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Hydrological analysis of the Danube regime on the section through the Republic of Croatia and the Republic of Serbia

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The flow regime of the Danube in the area of the middle part of the basin, on the section of the Danube through Croatia and Serbia, was analyzed. This paper contains a hydrological analysis of the Danube regime using measured flow data at four regression stations; Batina in the Republic of Croatia, and the regression stations Bezdan, Bogojevo and Smederevo in the Republic of Serbia for the period 1992–2018. On this section, two large rivers, the Drava and the Sava, flow into the Danube, which significantly affect the Danube regime. Parde's method of modular coefficients was used to classify the flow regime. Comparing the curves of mean monthly flows expressed through modular coefficients for the Danube, Drava and Sava, it can be concluded that the Danube has an alpine snow regime at the top of the analyzed section, just like the Drava that flows into the Danube. At the regression station Smederevo, the curve of mean monthly flows expressed in modular coefficients is similar to the curve for the Sava, which flows into the Danube upstream from Smederevo, and the Danube has a combined flow regime like the Sava.

KEY WORDS: flow regime, modular coefficients, „central Danube region"

Introduction

The Danube is the second longest and water richest river in Europe, with a length of 2 857 km and a catchment area of 817 000 km^2. (Fig. 1.) The Central Danube Region is an imposing and unique geographical entity in Europe. It is bounded by Carpathian sand, part of the Balkan Mountains in the north and east, near the Alps in the west and the Dinarides in the south. This closed circle of mountains includes the "Pannonian Basin System", which consists of the south-eastern and Slovak lands, the Lesser and Great Hungarian Plain, the Transylvanian Basin, the Slavonian Middle Range, the Sava Basin and part of the Great Morava Basin. (Schiller et al., 2010).

With its middle part, the Danube flows through Croatia and Serbia and represents the border between these countries. In this part of the Danube basin, the Danube flows along the Kopački rit swamp, and two large rivers, the Drava and the Sava, flow into it, which significantly

Fig. 1. Danube River basin.

affects the Danube flow regime itself. The surface area of the Danube basin in Croatia is 35 101 km^2, which represents 62% of the Croatian mainland. (Croatian River Basin Management, CRBM 2016–2021).

When analyzing the flow regimes of rivers, including the Danube, special attention should be paid to hydrological extremes: floods (Prohaska and Iličić, 2009; Hattermann et al., 2018) and droughts (Koleva, 1995; Stojanovic et al., 2017). analysis of the Danube flow regime (in Slovakia) through the period from 1840 to 2015 was presented by Pekarova et al. (2019). Romanova et al. (2019). investigated natural and anthropogenic impacts on the course of the Danube in the area from Reni to Izmail. Changes in the flow regimes of rivers due to changes in climatic elements in Europe are primarily related to the way rivers are supplied, ie the type of their recharge. (Čanjevac, 2012) At the national level (and level of large regions of Croatia), certain climatic changes have already been recorded, and their influence on changes in the water balance observed (Bonacci and Gereš, 2001; Pandžić et al., 2009) or their influence on changes of the discharge regime (Gajić-Čapka and Cesarec, 2010; Čanjevac, 2012; Barbalić and Kuspilić, 2014; Čanjevac and Orešić, 2015; 2018). Changes to discharge on the Sava River were examined by Bonacci and Ljubenkov (2004), Šegota and Filipčić (2007), Trninić and Bošnjak (2009), Bonacci and Oskoruš (2011) and Orešić et al. (2017), while changes on the Drava River by Bonacci and Oskoruš (2010) and Gajić-Čapka and Cesarec (2010).

This paper contains a hydrological analysis of the Danube regime using measured flow data at four regression stations; regression station Batina in the Republic of Croatia, and the regression stations Bezdan, Bogojevo and Smederevo in the Republic of Serbia for the period 1992–2018.

Material and methods

The paper analyzes databases on measured flows at regression stations Batina, Bezdan, Bogojevo and Smederevo. Due to the insufficient length of the series of available data for the regression station Batina, it was performed correlation analysis between that regression station and the closest one in the Republic of Serbia – regression station Bezdan. How is it analysis determined extremely strong correlation ratio (correlation coefficient is 0.998), flow analysis was performed for the regression station Bezdan, the results of which can be considered representative for the regression station Batina as well Republic of Croatia. Based on the data on mean daily flows, the minimum, mean and maximum annual flows were obtained. Statistical processing of data constructed flow duration curves and frequency histograms for the average daily flows of the Danube River for the regression stations Bezdan (Batina), Bogojevo and Smederevo, and additionally singled out characteristic curves for the dry, normal and wet years recorded for the given series 1992–2018. The flow regime classification is defined according to Parde's modulus coefficients. The flows expresed in modular coefficients are suitable for comparing individual hydrological features at different hydrological stations. The hydrological analysis of the seasons was performed, ie the flow tendencies for the warm and cold seasons for the observed period were shown.

