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Analysis and Evaluation of the Maximum Runoff Formed in the River Basin of the Arda River to the Dam Wall of the Kardzhali Dam in Bulgaria

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Abstract: The current study tracks the change in the maximum outflow formed in the watershed of Kardjali dam, which is among the complex and nationally significant dams in Bulgaria and is subject to annual monitoring by the Ministry of environment and waters (MOEW). The maximum runoff is an extreme hydrological phenomenon with spatio-temporal variation, the exact determination of which requires in-depth knowledge of hydrographic, climatic, soil, vegetation conditions, as well as anthropogenic factors for each individual region. Investigating it in a certain territory during the operation of hydrotechnical facilities has been a current topic in recent decades. The purpose of the present study is to track the change in the maximum runoff in Arda River catchment to Kardzhali Dam for the period 1961-2021, which also includes the period recommended by the World Meteorological Organization (1961-1990). GIS database was created as a basis for analyzing the results, containing information from the soil map of Bulgaria 1968, land cover from Corine 2012, JICA project finished in 2005. As for the estimation of the maximum runoff information array of hydrometric data observed in hydrometric station 315/61700 on Arda River and data from the operation of Kardzhali Dam has been used for the purposes of the present study. The study shows that with proper management of the reservoir, there is no danger of flooding the surrounding terrain after the dam wall. The research contributes to improving the process of monitoring on the maximum outflow to the Kardzhali Dam and supports decision-making by the responsible institutions in the management of water volumes in the dam lake cup when a high wave occurs.

Keywords: Maximum runoff, Statistical analysis, Hydrometric data, GIS

Introduction

The study of the maximum runoff in a given territory and certain river basins has been an actual task in recent decades. The changes in its parameters have been subjected to additional analyzes and evaluations in consideration of climate changes, which in some cases have led to significant changes in its regime. This new challenge of engineering hydrology has led to searching for solutions on application of new computational procedures, such as mathematical modeling methods, use of analog stations, satellite observations, etc (Nedkov R. et al., 2020). Through the application of these methods and approaches, it is aimed that the maximum runoff and its parameters reach maximum correlation with the processes and phenomena that form it. With the manifestation of climate changes and with the often realized high water in the riverbeds, it is mandatory to apply the above-mentioned methods for recalculation and analysis of the maximum runoff formed within the studied watershed.

The analysis of the maximum outflow is based on the collected data in the hydrometric stations located along Arda River. The accepted period for the analysis of the maximum runoff is from 1961 until 2021, including the reference period from 1961 to 1990 adopted by the World Meteorological Organization (2017 edition, WMO-

- Selection and peer-review under responsibility of the Organizing Committee of the Conference

№1203). The calculation and formation of a hydrological series of maximum water quantities to the retaining wall of the Kardzhali dam is based on interpolation dependencies (Murdock & Gulliver, 1993), derived on the basis of maximum outflow data collected in the hydrometric stations built in the river system of the studied catchment and on data about the maximum volumes realized in the dam. The range of maximum runoff values is analyzed using non-parametric criteria for uniformity, representativeness and significance to confirm the homogeneity of the study area. Through the apparatus of mathematical statistics, the theoretical approximation of the empirical points of the hydrological order is presented and maximum water quantities with characteristic security are calculated, based on which the volume of the high wave in the water reservoir is determined. The results of the study will be of benefit for the responsible institutions to make decisions and undertake management actions for the appropriate operation of the reservoir and for maintaining the ecological balance in the area of the dam wall.

Studied Area

The present study covers the catchment of Arda River from its originating points to Kardjali Dam. The river basin is developed entirely on the territory of the country, in the south-eastern part of the Eastern Rhodopes, within the borders of the Eastern White Sea Basin Water Management Region. The catchment of Arda River borders to the north and northwest with the catchment basin of Maritsa River, to the south and southwest with our border with Greece, to the east and southeast with the catchment of Varbitsa River. The river basin is oriented from southwest to northeast and is localated in the mountain and mid-mountain hypsometric belt (Figure 1).

