АНАЛИЗА НА ПОПЛАВНИ ВОДИ НА РЕКАТА ЗРМАЊА ВО ОБРОВАЦ (ХРВАТСКА)

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Резиме

Реката Зрмања е еден од најважните водотеци во Далмација. Нејзината должина од изворот (Врело Зрмања, 395 mнв) до устието во Новиградско море е околу 70 km. Таа прима води од нејзиниот извор и придружниот топографски басен, но и од бројни помали извори и притоки. Ова особено се однесува на т.н. Лички води, кои понираат во околината на Грачац (550 mнв) и достигаат до Зрмања. Водотекот во Динарскиот карст е со мошне сложен процес на истекување и интеракција на површински и подземни води.

Најзначајно населено место во овој предел е Обровац, чии бројни инфраструктурни објекти се изградени веднаш до Зрмања. Во мај 2023 год., гратчето беше погодено од голема поплава со максимално регистрирани нивоа на вода од почетокот на мерењата. Причината за поплавите беа екстремно големи врнежи во околината на Грачац: околу 500 mm во две недели. Трудот ги анализира карактеристиките на големите води на река Зрмања во Обровац и влијанието на овогодишните поплави врз меродавните нивоа на вода што треба да се земат предвид за димензионирање на регулациони и заштитни конструкции.

Клучни зборови

Зрмања, поплава, меродавни нивоа, Хрватска.

ANALYSIS OF THE RIVER ZRMANJA FLOOD WATERS IN OBROVAC (CROATIA)

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Summary

The Zrmanja River is one of the most important watercourses in Dalmatia. The length of its course is about 70 km, from the source (Vrelo Zrmanja, 395 m a.s.l.) to the mouth of the Novigrad Sea. The river receives water from its source and associated topographic basin, but also through numerous smaller sources and tributaries. This especially applies to the so-called the Lika waters, which sink in the area of Gračac (550 m a.s.l.) and reach Zrmanja. It is a watercourse in the Dinaric Karst with very complex runoff processes and the interaction of surface and underground waters.

The most significant settlement in this area is Obrovac. A number of infrastructure facilities were built in Obrovac next to Zrmanja itself. In May 2023, the small town was hit by a major flood with the maximum registered water levels since the beginning of measurements. The cause of the flood was extremely heavy rainfall in the Gračac area: approximately 500 mm in two weeks. The paper analyses the characteristics of the large waters of the Zrmanja River in Obrovac and the impact of this year's flood on the authoritative water levels that should be used for sizing regulatory and protective water structures.

Key words

Zrmanja, flood, authoritative water levels, Croatia**.**

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1. INTRODUCTION

Hydrological problems of large waters are studied from two aspects: theoretical and practical. From a theoretical point of view, the interest is in variations of the water level (flow) in time, and especially the maximum values as the culmination of large water waves. It is certain that variations in hydrological parameters related to watershed factors and climatic elements are relevant for the genesis of runoff. Due to the large number of factors (causes), hydrological phenomena can generally be considered as random variables. This is based on the basic assumption that high water is a random phenomenon that can be observed according to the laws of statistical distribution. These are calculations of the probability of the occurrence of large floods, based on a statistical analysis of events from the past.

In a practical sense, the theoretical results are needed for the design of hydrotechnical structures that serve various needs, from protection against the harmful effects of water to different ways of using water. In general, there are no hydrotechnical facilities that do not require, to a greater or lesser extent, knowledge of extreme hydrological phenomena.

The entire area of Dalmatia, southern coastal Croatian region, belongs to the Dinaric Karst. Karst is characterized by soluble rocks (limestone, chalk, dolomite, gypsum etc.) located near or at the surface. It is an area with very complex processes of underground and surface runoff. The water circulation processes have been studied by many researchers ([1-5], [9]). Dalmatia has several larger rivers (Neretva, Krka, Cetina, Zrmanja) and a large number of small permanent and occasional streams ([1], [6]). Zrmanja is one of the larger rivers in Dalmatia, located in its northern part, which administratively belongs to Zadar County.

The Department of Hydrology DHMZ (Croatian Meteorological and Hydrological Service) and "Hrvatske vode" (Croatian Waters) carry out measurements and monitoring of surface and underground waters in the territory of the Republic of Croatia. Hydrological measurements are used for numerous analyses, tasks, studies and projects in the field of water management. In the territory of the Republic of Croatia, this Sector has about 440 hydrological surface water stations and about 700 underground water stations. Hydrological measurements are necessary for us in the research of very complex processes of runoff and thus in making conclusions for practical action. Sometimes it happens that, despite detailed monitoring and numerous continuously observed parameters, it is not possible to find complete answers to the challenges posed by karst when solving the basic hydrological problem - the transformation of precipitation into runoff.