Results

By processing the database on mean daily flows, the following results were obtained: for the regression stations Bezdan (Batina) the lowest mean daily flow of 742 m^3 s^{-1} was recorded in October 1992, and the largest of 8 380 m^3 s^{-1} in June 2013. A slight upward trend is visible minimum and medium annual flows, while for maximum the trend is negative. (Fig. 2)

For the regression station Bogojevo, the lowest mean daily flow of 926 m^3 s^{-1} was recorded in September 2003, and the largest of 8700 m^3 s^{-1} in June 2013. There is a considerable upward trend in the minimum and mean annual flows, while for maximum annual flows the upward trend is slightly negative. (Fig. 3)

For the regression station Smederevo, the lowest mean daily flow of 1400 m^3 s^{-1} was recorded in September 2003, and the highest of 14800 m^3 s^{-1} in April 2006. At the minimum annual flows for this regression station, a strong positive trend is visible. A very slight upward trend is visible for medium annual flows, and a slight decrease for maximum annual flows. (Fig. 4)

Correlation analysis of mean flows (Table 1) confirmed the strong dependence between regression stations Batina and Bezdan (located opposite each other), and Bezdan and Bogojevo, which means that on the section Batina – Bogojevo flow regime does not change, while the results of correlation analysis for regression stations Bogojevo and Smederevo showed that there is almost no correlation between them – which indicates the fact that the flow regime changes significantly.

Flow duration curves expressed by Parde modular coefficients

Various methods are used in the literature to classify the flow regime of fluids. One of the better known classifications is the classification made by the French geographer hydrologist Maurice Pardé. Pardé introduced a modular coefficient that represents the ratio between two quantities of a given period and the corresponding average (Pardé, 1933). In practice, the values of mean monthly and annual flows are most often used in these comparisons.

It is obtained by dividing the mean flow of each month by the mean annual flow.Pardé's simple formula makes it possible to compare the flow regimes of rivers of different flows.

Modular coefficient (Mk) formula:

$$Mk=\frac{MQ-The\ average\ flow\ of\ an\ individual\ month}{MQ-mean\ annual\ flow} \qquad (1)$$

On the basis of modular coefficients, ie flow regimes obtained by such an approach, Pardé divided all fluids

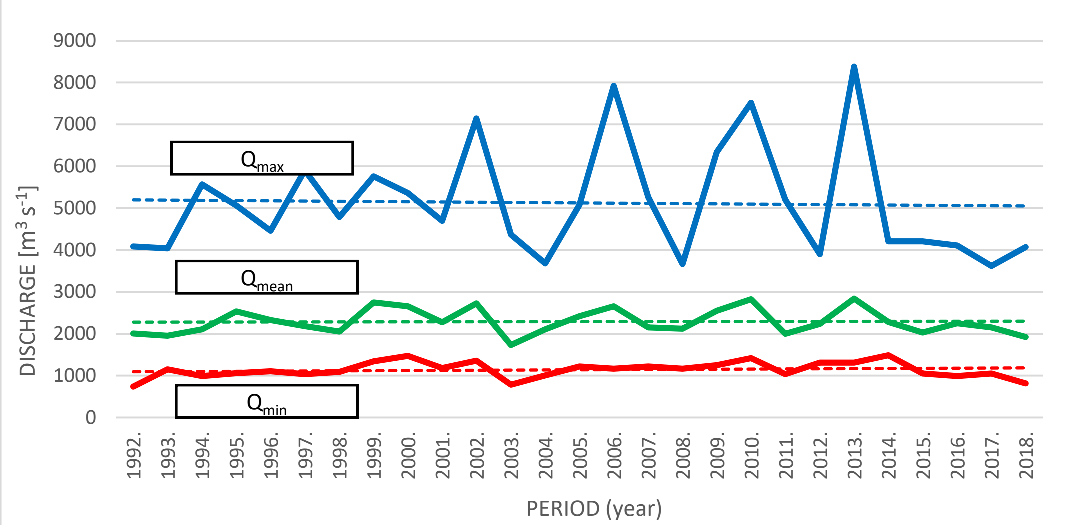

Fig. 2. Annual mean minimum, mean and maximum flows for the period 1992–2018 (regression stations Batina/Bezdan).