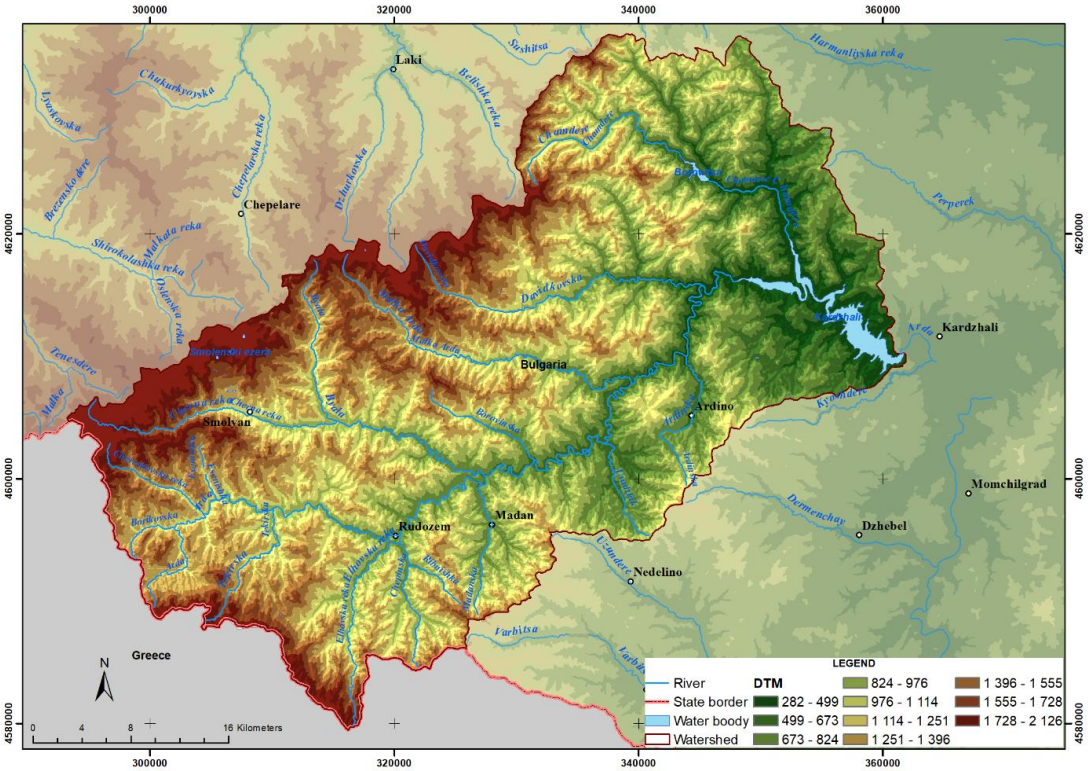

Figure1. Relief, river network and hydrometric stations in Arda river basin

The Arda River, in the section from the springs to "Kardjali" dam, forms its outflow through a well-developed river network located on the Prespa section of the Western Rhodopes and the northwestern slopes of the Yellow section of the Eastern Rhodopes. A characteristic feature of the river network's watershed is the deep valleys and steep slopes along which the river's outflow is formed with slopes reaching up to 40°. Along the length of the river section within the studied watershed, several expansions in its river bed appear, as well as mountain meanders in the area of the town of Rudozem. The section of the studied watershed falling in the foothills of the river course enters a deep, rocky and difficult-to-navigate gorge, from which it exits after the area of the Devil's Bridge (Sheitan cuprue). In this area, the gradients of the catchment slopes reach up to 45°, and the river bed reaches a width of 50 to 60 m. Its right slopes are forested with broad-leaved forests, and the left slopes are bare and collapsed by screes as shown in figure 2.

