{max} value of 0.034 among all distributions tested. These values indicate that the log-normal distribution closely matches the observed data and is therefore the best-fitting model for the Serava. Together, these results illustrate the importance of using multiple statistical tests to determine the best-fit distribution for hydrological data to ensure accurate and reliable modelling for each river.

The return period analysis reveals increasing discharge values for various return periods across the Vardar, Treska, Lepenac, and Serava rivers. These findings highlight the necessity of precise probability distributions in estimating extreme flood magnitudes, which are essential for effective risk management strategies in the northern regions of North Macedonia.

Analysing the seasonal flooding frequency of rivers is crucial for effective water resources management, flood risk mitigation and climate resilience (Yu, X. *et al.* 2015). As shown in Figure 2, significant seasonal fluctuations can be observed in these rivers as a result of seasonal variations in precipita-

tion and temperature, leading to differences in the frequency and magnitude of floods. Understanding these seasonal dynamics is crucial for the prediction of extreme hydrological events. Winter maximum discharges are often caused by snowmelt in combination with rainfall, while summer floods are caused by intense, short-duration rainfall.

This analysis identifies vulnerable periods, informs climate adaptation strategies, and helps in the design of hydraulic structures and land use planning to ensure socio-economic stability and environmental sustainability in North Macedonia. The comparative analysis of the best-fit distributions for these rivers shows significant seasonal variations, which underlines the need for a seasonal analysis of flood frequency for accurate hydrological modelling (see *Appendix*).

The seasons are defined as hydrological winter (from October to March) and hydrological summer (from April to September). For the Vardar, the Pearson III distribution is most appropriate for both winter and summer. In winter, it reaches an χ^2 significance level of 19.17 percent, with a Pearson parameter of 20.67 and a K-S test D_{max} of 0.05. In summer, it remains robust with an χ^2 test significance level of 36.38 percent, a Pearson parameter of 17.34, and a K-S test D_{max} of 0.04, confirming a high fit (98.23% for the K-S test). For the Treska, the Gamma distribution is the best fit for winter, as evidenced by a significance level of 88.17 percent in the χ^2 test, a Pearson parameter of 10.49, and a K-S test D_{max} of 0.05. In summer, the Pearson III distribution is more suitable, with an χ^2 test significance level of 28.62 percent, a Pearson parameter of 18.67, and a K-S test D_{max} of 0.04. In winter, the Lepenac flow shows a strong preference for the Pearson III distribution, which achieves an χ^2 test significance level of 100.00, a Pearson parameter of 397.56, and a K-S test D_{max} of 0.19. In summer, the Gamma distribution is more suitable, with an χ^2 test significance of 3.16 percent, a Pearson

parameter of 29.33, and a K-S test D_{max} of 0.06. For the Serava, the Log-Pearson III distribution performs excellently in the winter season, with a K-S test significance level of 44.60 percent and a D_{max} of 0.06. In summer, the log-normal distribution is the most suitable, with an χ^2 test significance of 37.50 percent, a Pearson parameter of 18.22, and a K-S test D_{max} of 0.04. *Table 5* presents the obtained results of the seasonal theoretical maximum discharges using of best-fit seasonal theoretical probability distributions.

Table 5 provides a comprehensive overview of the theoretical discharges for different return periods on these four rivers. In particular, seasonal and annual data are compared (see *Figure 4*), which highlights the importance of considering seasonal variations in

Table 5. Theoretical discharges for various return periods according to best-fit seasonal probability distributions

River		Vardar		Treska	
Season		Summer	Winter	Summer	Winter
Distribution		PIII	PIII	PIII	Gamma
Return period	10	171.89	174.53	99.84	128.82
	20	210.19	207.401	134.02	171.03
	50	259.66	249.03	180.51	227.42
	100	296.48	279.58	216.35	270.37
	200	332.92	309.54	252.60	313.52
	500	380.641	348.43	301.01	370.78