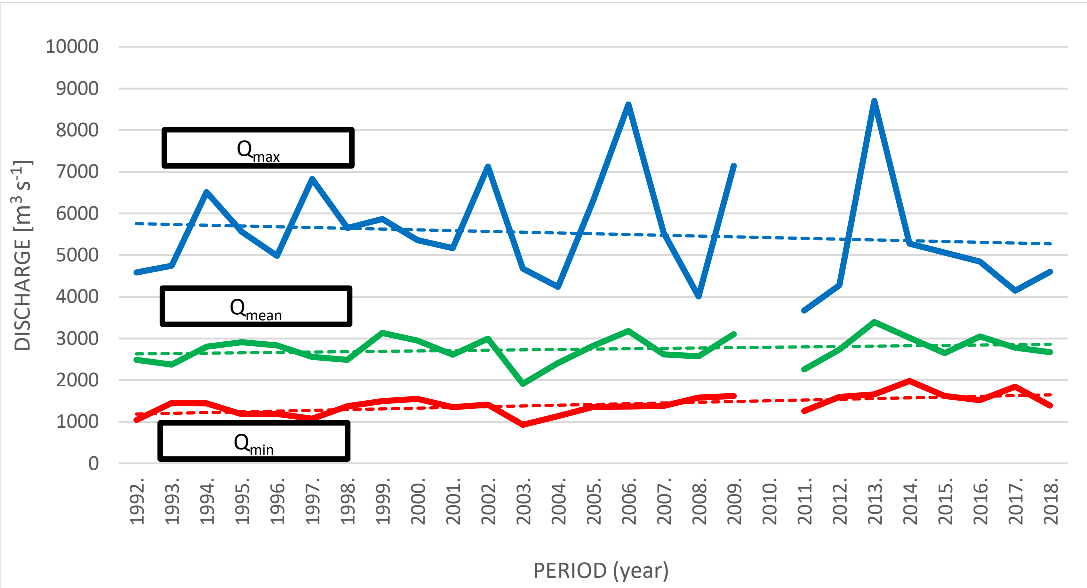

Fig. 3. Annual mean minimum, mean and maximum flows for the period 1992–2018 (regression station Bogojevo).

Table 1. Flow correlation coefficients between measuring stations

Regression Statistics	Batina – Bezdan	Bezdan – Bogojevo	Bogojevo – Smederevo
Multiple R	**0.997983378**	**0.968586032**	**0.118338021**
R Square	0.995970822	0.938158902	0.014003887
Adjusted R Square	0.995913263	0.937959415	0.010240543
Standard Error	57.94458563	216.1527741	1458.720637
Observations	72	312	264

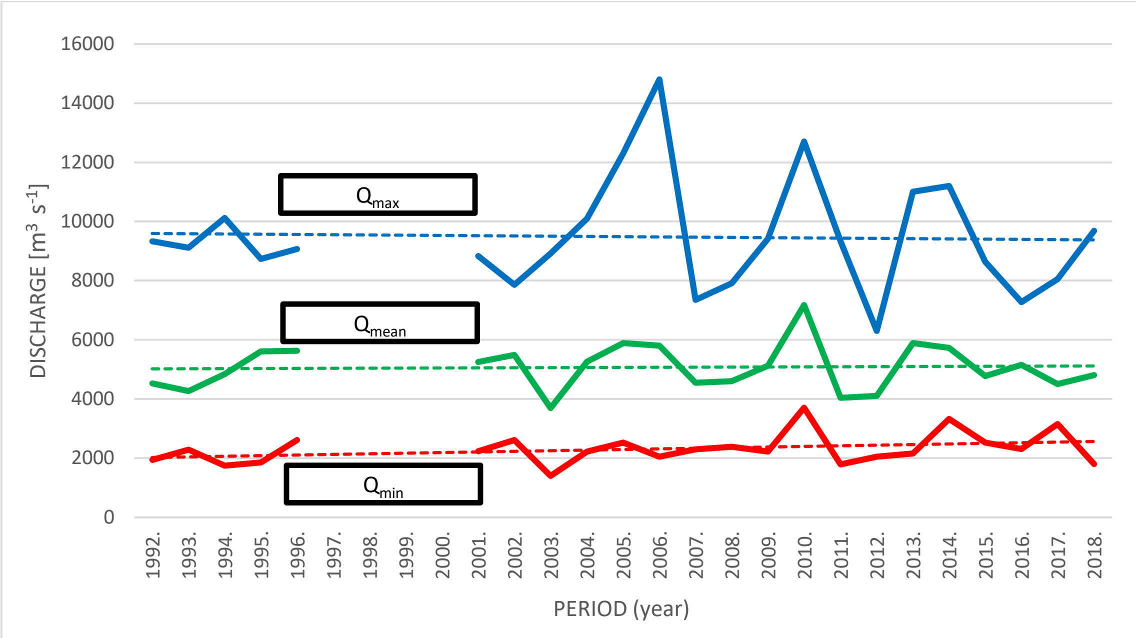

Fig. 4. Annual mean minimum, mean and maximum flows for the period 1992–2018 (regression station Smederevo).

into those with simple and those with complex regimes. "S. Ilešič (1947) used Pardé's coefficients for the sixteen-year period 1923–1938 when researching and determining the typology of Yugoslav fluids and determined the existence of the following types in Croatia:

- snow regime
  - mild (Drava)
  - transitional (Mura)
- rain-snow regime
  - transitional Central European or Posavina variant (Sutla, Sava downstream from Zagreb)
  - moderately Mediterranean variant (Kupa)
  - Mediterranean variant (Neretva, Cetina, Krka, Zrmanja and Rječina)
- clean or almost clean rain regime (Čazma and Istrian rivers)
- combined-complex regime (Danube).” (Čanjevac 2012)

Their importance comes to the fore when it comes to comparing a certain hydrological quantity on the same river, in the same time period, but in different profiles, or when comparing these same quantities, but for different watercourses.

If a certain similarity is established in the forms of flow duration curves in modular coefficients for individual watercourses, it is possible to define the flow duration curve by interpolation between two profiles with similar duration curves.