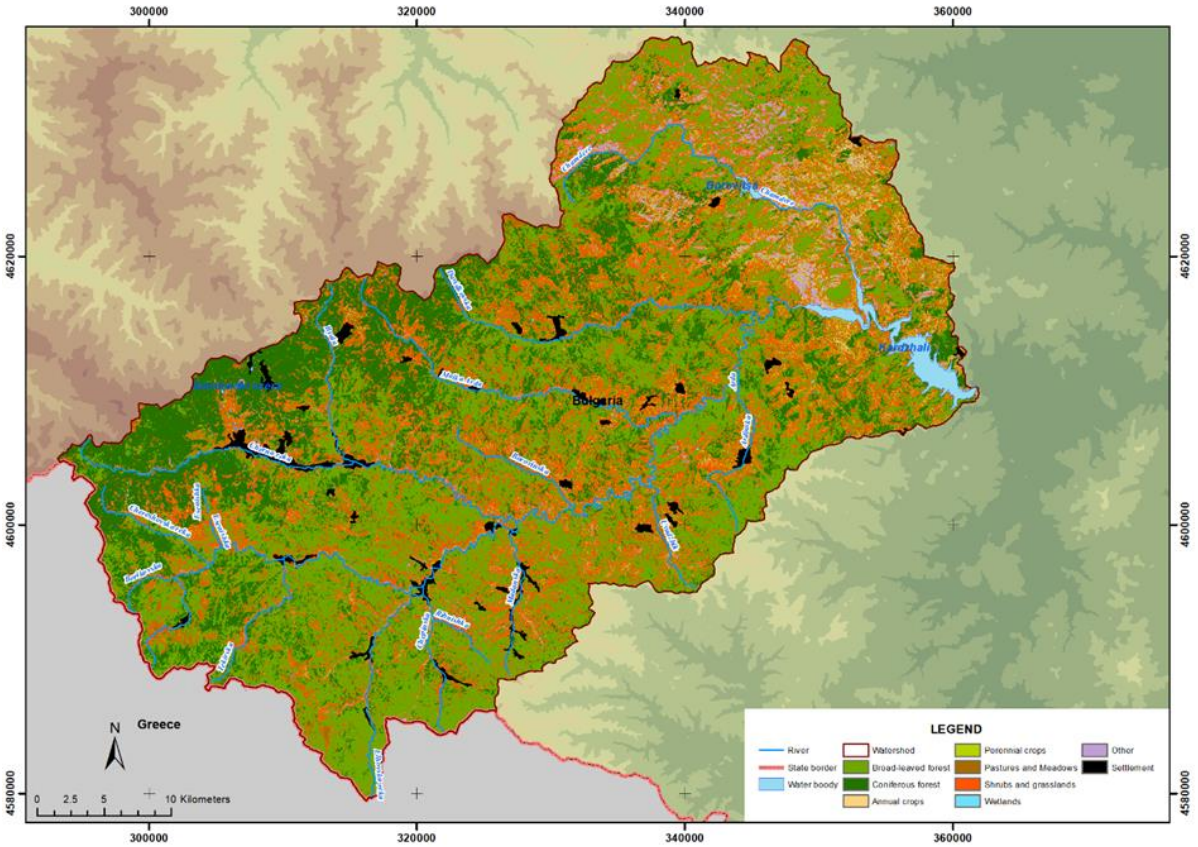

Figure 2. Land cover within the study watershed.

The main orographic characteristics of the studied watershed to Kardzhali Dam determined by GIS are presented in Table 1.

Table 1. Orographic characteristics of the studied area

River	Catchment area	Average altitude	River length	Average river slope	Average catchment slope	River network density	Forestry	Lake area incl. peatlands
-	A km^2	H m	L km	‰	Ir ‰	km^{-1}	%	%
Arda river to Kardjali Dam	1882,0	997	134,0	9.6	328	1.53	35.4	0.32

According to the classification of water bodies that have main characteristics of the river system and water bodies accepted by the Ministry of Environment and Water the surveyed watershed of this section of Arda River falls into a surface water body with code BG3AR500R020 and type code R5 (MOEW, 2016-2021).

Materials and Methods

The methodology in the present study includes determination of sustainable physicogeographical parameters, such as boundaries of the catchment basin of the dam, area, and altitude, analysis and evaluation of the data from the available monitoring system for the formation of hydrological series from maximum values of the river runoff for the surveyed area and application of a suitable mathematical apparatus for statistical processing of the data arrays for the maximum runoff (Mamdouh Sh. et al., 1993) with a view to achieving results as close as possible to the real runoff regime.

