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ANNUAL FLOW DYNAMICS IN LARGE AND SMALL DRAINAGE BASINS IN NORTHERN BULGARIA DURING THE LAST TWO DECADES

Abstract: The study of the river runoff fluctuations under uncertain and changing climate, as well as human-influenced changes is an important task of hydrology in the context of new Scientific Decade 2013–2022 "Panta Rhei – Everything Flows" (of International Association of Hydrological Sciences) and of the integrated scientific framework "coupled human and natural system" (CHANS). The knowledge of runoff variations in the last decades is critical not just for developing the integrated management plan but and for the politics for improving human well-being also. This work documents the variations in annual runoff during the last two decades in the Danube catchment area in Bulgaria – one of the four water districts (Danube River Basin District) in the country, and for two local drainage basins – Voynishka River and Cherni Vit River. Both the integral difference curve and smoothing techniques (the 3-years weighted moving averages) were conducted. The volume of streamflow compares with three reference periods –1961–1990, 1971–2000 and 1946–1975. The results show that the fluctuations of hydrological variables of Danube catchment area are around the norm, but with larger amplitude compared to the reference periods. The annual runoff in 2005 is the absolute maximum within the Danube watershed from the beginning of hydrometric observations. The annual runoff for Voynishka River and Cherni Vit River during 2000–2016 decreases toward the reference periods. The time series of the annual flow of Danube catchment area is trendless. The results for runoff dynamics of the two small watersheds present annual flow exhibited a positive trend. The current work gives new information about hydrological processes in the Danube watershed in Bulgaria which is important for the aim of achieving the objectives of the Water Framework Directive throughout the international Danube river basin district and for coordination with others Danube countries.

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Danube catchment area, runoff fluctuation, annual flow duration analysis, integral difference curve, smoothing techniques

INTRODUCTION

The International Association of Hydrological Sciences (IAHS) assigned a new task for hydrological studies during the decade 2013–2022 through the framework "Panta Rhei – Everything Flows" – "to improve our capability to make predictions of water resources dynamics to support sustainable societal development in a changing environment" [1]. The concept corresponds to the aims for monitoring, planning, design, and adaptive management of water resources of River Basin Directorates in the European Union (EU) and especially for transboundary rivers and catchments area like Danube River basin. This new scientific framework looks to improve dynamic interactions between human and hydrologic systems, and how human use water. One step for studying of couple human and hydrological system is the analysis of runoff dynamics as "the basis for the integration of hydrological processes in the climate system and with human activity..." [2]. The runoff dynamics studies are important for the analysis of the water resources, for the understanding of the coevolution and self-organization of the hydrological cycle and social processes - a socio-hydrology task [3][4]. The time series analysis of annual runoff is important for building mathematical models and to forecast hydrologic events too. The mean annual runoff “depicts the amount of uncertainty or chaos (implicitly information content) of the catchment” also [5]. Therefore, the current work investigates fluctuations of the annual runoff for one of the regional water management authority of the Bulgarian Ministry of Environment and Water (in line with the provisions of the EU Water Framework Directive) – Danube River Basin District. The study includes analysis of annual streamflow for two local drainage basins as well. All previous studies in the country document dynamics of annual streamflow are till 2000 [6] [7] [8]. These works ascertain decrease of the annual streamflow till 2000 and a dry period during 1982–1994 for the Danube watershed, when the runoff decreases to 31% (the most decrease of the runoff in the country in this period). The hydrological studies after 2000 investigate models for flood simulations [9] [10] [11] [12] [13] [14] and for water budget [15], ARIMA model [16], furcating [17] and analysis of water resources statistical [18] [19] for isolated (single) river basins in the country. The main aim of this research is to estimate the annual runoff dynamics in the Danube River Basin District in Bulgaria during the last two decades. The study investigates the fluctuation of annual streamflow in comparison with the referent periods and temporal variability during 2000–2016. The paper analyzes the runoff dynamic of several river basins also and juxtaposes their fluctuation with the main watershed. The work is the second paper of the series studies, describing the key features of annual runoff in Bulgaria in XXI century [20].