In the further part of this chapter, the flow duration curves for the regression stations Bezdan (Batina) (Fig. 5), Bogojevo (Fig. 6) and Smederevo (Fig. 7) for the period 1992–2018 are attached year, with the proviso that when grouping their data, the flow class interval was 250 $m^3 s^{-1}$. The characteristic curves for the dry, normal and wet years recorded for the given series 1992–2018 are separated.

The analysis of mean monthly flows expressed in Parde's modular coefficients shows that the Danube at the regression stations Batina (Bezdan) and Bogojevo has an alpine snow regime. The primary maximum occurs in May and June, when the values of modular coefficients are from 1.25 to 1.45, while the much less pronounced second maximum occurs in October and November with values of modular coefficients slightly higher than 1. At the regression station Smederevo Danube has a combined complex mode. It is characterized by a complex regime with two annual highs and lows. The first maximum occurs in March or April, when the values of the modular coefficients range from 1.14 to 1.66. The second, mostly more pronounced maximum occurs in December (exceptionally in November), when the modular coefficients range from 1.37 to 2.04. The primary minimum occurs in August and only at a few stations in July, when the values of the modular coefficients range between 0.31 and 0.74. The second, less pronounced minimum occurs regularly in February with coefficient values from 0.78 to 1.31. Insight into the graphs of mean monthly flows expressed in modular coefficients for the Danube (Fig. 8) and the Drava (regression station Terezino polje) and Sava (regression station Županja stepenica) (Fig. 9) (Čanjevac and Orešić, 2018), rivers flowing into the Danube, a similar shape of curves is visible for the Drava and Danube at the stations Batina and Bogojevo, while similar graphs for the Sava and Smederevo. These similarities indicate the strong influences of the Drava and Sava rivers on the changes in the flow regime of the Danube.

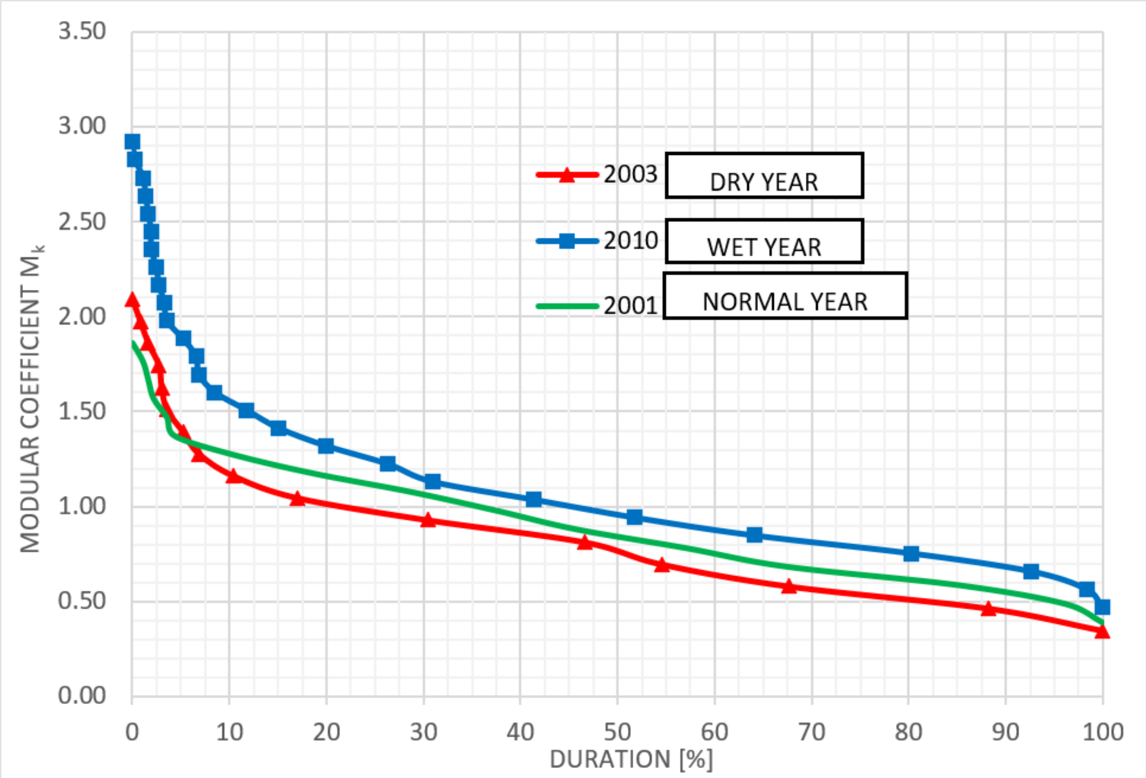

Fig. 5. *Characteristic flow duration curves for the Danube River represented in modular coefficients (regression stations Batina/Bezdan).*