The watershed outline of the river basin and its orographic features are generated in a GIS environment using the Geospatial Hydrologic Modeling Extension (HEC-geoHMC) model. (Feldman, 2000). The model precisely and reasonably determines the orographic parameters for each specific catchment basin (Baumbach et al, 2015).

The work of the algorithm implementing the model is the verification of the input data for a digital model of the relief and the generation of raster layers, necessary for the more accurate formation and reporting of the river outflow in the specific basin (Modev & Kirilova, 2013).

The materials on which the present study was carried out are the arrays of data on the flow regime of the river within the studied watershed collected at the specific hydrometric stations from the national reference hydrometric network. These materials are determined by the number of hydrometric points and programs for monitoring and measuring runoff parameters performed with the appropriate discretization. The hydrometric stations in the watershed are presented in Table 2 and Figure 1.

Table 2. Hydrometric station from the main monitoring network of Bulgaria.

Hydrometric station N	Opening/ Closing year	River	Settlement	Catchment basin area	Average altitude	Average slope of the water basin	River length	Average River slope	River network density	Forestry
-	- / -	-	-	km^2	m	‰	km	‰	km^{-1}	%
320	1950/ 1956	Arda	Rudozem	257.7	1162	288	37.15	20.6	1.53	35.4
346/ 61330	1950/	Elhovska	Rudozem	83.9	1147	362	18.95	47.0	1.65	32.3
322/ 61050	1953/ functioning	Byala	Bostina	52.9	1293	385	12.12	51.3	1.56	52.2
322A	1950/1953	Byala	Smolyan Ustovo	66.0	1250	379	16.80	47.7	1.62	57.5
319/ 61350	1951/ functioning	Cherna	Taran	242.1	1280	348	39.35	30.8	1.93	32.2
315/ 61700	1952/ 1955/ functioning	Arda	Vehtino	857.4 858.4	1209 1172	315 332	66.65 66.90	13.5 13.5	1.69 1.69	53.5 53.5
315A	1949/1952	Arda	Stoyanov bridge	870.0	1166	329	72.6	12.9	1.76	55.0
314/ 61400	1949/ functioning	Malka Arda	Banite	114.0	1172	352	30.54	34.2	2.02	56.5
316	1949/1958	Arda	Prileptzi	1899.50	992	328	132.8	9.15	1.65	40.0
140	1932/1950	Arda	Kardjali	1987.94	969	325	138.2	8.90	1.62	40.0

The scope of the study is focused on studying the regime and in general the fluctuations of the maximum runoff by evaluating the information arrays of the maximum runoff obtained as data from the individual hydrometric stations when applying analyzes through mathematical statistics covering the verification of representativeness, uniformity and significance of the hydrometric data. Determining the forming high waters and approaches to Kardzhali dam.

After 1970, regular observations of the outflow of Arda River have been carried out at Kardzhali dam wall point. These observations are processed by means of the balance equation of the dam and allow the determination of average daily water quantities with high accuracy between 1 - 3 %. It is not possible to determine instantaneous (extreme) water quantities by means of the measuring system of Kardzhali dam. They can be calculated by means of interpolation dependencies or by transferring terms from the hydrological series of neighboring stations. The formed hydrological order of maximum water quantities to Kardzhali dam was compiled by means of interpolation and by the volumes of high waves during simultaneous observations in stations located "above" and "below" the research point and by transferring water quantities using established in practice ratios between runoff modulus and catchment area (Sabahattin Isik et al , 2008).

The methodology used in carrying out the analysis and the information array of data created by it for the maximum outflow of Arda River to Kardzhali dam are based on the main criteria used in mathematical statistics for checking and validation of the information array, through non-parametric criteria for homogeneity, representativeness and significance of the hydrological order of maximum water quantities. To analyze the homogeneity of the time series of maximum values of the river runoff, the non-parametric criteria of Pettitt's test, Buishand's test, Standard normal homogeneity test (SNHT) and von Neumann's test two-sided limited and with a confidence probability of 5% are applied (Naghettini, 2017; Kirilova, 2019).