STUDY AREA

The Danube catchment area in Bulgaria coincides with the Danube River Basin District in Bulgaria and covers an area of 47 235 km (42.5% of Bulgaria’s territory). The relief is flat (Danubian Plain and Sofia Valley), hilly (Predbalkan) and mountainous (Rila, Vitosha and Balkan Mountains) (Figure 1). The climate is temperate-continental – with warm to hot (and often humid) summers and cold winters, with average rainfall from 450 mm to 1200 mm. Mean annual precipitation for 1981–2015 is 27 877.10^{6}m^3, evapotranspiration is 22 404.10^{6}m^3 (National Institute of Meteorology and Hydrology, 2016). River network includes ten major sub-river basins. The investigated local drainage basins of the Voynishka River and the Cherni Vit River are small catchments according to their area – 276,0 km^2 and 185,0 km^2. The drainage basin of the Voynishka River is flat and part of the Rivers west from Ogosta River. The drainage basin of the Cherni Vit River is mountainous and part of the Vit River basin. The work uses two small-scale watersheds in the Danube catchment area – Voynishka River at Tarnyane (an area of 269,0 km^2 and an altitude of 260 m) and the Cherni Vit River at Cherni Vit (an area of 159,2 km^2 and an altitude of 1032 m).

F i g u r e 1 Danube River Basin District in Bulgaria [source: 21]

There are 256 water bodies in the Danube catchment area, as 189 (74% of all) are under anthropogenic pressure (River Basin Management Plan…, 2016). A large number of reservoirs have been built to facilitate agriculture, industry, power generation, etc. Land use is predominantly agricultural (Table 1). Annual water consumption varies between $2595{,}410^3$ m^3 (2014) and $3093{,}4.10^3$ m^3 (2011).

T a b l e 1 Land use in the Danube catchment area in Bulgaria

River basin	Area (km^2)	Land use (%)				
		Urban	Industry	Agriculture	Forest	Others
Nishava	722,89	4	1	29	62	4
Rivers west from Ogosta	3910,57	4	1	68	26	1
Ogosta	4282,29	5	1	64	29	1
Iskar	8607,12	5	2	46	45	2
Vit	3227,56	3	1	59	36	1
Osam	2838,01	5	1	64	30	< 1
Yantra	7861,90	5	1	53	40	1
Rusenski Lom	2985,35	5	1	67	26	1
Danube Dobrudja Rivers	8027,15	5	1	74	20	< 1
Danube River's lowlands	4330,85	5	2	74	12	7

Source: River Basin Management Plan for the Danube River Basin District (2016–2021)

DATA AND METHODS

The annual runoff (m^3 s^{-1}) was obtained from "Annual bulletin", published by NIMH. The publicly available hydrological data for 2000–2016 gives 17-year time-series records for the annual runoff. The annual streamflow calculates 34 gauging stations in the Danube catchment area. "Annual bulletin" gives the norm of streamflow for 1961–1990, 1971–2000, 1981–2010 and data for annual precipitation and annual evapotranspiration after 2012. "Annual bulletin" gives the norm of streamflow for 1961–1990, 1971–2000, 1981–2010 and data for annual precipitation and annual evapotranspiration after 2012. The data for Voynishka River covers the period 1946–2017, for Cherni Vit River – 1946–2009.

This work uses the method-of-moments to compute a mean and standard deviation, as well as the coefficient of skewness (*S*), the coefficient of kurtosis (*K*) and coefficient of variation (as standard deviation/mean) – *Cv*: 1961–1990, 1971–2000 and 1946–1975. The first two periods are recommended by NIMH. 1946–1975 as reference period is our suggestion.

Flow Duration Analysis was applied as well. FDC was computed by the following formula:

$$p = (m - 0.3)/(n - 0.4)$$

where p is the probability, m – the rank (1 to n, largest to smallest), n – the number of values, 0,4 – a constant.

The tool two-sample assuming unequal variances (two-tailed) applied to the hydrological time series for the periods 2000–2016 and 1946–1975.

The temporal year-to-year variability estimated by the following formula or so-called method of integral difference curves [22]:

$$\frac{\sum_{i=1}^{t}(Ki-1)}{Cv} = f(t)$$

where $Ki = \frac{Q_i}{\bar{Q}}$, Q_i – the discharge of the *t-th* year, $\bar{Q}$ – the average discharge for the time period T, C_v – coefficient of variation. The curve indicates the periods with high water ($\Sigma\ (K_i - 1)/C_v < 1$) and with low water ($\Sigma\ (K_i - 1)/C_v > 1$). To investigate the long-term variability or trends in series, smoothing techniques – the *3*-years weighted moving averages used. The runoff oscillations analyzed by the calendar year.