River		Lepenac		Serava	
Season		Summer	Winter	Summer	Winter
Distribution		PIII	PIII	PIII	Gamma
Return period	10	36.98	60.138	0.65	0.68
	20	47.61	82.12	0.78	0.79
	50	61.58	111.91	0.95	0.95
	100	72.11	134.83	1.09	1.06
	200	82.62	157.98	1.23	1.17
	500	96.48	188.85	1.43	1.31

Source: Compiled by the authors.

the FFA. Due to the hydrological regime of the rivers, the calculated discharges in the winter season are higher than the calculated discharges when the monthly maximum discharges for the whole year are used for the calculations, especially when the discharges of the 10-, 20- and 50-year return periods are observed. On the other hand, the calculated discharges for the 200- and 500-year return periods are larger if the entire data set is used and the seasonal values are disregarded. This statement applies to the rivers Vardar, Treska and Serava, while the results for the Lepenac show that the calculated discharges based on the winter season data are much larger than the data obtained from the entire data set. The reason for this can be found in the different climate types in the northern part of the Lepenac river basin, which is under the influence of the Sub-Mediterranean climate. In general, the results presented in *Table 5* underscore the imperative of incorporating seasonal variations into FFA methodologies as well. Doing so not only enhances the precision of flood risk assessments but also underpins the development of robust flood management strategies, crucial for fostering environmental sustainability and community resilience in the face of evolving climatic conditions. As the main goal of FFA is to determine discharge values with a larger return period, it can be concluded that, even though seasonal analysis provides valuable information, the data for the whole year should be used.

Looking at the seasonal variations, winter and spring are expected to be wetter as precipitation will increase by 20 mm due to higher temperatures, as shown by the CC equation. These results indicate that climate change is the primary factor influencing the observed changes in flood events, with statistically significant increasing trends in winter and summer precipitation over North Macedonia (GJEŠOVSKA, V. *et al.* 2022). The results of various global climate models (GCM) predict that North Macedonia will experience an increase in air temperature

in summer compared to the winter season by 2050 (MONEVSKA, S.A. 2011), which will likely lead to more intense precipitation as warmer air can hold more moisture (LIU, J. *et al.* 2019). The CC relationship shows that daily precipitation intensity increases by around 7 percent per °C increase in ambient temperature (BLÖSCHL, G. *et al.* 2019; TABARI, H. 2020). This correlation is supported by observational data and modelling experiments (WESTRA, S. *et al.* 2013; O'GORMAN, P.A. 2015), both of which have tested the CC scaling hypothesis at different spatial and temporal scales. An analysis of air temperature in North Macedonia from 1926–2020 found that the last decade of the 20th century and the beginning of the 21st century were the warmest periods, with the last 14 consecutive years (2007–2020) showing the highest annual air temperatures (UHRM 2021). In North Macedonia, annual precipitation maxima have also increased over the last 65 years (GJEŠOVSKA, V. *et al.* 2022), while the analysis of seasonal precipitation indicates a negative trend in the winter and summer months (RADEVSKI, I. *et al.* 2024) and maximum discharges occur mainly in winter. Overall, the number of wet days has decreased in the Mediterranean region, including North Macedonia (ANDRÉ, J.C. *et al.* 2023), suggesting that a redistribution of precipitation has taken place, mainly the same or a lower monthly amount of rain in a shorter period of time.

Since the beginning of the 21st century, cyclonic activity in Europe has increased, leading to more frequent heavy rainfall (ARAGÃO, L. and PORCÙ, F. 2022; BERÉNYI, A. *et al.* 2023). An unusually high number of Mediterranean cyclones were observed in South Europe in the winter of 2012–2013 and spring of 2013 (KOUROUTZOGLOU, J. *et al.* 2011). These cyclonic events caused flooding in North Macedonia between 23 and 26 February 2013, damaging and breaching several dams, damaging agricultural fields, roads, railroad lines, and houses. Changes in these circulation patterns are likely to have an impact on rainfall totals

and significantly affect river flows and water levels. Further research is needed to investigate the relationship between circulation patterns, flood frequency, flood extent, and topography (NIED, M. *et al.* 2014). The results of this study underline the importance of a thorough analysis of changes in flood behaviour for flood planning and risk management (PETROW, T. and MERZ, B. 2009). Overall, North Macedonia faces increasing risks from climate change, including higher temperatures and changing precipitation patterns, which could further increase the likelihood of natural hazards such as flooding and forest fires (IMF 2024).