To analyze the representativeness of the hydrological order, the non-parametric Mann-Whitney criterion is applied, which asserts that two parts of the hydrological order belong to the same general aggregation. The advantage of the criterion is that no pre-accepted probability density distribution is required to confirm the null

hypothesis. To evaluate the significance of the trend of the hydrological series of maximum water quantities, the non-parametric Mann-Kendall criterion is applied to determine whether the given time series has a monotonic upward or downward trend. The statistical capabilities of the approaches used are quite sensitive to various properties of the sample data and most often detect a monotonic trend or a sudden change under the influence of sudden climate changes (Salas, 1993).

In the analysis of the hydrological sequence of probabilistic values of the maximum runoff, the apparatus of the mathematical statistics was used, assuming a theoretical distribution of the random values. A choice was also made to approximate the empirical curve with the theoretical one, and the choice was based on minimal deviations of the empirical points from the theoretical ones (Mamdouh Sh. et al., 1993). In order to determine the volume of high waves at Kardzhali Dam under characteristic water quantities, a functional dependence was constructed between the maximum water quantity and the volume of the high wave according to the data from observed single peak annual high waves at hydrometric station 315/61700 near the village of Vehtino and at hydrometric station 140 near the town of Kardzhali.

Results and Discussion

The formed hydrological series of values from the maximum outflow, as an inflow to Kardzhali dam, is also based on the construction of the hodograph from water quantities values to the point for the period 1961 - 2021. The construction results are presented in Figure 3.

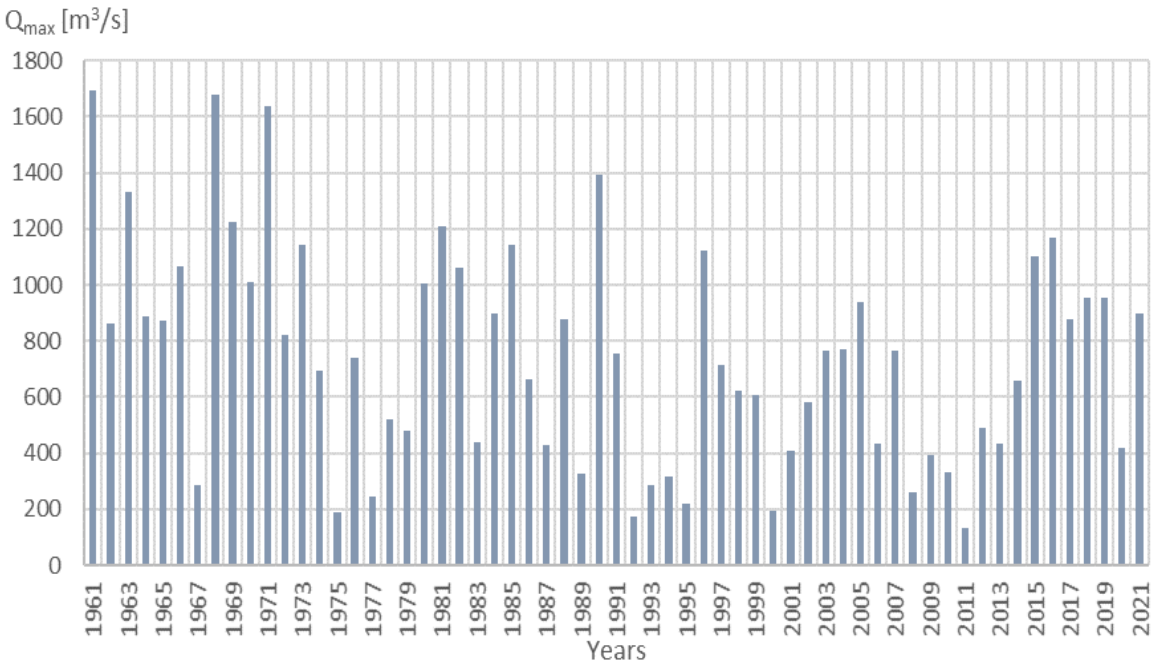

Figure 3. Hodograph of the maximum outflow for the studied period

The results of the adopted non-parametric criteria for homogeneity of the time series of maximum values of the river runoff confirm its non-homogeneity, i.e. a time change relative to the mean value of the hydrological data series is observed. Only the Pettitt's test confirms that the order is uniform.(Table3, Fig.4)