RESULTS

The mean annual streamflow of the Danube catchment area for 2000–2016 is 6324,1.10^6 m^3 – more with 9,4% and with 37,2% in comparison with 1961–1990 and 1971–2000 periods, respectively. This volume is below in comparison with the norm for 1946–1975 with 16,0 per cent (Table 2).

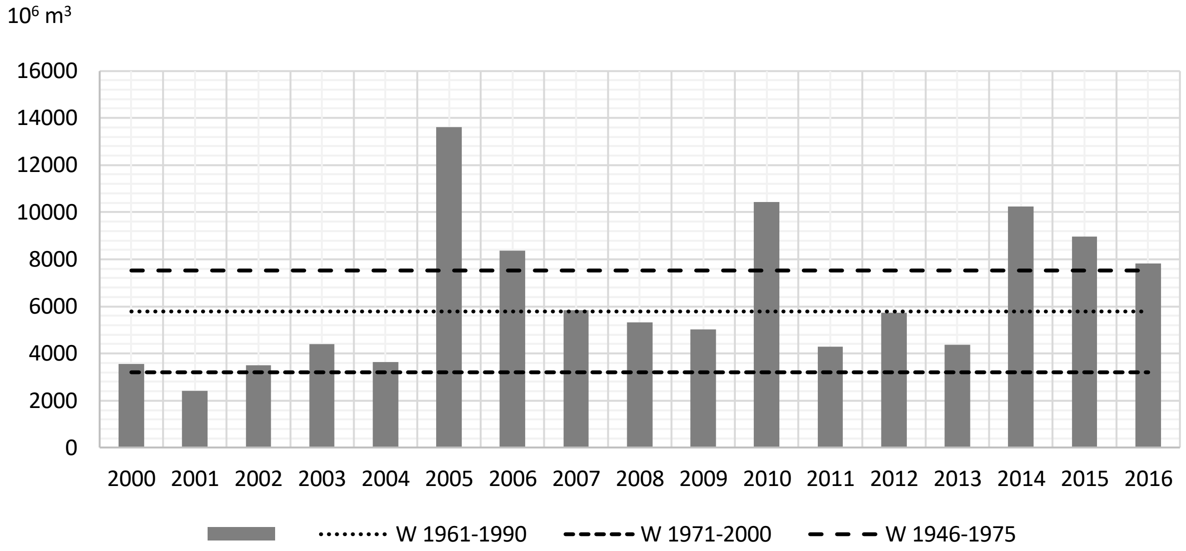
T a b l e 2 Statistics of annual streamflow

Watershed	Statistics	Period			
		1946–1975	1961–1990	1971–2000	2000–2016
Danube river basin	$\bar{Q}$, 10^6 m^3	7531,00	5783,90	4611,40	6324,10
	C_v	0,36	–	–	0,49
	S	0,12	–	–	0,96
	K	-0,88	–	–	0,25
Voynishka – Tarnyane	$\bar{Q}$, m^3 s^{-1}	0,93	0,87	0,71	0,69
	C_v	0,48	0,47	0,58	0,87
	S	0,43	0,53	0,71	0,87
	K	-1,07	-0,68	-0,08	-0,84
Cherni Vit – Cherni Vit	$\bar{Q}$, m^3 s^{-1}	3,22	3,13	2,92	2,88*
	C_v	0,27	0,21	0,27	0,47*
	S	0,21	-0,41	-0,35	2,34*
	K	-0,53	-1,00	-0,40	6,95*

*for 2000–2009

The comparison distribution of flow for the investigated period toward the norm of the three reference period reveals the following hydrological picture: large differences between very wet years toward the 1971-2000 period and toward norms of the rest two referential periods.