2. STUDY AREA

2.1 CATCHMENT OF THE ZRMANJA RIVER

The length of the Zrmanja River is about 70 km, from the source (Vrelo Zrmanja, 395 m a.s.l.) to the mouth of the Novigrad Sea (bay and part of the Adriatic Sea). The River catchment is located in the central part of the Dinaric karst region of Croatia (Fig. 1a) between 44°00' and 44°25'N, and 15°35' and 16°20'E. The exact hydrological catchment area and boundaries are not well known, although numerous investigations and groundwater tracings have been carried out ([2]). Figure 1 presents the topographic boundary of the River Zrmanja catchment and surrounding rivers. The topographic catchment area is approximately 700 km^2.

Previous research has shown that the waters that sink in the Gračac plateau in numerous sinkholes ("*ponors*") rise to the surface at numerous karst springs along the Zrmanja and Krupa rivers, but also at submarine springs ("*vrulja*") in the Adriatic Sea. Therefore, the upper Gračac plateau (550 m a.s.l) is indeed a part of the Zrmanja River catchment, i.e., a part of hydrogeological catchment. The area of the Gračac plateau from which the water gravitates through underground connections into the Zrmanja topographic basin is estimated at around 500 km^2. Therefore, the total hydrological-hydrogeological area of the Zrmanja basin is about 1200 km^2. So, the topographic basin of the Zrmanja River is significantly smaller than the hydrological-hydrogeological basin. It is a very complex and so far incompletely explained system of sinkholes and underground river courses ([1-2]).

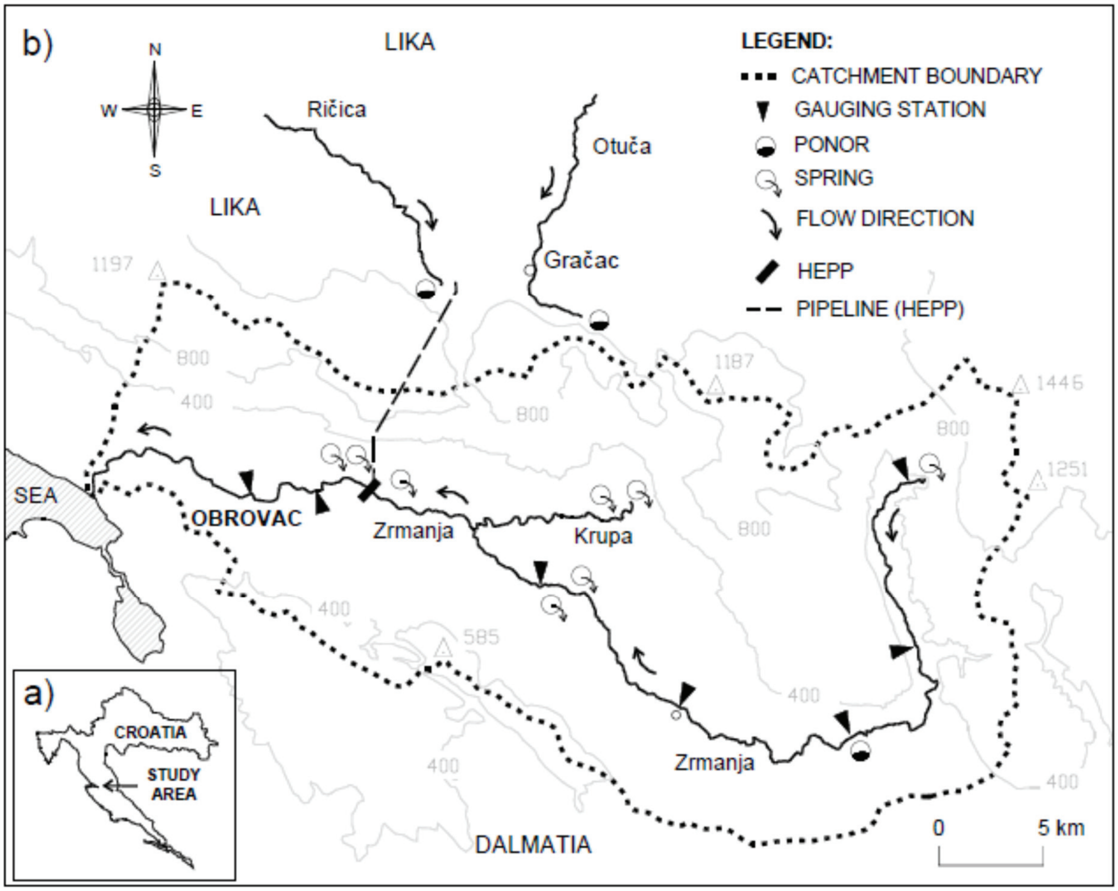

Figure 1. The Zrmanja River catchment (Croatia)

The only hydro power plant (HPP) in the Zrmanja basin is the reversible hydroelectric power plant (RHE) Velebit, which started operating in 1985. The upper basin of the RHE is located in the area of Gračac, and the waters of Ričica and Otuča flow into it. The lower basin is located on the river Zrmanja (Razovac basin): it is a RHE. Undoubtedly, the influence of RHE is very significant on the hydrological relations in the Zrmanja basin. The analysis of the impact of RHE work is not part of this paper, and that issue should be dealt with separately. This paper deals exclusively with the hydrological problem of large waters in Obrovac, and in the case of the recent (May 2023) flood events it is assumed that the RHE did not work.