Table3. Homogeneity of the hydrological order of maximum values

Dam wall Point	River basin	p-value (bilateral criteria)				Year of change
		Pettitt's test	(SNHT)	Buishand's test	von Neumann's test	
Kardjali Dam	Arda river	0,051	0,002	0,007	0,009	1973

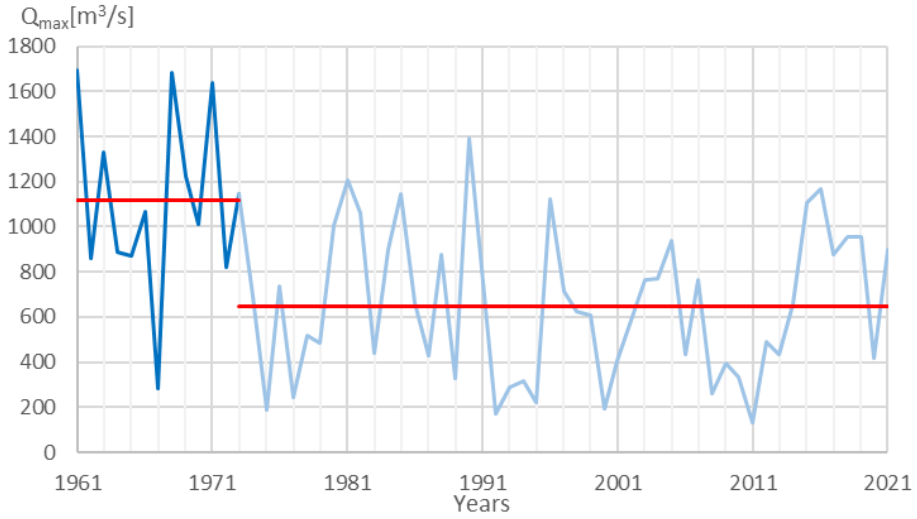

Figure 4. Chronological order of the maximum runoff with time change in 1973.

The result of the non-parametric Mann-Whitney criteria for representativeness of the hydrological series of maximum water quantities confirms that two parts of the hydrological series belong to the same general aggregation. The result of the non-parametric Mann-Whitney criteria for representativeness of the hydrological series of maximum water quantities at a confidence interval bounded from the left with a significance level α = 5% and with a quantitative estimate p = 0.998 > 0.05 confirms that the two parts of the hydrological series belong to the same general aggregation. The results of the trend significance assessment using the non-parametric Mann-Kendall test confirm that the order is statistically significant at a two-sided bounded confidence interval with a significance level α = 1% and with a quantitative assessment p = 0.029 > 0.01 where a trend is observed to reduce the maximum outflow in Kardzhali dam (WMO/TD-No. 1013, 2000).