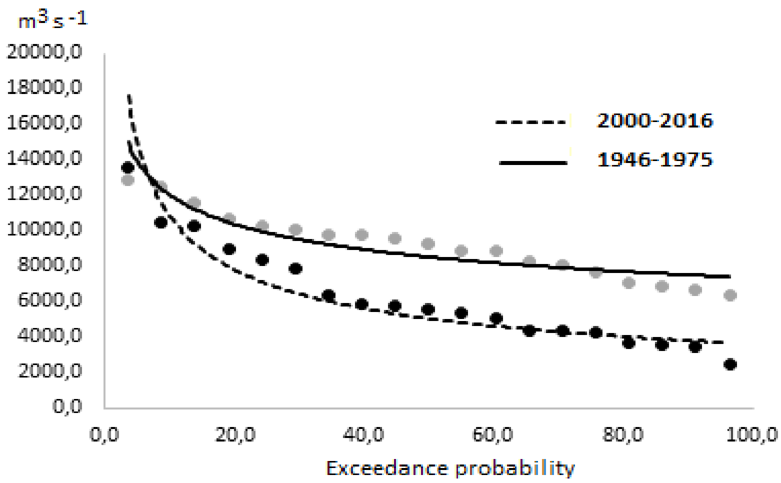
The largest difference between the annual streamflow mean for 2000–2016 and the norm of reference periods is with 1971–2000. All but one year are wet according to the norm. Only 2001 is dry (Figure 2). The reason for this difference is the meteorological and hydrological drought between 1984 and 2000 when measured the absolute minimum runoff for the catchment area – 1714,9.10^6 m^3 (1989) as well as another two extremely dry hydrological years – 1984/1985 with annual runoff 2064,2.10^6 m^3 and 1993/1994 with annual runoff 2109,7.10^6 m^3. Furthermore, the annual flow in 2005 is above the fixed maximum till 2000, measured in 1956 (10 582,8.10^6 m^3), or this is the absolute maximum for the Danube catchment area from the beginning of hydrometric observations in the country (since the middle of XX century). The volume of streamflow for the driest year (2001) during the investigated period – 2427,6.10^6 m^3 is above the runoff for absolute minimum till 2000 – 1714,9.10^6 m^3 (measured in 1990). All years after 2004 are wet according to the norm of the 1971–2000 period (Figure 2).



F i g u r e 2 Annual flow of the Danube catchment area during 2000–2016 in comparison with the norm of three reference periods

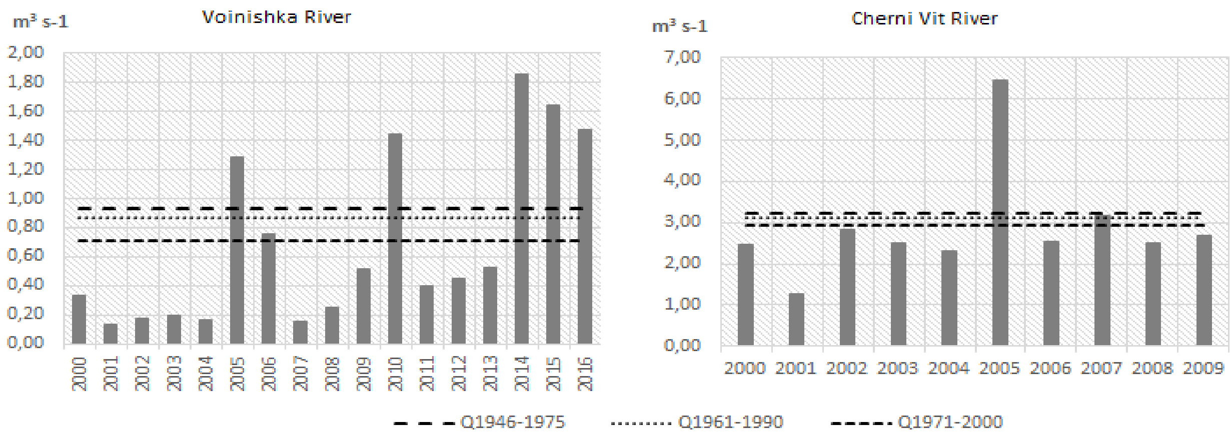
Quite different is the result when the annual streamflow of the Danube catchment area for 2000–2016 is compared with the 1946–1975 period. There is no difference between mean annual streamflow for the investigated period and the norm for 1946–2000 – t_{stat} is 1.490, i.e. greater than 0.05. The wet years in 2000–2016 according to the reference period 1946–1975 are 2005, 2006, 2010, 2014 and 2015. The annual streamflow for the rest of the years is less than the norm (Figure 2). Around the norm is only the annual streamflow in 2016. Since the t_{stat} is 1.490, i.e. greater than 0.05, it can be concluded that there is no difference between the means of the annual streamflow for the two hydrological time series – 2000–2016 and 1946–1975. The similar hydrological picture is obtained when the annual flow in 2000–2016 compared to the the reference period 1961–1990. The wet years are 2005, 2006, 2010, 2014, and 2015 (Figure 2). A difference is found in the years with streamflow volume near the norm. Very close to the norm for 1961–1990 are 2007 and 2012. This result is the closest to the distribution of annual flow of Danube catchment area around the norm for 1946–1975. When the wet years counted by flow duration curve, there are four wet years during 2000–2016 – 2005, 2010, 2014 and 2015 (The annual volume of the streamflow in 25% probability in Danube watershed, according to the theoretical flow-duration curve, is $8515,1.10^6$ m^3 and for 75% probability – $4344,010^6$ m^3). The dry years are 2001, 2002, 2000, 2004. It means that the reference period 1971–2000 is not representative. This our assertion stands in need of confirm. The variation coefficient (C_v) of annual runoff time series area is 0,46 for the investigated period. (Table 2). The temporal variability of streamflow is larger than 1946–1975 when C_v is 0,36 (Table 2). The larger fluctuation is in consequence of the very wet and the very dry hydrological years during 2000–2016. The same coefficient for 1946–1975 is 0,36 (Table 2). So, the result for annual flow of Danube catchment area for 2000–2016 doesn't show great difference with two reference periods. Explanation of this fact gives the result obtained by Popova, et al. [23]: there is not any statistically significant evidence for increasing or decreasing of temperature and rainfall in North Bulgaria during the period 1951–2004.