The study provides important insights to improve the resilience of energy infrastructure to flooding and supports better planning and design. Policymakers can use this information to develop strong flood protection policies to cope with increasing extreme flood events. The financial sector, including insurance companies and investors, can use these insights to manage evolving flood risks and guide investment strategies and risk assessments. In terms of environmental, social, and governance (ESG) policies, the study improves the understanding of the environmental impacts of climate change-induced flooding, helping to develop sustainable strategies. Overall, this research bridges the gap between scientific knowledge and practical applications and promotes informed decision-making and climate resilience.

While this study offers valuable insights into flood frequency analysis in the northern region of North Macedonia, it is important to acknowledge certain limitations. Firstly, the study's focus on the northern part of the country means that the results may not be applicable to other regions. Additionally, while the research provides an understanding of temporal and seasonal FFA, it does not explore the detailed mechanisms or causes behind the observed changes. Moreover, projections and implications for future flood events are not explicitly addressed, so caution should be exercised when generalizing

these findings to predict future hydrological scenarios. Despite these limitations, the study establishes a foundation for further research and highlights the need for a nuanced understanding of extreme flood dynamics in the context of climate change.

Conclusions

In this study, a comprehensive flood frequency analysis was conducted for the Vardar, Treska, Lepenac and Serava rivers in North Macedonia, using different probability distributions to estimate extreme flood heights. The analysis covered the period from 1991 to 2020 and the main objective was to identify the best-fitting distributions for each river in order to improve the accuracy of flood forecasts, which are crucial for effective water resource management and risk mitigation strategies.

The results showed that the Pearson III distribution provided the best fit for the Vardar, as evidenced by the better results of the chi-square and Kolmogorov-Smirnov tests. For the Treska, the Pareto distribution proved to be the best fit, while the Weibull distribution provided the best fit for the Lepenac. The discharge data of the Serava were best described by the log-normal distribution. These findings are crucial as they highlight the variability and complexity of hydrological responses across different rivers in the region, necessitating tailored approaches for flood risk assessment and management.

These results are of crucial importance as they highlight the variability and complexity of hydrological responses in the different rivers of the region, requiring tailored approaches to flood risk assessment and management. The analysis revealed significant discharge peaks in all rivers, with the Vardar and Treska rivers showing the most extreme variability, likely due to their larger watersheds and more dynamic hydrological systems. The Lepenac and Serava rivers had lower discharge values, but still showed

episodic high discharge events, emphasizing the importance of localized precipitation events and the dynamics of smaller catchments.

The seasonal FFA for the Vardar showed that the Pearson III distribution is most suitable for both winter and summer and achieves high significance levels in the χ^2 and K-S tests. The Treska requires the Gamma distribution for winter and Pearson III for summer, while the Lepenac shows a preference for Pearson III in winter and Gamma in summer. The best-fitting distribution for determining winter season discharges for the Serava is the Log-Pearson III distribution and Log-Normal in summer. Table 5 reveals that winter discharges are generally higher than annual discharges for shorter return periods, but for longer return periods, annual data yields higher discharges except for the Lepenac, influenced by its Mediterranean climate.

Results presented in this study underscore the necessity of accurate probability distributions in estimating extreme flood magnitudes. This information is crucial for designing effective flood mitigation infrastructure, helping stakeholders make well-informed decisions, and establishing and implementing emergency response strategies. As the frequency of extreme weather events is expected to increase due to climate change, the results of this study are particularly valuable for increasing the resilience of North Macedonia's water management systems.

Overall, the tailored FFA approach adopted in this study provides a robust framework for understanding and predicting flood risks in North Macedonia. The adoption of best-fitting probability distributions for each river not only improves the accuracy of flood forecasts but also supports the development of targeted risk management strategies. These contributions are vital for safeguarding communities, protecting infrastructure, and ensuring sustainable water resource management in the face of future climatic uncertainties.