The most significant settlement in the catchment is the small town of Obrovac (about 1,000 inhabitants), located right on the banks of the Zrmanja River, about 10 km from its mouth. A number of infrastructure facilities were built in Obrovac next to Zrmanja itself.

2.2 HYDROLOGICAL CHARACTERISTICS OF THE ZRMANJA IN OBROVAC

Hydrological conditions at the lower part of the Zrmanja River are registered at two stations: Obrovac and Jankovića buk. Station Obrovac is located in Obrovac, 10 km from river mouth, just downstream from the bridge (Fig. 1). It measures the water level. Due to sea tides, there is no unambiguous correlation between water level and discharge. Zero level is at 0.36 m a.s.l.

The station Obrovac started operating in 1983. In the meantime, it had some interruptions. This year (2023), the highest water level since the beginning of measurements was recorded, which was 302 cm. Station Jankovića buk is located about 2 km upstream from Obrovac. It registers water level and discharge. In this paper, an analysis of a hydrological profile of the Zrmanja River in Obrovac was carried out, as this is the area where the greatest damage was recorded in recent flood.

Figure 2 shows the maximum water levels of the Zrmanja River in Obrovac since the beginning of measurements.

Three periods should be observed in the past. The first from 1983 to 2006, when the construction of several infrastructure facilities on the shores of Obrovac began. Then, the second period from 1983 to 2022 and finally the third period from 1983 to 2023, in which the absolute maximum was recorded. Of course, for the mentioned periods the basic statistics differ, and they are presented in the table.

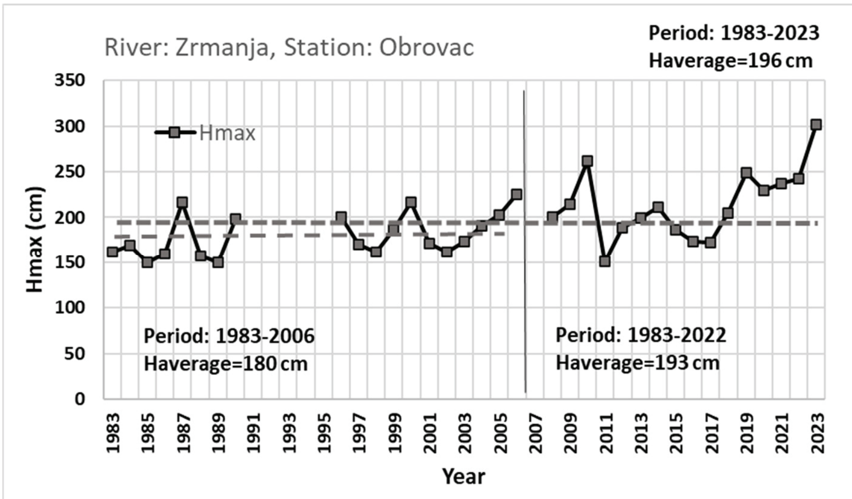

Figure 2. Series of maximum water levels in Obrovac (the Zrmanja River)

Table 1. Basic statistical parameters of selected periods (Water level in cm)

Parameter	Period		
	1983-2006	1983-2022	1983-2023
No. of data	19	34	35
Average	180	193	196
Max	225	262	302
Min	150	150	150
Standard dev.	24	30	35
Skewness	0.54	0.47	0.94

2.3 STATISTICAL ANALYSIS

Several (common) theoretical distribution curves were used to analyze the probability of maximum annual water levels: normal, log-normal, Gamma, Pearson III and Gumbel ([10-11]). Testing the agreement of the empirical and theoretical distributions was performed using the Kolmogorov Smirnov test. The Pearson III distribution had the best matching of the associated functions, so it was taken as authoritative for drawing conclusions.

The Pearson distribution is a family of continuous probability distributions. It was first published by Karl Pearson in 1895. It is the generalized Gamma distribution and widely used in hydrology. The probability density function of Pearson III distribution is:

$$f(x) = \frac{1}{\beta^{\alpha} \cdot \Gamma(\alpha)} \cdot (x - x_0)^{\alpha-1} \cdot e^{(x-x_0)/\beta} x_0 \leq x \leq +\infty \qquad (1)$$

where the corresponding parameters are: x_0 location, α shape and β scale.