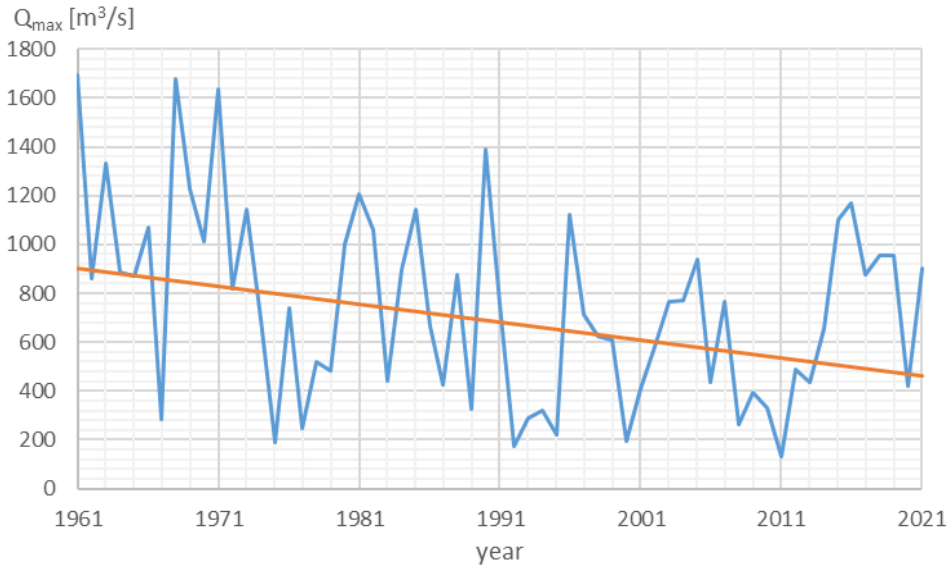

Figure 5. Chronological trend of maximum runoff for the period 1961 - 2021

The performed analyzes and evaluations show that the hydrological series is representative and can be studied with the methods of frequency analysis, which includes the statistical processing of the time series. The guarantee curve of the maximum outflow to Kardzhali dam is calculated and constructed. The statistical parameters of the hydrological order are calculated using the method of reference ordinates with an assumed lognormal distribution for the best approximation of the empirical points with the theoretical ones. The calculation results are given in Table 4 and Table 5.

Table 4. Statistical parameters of the series of maximum outflow values at Kardzhali dam

Dam wall Point	Statistic parameter			
	Qmax (m3/s)	σ (m3/s)	Cv -	Cs -
Kardjali Dam	795,0	472,9	0,60	1,35

Table 5. Values of the theoretical collateral curve of the Arda River to Kardzhali Dam

P %	0.01	0.1	1	5	10	20	50
Qp m^3/s	4252.2	3249.6	2313.2	1684.2	1409.9	1130.9	710.0