The next step is Flow Duration Analysis and the comparison of two flow duration curve – for 1946–1975 and for 2000–2016. The general shape of the flow duration curves does not vary significantly between the 17-year period of record and the 30-year period of record. The two graphs are with flat slope and mark a large natural (by large groundwater inflow) or artificial (by dams and reservoirs) flow regulation. In the same time the graphs present difference around small exceedance probability. The flow duration curve for 2000–2016 has steep slope at the upper end. The cause for this configuration is pouring rain-caused floods during 2005 and 2014 (Figure 3).



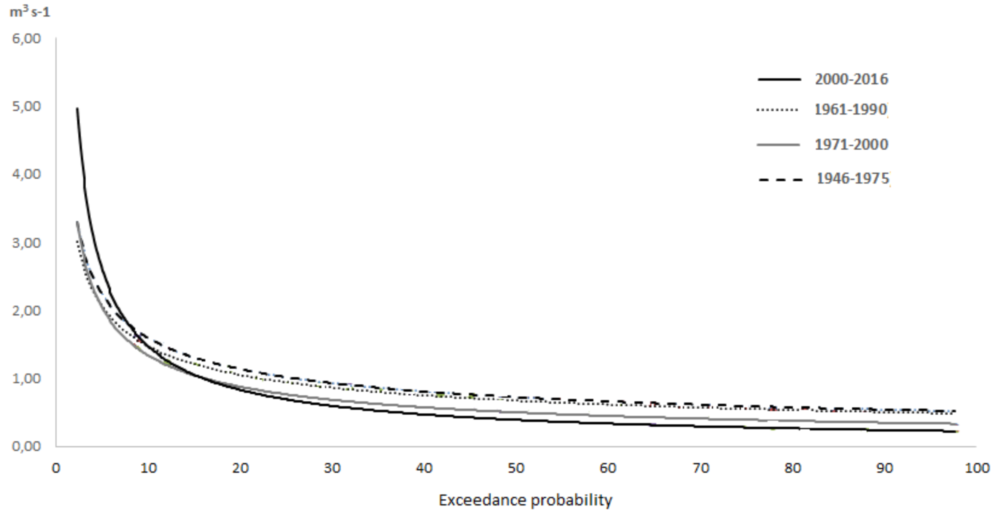
F i g u r e 3 Flow duration curves of the Danube watershed in Bulgaria

The results for annual flow and its dynamics of the two small-scale drainage basins (of Voynishka River and Cherni Vit River) differ from Danube catchment area (Figure 4). First, the mean annual flow for the three referential periods is very close (Table 2). Second, the runoff decrease fluctuates more than major catchment area: the Voynishka River annual runoff during 2000–2016 decreases between 2,81% and 31,5%, and for Cherni Vit River between 3,0% and 10,5% towards the referential periods (Table 2). An explanation of this result is that runoff oscillation of the large catchment area eliminates the local influence of effects of precipitation and temperature due to local orographic peculiarities. The small catchment areas are more sensitive and more vulnerable to the influence of effects of precipitation and temperature, as well as to the anthropogenic activities. The hydrograph of the Voynishka River toward the norm of the referential period shows several successions of years below the thresholds (Figure 4). The annual flow of the Cherni Vit River is closer to the norms. Very large difference between the two basins are found in 2002, 2007, 2008. The two hydrographs distinguish each other in 2002, 2007, 2008 (Figure 4). The geographical position and their size of the catchment area are the main reasons behind the different response of the two watersheds of climate variability.