The calculated values of high waters are given in the table below for the three selected periods. In the first period (1983-2006), which is also the shortest, the water level values are the lowest. According to these statistics, the recent flood would have a return period of more than 200 years. In the second period (1983-2022), the series is significantly longer, and the calculated water levels are 26-30 cm higher than in the previous period. Even in this period, the recent flood would have a return period of more than 200 years. Only in the third period (1983-2023), in which the highest recorded water level (302 cm) was taken into account in the basic series, the recent flood has an approximately 100-year return period. In the third period, the calculated water level values are 23-32 cm higher compared to the previous period, even though it is a series that has only one member more than the previous one. Therefore, the length of the series and the occurrence of extreme situations have a dominant influence on the calculated statistical quantities.

Table 2. Calculated high water levels (cm) by periods (Pearson III distribution)

Return period	Period		
(year)	1983-2006	1983-2022	1983-2023
200	253	283	315
100	245	273	300
50	236	262	285

3. FLOOD DEFENSE SYSTEM

In the period 2007-2010, several regulatory and protective structures were built along both coasts in Obrovac ([7-8]). Promenades with protective walls against high water were formed. Looking at the previous results, it is clear that the statistical characteristics of large waters have changed since then. Unfortunately, the recent flood confirmed this. So, for example, the 100-year high water increases by 55 cm when comparing the first and third periods!

However, the recent extreme hydrological situation in Obrovac is a consequence of extreme precipitation in the Lika area, i.e., Gračac plateau. In the first half of May, the total precipitation in Gračac was 500 mm, which indicates extremely rainy conditions with extreme daily precipitation on May 15 of 256 mm. Because of this, there were heavy floods in the Gračac area (Otuča and Ričica rivers), but also on the lower horizon, i.e., along the Zrmanja river. As stated previously, the waters of Lika are "connected" to Zrmanja by underground connections ([1-2]): it is a karst system with very complex relationships between surface and underground runoff.

With the raising of the Zrmanja river level in Obrovac (in May 2023), additional flood defense protection began (by stacking sandbags) (Fig. 3). However, such a large water wave could not be defended with temporary measures. Both banks of the Zrmanja River in Obrovac were flooded, affecting around 50 residential and commercial buildings (Fig. 4). The maximum water level in Obrovac (302 cm) remained almost the entire day (May 15), after which it slowly began to decrease. In such extreme conditions, the river level was 40-50 cm higher than the fixed protective structures (defensive walls).

Figure 3. Flood protection on the left bank of Zrmanja in Obrovac (May 2023) (photographed by I. Peša)

Figure 4. Flood in Obrovac (May 2023) (photographed by I. Peša)

4. CONCLUSION

Both banks of the Zrmanja River in Obrovac (Croatia) were regulated about 15 years ago. Promenades with protective walls were built in 2008. In the past period, there were generally no major problems with floods until May of this year, when the largest flood wave since the beginning of hydrological measurements (1983) was recorded.

In this paper, a statistical analysis of the maximum water levels of the Zrmanja River in Obrovac was made. Data were considered in three periods: 1983-2006, 1983-2022 and 1983-2023, i.e., with the same beginning of the series (1983). As the periods increased, so did the statistical levels of high water. The highest values are obtained for the last series, which includes the recent flood.

When calculating large waters, the longest series should be taken into account. In hydrological practice, the minimum length of series is usually 30 years. The analysis carried out indicates that, in addition to the length of the series, the frequency of extreme situations is also important. However, the occurrence of extreme events is also a consequence of the climate changes that we are witnessing more and more, which further complicates the set task - determining the relevant levels of large waters.

As for the flood defense in Obrovac, with today's available data, higher levels of high water would be obtained compared to the time when the development of the banks began (15-20 years ago). This means that coastal buildings should also be somewhat higher. Undoubtedly, similar things can be expected on other similar systems that are dimensioned based on the measurement of hydrological quantities. The input hydrological data obviously changes a lot under the influence of climate change. Also, the anthropogenic impact, that is, human action in the watersheds, which has an impact on hydrological parameters, is also important.

In this paper, a statistical analysis of only one hydrological profile was made, and the change of large waters was quantified, which is about 50 cm depending on the observed period and the return period.

In the rich and diverse karst area of Zrmanja, hydrological runoff represents a very complex process that is not easy to define mathematically. It includes numerous parameters (meteorological, hydrological, hydrogeological) both on the topographical and on the hydrogeological basin. When human influence (e.g., HPP operation) is added to this, climate change, nature protection (a large part of the watershed enters a nature park), etc. relations are further complicated. The research of such watersheds requires the serious engagement of various experts, good organization and, in general, a very serious approach. Such research can help us define all hydrological phenomena as precisely as possible, so the professional part - designing and implementing flood protection systems - will give us the most reliable protection.

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