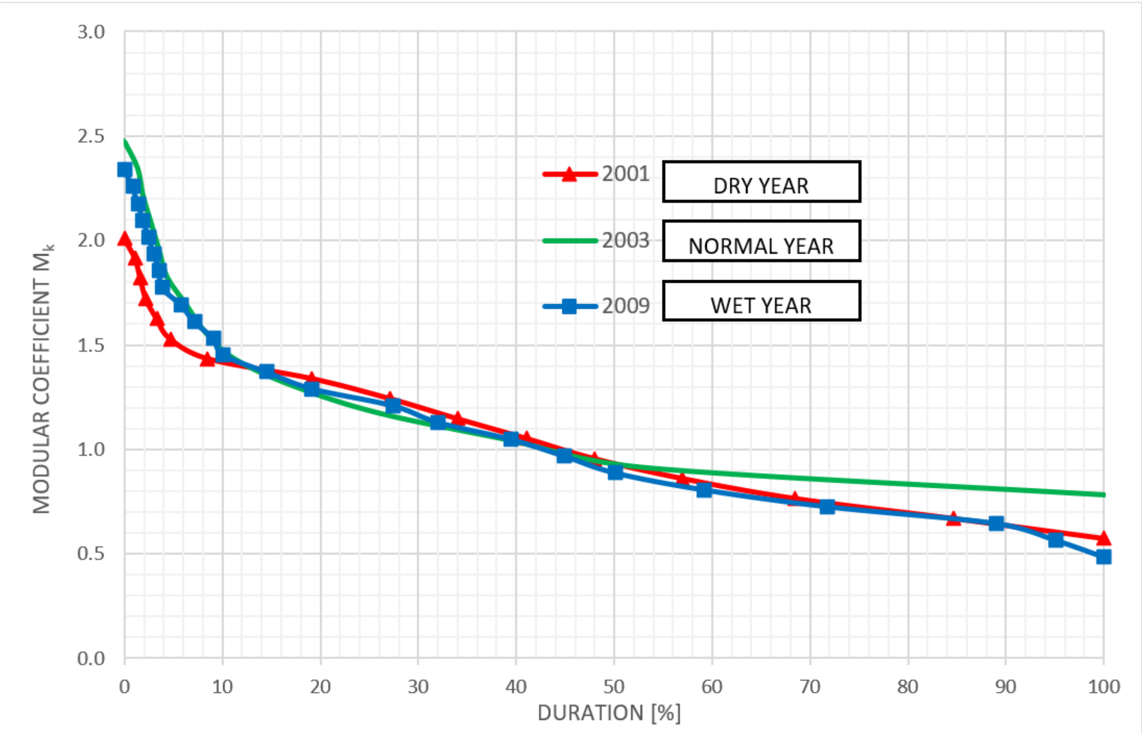

Fig. 6. *Characteristic flow duration curves for the Danube River represented in modular coefficients (regression station Bogojevo).*

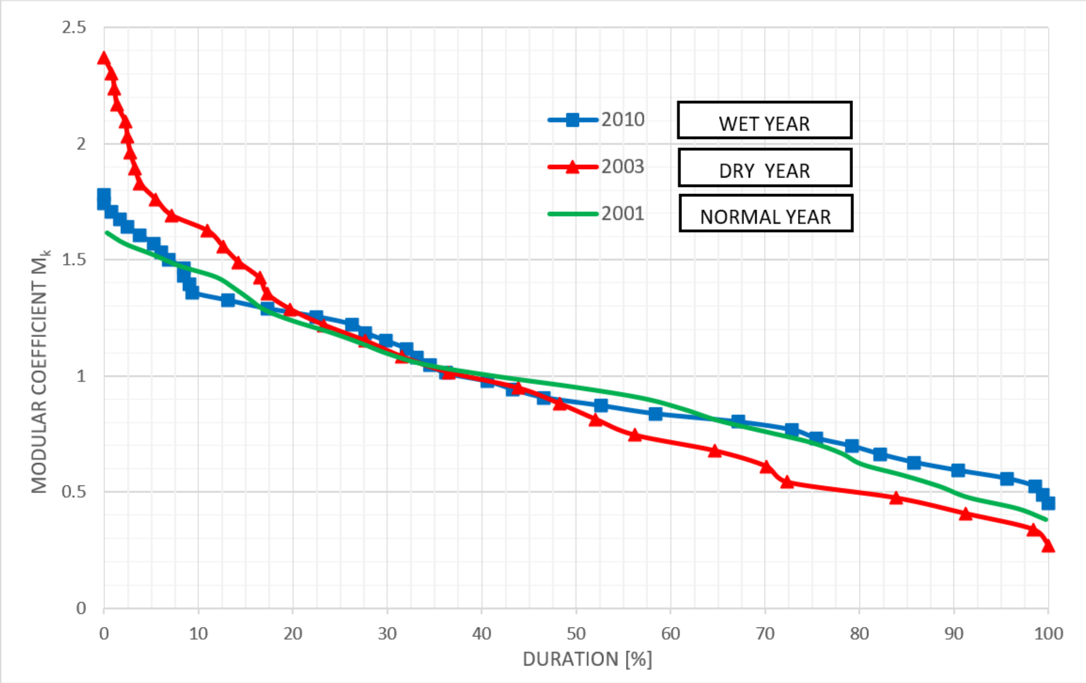

Fig. 7. Characteristic flow duration curves for the Danube River represented in modular coefficients (regression station Smederevo).