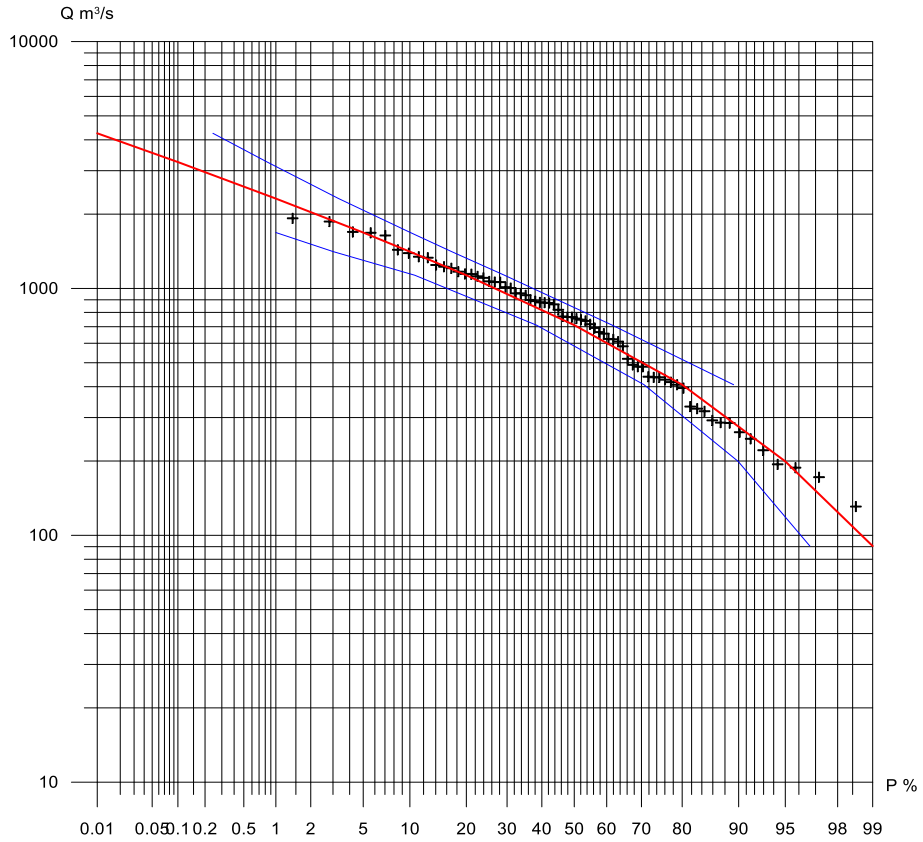

Figure 6. Theoretical supply curve of Arda River to Kardzhali Dam

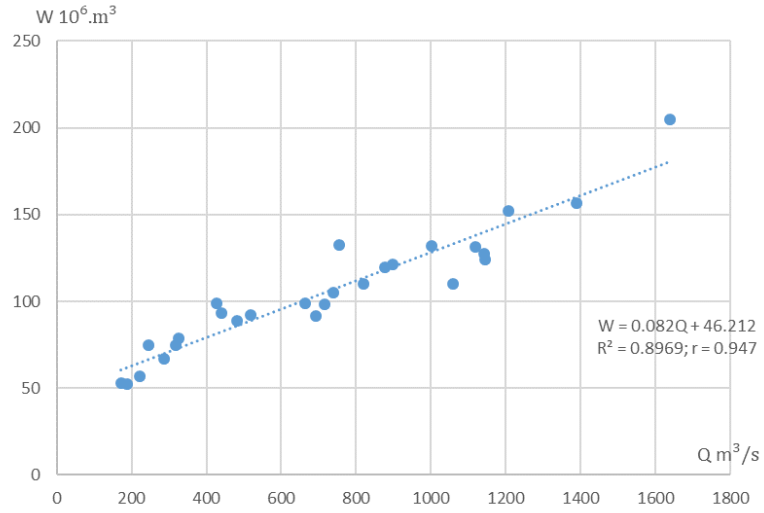

Figure 7. Dependence between the maximum amount of water and the volume of the high waves at HMS 315/61700 - Vehtino village and at HMS 140 in the town of Kardzhali

According to the data from observed single peak annual high waves at HMS 315 - village of Vehtino and at HMS 140 in the town of Kardzhali, a functional dependence between the maximum water quantity and the volume of the high wave was deduced. The results are presented graphically in Figure 7. The high correlative coefficient allows the dependence to be used to calculate the volumes of high waves with characteristic collateral to Kardzhali Dam. The results of the calculations are presented in Table 6.

Table 6. Recommended maximum water quantities and volumes of dimensional high waves determined by statistical methods

Probability %	0.01	0.1	1.0	5.0	10.0
HMS 315/61700					
Q_P [m^3/s]	3078.6	2442.4	1787.4	1309.3	1083.5
W [m^3x10^6]	298.66	246.49	192.78	153.57	135.06
Kardjali Dam					
Q_P [m^3/s]	4252.2	3249.6	2313.2	1684.2	1409.9
W [m^3x10^6]	394.89	312.68	235.89	184.32	161.82

The water quantities and volumes of dimensional high waves presented in Table 6 are obtained by a statistical method and are not tied to the rainfall that generated them.

Conclusion

The results of the present study provide prerequisites to accept that the anthropogenic pressure on the regime of the maximum runoff, expressed in dynamic changes in water consumption - for power generation, irrigation and water supply, as long as they are subject to internal balance, do not have a significant impact on structural uniformity and representativeness of the hydrological order. Additionally, with the climate change within the boundaries of the studied catchment, a trend for maximum outflow decrease of Arda River to Kardzhali Dam is observed. The results of the present study can be used with sufficient accuracy in the design, planning and exploitation of water resources, in conditions close to natural ones. The obtained values for the maximum water quantities at Kardzhali dam can be used as a basis for verification of results in subsequent developments and application of appropriate solutions related to the effective management of the hydroelectric node/Kardzhali dam.

Scientific Ethics Declaration

The authors declare that the scientific ethical and legal responsibility of this article published in EPSTEM journal belongs to the authors.

Acknowledgements or Notes

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