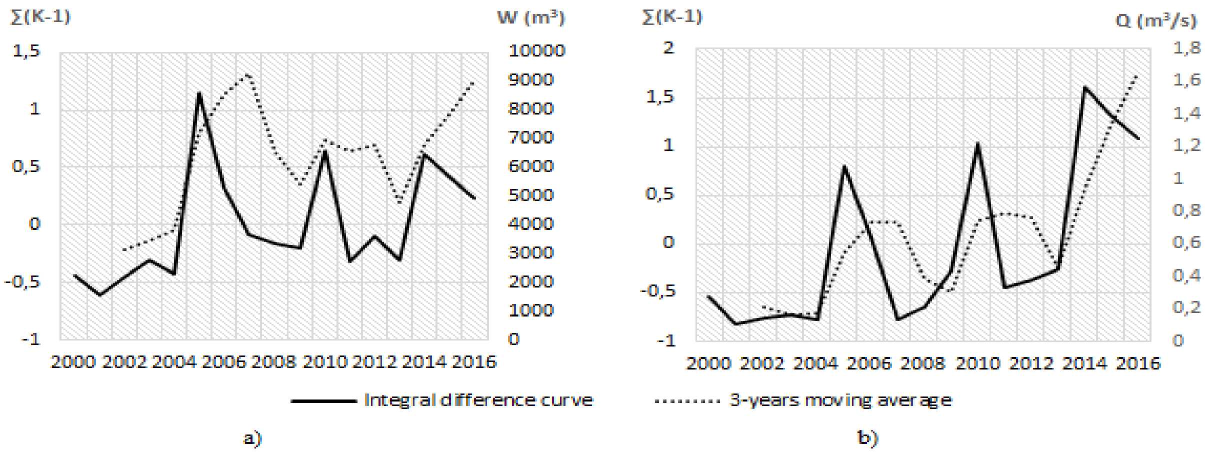
F i g u r e 4 Hydrographs for 2000–2016 in comparison with the norm of three reference periods for Voynishka River and Cherni Vit River

The Flow Duration Analysis of the Voynishka River proves the trend of decreasing of annual volumes. The streamflow decreases for all exceedance probabilities with the exception of maximum flow (Figure 5). There are not any changes in the catchment area as area of the agricultural fields and the crop type, as well as the water consumption. So, the streamflow decrease has to be searched in climate change. The results by Flow Duration Analysis of the Cherni Vit River are similar.



F i g u r e 5 Flow duration curves of the Voynishka River

The chronological annual runoff time-series of the Danube catchment area show alternation of series of dry and wet years without a definite order (Figure 2). An exception is the 2000-2004 period – a continuation of the dry period which has started during the 80–90s of the last century. The result is confirmed by the integral difference curve and by the *3*-years weighted moving averages (Figure 6a). The graphs are evident for free-trends in series of hydrological variables of the Danube watershed. They confirm our previous result which was obtained by other methods [20]. The graphs of the Voynishka River for flow dynamics in 2000-2016 show a slight tendency for increasing (Figure 6ba).



F i g u r e 6 Integral difference curve and *3*-years weighted moving averages:
a) Danube catchment area; b) Voynishka River drainage basin

CONCLUSION

The result of the current study doesn't find large changes in the annual water volume of Danube catchment area in Bulgaria for 2000–2016. The reduction of river flow compared to 1961–1990 and 1946–1975, as well as the increase compared to 1971–2000, are not statistically significant. The small-scale drainage basins of Voynishka River and Cherni Vit River reveal decrease of the annual streamflow for the referential periods. The 2000–2016 annual runoff decline is mainly attributed to precipitation decrease. The time series of the annual flow of Danube catchment area is trendless according to the results of the integral difference curve and the moving average test. The results for runoff dynamics of the two small watersheds presented the following: annual flow exhibited a positive trend; the annual flow is more sensitive to intra-annual climate variation.

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