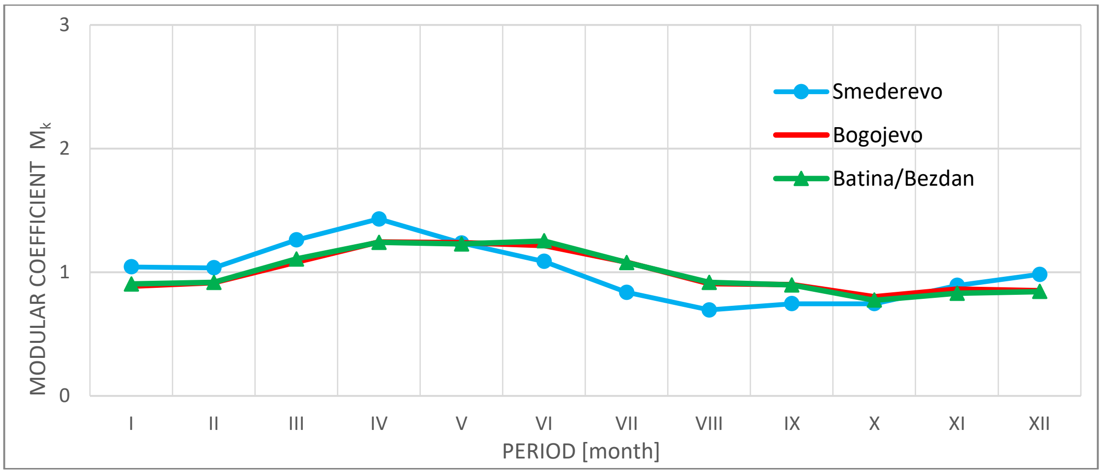

Fig. 8. Mean monthly flows represented in modular coefficients for the Danube River (regression stations Batina/Bezdan, Bogojevo and Smederevo).

Analysis of hydrological seasons

In order to better manage water resources, it is necessary to find such a solution that they are used rationally, conscientiously, environmentally and ultimately – economically. Analysis of hydrological seasons is an important basis for water resources management. The analysis of multi-year mean monthly flows on the observed section revealed two hydrological seasons: the warm season from April to September with higher flows and the cold season from October to March with a negative flow trend. The analysis of the obtained results for the regression stations Bezdan (Batina) (Fig. 10) shows a slight tendency of increase of mean monthly flows in the cold season as well as a slight trend of decrease of mean monthly flows in the warm season during the observed period. The lowest mean monthly flow of the warm season of 1562 $m^3 s^{-1}$ was recorded in 2003, and the cold one of 1700 $m^3 s^{-1}$ was recorded in 1997. The mean monthly flow of the warm season is 3016 $m^3 s^{-1}$, and the cold season is 2471 $m^3 s^{-1}$. The highest mean monthly flow of the warm season was 4250 $m^3 s^{-1}$ recorded in 2006, and in the cold season 3137 $m^3 s^{-1}$ was recorded in 2002.

For the regression station Bogojevo, a significant positive trend of mean monthly flows for the warm and cold seasons during the observed period is observed. (Fig. 11.) The lowest mean monthly flow of the warm season of 1701 $m^3 s^{-1}$ was recorded in 2003, and the cold season 2014 $m^3 s^{-1}$ recorded in 1997. The mean monthly flow of the warm season is 3016 m^3 s^{-1}, and the cold season 2471 $m^3 s^{-1}$. The highest mean monthly flow of the warm season was 4250 m^3 s^{-1} recorded in 2006, and in the cold season 3137 m^3 s^{-1} recorded in 2002.
For the regression station Smederevo (Fig. 12), the results show a slight increase in mean monthly flows for both season with the proviso that it should be noted that for the observed series from 1992 to 2018 one is missing data period from 1997 to 2000 so the results for this station should be taken with less dose of reliability. The lowest mean monthly flow of the warm season of 2893 m^3 s^{-1} was recorded in 2003, and the cold season one of 3898 m^3 s^{-1} was recorded in 2012. The mean monthly flow of the warm season is 5103 m^3 s^{-1}, and the cold season 5041 m^3 s^{-1}. The highest mean monthly flow of the warm season was 7368 m^3 s^{-1} recorded in 2006, and in the cold season 7018 m^3 s^{-1} recorded in 2010 (Djedović, 2020).

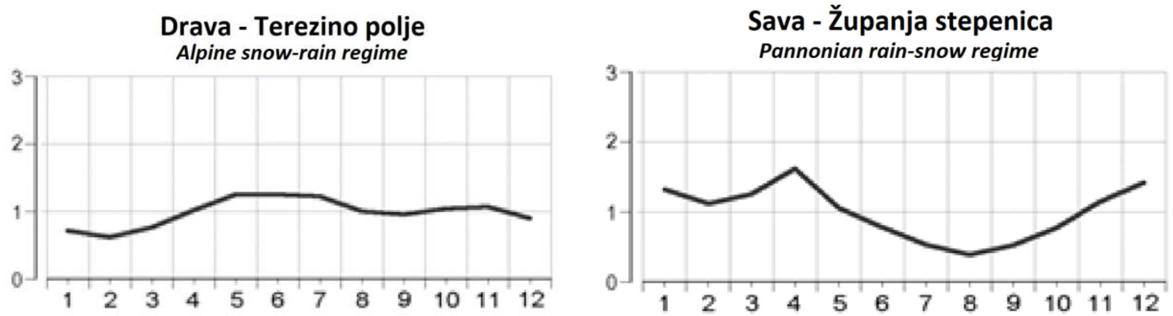

Fig. 9. Mean monthly flows represented in modular coefficients for the Sava River (regression station Županja stepenica) and Drava River (regression station Terezino polje).