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Appendix

Seasonal flood frequency analysis of the four rivers: Best-fit distributions according to χ^2 and Kolmogorov-Smirnov test

Vardar								
Distribution	Winter season				Summer season			
	χ^2 test for		Kolmogorov-Smirnov test		χ^2 test for		Kolmogorov-Smirnov test	
	Attained α , %	Pearson parameter	Attained α , %	D_{max}	Attained α , %	Pearson parameter	Attained α , %	D_{max}
Log-Normal	8.29	25.5556	26.17	0.07512	4.30	28.1713	50.68	0.06119
Gamma	1.82	31.3333	65.58	0.05464	77.02	12.4807	94.23	0.03932
Pearson III	19.17	20.6667	76.40	0.04977	36.38	17.3425	98.23	0.03452
Log-Pearson III	2.18	29.3333	2.00	0.11309	11.73	22.8674	16.16	0.08336
Gumbel	0.25	38.0000	35.82	0.0690	28.60	19.7735	62.56	0.05582
Weibull	0.20	38.6667	37.57	0.06801	0.81	34.1381	49.02	0.06198
GEV	2.47	28.8889	34.82	0.06958	42.14	16.4586	97.81	0.03525
Pareto	15.05	21.7778	–	0.47942	5.78	25.7403	0.37	–
Treska								
Log-Normal	34.79	18.6685	53.76	0.05976	0.04	43.8619	8.22	0.09390
Gamma	88.17	10.4917	85.66	0.04502	24.20	20.6575	83.82	0.04601
Pearson III	0.52	34.1381	21.04	0.07885	28.62	18.6685	97.33	0.03597
Log-Pearson III	1.83	29.9392	1.37	0.11736	0.18	37.4530	9.53	0.09170
Gumbel	5.71	27.0663	30.19	0.07221	0.06	42.5359	8.33	0.09370
Weibull	24.20	20.6575	70.15	0.05246	0.81	34.1381	51.97	0.06059
GEV	42.14	16.4586	99.58	0.03062	0.21	37.0110	49.67	0.06167
Pareto	1.72	30.1602	–	0.30591	13.00	22.4254	0.02	0.16069
Lepenac								
Log-Normal	1.94	31.1111	21.85	0.07840	–	86.0000	0.02	0.15900
Gamma	0.00	54.4444	0.02	0.16031	3.16	29.3333	48.52	0.06239
Pearson III	100.00	397.556	0.00	0.18622	2.32	29.1111	51.10	0.06116
Log-Pearson III	12.94	22.4444	49.99	0.06169	0.00	49.7778	5.60	0.09966
Gumbel	0.00	148.0000	–	0.22026	–	82.2222	1.34	0.11795
Weibull	0.05	42.6667	0.29	0.13463	6.31	26.6667	56.80	0.05855
GEV	10.00	72.8889	0.07	0.14823	0.00	61.5556	14.09	0.08583
Pareto	0.44	34.6667	18.07	0.08170	4.81	26.4444	57.15	0.05838
Serava								
Log-Normal	4.76	27.7778	44.58	0.06432	37.50	18.2222	94.07	0.03957
Gamma	0.06	42.4444	55.94	0.05893	1.32	32.4444	34.97	0.06949
Pearson III	4.27	26.8889	48.57	0.06237	14.32	22.0000	81.07	0.04754
Log-Pearson III	–	–	44.60	0.06431	–	–	92.58	0.04077
Gumbel	2.63	30.0000	40.45	0.06645	1.41	32.2222	40.63	0.06636
Weibull	0.01	48.4444	21.11	0.07901	0.11	40.4444	7.39	0.09572
GEV	0.76	32.8889	36.02	0.06889	6.06	25.5556	84.28	0.04589
Pareto	1.48	30.6667	–	0.25025	4.03	27.1111	–	0.27701

Source: Compiled by the authors.