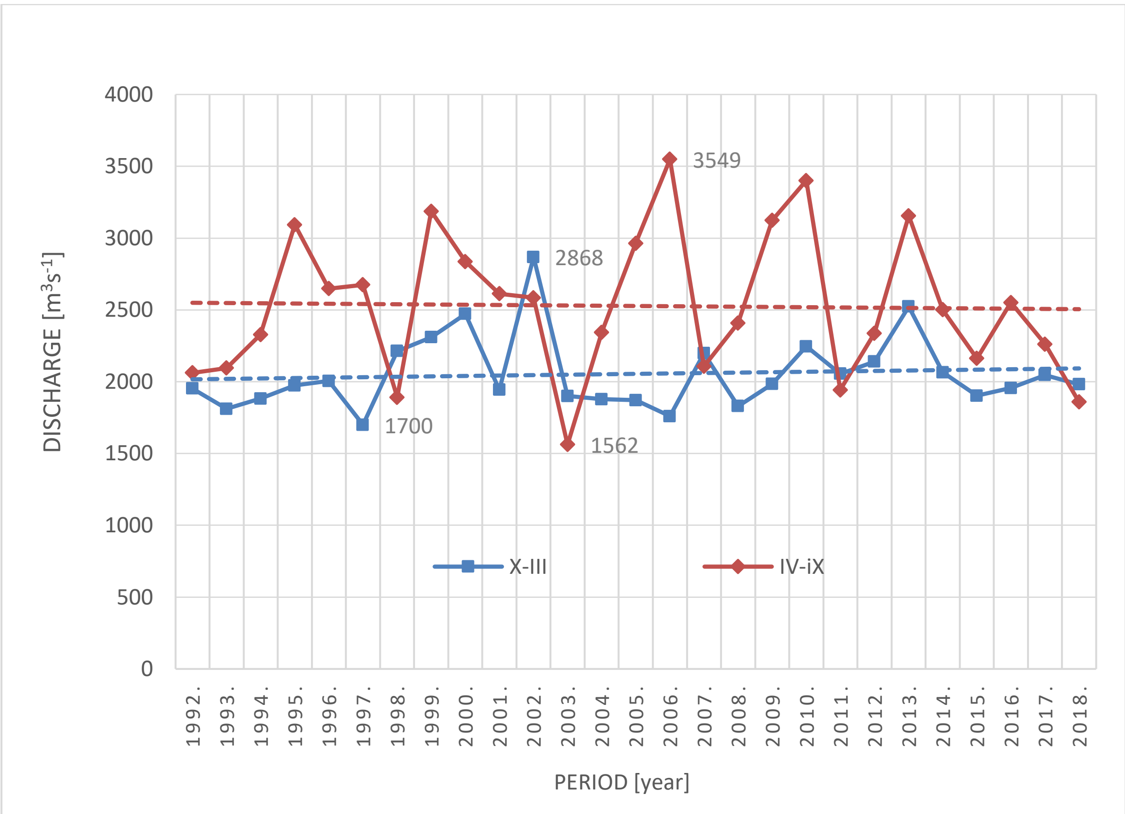

Fig. 10. Mean annual flows during warm (April–September) and cold (October–March) season for the period 1992–2018 (regression stations Batina/Bezdan).

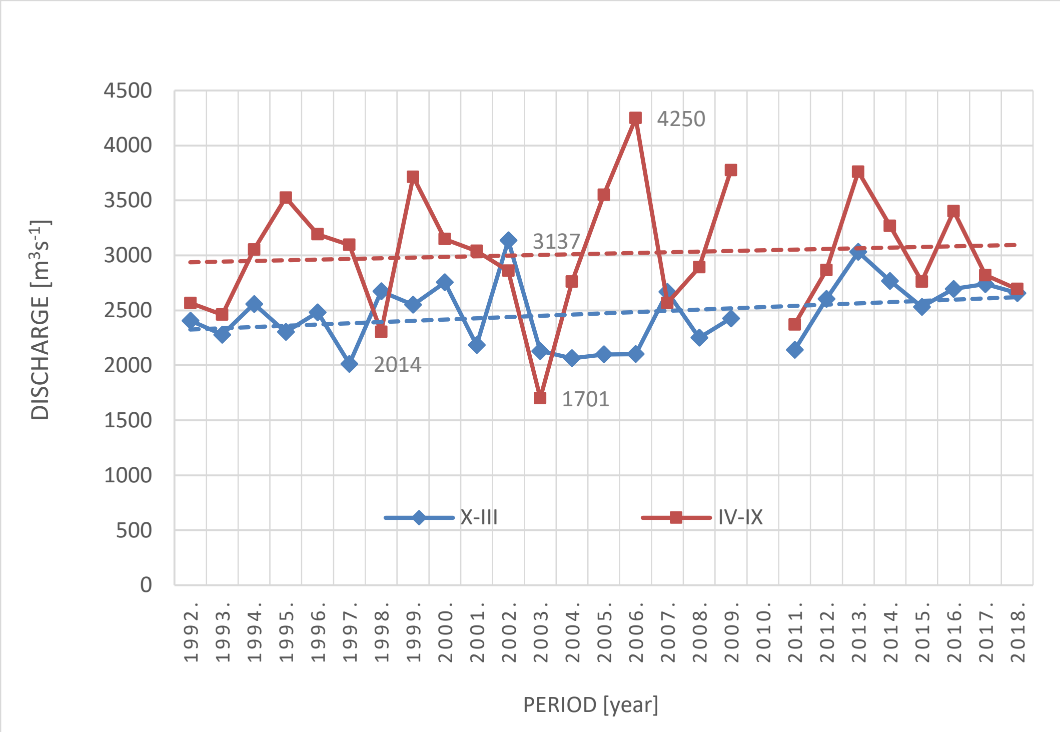

Fig. 11. Mean annual flows during warm (April–September) and cold (October–March) season for the period 1992–2018 (regression station Bogojevo).

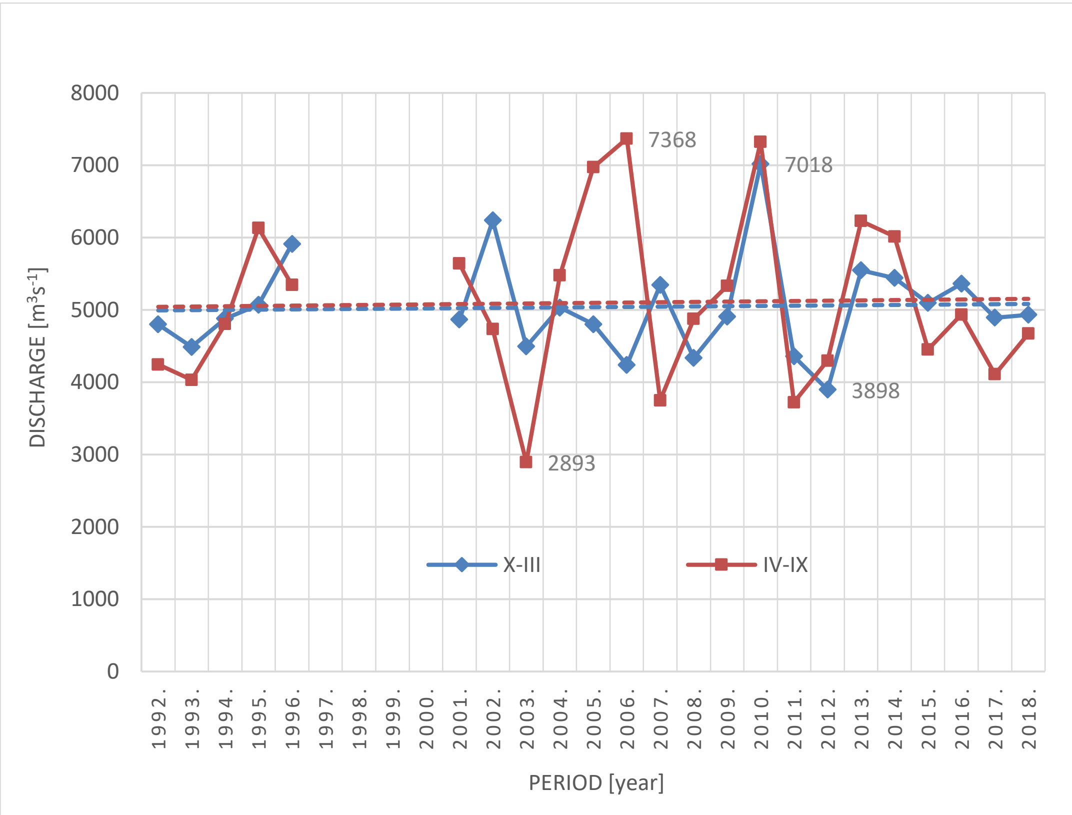

Fig. 12. Mean annual flows during warm (April–September) and cold (October–March) season for period 1992–2018 1992–2018 (regression station Smederevo).

Conclusion

The regime of the Danube along its entire course is variable, which is a consequence of natural and anthropogenic influences. Analysis of the flow regime of a watercourse, including the Danube, can be analyzed with regard to different parameters and time intervals. Given that the Danube is an international river with a large catchment area, consisting of a large number of countries, and a large number of different tributaries, it is advisable to analyze the flow regimes on certain sections with specific parameters of sections.

On the section of flow through Croatia and Serbia, the Danube River has two flow regimes (according to the Croatian classification of characteristic flow regimes): alpine rain-snow regime (regression stations Batina, Bezdan and Bogojevo) and combined-complex regime at regression station Smederevo. The change in the flow regime of the Danube is a consequence of the confluence of the Sava River with the Danube, which has a Pannonian rain-snow regime.

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